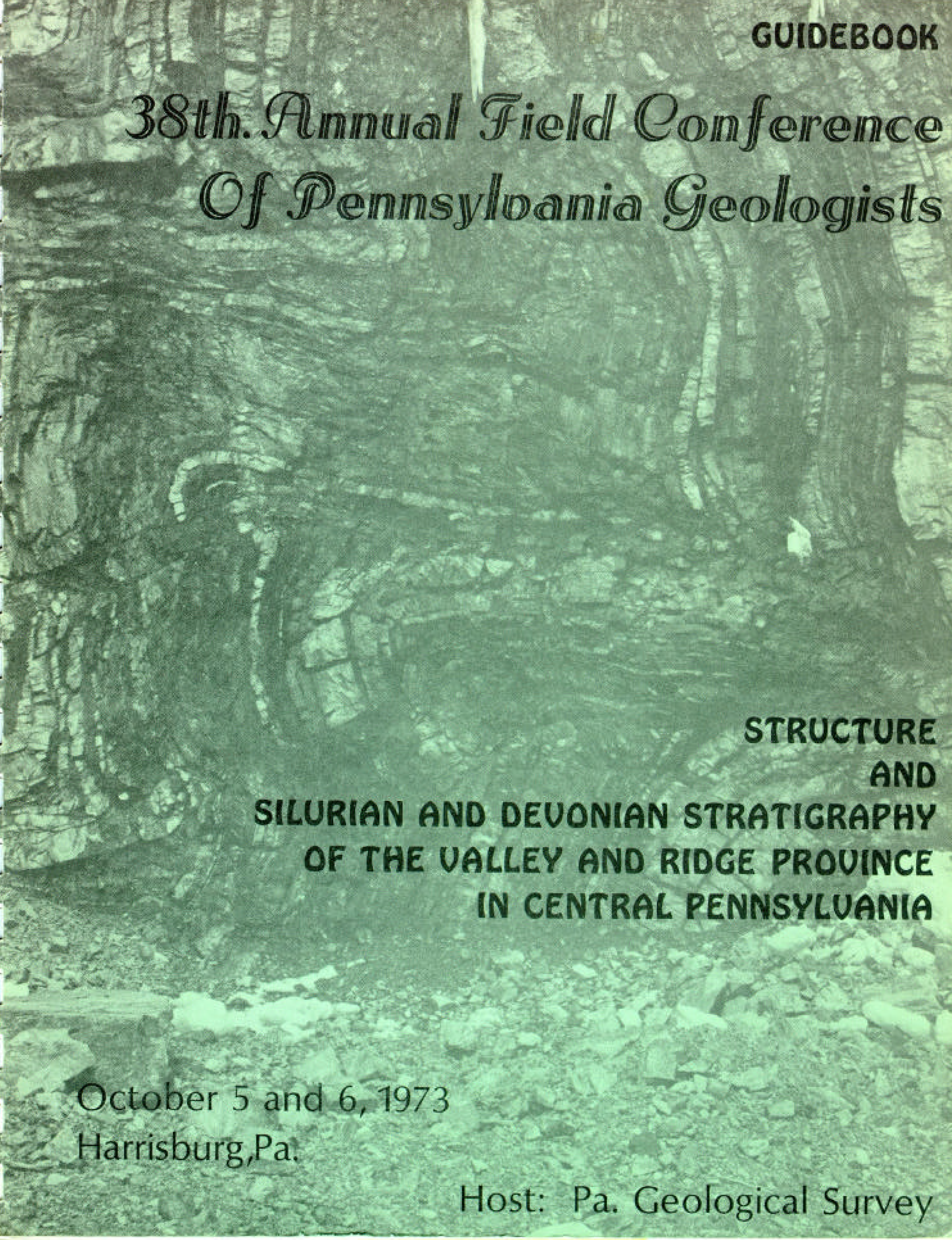

GUIDEBOOK

38th. Annual Field Conference Of Pennsylvania Geologists

STRUCTURE AND SILURIAN AND DEVONIAN STRATIGRAPHY OF THE VALLEY AND RIDGE PROVINCE IN CENTRAL PENNSYLVANIA

October 5 and 6, 1973
Harrisburg, Pa.

Host: Pa. Geological Survey

Guidebook for the 38th Annual Field Conference of Pennsylvania Geologists

October 5-6, 1973

STRUCTURE AND SILURIAN-DEVONIAN STRATIGRAPHY OF THE VALLEY AND RIDGE PROVINCE, CENTRAL PENNSYLVANIA

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INTRODUCTION

The long-studied Valley and Ridge province of the Appalachian Mountain System has been considered a classic area of relatively simple geologic structures and rather complete and undeformed Paleozoic stratigraphic section. Yet recent remapping of these rocks in central Pennsylvania has resulted in revisions of the structural geology, and has revealed new complexities in the stratigraphy and sedimentology. This 38th Annual Field Conference of Pennsylvania Geologists will demonstrate some of these new concepts at eleven of the better exposures in the Juniata and Susquehanna River valleys (Fig. 1).

Structurally, the simple view of open, concentric folds is replaced by kink band folding, a concept which not only explains the "angular" profiles of the folds, but also their complex three dimensional changes and terminations throughout the province (Fig. 2). But folding is only one part of the deformation -- cleavage, fossil distortion and solution effects point to an earlier penetrative and ductile deformation phase that has heretofore not been suspected in these rocks.

Stratigraphically, the Conference Stops present many of the Silurian and Devonian formations which represent a wide variety of depositional environments. Included are the deep water turbidite basins (Reedsville, Trimmers Rock formations), the shallow marine neritic, epineritic and intertidal shelfs (Middle and Upper Silurian rocks, plus the deltaic Mahantango Formation) and the non-marine fluvial environment of the Upper Devonian Catskill.

The influence of geology on the works of man are described in two accompanying engineering geology papers. In addition, an article relates the destructive effects of Agnes, the tropical storm that produced the 1972 record-breaking flood in this region.

Rodger T. Faill
Guidebook Editor 1973

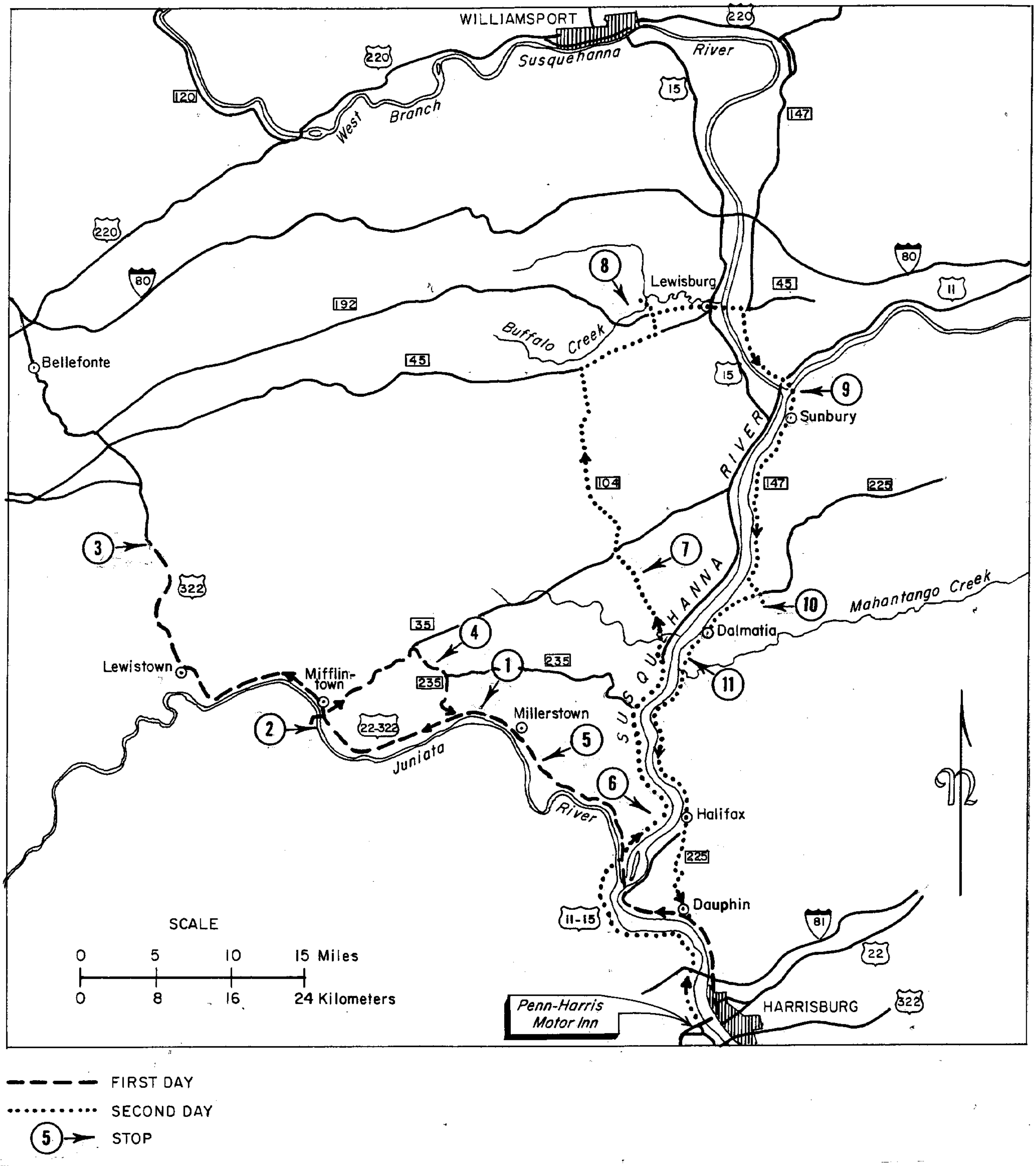

Figure 1 - Road map showing field trip routes and STOP locations.

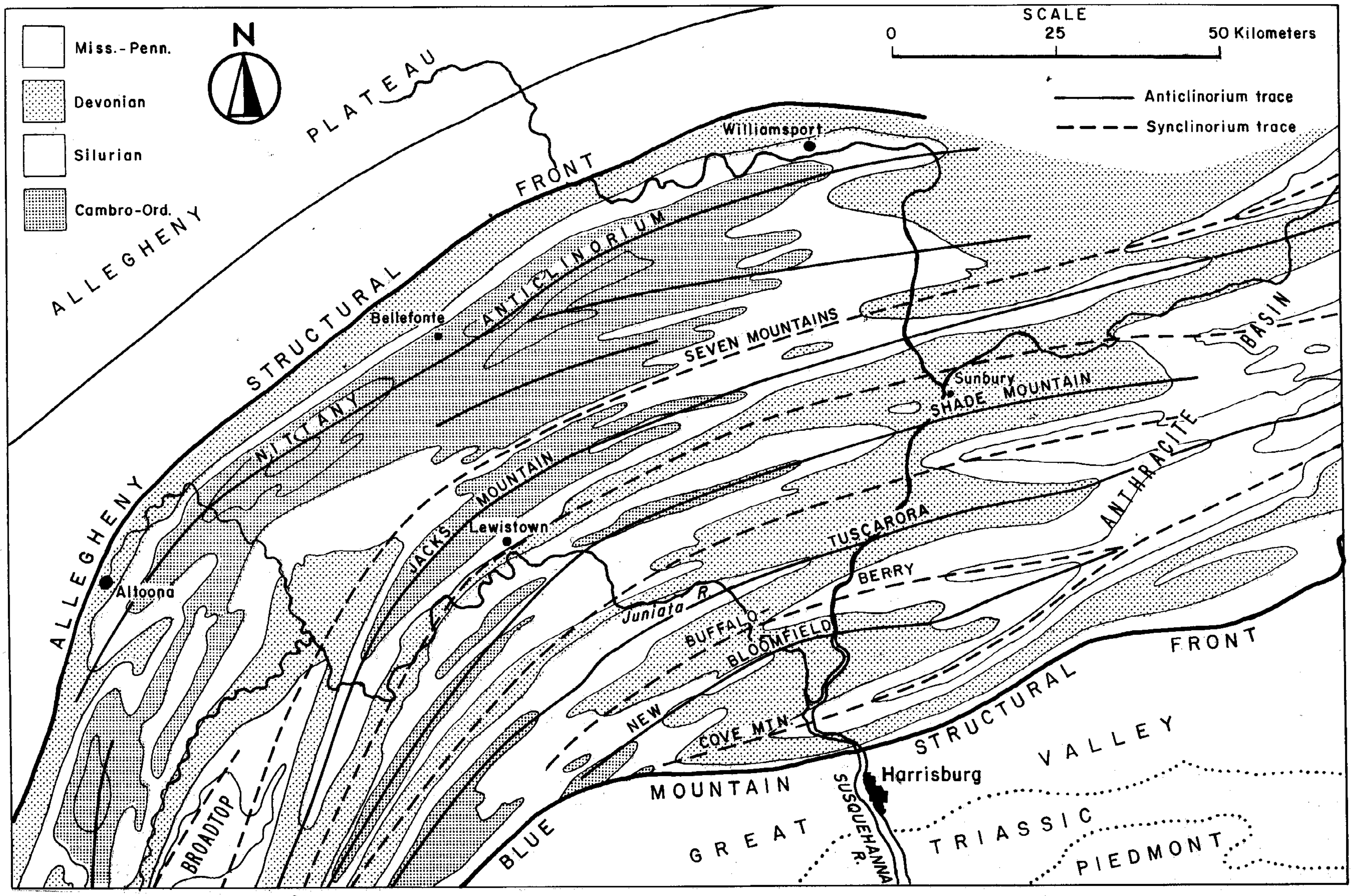

Figure 2 - Generalized geologic map of the Valley and Ridge province in central Pennsylvania, delineating the major stratigraphic units and fold structures.

STRATIGRAPHY

by Richard B. Wells and Rodger T. Faill

Stratigraphic units examined on this Field Conference include rocks from the Upper Ordovician Reedsville Formation to the Upper Devonian Catskill Formation. General lithic descriptions of all the intervening formations are presented in Table 1, and are supplemented by discussions at the various stops. Additional detail is available in the several recently published geologic maps and reports within the Field Conference area (Miller, 1961; Conlin and Hoskins, 1962; Dyson, 1962, 1967; Faill and Wells, 1973 (in press); Hoskins, in preparation).

The rocks of the Valley and Ridge province consist of a nearly continuous sequence from the Cambrian to the Pennsylvanian. This sequence contains two major clastic intervals, the Cambrian-Silurian Taconic cycle and the Devonian-Pennsylvanian Appalachian cycle (Potter and Pettijohn, 1963, p. 231). Each cycle is a systematic sequence of 1) pre-orogenic carbonates and orthoquartzite, overlain by 2) turbidite flysch deposits and 3) a subsequent molasse. The shallow marine shelf environment with open circulation, normal salinity and a rich marine fauna at the start of the cycle is succeeded by deeper, bathyal or abyssal conditions wherein most of the sediment is transported and deposited by turbidity currents. The shift to a non-marine environment of fluvial deposits constitutes the completion of the cycle. The upper parts of the Taconic cycle and most of the Appalachian cycle will be seen in this Field Conference.

The Cambrian and Lower and Middle Ordovician carbonates comprise the first phase of the Taconic cycle. The Upper Ordovician Reedsville represents the flysch phase and will be seen only in passing. The third phase (molasse) consists of the Bald Eagle, Juniata and Tuscarora formations, the upper portion of which is completely exposed at Stop III. The overlying Rose Hill, Keefer, Mifflintown (Stop I) and Bloomsburg (Stop VIII) formations reflect the waning of the molasse phase with a reintroduction of marine conditions to the Appalachian basin. The Bloomsburg delta apparently reflects a minor renewal of tectonic activity after the main Taconic tectonism.

The carbonates of the Upper Silurian and Lower Devonian Wills Creek to Onondaga (Stops II, IV, X) can be considered the first phase of the Appalachian cycle. This first carbonate phase did not proceed directly into turbidite deposition -- rather, as the basin deepened regionally in Middle Devonian time, a local sub-aqueous delta was formed in central Pennsylvania, represented by the Mahantango Formation (Stops VII and XI). This delta was followed by the widespread turbidite beds of the Upper Devonian Trimmers Rock Formation (Stop VI) which constitute the second phase of the Appalachian cycle. The third, molasse phase is complex, beginning with the Upper Devonian Catskill Formation (Stop V and VI) and culminating twice, first in the Mississippian Pocono Formation and then again in the Pennsylvanian rocks after an interruption by the Mississippian Mauch Chunk rocks.

Table 1. Sequence, thickness, and general description of the geologic column in central Pennsylvania. Number in parenthesis after unit name is the number of the Field Trip Stop where these units will be examined.

System	Series	Formation	Members	General description
Mississippian	Middle	Mauch Chunk 5000'		Grayish red and gray argillaceous siltstone and silty shale; gray medium and coarse grained, cross-bedded conglomeratic sandstone and light gray quartz pebble comglomerate in lower part.
Mississippian	Lower	Pocono 1600'	Mount Carbon 940'	Gray to buff, medium grained, medium to very thick bedded, cross-bedded sandstone with beds and lenses of white quartz pebble conglomerate in lower part.
Mississippian	Lower	Pocono 1600'	Beckville 225'	Gray to buff, medium grained, medium to very thick bedded, cross-bedded sandstone with beds and lenses of white quartz pebble conglomerate in lower part and rare thin coal seams.
Devonian	Upper	Pocono 1600'	Spechty Kopf 435'	Gray, fine and medium grained sandstone and dark gray argillaceous siltstone; prominent conglomerate beds near the middle and at the base.
Devonian	Upper	Catskill 7250'	Duncannon 2000' (5)	Asymmetric, upward-fining fluvial cycles in which a basal nonred, fine to medium grained, locally conglomeratic sandstone is overlain by very fine-grained, grayish red sandstone, grayish red siltstones and red silty claystone. Cycles have concave erosional bases.
Devonian	Upper	Catskill 7250'	Sherman Creek 2400'	Interbedded grayish red silty claystone, siltstone and very fine grained, cross-bedded sandstone.

System and Series		Formation and members		General Description
Devonian	Upper	Catskill	Irish Valley 2850' (6)	Interbedded, grayish red and light olive gray sandstone, siltstone, and shale, overlain by upward-fining cyclic deposits of gray sandstone and grayish red siltstone and silty claystone.
Devonian	Upper	Trimmers Rock 2000' (6)		Light olive gray and medium gray siltstone and silty shale, with interbedded very fine-grained sandstone in upper part. Graded bedding common in siltstone and sandstone beds.
Devonian	Upper	Harrell 200'		Dark to light olive gray and medium light gray silty shale, noncalcareous, nonfossiliferous, splintery fracture.
Devonian	Middle	Mahantango 1600'	Sherman Ridge 600' (7)	Light olive gray, fossiliferous, silty claystone with two interbedded siltstone/very fine sandstone units which have gradational bases, sharp tops, and coarsen upward.
Devonian	Middle	Mahantango 1600'	Montebello 900' (11)	Light olive gray, medium light gray to dusky yellow, very fine to medium grained, locally conglomeratic, siliceous, fossiliferous sandstone, interbedded with gray siliceous siltstone and silty claystone in upward-coarsening cycles.
Devonian	Middle	Mahantango 1600'	Fisher Ridge 700' (11)	Interbedded (laminated) olive gray and medium gray shale, siltstone, and very fine-grained sandstone. Unit is predominantly laminated silty shale.
Devonian	Middle	Mahantango 1600'	Dalmatia 300' (11)	Light olive gray, very fine to coarse grained sandstone.

System and Series		Formation and members		General Description
Devonian	Middle	Mahantango	Turkey Ridge 100' (11)	Light gray to olive gray, very fine to medium grained, medium and thick bedded, planar bedded, subgraywacke sandstone, which typically develops a spheroidal or ellipsoidal exfoliation.
Devonian	Middle	Marcellus 106'		Highly fissile, dark gray to black, carbonaceous, noncalcareous shale, commonly has dark yellowish orange limonite staining on fracture surfaces.
Devonian	Middle	Onondaga 165'	Selinsgrove 80'	Medium to dark gray, dense, fossiliferous argillaceous, locally carbonaceous, microcrystalline limestone.
Devonian	Lower		Needmore 85'	Lower part is medium gray, highly fissile shale, calcareous toward the top.
Devonian	Lower	Old Port 100'		Dark gray, whitish weathering chert, underlain by calcareous shale and thin graylimestone beds, and locally overlain by gray to buff, medium to coarse grained fossiliferous sandstone.
Devonian / Silurian	Lower / Upper	Keyser 200' (4, 10)		Medium gray, fossiliferous, lumpy or "pseudo-nodular" limestone.
Silurian	Upper	Tonoloway 600' (4, 10)		Medium gray, laminated to thin-bedded limestone with some thin beds of medium gray calcareous shale.
Silurian	Upper	Wills Creek 700' (2)		Predominantly gray or variegated calcareous shale with interbedded light gray, calcareous, fine-grained sand-stone, medium gray limestone and grayish red silty claystone.

System and Series		Formation and Members	General Description
Silurian	Middle	Bloomsburg 500' (1, 8)	Grayish red claystone and shale; locally fossiliferous; grayish red very fine to fine grained, silty, argillaceous, hematitic sandstones at base and near top; contains a few thin, light gray, fine to medium grained sandstones in upper part.
		Mifflintown 160' (1)	Dark gray, silty, calcareous shale; medium to dark gray, bioclastic and micritic to microcrystalline, medium to thin bedded, planar bedded limestone.
		Keefer 40' (1)	Light to dark gray, very fine to coarse grained, fossiliferous, siliceous, very thin to thick bedded, cross-bedded sandstone which is locally hematitic, locally conglomeratic.
		Rose Hill 950' (1, 3)	Light gray and light olive gray, slightly silty shale, calcareous in upper part; contains two units of grayish red to reddish black, very fine to coarse grained, siliceous, thin to medium bedded, hematitic sandstones and siltstone.
	Lower	Tuscarora 600' (3)	Light gray to white, fine to medium grained, medium bedded orthoquartzite, interbedded in the upper portions with medium gray and olive gray silty shale.
Ordovician	Upper	Juniata 750' (3)	Upper part is grayish red, very fine to medium grained, cross bedded, graywacke sandstone; lower part is grayish red siltstone and silty claystone.
		Bald Eagle 730'	Gray, medium to thick bedded, cross bedded, medium to coarse grained sandstone and quartz pebble conglomerate.
		Reedsville 900'	Light to medium olive gray siltstone and silty shale, with increasing interbeds of gray sandstone in upper part.

STRUCTURAL GEOLOGY

Rodger T. Faill and Richard P. Nickelsen

Folds and Faults

Introduction

The Valley and Ridge province of Pennsylvania, lying between nappes of the Great Valley province to the southeast and the low amplitude folds of the Plateau province to the northwest, has for decades been thought to contain fold structures of classic simplicity--open, parallel (concentric) folds complicated only by smaller folds and faults in the limbs of the major folds. The deformation was seen as bending of beds with slip between beds--minor cleavage and small scale folding comprised the only penetrative deformation. In this view the deformation was a moderately brittle, flexural-slip folding, without major faulting and with insignificant amounts of flow.

During the last decade, however, four major aspects of the Pennsylvania Valley and Ridge deformation have been recognized which invalidate this classic view.

1. Unpublished geophysical studies by oil companies (Gwinn, 1964) and surface studies (Arndt and others, 1959; Pierce and Armstrong, 1966; Wood and others, 1969; and Gwinn, 1970) have demonstrated the existence of major decollements beneath and within the folded rocks of the Valley and Ridge province.

2. The folding in several areas is now recognized to be disharmonic with stratigraphically delimited fold trains of different wavelength and amplitude (Nickelsen, 1963; Epstein, 1967).

3. It has been recognized that folds are not concentric but rather possess nearly planar limbs and narrow hinges, having the geometry of kink band (chevron) folds (Faill, 1967, 1969).

4. Penetrative deformation and/or solution loss representing strain or volume loss of up to 25% (?) in a northwest-southeast direction in some stratigraphic units has been widely documented. (Nickelsen, 1966, 1972; Groshong, 1971; Faill, in progress).

The field stops and this summary discussion will be largely concerned with demonstrating the newly discovered aspects of kink fold geometry and penetrative deformation.

Folds

It has been recognized for some time that the folds do not exhibit a parallel (concentric) form, but instead possess nearly planar limbs (Fig. 3; Arndt and others, 1959; Nickelsen, 1963). More recently Faill (1969) has demonstrated that the fold hinges are usually narrow with respect to the fold wavelength. These folds bear some resemblance to similar folds. Yet, the sinusoidal form, and the attenuation of limbs and thickening of hinges that are usually associated with similar folds are not seen. Therefore, the fold geometry is neither parallel (concentric) nor similar, nor is it of an intermediate type, for these folds possess features not common to either parallel or similar folds--namely, planar bedding in the fold limbs, and the narrow hinges.

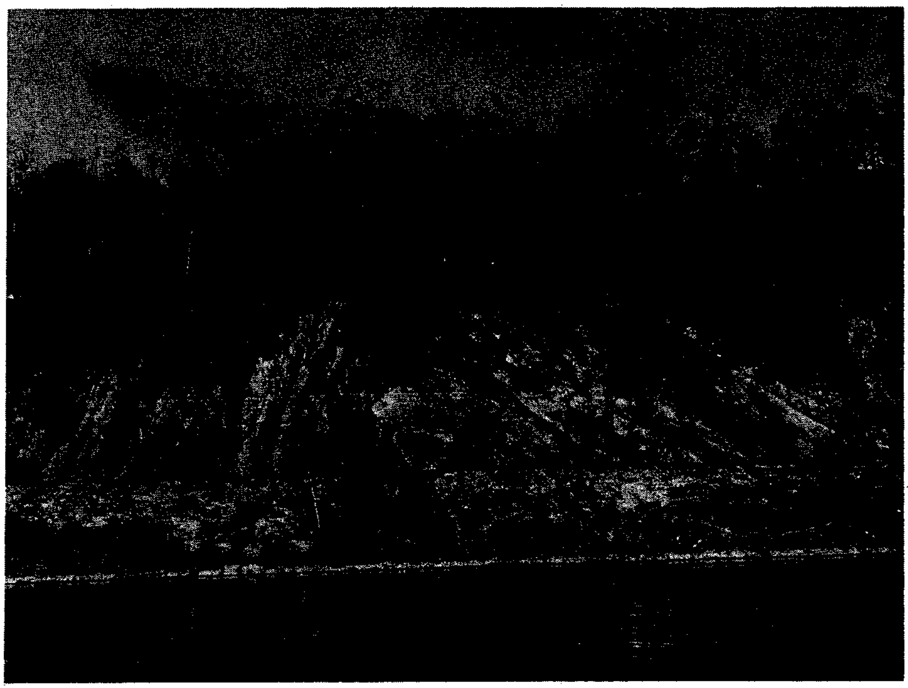

Figure 3 - Cross-section geometry characteristic of Valley and Ridge folds. Bedding in the limbs is planar, and the fold hinge is narrow relative to the fold wave length. Wills Creek Formation, along Penn-Central Railroad, 1/4 mile south of Mifflin, Pa. (STOP 11).

Although best seen in single outcrops this fold geometry is not confined to small folds. Folds at all scales in the province, from the smallest to the largest, exhibit planar bedding in the limbs and narrow hinges. The exceptions to this geometry are folds in which the bed thickness is 1/4 or more the wavelength of the fold, or where there has been a large contrast in ductilities. The cross-sectional geometry of the first-order folds* cannot be seen directly, but can be deduced from their map patterns.

*The wide range in size of folds in the Valley and Ridge province has led Nickelsen (1963) to divide folds into five orders: first-order folds include the largest in the province, those ranging in wavelength from 6 to 11 miles; the fifth-order folds include those of microscopic to hand specimen size; second-, third-, and fourth-order folds are of intermediate size.

A characteristic example is the Cove syncline, the southeastern-most first-order syncline in the Valley and Ridge province (Fig. 2 and 4). In this fold, as with most other folds in the province, the

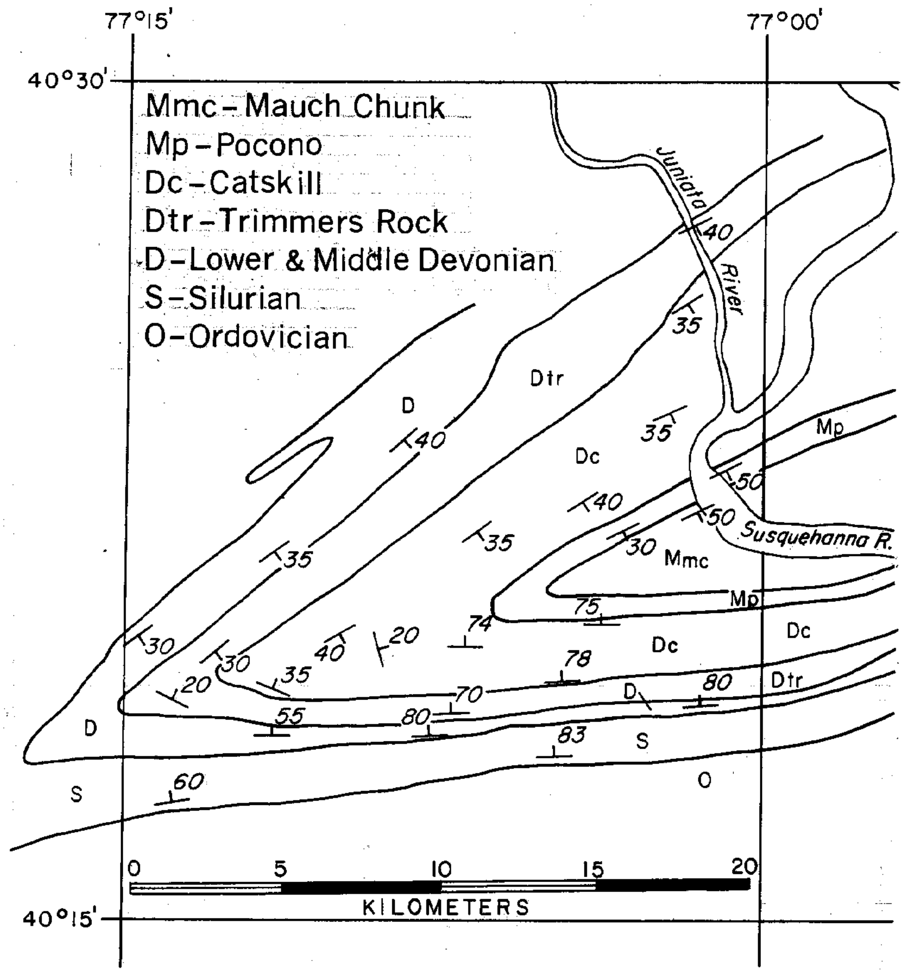

Figure 4 - Geologic map of the Cove syncline, the southernmost synclinorium in the province. The relatively straight formation contacts in the fold limbs, and the sharp trend change at the fold hinge indicate that this first-order fold possess the narrow hinge and planar bedding in the limbs that is characteristic of smaller folds. Map simplified from Dyson (1963, 1967).

formational contacts in the fold limbs are relatively straight. The large change in direction, representing the passage from one limb to another, occurs within a fairly narrow zone, the fold hinge. Looking down the plunge of the fold, one can visualize the cross-sectional geometry of planar limbs and narrow hinges. If this were a concentric fold, the formational contacts would curve gradually from one limb to another across a broad zone, and not be angular as in Figure 4.

Although these folds are not parallel (concentric), the deformational process by which they developed is identical to that by which concentric folds develop. The presence of slickensides on bedding surfaces, the associated wedge faults, and the absence of gross thickness changes by flow within the layers indicates that the folding process was flexural slip.

Kink Bands and Folds

Kink bands are parallel-sided zones transecting bedding, within which the bedding is rotated relative to the enveloping bedding outside the zone (Fig. 5). Although kink bands have usually been described as

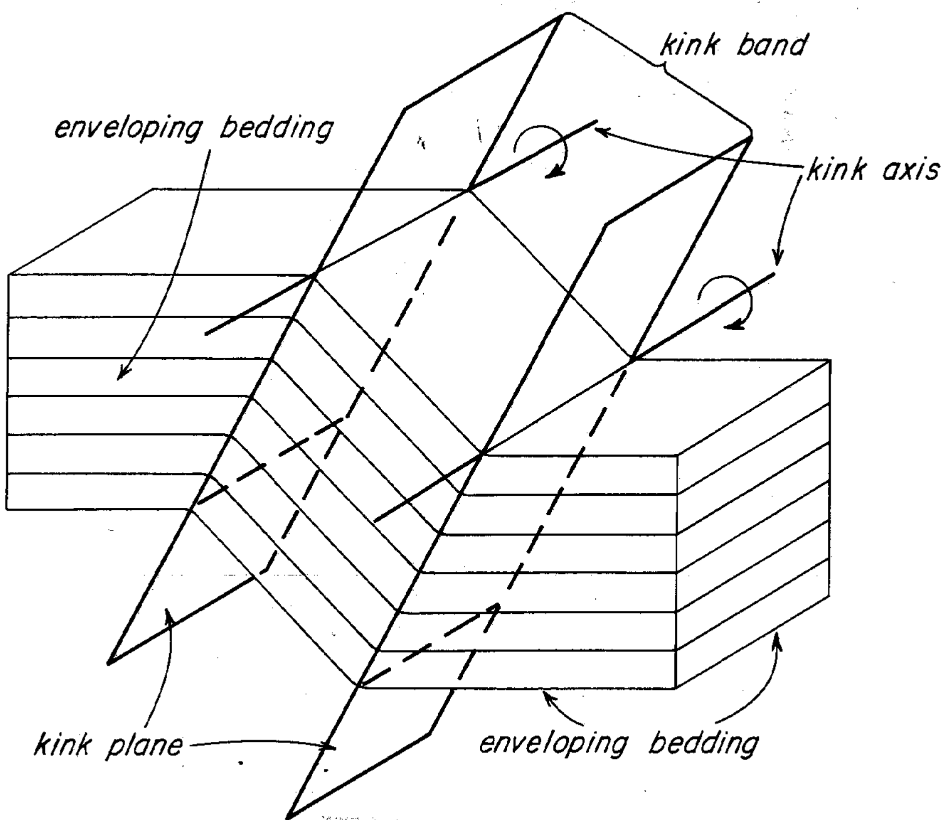

Figure 5 - Idealized kink band, within which bedding has been rotated relative to bedding outside the kink band (the enveloping bedding). Generally parallel-sided, the boundaries of the kink band are the kink planes, within which all of the bending of the layers occurs. The axis around which bedding appears to have been rotated is the kink axis, which lies in the intersection of bedding within the kink band and the enveloping bedding.

small structures in slates, phyllites and other well-foliated rocks, much larger kink bands occur within the bedded rocks of the Valley and Ridge province (Fig. 6; see also Faill, 1973, Fig. 4; 1974). Their large size (which can range up to hundreds of meters) is probably a result of the large spacing between the bedding surfaces. They develop by progressive rotation of beds within the kink band (Fig. 7)--the profusion of slickensides on bedding surfaces both within the kink bands and in the enveloping bedding indicates that the mechanism was slip on bedding surfaces. In these kink bands, the beds continue across the kink band without interruption, deformed only by bending at the kink planes. As a consequence,

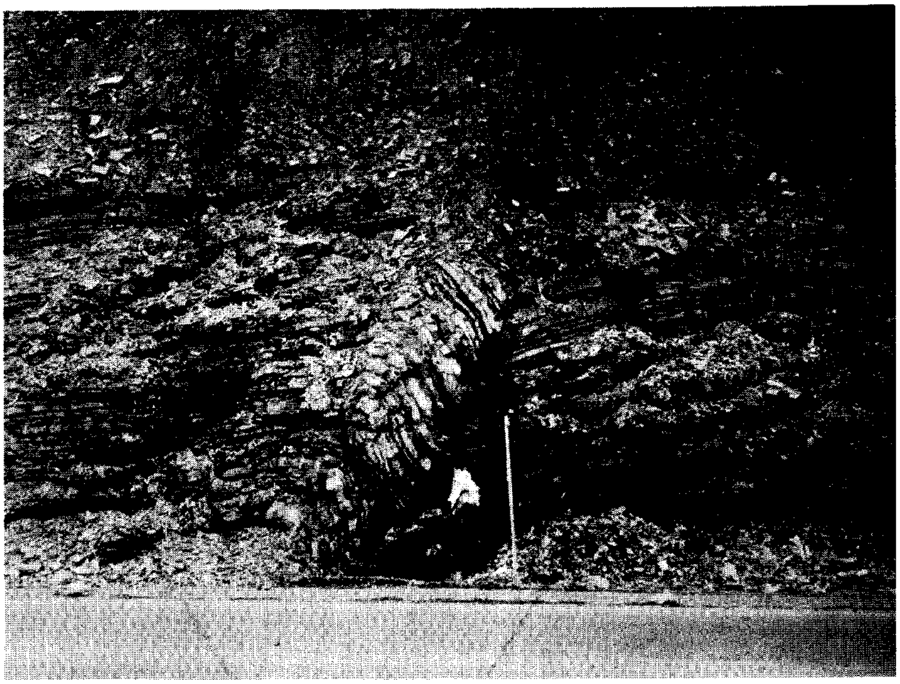

Figure 6 - Large kink band in the Rose Hill Formation, along Pa. Route 103, 2 miles southwest of Lewistown, Pa.

the thickness of the layers does not change appreciably across the structures. These aspects indicate that the mechanism of kink band deformation is identical with that of the angular flexural-slip folds.

Yet, a single kink band does not possess the observed fold geometry. However, two intersecting kink bands, which are inclined to each other, and which possess opposite senses of rotation, do produce an angular fold resembling those in the Valley and Ridge province (Fig. 8, 9). Each kink band constitutes one limb of the fold, and the junction between the two kink bands is the fold hinge, within which lies the axial surface of the fold. Bedding maintains a constant attitude throughout each limb because bedding within a kink band possesses a constant attitude. The bending of the beds occurs only at the junction of the two kink bands and thus the fold hinge is narrow with respect to the fold wavelength.

Where the two kink bands are joined, a simple two limbed fold results; where the same two kink bands are separated, a conjugate fold results (Fig. 8). In contrast to the single hinge of the simple fold, the conjugate fold has two hinges, between which is the interlimb, a zone of unrotated beds. Although the simple and the conjugate folds appear quite different, they are merely two different parts (structural levels) of the same kink band structure (Fig. 8).

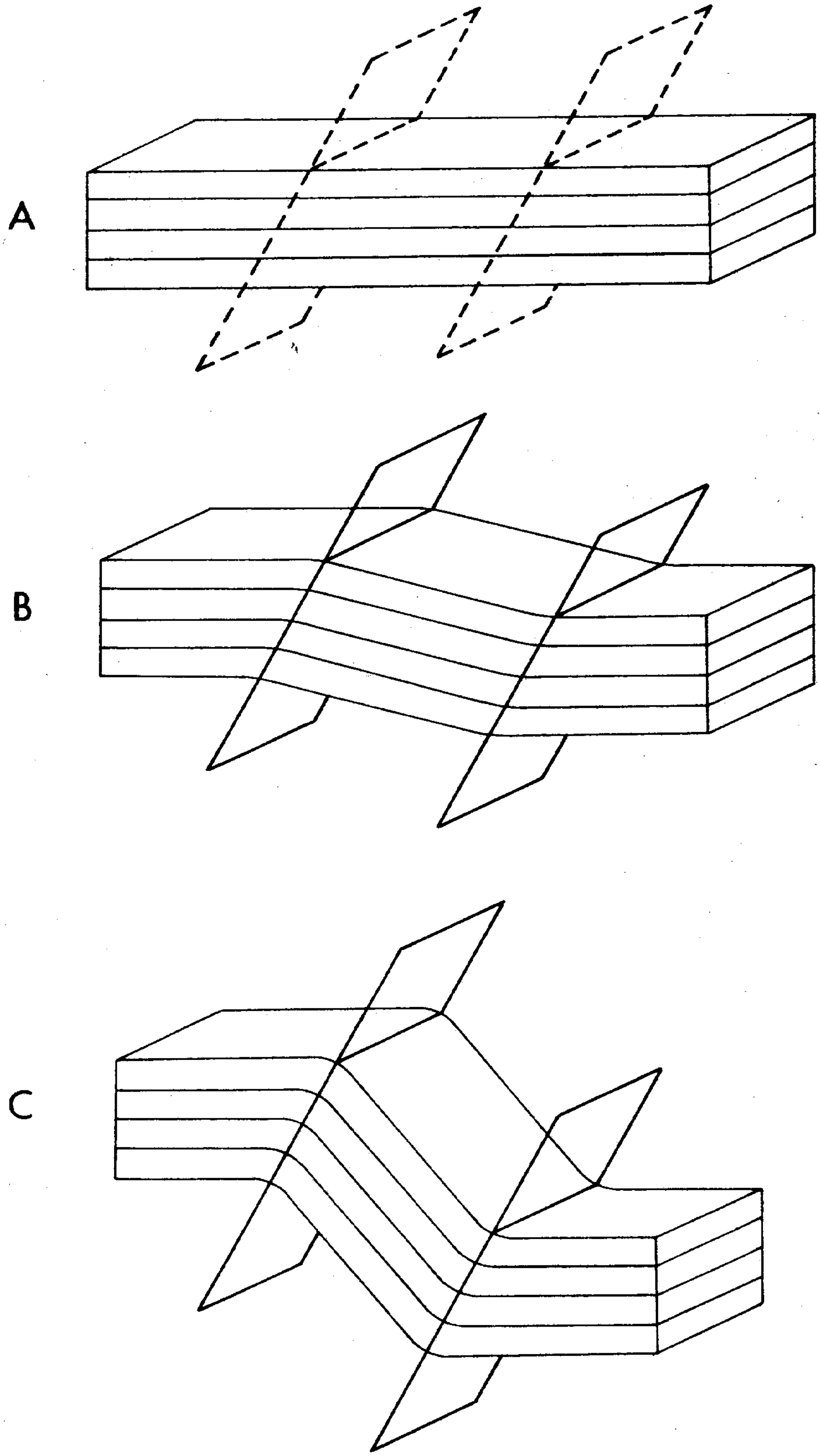

Figure 7 - Development of a kink band by progressive rotation of bedding by slip on bedding surfaces between the layers.

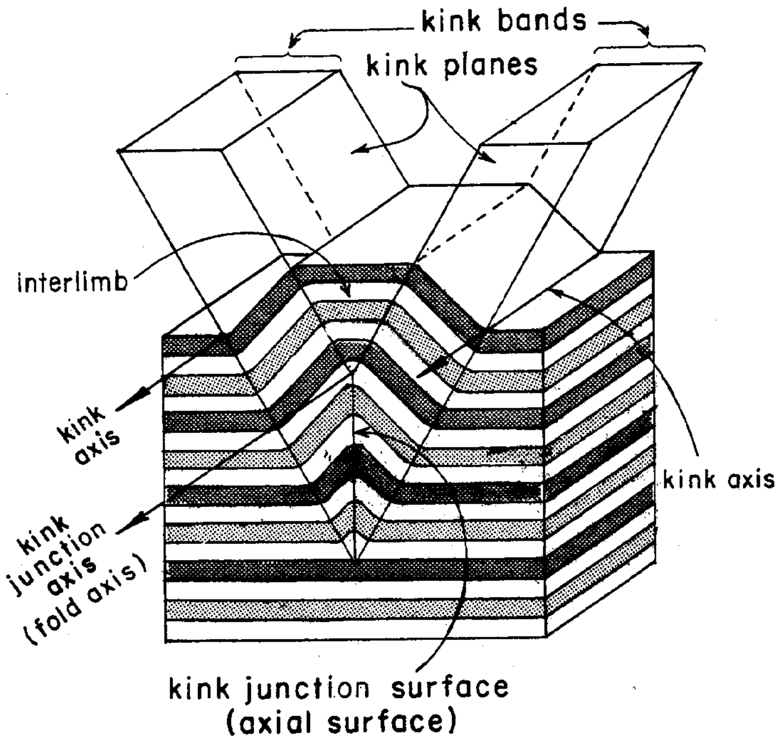

Figure 8 - Idealized kink-band fold, produced by the joining of two kink bands that are inclined toward each other and of opposite senses of rotation. Each kink bank constitutes one limb of the fold, and thus the planar bedding characteristic of the kink bands is incorporated into each limb of the fold. In the upper portion of the structure, where the kink bands are separated, the geometry is that of a conjugate fold. The two limbs are separated by an unrotated domain, the interlimb.

Figure 9 - Kink band fold in the Trimmers Rock Formation, in quarry 1/2 mile north of Williamsport, Pa. Notice that the fold diminishes in size downward (in both wavelength and amplitude).

If the two kink bands are of equal width, equal amount of bed rotation (but in opposite senses), and oppositely inclined to the enveloping bedding, then the resulting fold at their junction will be upright and symmetric (Fig. 10A). On the other hand, if the kink bands are of differing amount of bed rotation, and are inclined to the enveloping bedding at different angles, the fold at their junction will be upright and asymmetric (Fig. 10B), or inclined and asymmetric (Fig. 10C).

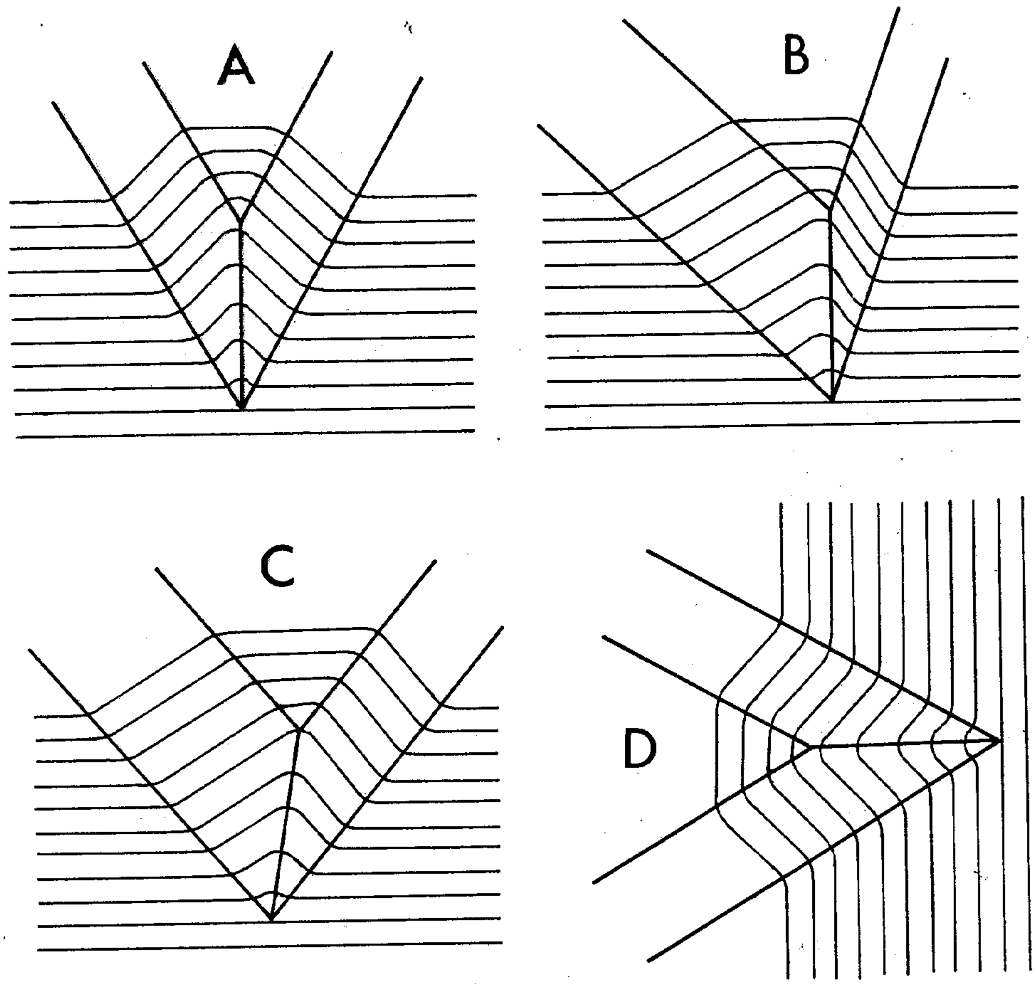

Figure 10 - Variation of fold profiles as a function of variations in the kink bands. (A) The kink bands are of equal width, amount of rotation (though opposite), and inclination to the enveloping bedding. The resulting fold is symmetric and upright. (B) The kink bands are of different widths, amounts of rotation, and inclination to the enveloping bedding: the resulting fold is asymmetric, though upright. (C) Similar to (B), except the resulting fold is both asymmetric and inclined. (D) Similar to (A), except the enveloping bedding is vertical instead of horizontal: the fold is thus symmetric and recumbent.

The presumption in these three examples has been that the enveloping bedding is horizontal. However, many small folds occur within the limbs of larger folds. Because the bedding in the larger fold limbs possesses dips between 1 and 90 degrees, all the smaller folds within that limb will be similarly inclined. As an extreme example, if the bedding in the larger fold limb is vertical, the enclosed fold is recumbent (relative to the horizontal datum) even though it is upright and symmetric relative to the enveloping bedding (Fig. 10D).

The large size and complexity of the folding obscures the underlying structural simplicity. Yet the wide variety of kink band sizes (and thus fold sizes) provides miniature replicas of what the larger folds must be like. In the laminated bed in Figure 11, two oppositely inclined sets of kink bands has resulted in a complex of folding which possess the geometries of the larger folds in the province, of which we see only small portions in single outcrops. Thus we can see that a complex fold train can be resolved into an intersecting array of simple kink bands.

The differences in fold sizes is attributable to different sizes of the constituent kink bands. The smaller folds (and kink bands) reside within the limbs of larger folds (and kink bands), producing a heirarchal nesting embodied in the five-order size scheme of Nickelsen (1963). Although the geometry of the folds is similar for all fold sizes, the largest first-order anticlines do not appear to be simple kink band folds (Fig. 12B; Faill, 1973). The presence of faults of large displacement (inferred from the large stratigraphic offsets encountered in deep drilling) in the anticlinal hinges suggests that these folds were produced by splays (Fig. 12A) from the hypothesized decollements at depth (Gwinn, 1964, 1970). Although these largest anticlines are faulted folds, they possess the geometry of kink band folds. In contrast the intervening first-order synclines (e.g., Fig. 4) are relatively free of faults and more nearly approximate the ideal kink band fold.

Fold Disharmony and Structural Lithic Units

Earlier illustrations of Valley and Ridge folds by Darton (1940) in the Anthracite region and Butts (1946) in the Hollidaysburg-Huntingdon Folio have suggested the existence of significant fold disharmony at different stratigraphic levels in the Paleozoic section of Pennsylvania. Neither of the above authors made special note of the disharmonies that they had illustrated in their maps or structure sections. More recently, Nickelsen (1963) in central Pennsylvania and Epstein and Epstein (1967) west of the Lehigh and Delaware Water Gaps have illustrated fold disharmonies, and have tentatively defined the structural lithic units and boundary zones delimiting fold trains of different wavelengths. To date, there has been no regional attempt to extend this work to other areas of the Valley and Ridge or to attempt correlation of rock properties and thickness-wavelength relationships with the theoretical work of, for example, Currie and others(1962). Indeed, because of the changes in facies occurring

Figure 11 - A relatively complex microfolding in this laminated bed can be resolved into two intersecting sets of kink bands, one inclined to the right, the other to the left (relative to the enveloping bedding). The microfolds possess the planar limb and narrow hinge geometry observed in larger folds. Wills Creek Formation, along U. S. Route 22, 6 miles northwest of Huntingdon, Pa.

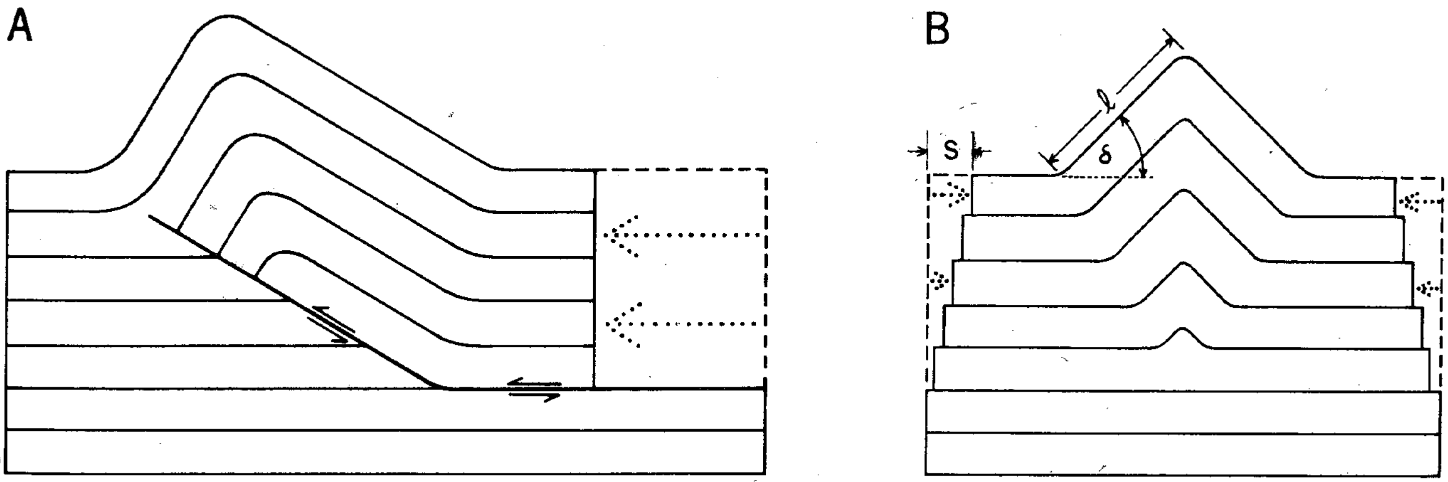

Figure 12 - (A) Fold with thrust fault in core to relieve congestion of beds. The implicit assumption is that all the folded layers have been equally shortened, and thus there must be a bed-parallel detachment fault between the folded and nonfolded layers. (B) Kink-band fold. For a given dip of bedding (δ), the amount of shortening (s) of a layer is a function of the length of the layer (l) in the fold. Because the layer length decreases toward the fold core, the amount of shortening similarly decreases, and thus there is no bed-parallel detachment fault between the folded and nonfolded layers.

between areas of outcrop it may be impossible to regionally delimit or correlate structural lithic units and boundary zones throughout the province. Also, our current hypothesis regarding initiation of folding prior to complete lithification may make present rock properties irrelevant in understanding conditons at the time of folding.

Yet, the regional distribution and stratigraphic position of disharmonic folds raise the question whether the concept of structural lithic units can be applied at all to the Valley and Ridge province. The underlying premise is that in a sequence of rocks, the most "competent" layers determine the wavelength of the folds. Although adjacent "incompetent" layers conform to the large folding of the dominant member, competent beds within the "incompetent" members prescribe a shorter wavelength folding, which gives rise to the disharmonic folding.

The critical point here is the meaning of the term "competency". Does it refer to strength? ductility? elasticity, viscosity or plasticty? In fact, this term is never adequately defined. It seems that what is meant is that large, simple folds occur in competent beds. Furthermore, quartzites, sandstones,and limestones and dolomites are associated with competent beds because they are more resistant to mechanical weathering. Thus, competency has come to mean, tacitly at least, strength. But, as pointed out above, what is "strong" today may not have been during the folding. The "tough" quartzites, as the Tuscarora, may have been unconsolidated sands (note the lack of brecciation in the fold hinges, in which the quartzite beds have undergone high strain, as seen at STOP III).

In addition, the stratiqraphic position of disharmonic folds and boundary zones is not constant. On many maps in the Valley and Ridge province, it appears that smaller folds occur in the Middle and Upper Silurian formations that are not present in the Lower Silurian Tuscarora, as at STOP VIII. Yet the folds (kink bands) in the "competent" Tuscarora at STOP III are an order of magnitude smaller than the folds in the "incompetent" Wills Creek Formation at STOP II. On a larger scale, north of the Broad Top region several third and second-order folds are developed in the "competent" Tuscarora. But southward these folds are fewer or absent in the "incompetent" Upper Silurian rocks (Fig. 13). The exposures at STOP III suggest another factor--before these structures were exposed in the roadcut and the dam quarry, there was no suggestion that they existed here, for the extensive colluvium covered up almost all the bedrock. One wonders how many other "simple" quartzite ridges may have complex, small structures hidden within them.

The laminated bed in Figure 11 points to another factor that may have more control on competency than do strength or ductility. Both the laminated bed and the adjacent massive beds are shaly limestones, the only difference being the presence of the bedding anisotropy, the laminations. In strength and ductility, the laminated and massive beds are porbably equivalent. It is the presence of the closely spaced anisotropy (the laminae) that enabled the development of the conjugate kink band sets. Perhaps similarly, smaller folds appear to occur in the Middle and Upper Silurian formations because they tend to be thinner bedded than the Tuscarora. However, there is no fixed fold size for a given bed thickness--just an apparent lower size limit.

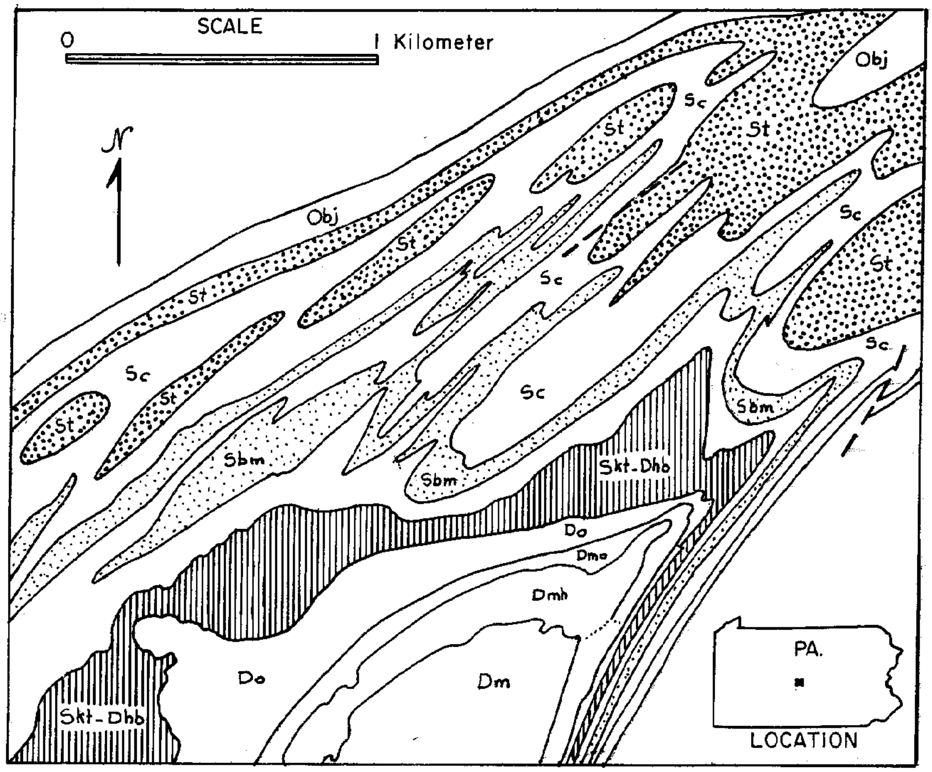

Figure 13 - In many parts of the Valley and Ridge province, the "competent" Tuscarora Formation is folded into first- and second-order folds whereas the overlying "incompetent" Middle and Upper Silurian formations exhibit second- and third-order folds. But this relationship is not universal. For example, north of Huntingdon, Pa., third-order folds in the Tuscarora (St) do not persist into the Upper Silurian Tonoloway, Keyser and Devonian Helderberg formations (Skt-Dhb).

Nevertheless, the concept of structural lithic units need not be discarded. Perhaps it can be useful once competency is defined more clearly (or broadly) and our understanding of the behavior of rocks is more complete.

The main point to be recognized is that important fold disharmonies are present in the Valley and Ridge province and must be explained in any analysis of the terrain.

Faults

Faults of greatly different sizes occur in the Valley and Ridge province, with displacements ranging from inches to hundreds or thousands of feet. There are also basal decollements which, for the most part, are not exposed at the surface within the province. Most of the faults which can be seen at the surface can be divided into two categories: wedge faults and cross faults. The wedge faults (Cloos, 1961) lie at a small angle to bedding, and terminate in bedding planes. Displacement on them results in lateral shortening and duplication of beds. The cross faults are subnormal to the tectonic grain (defined by the average of fold axes). Both types of faults represent local, discontinuous deformation subordinate to the folding.

Wedge Faults

Wedge faults represent a transfer of bed-parallel slip from one bedding surface to another along a slip surface that lies at a small angle to bedding (Fig. 14). They are contraction faults (Norris, 1958) in that the faulted beds were laterally shortened, with a consequent duplication of the faulted bed. Faults may show overthrusting to either northwest or southeast and the direction of overthrusting is not correlated with

Figure 14 - Wedge faults in interbedded siltstone and shale sequence. Trimmers Rock Formation (Upper Devonian U. S. Routes 22 and 322, 6.5 km north of Duncannon, Pennsylvania.

present location of faults on major or minor fold limbs. The congruency of slickensides on the wedge faults with those on the bedding surfaces (Fig. 15) indicates that the wedge fault movements were kinematically related to the flexural-slip folding. In many of the wedge faults, the intersection between the wedge surface and bedding is subparallel to the fold axis. These fault surfaces represent the main slip surface of the wedge block. In other wedge faults, the intersection between the wedge surface and bedding lies at a large angle, even subperpendicular, to the fold axis (although the slickensides on these surface are also normal to the fold axis). These wedge faults represent lateral terminations of the wedge block (Fig. 16). That is, many of the wedge blocks appear to be lens shaped, pinching out not only in the direction of transport but also laterally in the direction of the fold axis.

Wedge faults frequently occur as isolated structures in fold limbs. They are also encountered in the hinges of the folds, where the duplication of beds results in a thickening of the layers in the fold hinges.

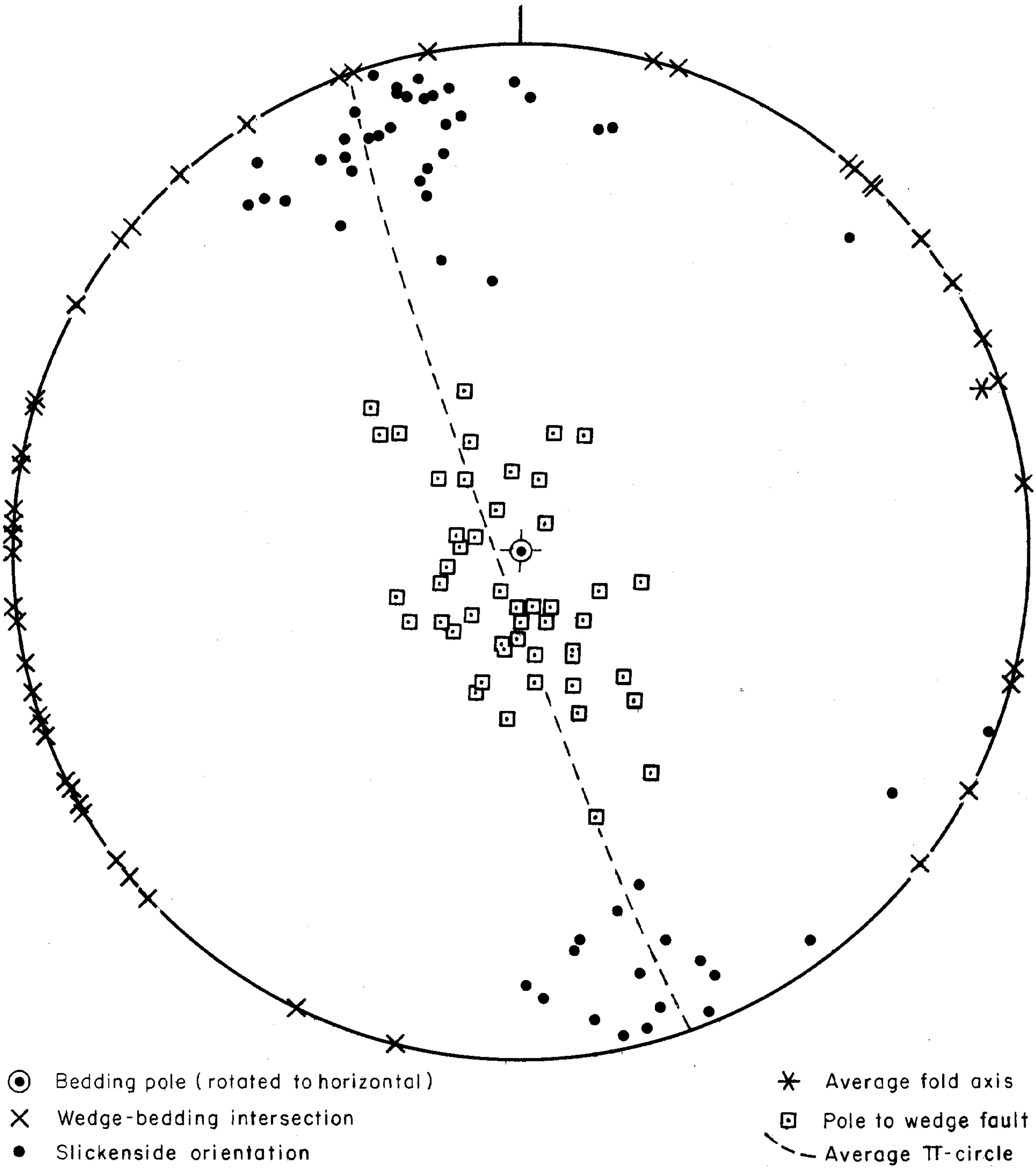

Figure 15 - Poles to wedge faults, slickenside orientations on wedges, and the intersections of wedges with bedding. For the purpose of comparing the angular relations between the wedges and adjacent bedding, each set of data has been rotated about horizontal axes (the strike of bedding) such that the bedding pole is vertical for all 35 stations. Data from Millerstown quadrangle (Faill and Wells, 1973).

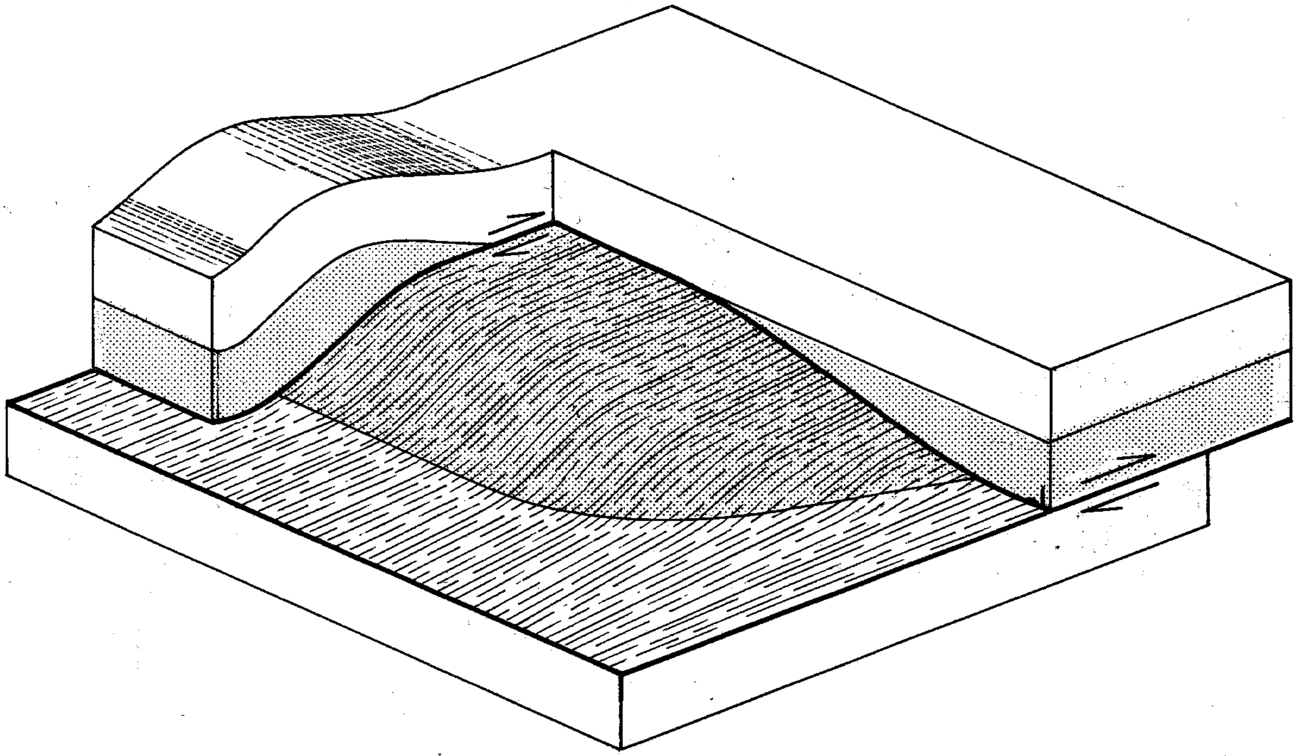

Figure 16 - Idealized lens-shaped wedge block. Heavy lines represent wedge-fault surface; discontinuous lines on this surface represent slickensides which are subnormal to the fold-axis direction.

Wedge faults usually occur in sequences of interbedded lithologies of contrasting mechanical properties. Commonly, wedge faults cross only beds of siltstones or sandstones that are surrounded by shale. Most of the large mappable faults in the province similarly occur in sequences of interlayered contrasting lithologies. The proliferation of faults (relative to the rest of the province) in the Anthracite Region is undoubtedly attributable in part to the contrasting mechanical properties in the Pennsylvanian sequences of interbedded coals and sandstones. Cloos (1961) has suggested that wedging is an early deformation process, preceding folding, and that wedges control the location of later folds. The evidence for this is equivocal in Pennsylvania but clearly wedging offers a mechanism for accomplishing bed parallel shortening in brittle beds suspended in more dutile, fracture-cleaved shales. Possible relations of wedging and early formed penetrative cleavage are discussed below.

Cross Faults

Cross faults, subperpendicular to the regional fold-axis direction, are less common than wedge faults. The cross faults are undoubtedly related to wedge faulting and the folding because their slickensides are invariably at a small angle to the fault-bedding intersection (Fig. 17), congruent with those on adjacent wedge faults. They probably represent vertical breaks between two parts of a wedge block, or lateral terminations of the block (Fig. 18). Large, mappable cross faults are not frequently encountered; the most prominent examples are cross faults in the southern Anthracite Region (Wood and others, 1969, p. 108-109), and the strike slip faults of the eastern edge of the Appalachian Plateau between Phillipsburg and Houtzdale (Nickelsen and Hough, 1967).

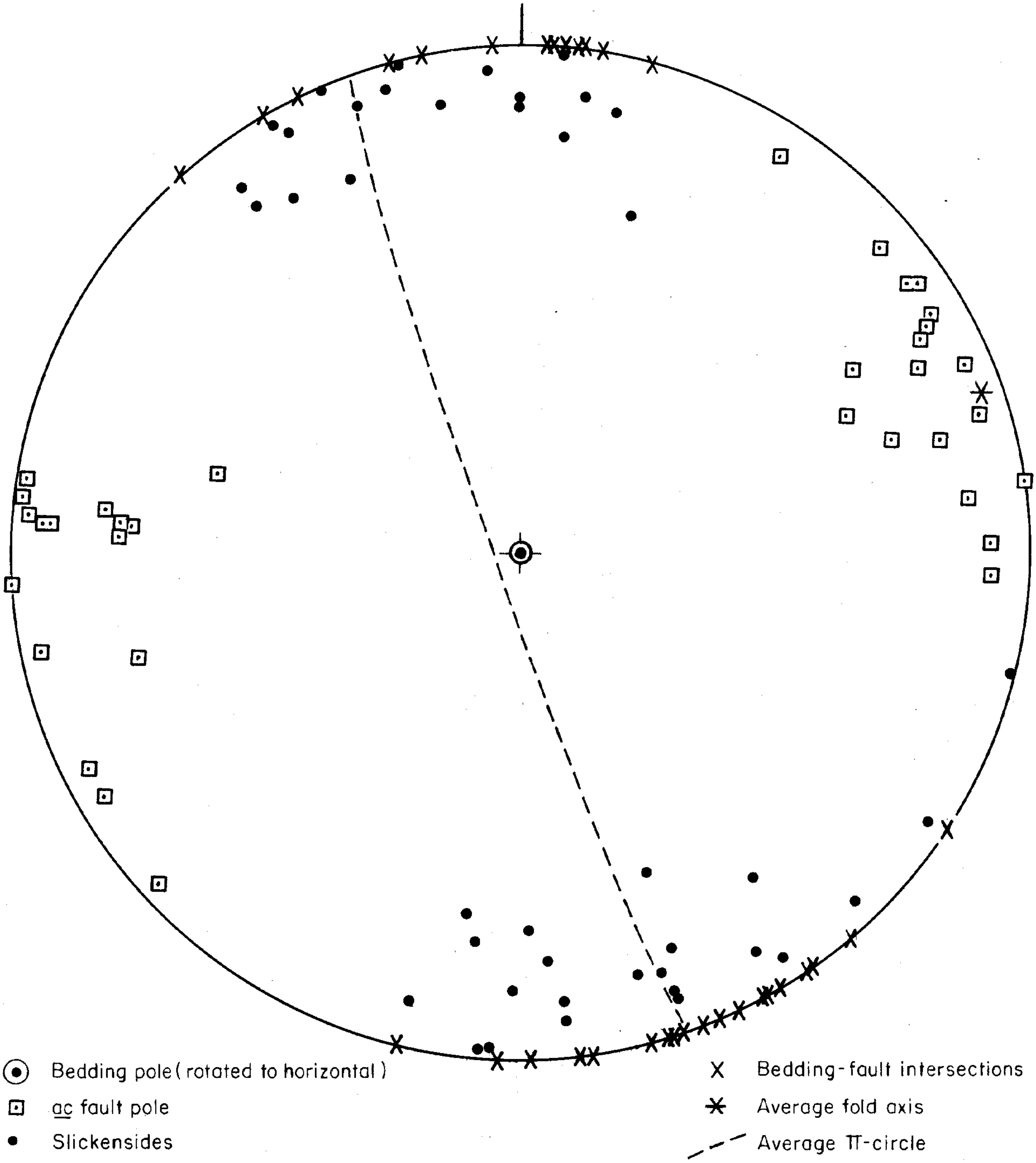

Figure 17 - Poles to cross faults, slickenside orientations, and intersection of cross faults with bedding. As in Figure 13, data have been rotated such that bedding poles are vertical for all 23 stations. Data from Millerstown quadrangle (Faill and Wells, 1973).

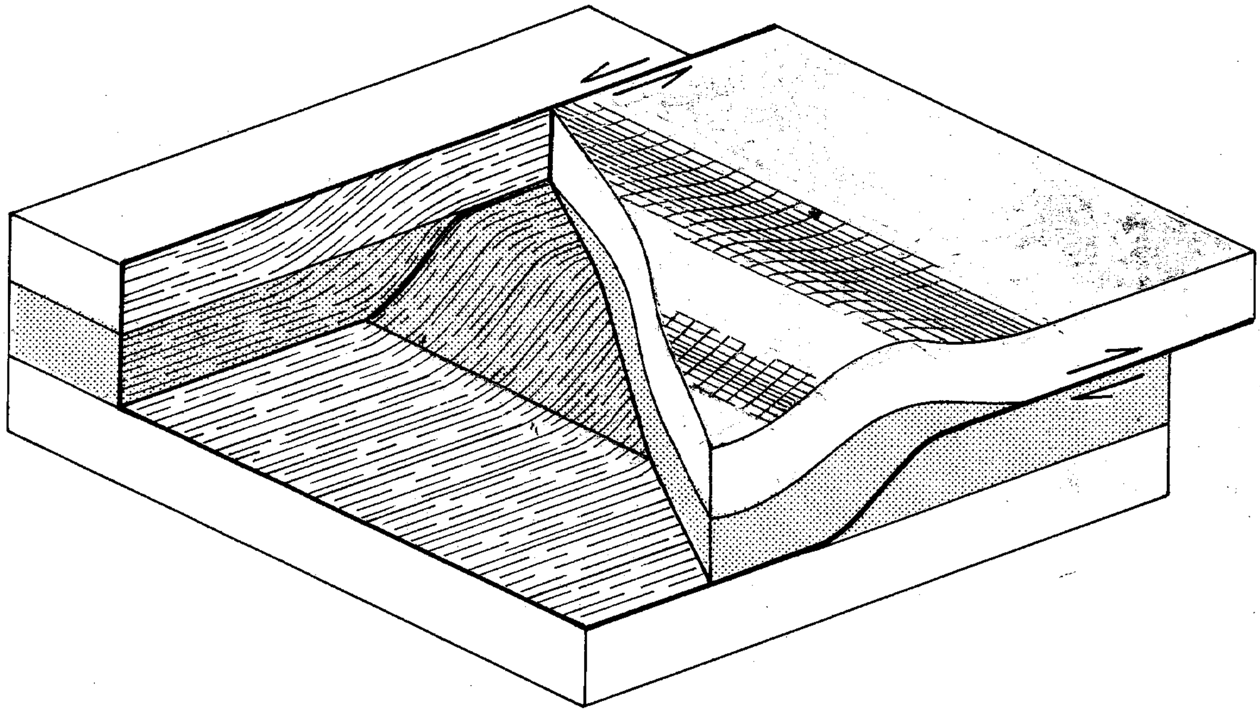

Figure 18 - Idealized wedge block terminated laterally by a cross-fault. Heavy lines represent the wedge and cross-fault surfaces; discontinuous lines on these surfaces represent slickensides, which are subnormal to the fold-axis direction.

Three Dimensional Geometry of Kink Band Folds

The apparent simplicity and great length of the largest folds in the province give the impression that the folds are cylindrical. Yet in detail, the folds exhibit considerable complexity: folds diminish in size and vanish in the limbs of other folds; folds abruptly change trend, plunge, and diminish in size to the point of losing definition; some exhibit an en echelon pattern; others bifurcate. These complexities produce a pattern of interfingering folds not easily interpreted by a simple flexural-slip fold model.

In analyzing these folds in three dimensions, it is most convenient to visualize the kink band structure separate from the bedded rocks in which it occurs. The simplest of kink band folds, consisting of two inclined kink bands (as in Fig. 8), appears as a V-shaped solid. The kink junction axis, the intersection of the kink planes, (parallel to the trough or point of the V-shaped solid) is the most critical geometrical element. When the kink junction axis lies in the enveloping bedding, the kink band structure is symmetrical with the bedding and the resulting fold is cylindrical. The fold does not change its shape or size along trend, and the kink and fold axes are all parallel to kink junction axis. There is one set of slickensides on the bedding surfaces, which are normal to the fold axis (hinge line) of the fold.

The kink band structure, however, need not be symmetrical with the enveloping bedding--it can be inclined, with kink junction axis making a small angle to the enveloping bedding (Fig. 19). Although the kink band

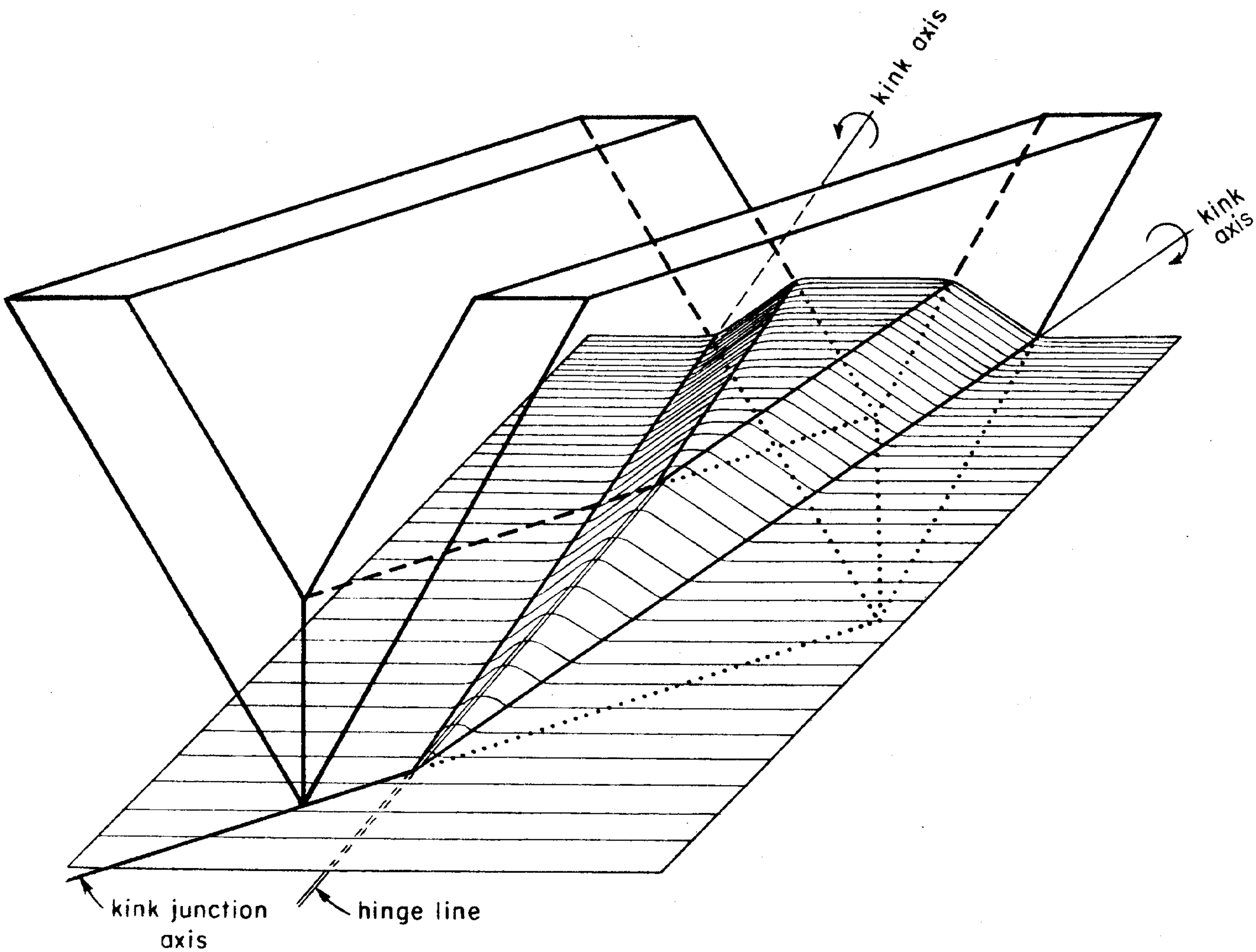

Figure 19 - Non-cylindrical fold. If the kink band structure (indicated by the heavy outline) is congruent with the enveloping bedding (as in Figure 8), the resulting fold is cylindrical and does not change along trend. If, however, the kink band structure is not congruent with the enveloping bedding (that is, if the kink junction axis is inclined to the bedding, as in this figure), the resulting fold is non-cylindrical, and it terminates.

structure is identical in both figures, the difference in orientation relative to the enveloping bedding results in quite different fold geometries. In Figure 19, the kink junction axis plunges toward the rear of the diagram; the two kink axes, both in the enveloping bedding, diverge from each other; and the hinge line plunges toward the front of the diagram. The fold is not cylindrical: the fold geometry, as expressed in a single bed, changes radically along trend from a conjugate fold in the rear to a simple fold in the middle, and diminishing and vanishing in the foreground (Fig. 20). If the rotations of bedding within each kink band (fold limb) occurred around the respective kink axes, two sets of slickensides on bedding surfaces will be present at a small angle to each other (see Faill, 1973 for a more extensive treatment of the three-dimensional geometry of noncylindrical kink band folds). Thus, in a small outcrop, if the fold is not extensively exposed as in Figure 20, the presence of two slickensides directions will indicate that the fold is noncylindrical.

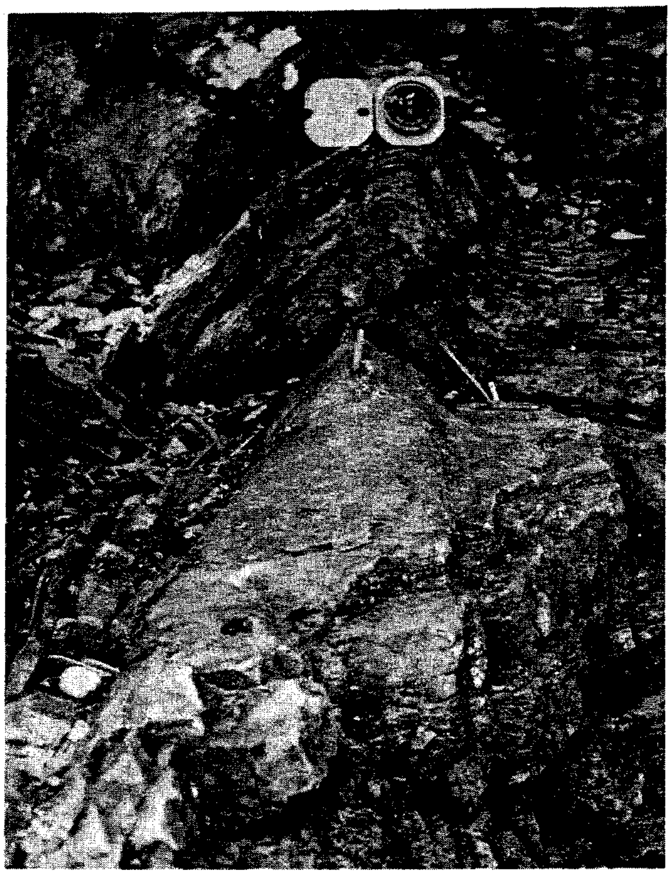

Figure 20 - Noncylindrical fold termination. In a single bed, the geometry changes from a kink-band fold in the background to a simple monocline in the foreground. Wills Creek Formation (Silurian), west bank of Juniata River 6 miles northwest of Huntingdon, Pa.

Penetrative Structures

Cleavage

Although cleavage occurs throughout the province its distribution is not uniform. Cleavage development depends upon lithic type, position on structure, and, less significantly, geographic location within the province. Cleavage has been observed in Reedsville shale, Rose Hill shale, McKenzie limestone-shale interbeds, Bloomsburg mudstones, Wills Creek shales, Keyser argillaceous limestones, Mahantango mudstones, and Catskill mudstones but is perhaps most ubiquitous in the Bloomsburg and Keyser Formations.

The cleavage is best described as fracture cleavage because it consists of approximately .2mm thick micro-lithons of uncleaved rock bounded by dark clay-carbon partings (Nickelsen, 1972). Within the micro-lithons, clay minerals retain their original sedimentary orientation parallel to bedding, but clay minerals in the clay-carbon partings apparently parallel the partings. Even where seemingly penetrative flow cleavage occurs, initial bedding orientation of clay minerals is preserved within micro-lithons and no growth micas or minerals are seen in thin section. Cleavage zones (Fig. 21) occur as groups of clay-carbon partings, are spaced millimeters to centimeters apart, and are at least partially controlled in their location by lithology, fauna or primary sedimentary structures. Clay-carbon partings in cleavage zones converge both along strike and dip near pebbles, fossils, and nodules and diverge in intervening areas where spacing between clay-carbon partings increases.

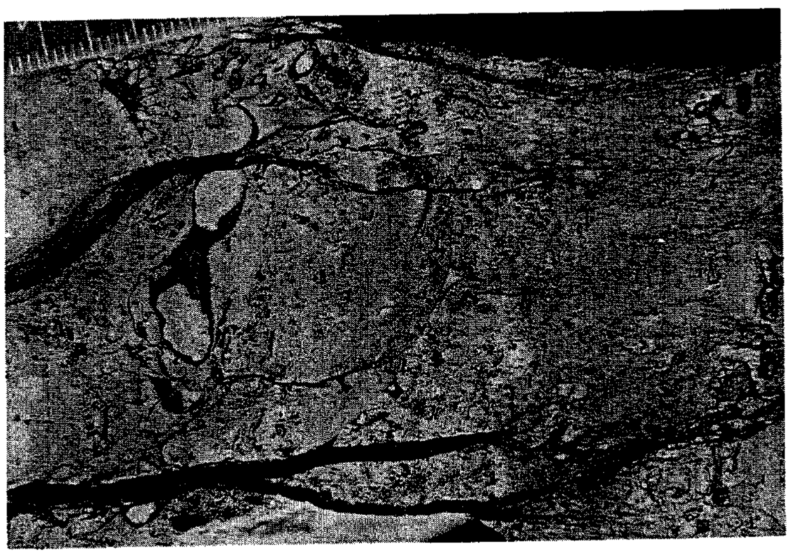

Figure 21 - Cleavage zones in the Keyser Formation (from the Meckley quarry at Mandata, STOP X), consisting of concentrations of clay-carbon partings. Note removal of fossil material by pressure solution in upper left.

Cleavage is best developed in argillaceous mudstones or sandstones such as the Bloomsburg or Mahantango or in argillaceous limestones such as the Keyser or McKenzie but may also occur in shales. Pure limestones, dolomites and sandstones are not cleaved and even some shales in structural positions where one would expect cleavage are not cleaved. An especially interesting occurrence is on Pa. Route 147 south of Sunbury, between STOPS IX and X (mileage 86.6). The upper part of the Mahantango mudstones (Fisher Ridge Member) are strongly cleaved, but the underlying mudstones to the south are not.

Cleavage can and does occur in all parts of folds but it is particularly well developed in or near hinges of tight second- or third-order folds or in local complexes of third- and fourth-order folds on the planar limbs of larger structures.

Although cleavage seems to be more generally developed in rocks to the southeast, location within the province doesn't seem to be a dominant factor in its existence. Cleavage appears equally well developed in the Bloomsburg Formation throughout the province. Excellent cleavage occurs in tight folds on the Nittany anticlinorium and along the Allegheny Front in the western part of the province. Only the Keyser which is not known to be cleaved along the Allegheny topographic front shows evidence of a northwestward diminishment of cleavage development.

It can be concluded generally that a descriptively and genetically similar fracture cleavage occurs throughout the province in suitable lithologies and structural positions.

Cleavage has originated by pressure solution regardless of the rock type in which the cleavage occurs. In both the argillaceous limestones, and the silty mudstones, the cleavage consists of a thin zone of carbon and clay enrichment (clay-carbon partings) separated by rock preserving the original sedimentary fabric. In the argillaceous limestone, these partings lack the calcite that is present in adjacent micro-lithons. Where fossils occur, volume loss of up to 26% perpendicular to cleavage has been documented in cleavage zones (Nickelsen, 1972). This loss is not representative of the whole rock because cleavage zones alternate with zones on no recognizable shortening. In the silty mudstones, the partings either lack the quartz grains present in the adjacent micro-lithons or show etched quartz grains elongated in the cleavage. It appears that the limestone and/or quartz was dissolved by pressure solution, resulting in residual enrichment of argillaceous material. Sedimentary structures such as organic borings, dewatering tubes and mudcracks enhance the possibility of water movement and solution and are thus commonly the loci of cleavage zones.

It is inferred that the cleavage was developed before or during early stages of folding. Because it is frequently subnormal to bedding surfaces, it is thought to have developed intially vertical and perpendicular to bedding, and to have undergone subsequent rotation during the folding. In many folds there is fanning of the fracture cleavage resulting from the rotations inherent in the folding. As demonstrated at STOP VIII, early fracture cleavage and cleavage-bedding intersections have been folded around an axis which departs 8-10° from the cleavage-bedding intersection, adding credence to the view that cleavage was initiated early, and later externally rotated around folds of different orientation. Refraction of cleavage also occurs in some of the more ductile beds of argillaceous limestone where considerable internal rotation of the cleavage has occurred as a result of a flexural-slip movement on bedding. In places, two cleavages are present, one being the early prefolding cleavage, the other a later fracture cleavage that cuts through both early cleavage and bedding in an orientation parallel to axial planes of folds.

Micro Folds

In a number of very thin-bedded stratigraphic units (for example, the Wills Creek and the Tonoloway Formations), folds of wavelengths of 1 inch to 1 foot occur within narrow bed-parallel zones, consisting of very thin limestone beds interbedded with more argillaceous beds. These folds are lithically controlled, being restricted to thin limestones or well-bedded clay shales. The folds in these thin layers are disharmonic with adjacent more massive "muddy", poorly-laminated beds because the folds do not extend into the overlying or underlying massive beds. The geometries expressed by these folds are variable, ranging from a very uniform development of intersecting kink band arrays, to nearly concentric folds, to rather irregular folds. These folds possibly reflect the overall shortening of beds and their particular geometric aspect is a product of the lithic sequence in which they occur. For example, a uniform kink band array is developed in well-laminated beds (as in Fig. 11). In layers consisting of interbedded shale and thin limestone, the folds are either concentric or quite irregular, probably reflecting the large ductility contrast between the fairly pure limestone and the argillaceous material on either side. Some of this folding is interpreted as an early development, initiated simultaneously with bed parallel shortening mechanisms such as wedging, pressure solution and cleavage formation in adjacent layers.

Mudcracks

Mudcracks are rather common in the laminated carbonate beds of the Wills Creek Formation and the nodular beds of the Keyser Formation. Although these are an initial sedimentary structure, they apparently were utilized in the subsequent deformation. The bed-normal surfaces between the polygonal mudcracks apparently served as conduits for the solutions which carried calcareous and siliceous fluids away. Solution within these zones has led to a carbon-clay enrichment which now stands out as a cleavage in the rock.

The other interesting aspect of these mud crack polygons is that they are not equi-dimensional. Measurements at several localities show that they are preferentially elongated in the direction of the fold axis, with length to width ratios on the order of 2:1. Assuming that these mud crack polygons were initially equi-dimensional, this reflects a strain within the mud crack polygons normal to the fold axis. Whether this distortion of the mud cracks was accomplished by solution at its edges or by bulk deformation of the entire polygon is not known with certainty. The carbon-clay enrichment between the polygon suggests that some of the elongation was accomplished by solution at the polygon margin.

Deformed Fossils

Throughout the Valley and Ridge province, and in the adjacent Allegheny Plateau province to the northwest (Nickelsen, 1966), it has been observed that the fossils have been distorted from their initial shape. The initial right angle between brachiopod hinge line and sulcus has been changed in suitably oriented fossils; trilobites rarely exhibit their initial bilateral symmetry; the shapes of other bivalves vary in their length-to-width ratio depending on orientation with respect to principal strain axes; and crinoid stems are elliptical in shape rather than circular (Fig. 22).

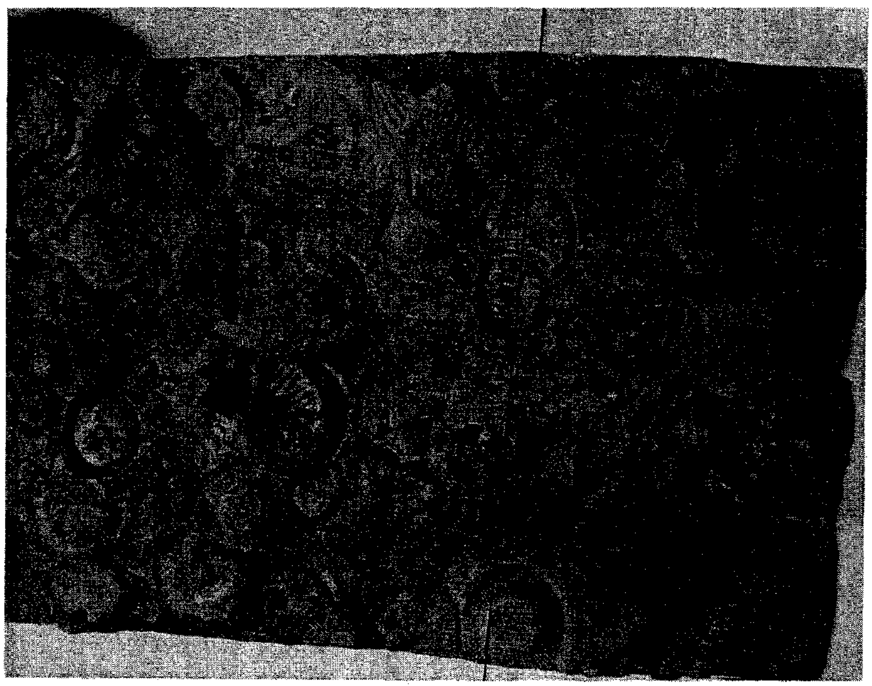

Figure 22 - Bedding plane of a siltstone bed from the Trimmers Rock Formation, along Pa. Route 54, 12 miles northeast of Sunbury, Pa. The disarticulated disks of crinoid stems lie flat in the bedding plane, and have been distorted into ellipses from their initial circular shape. The major (longest) axes of the ellipses are subparallel to the strike of bedding.

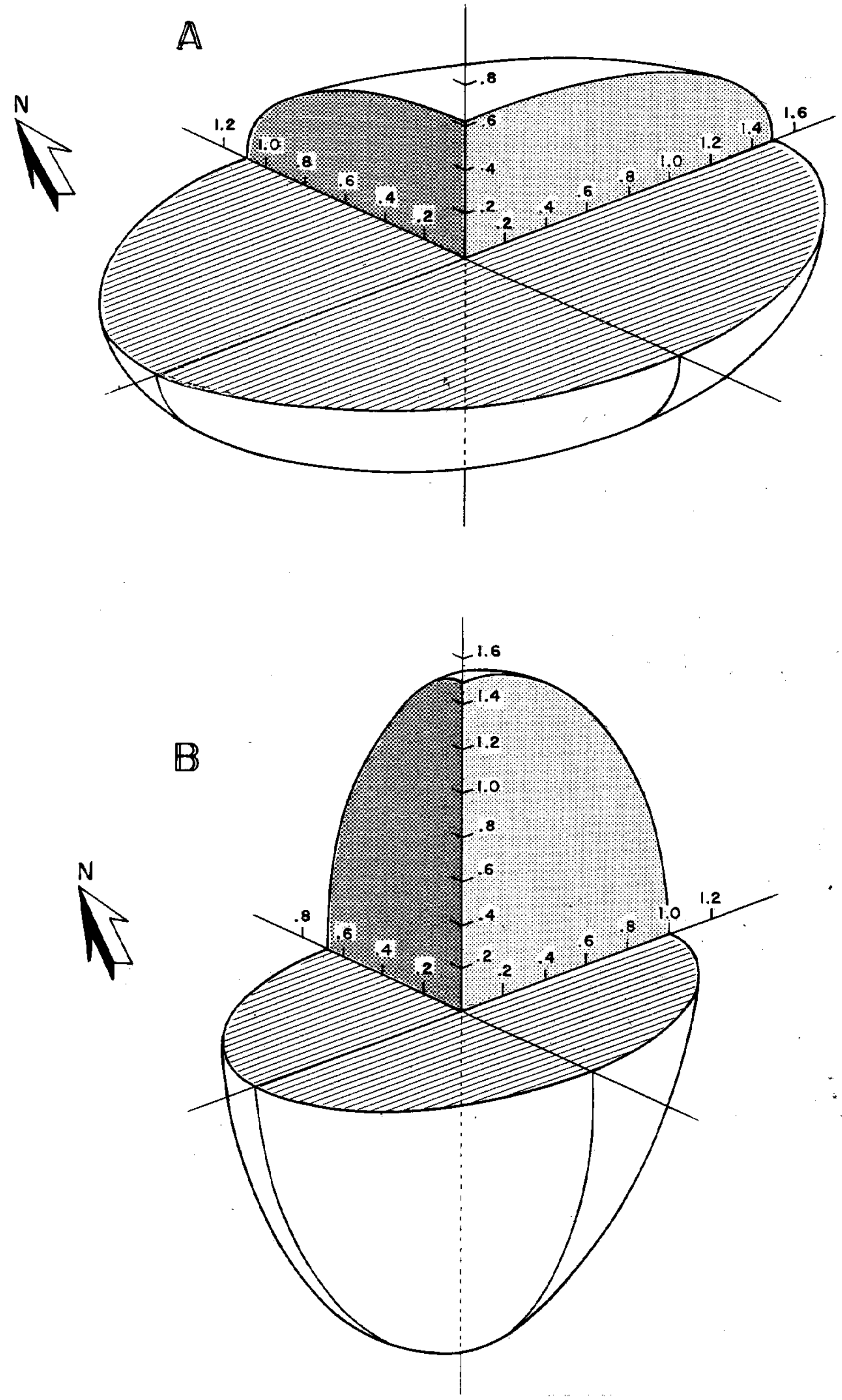

Figure 23 - Average strain ellipsoids based on data from Millerstown vicinity. A) Penetrative strain indicated by fossil distortion. The greatest extension was parallel to the fold axes; the largest shortening perpendicular to bedding; there was a small extension across the folds. B) Non-penetrative strain by flexural slip (kink band) folding. Because there appears to be no flexural slip movement parallel to the fold axes, strain in this direction is zero. Therefore, all the shortening normal to the fold axis went into vertical extension. Thus, the two different deformational processes have resulted in very different states of strain.

This fossil distortion reflects a bulk penetrative flow that pervaded all of the rocks, a deformation quite different from the nonpenetrative (at the scale of individual beds) kink band folding. This flow can be represented by a strain ellipsoid, a three-dimensional figure with three mutually perpendicular principal axes (Fig. 23A). The orientation and magnitude of these axes are the measure of the bulk flow strain. If this flow were merely a flattening normal to the fold axial surfaces (as in Fig. 23B), this strain ellipsoid would be symmetric to the fold. But this is not so! The strain ellipsoid is symmetric to bedding rather than to the folds because two of the ellipsoid axes lie in bedding, and the third is normal to it, in both limbs and in the hinge of the fold (Fig. 24). In addition, the eccentricity of the ellipses does not vary with amount of dip, but is constant across the fold. This consistent relation relative to bedding indicates that the fossil distortion preceeded folding, and that the inferred strain ellipsoids were rotated with the beds during folding.

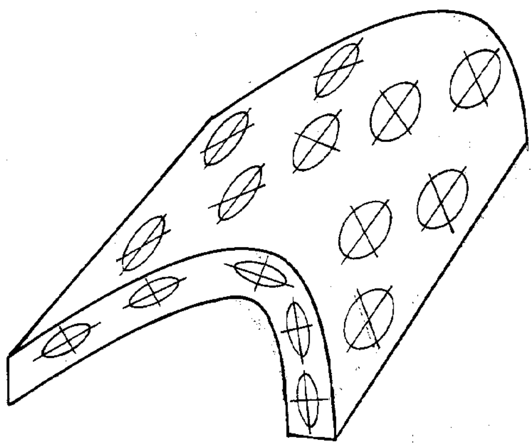

Figure 24 - Throughout the entire fold, the strain ellipses do not change in shape (the amount of distortion is constant). In the bedding planes, the major (longest) axes are parallel to the fold axis. In cross-section, the major axes are parallel to bedding.

Of the three principal axes of the strain ellipsoid, the major axis (the longest, representing the direction of maximum extension) commonly lies in bedding, subparallel to the local fold axis (subparallel to the strike of bedding). The minor principal axis (the shortest, representing the direction of maximum shortening) usually lies perpendicular to bedding. The intermediate axis (indicating either extension or shortening) perforce lies in bedding, normal to the local fold axis (in those few localities where the minor axis lies in bedding, the intermediate axis is subperpendicular to bedding).

Thus, in general, the bulk penetrative flow has extended the rocks parallel to the fold axes, and flattened them perpendicular to bedding. This strain is in contrast to that of the folding, in which the rocks have shortened horizontally (perpendicular to the axial surfaces) and extended vertically, with no obvious change parallel to the fold axis (Fig. 23 A and B). In addition, the process by which the fossils were distorted was by a penetrative flow, whereas the folding was by a nonpenetrative, distributed slip.

But the penetrative flow did not have a single cause--rather it was made up of contributions from three distinct deformational processes.

1. The first is compaction, reflected in the minimum strain axis (maximum shortening) perpendicular to bedding. However, the relative magnitude of this minimum axis varies, even within one collecting locality, apparently as a function of differences in lithology. For example, the bed-normal strain tends to be greater in silty and sandy layers compared to the finer-grained argillaceous layers (Fig. 25). The inference is that the fossils deformed more homogeneously with the coarser-grained matrix; in the shales and mudstones, the matrix was sufficiently mobile that it flowed around the fossils without imparting much strain to them.

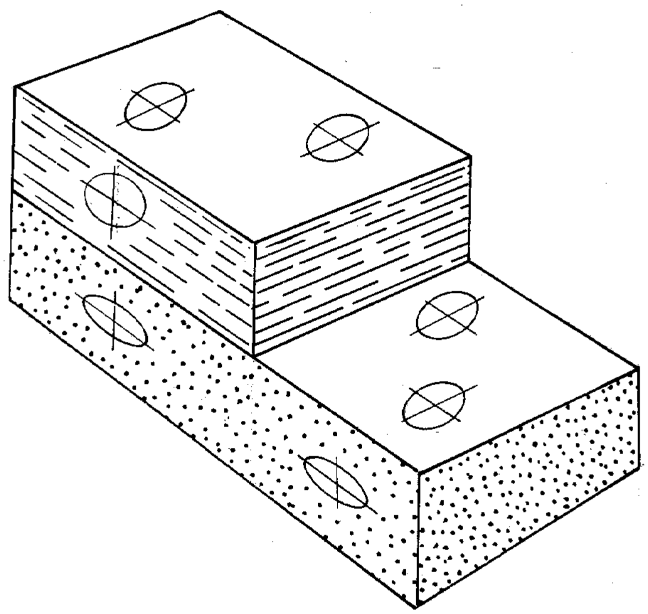

Figure 25 - The greater distortion of fossils by compaction in the sandier layers reflects a more homogeneous deformation. In the shaly layers, mobility of the matrix caused little of the compaction to be transmitted to the fossils, and thus the distortion was less, even though there probably was a greater amount of compaction. Despite these differences in compaction, the distortion in the bedding planes is uniform regardless of lithic type.

2. The intermediate principal strain axis (rather than the minor axis) is normal to bedding in silty and sandy beds at localities where cleavage is well developed in argillaceous layers. This indicates that cleavage development produced the second contribution to the total strain ellipsoid. As the non-penetrative fracture cleavage was developed in the argillaceous layers, the sandier layers were shortened an equal amount by a penetrative flow which is reflected by the distorted fossils (Fig. 26). This is reflected, for example, at STOP VIII, where deformed reduction spots have maximum extension in the cleavage plane perpendicular to bedding rather than parallel to the fold axis. In these beds (Bloomsburg), a strong cleavage has been developed, to which this distortion of the reduction spots may be attributed.

Although compaction and cleavage are two contributors to the total strain ellipsoid, there was apparently a third major contribution.

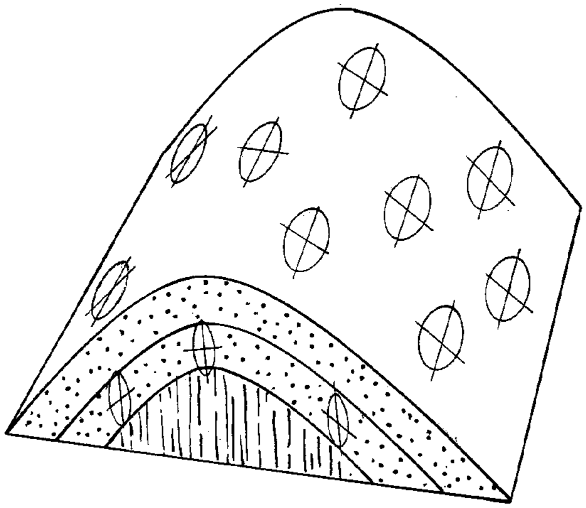

Figure 26 - At localities where cleavage is well developed in argillaceous layers, the major axes of the ellipses in the sandier layers lie between perpendicular to bedding and parallel to the axial-plane cleavage. These orientations reflect flattening of the fold, by cleavage development in the argillaceous layers, by flow in the sandier layers.

3. In all localities across the province, the major strain axis (axis of maximum extension) in the bedding surfaces is subparallel to the local fold axes, parallel to the arcuation (Fig. 27). This elongation is particularly well expressed by crinoid disks lying in bedding planes. This distortion could not have been induced by compaction, for bed-normal compaction would extend the fossils equally in all directions in the bedding plane. Although the cleavage contribution shortens the rock normal to the fold axis, it does not produce a real extension parallel to the axis. Thus, combinations of compaction and cleavage strains cannot reproduce all the strain ellipsoids observed throughout the province--there must be a third contribution. In general, the extension parallel to the fold axes is greater in the southeast than in the northwest, suggesting that the third contribution resulted from the divergent northwestward movement of the

Paleozoic rocks on the deep decollements. As these rocks moved the radially outward (to the west, northwest, and north) on the decollements, they were extended tangentially (parallel to the fold axes). Because the rocks in the southeast moved a greater distance to the northwest than those near the Allegheny structural front, they underwent greater elongation parallel to the fold axes.

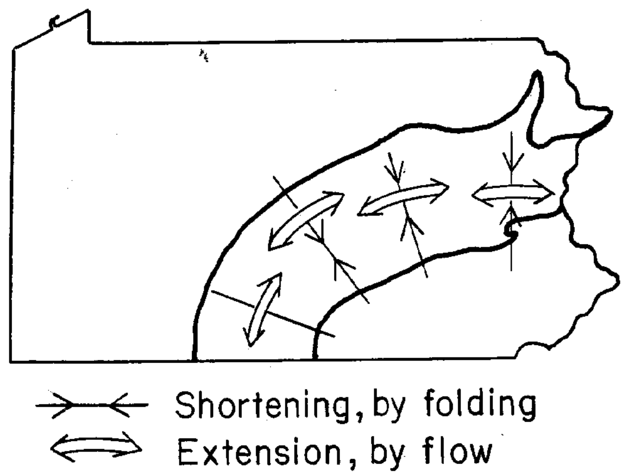

Figure 27 - The Paleozoic rocks were shortened radially by folding. But because of the outward radial movement on the decollements, they were also extended tangentially by flow.

Structural Synthesis

The presence of kink band folds, major decollements, disharmonic folds, and the various penetrative deformational structures presents a more complex structure than has been generally assumed to be in the Valley and Ridge province.

The folds, including the disharmonies, appear at first glance to be rather complex. Yet, utilizing the concept of the kink band as a basic structural element, these kink bands can be combined to reproduce all the fold cross-sections that are observed in the province. In addition, recognition that two adjacent kink bands can have different kinematic trends enables the kink bands to be combined in various manners so as to provide plunging folds, en echelon folds, and simple and complex fold terminations and the regional arcuation. With these two concepts, the kink band and the diverging trends, the entire fold structure of the Valley and Ridge province can be reproduced and the arcuation can be explained as an interfingering of divergent kinematic kink domains (as described in Faill, 1973).

Correlating the folds both geometrically and in a deformational sequence with the other major structural features is more of a problem, and the following interpretation is still in an evolutionary stage. It seems quite clear that rocks were vertically compacted due to gravitational load before horizontal stresses became dominant. Fossils were flattened perpendicular to bedding during this "pre-deformational" time, but those in more fluid rocks apparently suffered less distortion, and thus do not reflect the entire magnitude of this very early, bed-normal (vertical) compaction. Structural manifestations of the regional, increasing, northwest-southeast directed horizontal stress reflect variations of: 1. rock types (composition) and their state of lithification at the time of deformation; and 2. presence of sedimentary structures such as mud cracks, burrows and dewatering tubes that could conduct water vertically through bedding. Structures initiated early while beds were still horizontal include solution cleavage, bulk strain of fossils, and micro-folding in shales and limestones possessing layers of marked ductility contrast. It is open to question how these three manifestations relate in a time sequence, but, because rock behavior tends to change from ductile to brittle with increasing strain, the thoroughly penetrative flow reflected by the fossil distortion probably preceeded the more discontinuously distributed cleavage formation and micro-folding. Major decollements were probably initiated during this early stage: in fact, northwestward movement on the decollements probably generated some of the increase in horizontal stress; the remainder was derived from body forces or from an externally applied force from the southeast (depending on whether the decollement movements were induced by gravity or horizontal forces, respectively). The result was a radial shortening (in plan view) and a tangential (northeast-southwest) extension (Fig. 27), reflected by the various early structures. The nature of these structures naturally depended on the rock composition.

Buckling and kink band folding followed this 10% or more early lateral shortening and represents conversion of movement of the Paleozoic rock above the decollements into deformation of these rocks. However, the fold axes in places do not exactly conform to the cleavage planes and fossil distortion axes. Total strain due to folding <u>may</u> be equal at different stratigraphic levels. It seems certain that different beds within the lithotectonic units responded differently to horizontal pressure, leading to folds of different characteristic wavelengths and amplitude, but differences in wavelength does not necessarily indicate differences in strain or shortening. Some relationship probably exists between thickness and relative ductility of lithotectonic units and the wavelength of folds, but complete understanding will have to await a clearer definition of lithotectonic units and boundary zones, and a better knowledge of the probable state of these sedimentary rocks during folding.

Alternatively, total folding strain <u>may not</u> be the same at different stratigraphic levels and major decollements following boundary zones may then play a role in superimposing fold trains of different strain value. However, such decollements at supposed boundary zones are rarely observed in the province.

Secondary effects of folding include faults generated in the fold hinges because of crowding, and some of the wedge and cross faults that cut through beds of lesser ductility. Also formed during this later, more brittle phase of deformation is a fracture cleavage (or close-spaced jointing) which parallels fold axial planes and cuts through both beds and early (now fanned) cleavage.

In some areas, such as the profile from Water Street to Tyrone across the region of the Birmingham Window (across the Nittany anticlinorium), the latest structure is steeply northwest dipping kink folding which is always down-to-the-northwest in sense whether observed in the right side up, southeast dipping beds southeast of the window, or in the overturned, southeast dipping beds northwest of the window.

The sequence of structural events thus proceeds from a ductile penetrative flow and solution phenomena toward a more brittle flexural-slip kink banding and faulting phenomena. The variety of early structures reflects differing responses to the same stress environment because of differences in lithic type, degree of lithification of the sediments, and the presence of different sedimentary structures. This explains the mingling of solution, bulk flow, cleavage development, and microfolding, all as constituent parts of the early lateral shortening. As the folding was initiated and developed, the behavior of all the rock types passed from relatively ductile to the relatively brittle behavior of kink band folding and subordinate faulting.

ENGINEERING GEOLOGY INVESTIGATION OF TALUS SLOPES IN LEWISTOWN NARROWS, PENNSYLVANIA

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Pennsylvania Department of Transportation

In the Valley and Ridge province of central Pennsylvania, unconsolidated deposits of talus and colluvium cover most of the mountain slopes. Because of the excessive cost of routing roads over the long parallel ridges which extend through this province, water and wind gaps are extensively utilized for the location of highways. However, the talus and colluvium present particularly difficult and challenging problems in the design and construction of roads through these gaps, problems which require geologically based investigation and analysis.

The "Lewistown Narrows" is an exceptional example of the type of problems that are encountered. Being a synclinal valley underlain by steeply dipping Tuscarora and Juniata sandstone on both sides, a thick talus covers the slopes. As part of the reconstruction of U.S. Routes 22-322 from Clark's Ferry to Lewistown, a location for the four-lane highway was sought through this narrow valley (Fig. 28). But because the existing road, railroad and river are presently crowded into the narrow flood plain, it was necessary to study a route location on the mountain slopes, which would involve sidehill construction. The unconsolidated "talus" covering on the slopes presented such gross stability problems that it was necessary to provide the highway designer with a detailed report delineating the types of problems that would be encountered.

Several alternate routes were considered. Initially, a route following the present course of U.S. Routes 22-322 was planned, but local desires for access from the south side of the Juniata River required consideration of a route parallel to Pa. Route 333 (Fig. 28). However, the topography of the valley changes along its length, and this change opened up additional alignment possibilities. In the western two-thirds of the valley, the Juniata River tends to flow against the north side of the valley, with the result that a relatively gentler slope exists south of the river (Fig. 29). In contrast, along the eastern third of the Narrows the river crowds against the southern side of the valley with the relatively gentler slope north of the river. It was this steep southern side on which Pa. Route 333 had been built that was of critical importance, and thus the geological investigations were concentrated here.

The initial field investigation began with a fairly comprehensive examination and data gathering of the bedrock geology. Concurrently, a seismic refraction survey (Richards, 1971) delineated the extent and thickness of the talus. The resulting seismic profiles delineated several velocity zones (Fig. 30). Drill hole data established the relation of these zones with the type of material as follows.

1000 - 1500 fps	-	Near-surface colluvium and overburden.
1500 - 3000 fps	-	Overburden; talus.
3000 - 4000 fps	-	Overburden and/or weathered rock, mostly talus.
4000 - 8000 fps	-	Weathered bedrock. Mostly quartzitic sandstone.
8000 - 14,000 fps	-	Unweathered bedrock. The higher velocities indicate sandstone and some quartzite.

As can be seen in Figure 30 , the talus deposits are quite deep in places, ranging in depth from 40 to 50 feet.

Stability-Hillside and Cuts

The long-term settling of Pa. Route 333, and the continual shedding of colluvium and talus from the small cuts along the road, indicate that a serious slope-stability problem existed along this eastern third of the valley. This stability problem was evaluated from three points of view: the condition and stability of the talus; the mass stability of the hillside; and the stability of fracture systems in the bedrock.

Talus Stability

The talus consists of large boulders ranging in size from one foot to tens of feet in diameter, most being rectangular in shape and lying with the longest dimension parallel to the slope. Although trees cover much of the hillside, several large barren areas occur, consisting of deep accumulations of boulders with little if any fine material.

It is assumed that these talus deposits are at or near static equilibrium (and the presence of the forests tends to support this assumption). That is, for a given slope steepness, each rock of the talus slope has come to rest and further movement can occur only as a result of some disturbance. If the slope is artificially steepened (as in roadcut), then the talus material is put into disequilibrium, and movement will occur.

An example of such instability is presently occurring along Pa. Route 333 in the small roadcuts. The talus is in constant movement even though the cut slopes are near the same angle of repose as the natural talus slopes. Continued removal of the debris at the toe of the slopes (i.e., maintanance on the cuts) results in a permanent state of inequilibrium and perpetuates continual downward movement of rock debris.

Mass Stability

The second consideration is the effect the construction would have on the steep talus slopes above the proposed cuts. Having developed the surface and subsurface profiles (Fig. 30), the nature of the soil and rock material was determined by field investigation.

From this information, stability calculations (see Branthoover, 1972) indicated that the internal friction required for equilibrium (safety factor of 1.0) is higher than can normally be expected in this type of material. Adding a safety factor of 1.25 augments the problem.

Although the talus generally is above the water table, it appears that during periods of sustained precipitation, considerable ground water flow occurs between the overburden and the bedrock. A zone of clay has developed at the base of the talus through weathering processes. Undoubtedly, the effective strength of this zone is reduced by prolonged presence of water and by elevated water levels in the talus slopes.

Rock Stability

The third phase of the investigation consisted of an evaluation of the fracture patterns and their effect on the proposed cuts. Measurements from bedrock exposures constituted the bulk of the data. The fractures maintain a fairly constant orientation to the fold axes, with both strike and dip fractures nearly perpendicular to bedding. The strike fractures thus dip gently into the slope and produce no instabilities in the slope. The dip fractures trend down the slope and similarly do not adversely affect slope stability. However, these fractures in combination with steep bedding (42°) created a potentially unstable condition. This relation holds for both the quartzitic Tuscarora Formation and the argillaceous Rose Hill Formation, and thus it was concluded that slopes of 1:1 in bedrock were necessary to minimize rock fall in both formations. But to construct a slope of 45° in these rock formations would entail enormous removal of material at a large expense.

Conclusions

Based on these three slope stability analyses for the eastern end of the valley, it was concluded that construction on the south side of the river was neither feasible nor economical. Because of excessive slope instability exhibited by the talus, exorbitant excavation costs would be involved in construction of the necessary roadcuts, and considerable effort would be necessary to maintain the cuts in a safe condition.

Although the results of this study were somewhat pessimistic, particularly with respect to the eastern end of the Lewistown Narrows, it was particularly gratifying because the recommendations of the geologic report were heeded and taken into account in the final route location. Because of the excessive slope stability problems in the eastern end of the valley, local desires for placement of the road there were overruled, and the four-lane highway location was placed entirely north of the river.

In contrast, the different topographic relationships in the western two thirds of the valley resulted in a different highway design. Because the Juniata River crowds against the north side of the valley, there is room for only two lanes along the present route if extensive construction is to be avoided. As a consequence, it was decided to bifurcate the highway in the western two thirds of the valley--there the eastbound lanes would be built upon the flatter slopes south of the river.

Thus, the highway designer has responded very sensitively to the geologic and topographic problems present in this valley. But the problems posed by this valley are not unique; although less severe in other gaps, the same geologic problems confront the highway engineer and require the advice of the engineering geologist to evaluate the slope stabilities involved.

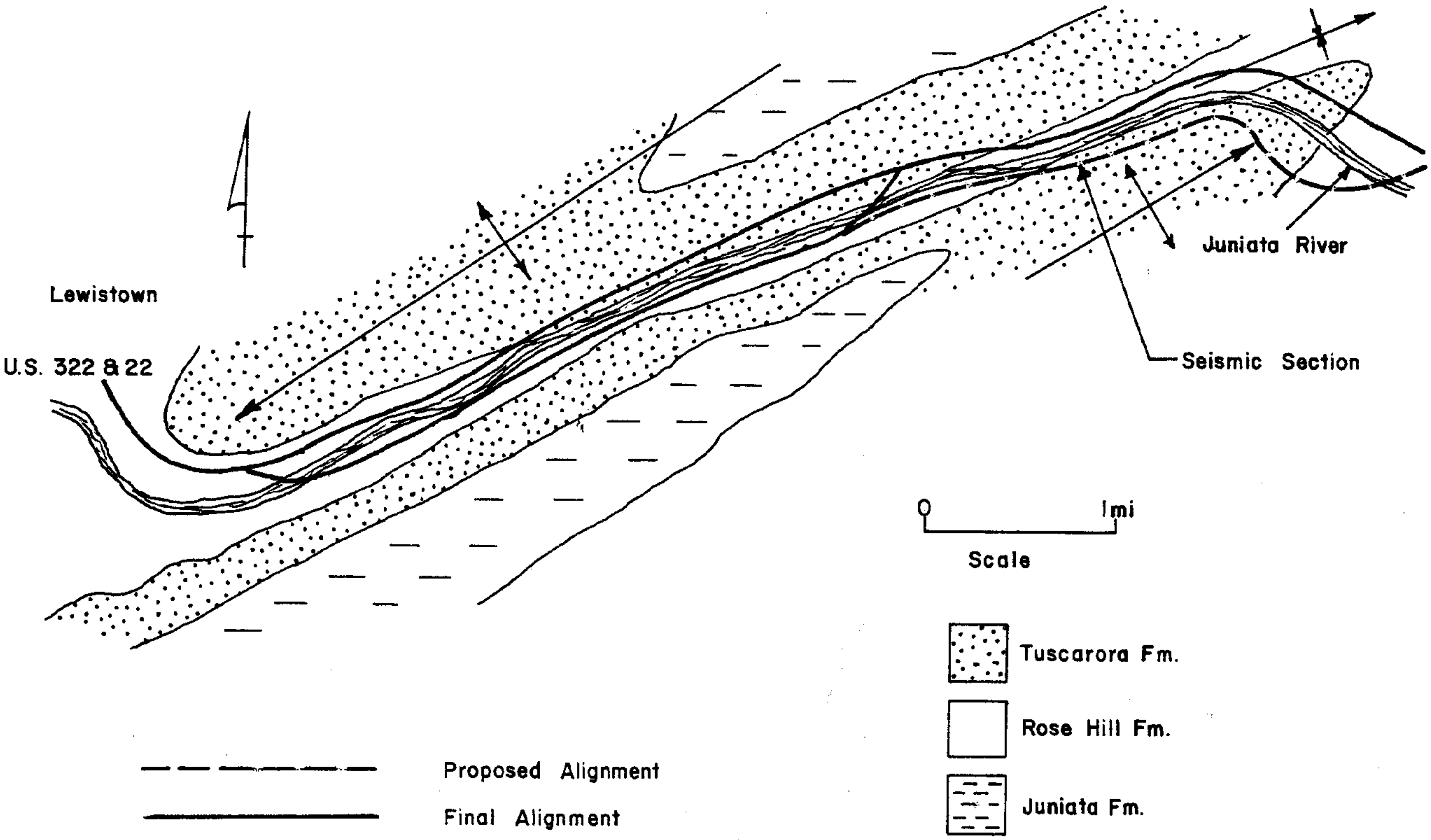

Figure 28

Photograph by Robert Stickel, Geo-Surveys, Inc.

Figure 29

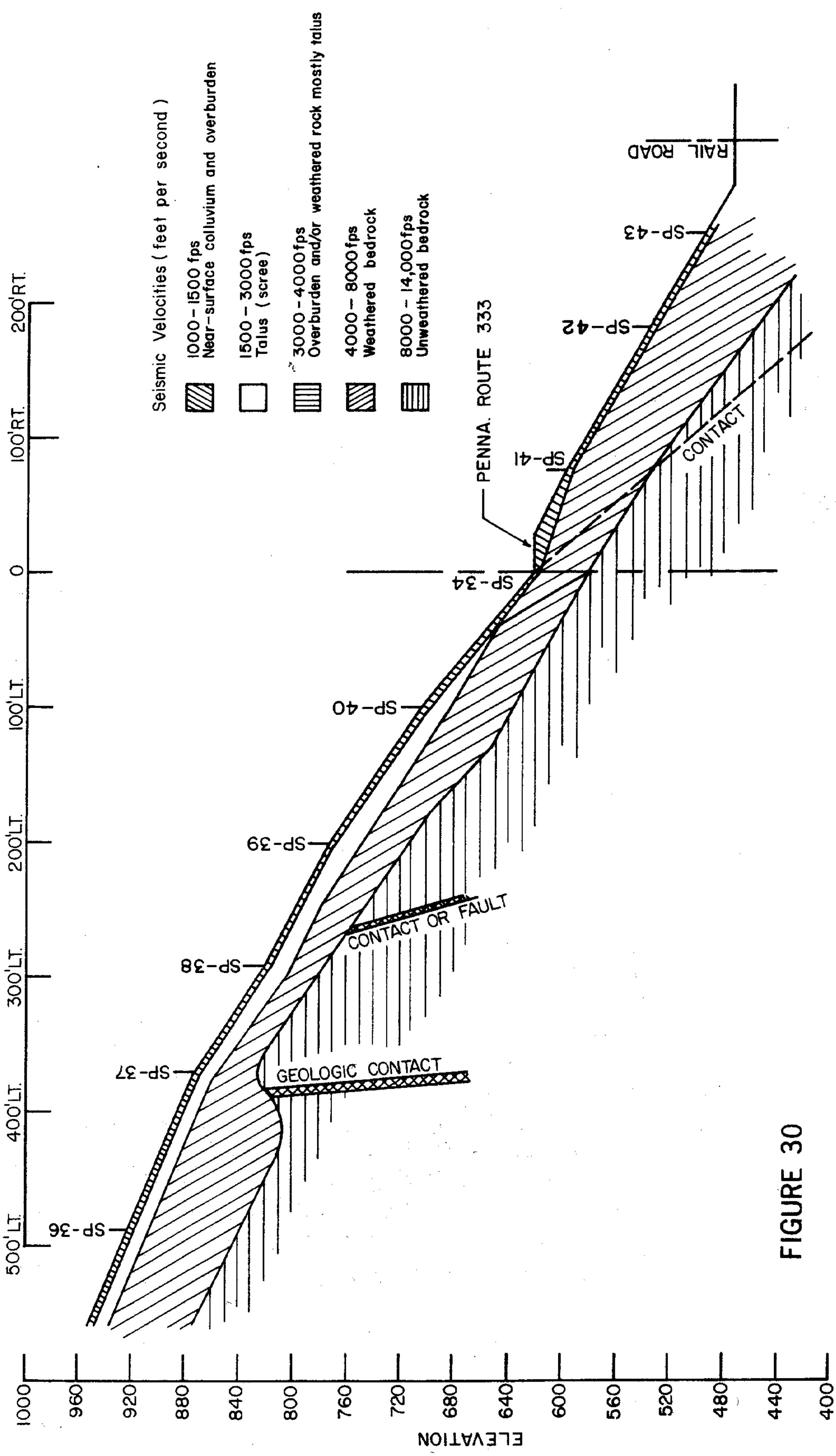
Seismic Velocities (feet per second)
1000 - 1500 fps
Near-surface colluvium and overburden
1500 - 3000 fps
Talus (scree)
3000 - 4000 fps
Overburden and/or weathered rock mostly talus
4000 - 8000 fps
Weathered bedrock
8000 - 14,000 fps
Unweathered bedrock
500'LT.
400'LT.
300'LT.
200'LT.
100'LT.
0
100'RT.
200'RT.
SP-36
SP-37
SP-38
SP-39
SP-40
SP-34
SP-41
SP-42
SP-43
GEOLOGIC CONTACT
CONTACT OR FAULT
CONTACT
PENNA. ROUTE 333
RAIL ROAD
ELEVATION
1000
960
920
880
840
800
760
720
680
640
600
560
520
480
440
400

FIGURE 30

LEWISTOWN LAUREL CREEK DAM
Geologic Related Conditions in Construction

Kenneth A. Young, P.E.

Project Engineer
Gwin, Dobson & Foreman, Inc.
Consulting Engineers
Altoona, Pennsylvania

General Comments

Green Construction Company of Des Moines, Iowa was the General Contractor that built the dam. It should be noted that Green Construction Company has a wealth of experience in this type of construction and some very fine talent within their organization to solve a wide range of construction problems. Some of the people with Green Construction Company made the comment from time to time that this was "a tough little dam to build". This comment was made because there was "no room to work", and there was comparatively little room to set up construction operations of the type required. If you want to think of the formation of the mountains and the narrow valley and the steep slopes as geologic formations--then geology was a problem--but the "gap" through the mountain made the dam site feasible.

Gwin, Dobson & Foreman, Inc. were the Consulting Engineers that designed the dam and supervised the construction. It is the opinion of the Engineer, that there were relatively few construction problems for a project of this type and size, mostly because of the ability of the Contractor.

Core Drilling

Diamond core drilling was done as part of the Geologic Study and design, but difficulties encountered with the core drilling encouraged the decision to use "percussion drilling" for the dam foundation grouting. Core drilling was difficult, slow, and tedious because the quartzite rock was fractured, and hard with vertical bedding planes.

Trench for 60" Conduit

The excavation (in bedrock) of the trench for 60" conduit (between intake tower and outlet control pit-westerly abutment) was very difficult. The fact that the bedding planes of the quartzite are nearly vertical and perpendicular to the alignment of the trench posed a problem in securing the required "vertical" trench side walls. The Contractor used a method of "line drilling" the trench walls, "presplitting" between drill holes, and very careful blasting to secure the desired results. The trench was approximately 11 feet wide and approximately 20 feet to 30 feet deep.

Grouting (To Impound Water)

A reinforced concrete cutoff wall was constructed on the upstream side of the dam along the "contact line" between the dam embankment and bedrock. This cutoff wall was approximately 3 or 4 feet wide and 10 or 12 feet deep (dimensions of wall varied to meet conditions) and was constructed to receive the asphaltic concrete deck and to construct a water tight "grout curtain" into the underlying bedrock foundation. There was provision in the Contract (to construct the dam) to drill and grout through the "cutoff wall" up to a depth of 150 feet. Very few holes were drilled (and tested and/or grouted) to this depth. Mostly the grout holes average 60 feet in depth (holes were drilled and grouted on 3 foot centers). If the bedding planes had been horizontal (instead of nearly vertical), we think that the "grout take" would have been greater and more uniform than it actually was. The fact that the bedrock bedding planes are nearly vertical and the "strike" of the rock is nearly parallel to the axis (alignment) of the dam makes each layer of bedrock (with the exception of some fractures, of course) a potential "watertight curtain". We were a little surprised during construction that more grout was not required.

Rock Quarry

The rock quarry adjacent to the spillway "ogee section" produced a lot of "dirt" and "fines" along with the quartzite stone. The fact that there would be a lot of dirt and fines (material unacceptable for dam embankment) in the "bedrock" in this quarry was not anticipated by anyone. The Contractor had to solve the problem of separating a great volume of fines from the quarried rock to secure acceptable embankment material. Various innovations were made to the rock processing plant in order to mass produce the embankment material.

The highway excavation through the quartzite (above the westerly abutment of the dam) did not indicate that so much "dirt" would be found in the rock taken from our quarry. The geologic study made for the dam indicated that we would get a much larger volume of large rock than was actually produced.

Major Excavations in Bedrock

The excavations for the intake tower and for the spillway structure did not pose any notable problems to the Contractor, because of the background and experience of the key personnel employed by the Contractor.

TROPICAL STORM AGNES
COMMENTS ON THE STORM AND FLOODING

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Harrisburg, Pa. 17105

The great flood of 1936 has been high on the hit parade of historical events in central Pennsylvania for many years. As each successive March anniversary approached, newspaper articles would remind us of its destruction. But, like Henry Aaron swatting away at Babe's 714, Tropical Storm Agnes came along in June of 1972 and made a new mark to be remembered. No one could hit that many homers again, and no storm would ever beat '36! But last March came and went, with hardly a whisper of remembrance. Now it is late June when the "Great Flood" articles appear. Agnes has indeed set a new record to stand for a time. She was a freak, an improbable successor to the title, but she passed the old record with a roar and left one of far greater magnitude, despite her unusual birth.

Weathermen tell us that tropical storms develop in June in the North Atlantic, only once every 2 years. About half of these storms reach hurricane strength. Usually forming in the Gulf of Mexico or the Caribbean, they typically move to the north and into the United States somewhere along the Gulf Coast. They often cause heavy, local rain, and a few have been responsible for extensive damage near their landfall.

Within this probability, Agnes was spawned off Yucatan on June 14, 1972. For a brief period on the 18th and 19th, she was a minimal hurricane, with winds reaching 85 m.p.h. for a short time. Her landfall was near Panama City, Florida, on the 19th, and she rapidly decreased in intensity, as usually happens with hurricanes over land. Her most unusual characteristic, throughout her entire life, was an extremely large area of influence. Satellite photos show her spiral cloud cover to have blanketed an area considerably larger than the Gulf of Mexico on the 14th and 15th. While she tightened-up some during the 17th to 19th, she spread out again over land to immense proportions. At one point, surface pressures were reported to be less than 1,000 mb. from upstate New York to the North Carolina Capes.

Heavy rains in Cuba and along the Gulf caused flooding and serious damage. But the storm's real destruction was to be felt in the Mid-Atlantic States, well after she should have disintegrated. Agnes was not normal. She moved northeastward, from Florida, to the Atlantic Coast near the Virginia-North Carolina line, there to pick up strength and plunge back ashore. Her merger with an extra-tropical low over western New York added hours to her life and inches to her rainfall. Her path was erratic, the rain she dumped was unprecedented over this area, and the resultant flooding and destruction turned the '36 event into an also-ran.

An isohyetal map, showing accumulative precipitation for the period of June 18 to 25, gives the impression that the Susquehanna River Basin was the bull's-eye of an immense, misshapen target. The entire area covered by the 38th Annual Field Conference of Pennsylvania Geologists, received over 14 inches of rain, with a maximum of about 18 inches. Nearly all of the Susquehanna River Basin received over 6 inches in this same period. Complicating the results were moderate amounts of rain, well saturating the ground, in the week before Agnes arrived. With the ground already soaked, most of what Agnes dumped, ran off.

Small streams, already high, flooded quickly. Harrisburg received 5.81 inches of rain on Wednesday, June 21, and by morning, on the 22nd, many small streams were at flood. But Agnes was just getting warmed up. On the evening of the 21st she really began to bear down. Harrisburg measured 12.53 inches in the 24 hours from about 8:00 P.M. on Wednesday.

Most flooding along rivers begins in the headwaters. The '36 occurrence was typical. Heavy snow cover, coupled with warm rains, caused an accumulation of runoff from upstream. As the flows from many tributaries began to combine and move downstream, the flooding progressed from the headwaters toward the river mouth. A flood crest could be followed along and its size and time of arrival reasonably predicted. Not so with the Agnes' flood. Heavy rainfall moved slowly up the basin, and the combination of tributary flows, joining together irregularly, made a shambles of regular predictability. The Susquehanna at Marietta crested on the 23rd at 2400 hours; at Harrisburg on the 24th at 0100 hours; at Sunbury on the 24th at 1300 hours; at Danville on the 24th at 2100 hours; and at Wilkes-Barre on the 24th at 1900 hours. Attempts to plot the travel time of peak prove largely futile, even now. The problems of predicting this same phenomenon, during the storm, can easily be understood.

For most recording stations along the Susquehanna River and its major tributaries, the flood of March 1936 provided the previous flow of record. Many of these stations now have a new standard. In '36, the river at Harrisburg passed 740,000 c.f.s. and reached a gage height of 29.2 feet. Agnes gave a flow of 1,020,000 c.f.s. and a gage reading of 32.5 feet. Some small streams exceeded their old record by several times. Swatara Creek at Harper's Tavern carried 66,700 c.f.s., while its previous high was only 25,300 c.f.s. The Yellow Breeches discharged 15,900 c.f.s. from Agnes, and the previous record was 5,500 c.f.s. The Juniata River at Newport didn't quite make the '36 flow of 190,000 c.f.s., reaching only 187,000 on June 23.

Another measure of the storm's magnitude is the damage she caused. Most of the same areas flooded in '36 were again inundated. Major exceptions are those locations where flood control structures, built in the interim, were effective. The largest difference in loss is the increased value of structures now occupying these same areas. Increased demands for space have brought more and larger developments to the flood plain areas. Losses in the Susquehanna River Basin within Pennsylvania were estimated at about 55,000,000 in 1936. Using an approximate inflationary factor of 5, this amounts to 275,000,000 1972 dollars. While studies to evaluate the Agnes loss are not yet complete, preliminary figures indicate a magnitude of about 10 times the '36 figure. Loss of life, on the other hand, was somewhat less, with 80 known dead in Pennsylvania in '36 and about 50 in '72.

Some lessons were learned in 1936 that were helpful in reducing the loss to Agnes. It was evident that a flood warning system was needed to alert residents and activate protective measures. Such a system was developed in the Federal-State River Forecast Service, and, while severely taxed by the unusual nature of the storm and by failures to portions of its communications system and hardware, it did provide timely warnings to many areas. Although some communities received little warning, the low toll of lives lost to Agnes attests to the systems' worth. This is despite the fact that the '72 storm presented severe problems in prediction. It was apparent in '36 that many of the State's communities were vulnerable. Control dams were placed on many tributaries and were significantly effective in reducing losses in upstream areas. Protective works were constructed for many cities and were effective in most cases. The levee-floodwall system at Sunbury is a notable example. Williamsport was similarly fortunate. Neither community was seriously damaged by Agnes, while both had been devastated in '36.

The example of protective works, which were completely inadequate, is, of course, in the Wyoming Valley. Wilkes-Barre, Kingston, Edwardsville, Swoyersville, Forty-Fort, Pittston and surrounding areas were damaged almost beyond belief when levees were overtopped by several feet. While the protection provided was to the '36 level, it was far short of the task. Timely warnings enabled evacuation and minimal loss of life, but property damages in the valley were near a billion dollars. The levees do not tell the entire story for Wilkes-Barre, however, as additional protection for this and the upstream areas of Corning and Elmira have not yet been completely constructed. Storage dams on the upper reaches have been long proposed, and though under design at present, are not complete.

Some lessons from '36 which may seem apparent were overlooked or ignored. Foremost among these is the fact that river flooding is a natural, recurring event. While we have made attempts to quantify the probability of such recurrence, we must recognize that our period of record is short (less than 100 years in most cases). Our studies of meteorology, while making significant advances in the recent past, only serve to reinforce the unpredictability of so large an event as Agnes. Yet, we continue to develop and build in areas which have been muddied before, perhaps many times. If we continue to washup and cleanup, and nothing more, we can only expect more damage and loss. Maybe this year, maybe next, maybe in 500 years, but sooner-or-later another flood will come.

Arguments can be heard, which advance two extremes of opinion regarding the course of action we should now follow. There are those who advocate the abandonment of all flood plain areas, with reconstruction on higher ground. There are those who advocate total protection with dams and levees. A reasonable compromise must result. That floods will recur, and lowlands be covered, must be accepted. Our use of these areas must be geared to tolerate this fact. But to leave all of the locations we now occupy, move and rebuild, is as unreasonable as ignoring flood recurrence. The cost would be immense, and the additional land lost to urbanization in prime areas would be a severe environmental detriment. A combination of wise control and use must result. We must accept the fact that such locations as along Cameron Street in Harrisburg, clearly part of the river's channel in recent geologic past, are vulnerable. While we can control floodwaters to a degree with storage impoundments, such heavy rainfall as in June 1972 will cause local effects often as severe as main stream inundations. Harrisburg would have had serious problems from Agnes even if the river had been dammed at First Mountain.

To be realistic, our planning for the combined use and control of river basin areas must be comprehensive. We must include an overview of not only local flooding but of the topography, geology, meteorology and land use. We must examine environmental effects as diverse as land surface loss from impoundment and urban relocation, to the estuarine damage from siltation and migration of the saltwater-fresh water interface. Changes in runoff characteristics must also be examined. If we forget, overlook, or ignore the lessons of '36, as reinforced in '72, the next record flood will establish new highs in loss. Agnes did not produce the maximum possible flood. Care to guess when it will happen?!?!

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HISTORICAL SKETCH - JUNIATA AND SUSQUEHANNA RIVERS

Richard B. Wells

The area traversed by the field trip is not only fascinating from a geological point of view, but is also rich in human history and culture. Many historical events and sites are marked by roadside signs; most of those seen on the field trip are entered in the road log. This brief sketch is included here to supplement the road log and focuses on the main historical events that occurred in this area: early Indian history, the French and Indian War, and the development of the canal system.

The cultural history of this region begins with Indian history. The oldest known evidence for Indian activity, dated at 10,000 years B.P., is from the Sheep Rock site on the Raystown Branch of the Juniata River near Huntingdon. According to legend, the earliest occupants were the Allegheny or Alligewi Indians, who were probably the moundbuilders of western Pennsylvania. Before the arrival of European settlers, they were overrun and exterminated by two strong tribes; the Algonquins (Lenni Lenape or Delawares) who occupied the Delaware Valley; and the Iroquois who lived in central New York.

During the early 1600's war over the fur trade occurred between the Iroquois and the Susquehannocks, so named by Capt. John Smith of Virginia. The French called these Indians Andaste and Gandastaques from which came the name Conestoga, a name applied to the Susquehannocks in later colonial history. The Iroquois did not fare well in this war until the Dutch began selling them firearms in 1640. This enabled them to turn the tide, and started the Iroquois on a military conquest in which they defeated the Juniata tribe, and, by 1675, the Susquehannock tribe. With their new weapons, the Iroquois were well on their way to establishing a "Roman Empire, Indian Style" in North America, reaching as far as Minnesota and Missouri. In so doing, however, they overextended themselves, and unintentially aided European colonization by leaving vast areas occupied only by disarmed, defeated, and somewhat disorganized Indians. This inter-tribal warfare was a big factor in the rapid and relatively peaceful early expansion into large areas of Pennsylvania.

When William Penn arrived on the scene in 1682, the Iroquois had claimed all of the interior of Pennsylvania by right of conquest. This was recognized as a legal right by the Penns, who regarded Indians as equals and who then proceeded to purchase these conquered lands from the

Iroquois. Excluded was the land in Delaware Valley, which was purchased from the Delaware Indians.

The Indian policy of Penn, that of purchasing land rather than forceful taking, contributed strongly to the rapid settlement of Pennsylvania. His contacts with Indians resulted in relative peace until the French and Indian War of 1747 and was contributory to the peace agreement signed in 1758 between the Province of Pennsylvania and the Iroquois. The neutrality of the Iroquois during the French and Indian War was a decisive factor in early Pennsylvania history.

The Delaware and Shawnee Indians joined with the French in attacking western Pennsylvania. After the defeat of General Braddock's army the frontier was defenseless and raids occurred in central Pennsylvania. Out of this crisis came approximately 200 defense forts largely located just south of Blue Mountain paralleling the north edge of the Great Valley. Simon Girty, the famous renegade, was captured near Lewistown during one of the raids.

The eventual defeat of the French and their Indian allies opened the Pennsylvania Frontier to further rapid settlement and additional purchases of land by the Penns.

In the early part of the 19th century, following the forming of our nation, westward migration began in earnest as a period of relatively peaceful expansion returned to the frontier. The major ports for immigration were New York, which provided access to the west via the Hudson River and the Erie Canal, built in 1825 across New York State, and Baltimore, which lay at the beginning of the trail across the Cumberland Gap. The businessmen of Philadelphia could see the decline of that port as the major immigration and trade business was siphoned off through New York and Baltimore.

In order to keep Philadelphia competitive, a major trade route to the interior had to be established across Pennsylvania. This route was a combination of rivers, an extensive canal system, and a portage railroad across the Susquehanna - Mississippi drainage divide. By 1834, the canal system was opened to Pittsburgh, with a branch serving the upper Susquehanna Valley as far as Lewisburg. The system was built by the State and nearly bankrupted by it. Most of the canals were sold to the Pennsylvania Railroad in 1857, and were used until 1900. It was a major factor in the settlement of central and western Pennsylvania, and the western interior of the United States, and, fulfilled its original purpose of maintaining Philadelphia as a major port on the eastern seaboard.

ROAD LOG OF FIELD TRIP

Friday, October 5, 1973

Mileage

0.0 Entrance to parking lot behind (south of) Penn Harris Motor Inn. Turn left (north) onto Erford Road. Time of departure: 8:00 A.M. Approximate travel time to Stop 1: 40 minutes.

0.1 Turn left onto ramp to Harrisburg bypass. Proceed eastward to Harrisburg.

0.9 West bank of Susquehanna River.

1.7 East bank of Susquehanna River, Front Street. Proceed one block eastward to Second Street.

1.8 Second Street. Turn left and proceed north on Second Street, U.S. Routes 22-322.

2.8 The Executive Mansion is on the left, the official residence of the Governor of Pennsylvania. This mansion was completed just 5 years ago, and was flooded on the first floor in the June, 1972 flood.

3.8 Division Street. Turn left, following U.S. Routes 22-322.

3.9 Front Street. Turn right, proceed northward on Front Street, following U.S. Routes 22-322.

5.3 Overpass of Interstate 81 bridge across the Susquehanna River. Ahead is the famous Susquehanna River Gap, one of the few major water courses through Blue Mountain, the southern edge of the Valley and Ridge province. On each side of the river, the first ridge (from the south) is underlain by the Tuscarora Formation (Silurian), with a lesser ridge immediately to the north underlain by the Montebello Member of the Mahantango Formation (Middle Devonian). The next major ridge, Second Mountain on the east and Cove Mountain on the west, is underlain by the Catskill Formation (Upper Devonian) and the Pocono Formation (Mississippian). These two clastic sequences underlie most of the major ridges and mountains throughout the entire Valley and Ridge province. The third major clastic sequence, the Pottsville Formation (Pennsylvanian) will not be encountered on this field trip, although a number of ridges underlain by the Pottsville Formation occur only 10 to 30 miles east of the Susquehanna River.

6.2 Intersection with Pa. Route 39. Proceed northward on U.S. Routes 22-322. Ahead is the Rockville Railroad Bridge, the longest stone arch railroad bridge in the world. It is 3,830 feet long and consists of 48 arches, each of which span 70 feet. Built only of large quartzite blocks and mortar, it has withstood the numerous floods which have destroyed many other bridges across the Susquehanna.

7.0 Rockville Railroad Bridge. The riffles (rock exposures) in the river south of the bridge are outcroppings of the Tuscarora Formation; the riffles north of the bridge are the sandstones of the Montebello Member of the Mahantango Formation. These beds are vertical to overturned, and constitute the southernmost exposures of the Valley and Ridge province. The large descent in structural level, at this point, called the Blue Mountain Structural Front, is the boundary between the Valley and Ridge province to the north and the Great Valley terrain to the south. Although this is a very significant structural boundary, the rocks here do not appear to be greatly deformed--aside from the subvertical bed attitude, only small subhorizontal faults are present. However, in new exposures in Blue Mountain just east of and above the Rockville Bridge, more extensive faulting in the Tuscarora Formation may represent a significant zone of disruption or distortion.

7.8 Intersection with Pa. Route 443. Proceed northward on U.S. Routes 22-322.

8.4 Exposures on the right above the railroad tracks are of the Catskill Formation, Clark's Ferry and Duncannon Members. At mileage 9.4 is the contact between the Catskill and Pocono formations. In contrast to the subvertical beds at Rockville Bridge, these rocks are considerably overturned. This overturning, though, appears to be restricted to a relatively small area, for these attitudes do not persist for any great distance to the east or west along this ridge, Second Mountain.

9.5 Intersection with Pa. Route 225. Proceed northward on U.S. Routes 22-322.

9.7 Borough of Dauphin.

10.6 Large borrow pit in the Mauch Chunk Formation (Mississippian). The material excavated from here was used in making the ramps for the Interstate 81 bridge approaches because the mudrock and silty shale compact well. Notice that the excavation has been graded and planted with grass rather than abandoned as an open borrow pit.

10.8 Small borrow pit in the Mauch Chunk Formation that is sporadically used for local fill purposes.

11.4 Mauch Chunk Formation in roadcut on the right.

11.7 Scenic overlook tower. This is approximately the hinge of the Cove Mountain syncline, the southernmost first-order syncline in the Valley and Ridge province. As we have seen from the Rockville Bridge to here, the rocks are subvertical to overturned. In the north limb of this syncline, the beds are only moderately (south) dipping. As with most first-order folds in the province, the Cove syncline is doubly plunging. The western end (eastward plunging) begins at approximately the Susquehanna River and extends for 10 miles to the west. Through the trees on the left (west) one can obtain an occasional glimpse of Cove Mountain (underlain by Pocono and upper Catskill) on the horizon as it doubles back from the west to join Peters Mountain north of us. Approximately 30 miles east of here, this syncline merges with the Buffalo-Berry syncline (the next first-order syncline to the north) to form the Southern Anthracite Field, the eastern end of which occurs (in a westward plunge) some 40 miles further to the east. The entire valley we are driving through now, from Second Mountain on the south to Peters Mountain ahead, is underlain by the Mauch Chunk Formation. One mile to the east is the end of Third Mountain, the westernmost extent of the Pottsville Formation (Pennsylvanian) in the hinge of this syncline.

12.0 Small outcrops of the Mauch Chunk Formation intermittently for the next mile or so.

13.8 Intersection with Pa. Route 325, Village of Speeceville.
Large outcrop of Mauch Chunk Formation just north of intersection on the right.

14.5 Beginning a long cut exposing the Pocono and Catskill formations. The cut begins (on the south end) with the lower portion of the Pottsville Formation (Spechty Kopf Member) and continues stratigraphically downward through the Duncannon (type section), Clark's Ferry (type section), and much of the Sherman Creek members of the Catskill Formation. The Clark's Ferry Member is areally the most restricted of the three -- although it is recognized 80 miles to the northeast at the Lehigh River, it extends for less than 10 miles to the north along the Susquehanna. In contrast, both the Sherman Creek and the Duncannon can be recognized along the Allegheny Front, some 65 miles to the north at Williamsport and 80 miles to the west at Altoona.

14.8 Vertical 100-foot-wide Triassic diabase dike occurs behind low concrete retaining wall.

15.8 Intersection with Pa. Route 147. Turn left onto Clark's Ferry Bridge across the Susquehanna River. This is the confluence of the Susquehanna and Juniata rivers. The Susquehanna, one of the major rivers of eastern United States, drains most of central and north-central Pennsylvania, as well as portions of western New York. It is 448 miles long, originating at Otsego Lake, New York, and emptying into the Chesapeake Bay at Havre-de-Grace, Maryland. The name Susquehanna was derived from the Susquehannock Indian tribe that lived in its lower valley until the late 1600's. The Juniata River, its major tributary, drains most of the western and southwestern part of the Valley and Ridge province. Its name was derived from the Juniata, Chiniata, or Onojutta Indian tribe, which occupied this river valley until the mid-1600's.

16.3 North end of Clark's Ferry Bridge. Proceed north on U.S. Routes 22-322.

17.0 U.S. Routes 11-15 exit to the right. Proceed north on U.S. Routes 22-322. The Pennsylvania Canal System was constructed in the early 1800's along most of the State's major waterways to provide easy transportation of goods around the State. The Juniata Division was built in 1828 to 1833, and extended from here, where it joined the Susquehanna Division, to the eastern end of the Allegheny-Portage Railroad at Holidaysburg, a distance of 127 miles. Just west of here, the canal crossed the Juniata by an aquaduct which was used until 1901. The abutments and piers of this aquaduct remain to this day.

19.6 Exit to Watts (Township). Basal Catskill is exposed in adjacent roadcut on the right. In addition, a rather large kink band (40 feet across) dips approximately 45 degrees to the north. Beds within the kink band have been rotated southward some 60 degrees from the 10 degree south dip of the enveloping bedding.

20.0 Approximate contact between the Trimmers Rock and Catskill formations. The next several large roadcuts are in the Trimmers Rock Formation. A few faults and a number of small folds of various complexities can be seen throughout these exposures, both along this northbound lane and along the southbound lane below us on the left.

20.7 Anticlinal fold hinge in the uppermost conglomeratic sandstones of the Montebello Member of the Mahantango Formation (Middle Devonian). Overlying these sandstones and exposed to the south, particularly on the southbound lane below us to the left, are the 2-plus upward-coarsening cycles of the Sherman Ridge Member of the Mahantango Formation.

21.2 To the right is an outcrop of the Montebello sandstone, which also forms the riffles in the Juniata River to the left.

21.8 Riffles in the river formed by the Ridgeley sandstone member of the Old Port Formation. The Ridgeley is exposed to the right at the "Midway sign". The Onondaga Formation is exposed in an old quarry just to the right, hidden behind trees. Exposures at the top of the cliff above the road are the sandstones of the Montebello as they pass through the hinge of the New Bloomfield anticlinorium, the southernmost first-order anticlinorium in the Valley and Ridge province.

22.1 Midway exit ramp. Roadcut on the right exposes vertical beds of the Montebello sandstone in the north limb of the New Bloomfield anticlinorium. The valley just to the north is underlain by the Sherman Ridge and Tully Members of the Mahantango Formation (Middle Devonian) and Harrell Formation (Upper Devonian).

22.6 These next three large cuts expose the lower part of the Trimmers Rock Formation (Upper Devonian). Along the south shore of the Juniata River on the left are steeply north dipping beds of the Montebello sandstone. Note that the dips in this north limb of the New Bloomfield anticlinorium, as well as in the south limb of the Cove Mountain synclinorium, are much steeper than those in the other limb of the folds, indicating an apparent asymmetry in these first-order folds.

24.9 First exposures of the red beds in the Catskill Formation peeking out underneath the ubiquitous Crown Vetch.

25.9 Exit ramp to Newport. Intersection with Pa. Route 34.

26.1 Bridge over Route 34. To the left, along Pa. Route 34, are excellent exposures of the Catskill Formation, Sherman Creek Member. The transition between the Irish Valley and Sherman Creek Members is exposed in cuts visible further south along the same road.

27.4 Beginning of Catskill Formation (Duncannon Member) exposures in hinge of the Buffalo-Berry synclinorium. The outstanding feature is the upward-fining fluvial cyclicity that is characteristic of the upper part of the Catskill throughout the Valley and Ridge province in Pennsylvania. STOP V today will be below us on the left along the southbound lane.

28.6 Crossing Perry Valley which is underlain by Upper Devonian Trimmers Rock and Catskill formations in the south limb of the Tuscarora anticlinorium (north limb of the Buffalo-Berry synclinorium). The fairly continuous exposures of the Catskill and Trimmers Rock formations along the Penn-Central Railroad tracks on the west side of the Juniata River can be seen intermittently on the left. The dip is a rather constant 40 degrees south ($\pm$ 10 degrees) for 2.3 miles from near the Buffalo-Berry hinge to a faulted fold structure just south of Millerstown, and constitutes one of the better examples of the planar bedding even in the largest of the folds in the province.

29.8 Contact between the Catskill and Trimmers Rock formations (not well exposed along this road).

30.5 Exit ramp to Millerstown and Pa. Route 17. On the left are exposures of the Montebello Member; on the right the Turkey Ridge Member, both of the Mahantango Formation. Just before the overpass on the right (this side of the ramp) is the grass hidden Marcellus Formation in the hinge of a third-order fold.

31.2 Bridge (Pa. Route 17) across the Juniata River on the left.

32.0 Beginning of Tuscarora sandstone exposure and hinge of the Tuscarora anticlinorium. See STOP I Appendix for discussion of structure.

32.4 Exposure of erosional scours and channels in the Tuscarora quartzite on the right.

32.5 On the slope on the right is the base of the Silurian Rose Hill Formation in contact with the Tuscarora. There are two thin green sandstones at the base of the Rose Hill which may correlate with the Castenea Member of the Tuscarora.

32.6 Perry County - Juniata County Line.

33.3 The Center iron sandstone, which extends from the top of the roadcut eastward into the woods.

33.7 STOP I. THE MIDDLE SILURIAN FORMATIONS AND SOME COMMENTS ON FOLD GEOMETRY. Allotted time: 60 minutes. Estimated time: 8:40 A.M.

DISCUSSANTS: Richard Wells, Rodger Faill

This stop is located just north of the hinge of the Tuscarora anticlinorium. Throughout this entire roadcut, the beds dip moderately and uniformly to the north-northwest at about 30 degrees. So there are no interesting folds or kink bands present in this exposure. However, interesting fold structures do occur nearby, particularly the geometry of Tuscarora anticlinorium, which is discussed in the Appendix at the end of this Stop I description. In this exposure itself, the ubiquitous fractures are the primary structure in this exposure, two aspects of which are worth noting. In contrast to the more or less poorly to well-developed fractures in the rest of the rocks, the fracture sets in the sandstones in the Rose Hill Formation are particularly well organized into two planar sets. In most of the exposures in this region, there are two fracture sets in the rocks, both of which are perpendicular to bedding and subperpendicular to each other. In these Rose Hill sandstones however, the two fracture sets are both subperpendicular to bedding, but only 50 degrees apart from each other.

These two non-orthogonal orientations produce a distinctive angular effect to the rock in this exposure. These fracture orientations are not developed in the finer grained and less silicified shales and siltstones above and below the sandstone beds.

Another feature worth noting in this exposure are slickensides on one set of fractures in the sandstone beds (Fig. I-A). Slickensides are indicative of movement on fracture surfaces, and so their orientations are significant. First, the slickensides are restricted only to those fractures that are subnormal to the bedding strike--slickensides on other fractures have not been observed. The other aspect of the slickensides are their attitude relative to bedding. Without exception, the slickensides are at a very small angle (less than 10 degrees) to the fracture-bedding intersection (Fig. 1-A). This indicates that there was bed-parallel movement on these fractures which are normal to the bedding strike. These slickensides are not observed on fractures in other rock types nor are they observed on bedding surfaces. Although elsewhere they can be related to movement on wedge blocks, there is no evidence of wedging in this outcrop. Therefore, the significance of these slickensides is not well understood.

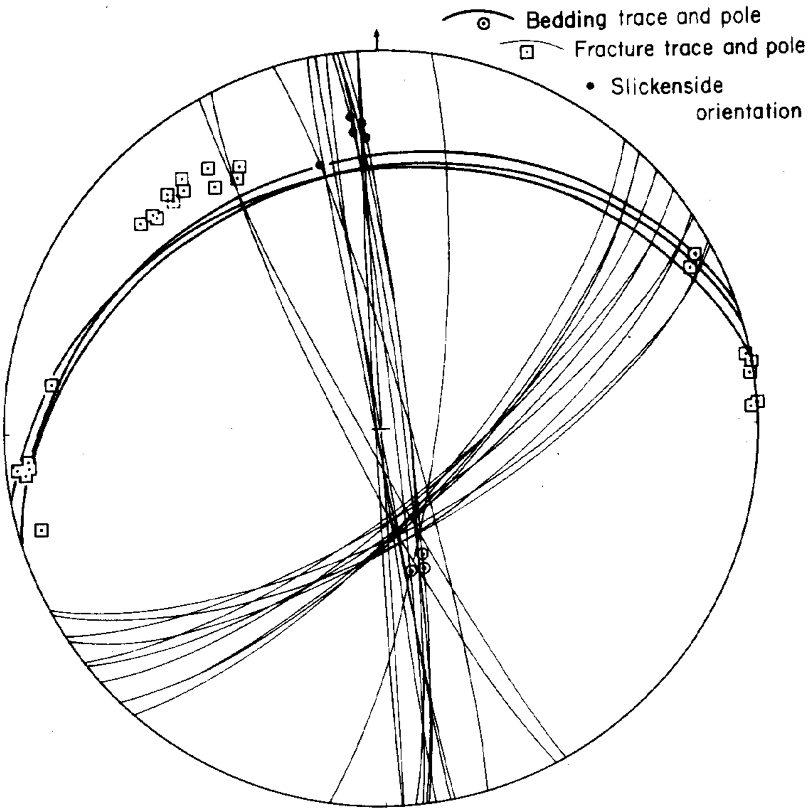


Figure 1-A Stereonet display (equal area) of the two sets of fractures in the siliceous sandstones of the Rose Hill Formation. Fractures of both sets are subnormal to bedding, but fractures of one set are only 50 to 60 degrees to the other set. Slickensides subparallel to bedding only on the one set.

STRATIGRAPHY

<u>The Middle Silurian (Niagaran)</u>: the Rose Hill, Keefer, Mifflintown and Bloomsburg formations.

This recent roadcut, virtually 100 percent exposure of the upper part of the Middle Silurian, is the most complete in central Pennsylvania and has been designated a reference section (Faill and Wells, in press).

Rose Hill Formation

The gray shales of the Rose Hill are punctuated by two thick, red hematitic sandstone units, the Cabin Hill and Center Members, which impart a five-fold subdivision to the formation. The lower units of the Rose Hill are well exposed a mile or so farther southeast along this highway, and the lowest beds to be seen at STOP I are in the middle shaly member. The Rose Hill shales are slightly silty, at best only moderately fissile, have a dull to sub-waxy lustre, and become highly calcareous only in the upper member. They are interbedded with thin beds of gray, ripple-marked siltstone, and, in the upper member, with gray, thin-bedded bioclastic calcarenite limestones.

Up-section (to the west) the gradually increasing amount of sandstone marks the transition from the middle shaly member to the Center "iron sandstone" Member. The "iron sandstones" are dark reddish gray, nearly black, very fine grained hematitic sandstone and sandy siltstone, with ripple marks, flaser bedding, load casts, and a great variety of miscellaneous twig-like burrows and sole markings. Interbedded gray to grayish-green shales reflect varying iron content or differences in oxidation state. Notice that, although the sandstones may appear at first glance to be very constant in thickness, some beds pinch out within 50 or so feet, and commonly occur as discrete lenses and laminae in the enclosing shales.

The first fossiliferous bed, characteristic of the upper shaly member, occurs approximately 70 feet east of Milepost 0-65, yet they are not common until one reaches this milepost. Beyond here, the fossil hash beds are dominant, and the iron sandstone beds are almost completely absent. The uppermost 30 to 40 feet of this member is quite calcareous.

Keefer Formation

The prominent light gray sandstone unit at the top of the Rose Hill is the Keefer Formation. The Keefer is a very fine to coarse grained, silty fossiliferous sandstone that locally contains hematitic layers rich enough for exploitation by a local iron ore industry during the Nineteenth Century. Cementation is quite variable in the Keefer. Part of it is highly siliceous, part is cemented by calcite or hematite, and part is very porous and friable. In this section it is thin to medium bedded, but elsewhere in this vicinity it is thick bedded to massive, yielding float blocks one or two meters in diameter. Silica-cemented Keefer beds are distinguishable from the Tuscarora quartzite only by the fossils in the Keefer.

Mifflintown Formation

The Mifflintown is an interbedded sequence of gray calcareous shale and thin bedded, bioclastic limestone. The shales come in various shades of gray and olive, are locally very fossiliferous, and in the lower part bear a strong resemblance to the upper part of the underlying Rose Hill Formation. In the middle part of the Mifflintown, some of the shale beds become high carbonaceous, almost black in color, and carry small pyrite crystals.

The limestones in the Mifflintown are dark gray bioclastic calcisiltite, composed of silt-size calcite grains and disarticulated ostracod fragments. Traces of pyrite, hematite, limonite, and carbonaceous matter are common in many of the limestone beds, and locally there are traces of oil staining. There are also a number of beds of intraformational limestone breccia.

Bloomsburg Formation

Regionally, the Bloomsburg is primarily a red shale and claystone interval, with two sandy units, one near the top and the other at the base. Only the basal 23 feet of the Bloomsburg is exposed here, but more of it will be seen at STOP VIII.

The lower sandstone in the Bloomsburg is a grayish red, fine grained, poorly sorted hematitic subgraywacke, which is usually quite argillaceous and silty. It is medium and thin bedded, planar bedded, and commonly has between 5 and 10 percent porosity (estimated from thin sections).

SEDIMENTATION

The Middle Silurian reflects the generally "quieter" environment that followed the termination of the Upper Ordovician-Lower Silurian clastic wedge, the Taconic cycle.

The Rose Hill Formation was deposited in a variety of transgressive nearshore environments (tidal flats, lagoons and offshore). Most of the sands were deposited above wave base, along a shoreline that supported an active community of burrowing organisms. Other organisms, principally trilobites, lived over muddy bottoms in water that was probably somewhat deeper and quieter. The red color and high hematite content in the Center Member indicates that iron was being brought in and deposited along a coastline where either (1) oxidizing conditions prevailed or (2) deposition was so rapid that equilibrium could not become established.

The thin fossiliferous limestone stringers suggest times when sediment supply was diminished, and conditions of more normal marine temperature and salinity prevailed with communities of bryozoans, brachiopods and pelecypods.

The Keefer sandstone likewise represents shallow marine conditions, in an environment where sediment supply was abundant, wave and current action was effectively removing most of the silt and clay, and a variety of organisms could flourish. Regionally, the Keefer is a widespread, thin blanket of sand with a very small thickness-to-area ratio, which occurs between two thick, shaly marine units. This implies deposition in a shoreline or barrier island environment which was migrating across a wide marine shelf without being localized at any one place for very long. The upper and lower contacts of the Keefer suggests it is a regressive deposit. The interfingering at the base indicates a gradual shoaling and westward advance of the shoreline. The sharp upper contact, which may be erosional, represents a rapid transgression which left little sedimentary record.

The Mifflintown Formation marks the return of shallow marine shale and limestone deposition in an offshore neritic and intertidal environment near a low lying coastal plain. The presence of intraclasts and intraformational breccias represent disruption and resedimentation of semi-consolidated lime mud within the reach of storm waves. The ostracods and oolites suggest sedimentation in lagoonal areas, periodically made brackish by the inflow of fresh water from coastal streams.

The Bloomsburg Formation is part of the widespread Bloomsburg-Vernon delta complex which covered much of central New York and Pennsylvania. Farther east, the Bloomsburg is a non-marine, fluvial deposit, the product of sedimentation in meandering rivers and on floodplains. In central Pennsylvania, the Bloomsburg is apparently transitional between this eastern, continental facies and the predominantly marine carbonates, shales, and marls which are present farther west.

STOP 1, APPENDIX

The Tuscarora anticlinorium is characteristic of many of the first-order folds in the Valley and Ridge province. These major folds have been described for many years as parallel, or concentric, and at first glance they appear to be so, particularly in exposures such as the Tuscarora hinge that we just passed on our way to this stop (Fig. 1-B). However, what we are seeing in this exposure is only a part of the Tuscarora fold, and a very small part indeed. This exposure is only 0.6 miles long, yet the wavelength of the Tuscarora anticline is 11 miles.

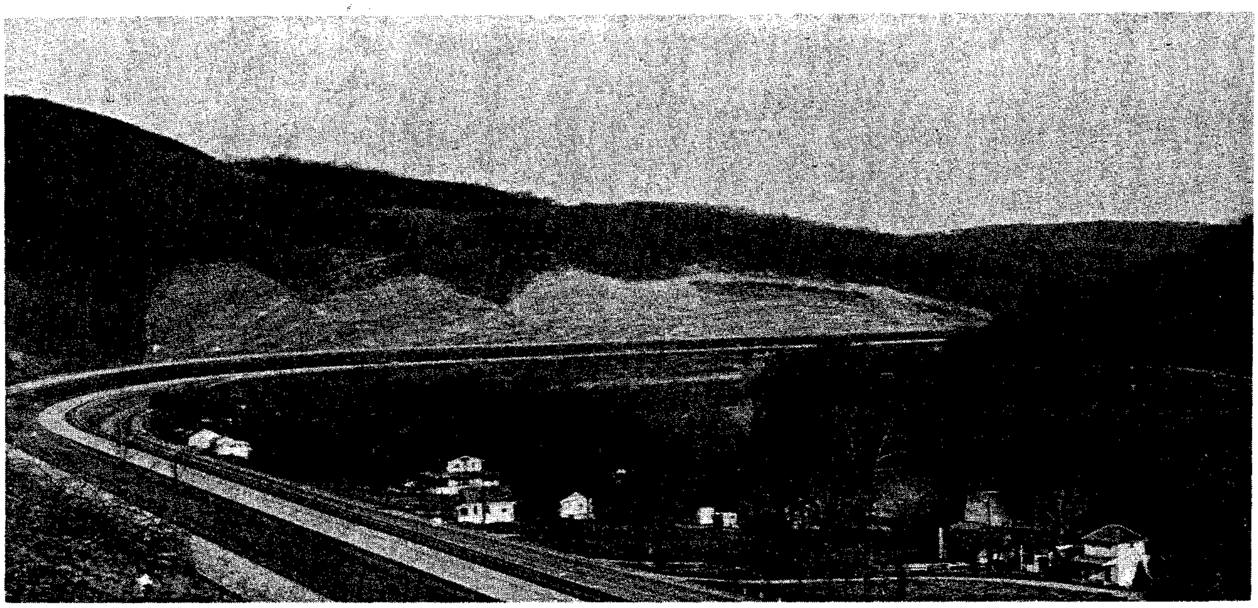


Figure 1-B Hinge of the Tuscarora anticlinorium in the Juniata River gap north of Millerstown. Although the hinge possesses a concentric geometry, it is but a small part of a non-concentric, kink band fold.

But it is the total geometry of this fold that does not fit the concentric fold model. In a concentric fold, the radius of curvature must be at least 1/2 of the fold wavelength, and 1/2 of the structural relief. The radius of curvature in the hinge of the Tuscarora anticline in this exposure is 4,200 feet (0.8 miles)--yet the wavelength is 9 miles and the structural relief is 2.7 miles (Fig. I-C). Clearly, this fold does not possess a concentric profile. Furthermore, the bed attitude does not progressively increase as one moves away from the hinge as it should in concentric folds. In this anticline, the bed attitude increases 50 to 60 degrees within 1/2 mile of the fold hinge--from this point southward to the Buffalo-Berry synclinorium hinge (with the exception of a faulted fold) the bed attitude remains fairly constant at approximately 40 degrees south dip. This constancy of bed attitude over rather large areas is an aspect of the structure that is encountered over and over again throughout the entire province, as in the Cove syncline, illustrated in Figure 4 of the Structural Geology text. As a consequence, folds in the Valley and Ridge province cannot be reconstructed in cross section using the concentric arc methods of Busk (1929).

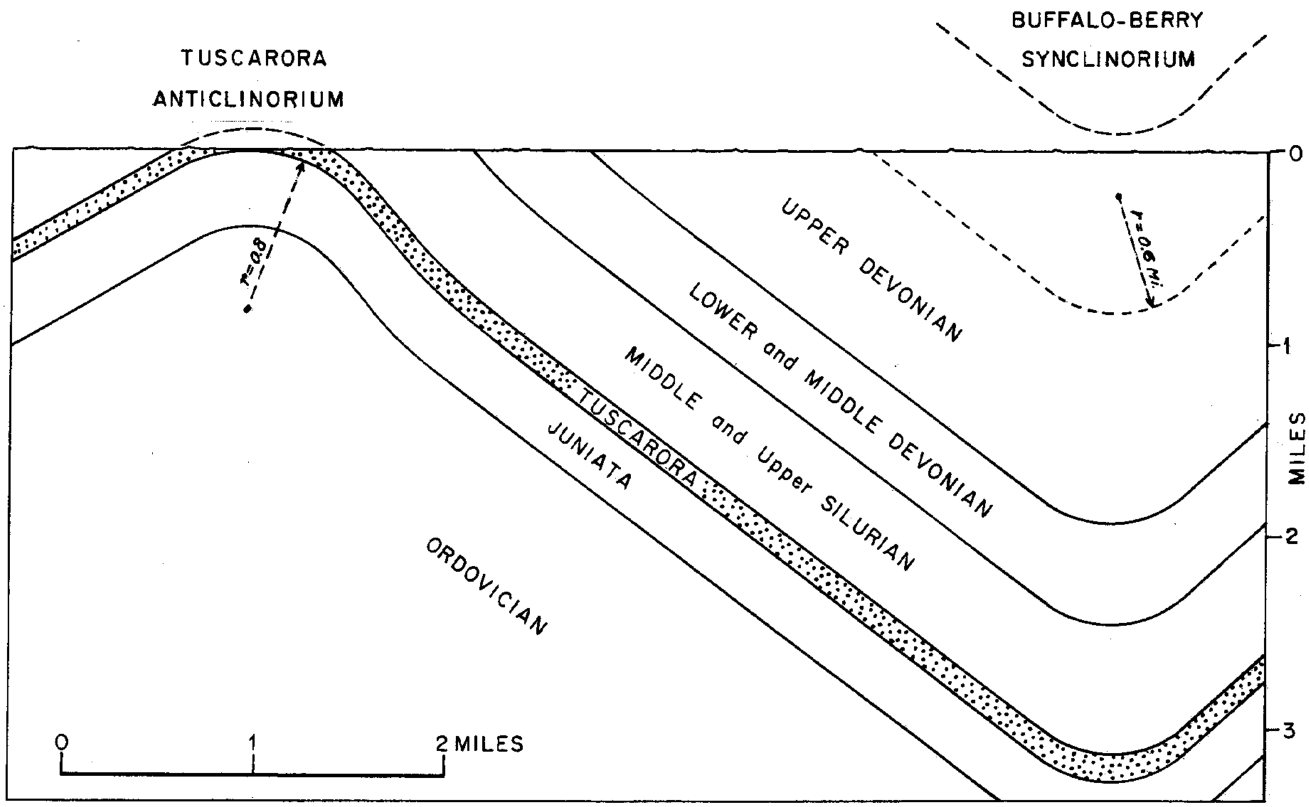


Figure I-C Simplified cross-section of south limb of the Tuscarora anticlinorium (north limb of the Buffalo-Berry synclinorium). The radii of curvature calculated from exposures in both hinges are much too small for these folds to be concentric.

Returning to the Tuscarora anticline, another aspect of it should be discussed--the change in geometry of its hinge. The Tuscarora anticlinorium plunges about 4 degrees to the east-northeast. At the Juniata River, the cross-sectional geometry of the hinge is a simple anticline (Fig. I-D). 0.3 miles to the east, the hinge is conjugate, with an interlimb 0.1 miles across. 0.2 miles further east, two small anticlines are present on each side of the interlimb. Further eastward, both of these anticlines plunge to the east and enlarge, with a decrease in the flat bottom syncline (interlimb) between them. The fold on the north changes trend to a more easterly direction and becomes the hinge of the anticlinorium; the anticline on the south persists in its trend, and diminishes in size and vanishes. Four miles east of the Juniata River, the hinge of the anticline is once again a simple fold area.

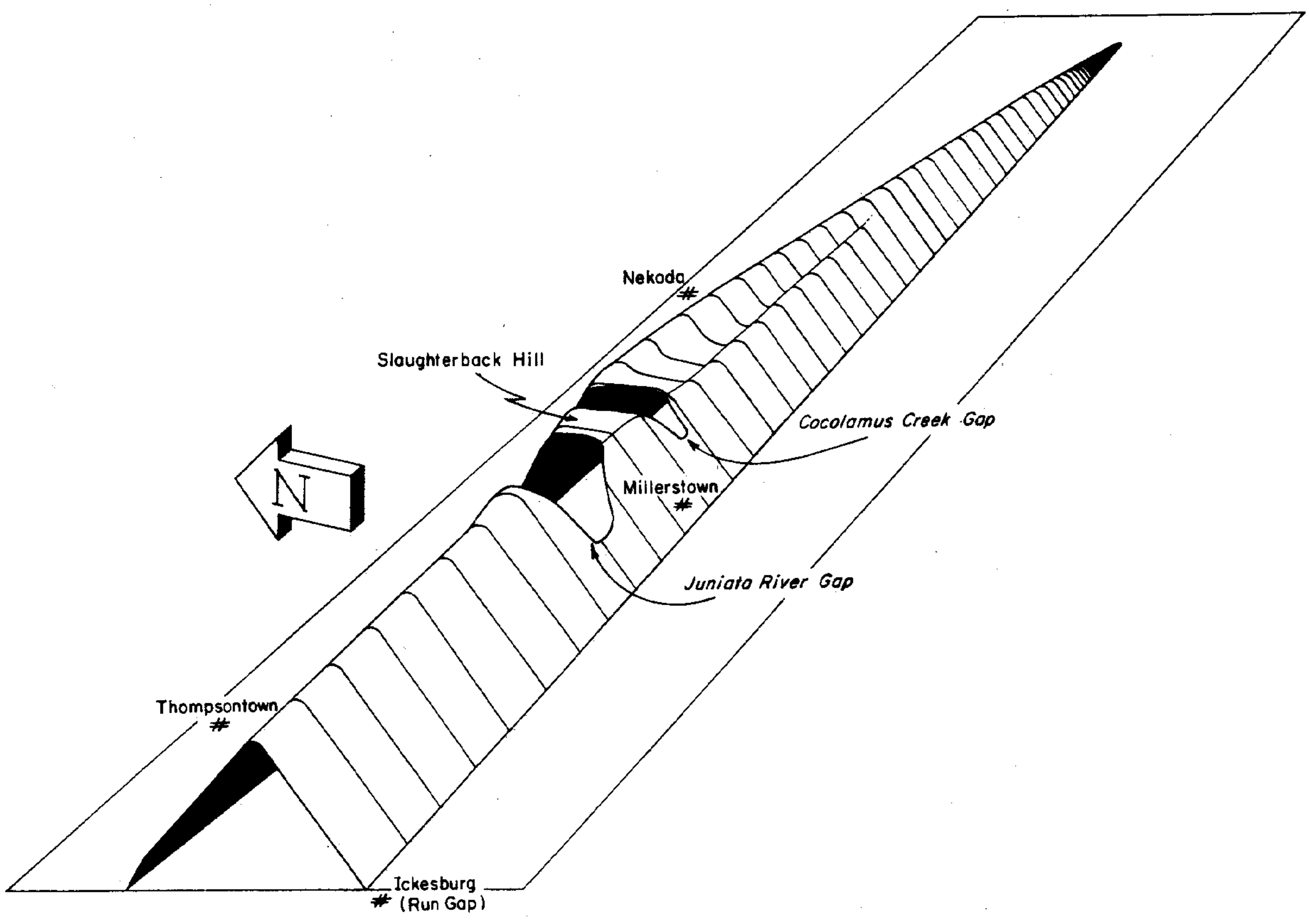


Figure I-D Variation of the Geometry of the Tuscarora anticlinorium hinge along trend where it changes from a cylindrical fold in the west to a plunging non-cylindrical fold in the east.

Now, this interpretation can be argued. No single cross-section exhibits all of these fold forms, and no single bed exhibits all these changes in structure along trend. The Tuscarora Formation exhibits the simple anticline at the Juniata River. The conjugate form and the two small anticlines are expressed in the Rose Hill, Keefer and Bloomsburg formations. The larger pair of anticlines with the diminishing intervening syncline are expressed in the Bloomsburg, Wills Creek and Tonoloway formations. The simple anticline at the east end is expressed in the Keyser and Old Port formations. The point that can be argued is whether this change in geometry is real regardless of a lithic type involved. That is, are these small structures on the hinge of this major fold a result of a major tectonic trend change, or are they a reflection of different responses of different lithic sequences (formations) to a fairly uniform tectonic environment. This difference in interpretation bears directly on the discussion of the applicability of a concept of lithic tectonic units to this province as discussed in the Structural Geology text. Evidence for and against each interpretation will be found at a number of the stops for the next two days.

33.9 Reboard buses parked at Milepost 0-70 at west end of roadcut. Estimated time: 9:40 A.M. Approximate travel time to STOP II: 20 minutes. At the time of this Field Conference, construction of the new U.S. Routes 22-322 was well in progress. An alternate log to STOP II is provided after the one for the old route.

34.5 Intersection with road down Little Pfoutz Valley, which is underlain by the Upper Silurian shales and limestones (Wills Creek, Tonoloway and Keyser formations). The ridge on the right is underlain by the sandstones of the Mahantango Formation. 3 1/2 miles to the east, in the Cocolamus Creek gap through these ridges, are excellent exposures of the Lower and Middle Devonian Old Port, Onondaga, Marcellus and Mahantango formations.

35.9 Intersection with road to East Salem and McAlisterville, eastern part of Thompsontown.

36.2 Center of Thompsontown and intersection with Pa. Route 333.

36.7 U.S. Routes 22-322 follows this valley for 6 miles to the village of Mexico. The rolling topography in the fields is underlain by the Tonoloway Formation, a land form characteristic of this stratigraphic unit developed in response to the extensive underground solution weathering. The low ridges on the north side (to the right) are underlain by the Middle Devonian sandstones and siltstones of the Mahantango Formation. To the south (on the left), Tuscarora Mountain, is underlain by the Silurian Tuscarora and Ordovician Juniata formations. This mountain, constituting the hinge of the Tuscarora anticlinorium, extends from Millerstown southwestward for nearly 25 miles. At this point, the Tuscarora anticline plunges and terminates, and the hinge of the Tuscarora anticlinorium shifts southward two miles to the Conococheague anticline. The Juniata River follows the southern edge of this valley along the north flank of Tuscarora Mountain from

Mexico to Millerstown, where it turns southward across the plunging nose to resume its southeastward course across the structural grain. The fairly extensive cover of alluvium with rounded cobbles and boulders over much of this valley indicates that the Juniata River flowed over the rest of the valley in the not too distant past, perhaps during the waning stage of the Illinoian and/or Wisconsinan ice advances. The cleared areas on the side of the mountain belong to the Susquenita Ski Area that had been under development for several years.

38.1 Village of Locust Run.

40.3 Village of Center.

42.7 Village of Mexico.

43.7 Intersection with Pa. Route 75. In the vicinity of Port Royal, about a mile west of here, was the beginning of the Tuscarora Path which terminated in the Tuscarora Region of North Carolina. It was initially used by the Five Nation Iroquois in raiding Indian tribes to the south, and later by early traders and settlers.

45.3 The railroad cut along the low hills to the left across the Juniata River is STOP II, called Rainbow Rocks because of the folded alternating red and buff colored layers of the Wills Creek Formation.

46.0 Center of Mifflintown. Intersection with Pa. Route 35 at stop light. Turn left onto Pa. Route 35, cross the Juniata River.

46.3 Center of Mifflin, on west side of the Juniata River across from Mifflintown. Turn left onto Juniata Street (Pa. Route 35). Proceed south on Juniata Street for 4 blocks to Parker Street. Turn left, go one block, turn right on River Drive. Proceed south on River Drive to end of road at sewage treatment plant.

46.8 Park in gravel parking lot next to baseball field. Estimated time: 10:00 A.M.

Alternate Route to STOP II, following the new, 4-lane U.S.Routes 22-322

33.9 Reboard buses parked at Milepost 0-70 at west end of roadcut. Estimated time: 9:40 A.M.

34.2 Exit ramp to local roads, with low cut in Bloomsburg Formation.

34.9 Roadcut to north along exit ramp to Thompsontown. Exposed are Middle Devonian Onondaga, Marcellus and Turkey Ridge units.

35.1 Bridge over Delaware Creek.

35.3 Mahantango Formation (Turkey Ridge and Dalmatia Members) in cuts on southbound lane, with steep north dip.

35.7 Vertical to steeply south dipping dark shales and sandstones of the Dalmatia Member.

37.0 East dipping Dalmatia sandstones exposed in steep cuts to right and left.

37.6 Massive bedded Turkey Ridge sandstone, east dipping in cut to north.

38.0 Nearly flat lying black shales of the Marcellus Formation exposed in south and northbound lanes.

38.7 Light gray layers of argillaceous limestone in contact with Marcellus in drainage gutter to north.

39.0 Cut to right shows poor exposure of black Marcellus shale with Turkey Ridge at top of hill. Onondaga Formation is exposed to the left in a small hill left between north and southbound lanes. Contact of Onondaga and Marcellus and exposure of Tioga metabentonite occur approximately halfway up on this small medial hill.

40.3 Onondaga shale and limestone exposed in low cut to right.

40.7 Onondaga shale and limestone exposed in low cut to left in southbound lane.

41.5 Marcellus black shale exposed in road gutter to north.

41.7 Dalmatia sandstones exposed in hinge of Linestone Ridge syncline.

41.8 Contact of thick bedded Turkey Ridge and thin bedded Dalmatia sandstones in cut to right.

41.9 Fault-repeated Turkey Ridge sandstones in contact with underlying Marcellus black shale exposed to right.

42.0 Bridge over Doe Run.

43.2 Exit.

43.7 Long cut exposes grassed over red Bloomsburg and varicolored Wills Creek Formations.

45.0 Exit to Pa. Route 35. Turn left, follow Pa. Route 35 westward to center of Mifflintown.

46.5 Stop light, intersection with old U.S. Routes 22-322 in center of Mifflintown. Proceed straight (westward) on Pa. Route 35 across the Juniata River.

46.8 Center of Mifflin, on west side of the Juniata River across from Mifflintown. Turn left onto Juniata Street (Pa. Route 35). Proceed south on Juniata Street for 4 blocks to Parker Street. Turn left, go one block, turn right on River Drive. Proceed south on River Drive to end of road at sewage treatment plant.

47.3 Park in gravel parking lot next to baseball field. Estimated time: 10:00 A.M.

Walk westward across baseball field, across drainage ditch and onto cinder road parallel to the tracks. Turn left and walk south along this road. In the first few hundred feet, an anticline and syncline are poorly to moderately well exposed. At the end of a moderately long stretch of north dipping beds (the south limb of the syncline) is an anticlinal hinge, which is Station 2 of Figure II-B.

STOP II: "RAINBOW ROCKS", AN EXPOSURE OF FOLD GEOMETRY AND MINOR STRUCTURES IN THE WILLS CREEK FORMATION.
Allotted time: 90 minutes.

DISCUSSANTS: Richard Nickelsen, Rodger Faill

Stratigraphy: Wills Creek and Tonoloway formations.
The succession of calcareous shale and limestone cycles of the Wills Creek Formation over the red mudstones of the Bloomsburg Formation reflects the eastward retreat of the shoreline of the Bloomsburg-Vernon delta. The cyclicity, the presence of algal mats, and evidence of high salinity indicate that the Wills Creek environment was an arid tidal flat with very low wave energy, in which alternating subtidal, intertidal, and supratidal sediments were deposited. Two successions of calcareous siltstones and sandstones in the middle and upper part represent influxes of quartz-rich detritus.

The lower part of the Wills Creek exhibits extensive large-scale (10 to 30 feet) interbedding of gray shales and limestones and grayish red silty mudstones, which represents a lateral shoreline fluctuation. The increasing amount of red beds to the east points to an interfingering of the Wills Creek into the Bloomsburg, and an eastward shift up-section of the contact between the two. To the west and south, the Wills Creek occurs lower in the section than here, at the expense of the Bloomsburg.

The upper contact of the Wills Creek with the Tonoloway Formation is very gradational and interbedded. The upper part of the Wills Creek (apart from the siltstones and sandstones) contains more limestone than the underlying parts, and the lower part of the Tonoloway contains a fair proportion of gray shale interbedded with limestone. To the north and

Folds along Railroad tracks and Juniata River south of Mifflin, Pa.

and west, the upper part of the Wills Creek increases in limestone content, and thus grades laterally into the Tonoloway Formation.

The lesser amount of fine detritus in the Tonoloway indicates deposition further from the source area than suggested by the Wills Creek lithologies, yet the laminated beds, dessication cracks, and anhydrite laminae throughout much of the Tonoloway point to a continued intertidal environment, one that was occasionally interrupted by a more normal marine environment in which medium bedded, fossiliferous micrites were deposited.

In this exposure at Rainbow Rocks, the lower part of the Wills Creek Formation is displayed, with portions of it repeated along the railroad cut because of the extensive folding. Many of the sedimentary structures and features typical of the Wills Creek are present here, such as the interbedding of red and gray mudstones, thin limestone beds alternating with calcareous shales, dessication cracks etc. These features will be pointed out during the structure discussion, for the variation of structure with lithology is an important aspect of the Valley and Ridge deformation observable here.

Structure. First, a short note on the regional setting. STOP II is located in the center of the Valley and Ridge province (Fig. I, Introduction). To the north is the Shade Mountain anticlinorium, and to the south is the Tuscarora Mountain anticlinorium, both of which expose Upper Ordovician and Lower Silurian rocks. STOP II rests in the hinge of the intervening synclinorium (Fig. 2, Introduction), underlain by Middle and Upper Silurian and Lower Devonian rocks. As is so common in the Valley and Ridge province, this synclinorial hinge is comprised of several second-order synclines arranged in an en echelon pattern. The exposure along these tracks occurs in the hinge of one of these second-order synclines, and consists of a train of third-order folds.

Turning now to the fold geometry, recall that the Appendix to STOP I pointed out that the large, first-order folds in the Valley and Ridge province are not concentric, but, rather, possess narrow hinges and planar bedding (constant bed attitude) in the limbs. But this geometry is not easily appreciated in folds this large, for nowhere can such a fold be seen in its entirety from a single vantage point. This railroad cut at Mifflin exposes much smaller third-order folds which can be examined along their entire length. As with the first-order folds, these third-order folds are not concentric--rather, they possess narrow hinges and planar bedding in the fold limbs (Fig. II-A). In each of the 3 anticlines and 2 synclines, the change in bed orientation from one limb to the other occurs within a narrow zone (the fold hinge). Thus, the radius of curvatures are much less than the fold wavelengths.

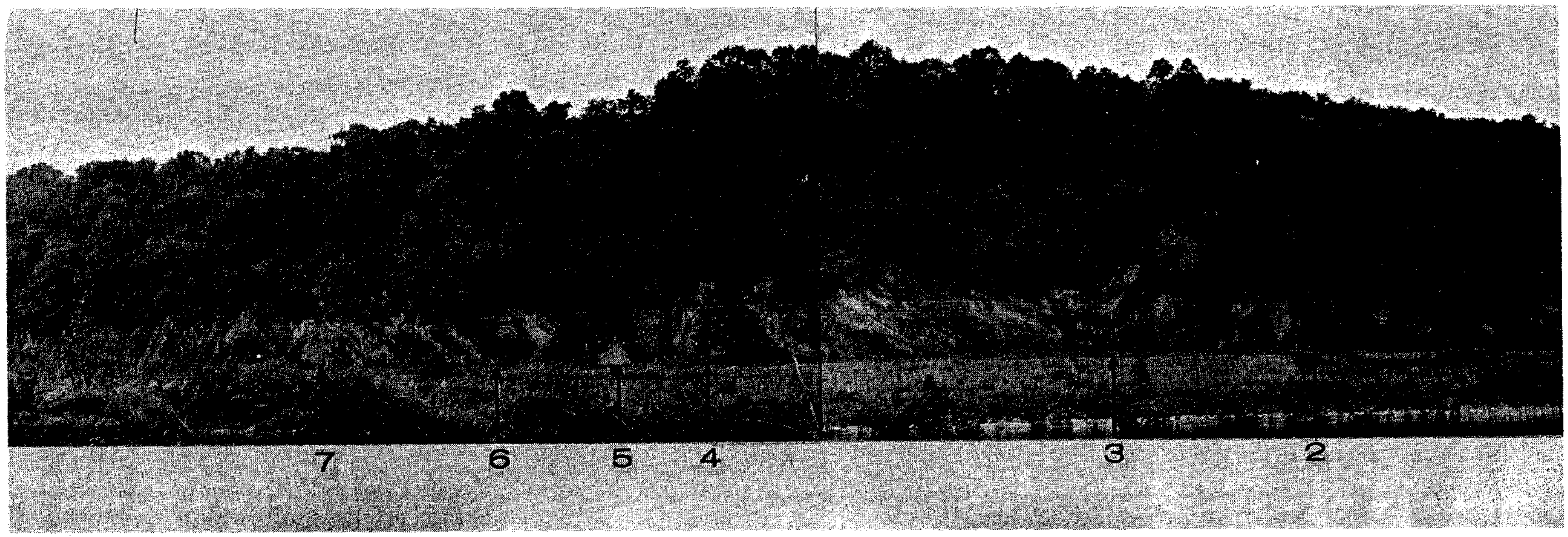


Figure II-A Rainbow Rocks, the exposure of several third-order anticlines and synclines in the Wills Creek Formation on the west side of the Juniata River south of Mifflin. Stations to be visited along the outcrop are indicated by numbered arrows.

Between the fold hinges, the bed attitude remains fairly constant. As pointed out before, this geometry is common throughout the entire Valley and Ridge province, in folds of all sizes, ranging from hand specimen size to the largest in the province. And, this geometry conforms neither to concentric (parallel) folds, nor to similar folds.

Although slickensides are not common on the bedding surfaces in this exposure, they are frequently encountered throughout this province. The presence of these slickensides on bedding surfaces indicates that slip has occurred along the bedding surfaces. In addition (and this can be seen in this exposure), the bed-normal thickness of the layers does not change appreciably around the fold. There is little or no thinning or thickening of beds in one limb as opposed to the other limb, even though the steepness of bedding can differ greatly between the two. Although there is some thickening of beds within the fold hinges (to accomodate local space problems), it is remarkable that so many of the beds pass through the hinge with virtually no change in bed-normal thickness. These two aspects of folds, the constant bed-normal thickness and the slickensides on bedding, indicate that the deformational mechanism by which these folds developed was flexural slip. In flexural slip folds, deformation within layers is confined to bedding surfaces and associated low-angle faults (wedges).

Yet, the natural world is never as simple as the theoretical model that one creates to explain it, and this is amply demonstrated in this railroad cut. In walking through this exposure, one will see numerous structures in the rocks which do not accord well, or are even inconsistant, with the flexural slip mechanism just described. In that Dr. Richard Nickelsen will describe these "inconsistant" structures, it may seem that two geologists looking at the same rocks see two entirely different deformations. In a sense, this impression is correct, for the total deformation in these rocks is more complex than the simple fold geometry suggests. However, the apparently contradictory details should not obscure appreciation of the overall fold geometry. In walking from one fold hinge to the next, keep in mind that the monotonously constant dip of bedding in the fold limb you are passing is just as much a part of the fold as is the more interesting hinge.

We turn now to the "inconsistant", minor structures which consist of cleavage, "micro-folding", and stylolite-like clay-carbon partings. (They are minor only with respect to size as compared to the third-order folds--they have as much significance as the folds in terms of the total deformation). This Stop is broken into 6 stations along the railroad cut, beginning with Station 2 (Fig. II-B).

Station 2 - At this station a tight anticline with an interlimb angle of 65° shows excellent fracture cleavage in ductile shales fanning upward through an angle of 45°. This cleavage has been rotated 10° toward the axial plane on each limb of the fold. In less ductile thin limestones and sandstones, cleavage remains nearly perpendicular to bedding. On the crest and south limb of the fold a later fracture cleavage dipping 65° to 80° north has been superimposed on bedding and the early cleavage. In the crest of the fold, faulting and drag along planes parallel to the cleavage has disrupted and folded the early cleavage. The core of the fold shows characteristic complex folding in limestones, probably related to late fold flattening or lack of room for flexing below the fold center of curvature.

Station 3 - At this open syncline with an interlimb angle of 120°, homogeneous strain in different rock types has been accomplished by either micro-folding, wedging or cleavage development. Ductile shales have cleaved, sandy mudstones have shortened by wedging, and thin-bedded limestones and sandstones have micro-folded. If we assume that strain has been approximately equal from bed to bed it is possible to compute how much shortening is associated with the penetrative strain that has led to cleavage development, using the shortening expressed by trains of disharmonic, intrabed micro-folds. Two such determinations have been made. In the limestone layers exposed at (a) just to the south of the trough of the syncline 30% shortening is recorded in a train of small amplitude folds that extends for a distance of approximately 3 feet. In thin sandstone beds at the top of the sandy mudstone to the north of the synclinal trough (b) 57% shortening is recorded in a train of folds extending for a distance of 6 inches. These amounts of shortening are both probably unrepresentative and too high in value - similar determinations elsewhere have yielded values of 15 to 20% in folded layers adjacent to well-cleaved rock. Although no late cleavages are present here as they were at Station 2, it is possible that post-folding flattening has occurred locally near the trough of the fold to increase shortening. If it could be measured accurately at all points on the large folds, the shortening expressed as wedging, cleavage development and micro-folding should be added to the strain recorded by the folds, in order to find the total strain.

Station 4 - South of the faulted anticline of Station 4, interesting features are present at a, b, and c. At a a micro-folded thinly-bedded limestone shows 27% shortening parallel to bedding, whereas at the next thinly-bedded limestone b 12% shortening is recorded. In the thicker limestone at c no micro-folding is present but bed parallel shortening of unknown amount has occurred by pressure solution. The bedding surface is intersected by strike joints containing thick, clay-carbon partings resulting from solution of calcite and residual accumulation of clay. Fracture-bounded blocks of the bed have been displaced perpendicular to bedding either by slip along cleavage or solution juxtaposition of irregularities. Figures II-C and II-D show that the thick, clay-carbon partings are not part of a penetrative structure; they are separated by intervals of 1/2 to 2 inches of uncleaved limestone.

Station 5 - A prominent syncline with fanning cleavage - used only as a reference point.

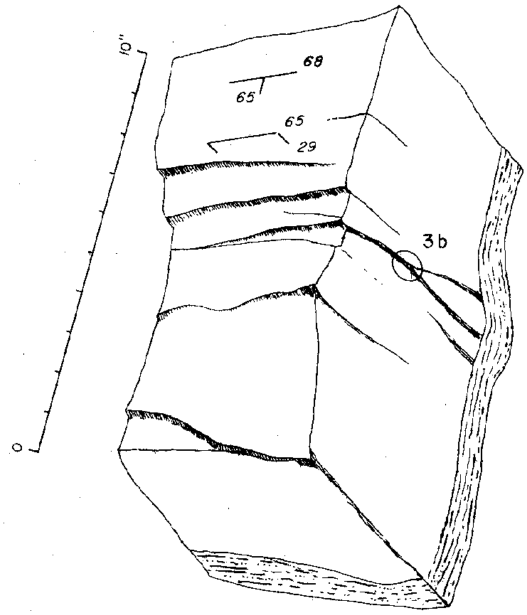


Figure II-C Schematic drawing of a block collected from a limestone bed at Station 4, c, illustrating the strike-parallel clay-carbon partings formed by pressure solution. These partings have also been zones of displacement between adjacent, intact blocks, resulting in a stepped bedding surface.

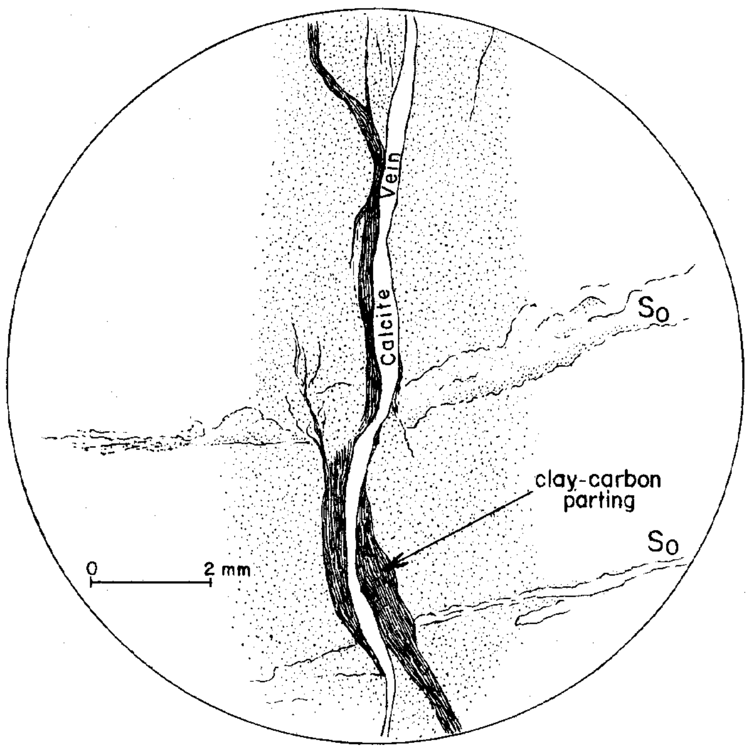


Figure II-D Camera lucida sketch of a clay-carbon parting in thin-section. The partings developed by solution of the calcite and residual accumulation of clay.

Station 6 - A variety of sedimentary rock types on the south limb of the syncline at Station 3 demonstrates the different structural behavior of different lithologies. From north to south we encounter:

a. thin-bedded limestone with micro-folding
b. thin-bedded sandstone with micro-folding
c. thin-bedded limestone with micro-folding beheaded by bedding plane slip during flexural slip folding
d. well-cleaved reddish mudstone
e. intensely micro-folded, thin-bedded, fissile limy shale
f. dolomitic limestone with larger folds and stylolite-like clay-carbon partings perpendicular to bedding

Bed parallel shortening is accomplished by micro-folding in thin bedded limestone and sandstone, by fracture cleavage development in mudstones, by micro-folding in thin-bedded fissile shales, and by longer wavelength folding and solution in thicker-bedded dolomitic limestone.

Station 7 - This major anticline is faulted and asymmetric to the south. Beds have been thickened in the core by fracture cleavage, by intra-bed wedging as in the lower beds of the core, and by wedging duplication of bed as in the upper part of the anticline. The south limb has ridden up over the crest and north limb along a bedding fault that contributes to thinning along the south limb and breaks through the crest of the anticline.

South of Station 7 nothing new is seen but there are repetitions of features previously pointed out; micro-folds in thin-bedded limestones, well-cleaved mudstones and sandy mudstones, and thick, clay-carbon partings in thicker-bedded limestones produced by solution and residual accumulation of insoluble clay.

<u>Summary</u> This railroad cut at Mifflin exposed two general aspects of the Valley and Ridge deformation: 1) a moderately brittle, non-penetrative folding by slip on bedding surfaces and associated wedges; and 2) a more ductile, penetrative deformation consisting of cleavage development, micro-folding, and solution activity. Mechanically, these two aspects are mutually exclusive, but the evidence suggests that the more ductile, penetrative processes preceeded the more brittle folding. The implication then, is that the deformation proceeded from a ductile phase to a more brittle phase. Apparently cleavage development spanned both phases to some extent.

In addition, we have seen how different lithologies (or lithic sequences) have responded differently under the same deforming environment. Thick, argillaceous beds have developed cleavage, less argillaceous beds solution clay-carbon partings, and laminated beds micro-folding. This pattern of different responses seems to lend credence to the concept of litho-tectonic structural units. Or does it?

Reboard buses. Estimated time: 11:30 A.M. Approximate time to STOP III: 35 minutes.

46.8 Return to center of Mifflin along River Drive, left on Parker Street, right on Juniata Street.

47.3 Intersection of Juniata Street and Main Street, center of Mifflin. Turn right on Pa. Route 36, and proceed eastward across bridge to Mifflintown.

47.6 Center of Mifflintown, intersection of Pa. Route 35 and U.S. Routes 22-322. Turn left at stop light, proceed north of U.S. Routes 22-322.

47.9 Red beds in the exposure on the right are in the Bloomsburg Formation. The buff-colored beds 200 to 300 feet to the south are in the lower Wills Creek Formation.

48.1 Limestones and calcareous shales exposed in the borrow pit and along the road on the right constitute the Type Section of the Mifflintown Formation, the central Pennsylvania replacement of the Rochester and McKenzie formations of older literature.

48.7 Crossing Lost Creek. Large mountain ahead is Shade Mountain, an anticlinal mountain underlain by the Tuscarora, Juniata and Bald Eagle formations. The lower terrains south of the mountain are underlain by the Lower and Middle Silurian Rose Hill to Wills Creek formations.

51.2 Junction of old U.S. Route 22 and new U.S. Route 22.

51.4 Tuscarora Formation exposure in hinge of Blue Mountain anticline.

52.1 Lewistown Narrows. For the next 5.5 miles to the west, the Juniata River and U.S. Routes 22-322 follow the synclinal valley between the anticlinal Shade Mountain on the north and the Blue Mountain on the south. Both of these mountains are underlain by the Tuscarora and Juniata formations; the Rose Hill Formation underlies the center of the valley. At mileage 51.4, we crossed the eastward plunging hinge of Blue Mountain; 6 miles ahead, our route crosses the westward plunging Shade Mountain hinge. Although the Shade Mountain anticlinorium extends for approximately 60 miles from the eastern Broad Top region southwest of here to the Anthracite region in the east, the hinge of this continuous structure is not a single fold. Rather, the hinge consists of six separate folds, ranging in length from 4 to 25 miles. These folds are offset from one another in an <u>en echelon</u> pattern, so that one is plunging as an adjacent one is rising. The opposing plunge and intervening syncline between the two anticlinal mountains (Shade and Blue Mountains) in the Lewistown Narrows here is a good example of the <u>en echelon</u> structure and the lateral shifting of the anticlinorium hinge.

As can be seen along the road side to the right, and on the mountain side across the river to the left, extensive talus and colluvium deposits cover these mountain slopes. Because this valley is so narrow, this talus material cannot be avoided when building roads through here, and it presents rather severe engineering problems. The article in this guidebook by Gerald L. Branthoover describes the engineering geology aspects of this valley.

53.3 Rose Hill Formation exposed on north side of road.

54.4 Mifflin County - Juniata County Line.

54.6 Scree slope of Tuscarora boulders on the right.

55.1 Across the river to the left is the small village of Hawstone. On the northern slopes of Blue Mountain above this village are several quarries in the Tuscarora quartzite, which is used for making silica brick. The numerous switchbacks on the side of the mountain are railroad grades, most of which are now abandoned, by which the quartzite was brought down to the furnaces in Hawstone. The quartzite is not "quarried" here in the usual sense of the word, but is obtained by simply removing weathered boulders and cobbles from the upper slopes and transporting them down the mountain.

55.7 Tuscarora sandstone on right side of road, dipping steeply to the south as part of the north limb of the syncline (south limb of the Shade Mountain anticline). In the fold structure at the west end of this exposure, the beds dip gently to the north, probably overturned.

57.3 Outcrop of dip slope Tuscarora sandstone dipping moderately to the south. Bear right on U.S. Route 322. Continuous outcrops of Tuscarora sandstones with a decreasing dip to the south changing to a westerly gentle dip as the road passes across the hinge of the Shade Mountain anticlinorium.

58.3 Bridge across Jack's Creek. We are now on the north limb of Shade Mountain anticlinorium. Long roadcut north of bridge, covered by Crown Vetch, is underlain by Rose Hill and higher Silurian formations.

59.3 Bridge across Kishacoquillas Creek. Kishacoquillas was the Shawnee Indian chief of Ohesson, a village at the mouth of this creek where it empties into the Juniata River one mile west of here. The Shawnees were apparently driven out about 1750, for on this site Fort Granville was built in early 1756, one of a series of forts throughout the region constructed to retain control during the French and Indian war. It was, however, captured and burned down by the French and Indians a few months after it was completed.

60.3 Exit to Electric Avenue, Lewistown, and U.S. Route 522 north.

60.6 Oriskany Formation exposed on right. Notice that this sandstone disintegrated readily into a sand. The Oriskany (Ridgeley) is rather variable in thickness, generally becoming thinner to the east, where it appears in isolated patches. To the north and west of here, it is sufficiently thick to be quarried for glass sand. Recently worked quarries are one mile to the northeast, and some six miles southwest along this same outcrop belt.

61.2 Exposure of Wills Creek and Tonoloway formations.

61.7 Exit to Burnham. Wills Creek exposed in cuts on both sides of road. North of this Wills Creek ridge the red soil in the fields is derived from the Bloomsburg Formation.

62.4 Wills Creek Formation exposures on the left.

62.6 Exposures on the left are in the Bloomsburg Formation.

63.3 Top of the Tuscarora Formation.

63.5 Top of Juniata Formation.

63.8 On the right is a large exposure of the lower sandstones of the Juniata Formation.

64.0 Top of Bald Eagle Formation on the right along road above U.S. Route 322.

64.2 Top of Reedsville Formation in large roadcut on the left. Notice the progressive downward decrease in the number and thicknesses of the sandstone layers, illustrating the gradational nature of the contact of the Reedsville with the overlying Bald Eagle.

64.8 Exit to Reedsville, Pa. Route 655. Salona Formation on both sides of road with folding. At the south end of the exposure the black shale at the top of the Salona limestones is the Antes shale.

67.7 Fork in road, the right fork leading to Milroy. Bear left, following U.S. Route 322.

68.2 Type Section of the Milroy Member of the Loysburg Formation.

69.9 Bald Eagle Formation exposed on the right. Road to the right leads to the Laurel Creek Reservoir Filtration plant. The exposures visited in STOP III are on private property, and permission should be obtained before entering upon the Laurel Creek Reservoir property. Permission can be obtained by proceeding for 0.8 miles up this side road to the cluster of low buildings enclosed by a fence. Quite a number of geologists have visited these exposures, and permission has always been freely granted. Although the view from the west end of the dam is quite spectacular, the parking is quite restricted, there being room for only 1 or 2 cars. As an alternate route, one can park at the filtration plant and walk up an access road to the quarry exposures. From there it is possible to walk across the dam to obtain an overall view of the exposures.

70.3 Overturned Juniata Formation on the left and vertical folds in the Juniata and Tuscarora formations straight ahead and to the right.

70.7 Filtration plant on the right at the bottom of the valley.

71.0 Gate to crest of Laurel Creek Dam. Buses will pull off road onto the top of the dam for disembarking. Estimated time: 12:05 P.M.

LUNCH STOP. 45 minutes

Lunches will be distributed here, and may be eaten on the dam or along the west side of the reservoir. As this reservoir is the water supply for Lewistown, please take care that papers, etc. do not blow or fall into the water, nor are left on the surrounding grounds.

STOP III. LAUREL CREEK RESERVOIR AND FILTRATION PLANT, LEWISTOWN WATER SUPPLY SYSTEM. Allotted time: 90 minutes

DISCUSSANTS: Rodger Faill, Richard Wells

We are presently standing on the west end of the dam built two years ago across Laurel Creek by the Lewistown Water Authority (see discussion of engineering geology by Kenneth A. Young, P.E., in separate article in this guidebook). This locality is in the north limb of the Kishacoquillas or Jack's Mountain anticlinorium, which consists of a series of second-order folds exposing the Upper Ordovician-Lower Silurian clastic wedge, comprised of the Bald Eagle, Juniata and Tuscarora formations. Because these formations consist predominantly of siliceous sandstones, their resistance to erosion has resulted in a series of ridges and intervening valleys that has been called the Seven Mountains Area. The dam lies across Laurel Creek in line with one of these ridges, Spruce Mountain.

STRATIGRAPHY

The rocks underlying Spruce Mountain are the Tuscarora and upper Juniata sandstones, which are exposed on the west side of the valley in the roadcut, and along the dam construction road on the opposite (east) side. To the north along the east edge of the reservoir is the Castanea, the red sandstone at or near the top of the Tuscarora, and the lower portion of the Rose Hill Formation.

The oldest beds exposed are the upper part of the Ordovician Juniata Formation, along the road leading south from the dam (Fig. III-A, Stations 1 and 2). The Juniata Formation is predominantly sandstone: brownish gray, fine to very fine grained, medium and thick bedded subgraywacke, containing occasional thin zones of grayish red shale pebbles. Interbedded with these sandstones are beds of siltstone: grayish red, argillaceous, medium bedded, with locally well-developed cleavage. The contact of the Juniata with the overlying Tuscarora Formation lies in an interbedded zone, approximately 150 feet thick (Station 3), of gray and reddish sandstones.

The Tuscarora Formation (Fig. III-A, Stations 4, 5 and 6) is sandstone: mostly light gray, medium grained, siliceous, and ranging from a very pure quartz arenite in the lighter beds to an argillaceous subgraywacke in the dark gray beds. This contrast in composition between adjacent layers accentuates the fold and kink band structures in the quarry (Station 5).

The red sandstones in the uppermost part of the Tuscarora Formation comprise the Castanea Member (Fig. III-A, Station 7). The ten feet of Castanea sandstone is lithically similar to the Juniata, being grayish red, very fine grained, argillaceous and silty. It also contains distinctive closely spaced burrows perpendicular to bedding which are nearly cylindrical and less than one inch across. These burrows were formed by some unknown animal and are characteristic of the Castanea.

At the north end of this exposure, approximately the lower 200 feet of the Rose Hill Formation can be seen (Fig. III-A, Station 8). It consists of a brownish gray to light olive gray silty shale. The "Iron Sandstones" seen at STOP I do not extend this far to the northwest.

STRUCTURAL GEOLOGY

The overall structure, that is, the enveloping bedding, is vertical, with beds becoming younger towards the north, upstream. The most prominent structures within this framework of vertical enveloping beds are large kink bands, the parallel-sided structures which dip moderately to the south in the quarry across the valley. Bedding is continuous across these kink bands, and has been rotated (within these kinks) 90 to 120 degrees relative to the enveloping bedding. Smaller kink bands with an opposite sense of rotation are gently north dipping. These two kink band sets form a conjugate kink band fold system. In addition, conjugate faulting is developed, and seems to be somewhat related to the kink banding. In the Rose Hill Formation to the north is a well-developed cleavage and passive folding.

STOP III consists of 8 stations along the road on the east side of the reservoir, beginning with Station 1 at the south in the Juniata Formation (Fig. III-A).

Station 1: (approximately 350 feet south of crest of dam) These solid grayish-red sandstones and interbedded silty shales constitute the resistant, upper sandstone portion of the Juniata Formation.

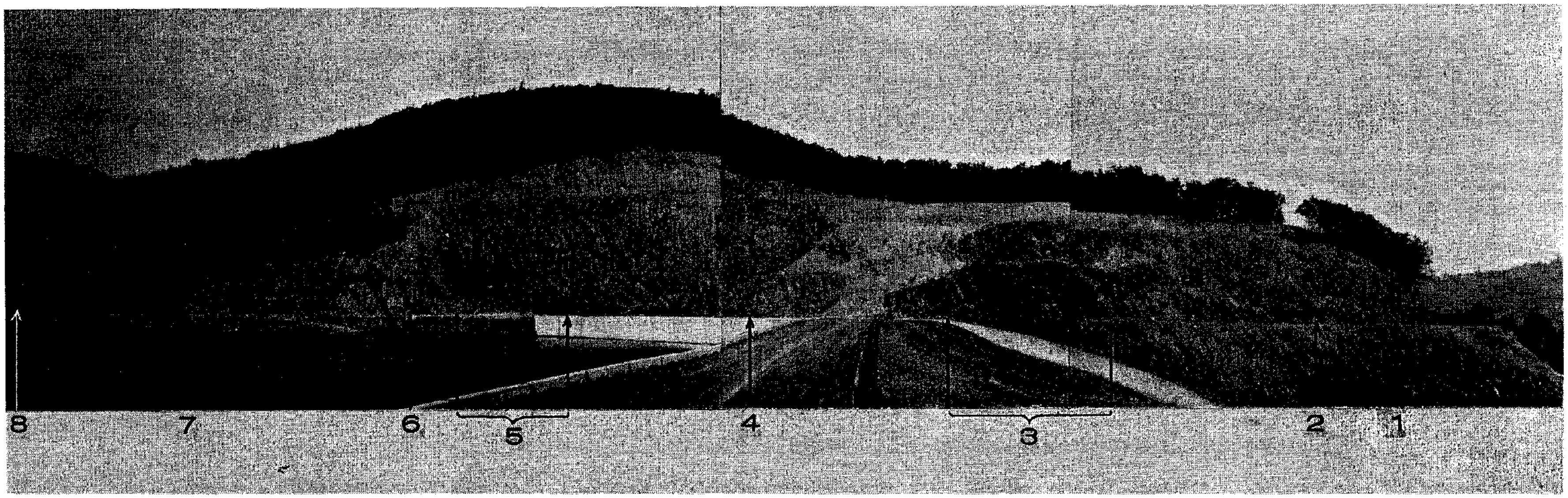


Figure III-A. Panoramic view of STOP III, with the locations of the eight Stations indicated. The grayish-red Juniata Formation is exposed on the right (south end), with the overlying whitish Tuscarora Formation in the center. The olive-gray shales on the left (north end) belong to the Rose Hill Formation. Bedding is vertical to overturned throughout most of the exposure.

Two types of structures are present in the steeply south dipping (overturned) enveloping bedding. The beds are not planar, but have been "bent" in a number of places by kink bands that dip gently to moderately to the north. Rotation in the kink planes has resulted in the overlying beds moving north relative to those under the kink band (Fig. III-B). Faulting has also occurred in these rocks. Some faults are parallel to the kink planes, with movement of the upper block to the north. In addition, steeply north dipping faults have caused the north block to be displaced upwards relative to the south block. Because the geometries (and the slickensides) of the faults and the kink bands are concordant (Fig. III-C), these two types of structures are probably related. In fact, in places, the low dipping faults appear to replace the kink bands suggesting contemporaneity or penecontemporaneity of development.

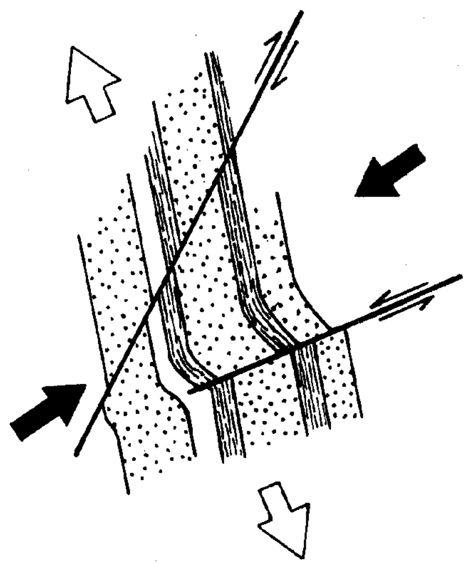


Figure III-B. Schematic relation of the faults and kink bands at Station 1, and the faults at Station 4. The solid arrows parallel the acute bisectrix of the faults, indicating the direction of maximum shortening. Maximum extension was subparallel to bedding, as indicated by the open arrows.

A word about fault terminology and the efficacy of the concept of the enveloping bedding--calling these faults low angle normal or high angle reverse faults does not help in explaining the structures and

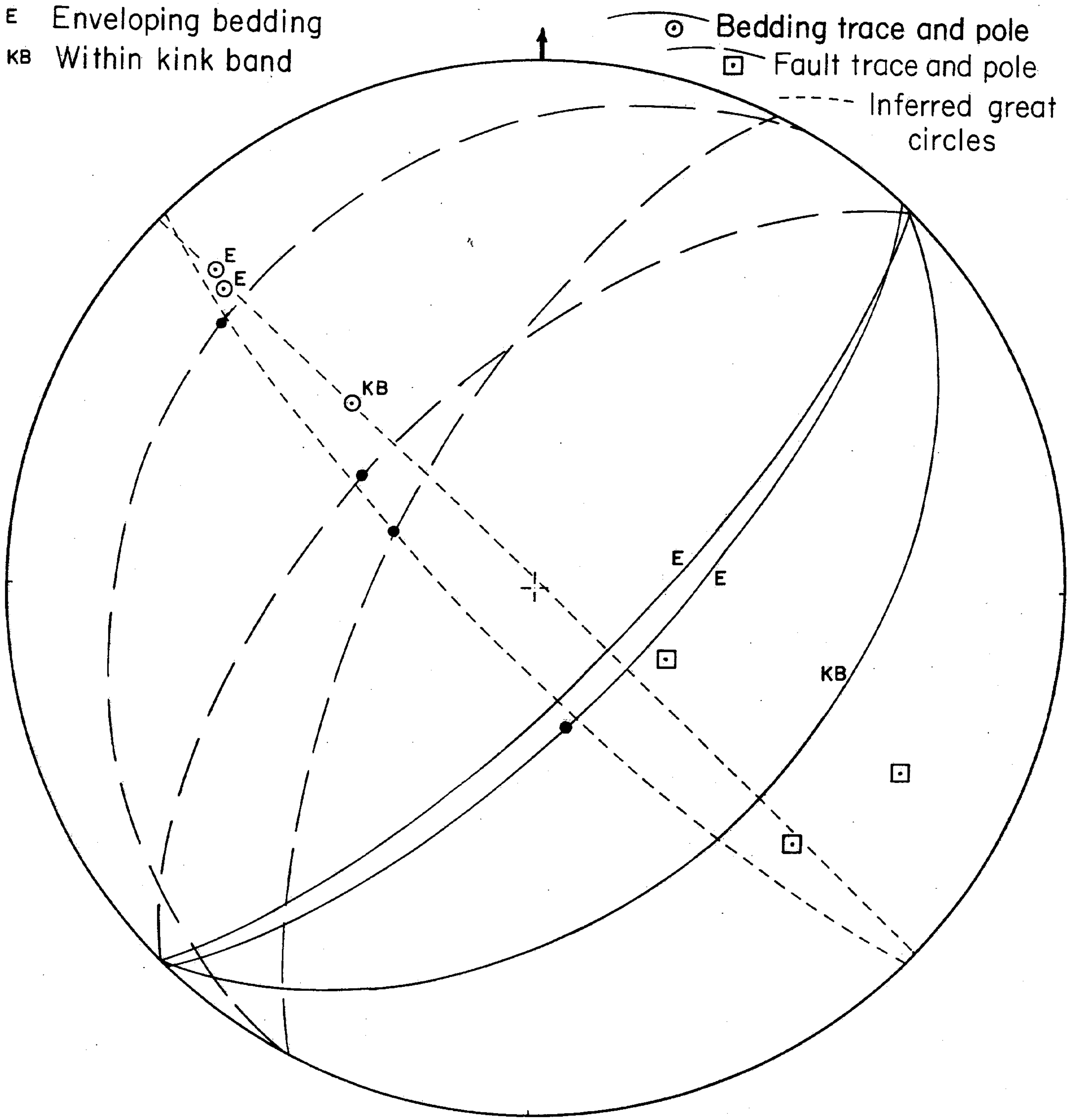


Figure III-C. Stereonet display of the fault, kink band and enveloping bedding geometry at Station 1. The clustering of mutual intersections at the southwest perimeter, and the alignment of slickensides along a single great circle indicates that all these structures are kinematically related and that they probably developed under the same stress system.

their relation to the overall folding. Use of the enveloping bedding as a datum, rather than the horizontal plane, aids in deciphering the structural sequence. Relative to the enveloping bedding, the two fault orientations constitute a conjugate fault system somewhat inclined to bedding, movements on which resulted in a lateral extension of bedding (indicated by open arrows in Fig. III-B). This implies a subhorizontal shortening of the rocks in a direction subperpendicular to bedding (indicated by the solid arrows). This type of movement accords well with the overall horizontal maximum principal stress that produced the major folds here. The kink bands, with a similar sense of displacement as the gently dipping faults, indicate an alternation of mechanism for movements in this orientation.

Station 2: (approximately 300 feet south of crest of dam) The structure is a much larger kink band which is dipping moderately to the south, similar to those in the quarry. As at Station 1, the enveloping bedding is overturned, dipping 65° to the south. Bedding in the kink band has been rotated to 40° to the north, a rotation of 75°. Virtually all this change in orientation occurs within a three to four foot length of the bed. The locus of these sharply bent beds are the kink planes, the boundaries of the kink bands. This sharp bending of beds represent a high amount of strain within each layer, yet there is little megascopic evidence of brecciation, flow or thickening of beds. The bed-normal thickness is remarkably constant across the kink planes, and bed thicknesses within the kink bands are nearly identical to those outside the kink bands. Slickensides on the bedding surfaces indicate that the primary mechanism of deformation was by slip on the bedding surfaces. Although this kink bank is only 15 to 20 feet wide, its extent is considerable--it continues downward along this slope and extends up the other side of the valley to the Juniata exposures in the roadcut.

Station 3: (50 to 200 feet south of dam crest) The Tuscarora and the upper part of the Juniata together constitute a single, resistant sandstone unit which underlies many of the major ridges in the province. Lithically, they are quite different, the major factor being the nature and grain size of the matrix. The sandstones characteristic of the Tuscarora are very pure quartz arenites, being 95+ percent detrital quartz and silica cement; the sandstones typical of the Juniata are subgraywacke and graywacke with a minimum of 10 percent silt and clay matrix and generally about 20 percent rock fragments. This contrast in composition is responsible for the color contrast between the grayish-red Juniata and the very light gray Tuscarora.

The contact between these two stratigraphic units varies--in some localities, the change from grayish-red subgraywackes to quartz arenites is singular, providing a sharp, well-defined contact. Generally, however, as here at STOP III, the change in lithology is repeated, resulting in an interbedded contact. This interbedding probably reflects lateral shifting, back and forth over this locality, of the two depositional environments, one (Juniata) of rapid deposition and burial that preserved the rock fragments and fine matrix, the other (Tuscarora) a more mature one in which the sands were reworked and the fine material winnowed out.

At 140 feet south of dam crest is a steeply south dipping fault with displacement down on the south--a good normal fault. But what is its relation to the other structures? Relative to the subvertical enveloping bedding, this is a low angle wedge fault of the type common to the flexural slip folds in this province which resulted in a lateral shortening of the beds. However, note that it offsets the gently north dipping kink bands, an indication that it was developed late in the deformation.

Station 4: (130 feet north of dam crest) At this station faults are of two orientations. One orientation is gently north dipping with displacement of beds above the fault northward relative to those underneath, a displacement similar to that at Station 1 (Fig. III-B). The other fault set dips steeply to the north, with displacement of the northern beds upwards.

These two faults, then, constitute a conjugate system (although mutual offsets cannot be proven here), in which the acute bisectrix (the line dividing the acute angle between the faults) plunges moderately to the north at approximately 40 degrees. This is the direction of the maximum principal stress (compression) which produced this conjugate system, which in turn resulted in lateral extension of the beds. That is, the major axis of extension (lengthening) plunges steeply south at 50 degrees, subparallel to the steeply south dipping (overturned) enveloping bedding.

Station 5: (315 feet north of dan crest) This quarry was opened to provide the fill for the dam. The rocks exposed are entirely within the Tuscarora Formation, consisting of light gray, medium to thick bedded quartzite with some interbeds of thin to medium bedded dark gray silty shale. This contact in lithologies accentuates the structure present here.

In detail, one can see that there are two south dipping kink bands, one completely exposed, and the second one underneath it only partly exposed. Both are similar in size and orientation as the one at Station 2. Within both kink bands, bedding has been rotated 90 to 120° from the vertical to slightly overturned enveloping bedding. As with other kink bands and folds in this province, the most prominent aspect is the planarity of the bedding across the kink band, and the sharp bending at the kink planes. Comparing this exposure with the folds at Mifflin (STOP 2), the similarities are quite obvious because both exhibit the planar bedding, narrow hinges and constant bed thickness, the kink band and the Valley and

Ridge folds are inferred to be closely related, geometrically and mechanically. And, in fact, these folds can be constructed from two joined kink bands, as described in the article "Structural Geology".

In the upper kink band one can see a considerable change in geometry from bottom to top, induced not only by the subsequent faulting, but also to a lesser extent by flow within the shalier beds. Yet, the width of the kink band and its attitude remain relatively unchanged from the lowest to the highest. The adjacent kink band to the left (to the north or underneath) shows a similar change in geometry. Near the upper part, a 1-foot thick quartzite bed is so tightly appressed that it possesses the geometry of an isoclinal fold. Immediately to its left, is a "box" or conjugate fold.

The other structures that are common in this exposure are gently north dipping faults similar to those seen at Stations 1 and 4. The four or five faults in this exposure, with displacements of 1 to 2 feet offset the kink band structures and thus are later than the south dipping kink banding (Figure III-D).

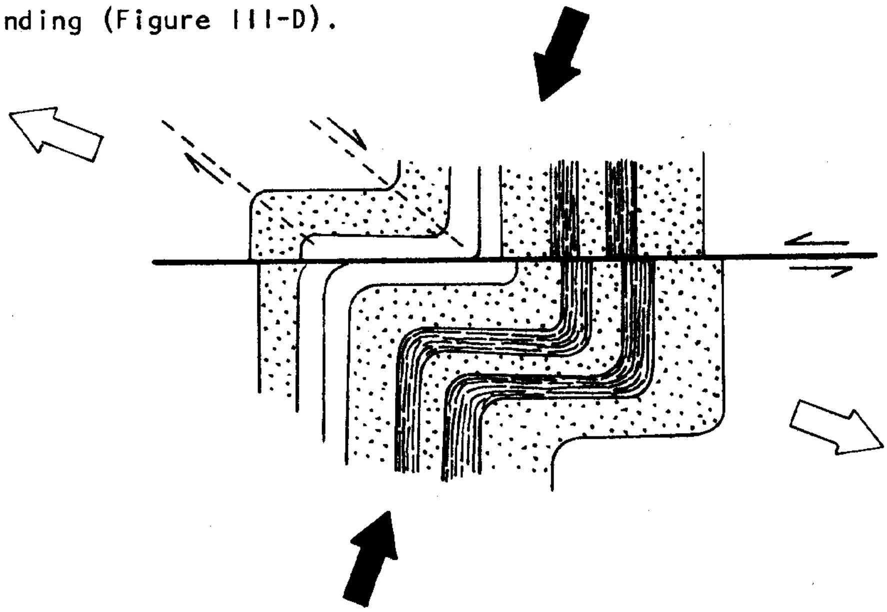


Figure III-D. Schematic relation of kink bands and faults at Station 5. Offset of the kink bands by the faults indicates the faulting is later. Although these two structures are not contemporaneous, the net effect of both is a shortening parallel to the obtuse bisectrix (shown by the solid arrows), with the maximum extension at right angles (open arrows).

Station 6: (400 feet north of dam crest at corner on north side of entrance to quarry) At the top of this exposure is the lower part of the kink band partially exposed at Station 5 dipping moderately southward.

Below it is a smaller kink band dipping gently to the north, but with opposite sense of bed rotation, similar to those at Station 1. Together, these two kink bands produce a conjugate fold geometry. As with the conjugate fault system observed at Station 4, the acute bisectrix of the two kink planes is at a large angle to bedding; but plunging gently to the south, rather than to the north. In addition, these kink bands have resulted in lateral shortening of the enveloping bedding in contrast to the lateral extension of the enveloping bedding resulting from the conjugate faults. Although one set of kink bands and one set of faults of both deformational systems possess an identical orientation and sense of displacement, mechanically they are different.

The simplest explanation is as follows: In the initial stages of the folding of the Jack's Mountain anticlinorium, when the dips in the north limb (here) were still quite low, the subhorizontal maximum principal stress caused a conjugate kink band structure to be developed within this north limb. Because the enveloping bedding had some dip to it, the deforming stress was not symmetrically oriented with it (Fig. III-E) and the kink band array was consequently asymmetric, with the larger ones being north dipping (presently south dipping and thus overturned). It can be inferred that the rocks at this stage were moderately ductile to moderately brittle, because the kink banding is a continuous (though not really a penetrative) deformation.

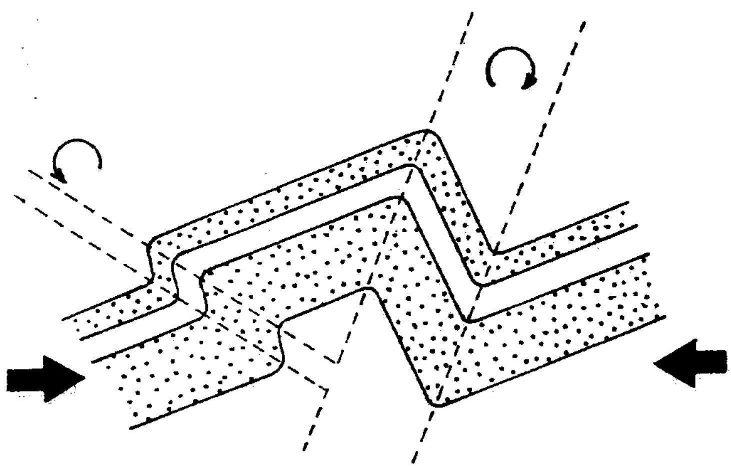


Figure III-E. Asymmetric conjugate kink band array developed at an early stage in the overall folding when the dip of the enveloping bedding was low and its angle to the deforming stress (solid arrows) was small.

As folding proceeded and the enveloping bedding steepened, the angle of the deforming stress to the bedding increased and further deformation by kink banding was thereby suppressed. Instead, particularly in the larger, initially north dipping kink bands the local deformation was replaced by a conjugate fault system (Fig. III-F), with one set of faults parallel to the smaller, initially south dipping kink bands (as in Fig. III-B). Because of this change in mechanism to a discontinuous deformation (faulting), it can be inferred that the rocks at this stage in the overall folding had become more brittle. (On the other hand, though, this change may not reflect a changing character of the rocks, but merely the increasing angle between the enveloping bedding and the deforming stress.) Thus, as the dip of the enveloping bedding in this north limb of the Jack's Mountain anticlinorium increased to its present overturned attitude, an initial shortening of the beds by kink banding was followed by an extension of beds by conjugate faulting.

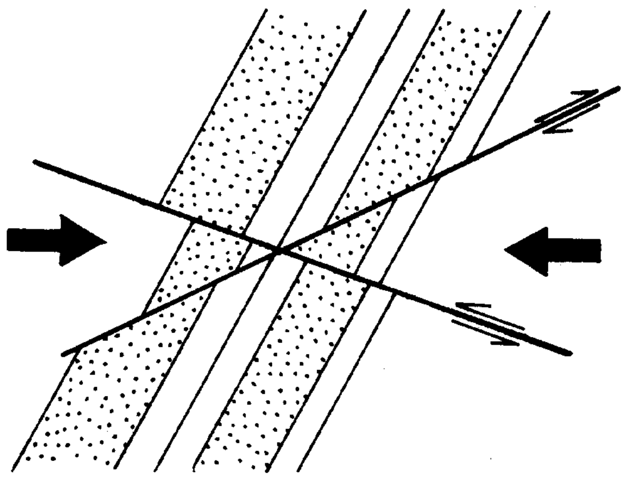


Figure III-F. Conjugate fault system developed at a later stage in the folding when the dip of the enveloping bedding was steep, at too large an angle to the deforming stress (solid arrows) for continued kink banding. The change in mechanism from kink banding to faulting may represent an increasing brittleness of the rock as the deformation proceeded. On the other hand, the alternation of kink band and fault at Station 1 suggests that the material itself did not change, but rather the change in mechanism was solely a result in change of attitude of the enveloping bedding.

Station 7: (720 to 740 feet north of dam crest) In the southeastern part of the Conference area, the Tuscarora grades upwards directly into the olive gray shales of the Rose Hill. To the northwest, an interval of grayish-red sandstones (Castanea Member) occurs at or near the top of the Tuscarora. Because these beds are lithically similar to the Juniata sandstones, they apparently represent a return of the Juniata depositional environment. In places, as here, there is only one set of red beds; elsewhere, two or three intervals of red sandstones are interbedded with white sandstones.

Station 8: (980 feet north of dam crest) In contrast to the rocks to the south, the Rose Hill shale has a strong cleavage developed throughout, which does not quite obliterate bedding. At this station, an approximate kink band fold has been formed, with a strong axial plane cleavage. Within the synclinal hinge is a small fold which appears not to have developed by kink banding (flexural slip) but rather appears to be a passive flow or passive slip fold, one produced as a consequence of the cleavage development and lateral shortening. This marked contrast in deformational style and mechanism reflects the contrast in rock material between the Rose Hill and the Tuscarora.

Scattered about in the rubble fallen from this cut are a few specimens of deformed fossils, particularly crinoid stems. Their present ellipticity indicates a penetrative deformation in the rocks which may or may not be related to the cleavage development.

71.0 Reboard buses in quarry. From gate at crest of dam proceed northward on U.S. Route 322, 0.4 miles to Stone Creek Road, make a U-turn and proceed south on U.S. Route 322. Resume mileage at dam crest. Estimated time: 2:20 P.M. Approximate travel time to STOP IV: 60 minutes.

73.4 Crossroad: road to right leading to Barrville; road to left to Milroy.

73.6 Type Section of the Milroy Member of the Loysburg Formation.

75.9 Road bears left off to Reedsville.

76.5 Exit to Pa. Route 655, Reedsville. At stop sign, turn left on Pa. Route 655. After passing under U.S. Route 322, exposure on the right side of road is the Salona Formation and underlying Middle Ordovician units.

77.0 T - intersection, end of Pa. Route 655. Turn right, continue into Reedsville.

77.3 Stoplight, center of Reedsville. Proceed south on same road.

The roadcuts in the Kishacoquillas Gap through Jack's Mountain are one of the most complete exposures of the Upper Ordovician clastic rocks, the flysch and lower molasse rocks of the Taconic clastic wedge. Unfortunately, lack of time precludes a formal stop here, but a slow drive-by has been scheduled to enable the Conference members to appreciate the more obvious lithic features in these units. This locality was Stop 2A in the 1970 SEPM (Eastern Section) Field Trip and is thoroughly described therein (Thompson, 1970). The following description is based primarily on that guidebook, and points out only the most important aspects of this stratigraphic interval.

The succession of lithofacies from gray marine shales and siltstones (A), through fossiliferous (B) and unfossiliferous (C) sandstones and shales, to unfossiliferous, conglomeratic gray and/or red sandstones (D), and through an overlying fine grained, generally red, unfossiliferous unit (E), to an interval of coarse grained unfossiliferous, red sandstone (F) comprises the transition from the marine flysch to the continental molasse of the Taconic cycle. Traditionally, this interval has been divided into three stratigraphic units, the Reedsville, Bald Eagle and Juniata formations. The Reedsville included the gray shales and fossiliferous sandstones, the Bald Eagle the unfossiliferous gray sandstones and conglomerates, and the Juniata the red sandstones and shales. One of the important conclusions of Thompson's work was that the color change from gray to red, which had been the basis of dividing the Bald Eagle from the Juniata, occurs irregularly at different positions in these rocks across the province. The color change appears to be of secondary origin and is not closely related to the other lithic characteristics which define the six lithofacies.

It seems, then, more consistent (to the rocks rather than tradition) to base the stratigraphic nomenclature on the lithofacies rather than on the color change. Not only is a lithofacies basis more meaningful in relating these rocks across the province, but it also simplifies their mapping. Color change is virtually impossible to trace through the thick colluvium that usually covers these rocks, whereas the lithic change from lithofacies D (conglomeratic sandstone) to lithofacies E (interbedded shales and sandstones) is reflected in a distinctive change in topographic slope. Mapping in the Williamsport area (Faill and Wells, 1974) has utilized this particular change in slope, and the Bald Eagle-Juniata contact was placed at this lithofacies boundary.

Exposures in Kishacoquillas Gap.

75.5 Road crosses railroad tracks and Honey Creek. Exposures to the south along the east side of road constitute the Type Section of the Reedsville Formation, comprising lithofacies A and B. Much of the Reedsville (lithofacies A) consists of turbidites with graded bedding, and interbedded sandstones and shales.

The contact between lithofacies A and B is covered here (but is well exposed along the newer, 4-lane U.S. Route 322 on the west side of the gap). Lithofacies B, the upper part of the Reedsville Formation, consists predominantly of 60 feet of richly fossiliferous sandstones, the *Orthorhynchula* zone that has traditionally defined the top of the Reedsville.

77.7 Contact between the Reedsville and Bald Eagle formations (marked by an old yellow paint strip). The basal portion of the Bald Eagle is a 150-foot thick interbedded sequence of laminated and cross-bedded sandstone and shale (lithofacies C).

77.8 Most of the Bald Eagle is comprised of the 750 feet of sandstones of lithofacies D. Seventy-five feet of trough cross bedded, grayish-green sandstones underlie the lowest conglomeratic sandstones. This conglomeratic zone, approximately 350 feet thick, consists of sparsely scattered, rounded, siliceous pebbles in the lower part, with upwardly increasing amounts of lithic pebbles (sandstones and greenstones), pebble size, and angularity. In the upper portion, the grain size of the sandstones, the pebble sizes, and the pebble density decreases, and the lithic pebbles are absent. Throughout this conglomeratic interval, the color of the sandstones gradually changes to red.

77.9 Large-scale trough cross bedding is the most prominent sedimentologic feature in this thick bedded, upper portion of lithofacies D. The strong grayish-red color would traditionally place these sandstones in the Juniata Formation.

78.0 A rather abrupt decrease in grain size, which marks the contact between the Bald Eagle and the Juniata (and the boundary between lithofacies D and E). This rather thick interbedded sequence of grayish red shales, siltstones and sandstones (of which only the very base is exposed here) comprise the lower part of the Juniata Formation, and underlies a valley usually developed between the double ridges underlain by the Tuscarora and Bald Eagle sandstones.

78.1 End of continuous Reedsville-Bald Eagle-Juniata exposure.

78.4 Bridge across Kishacoquillas Creek. Exposures on steep slope to the left are in Juniata Formation, upper sandstone member (lithofacies F).

78.6 Entering Village of Yeagertown.

79.9 Entering Borough of Burnham, leaving Village of Yeagertown.

80.0 Quarry to right at north end of shopping center is Wills Creek.

80.3 Intersection with road at stop light. Turn right to return to U.S. Route 322.

81.0 Wills Creek exposed on both sides of road.

81.2 Turn right onto entrance ramp for U.S. Route 322 east.

81.4 Contact between Bloomsburg and Wills Creek formations.

81.8 Large (15 meter wide) moderately north dipping kink band in Tonoloway beds in roadcut on both sides of road. Mostly obscured by Crown Vetch.

83.1 Walnut Street exit to U.S. Route 522 north.

85.8 Junction with U.S. Route 22. Proceed eastward through Lewistown Narrows between Shade and Blue Mountains.

88.7 Juniata County Line.

91.8 The newly constructed U.S. Routes 22-322 branch off from older route at this point. Road log continues along old U.S. Routes 22-322. Alternate road log for the new road is included below, following mileage 97.0.

95.5 Intersection of Pa. Route 35 and U.S. Routes 22-322. Turn left at stop light, proceed east on Pa. Route 35.

97.0 Intersection with new U.S. Routes 22-322.

Alternate log for the new U.S. Routes 22-322 (4-lane highway) around Mifflintown.

91.8 Proceed south on new U.S. Routes 22-322.

92.1 Large roadcut on east side of road exposes upper part of Rose Hill Formation. Keefer sandstone covers the crest of hill and dip slope.

92.7 Mifflintown Formation in cut on east side of road.

92.9 Exit. Cut on northeast side of road is Bloomsburg.

93.0 Wills Creek exposed in cut on south side of exit ramp. To the east the highway follows Wills Creek for one mile.

94.6 Cross Lost Creek -- Bloomsburg is exposed in creek below bridge.

95.0 Large cuts in Rose Hill Formation on Moyer Ridge. Exposure starts in steeply south dipping Rose Hill. Dip decreases to moderately gentle with exposure of Keefer just before first small valley. This small valley is a syncline with north dipping Keefer exposed on south side of valley. The long cut south of the small valley consists mostly of Rose Hill with very gentle dips and a broad anticlinal structure.

95.9 Crest of broad hinge of Moyer Ridge anticline.

96.4 Change in soil color to dark red represents base of Bloomsburg. Exit ramp to Pa. Route 35 is just ahead.

96.6 Bear right onto exit ramp. Wills Creek Formation is exposed along ramp.

96.8 Turn left at intersection with Pa. Route 35.

97.0 Proceed eastward on Pa. Route 35.

98.1 Low ridges on right are in the Bloomsburg Formation. To the left, north of the road, the lower hills are underlain by the Mifflintown Formation. The slightly higher ridge in the rear is Moyer Ridge, which is capped by the Keefer Formation.

100.2 Due north is Shade Mountain. The serrated ridge effect is due to the several valleys cutting through the Tuscarora Formation.

101.2 Village of Oakland Mills.

104.0 McAllisterville. Traffic light, turn right on Pa. Route 235. South of town, the two hills on the left (to the east) are synclinal ridges underlain by the Keyser and Old Port formations. The straight ridge ahead (south) is south dipping Old Port and Keyser formations.

106.0 Crest of hill where Old Port Formation crosses road. Covered by Crown Vetch.

106.7 Turn left up tarred gravel road to D.E. Smith Quarry. (This road is about 1/10 of a mile before the T-intersection and stop sign ahead.)

107.1 STOP IV. OFFICE AND WEIGH STATION OF D.E. SMITH QUARRY, LOST CREEK RIDGE. Estimated time: 3:20 P.M. Allotted time: 45 minutes.

Permission to enter the quarry should be obtained from this office. This is an active quarry, so visitors are cautioned to remain aware of, and to avoid, the numerous trucks and other equipment that seems to appear from nowhere.

STRATIGRAPHY

DISCUSSANTS: Rodger Faill, Richard Wells

Strata exposed in this quarry include the upper 15 feet of the Upper Silurian Tonoloway Formation, and the lower 63 feet of the Silurian-Devonian Keyser Formation.

The <u>Tonoloway Formation</u> consists primarily of laminated to thin-bedded limestone, with some thin beds of medium gray calcareous shale. The lamination is an alternation of micrite or calcisiltite with argillaceous and silty layers. A few thin to medium beds of dense, gray, microcrystalline limestone are interbedded with the laminated beds. Pellet texture, scattered ostracod shells, lenses of sparry calcite and sedimentary boudinage structures are also present. Although dolomite has been reported to the west (Gwinn and Bain, 1964), no dolomite has been found in the Tonoloway in this vicinity.

The contact of the Tonoloway with the overlying Keyser limestone appears as a distinct, persistent bedding plane which separates predominantly laminated limestone below from thicker bedded, locally nodular, cobbly weathering fossiliferous limestone above. This horizon can be seen in the north wall of the quarry, approximately 15 feet above the quarry floor.

The lower part of the Keyser Formation is predominantly a medium gray, fossiliferous, lumpy or "pseudo-nodular" limestone which is very cobbly when weathered. The limestones are predominantly micritic calcisiltites, bioclastic calcarenites and skeletal micrites. The upper part of the formation contains laminated to thin-bedded limestone similar to the underlying Tonoloway beds, and dark gray chert nodules are common in the upper few feet.

The Keyser is thin to very thick bedded, and often appears massive, with no visible bedding planes. Stylolite surfaces are common. The thin to medium-bedded units are generally nonfossiliferous calcisiltite, subordinately bioclastic calcarenite, interbedded with calcareous shale. The calcisiltite and calcarenite beds are commonly fragmented and separated into roughly equidimensional cobbles.

Insoluble residues of the Keyser limestone consist entirely of light to very light gray clay and very fine quartz silt. The insoluble content ranges from 8.8 to 20.8 percent. Chemical analysis of limestone from this quarry show 85.8 percent $CaCO_3$, 5.7 percent $MgCO_3$, and 6.3 percent SiO_2. Some extensive but discontinuous veins of white crystalline calcite occur in this quarry, as well as minor amounts of white and purple flourite.

Locally, extensive travertine deposits occur in small caves and sinkholes in the Keyser (e.g., in the quarries on Lime Ridge north of Mount Pleasant Mills), and in the caves at Freeburg.

The Keyser limestone in the upper 17 feet of outcrop in this quarry--above the steep quarry walls--is very cobbly and fossiliferous. It contains disarticulated brachiopod and pelecypod shells, crinoid columnals, bryozoans and ostracods.

STRUCTURAL GEOLOGY

This quarry exposes the hinge of the Cocolamus anticline, an eastward plunging third-order fold. In the east wall across the quarry from us the fold appears to be a very open anticline. The form is grossly concentric with a change in attitude of 25° from one side of the quarry to the other. However, at the entrance of the quarry behind the crushers, the bedding abruptly increases in steepness from 10° to 45°, and persists (unchanged southward) for 3/4 mile to the hinge of the Quaker Valley syncline. Thus, this third-order anticline is similar to the Tuscarora anticline near STOP I, and described in the Appendix. As at Millerstown, the exposure that we see here is but a small part (the "concentric" hinge) of the total fold. The fold wavelength is more than one mile yet the hinge is no more than only 1/8 mile across.

There is one other feature in this quarry which unfortunately cannot be shown at this time--slickensides on bedding. They were exposed 3 or 4 years ago on the east end of the quarry, but the rock there has since been removed, crushed, and spread around and under the new U.S. Routes 22-322 being built south of here at Thompsontown. Of the two aspects of the slickensides that are worth noting, the first is that they occurred at the crest of the fold. In the conventional concentric (parallel) fold, displacement along bedding surfaces is zero at the crest of the fold and increases progressively away from the crest as the bedding dip increases. If this were a concentric fold, there should be no slickensides at its crest. Now, in kink band deformation, displacement between beds extends beyond the kink bands into the enveloping bedding. Therefore, in kink band folds, slickensides at the fold crest (hinge) are to be expected, for the hinge is the boundary of two kink bands.

The other aspect of interest is that not just one, but two directions of slickensides were present on the crest (Fig. IV-A). Each slickenside direction represented the kinematic movements related to one kink band: two slickenside directions indicates that the two kink bands that form this fold are not parallel. And in general, where two non-parallel kink bands join to form a fold, the fold plunges and terminates along trend. The Cocolamus anticline in this quarry plunges to the east at about 3° and within 2 miles it diminishes in size and vanishes (Faill, 1969). This plunging and terminating geometry is characteristic of many of the folds throughout the Valley and Ridge province, a geometry easily explained by kink band deformation.

107.1 Reboard buses. Estimated time: 4:05 P.M. Approximate time to STOP VI: 20 minutes. Return to Pa. Route 235 by the same tarred gravel road.

107.5 Stop sign. Turn left on Pa. Route 235.

107.6 T-intersection of Pa. Route 235 with the road to Cocolamus. Turn right, following Pa. Route 235 southward. On east side of this intersection is south dipping Montebello sandstone member of the Mahantango Formation.

107.9 0.2 mile long exposure of horizontally bedded Harrell shale in hinge of the Quaker Valley synclinorium.

108.3 East Salem, Pa. Route 235 turns eastward (left). Proceed southward on unnumbered road to Thompsontown.

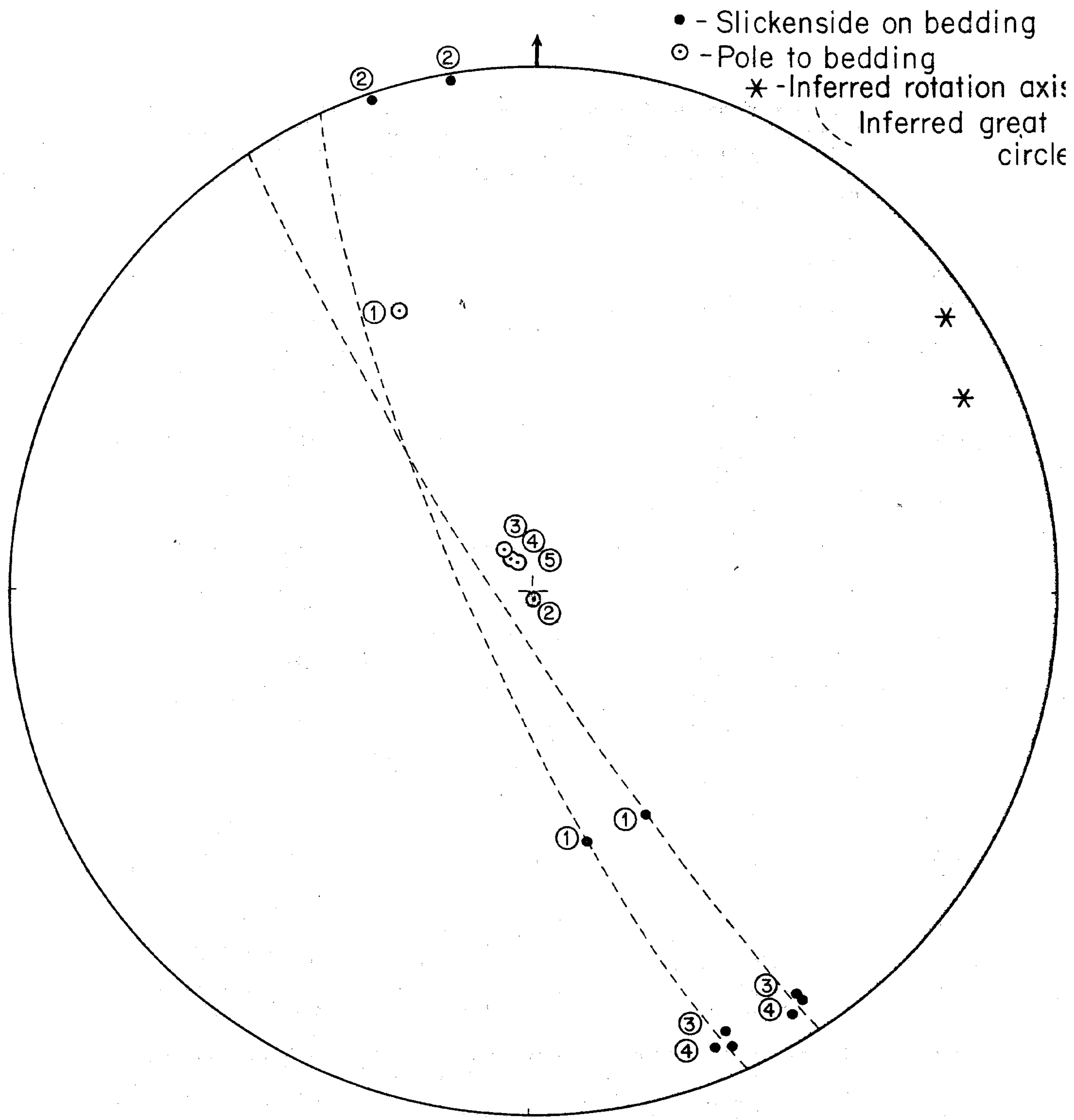


Figure IV-A. Stereonet display of bedding poles across the hinge of the fold, and in the south limb at the quarry entrance. Two sets of slickensides occur on the bedding surfaces both across the hinge and in the south limb. Great circles constructed through these two sets define two divergent rotation axes, about which each limb of this fold was rotated respectively.

108.4 Exposure of north dipping Montebello sandstone member of Mahantango Formation on both sides of road, in the south limb of the Quaker Valley synclinorium. Two upward-coarsening cycles, similar to those which will be seen tomorrow at Shadle (STOP VII) are exposed here.

108.9 This valley is underlain by gently eastward dipping Keyser and Tonoloway formations.

110.1 Exposure of Onondaga Formation (limestone and shale) on right side of road.

110.3 Type Section of the Turkey Ridge sandstone member of the Mahantango Formation on right side of road.

110.5 Gently dipping to horizontal Turkey Ridge sandstone in hinge of syncline on east bank of Delaware Creek.

111.3 Overpass of new U.S. Routes 22-322.

111.7 Thompsontown. Turn left at intersection with old Routes 22-322.

113.7 STOP I is on the left.

114.4 On the left is the lower shaly member of the Rose Hill Formation with the Center Iron sandstone member exposed in the upper part of the cut and in the woods to the east. Ahead, above the Tuscarora Formation exposure, is Slaughterback Hill, underlain by the Rose Hill and Keefer formations in the hinge of the Tuscarora anticlinorium. Prior to and during the 1880's iron mines were operating on the flanks of Slaughterback Hill and Tuscarora Mountain.

115.1 Entering Juniata County.

116.5 Pa. Route 17 bridge across the Juniata River on the right; Millerstown is on the left.

116.8 Exit ramp to Millerstown and Pa. Route 17. The ridge to the west across the Juniata River is Racoon Ridge, underlain by the sandstones of the Mahantango Formation. In the winter time, when there is a cover of snow, the several upward-coarsening cycles within the Montebello and Sherman Ridge members of the Mahantango stand out clearly.

118.4 The ridge straight ahead is Buffalo Mountain which forms the south dipping north limb of the Buffalo-Berry synclinorium. The Mississippian Pocono Formation crops out along the skyline. STOP V is at the roadcut where Buffalo and Berry Mountains join in the hinge of the Buffalo-Berry synclinorium.

119.9 Beginning of Catskill exposure of STOP V.

120.1 STOP V. BUFFALO-BERRY SYNCLINE: THE UPPER DEVONIAN CATSKILL FORMATION, DUNCANNON MEMBER. Estimated time: 4:25 P.M. Allotted time: 60 minutes.

DISCUSSANTS: Richard Wells, Rodger Faill

The exposures at STOP V consist of three separate outcrops on the southbound (lower) lane, and one long continuous outcrop on the northbound lane. The main part of STOP V is the middle outcrop on the southbound lane (at Milepost 5-10). After discussion of the geology, the road may be crossed to examine the outcrops along the southbound lane. If time permits, we will climb to the top of the median strip for a spectacular view of the exposures on the east side of the northbound lane. (The ascent can be made between the middle and northern outcrops, or below (to the north of) the northern outcrop.) Do not approach the base of the cliff on the east side of the northbound lane, because of meta-stable slope conditions and danger from falling loose rock.

STRATIGRAPHY

The Catskill Formation is divisible into three members in the lower Juniata and Susquehanna valleys. The basal Irish Valley Member consists of gray sandstones and siltstones, grayish-red siltstones and silty claystones and includes the marine-non-marine transitional beds ("motifs") that will be seen at STOP VI. Above this is a sequence of interbedded red siltstones and very fine-grained sandstones, the medial Sherman Creek Member. The upper Duncannon Member, consists of light olive gray sandstones, reddish-gray silty sandstone, red siltstone and red silty claystone arranged in upward-fining cycles (Fig. V-A). This pattern of upward-fining cyclicity is characteristic through the entire Catskill Formation: they are present in the Irish Valley Member, they are thicker and better organized in the Duncannon Member.

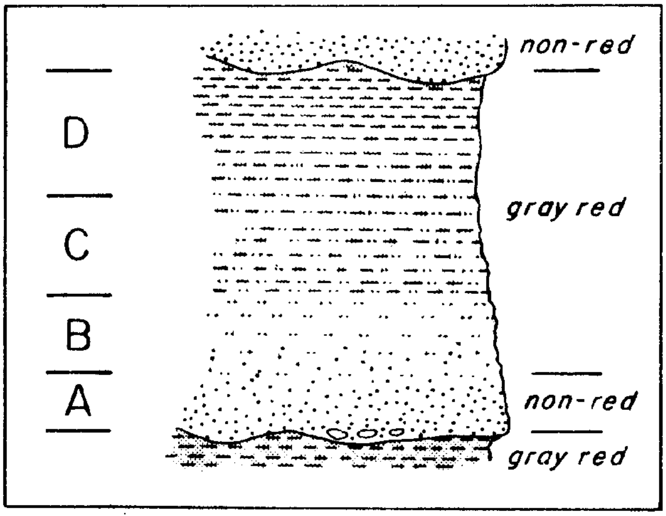


Figure V-A. Idealized Duncannon Member fining-upward cycle, as seen in the exposures in Buffalo-Berry Mountain syncline.

The ideal cycle consists of a basal light olive gray, fine and very fine grained, micaceous, cross-bedded sandstone which generally occupies a channel or irregular erosional surface cut into the top of the underlying cycle. Lenses of carbonate nodules, shale chips, fish teeth, and occasional plant fragments commonly occur lying directly upon this erosional surface, and can be seen at the north end of the southernmost outcrop on the southbound lane. Part A, the gray sandstone, is overlain by B, reddish gray, very fine-grained silty sandstone, part C, grayish red siltstone, and part D, grayish red silty claystone. The boundaries between segments of the cycles may be sharp or gradational and indistinct; boundaries between cycles are generally distinct.

The 11 fining-upward cycles exposed here at STOP V are near the middle of the Duncannon Member, and have an aggregate thickness of more than 200 feet. In most of these cycles, the four basic elements A-B-C-D are preserved. The upward-fining cycles represent fluvial deposition in natural levees, flood plains and flood basins in the upper (subaerial) portion of the regional Catskill delta. The scoured bases and the upward decrease in grain size from element A to D is evidence of a regular decrease in available energy and fluid velocity during a single depositional pulse. Gradation from one element to another occurs laterally as well as vertically. The laterally finer beds were deposited near the edges of the flood deposit. Lateral migration of the main flood channels has resulted in continued erosion of previously deposited cycles, with preservation of only a few cycles during a period of fairly continuous subsidence.

A number of clastic dikes (Wells, 1969) occur in the siltstone of at least one of the cycles in the Buffalo Mountain West Section. These dikes are composed of dark to light grayish red and greenish gray, medium to coarse silt which locally grades into very fine-grained sandstone. The dike material is argillaceous, micaceous, slightly hematitic, poorly sorted and has little porosity or permeability. The host rock is a fine grained, argillaceous siltstone, which is grayish red to dark grayish red. The dikes penetrate downward into the host rock from an overlying bed of sandy siltstone usually two to three inches thick, of the same color and lithology as the dikes themselves. These beds are minor interruptions of the fining-upward pattern, and are of limited lateral extent. The dikes are connected to the overlying beds and apparently formed from the same sediment. Angular fragments of the host rock sometimes occur in the upper parts of the dikes, and in the associated overlying beds.

The geometric form of these dikes is usually that of a slightly tapering sub-vertical wedge, and the dike walls are sharp. The dikes are straight, slightly irregular or have a zig-zag cross section.

Six of these dikes were measured in detail, and range in height from four to twelve inches, and taper from a width of 3/8 to one inch at the top to a width of 1/2 to 1/16 inch or less at the base. The four dikes on which a strike could be determined trend from 115° to 150°, and dip from 50° southwest, through vertical to 67° northeast. The dikes are restricted to a lateral distance of thirty-five feet, at two stratigraphic levels three feet apart.

These dikes can be seen near the center of the middle outcrop on the southbound lane; however; good exposures such as this are rare so please do not hammer on them!

STRUCTURAL GEOLOGY

Although the spectacular aspects of this exposure are the sedimentologic cycles of the Duncannon Member, there are some deformational structures worth noting. Perhaps the most noticeable is the wedge fault which rises out of the base of the middle outcrop (southbound lane), crosses the sandstone base of the cycle, and passes upward through the section (to the left). The displacement of this fault is only two or three feet. Yet near the top of the gray sandstone in this cycle, the displacement appears to be much greater, on the order of 15 to 20 feet. This is purely illusory. The fault happens to parallel the edge of a sandstone channel, and the apparent offset of the gray sandstone represents the feather edge of a channel and not a duplication of the underlying sandstone beds. A few other similar wedges can be observed throughout these outcrops.

Another structure present in this outcrop are two sets of slickensided fractures that dip steeply (one to the north, the other to the south) at a large angle (60 degrees or more) to the bedding (Fig. V-B). Fractures of one set offset fractures of the other set (they are mutually offset), they intersect each other at approximately 60 degrees (they possess a conjugate geometry), and thus they are conjugate (the movements on them were contemporaneous with each other). These movements have resulted in a lateral extension of these beds (i.e., they are extension faults, Norris, 1958), in direct contradiction with the lateral contraction, or shortening, represented by the wedging on the beds. But the extension faults offset the wedge (contraction) faults, and are not offset by them. This indicates that in this outcrop a period of bed-parallel shortening was followed by bed-parallel extension. A possible explanation derives from the fact that this exposure lies in the hinge of the Buffalo-Berry synclinorium. As the fold developed, the (relatively) sharp bending of beds in this fold hinge produced a local reorientation of stress within the hinge. That is, after an initial bed-parallel shortening (by wedging), the beds in the fold hinge were extended in response to the bending of the beds. This explanation differs from the one given for the conjugate extension faults at Laurel Creek (STOP III). However, the position in the fold is different--there was no reorientation of stress in the fold limb as there was here in the fold hinge.

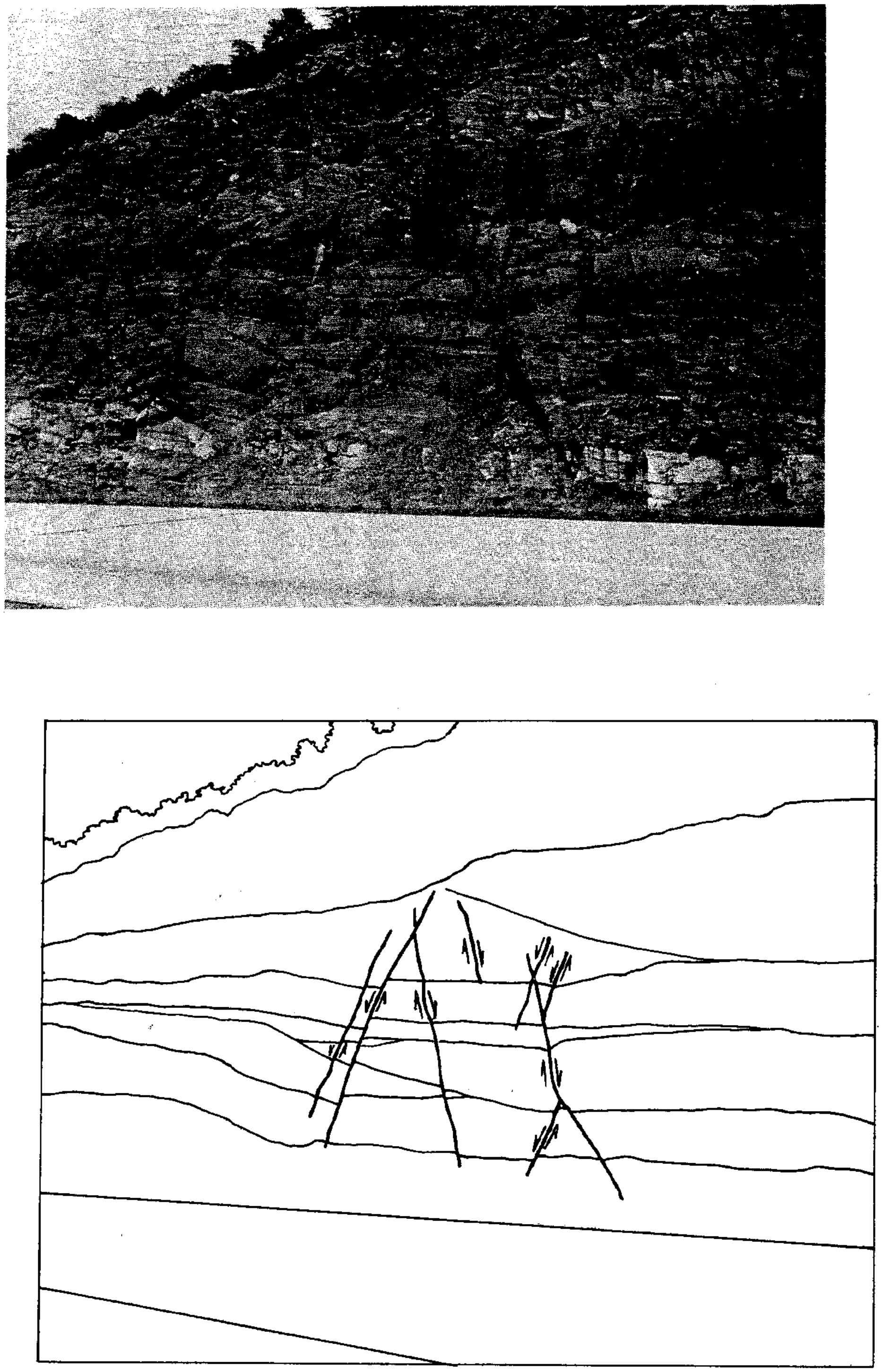


Figure V-B. Conjugate extension faults in the Duncannon Member of the Catskill Formation at the hinge of the Buffalo-Berry syncline. U.S. Routes 22-322, southbound lane, middle outcrop, 1 mile north of Newport.

At the top of this exposure (between the two road ways) one can find slickensides on a number of bedding surfaces. As described at the previous stop, there are two directions of slickensides present, representing two different kinamatic domains in this area.

The variety of lithic types in this exposure demonstrates an apparent effect of lithology on the fractures in the rocks. The sandstones generally have fairly regular and planar fracture sets, whereas some of the mudstones have rather curved and irregular fractures (joints). In addition, some beds exhibit two given fracture orientations, whereas beds below or above exhibit fractures of different orientations. No explanation for these features is being offered.

120.1 Reboard buses. Estimated time: 5:25 P.M. Approximate time to return to the Penn-Harris Motor Lodge: 35 minutes.

121.5 Pa. Route 34. To the southwest are deep extensive cuts in the Catskill Formation, exposing the steeply north dipping beds of the Sherman Creek Member in the north-south limb of the Buffalo-Berry synclinorium. These rocks are nearly entirely red. At the south end of the far cut is the uppermost part of the Irish Valley Member, exhibiting upward-fining cycles similar to those in the Duncannon at STOP V, but thinner. At the base of several of these cycles are fossil branches and other plant material. One mile to the southwest, where Pa. Route 34 intersects with the old U.S. Routes 22-322 at the Juniata River (across from Newport), the Irish Valley Member of the Catskill Formation is well exposed northward along old U.S. Routes 22-322.

125.8 Center line of Midway exit. To the south are the vertical beds of the Montebello Member of the Mahantango Formation in the north limb of the New Bloomfield anticlinorium.

125.9 The riffles in the river are sandstones of the Ridgeley Member of the Old Port Formation.

126.5 The riffles in the river are the Turkey Ridge and Montebello members of the Mahantango Formation.

127.0 Anticlinal fold in the Montebello Member of the Mahantango Formation. Just to the south, the Sherman Ridge Member is nearly completely exposed. From this point southward to the Watts exit, a number of kink bands, folds and faults are well exposed in the Trimmers Rock Formation.

127.9 Watts exit.

130.5 Overpass of U.S. Routes 11-15.

131.9 South end of Clark's Ferry bridge and intersection with Pa. Route 147. Turn right and follow U.S. Routes 22-322.

132.7 Riffles in the Susquehanna River on the right expose sandstones of the Sherman Creek and Clark's Ferry members of the Catskill Formation. Across the river, on the end of Cove Mountain, is a long exposure along U.S. Routes 11-15 of the uppermost Catskill Formation, and much of the Pocono Formation.

133.9 Speeceville, intersection with Pa. Route 325.

138.0 Borough of Dauphin.

138.5 Overturned beds of the Pocono Formation. Riffles in the river to the right.

140.1 Historic Fort Hunter, a stockaded blockhouse built in 1755 to 1756, during the French and Indian War. The Augusta Regiment was organized and trained here, prior to its northward march to establish Fort Halifax and Fort Augusta in Sunbury. Although Fort Hunter was used to protect the frontier, its main purpose was as a supply base in building the forts to the north. It was abandoned and fell into ruins after 1763.

140.7 Rockville bridge.

141.5 Intersection with Pa. Route 39. Proceed southward on U. S. Routes 22-322.

142.4 Interstate 81 bridge across Susquehanna River.

144.9 Executive Mansion of the Governor of Pennsylvania.

145.8 Forster Street. U. S. Routes 22-322 turn left. Turn right across bridge across the Susquehanna River.

146.7 West end of bridge.

147.3 Turn right onto exit for Erford Road.

147.5 Turn right onto Erford Road.

147.8 Entrance to Penn-Harris Motor Inn parking lot. End of first day.

Saturday, October 6, 1973

Mileage

0.0	Entrance to parking lot behind the Penn-Harris Motor Inn. Turn right onto Erford Road. Time of Departure: 8:00 a.m. Approximate travel time to STOP VI: 30 minutes.
0.1	Stop sign, intersection with U. S. Routes 11-15. Turn left.
0.7	Stop light. Proceed straight ahead.
0.8	Stop light. Turn left, following U. S. Routes 11-15 north.
1.3	Stop light. Proceed straight ahead.
1.6	On the right is an exceptional view of Harrisburg.
2.1	Bridge over Conodoquinet Creek, a superimposed stream with deeply entrenched meanders. Ordovician/Martinsburg Formation exposed on south bank and above along railroad tracks.
2.3	Stop light. Proceed straight ahead.
2.5	Bridge over railroad tracks.
3.1	Beginning of the Enola railroad yard on the right, a major switching yard on the Penn-Central System. The yard is built on an ancestral meander of the Susquehanna. The hill on the right was a Pleistocene island. Engines are changed here and across the river in the Harrisburg yard. At this end of the yard, the numerous overhead catenaries supply power for the electric engines that operate east and south of Harrisburg. At the other end of the yard, to the north, the catenaries are absent, all motive power being diesel north and west of here.
4.2	Susquehanna Gap can be seen in the distance ahead. The Enola yards are still to the right and ahead for another two miles.
4.8	Small exposure of Martinsburg Formation (Ordovician) on the left side of the road.
5.6	U. S. Routes 11-15 passes over Interstate 81.
6.4	Beginning of Bald Eagle-Juniata-Tuscarora exposure in roadcuts.
6.5	Contact between Tuscarora and Rose Hill Formations.
6.7	The double ridge of Blue or First Mountain (underlain by the Tuscarora and Mahantango Formations) can be seen across the river.

7.1 Beginning of Montebello member of Mahantango Formation exposure in roadcuts on both sides. Well exposed low angle faults are abundant in this outcrop. These faults appear to have a similar relation to the folds as do the conjugate faults at Laurel Creek (STOP III).

7.9 Center of Marysville, intersection with Pa. Route 850. Continue northward on U. S. Routes 11-15.

8.8 Beginning of Pocono Formation exposure on the left. On the right, across the river, is an excellent view of the overturned Catskill and Pocono beds in the south limb of the Cove Syncline.

10.2 Center of Perdix.

11.3 Center of Cove

12.4 The large flat area in this vicinity is the flood plain of the Susquehanna River nestled in the Cove Mountain Syncline, the hinge of which we are now crossing. On the right is the main east-west line of the Penn-Central, which follows the Juniata River Valley to Altoona, where it climbs up the Allegheny Front (through the Horseshoe Curve) to continue to Pittsburgh and points west.

13.6 Mississippian Mauch Chunk Formation on the left intermittently for the next 1/2 mile.

14.4 Beginning of Pocono Formation exposure in road cut on the left.

14.8 On the right is a good view of the Catskill and Pocono exposures across the river, with the vertical Triassic dike in the middle of the cut.

15.1 Crossing Shermans Creek.

15.2 Exit ramp to Pa. Route 274, and Duncannon. Continue north on U. S. Routes 11-15.

16.2 Intermittent exposures of Catskill Formation redbeds, considerably covered by grass and Crown Vetch.

17.9 Bridge across the Juniata River. Catskill exposed on west bank.

18.8 U. S. Routes 11-15 passes over U. S. Routes 22-322.

19.3 Road to right to Pennsy Supply sand and gravel quarries. At this point along the Susquehanna River are extensive deposits of sand and gravel, which are being utilized as a major supply source for construction in the Harrisburg vicinity.

21.6 Road on left to New Buffalo.

23.3 Beginning of long exposure in the Catskill Formation, with a number of fold and fault structures. Note that the folds have narrow hinges and planar limbs.

24.1 STOP VI. Girtys Notch Section. Estimated time: 8:30. Allotted time: 60 minutes.

DISCUSSANTS: Rodger Faill, Richard Wells

The beginning of STOP VI is near utility pole 619, at the south end of a long and high road cut that exposes much of the Trimmers Rock Formation. From this point, the stop continues southward for 1/2 mile--past a valley in which is nestled a house; past a long, benched road cut exposing the upper Trimmers Rock, the basal Catskill and the contact between the two; past another valley in which sits a "Rock and Mineral Shop"; to utility pole 611 at the north end of a long road cut in the Catskill Formation.

Although police protection will be available at this stop, everyone is cautioned that this road is heavily traveled at high speed, and care must be taken while walking along the shoulders.

Structural Geology--fossil deformation.

Throughout this 1/2 mile long stop, the dip does not vary appreciably from a moderate south dip. Some large and small north dipping kink bands are present, but not particularly obvious. Some gently dipping faults, and a few steeply south dipping wedge faults are also present, as is cleavage. And slickensides can be observed on numberous bedding surfaces along the way. These fairly obvious deformational structures have been seen at previous stops, and will be discussed again at subsequent stops. The structure to be noted here are the distorted fossils (crinoid disks).

The fossil distortion occurs throughout the entire Valley and Ridge Province, and has been noted in every stratigraphic formation and rock type that contains fossils. All the fossils are distorted regardless of species or size. This fossil distortion represents a more penetrative deformation then the cleavage and other solution features, because no discrete structures have been associated with them. (In contrast, the Lingulas examined by Nickelsen, 1966, in the Allegheny Plateau exhibited a fine crenulation and microjointing.) Although the fossil distortion represents a bulk, uniform flow throughout the rocks, the precise mechanism by which the deformation occurred (intergranular movement, solution activity, etc.) is not known.

The fossil distortion evinces itself in various manners, depending on the initial shape and geometry of the fossil. Brachiopods in which the sulcus and hinge lines were initially perpendicular frequently exhibit an angular distortion. Similarly, trilobites no longer possess a bilateral symmetry. In addition to angular distortions, all the fossils exhibit an external shape distortion. They are generally elongated in one direction and shortened in a direction perpendicular to this. This is particularly well shown in disarticulated crinoid disks lying in the bedding plain. These initially circular objects now possess a marked elliptical eccentricity, as can be seen in several blocks scattered about as float, and in place, at this locality.

Although most of these fossils could be used for strain determination, the crinoid disks are particularly suitable-- 1) measurements of shape distortion are more precise than those of angular distortion (because angular distortion is usually less than 5 degrees) and 2) the crinoid disks were initially circular, and thus they represent strain ellipses. Therefore, the strain in the plane in which the disk lies can be measured directly from its exterior shape. In actual practice, the lengths of the major and minor axes (the longest and shortest diameters, which are perpendicular to each other) are measured. These two lengths are used to calculate the amount of strain. Specimens have been collected from here, but the measurements are not completed. Crinoids collected 4 miles west of here exhibit a 21 percent strain.

But it is also important to know the orientation of the strain. To determine this, the angle between the major axis of the crinoid disk (ellipse) and some reference line (usually the strike of bedding) is measured. Knowing this angle, and the attitude of the plane containing the crinoid disk (frequently a bedding plane), one can then determine the orientation of the strain ellipse.

Strain is not, however, usually confined to a two-dimenstional plane--generally distortion is three-dimensional. The drawback of disarticulated crinoid disks is that they usually lie flat in bedding, and thus give no information about the strain perpendicular to bedding. Fortunately, though, not all the crinoid stems are broken apart--a number of them are preserved intact, lying on their side. Thus, the cross sections of the stems provide directly measurable ellipses for determining the strain in the third dimension, normal to bedding.

Preliminary results of a province-wide collecting program are discussed in the Structural Geology paper at the beginning of this guidebook. Briefly, this penetrative deformation is composed of contributions from three processes: compaction, cleavage development, and the outward radial movement of these rocks on the deeply buried decollements. The symmetrical relation of the strain ellipsoids with bedding rather than with the folds indicates that this deformation took place prior to the folding, yet the persistent elongations sub-parallel to the fold axes suggests that this flow was an early phase of the deformation that culminated in the folds we see throughout the province.

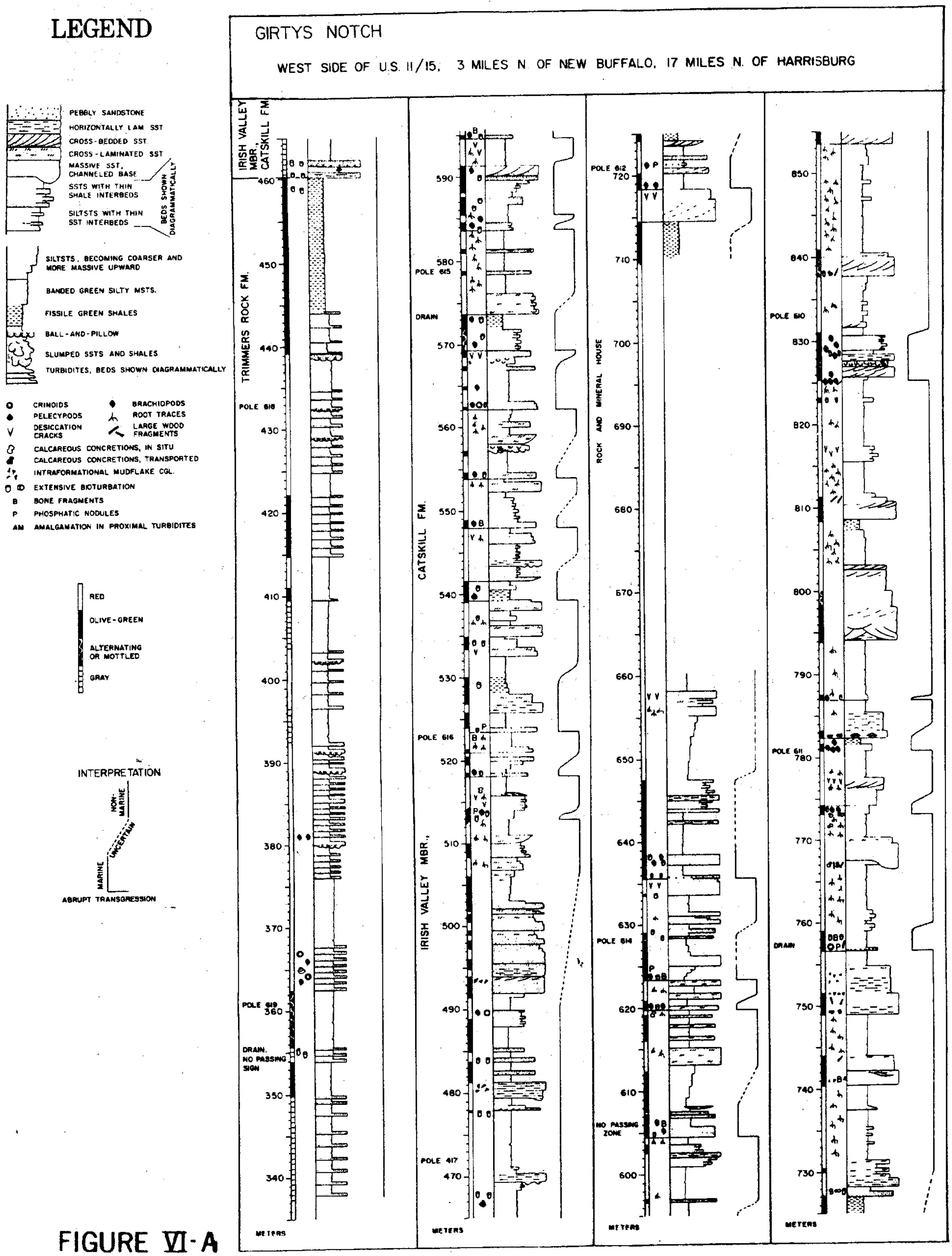
Stratigraphy

The Upper Devonian Trimmers Rock Formation consists of an interbedded sequence of thin to medium bedded, medium gray siltstones and medium gray, slightly silty, somewhat fissile shales. Graded bedding, groove casts and flute casts in some of the siltstone beds indicated deposition by turbidity currents. Load casts or ball and pillow structures, thin veins of quartz and occasionally calcite, crinoid columnals, pelecypod, brachiopod and occasional gastropod shells are common in some of these siltstone beds. Near the top of the Trimmers Rock, the shales are brownish gray or slightly reddish gray.

Traditionally, the contact between the Trimmers Rock and Catskill Formations has been placed at the base of the lowest thick redbed in the Upper Devonian. However, recent mapping in the central Valley and Ridge province (Miller, 1959; Dyson, 1963, 1967; Faill and Wells, 1974) shows that the lowest redbed does not maintain a constant position with regard to specific sandstone bodies, occurrence of sedimentary cycles, or inferred depositional environments.

A more consistent and mappable criteria for a contact is the presence and nature of sandstones. Walker (1972), in his study of the section exposed at this stop, placed the contact at 460 meters, some 60 feet north of utility pole 417 (Fig. VI-A). At this point he feels the style of deposition changes from that below, with increasing amounts of sand in the section. However, the thick sandstone interval at 492-503 meters (Fig. VI-A) is the lowest occurrence of thick fining upward cycles, a pattern that pervades much of the Catskill Formation and can be said to be characteristic of it. This unit is apparently a delta-front sandstone, and thus a harbinger of the emergence of the Catskill delta. The authors therefore place the contact at the base of this sand body, some 100 feet south of utility pole 417. Placement of the contact at this sandstone is advantageous because it can be easily mapped.

The cyclicity within the Catskill is not uniform. at STOP V, Buffalo-Berry Mountain; the upward-fining cycles in the Duncannon member are definitely fluvial. In contrast, the cycles in the lower part of the Irish Valley member represent marine-nonmarine alternations, produced by a repeated lateral shifting of the shoreline. These cycles (motifs of Walker) begin with a marine transgression, and pass through a marine shoaling phase, a shoreline shift, and a coastal plain aggradation (Fig. VI-B). The principal criteria for interpreting these marine-nonmarine alternations are the presence of marine fossils in the grayish green and light olive gray shale and siltstone in the lower part of the motif, extensive bioturbation in the transitional beds, and the presence of rootlets and sun or mud cracks in the red mudstones in the upper portion of the motif.



LEGEND
PEBBLY SANDSTONE
HORIZONTALLY LAM SST
CROSS-BEDDED SST
CROSS-LAMINATED SST
MASSIVE SST, CHANNELED BASE
SSTS WITH THIN SHALE INTERBEDS
SILTSTS WITH THIN SST INTERBEDS
BEDS SHOWN DIAGRAMMATICALLY
SILTSTS, BECOMING COARSER AND MORE MASSIVE UPWARD
BANDED GREEN SILTY MSTS.
FISSILE GREEN SHALES
BALL-AND-PILLOW
SLUMPED SSTS AND SHALES
TURBIDITES, BEDS SHOWN DIAGRAMMATICALLY
CRINOIDS
PELECYPODS
DESICCATION CRACKS
BRACHIOPODS
ROOT TRACES
LARGE WOOD FRAGMENTS
CALCAREOUS CONCRETIONS, IN SITU
CALCAREOUS CONCRETIONS, TRANSPORTED
INTRAFORMATIONAL MUDFLAKE CGL.
EXTENSIVE BIOTURBATION
B BONE FRAGMENTS
P PHOSPHATIC NODULES
AM AMALGAMATION IN PROXIMAL TURBIDITES
RED
OLIVE-GREEN
ALTERNATING OR MOTTLED
GRAY
INTERPRETATION
NON-MARINE
UNCERTAIN
MARINE
ABRUPT TRANSGRESSION
GIRTYS NOTCH
WEST SIDE OF U.S. 11/15, 3 MILES N. OF NEW BUFFALO, 17 MILES N. OF HARRISBURG
IRISH VALLEY MBR., CATSKILL FM.
TRIMMERS ROCK FM.
POLE 618
POLE 619
DRAIN. NO PASSING SIGN
CATSKILL FM.
IRISH VALLEY MBR.,
POLE 615
DRAIN
POLE 616
POLE 617
POLE 612
ROCK AND MINERAL HOUSE
POLE 614
NO PASSING ZONE
POLE 610
POLE 611
DRAIN
METERS

FIGURE VI-A

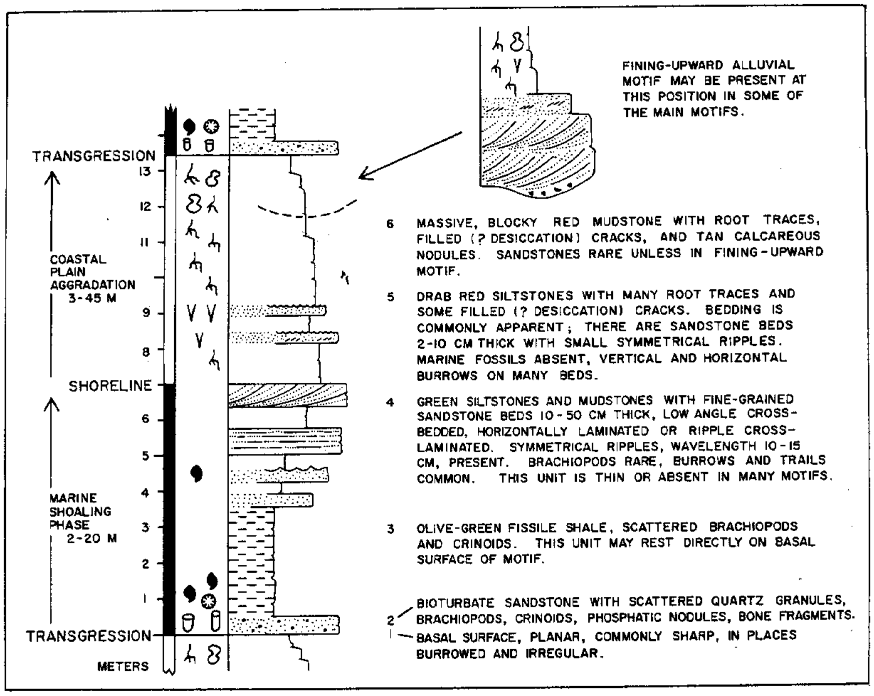


Figure VI-B. The Irish Valley motif, from Walker, 1972.

(opposite page)
Figure VI-A. Stratigraphic section in the Trimmers Rock-Catskill transition zone at Girty's Notch. STOP VI begins below the base of the section, at the lower left, and includes all the overlying rocks up to pole #611 in the right-hand column. From Walker (1972).

There are approximately 20 motifs between the base of the Catskill and the end of STOP VI at utility pole 611. Several of them are present in the exposures north of the Rock and Mineral Shop, but the motifs further south, between utility poles 612 and 611, are more completely developed. In walking southward (up-section), it is evident that the small amount of sandstone in the many motifs indicates that the shoreline was rather muddy, and passed back and forth through here with little winnowing of nearshore sands.

According to Walker (1972), the system was mainly being supplied by sediment through long-shore drift rather than by major rivers crossing the coastal plain. For this reason, Walker suggests that the Catskill Formation should be considered a progradational clastic wedge rather than a deltaic system. Woodrow and others (1973) summarized much of the recent work on the Catskill and its assumed equivalent, the Old Red Sandstone, and have drawn Upper Devonian paleogeography and climatic zones on a reconstructed, pre-drift base map. They suggest that repeated intertonguing of marine and nonmarine environments (that we now see as motifs) was possible because of a low slope angle on the coastal plain which "permitted large-scale shoreline shifts in response to slight changes in relative sea level."

24.7 End of STOP VI. Reboard buses. Estimated time: 9:30 a.m. Approximate travel time to STOP VII: 25 minutes.

25.2 Beginning of STOP VI. Exposure north of here is in Trimmers Rock Formation.

25.8 Girty's Notch. Exposures on east side of road are in Montebello sandstone Member of the Mahantango Formation. At low water the Montebello can be seen as riffles outlining a plunging anticline (New Bloomfield anticlinorium) in the river to the east.

The picturesque picnic road stop to the right is a location to which much erroneous reknown has been given. Tradition would have this promontary be the lair of the famous renegade white man who turned Indian, Simon Girty. It was said that he used a cave or "notch" at the top of Half Falls Mountain (on the left above the road) as an observation point and hideout during the Indian unrest of 1754 to 1764. Hence this locality is known as "Girty's Notch".

Old photographs of the mountainside, before the road cut was made, show a dirt road with a profile of an Indian face high on the cliff-like exposure. This portion of the outcrop is present just to the west of the picnic tables. Quoted from the History of Perry County--"On approaching this promontary from the northeast there can be seen, halfway up the craggy rocks, the face of a man--albeit an Indian--the outline of which no sculptor could improve, put there by the Great Creator of the universe and which tradition would have us believe is the counterpart of the Girty profile."

Careful attention to historical records prove that, although the renegade's father owned property in Dauphin County, the evil doings of Simon Girty were carried on mostly near Fort Pitt, a place more suited to his talents, and not at this idyllic spot of greenery and pastoral view of mountain and river.

27.3 Montgomerys Ferry Access Area, one of many created by the Pa. Fish Commission to provide parking and access via a boat ramp to the Susquehanna River.

27.5 Intersection with road. Village of Montgomerys Ferry.

28.6 Base of Pocono Formation, Spechty Kopf Member. Cut exposes the lower one-half of the Pocono and all of the Spechty Kopf Member. Immediately to the south, several of the uppermost fluvial cycles of the Duncannon Member of the Catskill Formation are partially exposed.

29.0 Riffles in river to the right created by sandstones of the Pocono Formation. The broad, somewhat hilly, valley to the north is underlain by the Mauch Chunk Formation. Within this valley is the hinge of the Buffalo-Berry synclinorium.

30.3 Intersection with Pa. Route 34. Three hundred (300) feet to the south, a road to the right leads to the Millersburg Ferry. The Millersburg Ferry is the only surviving ferry service across the Susquehanna. When it began in 1825, the boats were poled by manpower. After 1873, the first paddle wheeler was acquired powered by a steam engine. In the 1920's, gasoline engines replaced the steam power, and the paddle wheels were shifted from the side of the ferry to the stern. The ferry landing is a short distance east of here.

31.3 Double mountain on the left side of the road consists of a faulted fold structure in the Pocono Formation. Across the river to the east the fold lies within the Mauch Chunk Formation, and there is only a single ridge underlain by steeply south dipping Pocono Formation.

32.1 Intersection with Pa. Route 17.

32.5 Village of Liverpool.

33.4 Just north of Liverpool was located Lift Lock No. 5 of the Pennsylvania Canal, Susquehanna Division. This system was developed throughout the Susquehanna River basin and was used by thousands of canal boats. These boats carried products from various points along the north and west branches of the Susquehanna River to Philadelphia, New York and Baltimore until 1901, when the canal system was discontinued.

34.6 Beginning of intermittent exposures of the Catskill Formation on the left.

35.3 Contact between the Catskill and Trimmers Rock formations.

35.8 End of Trimmers Rock exposure.

36.4 Intersection with Pa. Route 104. Bear left and follow Pa. Route 104.

37.0 Entering Juniata County.

37.6 Crossing trace of Old Port Formation. On the far hill to the east are Susquehanna Quarry Co. quarries in the Turkey Ridge Member of Mahantango Formation, one of which is STOP XI.

38.2 Outcrop on the right of Old Port Formation.

38.6 Entering Snyder County, crossing West Mahantango Creek. Exposures just north of bridge are in the Montebello Member of the Mahantango Formation. The exposures here and along the creek constitute the type section of the Mahantango Formation.

39.3 Exposures on the right side are in the Trimmers Rock Formation.

39.9 Exposures on the right are in the upper part of the Trimmers Rock Formation.

40.2 Town of Meiserville. Small anticline on the right is in the lower part of the Catskill Formation. Continuing intermittent cuts in the Irish Valley Member of the Catskill Formation.

40.9 Covered bridge on left side of road. South dipping Catskill on right side of road north of intersection.

41.5 Intersection with road to left.

41.9 Beginning of Catskill basal exposure.

42.4 Exposure on right in Trimmers Rock Formation.

42.7 Borrow pit on right is in Pleistocene shale-chip conglomerate and scree which developed as a periglacial effect.

42.9 STOP VII. Coarsening-upward cycles in the Middle Devonian Mahantango Formation. Estimated time: 9:55 a.m. Allotted time: 45 minutes.

DISCUSSANT: Richard Wells

Stop on the right (east) side of Route 104 opposite the Shadle general store. Walk north to the prominent sandstone outcrop at the north end of the parking lot. After examining the Montebello sandstone proceed southward, passing behind the Spotts Camper building, past the prominent "Shadle sandstone" outcrop along the road, and to the large borrow pit behind the house at Legislative Route (L.R.) 54010.

This stop is included because relationships can be seen here on a relatively small scale and in a simple structural setting, which are important to understanding the cyclicity of the Mahantango Formation. Some of the lower Mahantango cycles will be seen at STOP XI in a more complex structural setting.

The Mahantango Formation consists of light olive gray sandstone, siltstone, silty claystone, and (rarely) conglomerate. These rock types are not randomly interbedded, but are systematically arranged in cycles which become progressively coarser towards the top. This "reverse-grading", or coarsening-upward pattern pervades the entire formation (Fig. VII-A). Here at Shadle, the exposed Montebello sandstones mark the upper part of one such cycle; the sequence from the top of the Montebello to the top of the "Shadle" sandstone constitutes the lower cycle in the Sherman Ridge Member, and the rocks from the top of the "Shadle" sandstone to the top of the exposure in the north ditch of L.R. 54010 constitute the second cycle of the Sherman Ridge Member.

The cycles are asymmetric and characteristically begin with black to dark gray or olive gray silty claystone which grades upwards into argillaceous siltstone, silty sandstone, and culminate in fine to medium grained, locally conglomeratic, siliceous sandstone. Clay content decreases upwards, degree of cementation increases upwards, and the fauna changes markedly from a cosmopolitan crinoid, brachiopod, trilobite, gastropod, coral and bryozoa community (in the lower parts) to one dominated by large spirifer brachiopods (in the upper parts). The fossils in the lower part tend to occur as complete, articulated specimens, while those in the sandstones at the top of the cycles occur both as solitary individuals (in growth position) and as lenses of broken and transported shells. The contacts between cycles are sharp — an abrupt decrease in grain size from sandstone to silty claystone or silty shale. The upwards increase in grain size within cycles is generally gradual, although small abrupt changes do occur. Casts of fossil wood, plant material, bone fragments, and thin lenses of chamosite öolites occur in the upper parts of the cycles at different localities on the adjacent quadrangles.

The cycles range in thickness from 6 feet to 250 feet in Millerstown and Millersburg quadrangles. The thinner cycles occur predominantly in the coarser Montebello Member, and the thicker cycles in the finer-grained Fisher Ridge and Sherman Ridge Members. Because of the better cementation in the upper parts of the cycles, they are more resistant to erosion, and tend to form topographic ledges which can be mapped on aerial photographs. Mappable units (members and submembers) in the Mahantango range from 100 to 600 feet thick and consist of several cycles, except for the two submembers of the Sherman Ridge, both of which consist of a single thick cycle. The thicker cycles can usually be traced over distances of from 5 to 30 miles.

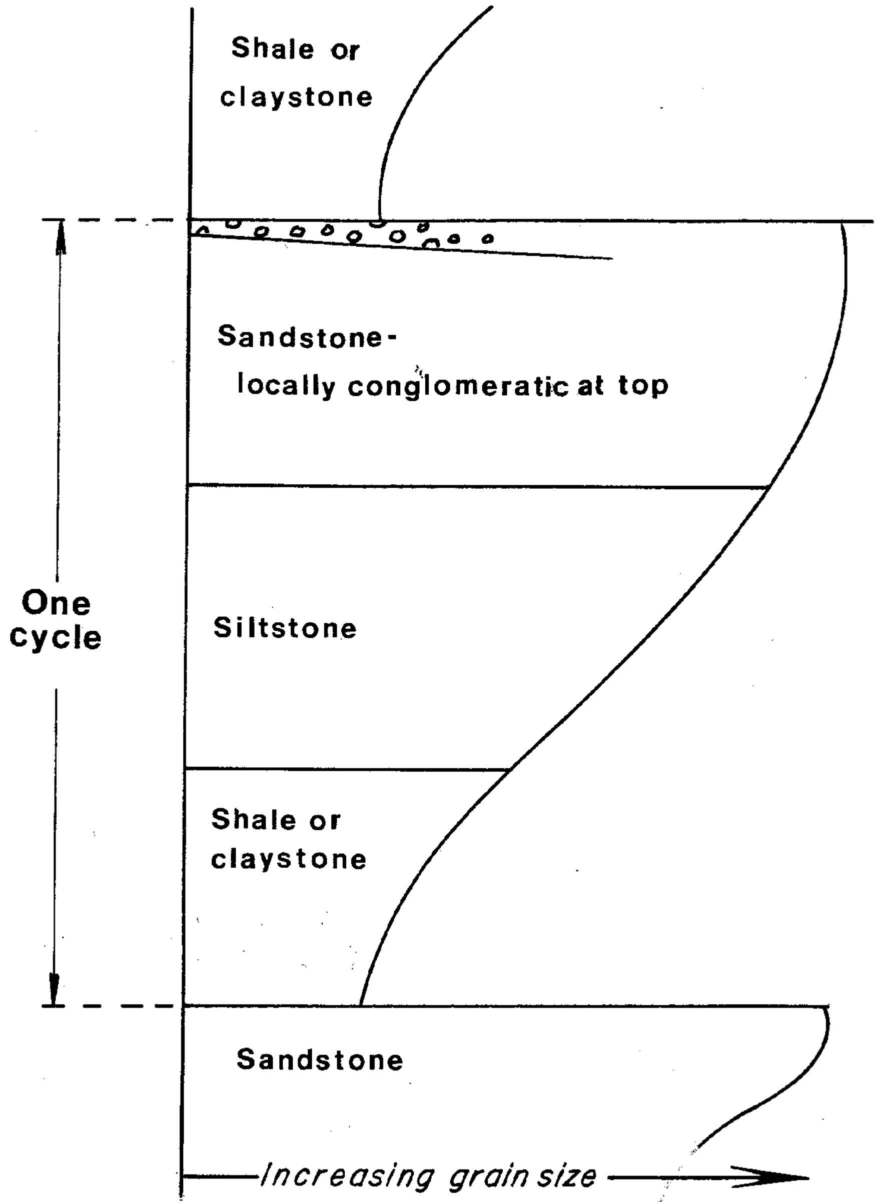


Figure VII-A. Idealized coarsening-upward cycle in the Middle Devonian Mahantango Formation. Maximum grain diamemter increases upwards within each cycle as clay content decreases. In many cycles the curve is not a smooth as shown here, as minor interruptions or "nested sub-cycles" occur.

Sedimentation

The similarity of the Mahantango cycles of the coarsening upward ("reverse graded") cycles in known deltaic sequences suggests that the Mahantango Formation is a product of deltaic sedimentation. The radial thinning and fining of the sandstones within 30-40 miles indicates that the delta was relatively small, with a source near Harrisburg (Faill, Hoskins, and Wells, 1974).

Sedimentation at the beginning of each cycle began well below wave base with deposition of clay and silt, which became progressively coarser, culminating in the deposition of clean, fine grained sand (with occasional medium grained sandstone pebbles) at the top. The upward increase in grain size, sorting and winnowing of the sediment within the cycles suggests a progressive increase in the effectiveness of wave and current action, perhaps reflecting a gradual decrease in water depth as sediment accumulated. The concentration of brachiopods and molluscs in the upper parts of the cycles suggests that during the late phases of the cycles conditions were favorable for these organisms.

"Complete" deltaic sequences generally have tidal flat, marsh and fluvial deposits overlying the marine sediments. The Mahantango cycles are apparently incomplete, because each cycle terminates at the shallow marine phase of the cycle, with a subsequent return to deeper, quiet water sedimentation. The interruption of sediment input at a given locality and the repetition of cycles probably resulted from the switching of distributary channels to other areas of the delta. Such a shift would result in an abrupt decrease in sediment supply and current activity at a site which had been receiving large amounts of relatively coarse sediment. Deposition would resume only after a period of gradual subsidence had enabled deeper water to return, initiating the development of a new cycle over the previous one. The absence of supratidal and fluvial deposits indicates that the sediment supply to the delta was never great enough, with respect to the rate of sediment dispersal and subsidence, for the delta to become subaerial.

42.9 End of STOP VII. Reboard buses. Estimated time: 10:40 a.m. Proceed northward on Pa. Route 104. Approximate travel time to STOP VIII: 40 minutes.

44.1 Intersection with gravel road to the right. Crossing hinge of the eastward plunging Western Middle Anthracite syncline. To the south are steeply north dipping to vertical beds in the Montebello sandstone; to the north are moderately south dipping beds, also in the Montebello. Although the Western Middle Anthracite syncline is a major first-order fold in the Anthracite region to the east, it diminishes in size towards the west, and terminates just one mile west of here as a minor third-order fold. The hinge of the Quaker Valley synclinorium, which coincides with the Western Middle Anthractie syncline to the east, jumps southward three miles to the Quaker Valley syncline, reflecting the en echelon fold structure that occurs in the synclinoria as well as the anticlinoria.

45.0 Intersection with Pa. Route 35. Low ridges on left and right side are underlain by the Old Port Formation.

45.2 Ahead and to the left is Shade Mountain which at this point terminates by plunging eastward.

45.7 Exposure of Keefer Formation. To the north are exposures of Rose Hill Formation. Low hills on each side of road are underlain by the Iron Sandstones of the Rose Hill Formation.

46.3 Exposure of Rose Hill Formation on left side of road, quite weathered.

47.4 Exposure of Tuscarora Formation on left and right side of road. Hinge of Shade Mountain anticline.

48.4 Beginning of rather continuous exposure of Rose Hill Formation on right side of road.

49.0 End of Rose Hill exposure.

49.1 Large borrow pit in Rose Hill on right side of road.

49.3 Small crest in road crossing through gap in low ridge underlain by Keefer sandstone and the upper Iron Sandstones of the Rose Hill Formation.

50.1 Kelly Road bearing off to left to Paxtonville.

50.3 Intersection of U. S. Route 522. Turn left and proceed across creek following Pa. Route 104.

50.6 Stop light, center of Middleburg. U. S. Route 522 turns left. Proceed north on Pa. Route 104.

51.1 Low ridges on each side of road are underlain by the Montebello Member, which is here much reduced in grain size and thickness as compared to it further south, e.g. at Shadle. Much of the Mahantango Formation is shale in this vicinity.

51.4 Beginning of Trimmers Rock Formation.

52.4 Exposures to the left are in the lower part of the Catskill Formation.

53.1 South dipping Catskill Formation. Intermittent exposures for next half mile are in the Trimmers Rock.

53.6 Approximate contact between Trimmers Rock and Catskill formations.

54.6 Approximate base of the Trimmers Rock Formation. Large mountain to north and west is Jack's Mountain underlain by the Tuscarora, Juniata and Bald Eagle formations. The Jack's Mountain anticline is plunging eastward in this vicinity.

55.6 Village of Penn's Creek. Note boulder field of Tuscarora Formation on Jack's Mountain.

55.9 Exposure of Bloomsburg Formation on each side of road.

56.2 Crossing Penn's Creek, entering Union County. Rose Hill exposed to west.

56.7 Tuscarora Formation exposed in cuts on both sides of road. Crest of eastward plunging Jack's Mountain anticlinorium.

57.1 Long cuts in both sides of the road are Rose Hill Formation.

57.4 Long cuts in the Rose Hill Formation. Throughout the cuts in the Rose Hill to the north, its bedding dips consistently to the north. A mile or so to the east, the Shamokin Mountain anticline originates and becomes the hinge of the Jack's Mountain anticlinorium to the east. The Jack's Mountain anticline similarly terminates a few miles east of here, but is the hinge of the anticlinorium to the west. Thus an en echelon fold structure is present.

57.9 Intersection of road to White Springs. Exposures of Bloomsburg Formation in borrow pit.

58.1 Exposures of Wills Creek Formation in cuts on both sides of road.

58.3 Site of Leroy Massacre, one of the Indian rampages following Braddocks defeat during the French and Indian War.

59.0 Crest of hill, cuts on both sides in very poorly exposed Old Port which is predominantly chert. A black sooty shale exposed as float on the right side of road is the Mandata Shale Member of the Old Port Formation.

59.3 Cobbly limestone on right side of road is Keyser Formation of the Helderberg Group. Attitude is subhorizontal to gently south dipping.

59.6 End of Pa. Route 104; intersection with Pa. Route 45. Turn right, enter borough of Mifflinburg.

60.0 Stop light, center of Mifflinburg. Pa. Route 304 turns off to right. Continue east on Pa. Route 45.

60.5 Turn left on Buffalo Road. NOTE: For vehicles in excess of 5 tons, see alternate route listed after mileage 65.6. The following route passes over bridge with a 5 ton weight limit.

61.2 Bridge across creek.

61.5 Second bridge across creek.

61.7 Turn right on unmarked road.

62.0 Turn left on Legislative Route 59034.

62.6 Quarries in nearly flat lying Bloomsburg Formation, with a 1 foot-thick green layer in the middle of the redbed sequence.

63.4 Bloomsburg red beds exposed as road follows resistant ridge in Bloomsburg for some distance. The low ridge to the north (left) is underlain by the Wills Creek Formation.

64.4 Cowan, intersection with Pa. Route 192. Continue straight ahead through intersection. Bridge with a 5 ton weight limit is a short distance ahead.

65.1 T-intersection with Cannon Road. Turn right onto Cannon Road, which follows the resistant Bloomsburg ridge to STOP VIII.

65.6 STOP VIII.

Alternate route for vehicles exceeding 5 tons.

60.5 Intersection with Buffalo Road. Proceed straight ahead (eastward) on Pa. Route 45.

61.8 Buffalo Creek Road to the left leads to Cowan.

63.7 Turn left onto Beaver Run Road at east end of Vicksburg, which was named for Grant's Victory at Vicksburg, Mississippi.

64.4 Wills Creek Formation exposed in road cut on left.

64.7 Wills Creek Formation exposed in road cut on both sides.

65.3 Intersection with Pa. Route 192. Proceed straight ahead.

65.6 Bridge over Buffalo Creek.

66.1 Sharp right bend in road. Turn left onto Shrawder Road.

66.5 Three-way intersection. Turn left onto Cannon Road.

66.7 Horizontal Bloomsburg beds in low road bank on right.

66.9 Beginning of STOP VIII at bottom of hill.

STOP VIII: Deformational structures in the Bloomsburg Formation, Cowan, Pa. Estimated time: 11:20 a.m. Allotted time: 75 minutes.

DISCUSSANT: Richard Nickelsen

As mentioned at STOP I, the Bloomsburg Formation in central Pennsylvania is a shallow-water, brackish marginal marine unit transitional between the fluvial continental facies (The Bloomsburg-Vernon delta) to the east and marine carbonates, shales and marls of the interfingering Wills Creek Formation to the west.

The dominant lithology is a grayish-red, silty claystone with a characteristically splintery fracture along a poorly developed cleavage. Bedding is thick to massive, and frequently so indistinct that it escapes attention. Occasional burrows and mudcracks are present. Fossils include Lingula, fish scales, foraminifera and ostracods.

Two intervals of sandstone are present, a relatively thin one at the base and a thicker, more prominent one near the top (the Moyer Ridge member). The sandstones are hematitic subgraywackes, grayish-red, fine-grained, silty and argillaceous, and poorly sorted. They are medium to thin bedded, with the planar bedding surfaces somewhat more distinct than those in the claystones. The Moyer Ridge sandstones at this stop are cut by sandstone dikes in which the grayish-red sandstone is only slightly coarser than the host rock. These dikes are about 2 or 3 cm. thick, occur perpendicular to bedding and parallel the cleavage.

Regional setting

The Bloomsburg Formation at this stop is exposed at three stations (A, B. C) on the south limb, north limb and crest, respectively, of a third-order anticline within the first-order

Buffalo Valley Synclinorium, a structure which can be traced down plunge to the northeast into the Northern Anthracite Synclinorium. Different size orders of folding have developed at different stratigraphic levels in the major synclinorium. The three third-order anticlines at this stop occur on a second-order anticline best expressed at the level of the Tuscarora Quartzite (see inset, Fig. VIII-A). Moreover, at the stratigraphic level of the Keefer sandstone (at the top of the Rose Hill Formation), between the Tuscarora and Bloomsburg, only two third-order anticlines are present east of the second-order anticline. The Wills Creek Formation above the Bloomsburg is folded into one second-order anticline but shows an extra third-order anticline and syncline in the syncline adjacent to the north (Fig. VII-A). These fold disharmonies are typical of the region and apparently result from homogeneous shortening of layers of different thickness and viscosity, which give rise to fold trains of different wave length and amplitude. Boundary zones between folds of different wave lengths and amplitude in this section seem to occur: 1. at the top of the Rose Hill, 2. in the McKenzie-Rochester members of the Mifflintown Formation or in the lower Bloomsburg, 3. in the lower Wills Creek Shale.

The exposures at Cowan

The Bloomsburg anticline at this top will be "walked out" to show the following features at stations A, B, and C (Fig. VII-A): bedding and fracture cleavage intersections, features bearing on cleavage origin, sandstone "dikes" thought to be mudcrack fillings, homogeneous strain as shown by distortion of organic borings, formerly spherical reduction spots, and mud-crack polygons, lack of correspondence of the bedding pole denoting the fold hinge and bedding-cleavage intersections.

Station A

At this outcrop of the sandy Moyer Ridge member of the Bloomsburg Formation, bedding dips 50 degrees south and cleavage dips 40 degrees north (Fig. VIII-B). Cleavage-bedding intersections are horizontal or southwest plunging and the northern part of the outcrop shows sandstone dikes approximately parallel to cleavage as well as organic burrows lying in the cleavage plane perpendicular to bedding. The dikes were formerly thought to represent sand-water injections during soft-state cleavage genesis but are now considered to be mudcrack fillings. They parallel cleavage because cleavage was initiated with a vertical attitude while beds were horizontal and because they have been rotated around the $\underline{a}$ axis (see Fig. VIII-C) by both volume loss perpendicular to cleavage and by volume constant flowage leading to strain of $\underline{a} > \underline{b} > \underline{c}$ (see discussion below).

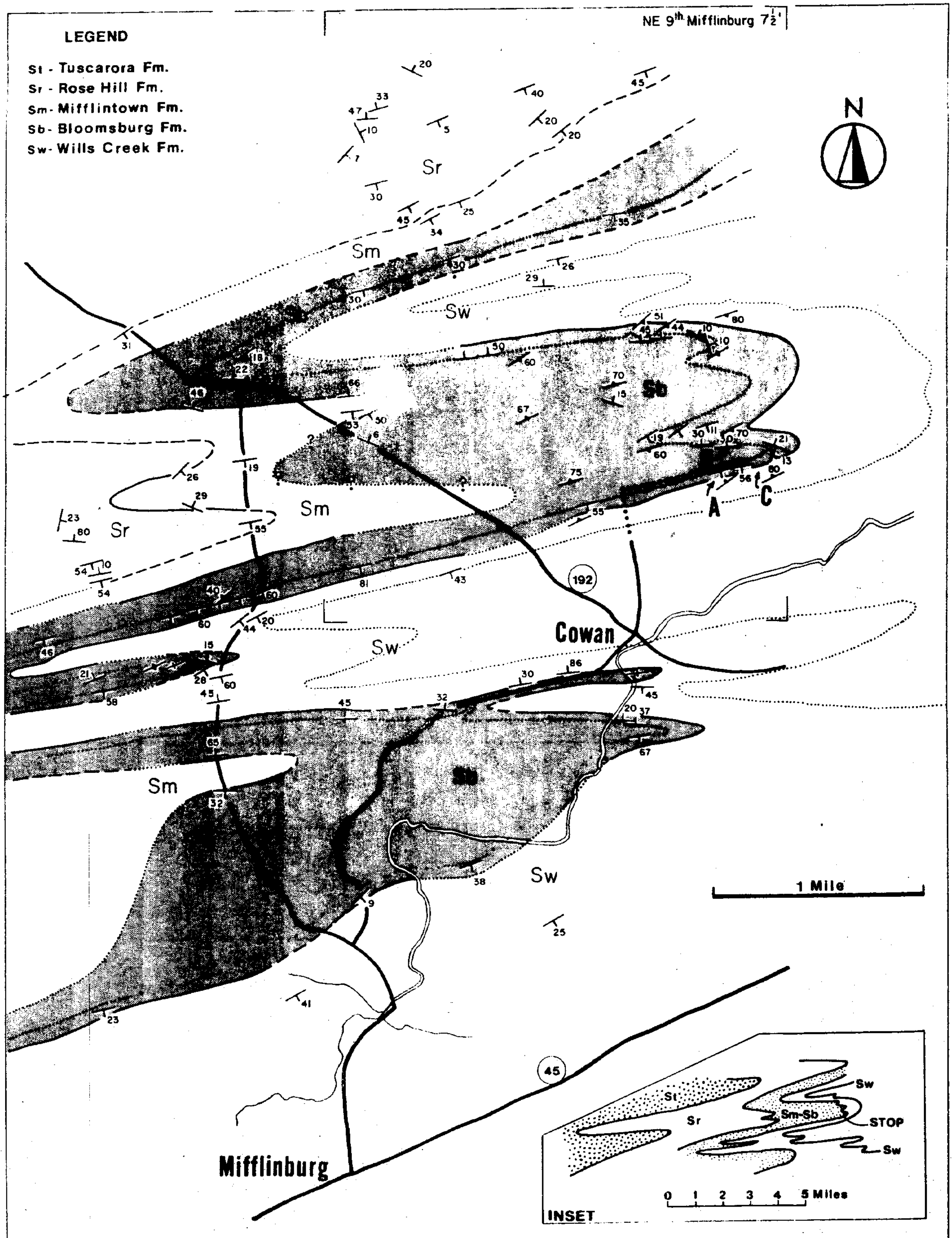


Figure VIII-A. Geologic map showing Stop 8 location and Stations A, B, and C.

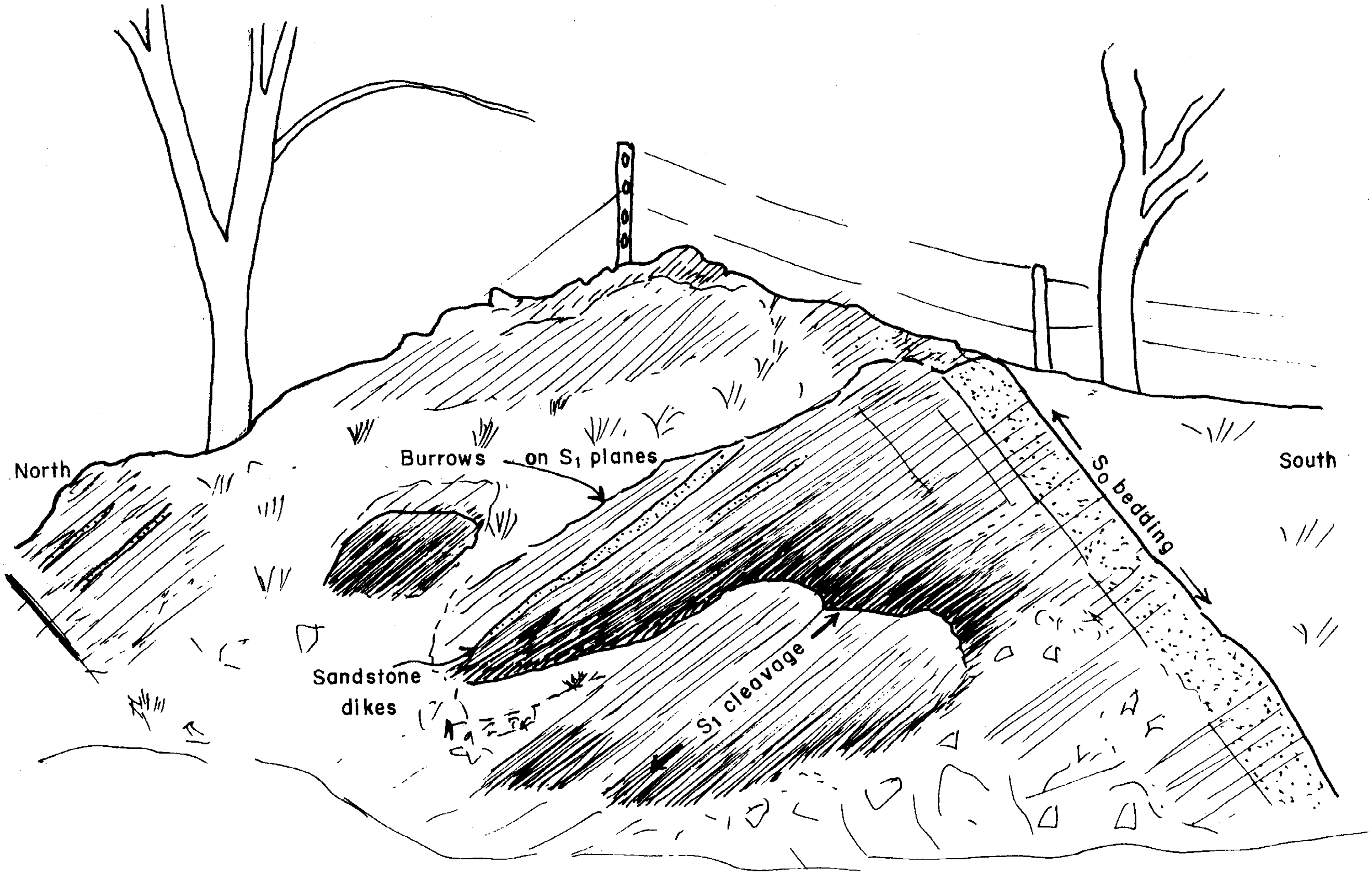


Figure VIII-B Drawing of outcrop at station A

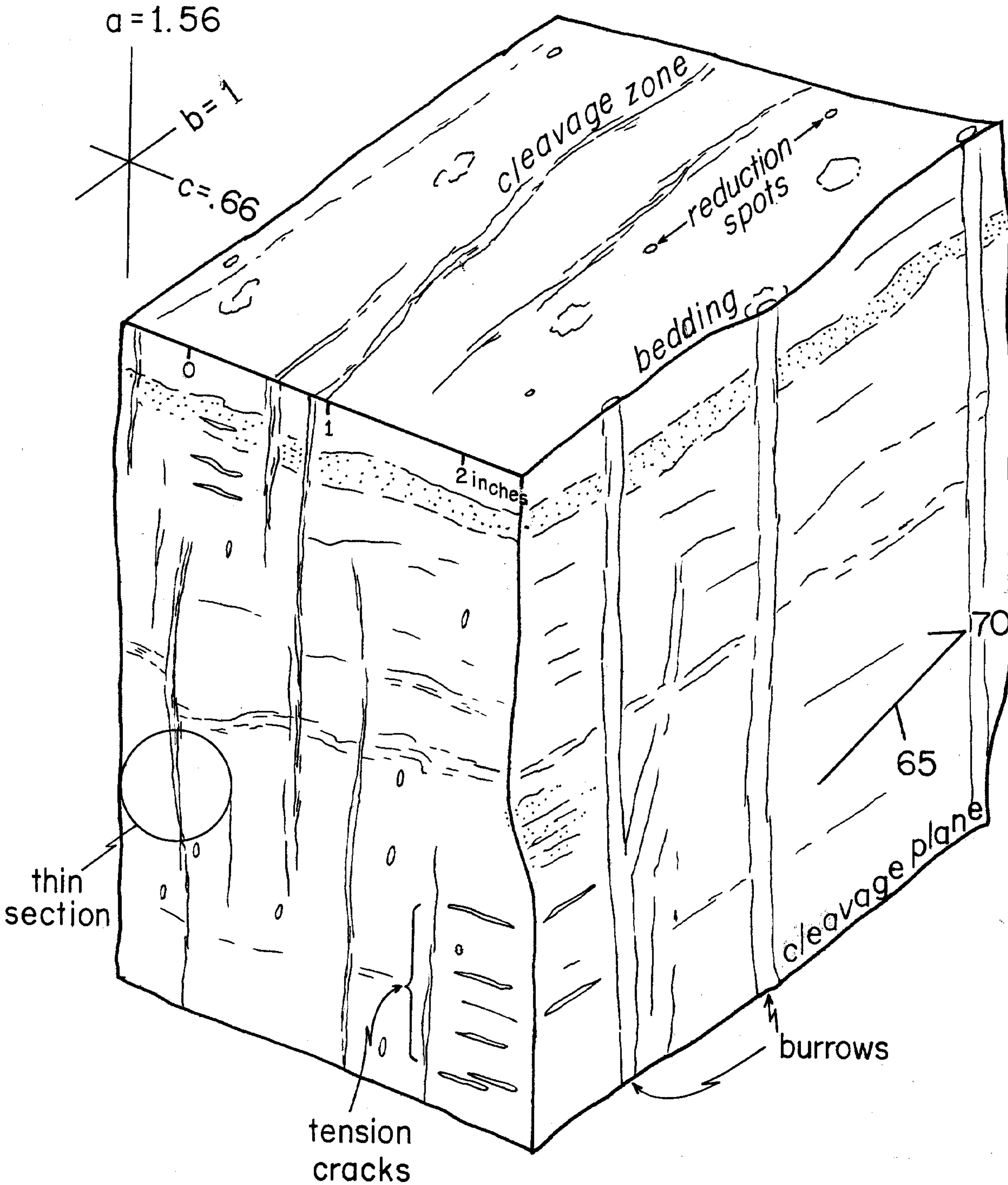


Figure VIII-C Drawing of block from station C showing bedding, cleavage, burrows, reduction spots, relative dimensions of strain axes - a, b, c.

Station B

Station B is reached by walking northeastward from Cannon Road across the open field and into the woods, where there is a good, fairly continuous exposure of the Moyer Ridge member in the north limb of the fold, particularly down the west-facing slope toward the gully. Note that cleavage-bedding intersections plunge obliquely down the bedding to the northeast off the structure, and that sandstone dikes in the mudstone beneath the sandy beds seem to originate at the base of the sandstone. The sandstone dikes are interpreted as fillings of mudcracks, filled from above as the Moyer Ridge Sandstone member was deposited. The block of Figure VIII-C was collected at this station, and all of the features illustrated on that block can be seen here. Of particular interest are the green reduction spots (maximum dimenstion several millimeters) which reflect the bulk strain illustrated in Figure VIII-D. The least strain axis is perpendicular to cleavage and the greatest strain axis is parallel to the organic burrows. Minute tension cracks commonly occur perpendicular to the greatest strain axis defined by the dimensions of the reduction spots (Fig. VIII-C). The camera lucida sketch of a thin section perpendicular to cleavage and bedding shows solution of quartz in contact with clay-carbon partings and the correspondence of a cleavage zone with an organic burrow (Fig. VIII-E). The important cleavage forming process here is solution of quartz along clay-carbon partings and residual accumulation of clay which may become oriented parallel to cleavage planes as volume is lost. Such solution seems to be enhanced by the availability of organic burrows, which, for a while at least during the diagenesis of the sediment, served as conduits for vertical migration of of fluids.

Station C

Station C is reached by walking eastward up through the woods and across an open field at the top of the hill. The best exposures are along Cannon Road and in the adjacent field to the north. Bedding at this station is approximately horizontal on the crest of the anticline, cleavage strikes N70E and dips nearly vertically. The sandstone dikes outline elongated polygonal areas inferred to be mudcracks (Fig. VIII-F). The ratio of long to short dimensions of the polygonal areas is roughly 2:1 and the long axes are parallel to cleavage. I believe that originally nearly equidimensional mudcracks have been distorted by preferential solution loss along cleavage and by bulk flowage to produce the present configuration. If the ratio of 2:1 is a valid measure of the shape of the poorly-visible distorted polygons, this represents more penetrative strain than is commonly associated with Valley and Ridge rocks. (Distorted mudcrack polygons in cleaved Wills Creek Shale 1 mile south of Forest Hill also show L:S ratios of 2:1).

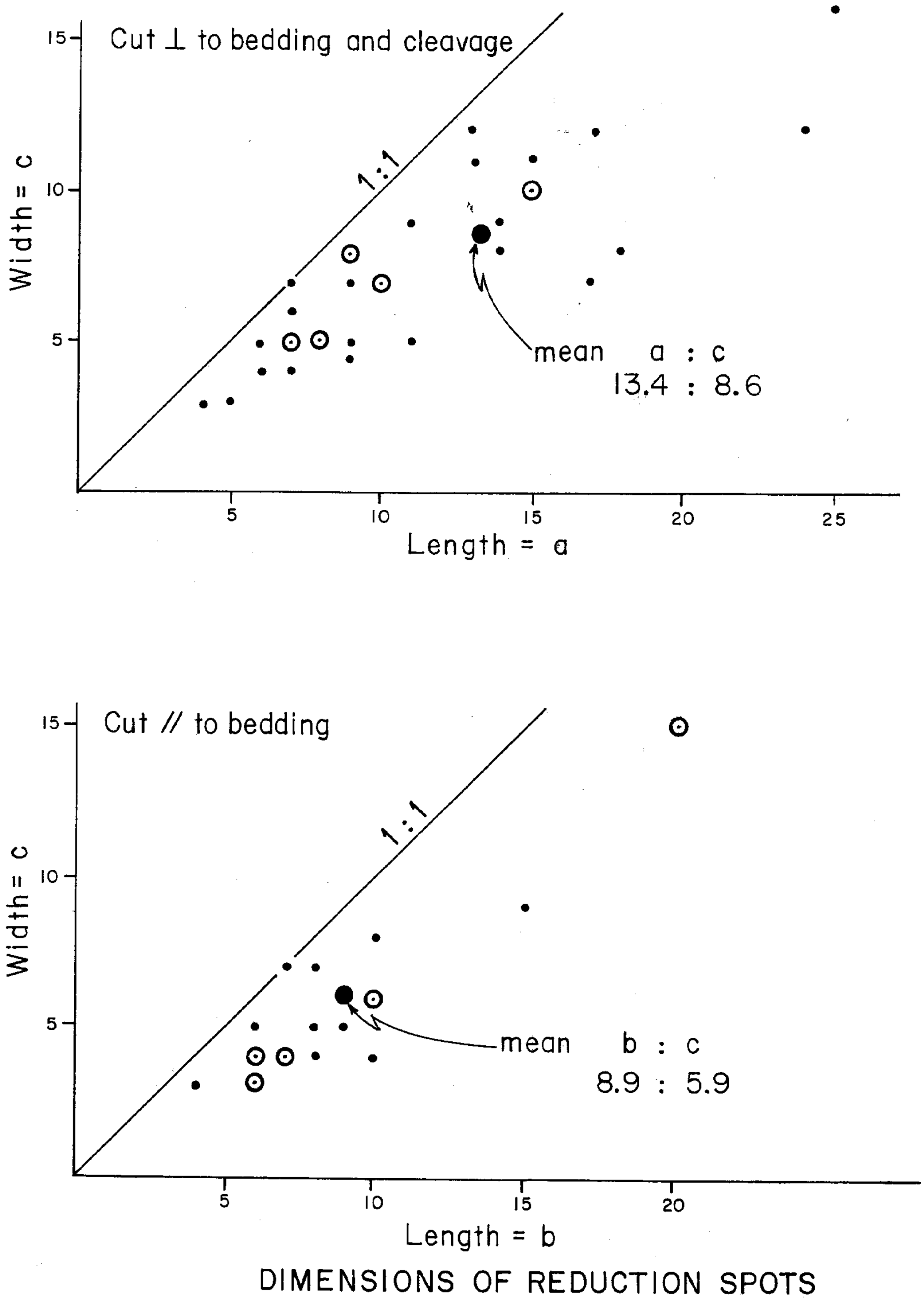
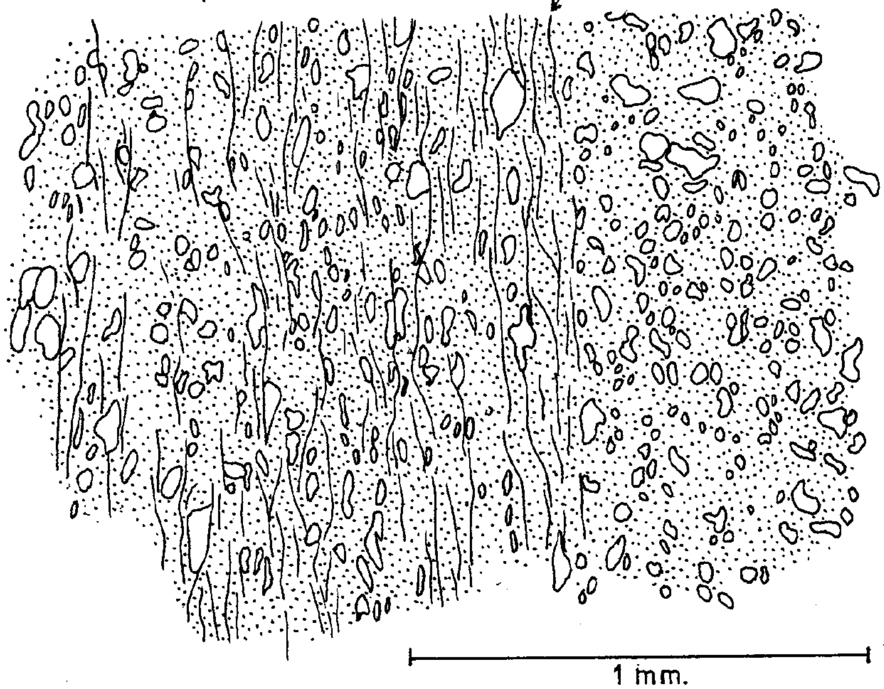
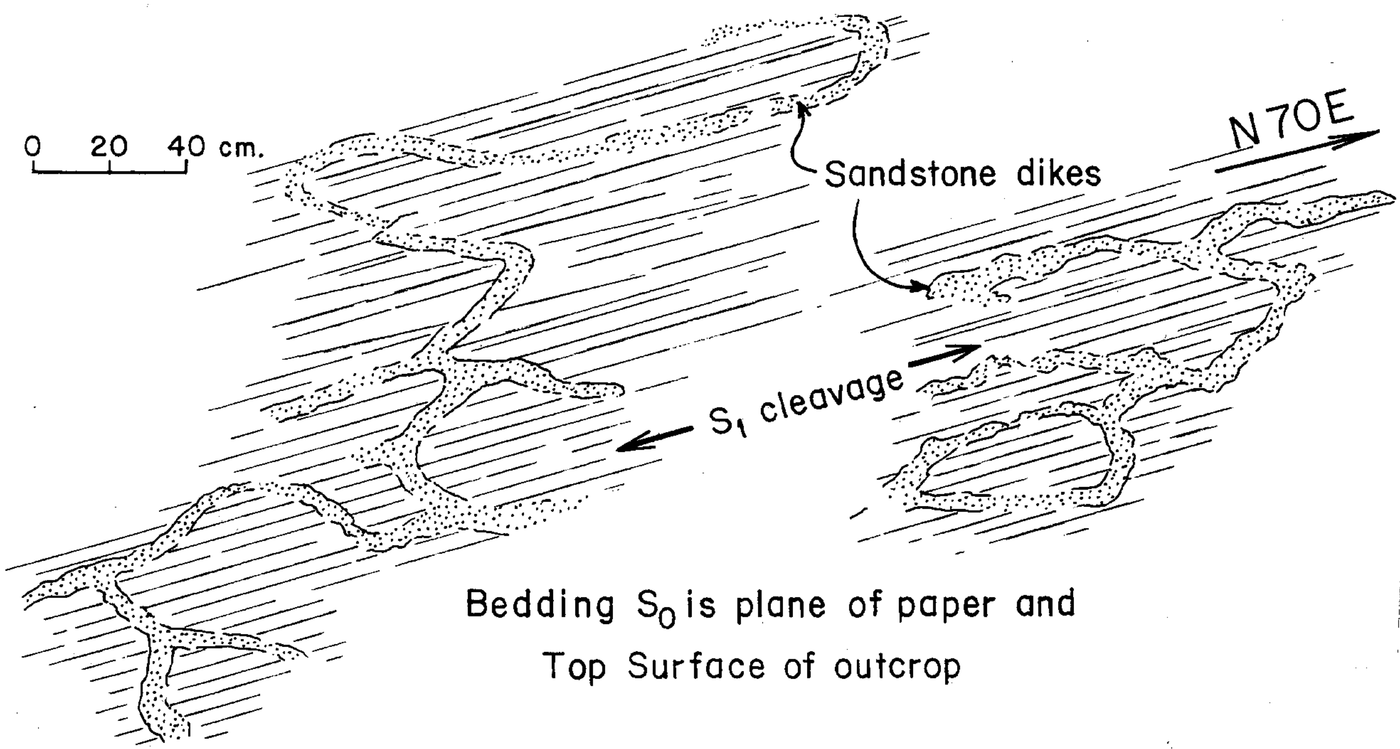


Figure VIII-D Dimensions of reduction spots on ac and bc cuts of Figure 6.



CAMERA LUCIDA - THIN SECTION $\perp$ S_0 and S_1

Figure VIII-E Camera lucida drawing showing solution of quartz in cleavage zone mimicking burrow.



Bedding S_0 is plane of paper and Top Surface of outcrop

Figure VIII-F Drawing of sandstone dike - cleavage relations at station B.

Summary Discussion

In these Bloomsburg beds, the rock cleavage (commonly referred to as fracture cleavage) apparently originated by a pre-folding differential solution of quartz in cleavage zones which often parallel organic burrows. The cleavage consists of zones of residual clay enrichment marked by inequidimensional etched quartz grains having their long dimensions in the plane of the cleavage. The burrows served the function of enhancing flow of dissolving fluids perpendicular to bedding, but this does not necessarily restrict the time of cleavage formation to the early diagenetic period.

Later fold hinges need not parallel earlier cleavage-bedding intersections. In this anticline, the fold hinge (bedding pole on Fig. VIII-G) diverges by 10 degrees clockwise from the cleavage pole, with the result that cleavage-bedding intersections on the north limb of the anticline plunge northeast at an angle down the limb, while cleavage bedding intersections on the south limb either parallel the fold hinge or plunge southwest. The pre-folding attitude of cleavage has been determined by rotating each cleavage plane around the strike of associated bedding; pre-folding cleavage had a mean strike of N75E and dipped vertically (Fig. VIII-H). This cleavage which originated perpendicular to bedding has either been externally rotated with bedding or, where steeper dips of bedding occur, has undergone some slip which has changed the former right angle between cleavage and bedding. On steeply dipping fold limbs cleavage-bedding intersection angles decrease to 70° (see lower half of Figure VIII-H). As the angle between cleavage and bedding departs from 90°, rotated cleavage poles no longer plot on the periphery of the net. Change in shape of the rock mass has taken place by both solution loss in the cleavage planes and by homogeneous, volume-constant(?) flowage which has distorted originally spherical reduction spots to ellipsoids. I have not yet been able to separate the effects of solution and flowage in producing the shape changes recognized in the rock by distorted mudcrack polygons and reduction spots. In a time sense, it appears that solution loss and early cleavage formation came first, followed by flowage which culminated in the elongation in a of reduction spots and eventual incipient brittle phase tension cracks oriented perpendicular to a. My current hypothesis is that the inequidimensional mudcrack polygons (long:short ratio 2:1) record the total shape change that the rock has undergone in the bc plane and this includes both solution loss and distortion. The reduction spots commonly are not intersected by solution planes and thus may record only the essentially volume constant distortion (ratio b:c - 1:.6). This ratio is close to the shape change recorded in distorted mudcracks. In three dimensions the reduction spots signify that volume constant distortion has lead to greatest elongation in the a direction (ratio a:c = 1.56:1). This is a completely new discovery in central Pennsylvania which has not been checked regionally.

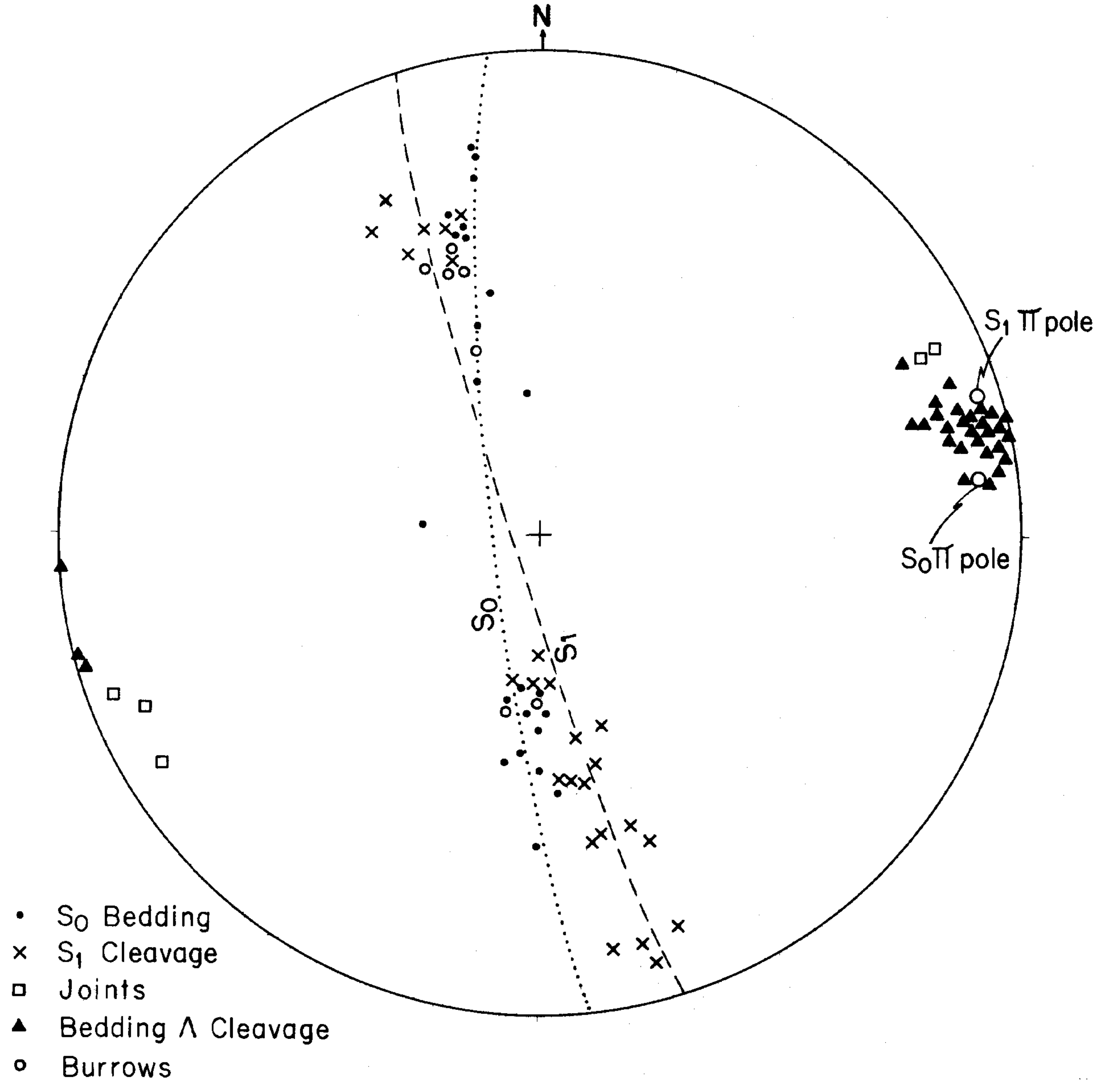


Figure VIII-G Stereonet plot of poles of bedding, cleavage, cleavage bedding intersections, bedding and cleavage poles, joints, organic burrows.

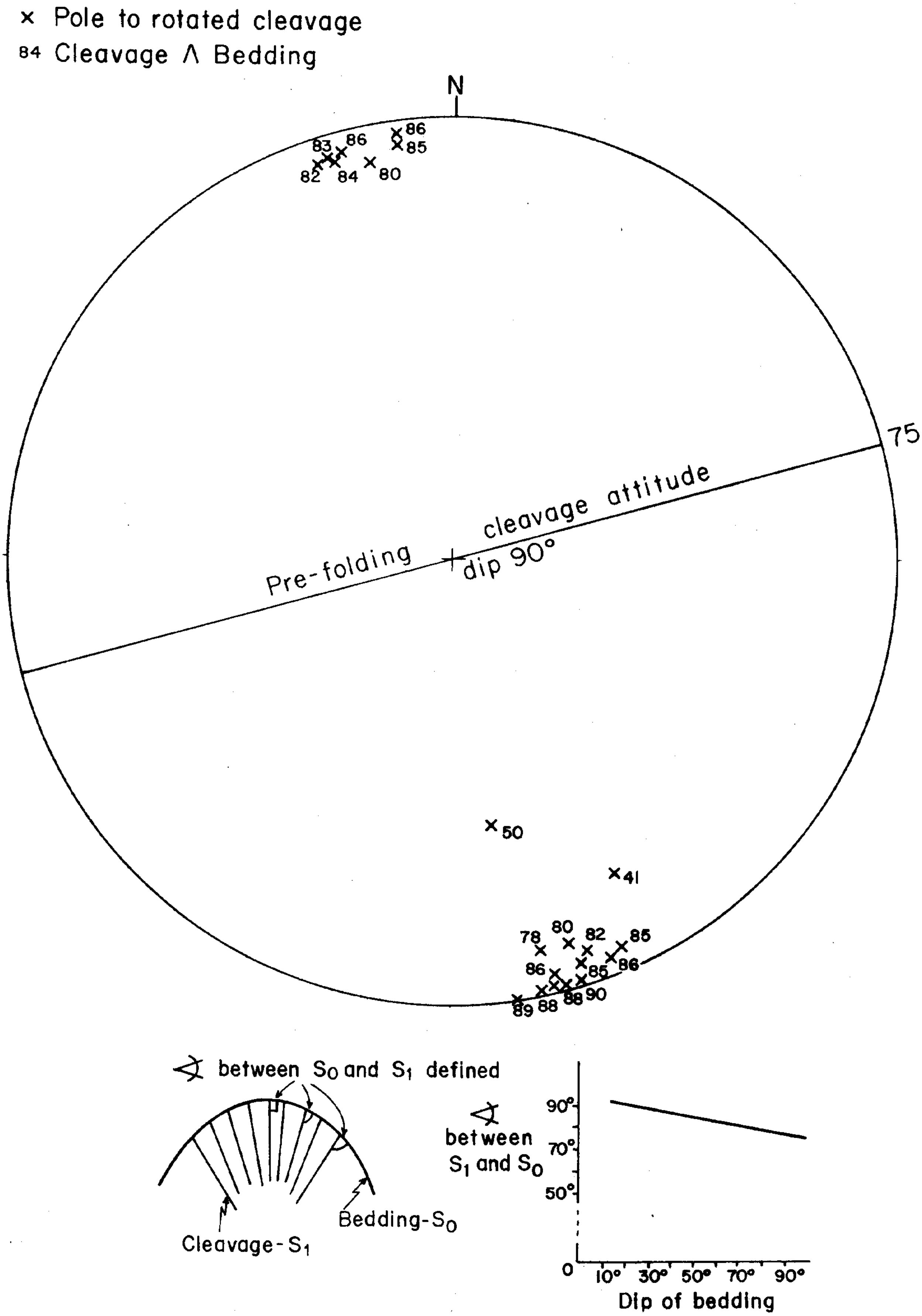


Figure VIII-H Stereonet plot of cleavage poles rotated around bedding strike to original attitude. Graphic plot of angle between bedding and cleavage vs. bedding dip.

65.8 End of STOP VIII. Estimated time: 12:35 P.M. Proceed eastward on Cannon Road. Approximate travel time to STOP IX: 30 minutes.

66.0 Intersection with Shrawder Road. Bear right.

66.4 Stop sign. Turn right on Beaver Run Road. Float around intersection is Wills Creek shale. Wills Creek Formation is exposed along road to the south.

66.9 Crossing Buffalo Creek.

67.2 Stop sign, intersection with Pa. Route 192, Buffalo Road. Turn left, proceed east. The ridge on the right, along which the road parallels, is underlain by the south dipping Keyser and Old Port formations. To the left is a wide valley of the Upper Silurian carbonates, but topographic expression has been removed by the meandering Buffalo Creek.

68.2 Village of Buffalo Cross Roads. Just past the intersection, the red brick Buffalo Church can be seen in the trees on the right behind the brick-walled cemetary. This church was first organized by Presbyterian pioneers in 1773, but was later broken up by Indian raids. It was resumed in 1787 with its first regular pastor. Initially a log church, it was replaced by stone in 1816 and by brick in 1826.

69.9 Active quarry in the Keyser limestone on the ridge to the left.

70.4 The doubly plunging Montour Ridge is ahead slightly to the right, underlain by the Tuscarora Formation, one of the en echelon anticlines comprising the hinge of the Jack's Mountain anticlinorium.

71.3 The large tower and water tanks to the north mark the residence of some of the more reknowned citizens of the U.S. who are now in the Northeast Federal Penitentiary (Lewisburg).

72.2 Stop light, intersection with U.S. Route 15. Proceed straight across.

72.5 Stop sign, bear off to left.

72.6 Turn right onto North Third Street.

72.8 Stop light, intersection with Pa. Route 45, Market Street, center of Lewisburg. Turn left on Market Street, proceed eastward. Bucknell University, established in 1846, is located a few blocks southeast of here.

73.0 West bank of Susquehanna River. At this point along the north branch of the river, it was desired to transfer the Pennsylvania Canal from the west to the east side by means of a cross-cut canal. Completed in 1833, it was 5/8 mile long and had three lift locks. A dam across the river provided slack water enabling boats to cross the river, thus creating a great trade center here.

73.3 East bank of the Susquehanna River, intersection with Pa. Route 405. Stop light. Proceed eastward on Pa. Route 45. To the right is the plunging western end of Montour Ridge.

73.8 Abandoned sand and gravel pits on the right. In the quarry walls are rounded pebbles and cobbles in a sand matrix that makes up the alluvial flood plain deposits of the Susquehanna River that extends for at least another mile to the east. Degradation of the quarry walls has covered cross-bedding, lenses and channels that are present.

74.6 Center of Montandon Village.

75.0 Turn right onto ramp for Pa. Route 147 South.

75.2 On the left is Montour Ridge. Ramp joins Pa. Route 147.

76.0 Exposure of Bloomsburg red shale in cut bank on right and left.

76.5 Rose Hill Formation indicated by brownish yellow shale chips in bank on left side of road.

77.0 Intersection with Pa. Route 405. Crossing hinge of Montour Ridge anticline at this point, with Tuscarora Formation closely underlying the road, but not exposed. The slope downwards from the east is a dip slope on the top of the Tuscarora down the hinge of the anticline.

79.5 Borrow pit on left is exposure of Mahantango rocks.

80.9 Entering the Borough of Northumberland. Joseph Priestley, the noted English scientist who discovered oxygen, lived in Northumberland from 1794 to 1804. His home and laboratory along the river are now a Priestley Memorial and Museum.

81.7 Stop sign, intersection with U.S. Route 11. Turn left, following Pa. Route 147.

81.9 Stop light, Pa. Route 147 turns right. Turn right, following Pa. Route 147 across bridge to Packers Island in the Susquehanna River, east branch.

82.3 Entrance to Shikellamy Marina. Turn right.

82.6 Bear right towards marina.

82.8 Turn left into parking lot. Disembark from buses.

STOP IX: LUNCH STOP at SHIKELLAMY STATE PARK AND MARINA. Estimated time: 1:05 P.M. Allotted time: 45 minutes.

DISCUSSANT: Frank Haas, Park Superintendent.

The Shikellamy State Park and Marina is located on an island at the confluence of the East and West Branches of the Susquehanna River and provided an attractive vista as a backdrop for this lunch stop.

Needless to say, the ground we are standing on and much of the adjacent Marina was under water during the June, 1972 flood, as the damage to the Marina attests. Although the Marina was isolated during the flood, it was not unoccupied--the Park Superintendent and another worker were trapped inside for many hours. Mr. Frank Haas, the Park Superintendent, has kindly offered to tell us about this remarkable experience. In an accompanying article in this guidebook, Mr. F. James Knight describes the more regional aspects of the storm Agnes and the resulting flood in the Susquehanna Valley.

For those who are still skeptical about the existence of large kink bands, your attention is directed to Blue Hill, the long promontory to the west across the river. Just to the left (south) of the bridge is a north kipping kink band in the Catskill Formation. Although even larger kink bands exist (indeed the larger folds require large kink bands), it is unlikely that they are exposed as well and as completely as this one.

Historically, this confluence has been a center of activity. Sunbury, which occupies the east bank just south of here, has been a trade center, first during the canal period, and subsequently with the development of the railroads. Earlier, a number of important Iroquois trails converged here. One of the paths (Karrondinhah) was located in the hollow in Blue Hill across the river and led westward to the Center County (Nittany Valley) area. The Great Shamokin Path led north and west along the West Branch to Kittanning and Clearfield; the Wyoming Path led up the East Branch to the Wyoming Valley; the Catawissa Path led eastward to Catawissa; the Tulpehocken Path led southward through the mountain gap at Klingerstown to the Reading and Philadelphia areas; and the Great Iroquois War Path led down the Susquehanna and southward to the Carolinas. It is thus not surprising that the Indian town Shamokin was located on the site where Sunbury now stands, and that the Oneida chief Shikellamy made his home here.

82.8 End of STOP IX (Lunch Stop). Reboard buses in parking lot, and proceed back to entrance of State Park. Estimated time: 1:50 P.M. Approximate travel time to STOP X: 35 minutes.

83.1 Entrance to Shikellamy State Park at Pa. Route 147. Turn right.

83.3 City limits of Sunbury, north end of bridge across East Branch of Susquehanna River. Sunbury was laid out in 1772 on the site of the Indian town Shamokin, which was the residence (from 1728-48) of Shikellamy, Oneida Chief of the Six Nations who asserted Iroquois dominion over the conquered Delaware and other tribes to the south.

83.5 Traffic light, turn right following Pa. Route 147. Pass under "Lionel" Railroad Bridge. From this bridge southward is the riverside concrete wall that was erected following the devastation of the 1936 flood. The June, 1972 flood waters, which inundated most of the other towns and cities along the Susquehanna River, were kept out of Sunbury by this wall, although the waters came within a breathtaking few inches of the top. Concrete walls of this type have been strongly criticized in the past for blocking the view of the river, yet appreciation for its presence is indicated by the graffiti painted on it--"WE LOVE YOU, WALL. 6-24-72".

83.9 Fort Augusta on the left was built in 1756 to 57 and was a key frontier outpost of the region during the French and Indian War. Named for Princess Augusta, widow of Frederick, the Prince of Wales.

84.9 Traffic light, intersection with Pa. Route 61. Continue southward on Pa. Route 147. To left, in the center of Sunbury, the first successful use of the three-wire electric system was made July 1883 in the City Hotel Building, directed by Thomas A. Edison. The Edison Illuminating Plant was at 4th and Vine Streets.

85.0 Turn left onto Chestnut Street, following Pa. Route 147.

85.1 Turn right onto South Second Street, following Pa. Route 147 South.

85.2 Cross railroad tracks. The Danville-Pottsville Railroad was completed in 1835 and provided access between Sunbury and the Anthracite region to the east. Initially operated on wood rails by horsepower, the horses were replaced three years later by steam locomotives. Iron rails were not introduced until 1853. In a nearby terminal, shipments were transferred from the railroad to canal boats, which carried the coal along the Pennsylvania Canal, Susquehanna Division, to Baltimore and Philadelphia.

86.3 Crossing railroad bridge. Exposures on the left are an anticline in the Montebello Member of the Mahantango Formation.

86.6 Montebello sandstones exposed at road level. Between the anticline at the bridge and here is another anticline with well-developed cleavage in the shalier layers.

87.0 Intersection with road leading to east. Large cliff-like exposures at intersection are dark gray shales of the lowest part of the Mahantango Formation (Fisher Ridge Member). Notice that, although there is relatively little change in lithology, cleavage is not developed nearly as well as in the shales 0.4 miles to the north. This outcrop has the superficial appearance of the Marcellus Formation because of its dark gray color and fissility. The black shales of the Marcellus are exposed, however, 300 yards to the south on the hill slope up which Pa. Route 147 climbs. Near the top, the hillside becomes a dip slope on the Old Port Formation.

87.7 Ridges to the east and south (left) are underlain by the Montebello Formation.

90.5 Two borrow pits on left are in Marcellus Formation. Limestone exposure 100 feet to the south is the Selinsgrove Member of the Onondaga Formation. The Type Section of the Selinsgrove Member of the Onondaga Formation is to the right below us along the Penn-Central Railroad, about 200 yards south of Selinsgrove Railroad Junction.

90.7 Crossing anticlinal axis. Selinsgrove limestone and Marcellus exposed in both road banks.

91.0 Long borrow pit exposure in the Marcellus Formation. Occasional gravel deposits have been attributed to high river levels during glaciation.

91.2 Small outcrops in roadcut are the Mahantango Formation.

91.7 Exposures in the Sherman Creek Member of the Mahantango Formation. The exposure is one of the sandier units of the Sherman Creek cycles similar to those seen at Shadle.

92.8 Well jointed exposure in Trimmers Rock on left.

93.3 Exposures on the left are in the Catskill Formation.

95.1 Exposures of Duncannon Member of the Catskill Formation showing fining-upward fluvial cycles. These north dipping rocks are near the hinge of the Line Mountain syncline which plunges to the east.

96.3 Bridge over Shamokin Creek.

96.3 Entering Borough of Herndon. The Indian trail, Tulpehocken Path, turned east near here and was used by Indian ambassadors (Iroquois chiefs, such as Shikellamy) carrying peace wampum from Onondaga (Syracuse) to Philadelphia.

97.4 Site of landslide which destroyed several houses in the borough after the flood of June 1972. Gently south dipping rocks exposed at cliff at top of hill is the Middle Devonian Trimmers Rock Formation.

98.2 Exposure on the left at the south side of Herndon is the basal Catskill Formation.

98.6 Beginning of the intermittent exposures of Trimmers Rock.

99.5 End of intermittent exposures of Trimmers Rock.

99.6 Intersection with Pa. Routes 225 and 147. Continue straight on Pa. Route 225.

99.7 Right turn onto Pa. Route 225 South.

99.8 Exposure in Sherman Ridge Member of Mahantango Formation on left. Enter Village of Mandata, named for an Indian girl who lived here.

100.1 Blocky sandstone exposure on right is Turkey Ridge Member of Mahantango Formation, in Hooflander Mountain.

100.4 Exposure on left is Old Port Formation and is the Type Section for the Mandata Member of this unit. The Mandata makes up the bulk of the Old Port at this exposure.

100.6 Turn right into Meckley Limestone Quarry,

STOP X. Estimated time: 2:25 P.M. Allotted time: 70 minutes

Discussants: Rodger Faill, Richard Nickelsen, Donald Hoskins.

The Meckley Quarry is located in the hinge of the Tuscarora anticlinorium, which in this area, consists of two *en echelon* third-order anticlines and an intervening syncline (Fig. X-A). The quarry exposes the hinge parts of both limbs of the northern anticline, on its westward plunging end (Fig. X-B).

STRATIGRAPHY

Meckley's Quarry at Mandata is largely in the lower portion (Byers Island Member, see Appendix to STOP X) of the Keyser Formation. These limestone beds have been quarried in this area since the latter part of the last century when many quarries were operated on the limb of two anticlines to the east and west. Most of the quarry stone originally was used for agricultural lime; the current operation is largely for road construction. Channel samples of the lower and upper half of the quarry stone analyzed in 1960 show respectively 69.5% and 84.1% $CaCo_3$, 8.3 and 2.9% $MgCo_3$, and 17.7 and 10.5% SiO_2.

Stratigraphic units exposed in the quarry are the Tonoloway Formation, and the Byers Island, Jersey Shore members and part of the La Vale Member of the Keyser Formation. The uppermost Keyser and overlying Old Port Formation may be examined 1/8 mile east on Pa. Route 225 (see Road Log).

The Tonoloway Formation is gray laminated limestone and dolomitic limestone with numerous mud cracks exposed on bedding surfaces. The top of the Tonoloway usually marks the lower limit of quarry and was the lowest that older quarries exposed because the rock did not burn well for

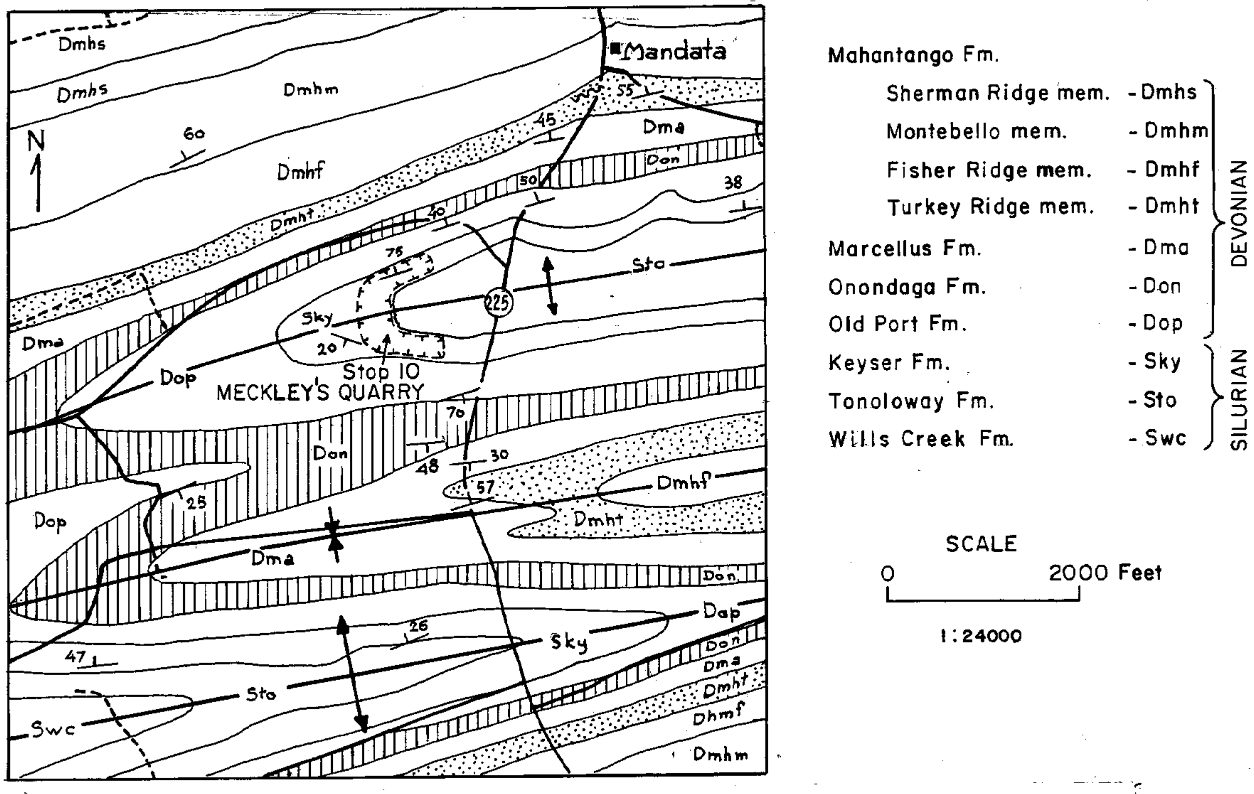


Figure X-A. Geologic map of the Meckley's Quarry vicinity.

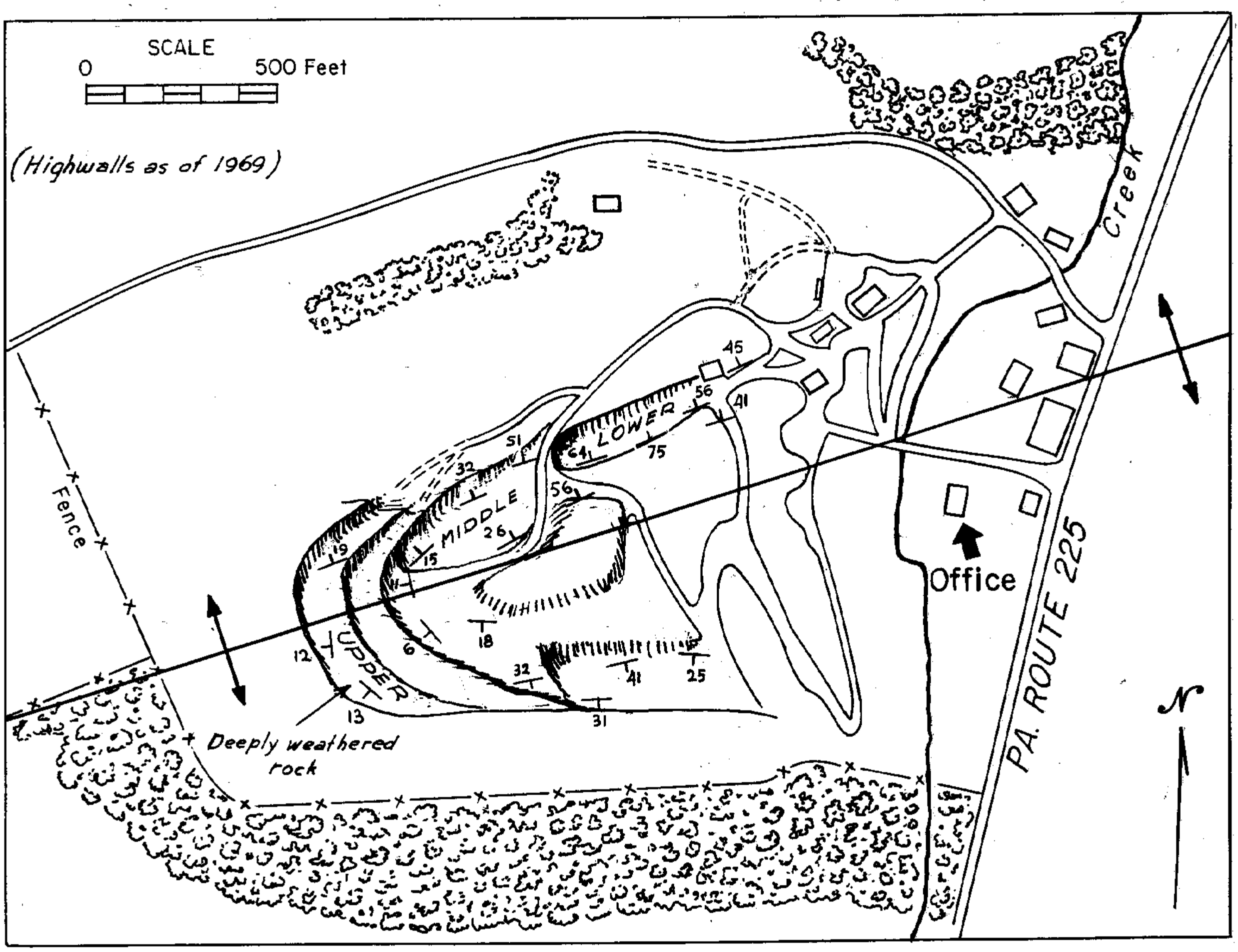


Figure X-B. Detailed map of Meckley's Quarry, showing the different parts (levels) and selected bed attitudes.

agricultural lime. The Tonoloway is exposed in the south wall of the oldest and deepest part of the current operation; it has been cut into a depth of 15 to 20 feet in the central part of the quarry but largely has been left in place.

The Tonoloway is interpreted to represent tidal flat deposition with the laminae representing successive layers of algal entrapped carbonate. The mud cracks give evidence of the alternating wetting and drying with consequent dessication.

Above the Tonoloway the Byers Island Member of the Keyser is composed of approximately 55 feet of limestone in beds up to 5 feet thick. The lower 15 feet is arenaceous and argillaceous with scattered laminated layers. The upper 40 feet is gray argillaceous limestone composed of nodular fossiliferous limestone surrounded by argillaceous material. These limestone layers weather into a rubbley mass of loose rounded nodular masses of limestone. Many fossils also weather loose from the argillaceous material. Brachiopods, bryozoa, corals and sundry other phyla can be collected.

Head (1969) has interpreted these nodules to represent sedimentary boudinage. He suggests the original lithology was "interbedded argillaceous to very argillaceous biomicrite and biopelmicrite, interbedded with essentially nonargillaceous biomicrites and biosparite. Compaction subsequent to deposition caused vertical compression and sedimentary boudinage was initiated because of the higher plasticity of the argillaceous beds. The combination of placticity differential and the vertical compression resulted in the boudinage of the more competent coarser grained interbeds into discrete nodules, and the injection of the more plastic beds between the nodules". The environment of deposition is interpreted to be subtidal.

Overlying the quarry rock is approximately 20 feet of olive gray shaly claystone, the upper part of which contains separated nodules and discontinuous layers of limestone. This grades upward to interbedded argillaceous limestone and claystone. This unit is referred by Head (1969) to the Jersey Shore Member. The Jersey Shore in its type area is characterized by abundant corals and stromatoporoids plus a variety of other lithologies. At the Meckley Quarry only the claystone lithology is present.

Above the claystone are banded and laminated limestone and calcareous claystone, the laminated part of which is a nearly identical repeat of the Tonoloway lithology. These units are included in the LaVale Member. Although widely present in this part of Pennsylvania, it is rarely seen except in minor scattered exposures because it is of little use in quarrying. The LaVale Member may be seen where soil has been stripped above the south pit.

The west part of the quarry, above the main workings where the rocks are on the plunge of the anticline, is deeply weathered to a depth of 20 or more feet. All of the carbonate has been removed and only the argillaceous and arenaceous material remains. The contact of the weathered-unweathered rock is very sharp and is exposed at the top of the quarry to the south side. The unweathered rock is interbedded olive gray claystone and dark gray laminated silty and sandy limestone. A few inches from this is the weathered rock consisting of buff clay and leached sandstone.

STRUCTURAL GEOLOGY

This quarry presents an outstanding illustration of a number of features seen elsewhere throughout the province: multiple slickenside directions on single bedding and fault surfaces which indicate that the fold is noncylindrical; fracture cleavage resulting from differential solution along clay-rich zones of the rock which has led to residual concentrations of clay in clay-carbon partings and cleavage zones; cleavage "refraction" resulting from rotation of cleavage away from the perpendicularity to bedding in zones of concentrated bedding slip; slip parallel to cleavage resulting in systematic bedding displacements along mud crack margins; bedding planes with distorted mud cracks; and the development of "tension gashes".

The anticline

Although the overall structure exposed in this quarry is a relatively simple third-order anticline, numerous smaller structures complicate the geometry. Several fourth-order folds are present in some parts of the quarry, but do not extend, even along trend, to other quarry walls. Faults are numerous, but not of great displacement nor extent, and cannot be traced from one side of the quarry to another. Yet all these minor structures create local variations which accounts for the rather large scatter of bedding poles (Fig. X-C) from the π-pole of this gently west plunging anticline.

Slickensides on bedding and faults

As with kink band folds elsewhere in the province, slickensides on bedding surfaces indicate that slip on bedding was the main deformational process. Rather than a single slip direction, many of the bedding and fault surfaces exhibit two striae orientations on the same surface (Fig. X-D). The angle between these striae ranges from 10 to 30 degrees, most frequently being 15 to 20 degrees apart. Apparently movements on these surfaces were in two different directions, and reflect two different axes of bed rotation in the fold (one for each limb). It is the presence

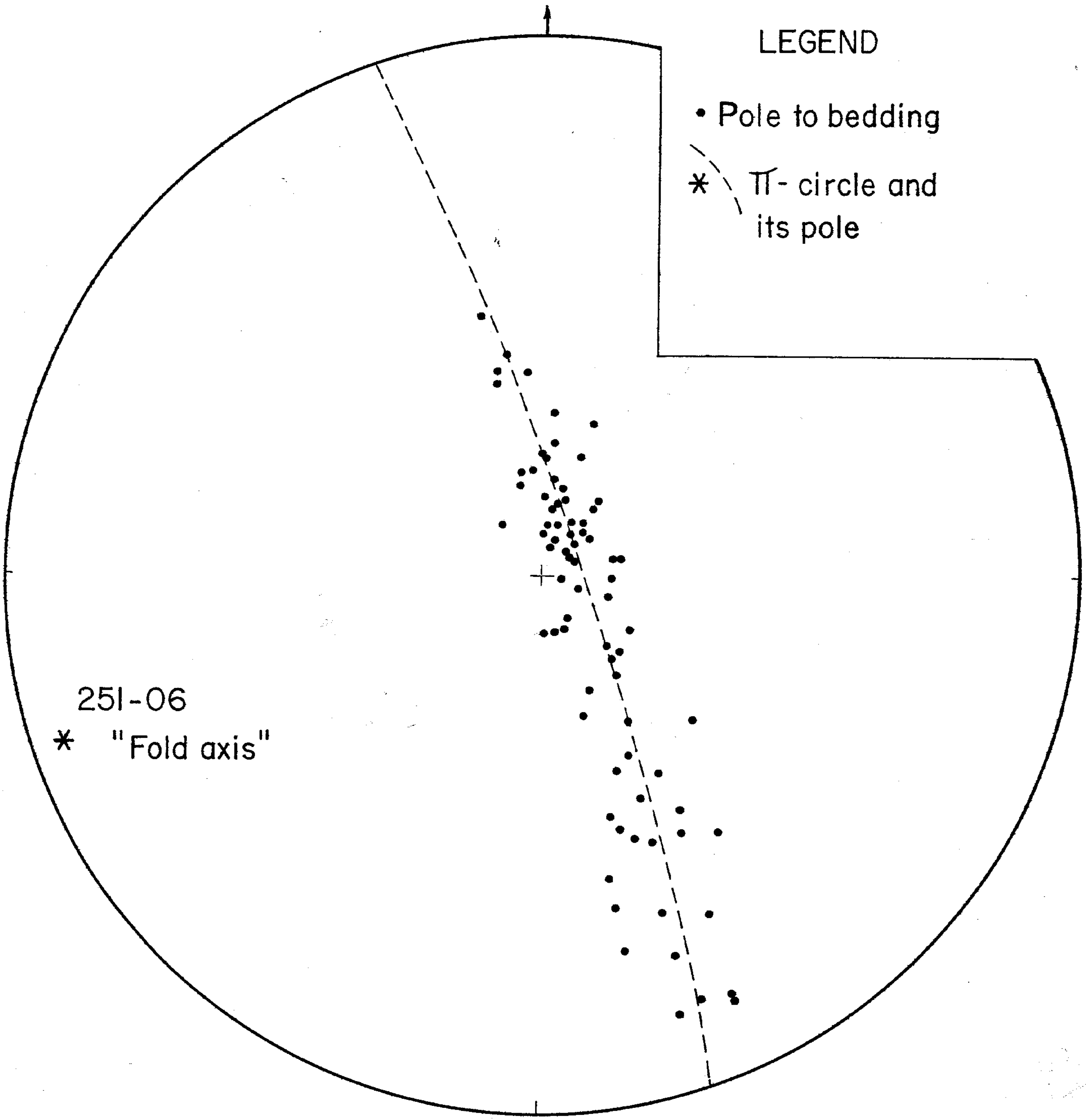


Figure X-C. Stereonet display of bedding readings throughout the quarry, with the π-circle and its pole, the "fold axis".

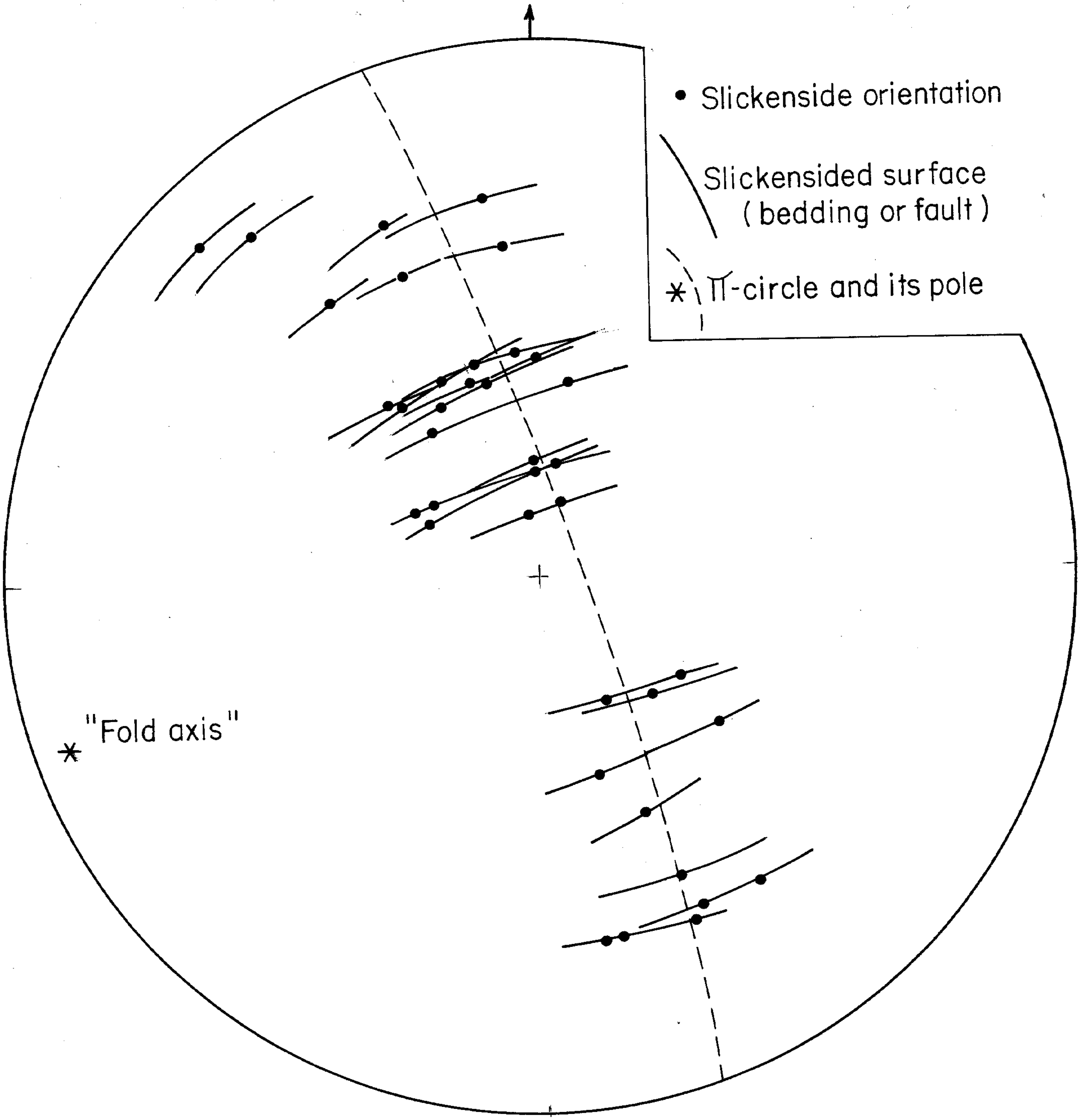


Figure X-D. Stereonet display of slickensides on bedding and fault surfaces, illustrating in particular the two slickenside orientations on the same surfaces, and the relation of the slickensides to the fold geometry.

of two different rotation axes in a fold which makes it noncylindrical, and causes the fold to plunge and terminate along trend (Faill, 1973), as this anticline does within three miles of here. In small, simple noncylindrical folds, the two directions of slickensides define two great circles on a stereonet, the poles of which are the rotation axes. The absence of this pattern in this quarry is attributed to the presence of the fourth-order folds, and the faults, which have caused considerable scatter of the data.

The cleavage

Origin of cleavage in this quarry was the subject of part of a recent paper by Nickelsen (1972). It was concluded that the cleavage originates by differential solution of calcite and residual concentration of clay and carbon. The cleavage occurs in zones of one or more centimeters apart passing around limestone nodules or large fossils and converging or diverging along both strike and dip. Thus, the fabric is heterogeneous and the clay-carbon partings making up the cleavage zone are restricted to argillaceous portions of the rock. Where the rock is more argillaceous, as in the upper quarry, the cleavage is more pervasive. Within cleavage zones, partial destruction of recognizable fossil material permits estimate of the minimum loss of volume by solution. In one such zone, 26% of the rock has been lost by solution, but, because of the heterogeneous distribution of cleavage zones, it cannot be assumed that the whole rock has dissolved this much. However, if unequal dimensions of mud crack result wholly from solution perpendicular to cleavage, the average L:S ratio of 14.3:8.6 indicates that 26% is a low estimate.

Cleavage seems to be best developed in nodular limestones rich in clay or in mud cracked beds. In both cases cleavage was enhanced by the ability of water to move vertically through the rock, either in argillaceous, presumably poorly-cemented rock or along the vertical mud crack fissures. Careful inspection of mud crack borders will show thick clay-carbon partings on the side of the mud crack paralleling cleavage and thinner partings on the ends of the mud cracks. This probably results from pressure solution and residual accumulation of the clays in the parts of mud cracks paralleling cleavage zones. It is highly unlikely that this rock would show such a magnificent development of cleavage if it were not for the mud cracks.

Slip on cleavage (mud crack) surfaces

During folding the cleavage which began perpendicular to bedding in mud crack fissures is rotated away from perpendicular to bedding and begins to serve as a slip plane contributing to the transition from flexural slip to passive folding. This is well shown in the lower quarry at "the wall" where the steeply north dipping bedding is systematically offset along mud crack borders in a sense which would enhance the growth of the anticline (Fig. X-E).

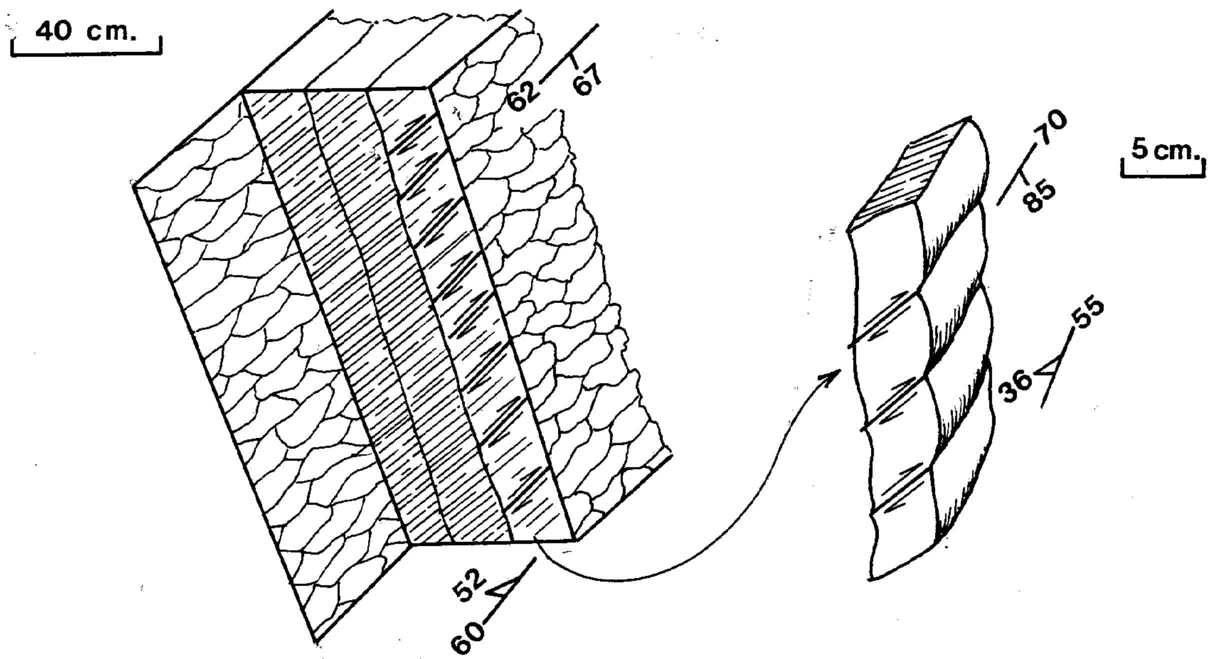


Figure X-E. Schematic drawing of the offsets along mud cracks, as seen at the steeply north dipping "wall" in the lower quarry, looking southeast.

Refracted cleavage

At the middle level of the quarry (Fig. X-B), along the north and west walls, an exposure on the north limb of the anticline shows the best example of early cleavage rotated by bedding slip (Figs. X-F and X-G).

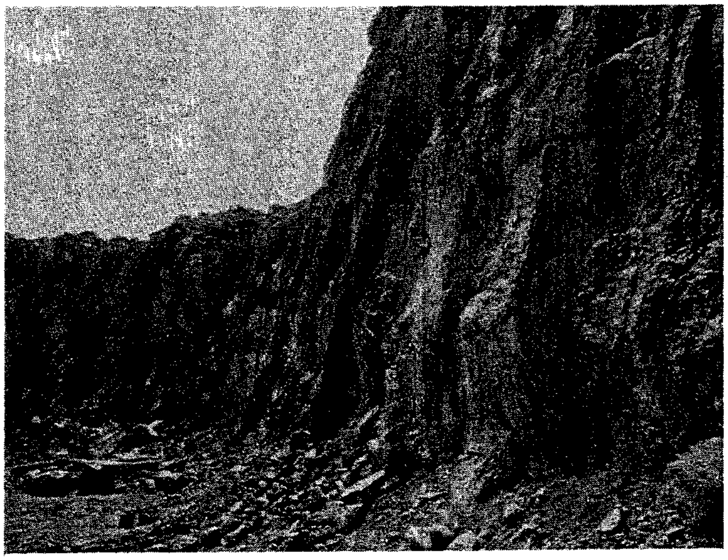


Figure X-F. Refracted cleavage in the north limb of the Meckley Quarry anticline, north wall of middle level.

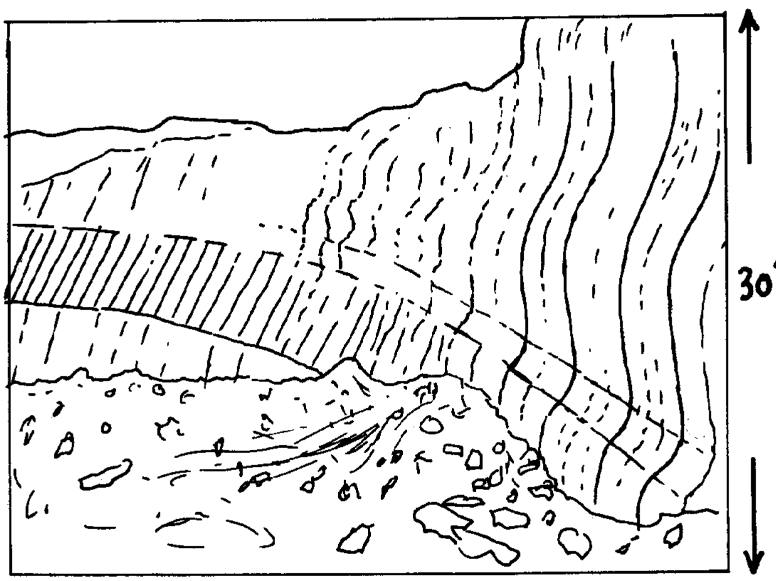


Figure X-G. Sketch of refracted cleavage shown in Figure X-F.

The cleavage has been rotated through angles of 40 to 60° (Fig. X-H) across beds of different composition (ductility?). Counterclockwise (c.c.) bending of cleavage can generally be correlated with differential slip due to flexural slip folding on this limb of the anticline. What is less clear is the reason for the clockwise (c.) rotation of cleavage which is also evident. One explanation is that the initial cleavage bedding intersection angle was 65 to 80° rather than the 90° that we have come to expect for the region.

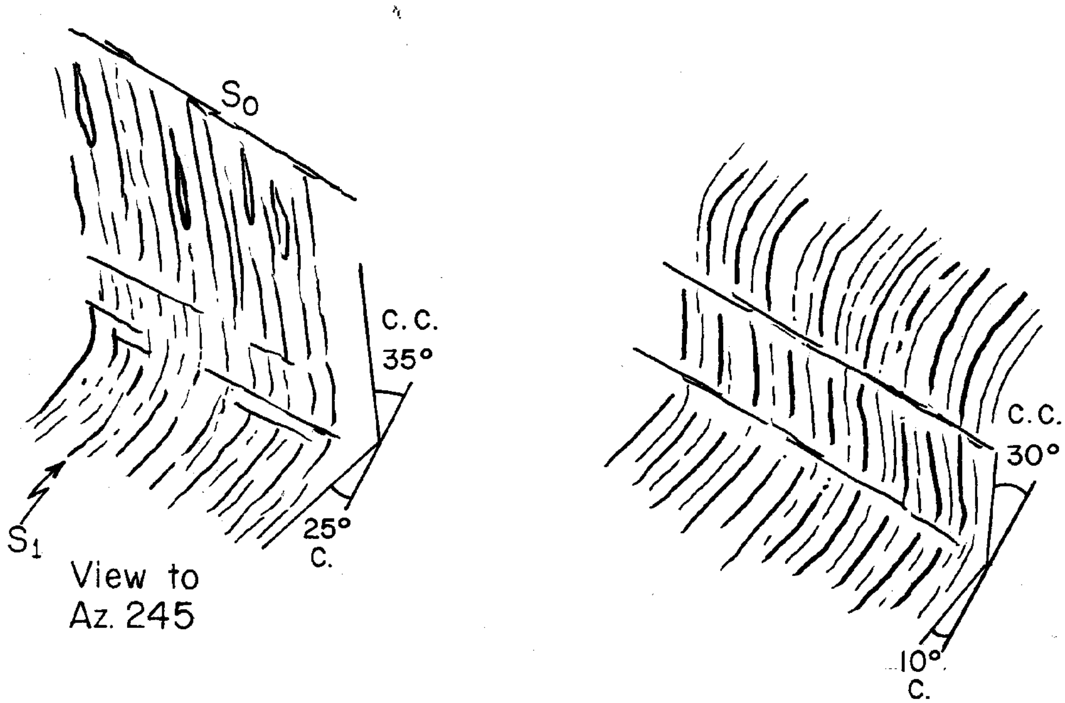


Figure X-H. Detail of refracted cleavage, illustrating counterclockwise (c.c.) and clockwise (c.) rotation of cleavage from its presumed initial bed-normal attitude.

Another aspect is that the axis of cleavage rotation is apparently different between the north and south limbs (Fig. X-I), and both of these axes diverge from the "fold axis" by about 6 degrees. This divergence is similar to that found between the bedding rotation axes in noncylindrical folds, and it may be that the bedding and cleavage rotation axes are identical.

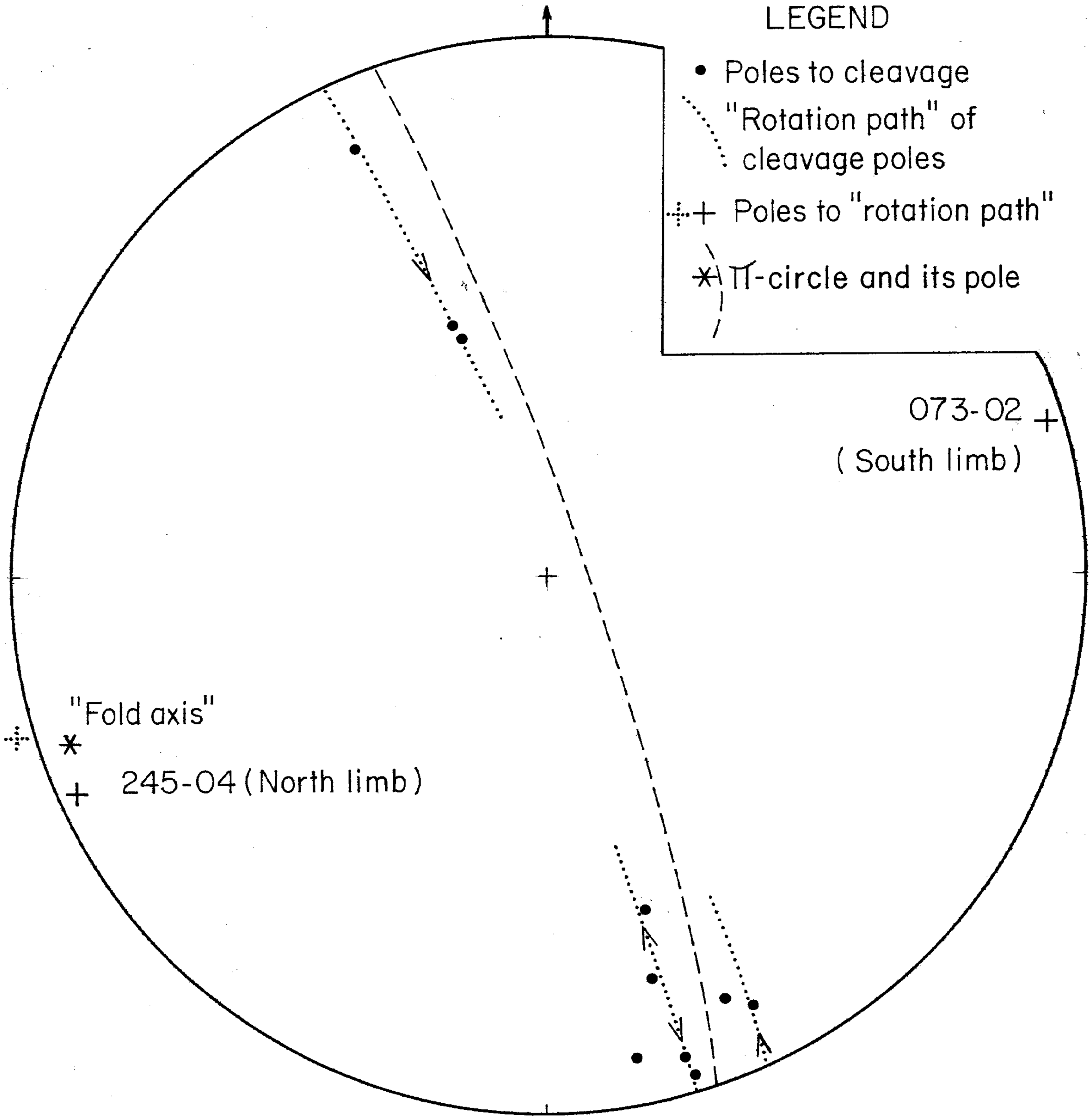


Figure X-1. Stereonet display of two refracted cleavage planes, with their inferred axes of rotation and relation to the fold geometry.

Distorted mud cracks

Numerous bedding plane surfaces on "the wall" in the lower part of the quarry, in the south part of the quarry where the south limb is exposed, and on loose blocks throughout the rest of the quarry demonstrate that mud cracks have long dimensions paralleling cleavage and short dimensions perpendicular to cleavage (Fig. X-J). The mean of 35 measurements of the Long and Short dimensions of mud cracks from the north limb gives a ratio of L:S = 14.3 : 8.6 (= 1.7); 15 measurements from the south limb yield a ratio of L:S = 16.1:8.9 (≈1.8), not a significant difference considering the small number of measurements. Most of this inequality of axial dimensions is due to solution loss in the plane of the cleavage. In a section perpendicular to cleavage and bedding on the side of the rectangular block of Figure X-J, 23 stylolite zones parallel to cleavage were observed over a distance of 53 centimeters. On the side of the block exposed the cleavage plane, no stylolites could be seen. As in the case of the Bloomsburg Formation, volume constant (?) distortion probably also contributed to the final distorted shape of the mud cracks but in the absence of suitable strain markers there is no way of measuring the amount of this contribution to the distortion.

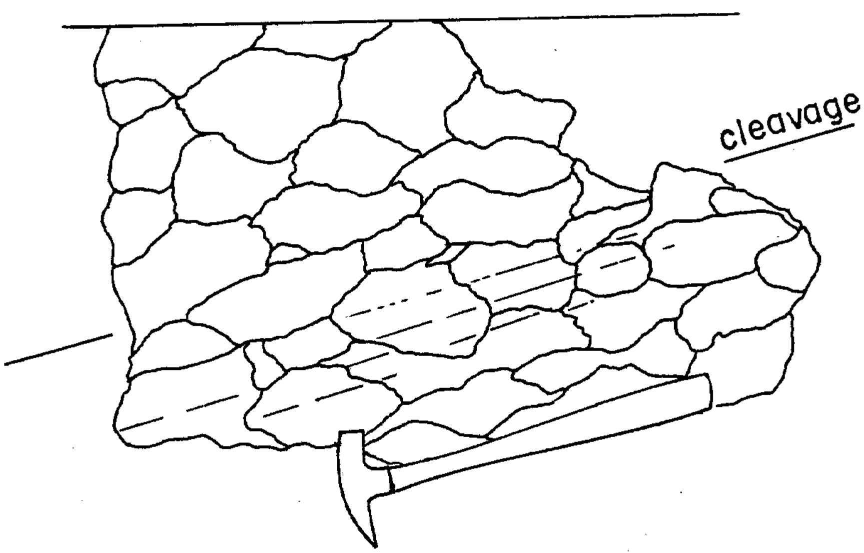


Figure X-J. Sketch of distorted mud cracks in a bedding plane, from which some of the north limb measurements were taken.

"Tension gashes"

The remaining structures to be considered are the "tension gashes" exceptionally well exposed in the bedding plane at "the wall" in the lower part of the quarry, and best seen from the top of the north wall of this lower part. Most of the calcite-filled fractures are dip fractures subperpendicular to the fold axis, and arranged in zones inclined at approximately 60 degrees to the fold axis (Figs. X-K and X-L).

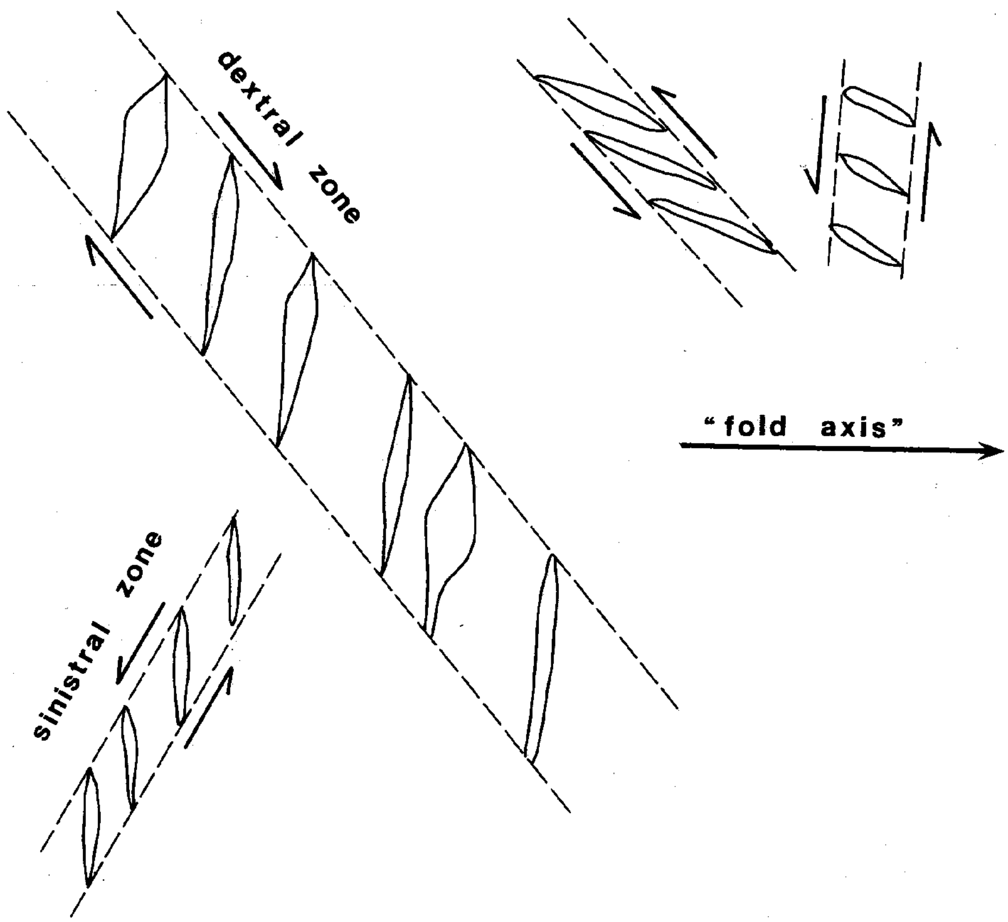


Figure X-K. Bed-normal, calcite-filled extension fractures ("tension gashes"), and their arrangement into shear zones with inferred movements indicated, as seen in a bedding plane.

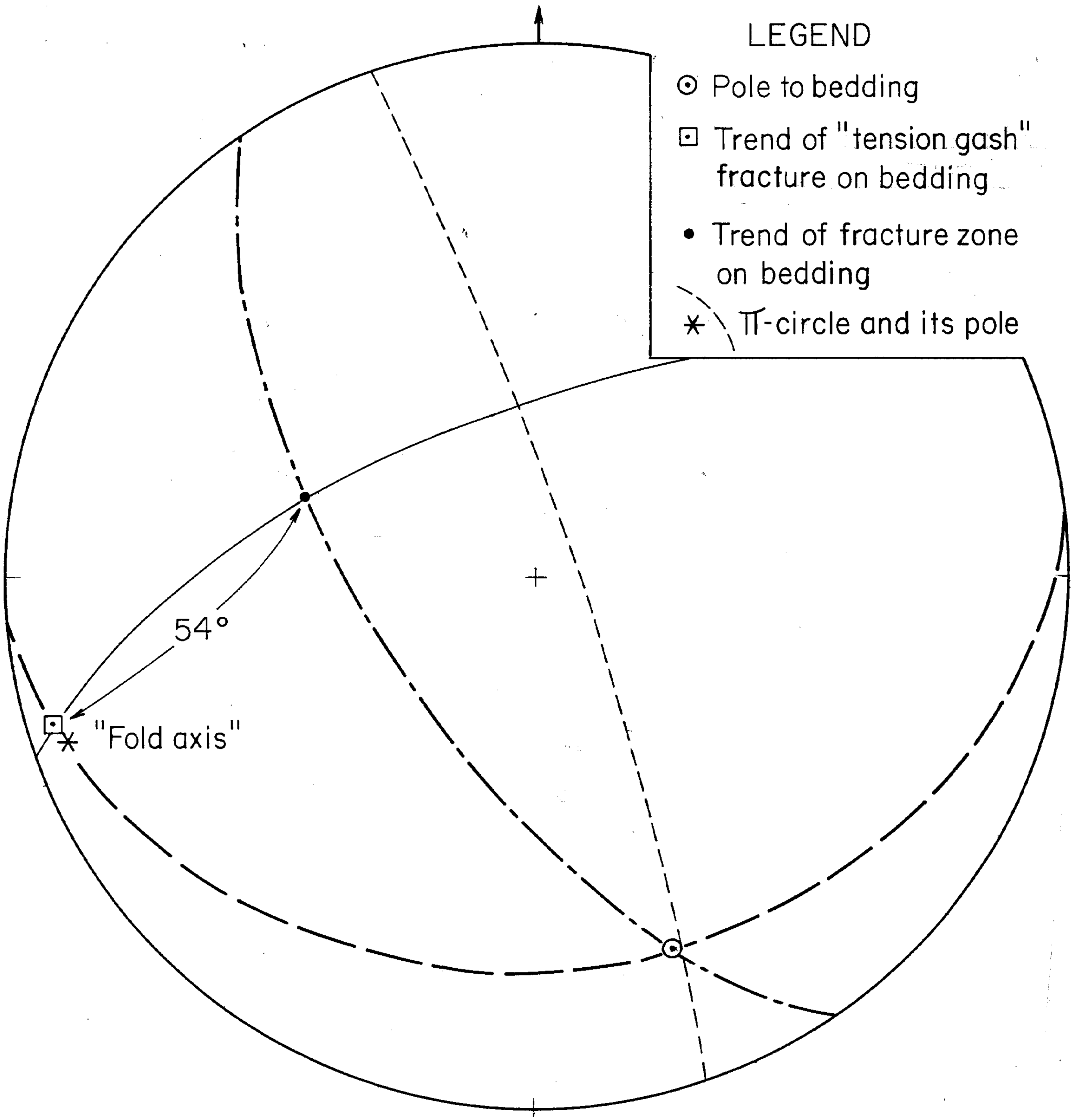


Figure X-L. Stereonet display of the "tension gashes" and shear zone orientations with respect to the fold geometry.

These filled "tension gashes" are extension fractures developed in a relatively brittle bed under a maximum stress perpendicular to the fold axis, presumably during or just prior to the folding. The calcite filling may have been derived from the solution activity of cleavage development. Their orientation implies a shortening across the fold, and an extension parallel to the fold axis, a strain resembling that of the fossil and mud crack distortions, but by a completely different mechanism (by brittle fracture rather than by ductile flow or solution).

The zones in which the "tension gashes" are arranged imply a displacement of the rocks on one side relative to those on the other side (Fig. X-K), and are either dextral or sinistral in movement. These two zone orientations and associated movements constitute a conjugate shear system, one that shortens across the fold and extends the rock parallel to the fold axis. Thus the individual extension fractures, and the conjugate shear zones are kinematically congruent.

In addition to these dip fractures are ones oblique to the fold axis and strike of bedding (Fig. X-K). They are not as common as the dip fractures, but are arranged in two zones approximately 60 degrees apart. However, the inferred movements are sinistral for both zones, and thus the two zone sets do not constitute a conjugate shear system. Their significance and relation to other structures is not particularly clear.

APPENDIX TO STOP X:

UPPER SILURIAN AND LOWER DEVONIAN

STRATIGRAPHY IN THE JUNIATA-SUSQUEHANNA VALLEYS

by

Donald M. Hoskins, Pennsylvania Geological Survey

Stratigraphic terminology for the Upper Silurian and Lower Devonian in central Pennsylvania has undergone many changes in the past 50 years. Early workers, while not ignoring lithologies, put major emphasis on paleontology as the best correlative tool. As a result, stratigraphic papers of this era (i.e. Swartz, 1939, Cleaves, 1939) tended to use names such as Coeymans, New Scotland, Helderberg, etc. that were derived from the rock units defined at the New York section in the Helderberg Mountains. But because the lithologies of the similar age rocks in Pennsylvania are significantly different from those of the New York section, extension of those names to Pennsylvania was not useful. The indiscriminate extension of the names deterred proper investigation. Where great differences of lithology occurred, local names such as Mandata and Licking Creek were proposed (Swartz, 1939). Other lithologically defined units were also introduced into Pennsylvania from Maryland, such as Shriver and Ridgeley (Cleaves, 1939) and Keyser (Reeside, 1918).

With the exception of the Keyser, most of these names are not usable in 1:24,000 scale mapping of the Susquehanna and Juniata valleys because the lithologic units are extremely thin and because they cannot be directly related to the type areas. Thus, Conlin and Hoskins (1962) proposed the term Old Port to include all of the rocks between the Keyser and Onondaga formations. The other names were used for member units within the Old Port only in an informal sense and without any real critical analysis until Head's (1969) detailed reexamination of rocks from the Keyser through the Shriver in Maryland, West Virginia and Pennsylvania. For this group of rocks, Head has reinstated the term Helderberg Group as an encompassing term.

From his detailed lithostratigraphic and biostratigraphic synthesis, Head (1969, and in press) has reconstructed the depositional sequence and correlation of Upper Silurian and Lower Devonian rocks, and has proposed stratigraphic nomenclatural changes. One of the significant features of his study is that specific lithologies (or lithic sequences) are restricted to discrete parts of the basin and that the names applied to these lithologies are also restricted in area in a manner different from previous workers who applied the same name to differing lithologies.

Regionally the sequence begins with the Keyser Formation, a limestone unit whose variation is predominantly vertical, rather than lateral.

Head (1969 and in press) introduced three new members for the Keyser Formation (Fig. X-M). These are the Byers Island, Jersey Shore and LaVale Members. The upper and lower members are relatively uniform in lithology throughout the Pennsylvania portion of the basin, while the middle member, the Jersey Shore, is characterized by a large number of different lithologies.

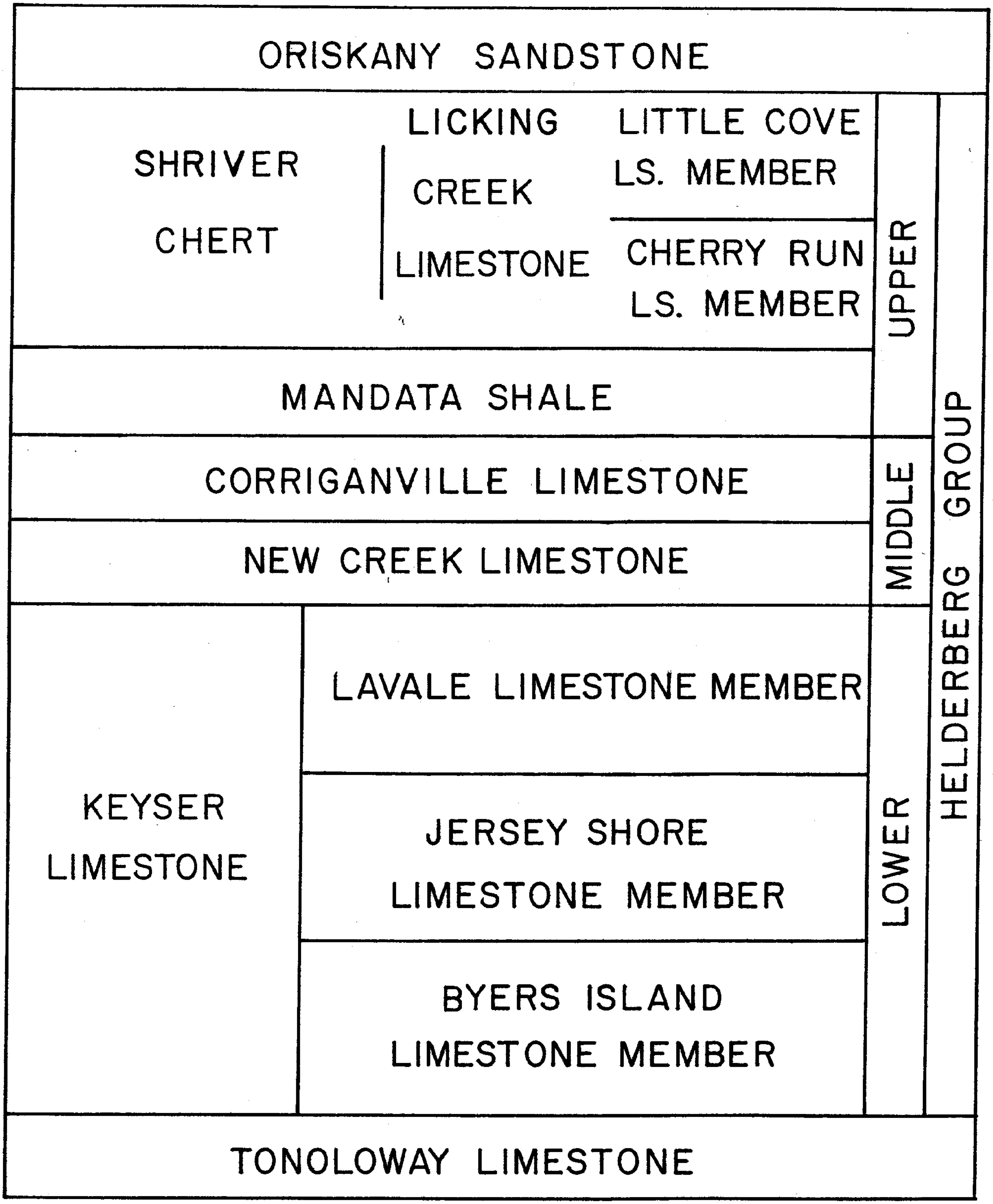


Figure X-M. Upper Silurian and Lower Devonian stratigraphic names (after Head, in press).

In its type area the Jersey Shore contains coral-stromatopora bioherms; in the Field Conference area, the Jersey Shore is largely unfossiliferous shale. The lower member, Byers Island, is characterized by "nodular" limestone and is the most frequently seen unit of the Keyser in the field trip area. The LaVale member consists of laminated and banded limestones similar to the underlying Tonoloway Formation. All three of the Keyser Members are seen at STOP X, Meckley's quarry; only the Byers Island Member is seen at STOP IV.

Bowen (1967) discontinued the use of "Coeymans" for the thin coarse calcarenites above the Keyser because they "can be neither correlated with nor traced into the Coeymans of the type area." He replaced Coeymans with the name New Creek. Head (1969) continues this usage of Bowen and correlated the New Creek with the Thacher Member of the Manlius and the Ravena Member of the Coeymans of eastern New York.

The rocks immediately above the Keyser in the Field Conference area are a problem. At Mandata no lithology exists that could be called New Creek. Instead, two feet of very fine grained sandstone and siltstone occur. Reeside (1918) and Swartz (1939) discuss the sandstones that occur above the Keyser in the Susquehanna and Juniata valleys but because of the poor outcrop little was done except to correlate them with the "Coeymans". To the east and south of this area more prominent sandstones (Stormville and Elbow Ridge) occur at or near this horizon. Swartz (1939) called the sandstones above the Keyser in Perry County "Falling Springs". I suggest that this name be used in the Susquehanna-Juniata valley area to supplant both Coeymans and New Creek.

Overlying the Falling Springs are limestones that were generally called "New Scotland" by previous workers. Head (1969) points out that the name New Scotland was applied to many different lithologies in Pennsylvania, Maryland and Virginia, largely on the presence of the characteristic brachiopod Hedeina macropleura and that the name should be dropped for use in these areas. Head (1969) renamed these limestones Corriganville. The Corriganville in the Field Conference area is argillaceous gray calcilutite to fine grained calcarenite with some bedded chert.

The rocks above the Corriganville are an additional problem in regard to their nomenclature. Head's detailed study (1969) amply demonstrates that different lithologies were forming in different parts of the basin after deposition of the Corriganville. This portion of the Helderberg Group was characterized by a thin shale and thick cherts in the central part of the basin, now exposed along the Allegheny front, and by interbedded limestone, shale and chert topped by limestone in the southeast part of the basin exposed along the Pennsylvania-Maryland border in Franklin County.

Head (1969, in press) calls these rocks Mandata and Shriver for the western belt and Licking Creek Limestone for the eastern belt. The Licking Creek Limestone was named by Swartz (1939) for limestones underlying the Oriskany in Franklin County, Pennsylvania. Head (1969, in press) has expanded the name Licking Creek to include the interbedded limestones, shales and chert below Swartz's Licking Creek and above the Corriganville, and has given each major sub-unit a member name, the Cherry Run and Little Cove Members. The Little Cove (the original Licking Creek of Swartz) does not extend northeast to the field trip area.

The name Mandata was created by Swartz (1939, p. 65) for the "shale and chert beds, which occur above the cherty New Scotland limestone throughout central Pennsylvania, and which are about 90 feet thick at the section one-quarter mile south of Mandata...". The type section of the Mandata was remeasured by Hoskins in 1962 as part of mapping of the Millersburg quadrangle. Figure X-N is a schematic representation of the section and includes the stratigraphic terminology applied by various workers.

Because the name Mandata was not used for mapping purposes, except in the western outcrop belt in western Maryland and Pennsylvania, Head (1969, in press) suggests restricting the name to that region, and to include the rocks at the type section of the Mandata as the Cherry Run Member of the Licking Creek Limestone.

As an alternative suggestion, I recommend that the name Mandata be retained for the rocks exposed at the type section and that this stratigraphic name be extended along the eastern outcrop belt to include those rocks called Cherry Run by Head (1969, in press). Use of the name Mandata along the eastern outcrop belt in the Franklin County area and to the south in Maryland and Virginia would follow the implied suggestion of Swartz who tentatively called the rocks below the Licking Creek, at its type section and in other sections to the south, Mandata (1939, p. 69 and Fig. 17).

The net effect of my suggestion would return the name Licking Creek to nearly its original definition, retain the name Mandata for rocks contiguous with its type area, and would not necessitate the two new names, Cherry Run and Little Cove. Since the shales below the Shriver of the western belt do not really relate to the type area of the Mandata, it would be preferable to introduce a new local name for that area and those rocks.

The upper part of the Mandata at the Mandata section are bedded cherts. Informally, these have been referred to as Shriver and, while they are correlative with the Shriver of the western belt, they should not be referred to by that name. Instead, Shriver is restricted to the western belt contiguous with its type area, following the example of Head.

The top of the section is marked by approximately one foot of coarse grained, fossiliferous sandstone which is called Ridgeley based on its position directly below the Onondaga. This sandstone varies considerably in the Millersburg quadrangle from a few lenses of sand in the chert layer to up to a reported eight feet (Cleaves, 1939) a few miles to the west of Mandata.

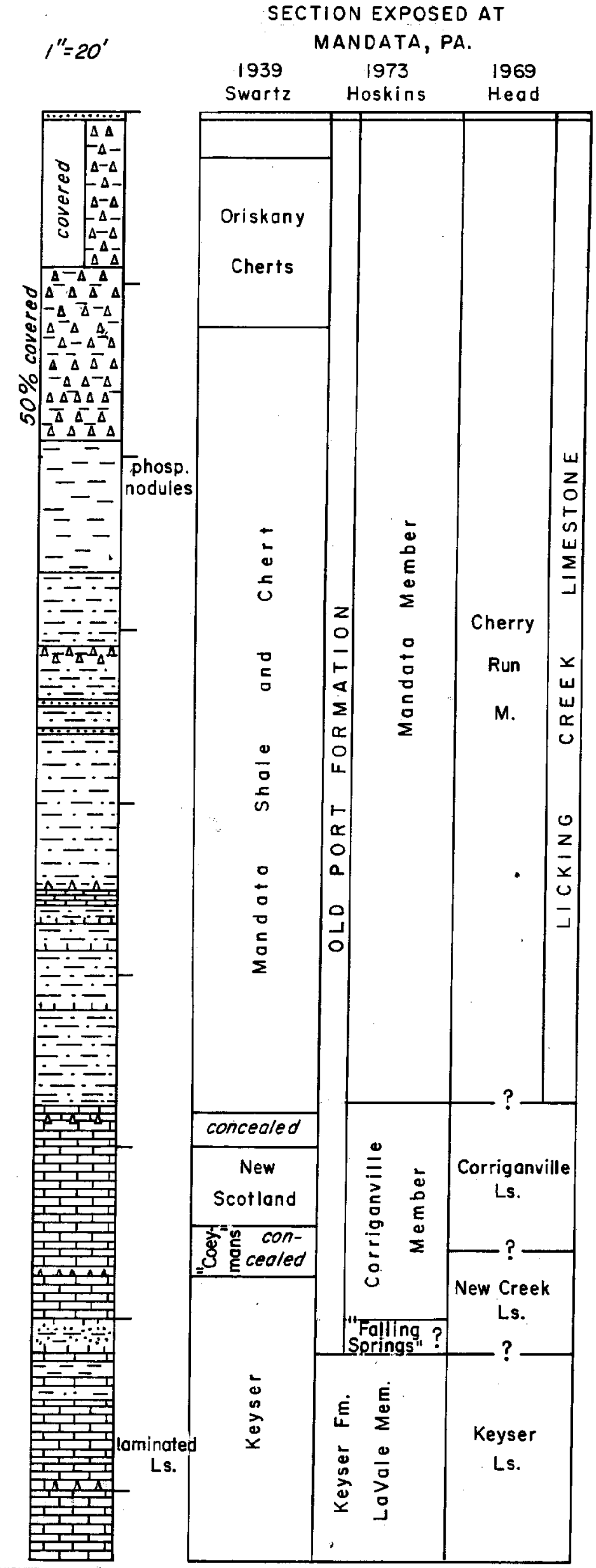


Figure X-N. Schematic stratigraphic section at Mandata showing various nomenclatures applied to the rocks.

100.6 End of STOP X. Turn left onto Pa. Route 225. Estimated time: 3:35 P.M. Approximate travel time to STOP XI: 15 minutes.

101.3 Exposure and float blocks of Montebello Member of Mahantango Formation on the hillside to the right. Bear left at "Y" intersection just beyond.

101.4 Stop sign, intersection with Pa. Route 147. Turn left.

101.5 Bear left and follow Pa. Route 147 South.

101.6 Hill slope on right exposes Harrell Formation and uppermost portion of the Mahantango Formation. Approximately 6 inches of very fossiliferous claystone here was called Tully by Willard (1939). Intermittent exposures in road banks for the next two miles are in the fossiliferous portion of the Sherman Ridge Member of the Mahantango Formation.

103.0 Ridge on left (south) is underlain by Montebello Member of the Mahantango Formation. The low ridge on the right (to the north) is the basal portion of the Trimmers Rock Formation. The bottom of the valley to the right is underlain by the upper part of the Sherman Ridge Member of the Mahantango Formation, and the Harrell shale. The road follows the second cycle of the Sherman Ridge Member.

105.2 North dipping Montebello sandstone member of the Mahantango Formation.

106.2 Center of Dalmatia.

106.6 Exposure of the Old Port Formation on left in road cuts.

106.9 Roadcut on left is Marcellus Formation, which locally here and on the west side of the Susquehanna River contains many thin and thick discontinuous sandstone layers interbedded with the black shale.

107.5 Entering anticlinal valley between two ridges underlain by the Montebello sandstone. Enclosed rocks on which we are driving are Fisher Ridge.

108.0 Large borrow pit in the Fisher Ridge Member of the Mahantango Formation.

108.4 Montebello Member of the Mahantango Formation exposed on right.

108.8 Scenic view of the Susquehanna River Valley and Berry Mountain Gap at Millersburg.

109.0 Just past the Sunoco Station on the left, stop and park on right (west) side of highway near road to the right. Although this side road can be driven in an automobile, it is in too poor a condition and is too steep for large buses. Disembark from buses and follow road to STOP XI, Dalmatia Quarries.

Additional Road Log for driving to STOP XI.

109.0 Turn right onto unimproved road down steep grade.

109.2 This very poor road turns sharply to the right, heading north.

109.3 Road passes between two 15-foot high concrete walls and runs parallel to the tracks just beyond.

109.4 Post and cable across road, usually passable.

109.5 First quarry, exposing simple south dipping beds. Intermittent exposures of Mahantango north of quarry.

109.7 Third quarry showing folds in the Dalmatia.

109.9 Fourth quarry showing north dipping beds and wedge fault in Turkey Ridge along north quarry wall. This road parallel to the tracks continues northeastward to Dalmatia, and exposes Lower Devonian and Upper Silurian.

STOP XI: DALMATIA QUARRIES. Estimated time: 3:50 P.M. Allotted time: 60 minutes.

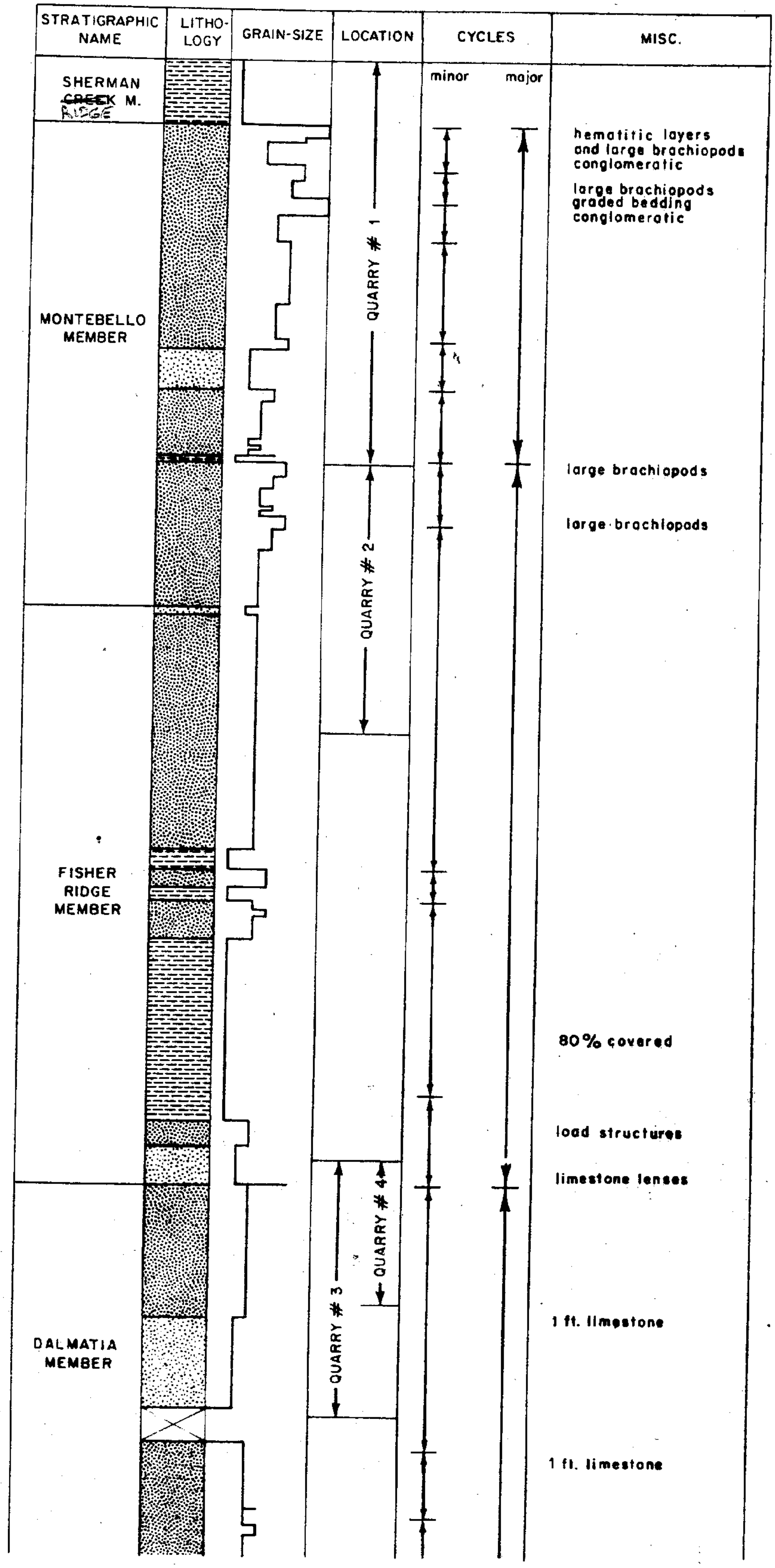
Discussant: Donald Hoskins

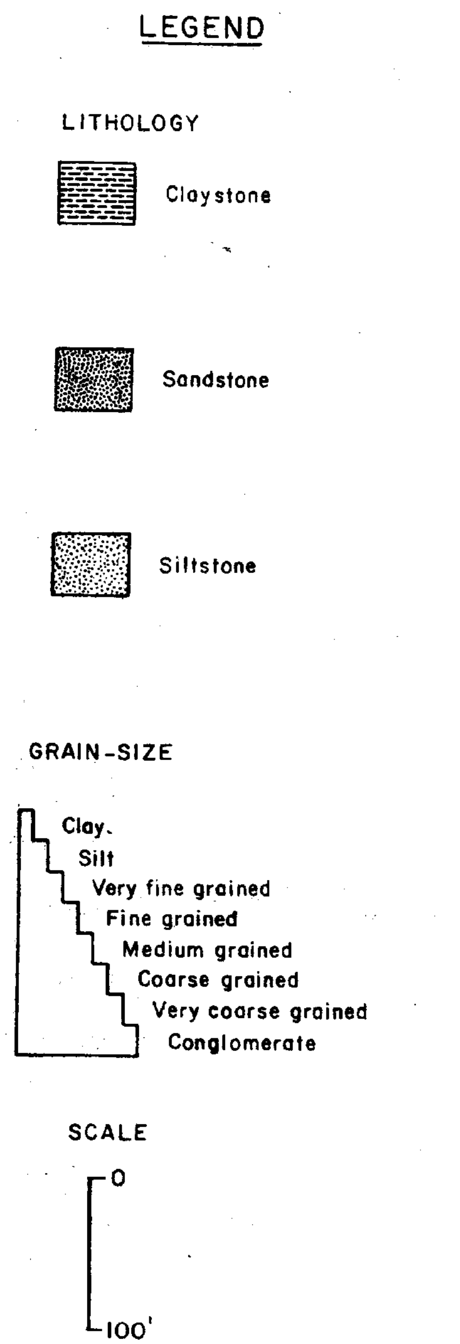
The four Dalmatia quarries along the Penn-Central Railroad (that were operated many years ago for road ballast) provide one of the most complete exposures of the Middle Devonian Mahantango Formation and contains the Type Sections for two of its members, the Dalmatia and Fisher Ridge (new names, Faill, Hoskins and Wells, in press).

These quarries are located on the south limb of a second-order anticline on the hinge of the Tuscarora anticlinorium, in an <u>en echelon</u> arrangement with the anticline exposed at Meckley's Quarry (STOP X). The first quarry (from the south), therefore, contains the youngest parts of the Mahantango and the northernmost the oldest (Fig. XI-A). Most of the Dalmatia, the Fisher Ridge and Montebello members are exposed in the quarries (Fig. XI-B). The Sherman Ridge is not, nor is the lowest member, the Turkey Ridge. The Turkey Ridge, along with lowest portion of the Dalmatia can be seen in the river as ledges at low water (Fig. XI-C).

Although not exposed in these quarries, the Marcellus Formation in this immediate area is unusual with respect to it elsewhere. Typically, it is a uniformly, massive sequence of sooty black, carbonaceous shale. In this vicinity it contains numerous discontinuous, thin and thick bedded, very fine and fine-grained sandstone beds similar to the sandstones of the Turkey Ridge and Dalmatia members. In that they are surrounded by the typical black shale, they may be slumped blocks or channel fillings introduced into the depositional basin of black shale. As such, they may indicate a close approach to the Marcellus shoreline and the inception of the location of the Devonian River System that produced the deltaic cycles of the Mahantango Formation.

FIGURE XIB. STRATIGRAPHIC SECTION OF THE MAHANTANGO FORMATION AT THE DALMATIA QUARRIES.





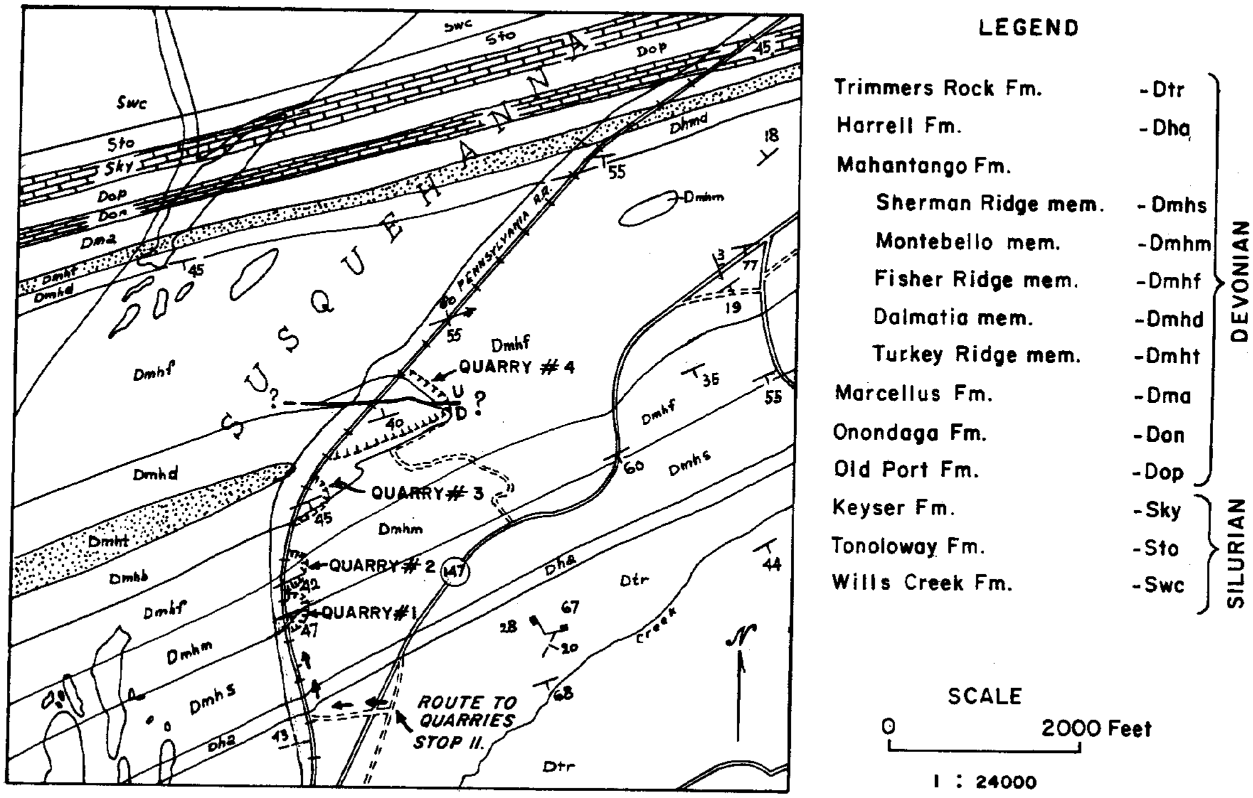


Figure XI-A. Geologic map of the vicinity surrounding the Dalmatia Quarries.

Figure XI-C. Turkey Ridge (nearest to viewer) and Dalmatia member sandstones seen from Quarry 3.

The Dalmatia Member, exposed in Quarry 4 (Fig. XI-D), and Quarry 3 (Fig. XI-E, our primary stop), is divisible into two main parts. The upper 110 feet is uniformly very fine grained, poorly bedded sandstone, with large spheroidal weathering surfaces. The uppermost one-half inch includes grains of sandstone up to very coarse size; to the west a thicker conglomeratic sandstone occupies the top of this member. At the base of this sandstone is one foot of silty and sandy limestone which contains Styliolina and poorly preserved brachiopods. (It is possible that this limestone may be equivalent to the "Upper Selinsgrove Limestone" of the Sunbury area described by I.C. White in 1883.)

The exposed lower portion of the Dalmatia Member consists of two primary units: 1) 70 feet of dark and light gray laminated silty and sandy shale, with the superficial aspect of the Marcellus shale, and 2) 120 feet of dark gray and olive gray shales, siltstone and thin bedded very fine-grained sandstones.

The Dalmatia Member thus represents, in overall aspect, one of the coarsening upward cycles prevalent in the Mahantango Formation in this part of Pennsylvania, a cyclicity also seen at Shadle (STOP VI). The cycle starts with shales and siltstones and thin-bedded sandstones, abruptly grades to very fine grained massive sandstone and abruptly, at the top of the cycle, to very coarse-grained sandstone.

The upper sandstones of the Dalmatia Member and the sandstones of the Turkey Ridge Member are, for mapping purposes, virtually identical and can be distinguished only by examination of the shalier units below the sandstones; only the Turkey Ridge is underlain by the distinctive black shales of the Marcellus.

The lowest part of the Fisher Ridge Member is exposed at the south part of Quarry 3 (Fig. XI-B) and at the north side of Quarry 4. It demonstrates the cyclic nature of the Mahantango by repeating lithologies seen a few feet below the base of the massive sandstones of the Dalmatia Member. The 30 feet of rock immediately above the Dalmatia Member are very dark and light gray, laminated silty shales with lenses of limestone and have a superficial resemblance again to the Marcellus. Above this is 15 feet of gray siltstone and very fine-grained sandstone with discontinuous beds of fine-grained sandstone that appear to be slumped. This sequence is the beginning of a new coarsening upward cycle.

The remainder of the Fisher Ridge Member consists of 140 feet of gray claystone, largely covered, and 230 feet of gray siltstone to very fine-grained sandstone. The Fisher Ridge Member is interpreted to represent the lower portion of a major coarsening upward cycle that culminates in the lower sandstone unit of the Montebello Member (Fig. XI-B).

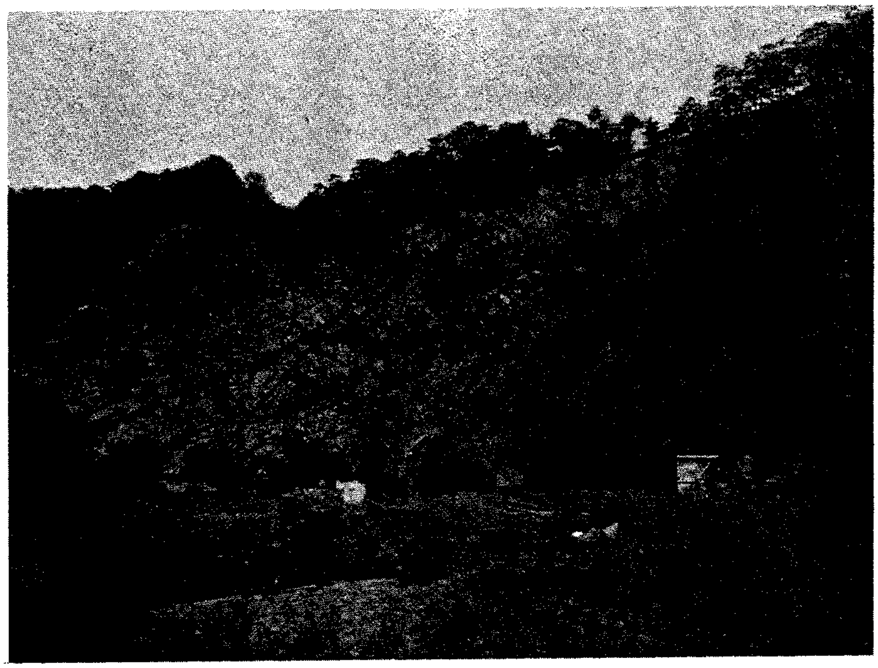


Figure XI-D. Faulted north-dipping layers of the Dalmatia Member and lower part of the Fisher Ridge Member in Quarry 4.

Figure XI-E. Syncline and anticline in the Dalmatia Member sandstone exposed in Quarry 3.

The Montebello Member consists of two coarsening upward sandstone units. The lower sandstone is 130 feet thick andis largely massive bedded, fine-grained sandstone that grades up to medium grained at its top. The coarser beds also contain large, robust spiriferoid brachiopods. This is immediately overlain by a few feet of claystone, the beginning of a new cycle which grades within a few feet to fine to medium-grained sandstone, and at the top of the 260-foot unit to conglomeratic sandstone, again associated with large brachiopods and hematitic layers. The upper cycle is exposed wholly in Quarry 1 and the lower unit of the Montebello is in Quarry 2.

End of STOP XI. Walk back up poor road to buses waiting on the shoulder of Pa. Route 147. Estimated time: 4:50 P.M. Turn right and proceed southward on Pa. Route 147. Approximate travel time to the Penn-Harris Motor Inn: 55 minutes.

109.9 Crossing Mahantango Creek, entering Dauphin County.

111.4 Village of Paxton.

113.5 Riffles in river are of the upper part of the Catskill Formation.

113.8 Beginning of 0.3 mile long exposure on left in roadcut of steeply north dipping (overturned) Pocono Formation.

114.4 Steeply south dipping Mauch Chunk Formation on the left intermittently exposed for the next mile.

116.2 Center square of Millersburg. Intersection with U.S. Route 209. Continue south of Pa. Route 147.

117.3 0.6 mile long cut in the Mississippian Pocono Formation where the Susquehanna River cuts through Berry Mountain. At the south end of the cut is the Devonian Catskill Formation, Duncannon Member. The contact between Catskill and Pocono is approximately 40 feet north of the south end of the protective fence.

122.2 Village of Halifax, turn left, following Pa. Route 147. Site of Fort Halifax, built by the Augusta Regiment in 1756.

122.3 Junction with Pa. Route 225. Turn right, continue south of Pa. Routes 147 and 225.

123.8 Divergence of Pa. Routes 225 and 147. Continue straight on Pa. Route 225.

124.8 Village of Matamoras.

125.2 Ahead is an excellent view of Peters Mountain which is underlain by the Catskill and Pocono formations. Intermittent red exposures of the Sherman Creek Member, Catskill Formation occur along this road.

126.7 Hairpin turn.

127.4 Beginning of steeply south dipping Pocono exposure on the right.

127.6 Hairpin turn at crest of Peters Mountain. Small exposures of Pocono Formation on each side of road.

129.0 Intersection with Pa. Route 325 to the west.

129.7 Intersection with Pa. Route 325 to the east.

129.9 Mountain to the east (on the left) is the easternmost extent of the Pottsville Formation in the Cove Mountain synclinorium. Red shale exposures in this valley belong to the Mauch Chunk Formation.

131.5 Borough of Dauphin.

131.6 Pa. Route 225 turns right under U.S. Routes 22-322.

131.7 End of Pa. Route 225. Follow U.S. Routes 22-322.

132.4 View of Rockville bridge to the south.

133.3 Intersection with Pa. Route 443 to the east.

135.0 Intersection with Pa. Route 39 to the east.

135.9 Overpass of Interstate Route 81.

139.3 Stop light, Forster Street. Turn right onto bridge across the Susquehanna River.

140.8 Turn right onto exit for Erford Road.

141.0 Turn right onto Erford Road.

141.3 Entrance to Penn-Harris Motor Inn parking lot. End of second day and the 38th Annual Field Conference of Pennsylvania Geologists.

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APPENDIX

Stop Locations

For the convenience of future users of this guidebook, the following list of Field Trip Stops is presented with their county, 7 1/2' quadrangle, and 15' quadrangle locations.

Stop		7 1/2' quadrangle	15' quadrangle	County
I.	Millerstown	Millerstown	Millerstown	Juniata
II.	Mifflin	Mifflintown	Mifflintown	Juniata
III.	Laurel Creek Dam	Barrville	Lewistown	Mifflin
IV.	D.E. Smith Quarry	Millerstown	Millerstown	Juniata
V.	Buffalo Mountain, Newport	Millerstown	Millerstown	Perry
VI.	Girty's Notch	Halifax	Harrisburg	Perry
VII.	Shadle	Dalmatia	Millersburg	Snyder
VIII.	Cowan	Mifflinburg	Mifflinburg	Union
IX.	Sunbury	Northumberland	Sunbury	Northumberland
X.	Meckley Quarry	Pillow	Millersburg	Northumberland
XI.	Dalmatia Quarries	Dalmatia	Millersburg	Northumberland