A STRUCTURAL ANALYSIS OF A PORTION OF THE VALLEY AND RIDGE PROVINCE OF PENNSYLVANIA

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ABSTRACT

The Valley and Ridge province of the Pennsylvania salient is representative of a blind-thrusted fold and thrust belt. Low-angle reverse thrust faults in the subsurface provided the means by which a Paleozoic rock sequence was transported to the northwest during the Allegheny Orogeny. The low-angle reverse thrust faults do not reach the erosion surface but terminate upwards into an upper detatchment or roof thrust which separates a lower, more competent rock sequence or 'stiff layer', from an overlying less competent sequence or 'cover layer'. The stiff layer is comprised of massive carbonates and the cover layer of clastics and thin carbonates.

The fold pattern at the surface reflects the underlying thin-skinned deformation processes and the fold geometry is predominantely a non- cylindrical kink-band form resulting from a combination of flexural- slip and flexural-flow folding processes. Layer parallel shortening strain mechanisms have occured in the cover layer rocks exposed at the surface but are scarce within the outcropping stiff layer lithologies. Previously reported estimates of LPS penetrative strain within the Valley and Ridge province range from 10% at the northwest boundary to 50% at the southeast boundary.

Layer parallel shortening strain mechanisms in the cover layer from a petrographic study of some carbonates, marls, and quartzites include the penetrative mechanisms of solution cleavage microselvages and deformation glide twinning in carbonates. Penciling (fracture cleavage) and fold crenulations occur within siltstones and shales, and the symmetric distribution of conjugate deformation lamallae may represent LPS strain in the quartzites. Estimates of LPS penetrative strain range to 20% as indicated by measured crinoid columnals from two Ordovician Reedsville specimens. Other layer-parallel shortening mechansisms existing within the cover layer include contraction faulting and folding.

A cross section interpretation is derived by combining surface field data with section construction constraints assumed from characteristic deformation response associated with the deformation of a non-metamorphosed, layered rock sequence. The constraints assume a break forward sequence of developement for a fracture-thrusted stiff layer which results in folds with kink- domain geometry. The cover layer conforms to the geometry of the underlying stiff layer and deforms in an incompetent manner having abundant third through fifth order folding and faulting.

The resulting cross section interpretation(s) for this portion of the Valley and Ridge province have hindward dipping duplexes for the stiff layer with an overlying, continuously folded cover layer. The cover layer is periodically cut by high-angle reverse thrust faults which have splayed off the low-angle thrust faults in the stiff layer.

The restored cross section displays a length disparity between the stiff and cover layers of 71 km.. This difference is accounted for by assuming a preferentially shortened cover layer resulting from the processes of LPS penetrative strain and contraction faulting and folding combined with the translation of the cover layer onto the Appalachian Plateau to the northwest. Suggested percentages of shortening strain for the cover layer are 28% layer-parallel shortening from the combined processes of LPS strain and contraction faulting and folding, and 12% shortening from translation of the cover layer. The contraction ratio for the stiff layer is .540.

A previous interpretation by the Pennsylvania Geologic Survey for this portion of the Valley and Ridge province resembles an imbricate splay thrust system. This interpretation lacks a roof thrust which enables the cover layer strain to be homogenously distributed along the line of section. A restortion diagram for a portion of the interpretation suggests that a concentration of cover layer strain occurs within the Juniata Culmination interval which is not supported from field data. Other balancing problems further suggest that an imbricate splay interpretation is improbable. A duplex thrust system solution does however result in a valid, balanced cross section interpretation and therefore is a more admissible solution.

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GENERAL INTRODUCTION

Recent studies which document recurring physical relations of thrust systems provide the tools for structurally evaluating complex fold and thrust belts to higher standards of admissibility. Techniques of improving cross section construction stem from geometric constraints resulting from characteristic deformation behavior in non-metamorphosed terraine. The methods and constraints for interpreting thrust systems are for both the current and pre-deformation (restored) configurations.

The purpose of this study is to structurally analyze a portion of the Valley and Ridge province of Pennsylvania. The primary emphasis of this analysis is to derive a current and restored cross section interpretation for a designated portion of the thrust belt. Additional emphasis is given to background information and a petrographic study of strain within some rocks exposed at the surface. The compiled background information includes the deformation mechanisms and physical data such as the stratigraphic column and surface structures. The petrographic analysis qualitatively assesses aspects of deformation which are applied in section balancing. The background and petrographic study also contribute to the development of the section modeling constraints.

Due to the interrelated character of deformation between the Valley and Ridge and it's bordering provinces, aspects of deformation in the Appalachian Plateau and Great Valley provinces are also cited. Such aspects are limited to manifestations of strain in these bordering areas which result from processes operating within the Valley and Ridge province or which contribute to the estimation of strain for the section balancing procedures. The cross section analysis is limited to the Valley and Ridge province only.

The presentation of this study consists of three parts: the geologic setting and background, the petrographic analysis of the cover layer, and the cross section interpretation. The geologic setting and background presents the summary of previous geologic work in the study area which is directly applicable to this structural analysis. The petrographic study examines penetrative strain in some surface rocks to aid in establishing the cross section construction constraints, and for section balancing procedures. Cross section analysis draws information from the first two parts and develops additional techniques within for establishing the current and restored configurations of a cross section within the Valley and Ridge province of Pennsylvania. The last part includes a comparison between the section interpretations developed in this study and a previous interpretation by the Pennsylvania Geologic Survey.

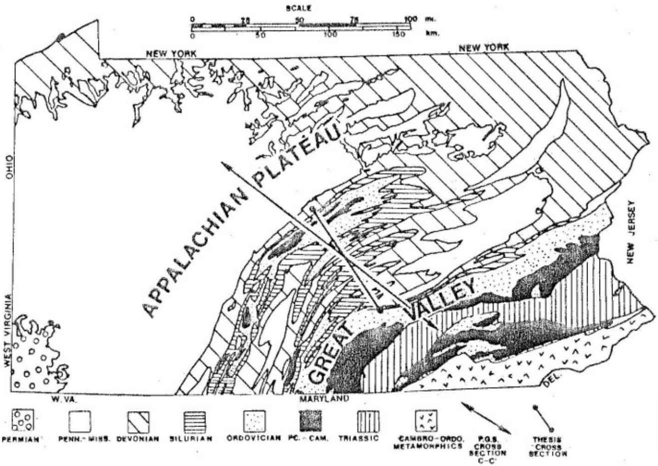
PART I

GEOLOGIC SETTING AND BACKGROUND

1. LOCATION AND GEOLOGIC SETTING

This study covers a strip 98 km. long and 3 km. wide within the Valley and Ridge province of the Pennsylvania salient. A transect line bisects the area lengthwise and corresponds to the line of cross section interpretation. The section extends from the Great Valley - Valley and Ridge province border to 5 km. past the Allegheny Front. The line is normal to structural strike and intersects the Juniata Culmination (Gwinn, 1970) approximately halfway along it's length (Figure 1).

FIGURE 1
GEOLOGIC MAP OF PENNSYLVANIA



According to Rodgers (1949), the chief structural features of the unmetamorphosed portions of the central and southern Appalachians appears to have been produced only by the Alleghenian orogeny, while the northern Appalachians were subjected to at least three periods of deformation. K/Ar dating of mylonites in central Pennsylvania (Pierce and Armstrong, 1966) suggest that deformation may have begun as early as the Early Carboniferous (340 +50,-15 m.y.).

The Pennsylvania salient displays almost no large scale thrusts toward the northwest in sharp contrast to the Gaspe-New England and Tennessee salients. This suggests that the Valley and Ridge province of Pennsylvania is blind-thrust terraine as opposed to the emergent terraine of the bordering salients. In blind-thrusting, the major thrust faults terminate upwards in an upper detachment zone rather than reaching the surface during thrusting (Dahlstrom 1970, Thompson 1981, Boyer & Elliot 1982). Nickelsen (1963) postulated this difference in structural behavior to possible foreland differences; the Gaspe-New England and Tennessee salients are buttressed to the northwest by the Adirondack upift and Cincinatti Arch respectively while the Pennsylvania salient is bordered by the broad Appalachian basin. Other reasons may be related to sediment thickness variations between respective salients, and differences in the depth of erosion (Gwinn, 1964).

2. REVIEW OF PREVIOUS WORK

Numerous geologic studies of the Valley and Ridge and Appalachian Plateau provinces of Pennsylvania have examined the stratigraphy, structure and deformation mechanics of the region. A brief summary follows.

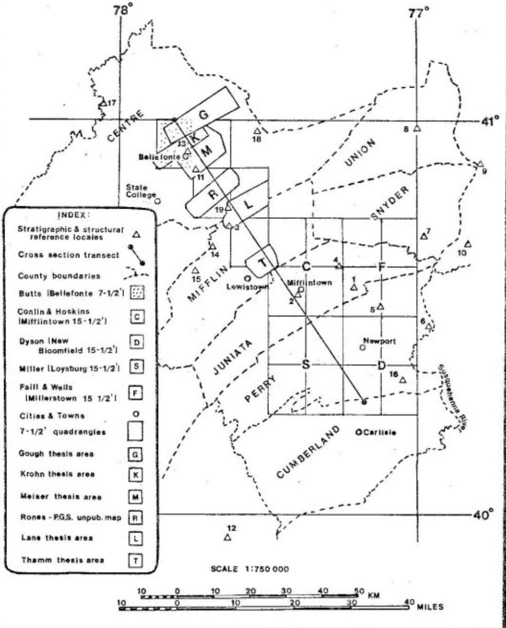
The Geologic Survey of Pennsylvania under Peter Lesley (1819-1903) restudied the folds of Pennsylvania to delineate them on fairly detailed geologic maps (Rodgers, 1949). The first completed description of the Valley and Ridge province resulting from this effort was by H.D. Rodgers (1858).

The first complete stratigraphic compilation within the study area was for the Bellefonte 7-1/2' quadrangle and surrounding area by Butts and Moores (1936) (Figure 2). It has served as a basis for the subsequent stratigraphic compilations throughout this region.

The Pennsylvania Geologic Survey (Pennsylvania Geologic-Survey) compiled the entire outcropping stratigraphic sequence between 1936 and 1974. The descriptive geology and accompanying maps of four 15-1/2' quadrangles were also compiled by Miller (1961-Loysville quadrangle), Conlin & Hoskins (1962-Mifflintown), and Dyson (1963,1967-New Bloomfield) (Figure 2).

The Cambro-Ordovician stratigraphy and structural details within central and south-central Pennsylvania were addressed during a field conference by Nickelsen and Wagner (1963). Faill et.al. (1973) covered the stratigraphy and structure

FIGURE 2
Location of the Study Area with
Stratigraphic and Structural References



for the Upper Ordovician to the Upper Devonian rocks during a subsequent field conference. Additional stratigraphic and structural studies conducted in the area include Masters theses by Gough (1977), Krohn (1976), Meiser (1971), Thamm (1956), and Lane (1956) (Figure 2).

The mechanical analysis of the Central Pennsylvania Valley and Ridge province was initiated by Rodgers (1963), who proposed that the folding in the Appalachian Plateau was a marginal effect of the deformation of the Valley and Ridge province. Gwinn (1964) suggested that the folding within the Valley and Ridge province involves allocthonous Paleozoic rocks which have been transported to the northwest above low-angle detatchment thrust faults.

By this time numerous related mechanical theories were proposed for bordering portions of the Appalachian system. The most relevant of these include Bailley Willis's (1891) concepts of stratigraphic competency and the effects of overburden, C. Willard Hayes (1891) recognition of thrust faults exhibiting low dips, having warped fault surfaces and great lateral displacements, and Rich's (1934) classic treatese on mechanical overthrusting in Virginia, Kentucky and Tennessee.

Additional contributions to the classification of the mechanics within the central Pennsylvania Valley and Ridge province include: Nickelsen and Wagner's (1963) designation of structural culminations and depressions, size order of folds, structural lithic units and related fold geometry; the recognition of the thin-skinned, non-outcropping style of thrust faulting (Rodgers 1963, Gwinn 1964,1970); the recognition of tear faulting and structural variations related to plunging folds (Gwinn, 1964); the documentation of penetrative deformation mechanisms by Nickelsen (1966,1972,1979), Geiser (1970,1974), Groshong (1975), Faill et.al. (1973), and Faill (1977); the recognition of kink-band geometry fold patterns, and contraction faulting (Faill, 1969,1973); the recognition of stages of deformation by Berger, et.al. (1979); and finally, Pohn and Purdy's (1983) treatise on distrubed zones and associated structures.

3. PREVIOUS CROSS SECTION INTERPRETATIONS

Gwinn (1970) constructed a series of cross section interpretations within the central Appalachians in south-central Pennsylvania. The sections were intended to roughly outline the major structural character of the Great Valley and Valley and Ridge provinces. Cross section c-c' (Gwinn, op.cit.- pg. 128) nearly parallels the cross section for this study but lacks the internal structural detail sought here.

The most critical aspect of Gwinn's (1970) work with respect to this study is the verification by proprietary seismic data of a lack of basement involvement in the Valley and Ridge province deformation. Sub-horizontal deep seismic reflectors were recognized at depths estimated at 18,000-25,000 ft. 3500 ft. (5486-7620 m. 1067 m.) in the Shade Mountain Anticlinorium. Steep dips were observed in the upper 15,000 ft. (4573 m.) of the profiles. Seismic indication of the lack of basement involvement also existed in adjoining areas. From these repeated occurances, Gwinn (op.cit.) proposed that a nearly planar basement descends southeastward toward the Great Valley at an inclination between 130-200 ft./mi. (25-38 m./km.) from a position about 23,000 - 25,000 ft. (7162 m.) beneath the surface at the Nittany Arch.

A series of interpretive structural cross sections for the Pennsylvania Appalachians were also made by the Pennsylvania Geologic Survey and accompany the Geologic Map of Pennsylvania (1980). One of the three sections (c-c') within the Valley and Ridge province crosses the line of section for this study. Problems arising from section restoration and balancing attempts on cross section c-c' helped motivate this reinterpretation. The arrangement between the two crossing lines of section is shown in Figure 1. Comparison and discussion of the respective section interpretations is presented at the end of this study.

4. STRATIGRAPHY

The stratigraphy encountered in this study ranges from the mid- Cambrian Waynesboro formation to the upper Devonian Catskill formation. The stratigraphic units cropping out in the study area range from the middle Cambrian Warrior formation to the Mississippian Pocono formation. General lithic descriptions with corresponding average formation thickness values are presented in Table 1.

Because of the extent of the study area, many lithologic changes occur within. Stratigraphic pinch outs, wedge outs, facies changes, and unconformities complicate the lithic sequence such that correlations often conflict. Consequently, the stratigraphic nomenclature for this region has experienced many revisions. Therefore for this study, the nomenclature assigned to the geologic columnn by Nickelsen and Wagner (1963) and Faill et.al. (1973) will serve as a basis from which the column will be further amended. A list of the additional references is given under the references and locations column of Table 2.

The Cambrian and lower to middle Ordovician carbonates comprise the first phase of the Taconic deposition cycle. The second phase is the turbidite (flysch) sequence which is represented by the upper Ordovician Reedsville formation. The third phase of the Taconic cycle is the molasse sequence which consists of the upper Ordovician Bald Eagle to lower Silurian Tuscarora formations. The overlying stratigraphy through the mid-Silurian Bloomsburg formation represents a waning molasse stage with a gradual reintroduction of marine conditions to the Appalachian Basin by upper Silurian time. The Bloomsburg may represent a minor renewal of tectonism subsequent to the main activity during the Taconic cycle (Faill, et.al., 1973).

The carbonates of the upper Silurian to lower Devonian Wills Creek through Onondaga formations represent the initial phase of the Alleghenian cycle. Succeeding this initial phase is a subaqueous deltaic unit (Mahantango formation) and a turbidite, flysch sequence represented by the upper Devonian Trimmers Rock formation. The last phase of this cycle is a complex molasse sequence beginning with the upper Devonian Catskill formation and progressing into the Pennsylvanian aged rocks.

Stratigraphic thickness values for the entire geologic column were compiled to aid in the cross section interpretation. Thickness values were obtained along the length of the section from thirteen reference sources around the study area. The stratigraphic thickness values and references are given in Table 2. The location of the references are given in Figure 2.

TABLE 1

Generalized stratigraphic sequence

SYSTEM	SERIES	GROUP	FORMATION AND AVERAGE THICKNESS (ft.)	GENERAL GEOLOGIC DESCRIPTION
MISS. / DEVONIAN	Lower / Upper		Pocono 1600'	Medium to very thick bedded, cross bedded sandstone with lenses and beds of white quartz pebble conglomerate; interbedded medium grained sandstones and dark argillaceous siltones towards the bottom.
DEVONIAN	Upper		Catskill 3600'	Gray to gray-red, interbedded cylic sequences of fine to locally conglomeratic sandstones, siltones and some shale; overlain by fining upward deposits of fine sandstone, siltstones and silty claystones.
DEVONIAN	Upper		Trimmers Rock 2100'	Interbedded grayish-red and light olive gray sandstone, siltstone and shale; overlain by fining upward cyclic deposits of gray-red sandstone,siltones, and claystones.
DEVONIAN	Upper		Harrell 250'	Dark to light olive gray and light gray silty shale, noncalcareous, nonfossiliferous, splintery fracture.
DEVONIAN	Middle		Mahantango 1280'	Light olive gray, interbedded, very fine to coarse, locally conglomeratic& fosilliferous sandstones; silty claystones and siliceous siltones. Some subgaywacke sandstones. Tully silty limestone member at top.
DEVONIAN	Middle		Marcellus 205'	Highly fissile, dark gray to black, carbonaceous, non-calcareous shale, with yellow-orange limonite fracture staining common.
DEVONIAN	Middle / Lower	Oriskany	Onondoga 125'	Medium to dark gray, dense, fossiliferous, argillaceous, microcrystalline limestones overlying highly fissile, medium grained and partially calacareous shale.
DEVONIAN	Lower	Oriskany	Old Port 280'	Upper dark gray, whitish weathering chert locally overlain by medium to course grained fossiliferous sandstone. Calcareous shale and thin gray limestone beds at bottom.

SYSTEM	SERIES	GROUP	FORMATION AND AVERAGE THICKNESS (ft.)	GENERAL GEOLOGIC DESCRIPTION
SILURIAN	Upper		Keyser 160'	Medium gray, fossiliferous, lumpy or "pseudo nodular", thick bedded limestone
SILURIAN	Upper		Tonoloway 470'	Medium to dark gray, thin bedded to laminated limestones with some thin beds of medium gray calcareous shale
SILURIAN	Upper		Wills Creek 560'	Gray calcareous shales interbedded with lighter gray calcareous, fine grained sandstones, medium gray limestones and gray-red silty claystones.
SILURIAN	Middle		Bloomsburg 300'	Gray-red to light gray, interbedded claystones and shales, hematitic sandstones and uppermost light gray, fine to medium grained sandstone.
SILURIAN	Middle		Mifflintown 200'	Dark gray-blue, medium bedded to thin planar microcrystalline to bioclastic limestone with dark gray calcareous shale towards the base. Underlain by the locally hematitic, gray-red, thin to thick bedded Keefer sandstone (30').
SILURIAN	Middle	Clinton	Rose Hill 860'	Gray to olive gray, silty and partially calcareous shale interbedded with very fine to coarse grained, hematitic, fossiliferous sandstones and siltstones.
SILURIAN	Lower		Tuscarora 510'	Light gray to white, fine to medium grained, medium bedded orthoquartzite, interbedded in upper portions with gray-olive silty shales.
ORDOVICIAN	Upper		Juniata 1100'	Gray-red, cross bedded, graywacke sandstones and lower siltones and silty claystones.
ORDOVICIAN	Upper		Bald Eagle 700'	Gray-buff, medium to thick bedded, cross bedded, medium to coarse grained sandstones, iron oxide speckling, and quartz pebble conglomerate basal layers.

SYSTEM	SERIES	GROUP	FORMATION AND AVERAGE THICKNESS (ft.)	GENERAL GEOLOGIC DESCRIPTION
ORDOVICIAN	Upper		Reedsville 1500'	Gray-olive siltstone and silty shale, and impure fossiliferous limestones with increasing interbeds of gray-buff sandstones in upper part. Antes black, fissile, shale member at base (400').
ORDOVICIAN	Middle	Trenton	Coburn & Salona 450'	Coburn is alternating, gray crystalline, highly fossiliferous limestones and black shaly limestones becoming more argillaceous in the upper parts. Salona differs only in that the limestones are non-fossiliferous.
ORDOVICIAN	Middle	Trenton	Nealmont 135'	Bluish-gray, finely crystalline, somewhat argillaceous limestone.
ORDOVICIAN	Middle	Black River	Benner & Hatter 450'	Bluish-gray weathering, moderately argillaceous limestones that may contain small amounts of silt. Curtin division (Valentine member) is a pure, high calcium limestone underlying the Nealmont formation in places.
ORDOVICIAN	Middle	Chazy	Loysburg 400'	An upper microcrystalline limestone 40-60 feet thick (Clover member), underlain by interbedded microcrystalline dolomites and limestones (Tiger-stripe member, 40-400 ft. thick).
ORDOVICIAN	Lower	Beekmantown	Bellefonte 1600'	Light to medium dark gray, fine to medium crystalline dolomite with small amounts of chert and quartz sand in lower parts.
ORDOVICIAN	Lower	Beekmantown	Axeman 700'	Dark gray, fine to coarsely crystalline, interbedded limestones, dolomites and dolomitic limestones.
ORDOVICIAN	Lower	Beekmantown	Nittany 1200'	Dark gray, fine to coarsely crystalline, thick bedded dolomite.

(continued)

SYSTEM	SERIES	GROUP	FORMATION AND AVERAGE THICKNESS (ft.)	GENERAL GEOLOGIC DESCRIPTION
ORDOVICIAN	Lower	Beekmantown	Stonehedge 500'	Medium gray, finely crystalline, thin bedded to finely laminated limestone with minor dolomite interbeds. Zones of chert, quartz sand and oolite in lower portions. Larke dolomite towards the base.
CAMBRIAN	Upper		Gatesburg 1700'	Sequence of interbedded buff-gray sandstone and blue-gray, coarse grained dolomite, which is replaced to the southeast by dark blue, banded and laminated limestone and subordinate dolomite (Conococheague formation). Thick bedded, oolitic Mines dolomite member at the top in central Pa..
			Warrior 700'	Thick bedded, bluish dolomite with limestone and sandstone in the middle. Limestone varies from pure to argillaceous and micaceous; oolitic limestone at many horizons, sparcely fossiliferous. Elbrook formation equivalent to the southeast; includes massive to thin bedded, argillaceous limestone and whitish to cream colored marble with sericitic partings (1000').
	Middle		Pleasant Hill 600'	Thin bedded, argillaceous and somewhat micaceous limestone overlain by thick bedded, somewhat more pure bluish limestone; mottled weathering.
	Middle / Lower		Waynesboro 620'	Lower member of gray limestone and calcareous sandstone, middle member of limestone and upper member consisting of purple-reddish silty shale and argillaceous sandstone.

Adapted from Butts and Moore (1936), Dobelbower (1953), Krohn (1976), Tompson (1974), Chafetz (1969), Dyson (1967), Swartz (1973), Fail, et.al. (1973), Miller (1961), Conlin and Hoskins (1962), Gough (1977), and the Pennsylvania Geologic Survey cross section c-c' (1980).

TABLE 2

Stratigraphic thicknesses

FORMATION	GROUP	Butts & Moore (1936) Bellefonte quad.	Dobelbower (1953) 11	Krohn - m.s. thesis K	Thompson (1974) 4	P.G.S. Cross section 16,17	Chafetz (1969) 15	Dyson (1967) D	Gwinn (1964) 18	Swartz (1973) 12,13	Faill, et. al.(1973) 1-8,10,11	Miller (1961) S	Conlin Hoskins (1962) C	Gough m.s. thesis G
Catskill	Dck	1600									7250 (5,6)	4900		4300
Trimmers Rock Harrell Mahantango Marcellus	Dmt	5350						7000-8000			3900 (7,11)	4510		2900
Onondaga Old Port	Doo	320	560	650							265	215-335	325-365	510
Keyser Tonoloway Wills Creek Bloomsburg Mifflintown Rose Hill	SDrk	1800	2070	2190-3320							3110 (1,2 3,4 8,10)	3089-3149	2680-3080	2080-1690
Tuscarora Juniata Bald Eagle	OSbt	2200	1680	2400							2080 (3)	1350-1760	2790-4130	2360-2590
Reedsville	Or	1000	1200	1200	1400						900 +	2000-3000	150	900 +
Coburn Salona Nealmont Benner Hatter Loysburg	Oct	1170-1240	1215	960	900	1150 (17) 1550 (16)		1600-1700		1700 (12) 1500 (13)				
Bellefonte Axeman Nittany Stonehedge	Ob	3890-4590	4000	3500	3400	4000 (17) 3250 (16)	3400			2050 (12)				
Gatesburg Warrior Pleasant Hill	Cgw	2800 +	2440 +	2400 +		2250 (17) 5750 (16)				4070 (12) 3450 (13)				
Waynesboro	Cw									900 (12) 340 (13)				
Detachment						6.1 km. (17) 10.1km. (16)			6.2km					

5. STRUCTURAL GEOLOGY AND MECHANICS

In the analyses of structure and rock fabrics, directions are generally referred to a tectonic co-ordinate system. The following system is after Cloos and Broedel (1943): a is the direction of transport, flowage, or displacement; b is an axis perpendicular to a which is an axis of rotation; and c is perpendicular to a and b or the ab -plane. In this study, b is the fold axis, and the plane perpendicular to b is the ac -plane. Inasmuch as the fold axes are mostly horizontal, the ac -plane is mostly vertical. The orientation of the bc -plane will strike parallel to the fold axes but will have various dips, depending on the attitude of the local bedding; horizontal beds will display a vertical bc -plane, but a folded bed which has a non-zero dip value will also have a dipping bc -plane. The general orientations for these respective planes of reference are shown in Figure 4.

Many studies have addressed the structural character and strain mechanisms of the Valley and Ridge province in central Pennsylvania. Structures varying in size from the map scale to the microscopic have been reported for lithologies of various ages. The following section briefly summarizes the structures and strain mechanisms. The structural details of folding and faulting are presented first. The penetrative strain mechanisms follow.

5.1 Fold Patterns

Map scale fold patterns are much longer parallel to their fold axes than they are wide in the profile view. Folds commonly display an 'en echelon' arrangement, and the traces of the fold hinge surfaces on the map are generally arcuate to linear and trend at approximately 054 within the field area (Figure 3). The fold axes are generally doubly-plunging at low (5-10) angles such that the lithologic contacts define elongate, 'cigar shaped' outcrop patterns parallel to structural strike (Plate 1). Smaller folds appear towards the lateral terminations of the larger folds. The smaller fold axes are also doubly-plunging, or preferentially plunging in the direction of the larger fold axis.

The largest folds in the province range in wavelength from 11 to 18 km., the structural relief is as much as 4 km. and the lengths range to more than 200 km.. Within the field area, a more representative length is 50 km.. The wide range in size of folds in the province led Nickelsen and Wagner (1963) to empirically classify folds into five orders: first order folds range in wavelength from 11 to 18 km.; fifth order includes microscopic and hand specimen size; second, third and fourth order folds are of intermediate size.

Within the Pennsylvania salient, the map fold pattern is dominated by various culmination and depression zones (Nickelsen and Wagner, 1963). The axis of a culmination is approximately defined by the structurally highest parts of doubly- plunging anticlines or anticlinoria where the oldest outcropping rocks appear. Axes of the depression zones correspond to the structurally lowest parts of the synclines or synclinoria. An increase in the fold frequency occurs on Plate 1 approximately halfway along the line of section from the southeast and continuing through the Allegheny Front. This variation of fold pattern corresponds to the line of section crossing into the Juniata Culmination upon leaving the lateral margin of the Anthracite Depression located to the east.

5.2 Fold Geometry and Mechanics

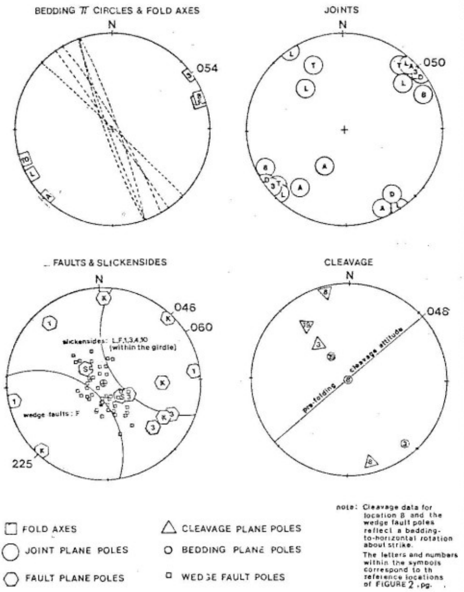
Significant contributions towards the understanding of the fold geometry within the Valley and Ridge province of Pennsylvania began with Sherrill's (1934) careful study of the asymmetry of the folds. He showed that if only the regional dip at the surface is taken into account, the folds show a slight southeast-facing asymmetry. Nickelsen and Wagner (1963) were next to report that the gross fold form approaches that of sine curves with nearly planar limbs and curved hinges. The limbs were reported to have unchanged thicknesses.

Faill (1969) further defines the geometry of the of folds as being non-cylindrical kink-band structures possessing planar limbs and narrow hinges. The thickening of the hinge

Figure 3

Lower hemisphere equal-area Pi diagrams of bedding π circles, fold axes, joints, slickensides, and cleavage orientations within the vicinity of the field area. The centers of the symbols represent the orientations corresponding to the centers of maxima ($>$ 4%) or the average orientations for point distributions, depending on the reference source. The grouping of orientations about the 046-054° and complimentary directions suggests a common deformation history for all mechanisms. Joint sets shown include cross (ac) and dip (bc) joints. Faults include cross faults, high-angle reverse faults, conjugate faults and wedge faults. Cleavage to bedding angular relations for three sets displays the rotation of cleavage with respect to bedding upon folding. The cleavage data for location 8 and the wedge fault poles reflect a bedding to horizontal rotation about strike. The slickenside girdle appearing on the lower left diagram encompasses 90% of an approximately uniform distribution of slickensides within - the slickenside distribution was omitted for clarity. The girdle corresponds to circular arcs centered about the 060° direction on the primitive circle.

FIGURE 3
STRUCTURAL DETAILS
(lower hemisphere equal-area Pi diagrams)



region is reported as being a result of the 'space problem' associated with flexural slip folds; the decrease in the radius of curvature towards the fold core results in a crowding of beds and eventually thrust faulting or disharmonic folding.

Faill (op.cit) also demonstrated that all of the different variations of fold profiles within the province can be appropriately produced by combining kink-band structures. Furthermore, by imposing a set of at least two divergent kink axes, the three dimensional aspects of non-cylindrical folding can be adequately explained. The abundant presence of slickensides on many bedding surfaces supports the flexural-slip folding process, while the presence of two differently oriented slickensides on a single bedding surface indicates that in many folds, each limb has been rotated about a different axis. This last phenomenon is an indication of the non-cylindrical fold geometry.

Overall, the mechanics of the folding within the Pennsylvania Valley and Ridge province can be considered a combination of flexural-slip and flexural-flow folding. The evidence for flexural-flow folding stems from the rarity of observable bedding slip planes, which necessarily accompany pure flexural-slip (Nickelsen and Wagner, 1963).

Structural details compiled by Lane (1956), Thamm (1956), Nickelsen and Wagner (1963), Faill (1969, 1973), Dyson (1967), Krohn (1976), and from my reconnaissance give further insight into the folding mechanics. 'Fracture cleavage', thought to originally exist sub-perpendicular to bedding, has apparently been rotated during the folding process (Figure 3, cleavage/bedding sets # 3 and 19). This indicates a flexural-slip or flexural-flow fold mechanism depending on the absence of slickenslides and is correlated to either a left lateral or right lateral bedding plane shear, depending on which fold limb is studied. Jointing, wedge faulting, slickensides, and cleavage orientations display a related symmetry (Figure 3) and thereby suggest a common deformation history.

Lithologic units of contrasting mechanical competency also effect the folding mechanics. Thick incompetent units sometimes allow shear folding due to slip on pre-developed cleavage planes (Nickelsen and Wagner, 1963, Faill et.al., 1973). This process can result in local axial thickening of folds. More competent lithologies display flexural-flow and/or flexural-slip folding depending on the component stratification and ease with which interlayer slip is accomplished. Usually, when competent layers (quartzites and thick carbonates) dominate most of the folded layer, folding is either by flexural-slip or flexural- flow, and the more incompetent layers tend to accomodate themselves to the space between competent members (Turner and Weiss, 1963).

5.3 Faults

Two dominant fault types crop out within the vicinity of the field area. The first type are high-angle reverse faults with displacements commonly measuring in hundreds of feet. They maintain either a steep (70) northwest dip (antithetic) or a steep southwest dip (synthetic) and generally parallel structural strike (Figure 3 - fault set S). The high-angle reverse faults commonly occur on the margins of second and third order anticlines and synclines and therefore suggest an origin related to the axial crowding associated with the flexural-slip folding process.

The second type of faults in the area are cross faults. Cross faults are generally sub-normal to the regional structural strike and group about the ac -plane orientation (Figure 3). Krohn (1976) discusses the occurence of cross faults within the central Appalachians with respect to the thrust faulting process. Briefly, Krohn reports an entire range of cross faults from the regional to the outcrop scale. Suggested origins fo the cross faults include: marginal tear faults associated with thrust sheets (Gwinn, 1964); lateral terminations of wedge faults associated with the developement of overlying kink-bands (Faill, 1973); perianticlinal structures related to the developement of the large anticlines in the Valley and Ridge (Meiser, 1971); and finally, faults related to torsion resulting from the change in strike observed in the central Appalachians (Butts, et.al., 1939).

Two additional fault types are found within the field area: wedge (contraction) faults and high-angle conjugate faults. Wedge faults were first reported in the province by Cloos (1940). Faill (1973) first documented their existence within the immediate study area. Wedge faults laterally shorten and consequently thicken the rock section in which they occur (Figure 4). They frequently occur as isolated structures in fold limbs and are also evidenced in the crowded hinge areas of folds. Wedge faults range in size from the outcrop to hand specimen scale. They represent the transfer of bed-parallel slip from one bedding surface to another. Slickensides on wedge fault surfaces generally parallel those on the bedding surfaces, thereby suggesting a kinematic link to the flexural-slip folding process. Wedge faults produce lense shaped blocks which either pinch out in the a and b directions, or have terminatons in the b direction resulting from cross faulting.

A concentration of wedge faulting occurs within the field area in certain lithologies exposed in the Juniata Culmination interval. Wedging is most abundant in exposures of the lower Reedsville formation, and seems to decrease in quantity and increase in size in both directions away from this horizon. The larger 'wedges' closely resemble small thrust slices within the Chazy through Trenton-aged carbonates. However, no wedge faulting was observed in the underlying Beekmantown lithologies.

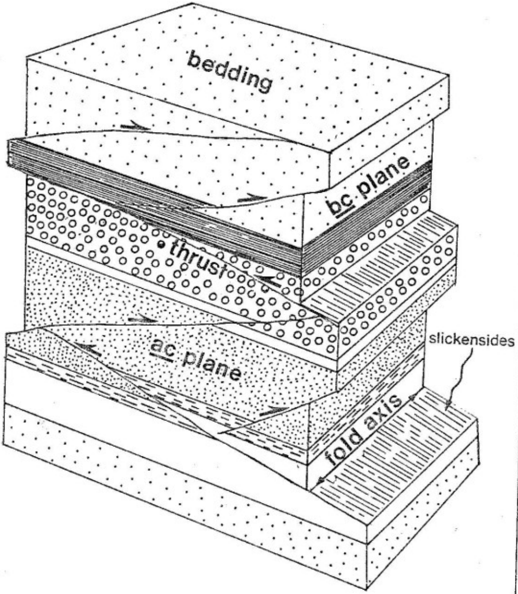


Figure 4. - Diagram showing wedge faulting and the structural coordinate system

Modified from Cloos and Broedel (1943, p. 1381). The inward movement of wedges has contracted and heightened the block.

The high-angle conjugate faults (Figure 3 - faults set 3) are documented by Faill, et.al. (1973). The conjugate faults occur at the outcrop scale and are sometimes associated with small order kink-band folding. Displacements associated with these faults are on the order of a few feet. The deformation effect of these faults is to either lengthen or shorten bedded sequences, depending on their orientations with respect to the enveloping bedding and their direction of slip.

Where associated with kink-band folding, both faults either correspond to kink-band axial surfaces, or one fault corresponds to an axial surface while the other develops in a region which suggests the replacement of an axial surface (Faill, et.al., 1973 - Figures III-B, pg.81 and III-D, pg.85). The conjugate faults are considered to form contemporaneous with and after the developement of the affected kink-band folds, but mostly at a late stage in the folding when the dip of the enveloping bedding was too steep, at too large an angle to the deforming stress for continued kink-folding (Faill, et.al., 1973 - Figure III-F, pg.87).

The last type of fault in this study is the subsurface, low-angle thrust fault. These faults do not crop out within the field area. The faults appearing on Plate 1 within the Juniata Culmination are better explained as high-angle reverse faults which have splayed off the major thrust faults at depth. This relation will become more clear in later sections of this study.

The evidence for the subsurface, low-angle thrust faults are three fold. First, studies of the thrusting mechanics in adjacent, emergent-thrusted terraine provides adequate proof that the low-angle thrust fault is the dominant displacement mechanism of thin-skinned deformation belts. Gwinn (1964, 1970) proved the thin-skinned deformation style within the Pennsylvania Valley and Ridge province with the use of proprietary seismic sections. Second, drill cores give evidence of large displacements which occur in a directon sub-parallel to bedding (Moebs and Hoy 1959, Gwinn 1970). Finally, Pierce and Armstrong (1966) document the existence of a folded, major bedding-plane fault within the lower Reedsville formation.

5.4 Penetrative Strain

Penetrative strain mechanisms indicate those strain mechanisms occuring at the grain scale. Penetrative strains reported for the region of study are a result of vertical compaction associated with sediment loading and tectonic compaction. Penetrative strain mechanisms include cleavage developement, fold crenulations, and various manifestations of a 'bulk penetrative flow' that affected the majority of rocks (Faill et.al., 1973). This part of the study is primarily concerned with the tectonic penetrative strains resulting in layer-parallel shortening fabrics. The term LPS fabric will refer to the assembledge of structures produced during the process of penetrative layer-parallel shortening (Geiser and Engelder 1983). LPS fabrics include cleavages, fold crenulations, and the bulk flow resulting from tectonic compaction. Other layer-parallel shortening mechanisms (non-penetrative) include intralayer contraction faulting (wedging) and folding. The penetrative strain from vertical compaction (loading strain) is not considered LPS strain. The effects of loading strains on the cross section interpretation are discussed towards the end of this study.

Cleavage developement includes two variations of a spaced solution cleavage; penciling or 'fracture cleavage' (Faill et.al. 1973, Geiser 1970, 1974, Engelder and Geiser 1979), and stylolitic solution cleavage (Geiser 1970, 1974, Faill, et.al. 1973). Penciling is characterized by the developement of microlithons or 'pencils' from millimeters to centimeters wide which are bounded by dark clay-carbon partings. Within the 'pencils' clay minerals retain their original sedimentary orientation parallel to bedding, but clay minerals and mica fragments in the clay-carbon partings are tectonically oriented parallel to the partings (Geiser 1974, Faill, et.al 1973). Penciling is best developed in argillaceous mudstone and sandstone and occurs in all parts of folds, although it is particularly well developed in or near hinge regions (Faill, et.al. 1973).

Stylolitic solution cleavage (solution selvages or seams) sometimes occur within the carbonate lithologies. This cleavage develops as a result of pressure dissolution, and results in the concentration of insoluable residues along stylolitic seams. In outcrop, stylolitic solution cleavage is spaced from millimeters to centimeters apart. All cleavages are reported by Faill et.al. (1973) and Geiser (1974) as seeming to be more generally developed to the southeast.

Fold crenulations occur in some argillaceous rocks of the Rose Hill formation in the Juniata Culmination. They appear in outcrop as subtle lineations with a spacing of fractions of millimeters. Geiser and Engelder (1983) suggest that fold crenulations seem to be soley the product of microbuckles without any associated pressure solution. Their sparse occurence within the study area may be a result of only local developement, and their contribution to LPS strain is uncertain.

Volume loss of up to 26% normal to cleavage has been estimated within the Valley and Ridge province from measuring deformed fossils (Nickelsen, 1972). This is not representative of the whole rock though, because cleavage zones alternate with zones of no recognizable shortening. Wright and Platt (1982) give evidence for as much as 50% volume loss shortening normal to cleavage in the Martinsburg formation in the bordering Great Valley. Nickelsen (1963) suggests that cleavage developement either preceeds or forms at an early stage of folding because most of the cleavage frequently displays sub-normal orientations with respect to bedding and a fanned distributions about axial surfaces of folds.

A 'bulk penetrative flow' also affected rocks throughout the province and the bordering Appalachian Plateau (Faill, et.al. 1973). Strain estimates resulting from this process are reported by workers employing varying strain measure techniques. By studying deformed bivalves just past the Allegheny front in central Pennsylvania, Nickelsen (1966) reports a LPS penetrative strain of up to 10% and an extensional strain parallel to b of 4.4%. He ascribes this phase of deformation to the first episode of lateral tectonism during which the rocks underwent a 'lateral compaction' before major folding.

Groshong (1975) calculated intragranular LPS strain in the hinge and limbs of minor folds to be up to -3.33 + 0.44% from calcite mechanical twinning measurements. He also concluded that pressure solution mechanisms probably account for more of the total strain than the intragranular mechanisms. Engelder (1979) reports similar strain results for the New York Appalachian Plateau: intragranular penetrative strain by mechanical twinning of calcite accounts for 1 to 5% layer-parallel shortening strain, whereas the developement of pressure solution cleavage planes accounts for 4 to 18% LPS strain.

Deformed strain markers such as mudcracks, reduction spots and fossil parts give additional penetrative strain estimates. Faill et.al. (1973) report length to width ratios of 2:1 for preferentially elongated (parallel to the fold axes) mudcrack polygons from the Wills Creek and Keyser formations within the vicinity of the study area. This ratio however reflects some pressure dissolution at the polygon edges and thus may represent a cumulative distortion.

Faill (1977) reports a mean LPS strain in the bedding plane using deformed crinoid columnals between 1.7 to 20.2% with standard deviations ranging from 1.5 to 5.5%. Slaughter (1982) reports up to 18% LPS strain from measuring deformed crinoid columnals for the New York Plateau.

Overall, Faill et.al.(1973) suggests that bulk penetrative flow is a cumulative result of three distinct processes, all contributing to the penetrative finite strain ellipsoid. The first is compaction perpendicular to bedding. The second is cleavage developement directed parallel to the fold axes in argillaceous layers simultaneous with penetrative flow in the sandier layers. Lastly, an outward radial extension occurs parallel to the fold axes resulting from divergent movement of the Paleozoic rocks on deep decollements.

6. SUMMARY

The Valley and Ridge province of the Pennsylvania salient is different from adjoining salients due to the lack of major outcropping thrust faults. It is therefore best represented as a blind-thrusted foreland fold-thrust belt.

The first historical efforts towards the understanding of the Pennsylvania Valley and Ridge structures were initiated by the Pennsylvania Geologic Survey in the mid 1800's. Since then, numerous studies within the region have provided a rigorous account of the stratigraphy and many of the structural and mechanical relations for the folded and faulted rock sequence.

The stratigraphy pertaining to this study ranges in time from the lower Cambrian to the upper Devonian. Included within this sequence are two major orogenic cycles of sedimentary deposition; the Taconic and Alleghenian cycles. Within each cycle, a carbonate bank environment is succeeded by first, a flysch turbidite phase, and then the mollase wedge.

The folds within the Valley and Ridge province consist of elongate, doubly plunging anticlinoria and synclinoria, with component folds ranging in size down to the microscopic level. The large scale folding pattern reflects underlying thin-skinned deformation processes. Fold geometry is predominantely non-cylindrical kink-band form and results from a combination of flexural-slip and flexural-flow folding mechanisms.

The larger faults evidenced at the surface within the field area are high-angle reverse and cross faults. Subordinate faults include wedge (contraction) faults and conjugate faults. The low-angle reverse thrust fault is the predominant fault mechanism existing in the subsurface, and provided the means by which a Paleozoic rock sequence was transported to the northwest during the Alleghenian Orogeny.

Besides the deformation mechanisms of faulting and folding, LPS strain mechanisms have also been documented within the study area. These include cleavage and fold crenulations, and a bulk penetrative flow resulting from tectonic compaction.

Strain markers used to determine the magnitude of layer-parallel shortening penetrative strains include deformed fossil parts, mechanical twins of calcite, deformed mudcrack polygons, and deformed reduction spots. LPS penetrative strain estimates for the Central Appalachians range from as high as 50% for the bordering Great Valley province to 10% in the Appalachian Plateau province. Pressure solution mechanisms probably account for a larger percentage of the net LPS strains than does the intragranular, bulk penetrative flow.

PART II

PETROGRAPHIC STUDY OF THE COVER LAYER

7. INTRODUCTION

Within the 'blind-thrust' terraine of the Valley and Ridge province of Pennsylvania, the character of deformation differs between the cover layer and stiff layer. The cover layer is the stratigraphic interval above an upper detatchment, and the stiff layer is the stratigraphic interval below the cover layer and above the decollement (Figure 5). The stiff layer is comprised of competent rocks which deform by fracture-thrusting (Geiser, 1984) and experience negligible LPS penetrative strains. In contrast, the less competent cover layer displays a significant tectonic component of LPS penetrative strain combined with internal faulting and folding.

Tectonic penetrative strains have been previously documented for both this and surrounding regions by many workers (Part 1, section 5.4). Invariably, tectonic penetrative strains have the maximum shortening strains in the plane of bedding and normal to the regional fold axis, the maximum extensional strains normal to bedding, and the intermediate strains parallel to the fold axes. Reported strain magnitudes vary depending upon the type of strain marker used, the structural position of the recorded strain, and the type of strain mechanism.

If the cover layer is preferentially shortened by penetrative strain in comparison to the stiff layer, then a length disparity between the cover layer and the stiff layer should result from length balancing a current section interpretation. In order to restore the cover layer to it's original length, an inverse LPS penetrative strain value would need to be applied. However, because no complete LPS penetrative strain data set currently exists for determining the integrated strain in the cover layer, corrective strain values may only be suggested for use in balancing methods.

In order to apply an inverse strain value to the cover layer, shortening should be uniform throughout a vertical section, that is, all of the lithologies should have been subject to the LPS penetrative processes. LPS penetrative strain is visible in the majority of the cover layer lithologies at the hand specimen scale. Solution cleavage selvages and distorted fossils reveal pressure dissolution and ductile flow in the carbonates, and penciling and fold crenulations are developed in argillaceous horizons. However, thick quartzite units lack any visible LPS strain fabrics. Therefore, in order to substantiate the pervasive nature of the LPS penetrative strains within the cover layer, the strain within the quartzites must be verified at the microscopic scale.

This section reports the results of a petrographic study designed to assess some different aspects of the LPS penetrative strain occuring within the cover layer. The strain mechanisms are not discussed in detail, nor is the distribution of the strain in all different lithologies determined. Instead, the study is limited to select stratigraphic horizons which either provide an estimate of the magnitude of strain or which prove the existence of the pervasive penetrative processes where elusive at the hand specimen scale.

The Reedsville, Onondaga, and Tuscarora formations are the most thoroughly examined. The upper Reedsville contains abundant disarticulated crinoid columnals which are used as strain markers. The Tuscarora quartzites and Onondaga limestones are intended to provide evidence for the LPS penetrative processes operating at the microscopic scale. Limited samples from the Cambro-Ordovician carbonates are used to evaluate the degree of penetrative strain within the stiff layer.

8. PROCEDURE

Fifteen oriented field specimens were collected along the transect. Their locations are recorded on Plates 1 & 9. The respective ages and the formations from which the specimens were collected follow:

5 - Lower Silurian Tuscarora formation (St)

4 - Middle Devonian Onondaga formation (Doo)

2 - Upper Ordovician Reedsville formation (Or)

1 - Lower Devonian Lock Haven formation (Dlh)

1 - Lower Ordovician Bellefonte formation (Obf)

1 - Lower Ordovician Stonehedge formation (Osl)

1 - Upper Cambrian Gatesburg formation (Cgl)

Oriented thin sections for the ac and bedding-planes were prepared for all of the specimens. However, the Reedsville and Onondaga samples also have thin sections for the bc -plane.

Due to the occurence of variously oriented crinoid columnals within concentrated horizons of the Reedsville specimens, an attempt was made to determine the three dimensional tectonic strain ellipsoid from the three orthogonal sections. Properly oriented crinoid columnals were included in each thin section so that an estimate of the strain could be recorded from measuring their elliptical axes. Properly oriented columnals are those having their cylindrical axis normal to the plane of thin section. They therefore display mirror symmetry about the elliptical axes. Properly oriented columnals were established by eye while viewing the thin sections with the microscope. Many properly oriented columnals were found in the bedding plane thin sections, fewer in the ac -plane thin sections, and very few were found in the bc -plane thin sections.

The strain estimates were derived by measuring the major (b) and minor (a) elliptical axes of the columnals in thin section with the graduated cross hairs of the microscope occular lens. Axial lengths were measured to .1 mm..

9. REEDSVILLE SAMPLES

The Reedsville specimens are fine to medium-grained calcareous siltstone having abundant fossil parts periodically concentrated in thin-bedded horizons. Spaced cleavage selvages occur in outcrop from 4-8 cm. apart and strike parallel to the local fold axes.

In thin section, dissolution of fossil parts preferentially occured normal to both the transport direction (in the bc -plane) and bedding. Dissolution is evidenced by the impingement of angular quartz grains into the fossil parts or by two or more interpenetrating fossil parts mutually impinging. Dark insoluable residues concentrate along dissolution boundaries and appear as serrate microselvages (Plates 2 & 3). Spaced microselvages also occur in portions of the matrix lacking fossil parts. They are typically branching (Plate 8) or anastomosing and have spacings of a few centimeters with variable concentration densities.

Abundant calcite mechanical twins are present in all three mutually orthogonal thin sections, but the quartz grains appeared unstrained. The calcite twins occur in fossil parts and in local patches of calcite cement, and have variable orientations and thicknesses. Some calcite displays more than one twin set, yet not all of the calcite is twinned.

Extension microjoints occur in some bedding plane and bc -plane thin sections with trends normal to tectonic strike. The microjoints either occur as single planes or as conjugate sets. The conjugate sets are oriented with the acute dihedral bisector sub-normal to tectonic strike.

Only the LPS penetrative strain for the bedding plane was successfully determined from the columnals. Non-tectonic loading strains for the ac and bc -planes distorted the original shape of the columnals such that tectonic strains for these principle directions could not be determined. For the bedding-plane, the minor elliptical axis of the columnals and tabular quartz grains within the selvages are tectonically aligned parallel to structural strike (Plate 2). Distortion of the crinoid columnals appears to be primarily a result of edge dissolution effects, because very little mechanical twinning is observed, and because septa interangles within the columnals appear to remain constant where observed.

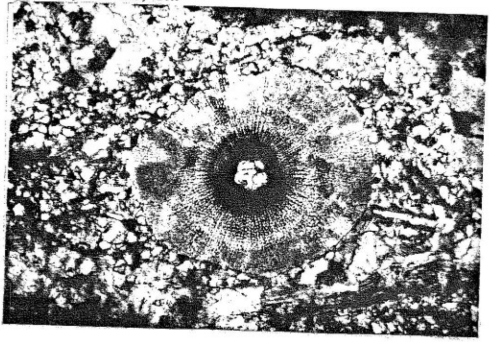
Suggested LPS penetrative strain values resulting from pressure dissolution for the bedding plane are derived from measuring 25 columnals from locations Or 1-1 and Or 5-9 (Table 3). The columnal axial ratios (b : a) are equated to LPS strain values. The ratios range from 1.02 to 1.23 ± .03. The range of error results from rounding-off axial lengths, and from measuring columnals with cylindrical axes which are not quite perpendicular to the plane of measurement (refer to Table 3). The mean ratio value is 1.08 and the mode is 1.05. The LPS strain estimates derived from using crinoid data may not represent the bulk rock strain because dissolution zones alternate with zones of no recognizable shortening. The strain estimates therefore may represent a lower limit of shortening strain.

Plate 2

Distortion of crinoid disks in the bedding plane for Reedsville specimens Or 1-1 and 5-9. Distortion occurs from edge dissolution effects in a direction normal to strike (a). Fine sand-sized quartz grains impinge upon the disks resulting in serrate micro-selvages along dissolution boundaries. Tabular quartz grains display alignment within the selvages parallel to strike. Calcite mechanical twins in Or 1-1 occur in the calcite surrounding the disk and display variable orientations. Or 5-9 displays extension microjoints.

Plate 2
bedding plane

Or 1-1, plane lt., 10X



a

strike (b)

1 mm.

Or 5-9, plane lt., 10X

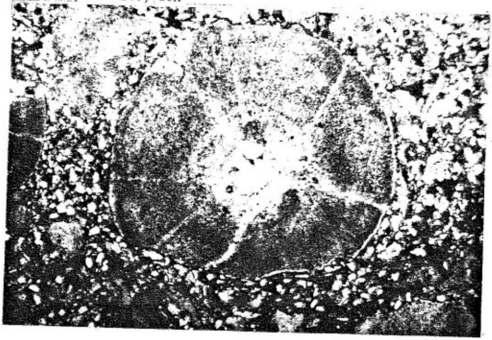


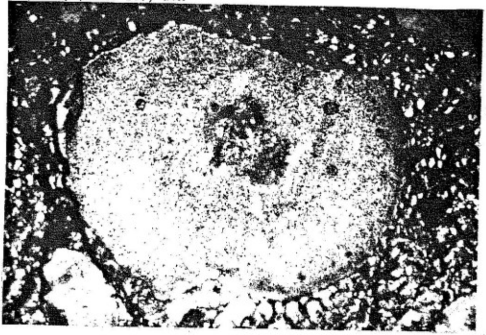
Plate 3

Distortion of crinoid disks in the ac-plane for Reedsville specimens Or 1-1 and 5-9. Dissolution occurs parallel to bedding (normal to c) and in the complimentary (a) direction. Increased dissolution occurs in the a direction. Tabular quartz grains display alignment in both sets of microselvages with the long axes of the grains normal to the direction of dissolution. Serrate microselvages display quartz grain impingement.

Plate 3

ac-plane

Or 1-1, plane lt., 10X



a

c

1 mm.

Or 5-9, plane lt., 10X

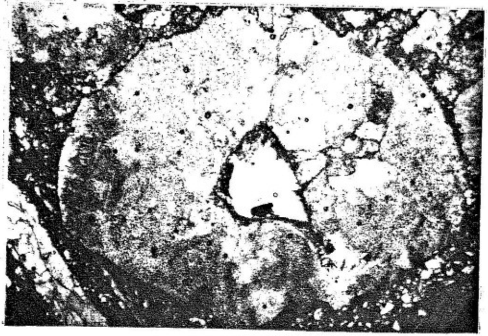


TABLE 3

Crinoid columnal measurements

Sample	Axial ratios (b:a)	Sample	Axial ratios (b:a)
Or 5-9	9.5:9.1 - 1.04	Or 1-1	9.0:8.6 - 1.05
"	8.7:8.0 - 1.09	"	8.2:7.7 - 1.06
"	9.6:9.1 - 1.05	"	7.3:7.0 - 1.04
"	9.8:9.3 - 1.05	"	7.3:6.1 - 1.20
Or 1-1a	9.5:9.1 - 1.04	"	8.8:8.5 - 1.04
"	10.0:9.5 - 1.05	"	9.0:8.8 - 1.02
"	9.0:8.5 - 1.06	"	10.1:9.5 - 1.06
"	11.8:9.8 - 1.20	"	6.5:5.9 - 1.10
"	10.2:9.7 - 1.05	"	6.8:6.6 - 1.03
"	9.0:7.7 - 1.17	"	7.5:6.4 - 1.17
"	7.6:7.3 - 1.04	"	6.0:5.5 - 1.09
"	16.0:13.0- 1.23	"	1.0:1.0 - 1.00
		"	8.7:8.3 - 1.05

range: 1.00 - 1.23
mean: 1.08
mode: 1.05

Note: the axial lengths are relative lengths from the graduated cross hairs of the occular lens.

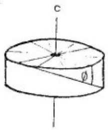
Error in measurement resulting from columnal inclination to plane of measurement:

Average columnal width: 0.7 mm.
Average columnal diameter: 2.8 mm.

Maximum error results at maximum inclination ($\emptyset$ = Cot .7/2.8 = 14.04°).

At 14.04° inclination, the apparent diameter = 2.8/Cos $\emptyset$ = 2.89.

An apparent diameter of 2.89 equals an apparent columnal axial ratio of 1.03 (2.89:2.80). The maximum error resulting from measuring an inclined columnal is thus taken to be .03.



10. TUSCARORA SAMPLES

Tuscarora quartzite composition ranges from pure, well sorted and well cemented orthoquartzite to impure, micaceous, clayey and/or hematitic, well-sorted but poorly cemented orthoquartzite. The only apparent penetrative strain within the quartzites is intragranular. No preferred alignment of tabular grains occurs in the impure specimens and no preferred intergrain relations are obvious.

The intragranular penetrative strains include Boehme, Tuttle, and normal deformation lamellae, deformation bands, subgrain boundaries, and undulatory extinction. All of these features are best developed in the pure, well-cemented quartzites and decrease in both quantity and intensity with an increase in the impurities, which is generally in a northwest direction (Plates 4,5, & 6).

For many quartz grains, the normal deformation lamellae continue from the grain into the surrounding silica cement. This suggests that tectonic deformation post-dated lithification. The normal lamellae viewed in the bedding plane display various orientations. However, the lamellae in the ac -plane display a consistent conjugate relation and orientation.

The conjugate relation displayed by the normal deformation lamallae arises from individual sets of the lamellae in single grains having a conjugate orientation with the lamellae of neighboring grains (Plates 5 & 6). Conjugate sets rarely occur within single grains. The conjugate sets are oriented with the acute dihedral angle-bisector parallel to bedding and normal to the local fold axes. This deformation pehenomenon may be related to LPS strain and merits further study.

Plate 4

Intragranular deformation fabrics in the Tuscarora quartzite specimens St 5-8 and 5-11 for the bedding plane. St 5-8 displays well developed deformation bands and sub-grain boundaries in the upper right quadrant. St 5-11 displays Boehme, Tuttle, and normal deformation lamallae. The normal lamallae are best developed in the upper right corner and the Boehme and Tuttle lamallae occur throughout. Both specimens display topotaxic grain overgrowths and dust rims.

Plate 4
bedding plane

St 5-8, x-nicols, 40X

0.1 mm

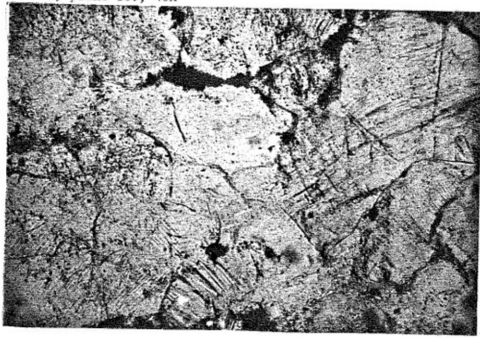
St 5-11, x-nicols, 40X

Plate 5

Intragranular deformation fabrics in the Tuscarora quartzite specimens St 5-8 and 4-3 for the ac-plane. Boehme and normal lamallae occur in both samples but are better developed within St 5-8. Continuation of the normal lamallae from the grains into topotaxic overgrowths testify to a post-lithification deformation. Normal lamallae developement in 5-8 displays a consistent conjugate relation with the acute dihedral angle-bisector parallel to a. Dust rims occur within both specimens.

Plate 5
ac-plane

St 5-8, plane lt., 40X



c
a

0.1 mm

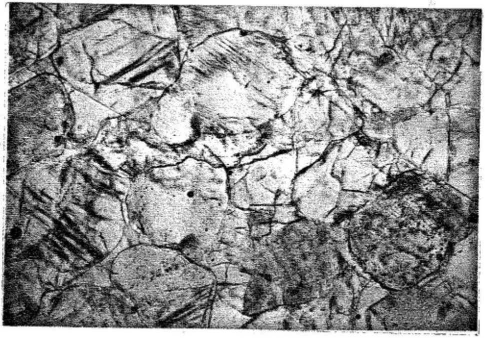
St 4-3, plane lt., 40X

Plate 6

Intragranular deformation fabrics in the Tuscarora quartzite specimen St 6-3 for the <u>ac</u>-plane. Boehme, Tuttle, and normal lamallae are developed. Normal lamallae are best developed and continue into topotaxic overgrowths. Normal lamallae display the consistent conjugate orientation as for the specimens in Plate 5. The normal lamallae developement between the specimens of Plates 5 and 6 display a northwest diminishing tendency with 6-3 the most and 4-3 the least developed. The topotaxic overgrowths and dust rims are best evidenced in the lower photomicrograph.

Plate 6
ac-plane

St 6-3, plane lt., 40X



c

a

0.1 mm

St 6-3, x-nicols, 40X

11. ONONDAGA SAMPLES

The Onondaga specimens are fossiliferous and/or pelletal marls with some containing minor silt-sized quartz grains and dolomite rhombs. Bedding-plane and bc -plane pressure solution stylolites diminish in quantity to the northwest and with a decrease in the abundance of fossil grains. Very few impingement textures were found. For the more pure marls, branching stylolites (Plate 8) occur at greater spaced intervals and appear thicker than the anastomosing variety associated with the fossiliferous specimens. A concentration of dark insolubles along the stylolites suggests that a greater degree of dissolution occurs along the spaced planes rather than a uniform, pervasive shortening distributed throughout the matrix.

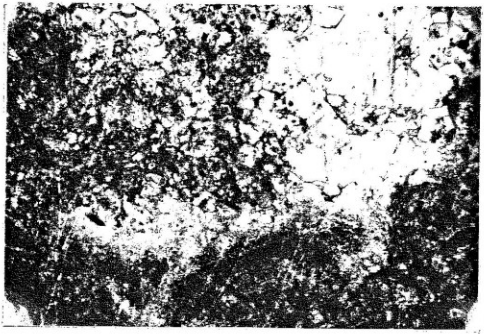
Abundant calcite mechanical twins occur within larger fossil grains and patches of calcite cement. The twins vary in both thickness and orientation. Extension microjoints also occur within a majority of the Onondaga samples. The microjoints are predominantly ac -plane, calcite-filled microjoints, or a conjugate microjoint set aligned with the acute dihedral angle-bisector subnormal to the local fold axes (Plate 7).

Plate 7

Deformation fabrics within the Onondaga specimens Doo 5-13 and 5-8 for the bedding plane. Calcite mechanical twins occur within patches of spar cement and display variable orientations. Extension microjoints have calcite filling and display a consistent orientation sub-normal to strike.

Plate 7
bedding plane

Doo 5-13, plane lt., 10X



a
b

1 mm

Doo 5-8, plane lt., 10X

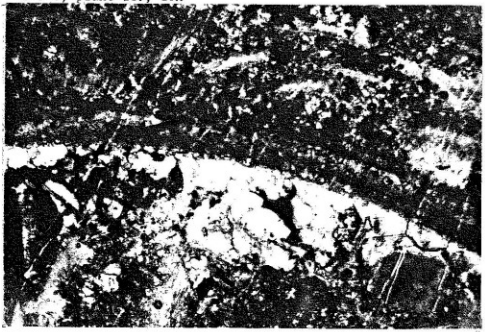
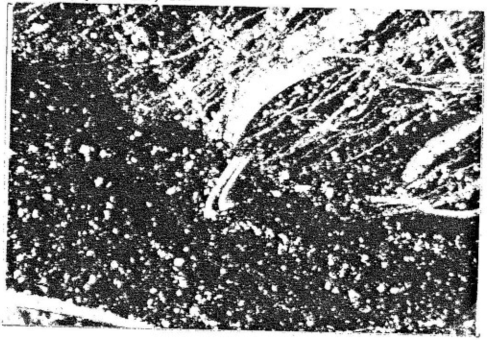


Plate 8

Deformation fabrics within the Onondaga specimens Doo 4-1 and 5-10 for the ac-plane. Specimen 4-1 displays pressure dissolution within the matrix without the formation of selvages or solution seams, and well developed extension microjoints which are calcite filled. Specimen 5-10 displays abundant calcite mechanical twins with variable orientations and a branching styolite resulting from pressure dissolution.

Plate 8
ac-plane

Doo 4-1, plane lt., 10X



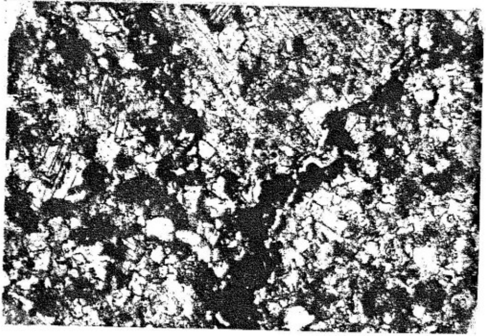
c

a

1 mm

0.1 mm

Doo 5-10, x-nicols, 40X



12. THREE SAMPLES OF THE CAMBRO-ORDOVICIAN CARBONATES

The remaining specimens studied are three carbonates from the Cambro-Ordovican stiff layer. All three specimens are fine to medium grained crystalline limestone and dolomite from the Nittany Anticlinorium region. Only the Stonehedge limestone sample displays any penetrative strain effects in thin section; deformation twins in calcite and dolomite crystals are rare and pressure dissolution fabrics are generally lacking.

13. DISCUSSION AND SUMMARY

The columnal axial ratios for the Reedsville specimens are in agreement with those reported by Faill (1977) for Central Pennsylvania. LPS penetrative strain within the Valley & Ridge province may be as high as 20% as suggested by crinoid data. Estimates of LPS penetrative strain from previous workers (see Part 1, section 5.4) range in value from 10% shortening at the Allegheny front to 50% in the bordering Great Valley province. However many of the strain measure techniques use strain markers which are non-passive and therefore may misrepresent the net rock distortion. Nevertheless, these estimates provide first approximation values for cover layer LPS penetrative strain.

LPS penetrative strain occurs throughout the cover layer but is generally lacking in the stiff layer exposed at the Nittany Anticlinorium. LPS fabrics include solution cleavage selvages and deformation glide twinning in the carbonates, and penciling and fold crenulations in siltstones and shales (section 5.4). Intragranular deformation in quartzites may represent LPS fabrics but remains unproven. Non-penetrative shortening strains such as contraction faulting and folding have also been reported within the cover layer (Part 1, sections 5.2 - 5.3). The interelation between the strain mechanisms is unclear. However, for section balancing, it is assumed that the cover layer deforms as a continuous unit with all of the LPS processes combining to produce necessary shortening.

PART III

CROSS SECTION INTERPRETATION

14. INTRODUCTION

Recent advances in establishing the dimensional and kinematic relations of thrust belts provide the tools for predicting the structure at depth. Concepts such as the three dimensional relations between faults, the geometric consequences of simple shear within deforming thrust sheets, styles of deformation, and 'retrodeformation' techniques combine to give cross section interpretations new standards of accuracy and precision.

The purpose of this part is to employ this combination of thrust belt relations in developing a re-interpretation of a portion of the Valley and Ridge province of Pennsylvania. The organization of this part consists of four sections. The first presents a summary of the section construction constraints. The second section presents the procedures used in developing the cross section interpretation and restoration. The third section presents the results of the interpretation and restoration procedures, and the fourth presents discussion on the problem areas of interpretation and compares the derived results to the cross section c-c' of the Pennsylvania Geologic Survey.

15. SECTION CONSTRUCTION CONSTRAINTS

The construction of a cross section represents a slice of physical reality as pointed out by Geiser (1984, class notes). A cross section interpretation relys upon a set of physical constraints for it's admissibility; if the interpretation retains physical compatibility, then the section is admissible with respect to those constraints. Cross sections which fail to uphold such constraints are considered inadmissible interpretations.

The physical constraints used in the developement of this cross cross section interpretation are geometric in form and stem from consistent structural relations involving the section boundary conditions and characteristic deformation responses in non-metamorphosed fold-and-thrust terraine. Three constraints stem from the section boundary conditions while an additional four are associated with characteristic deformation responses. A summary of the section construction constraints follows:

1. the basal decollement is within the upper Waynesboro formation
2. the foreland pinning point represents the position beyond which there has been no stiff layer thickening, and the hindward boundary corresponds to the Great Valley - Valley and Ridge province border
3. an upper detatchment exists at the stratigraphic horizon of the lower Reedsville formation
4. plane strain
5. the stiff layer deforms with a break-forward sequence by propagating fracture-thrusts
6. the fracture-thrusts result in fault-bend folding with kink-domain geometry
7. the fold map pattern in the cover layer is an indicator of the position and geometry of underlying thrust slices

15.1 Section boundary conditions

The section boundary conditions include the depth limit of deformation (sole thrust or decollement), the forward and hindward physical limits, and the location of the upper detatchment which separates the cover and stiff layers.

The depth limit of deformation is hypothetical for this interpretation but is derived from a series of closely agreeing physical relations which infer the stratigraphic location. These include data from a previous cross section interpretation, estimated seismic reflector depths, and depth values derived by stratigraphic complilation. The proposed position of the sole thrust is cross checked by cross section balancing and construction methods which are presented in later sections.

The upper Waynesboro formation is considered to be the sole thrust due to it's stratigraphic position and it's shale rich composition (Gwinn 1964, Swartz 1973). Depths to the sole thrust taken from cross section c-c' of the Pennsylvania Geologic Survey are used for this interpretation and closely agree with depth estimates from other sources. The depth values and reference locations from section c-c' are respectively given in Table 2 and Figure 2. The estimated depths of sub-horizontal seismic reflectors in the Juniata Culmination (see Part 1, Section 3) closely agree with the depth of the sole thrust resulting from interpolation between the reference locations of section c-c'. Also, the depth to the upper Waynesboro formation from compiling stratigraphic thicknesses at the Allegheny front (see Table 2 - Butts and Moore 1936, and Swartz 1973) closely agrees with the interpolated depth to the sole thrust. The sole thrust also displays a gradual southeast dip in support of Gwinn's (1970) hypothesis of an inclined basement.

The foreland limit for this interpretation is designated the foreland pinning point, and is located just beyond the sole thrust ramp from a mid-Cambrian shale across the Cambro-Ordovician carbonates into glide zones in the Upper Ordovician or Upper Silurian beneath the Plateau (Gwinn, 1964). The foreland pinning point is assumed to correspond to a foreland position of original stratigraphic thickness. All section construction and restoration methods will begin at the foreland pinning point. The hindward section boundary corrsponds to the Great Valley - Valley and Ridge province border.

The upper detatchment (roof thrust) corresponds to a thick shale member of the lower Reedsville formation. This position is suggested by the highly contorted strata observed in outcrop. Also, the lack of noticeable LPS penetrative strain in lithologies beneath the shale as opposed to an abundance in the overlying lithologies (see Part 2, Sections 9-12) suggests a deformation discontinuity at this horizon. In addition, a significant bedding-plane thrust is reported in the Reedsville formation directly to the southwest (Pierce and Armstrong, 1966). All of these factors warrant the use of this upper boundary constraint for section construction.

15.2 Characteristic deformation responses

Plane strain is a condition which limits tectonic strain to the plane of the section. From strain analyses in varied portions of the Central Appalachians, Engelder (1979), Nickelsen and Gross (1959), and Cloos (1947) conclude that major distortion is restricted to the ac -plane, and that strain parallel to b (the fold axis) is generally small in comparison. The effects on cross section accuracy from assuming plane strain and neglecting small extensional strains parallel to the fold axis follow in the discussion section.

Another characteristic deformation response includes a break-forward sequence of developement for the fracture-thrusted stiff layer. Perry (1978) and Boyer & Elliot (1982) use field relations and measured graphical experiments to substantiate the dominant break-forward tendency of developing thrust systems. The designation of a fracture-thrusted stiff layer encompasses many geometric constraints.

Geiser (1984) suggests that the fracture-thrusting process involves thrusts which propagate by breaking layers rather than by the geometric consequences of folding or LPS. The thrust sheet then slips on fractures, with fault-bend folding (Suppe, 1983) and internal strain the consequences of this motion. Where thrust faulting is evidenced within portions of exposed stiff layer (Beekmantown through Trenton carbonates) a fracture-thrusting style is observed.

The principles of fault-bend folding were developed by Suppe (1983) to geometrically and kinematically explore the two-dimensional consequences of folding due to slip of a bed sequence past a series of sharp bends in a fault. The critical elements incorporated here include Suppe's primary geometric assumptions of sharp fault bends, constant bedding thickness during folding, and conservation of area. General affine shear within a fault block unrelated to riding over fault bends is excluded under ~~this~~ the general two-dimensional theory. It follows that deformation is by slip parallel to bedding and that bed length is preserved during deformation. By these assumptions, the axial surface bisects the angle between fold limbs (Suppe, op.cit. - Figure 6). This angular relation produces what has been termed kink-domain geometry by Geiser (1984, class notes).

insert →

More complex fault-bend folding geometries occur when the constraint that requires the beds to only undergo shear as they pass through a fault-bend fold is relaxed. For a more thorough discussion see Suppe, 1983.

Two general circumstances are treated under the shearing of fault-bend folds:

1) shearing out of flat fold crests (hinge annihilation)
2) General layer-parallel shear in parallel fault-bend folding

Suppe (1983) points out that many actual fault-bend folds closely approximate the previous general assumptions. In instances where bedding is thickened tectonically, kink-domain geometry does not hold, however this condition is the exception. Therefore, the use of kink-domain geometry in section construction provides a standard against which the structure can be quantitatively compared.

The final characteristic deformation response is that the cover layer fold pattern reflects the position and geometry of underlying thrust slices. This stems from work by Dahlstrom (1979), Boyer and Elliot (1982), Hossack (1984), and Diegel (1984) concerning the geometric elements related to thrust systems. By using physical examples, these workers have illustrated the geometry of thrust faults and their relations to map patterns and three dimensional fault arrays.

For this blind-thrust terraine, such linear elements as branch and tip lines of exposed thrust faults (Boyer and Elliot, 1982) are unavailable for positioning major thrust slices. The branch and tip lines on the geologic map (Plate 1) are probably related to secondary splay faults originating from the primary thrust faults at depth as suggested by thier small displacements and stratigraphic position. The techniques of positioning thrust slices and discerning their general geometric form are thus limited to using the map fold pattern.

First or second order doubly-plunging anticlines on the map are assumed to correspond with the hinge regions of underlying thrust slices (Figure 5). Also, the folds lateral extent and position with respect to the transect line determines the structural relief and size of the underlying slice. For instance, if the transect line intersects an anticline along it's lateral margin, then the slice would possess a lower structural relief in comparison to the same fold if intersected towards the folds culmination (Figure 5). Also, anticlines with the largest lateral extent are considered to correspond with the largest thrust slices, and smaller antiforms correspond to smaller slices.

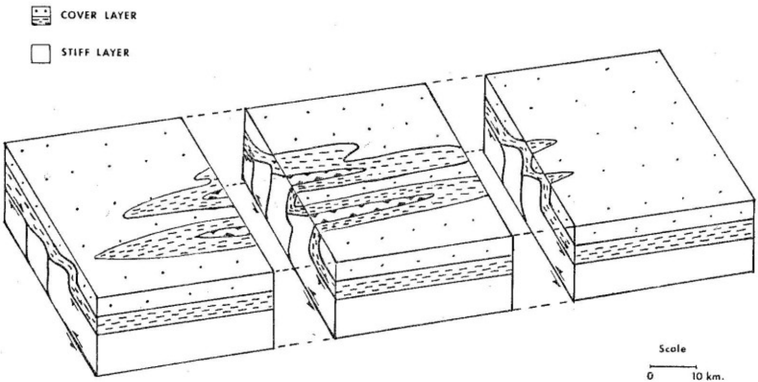


Figure 5 : Block diagram illustrating the assumed relation between thrust faulting and the fold map pattern

16. CONSTRUCTION PROCEDURES

Three procedures were used in the construction of the cross section interpretation. They include the collection of the data base, the application of the data base for section construction, and the section balancing and restoration procedures for checking the results.

16.1 Data base

The data base consists of the stratigraphic column and the structural features at the surface which are used to develop the cross section 'profile'. The structural features are bedding attitudes, and the locations and attitudes of cleavages, faults, and fold axial traces. The section profile is the framework within which the stiff layer's internal struture is developed.

16.1.1 Stratigraphic column

Individual formations are grouped into lithotectonic units of similar mechanical response based on Pohn and Purdys'(1983) scale of competency. The scale of competency is based on the number of 'disturbed zones' found within each lithic interval (Pohn and Purdy, op.cit - Table I). Their evaluation is skewed in favor of units that are well exposed in the area. The unit grouping is intended to aid in the developement of the section by providing lithic units which deform in a characteristic manner under given structural conditions; for example, incompetent lithic groups characteristically conform to the folding geometry resulting from competent layer folding.

Formation thickness values are combined into group thickness values as shown in Table 2. Combined group thickness values for the stiff layer in the current, or contracted state, result in a 'contracted wedge' (Figure 6). The 'contracted wedge' is a reference for approximating thickness values for the major stiff layer thrust slices. It is assumed that the thickness of the 'contracted wedge' for a particular position along the section closely approximates the actual thickness of the thrust slice occupying that interval. This technique is used only for initial approximations. Additional section construction and restoration procedures determine more accurate thrust slice thickness values at later stages of section developement.

The 'contracted wedge' is derived by interpolating between stiff layer thickness values at each end of the section in the current form. The foreland thickness reference corresponds to location 13 on Figure 2 and the thickness values are from Swartz (1973) and Butts and Moore (1936). The hinterland reference corresponds to the southeast limit of the transect on Figure 2 and the thickness values are from Miller (1961), Swartz (1973) and the Pennsylvania Geologic Survey cross section c-c'.

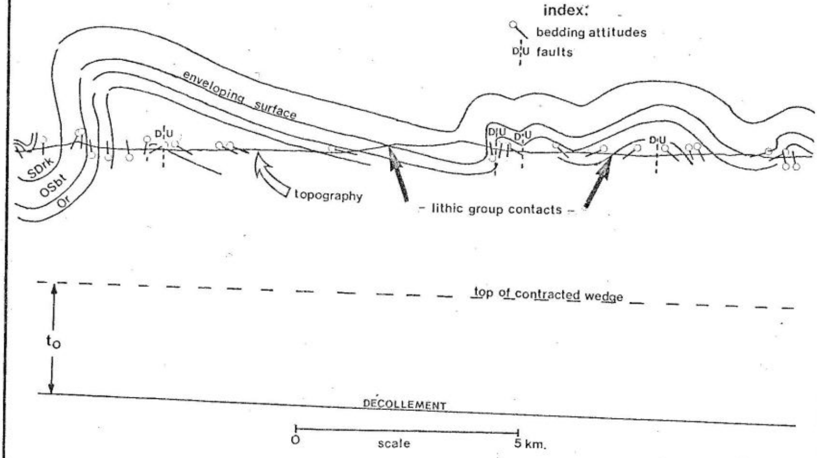


Figure 6 - Developement of the enveloping surface
Surface bedding attitudes, location of faults, topography, and lithic group contacts and thicknesses contribute to the developement of the enveloping surface configuration.

16.1.2 Section profile

The section profile consists of the cross section's physical boundaries, the topographic surface, and the top of the 'contracted wedge'. For preparing the section profile, 550 bedding attitudes were collected within an area of 1-1/2 kilometers on either side of the transect line. Of this total, 478 were compiled from previous works by Dyson (1967), Miller (1961), Conlin and Hoskins (1962), Gough (1977), Krohn (1976), Meiser (1971), Rones (unpublished map), Lane (1956), Thamm (1956), and Dobelbower (1953). The remaining 78 result from field reconnaisance in those areas lacking data from the previous workers.

From these data, 175 surface bedding attitudes were projected onto the transect line along it's length. In addition, the positions of 25 high-angle normal and reverse faults, 7 disturbed zones, and 24 second and third order fold axial traces were recorded along the transect. The recorded faults had displacements greater than ten feet. Cleavage data were not incorporated into the section profile due to the abundant distribution along the transect.

The foreward and hindward limits and the topographic surface were established from 7-1/2'quadrangles. The position of the sole thrust and roof thrust were determined as in section 15.1. The roof thrust is the enveloping surface for the stiff layer. The enveloping surface is established by the location of lithic group contacts from geologic maps and the collected surface features (Figure 6). The deformed cover layer is thus constructed for establishing the configuration of the enveloping surface.

16.2 Interpretation procedures

The cross section interpretation was developed on a computer aided drafting system (CAD) provided by Geo-Logic Systems, Inc.. A primary function of the CAD is to accurately generate the kink-domain geometry of faulted and folded rocks. Kink-domain geometry best describes fold forms in low grade and non-metamorphosed terraine (see Section 15.1.2). This CAD feature provides a speedy comparison of the proposed solutions for different thrust slice arrangements. In addition, the CAD was used for area-balancing the section and printing the resulting interpretations.

16.2.1 Procedure

The interpretation of the section began by digitizing the section profile. Figure 7 is a printout of the section profile. The internal structure of the profile was developed on the CAD terminal. The internal developement began by first positioning the outcropping thrust slices within the profile. These initial slices have known bedding attitudes and formation contacts and are considered well constrained. The only outcropping thrust slices occur within the Juniata Culmination.

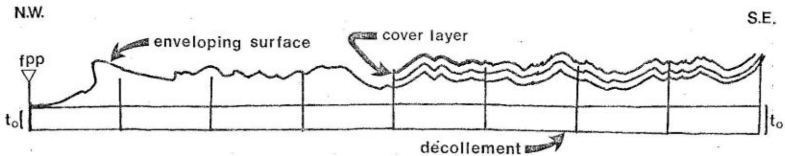


Figure 7. - Cross section profile

Printout from CAD system showing the cross section profile in the developemental stage. The complete enveloping surface is shown along with the lower, forward, and hindward section boundaries. An incomplete cover layer is developed for the southeast half, and the vertical lines within the profile correspond to the topographic surface level.

The initial slices were positioned by determining the attitude of the reference surface corresponding to the top of each stiff-layer slice. The top of the stiff-layer was assumed to be approximately parallel to and from 1000-4000' feet away from the enveloping surface (Figure 6). For these initial slices, the outcropping bedding attitudes helped constrain the position of the reference surfaces.

Kink-domain geometry was then generated from each reference surface downward for a distance equal to the stratigraphic thickness of the stiff-layer. The stratigraphic thicknesses were initially referenced from the 'contracted wedge' thicknesses on the section profile. Surfaces corresponding to the boundaries of the lithostratigraphic groups and to the bottom of each thrust slice were then generated at the appropriate stratigraphic level in each slice and saved in the CAD file. The bottom of the thrust slices are used to develop adjacent slices. Figure 8 is an example which shows how the section profile would appear at this stage of partial developement.

Having exhausted the well-constrained internal geometry, the rest of the section interpretation relied upon the configuration of the inital slices, the cover layer fold pattern, kink-domain geometry, and a fracture restoration diagram (see description page 49) for positioning the remaining thrust slices.

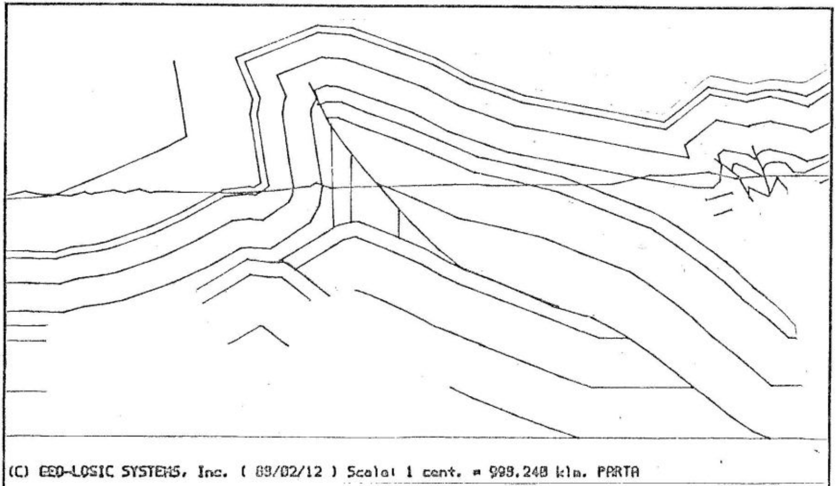


Figure 8. - Developement of the stiff layer
The configuration of the outcropping stiff layer slices and the cover layer combine to help position other thrust slices. Refer to text for further explanation.

The configuration of the initial slices provided surfaces from which the geometry for adjacent slices were referenced. The hinge regions of the remaining thrust slices were also positioned to correspond with the axial traces of first and second order anticlinoria. The kink-domain geometry was used to determine the bedding attitudes within each slice in the same manner as for the initial slices, except that the location of the reference surfaces were derived only by the configuration of the enveloping surface. The fracture restoration diagram aided in establishing footwall cutoffs for each slice.

Starting at the foreland pinning point, the configuration of the remaining thrust slices were thus first determined by positioning the hinge region for each slice. The backlimb region was then established by the geometry of the adjacent slice towards the foreland and/or the attitude of the enveloping surface. The forelimb attitude of each slice was then assumed to be approximately parallel to the overlying enveloping surface (Figure 8). The configuration of the hanging wall cutoff is dependant on the configuration of the backlimb of the adjacent slice towards the foreland. Finally, the footwall cutoff position and configuration for each slice was dervived by a trial-and-error basis with the aid of a geometric relation specified by Boyer & Elliot (1982), and a fracture restoration diagram.

The geometric relation of Boyer & Elliot (1982) helps to estimate the current position of the footwall cutoffs for thrust slices. Because the perpendicular distance between subsidiary faults bounding a 'horse' approximates the initial stratigraphic thickness (to), the spacing between subsidiary faults (p'), measured parallel with the floor thrust, is:

$$p' = to/\sin B', \qquad (1)$$

where B' is the current angle between floor thrust and the central portion of subsiding faults (Figure 9).

The fracture restoration diagram is a technique for evaluating the admissibility of current footwall cutoffs based on their fracture trajectories within the initial sedimentary wedge. The construction assumes that primary fracturing of the wedge preceeds folding (fracture- thrusting) and that all primary fractures have a hinterland dipping geometry (Boyer & Elliot, 1982). The length and gradient of the initial sedimentary wedge is determined from area balancing the stiff-layer and from the lateral boundary thicknesses (to1 & to2).

Restored fracture trajectories are derived by reconnecting stratigraphic cutoffs for the hanging wall of a thrust slice with the cutoffs of the accompanying footwall. This is accomplished by measuring bed lengths between cutoffs in the deformed slice and laying them off at the same horizon

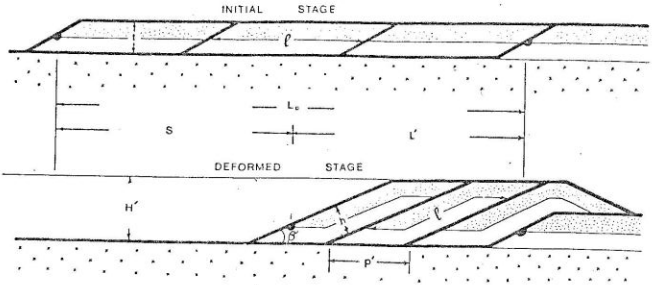


Figure 9. - Initial and deformed stages in formation of duplex

From Boyer and Elliot (1982, p. 1207). Quantities Lo, L', S, to, h, p', B' are used in equations 1 through 5.

on the initial sedimentary wedge. This process is started at the foreland pinning point and continued in the direction towards the hinterland for each slice. Admissible trajectory angles are considered to range from 20 to 40 in relation to the sole thrust.

The section interpretation was completed by adjusting the footwall cutoffs of each thrust slice to conform to admissible fracture trajectories. The fracture trajectories on the restoration diagram have an interdependant quality which necessitates restoring the the foreland slices first and working back in a systematic manner. This restoration procedure begins at the foreland pinnng point because the most external ramp is assumed to be undeformed and therefore acts as a 'pinning' surface.

Each slice is constructed and corrected in this way until the entire interpretation is complete. Alternate thrust slice arrangements are considered for complex areas where different configurations could result. The resulting interpretations are shown on Plate 9. The accompanying fracture restoration diagrams appears directly beneath the interpretation.

For constructing current and restored cross sections for duplex thrust systems, Boyer & Elliot (1982) suggest that a number of simple calculations be made. One such calculation has been previously mentioned for estimating the subsidiary fault spacing (equation 1). Some additional equations involving the complete length of the duplex are as follows:

Assuming plane strain, the cross section area (A) is:

$$A = H'L1 = toLo, \qquad (2)$$

where Lo is the restored duplex length, L1 is the current length, to is the original stiff layer thickness, and H' is the average current thickness of the duplex.

the overal shortening distance (S) is:

$$S = Lo - L1, \qquad (3)$$

and from equation 1:

$$S = A/to - L1, \qquad (4)$$

and finally, the contraction ratio equals:

$$L1/Lo, \qquad (5)$$

The values which result from applying equations 2 through 5 follow in in a later section.

16.3 Cross Section Balancing

The section balancing methods include area and bed-length balancing. The balancing methods assume that the bed lengths for the stiff layer and cover layer were initially equal in length, and were subsequently thickened and shortened by various tectonic processes resulting in the current configuration.

16.3.1 Area Balancing

Area balancing methods have been in use since originally proposed by Chamberlain (1911). Their initial purpose was for use in estimating the depth to the decollement underlying a deformed section. Bucher (1933) suggested that a more accurate estimate to the depth of decollement could be made if the calculation was carried out over the whole area of the section rather than in component segments.

Area balancing was applied to this section to establish the length of the initial sedimentary wedge (Lo), to check if the current and restored sections have equal area, and to verify the depth to the proposed sole-thrust derived from other sources. The length Lo is compared with bed-length balancing results and provides a reference for estimating tectonic strains. Bed lengths derived from the separate methods of area and bed-length balancing should agree.

Because of the plane strain assumption, the area of the deformed rock sequence equals that of the restored sequence minus any area (volume loss) processes, such as caused by pressure dissolution. Because the stiff-layer reflects negligible LPS penetrative strain, the area in the deformed state equals that for the restored state and thus provides a means for estimating Lo. Following Geiser's (1984, class notes) suggestion, the entire area of the stiff layer was calculated with the CAD from the section interpretation. The top of the stiff layer corresponds to the top of the Oct group (Plate 9). The results are given in section 17.0.

16.3.2 Bed-length balancing

According to Hossack (1979), the techniques of bed-length balancing originated in the Canadian Rocky forelands of Alberta and were formally documented by Dahlstrohm (1969). According to Dahlstrohm (op. cit.), if flexural-slip folding and area constant strain operates, bed length measurements around folds at different structural levels in the section must remain constant. Sinuous bed lengths should therefore balance across faults. If the bed lengths do not balance, there must be a convincing structural explanation.

The techniques for determining bed lengths for the stiff layer portion of the section have been described with the procedure for establishing restored fracture trajectories (see Section 16.2.1). The fracture restoration diagram is actually a by-product of determining bed lengths. By reconnecting cutoffs for adjacent slices on an initial sedimentary wedge, the stiff-layer bed lengths are progressively developed from the foreland pinning point backwards.

The cover layer bed lengths are determined from sinuous bed length measurements in the deformed state. The sinuous bed lengths are measured from the foreland pinning point to the most internal section boundary (Plate 9). The measured lengths are progressively layed off on the restoration diagram from the foreland boundary. The cover layer thickness values for the restored section are derived by interpolation using the thickness values of Butts and Moore (1936) and

Miller (1961) - refer to Figure 2 and Table 2. The resulting bed-lengths for both the cover layer and stiff layer are shown on the restoration diagram of Plate 9.

17. RESULTS

The section interpretations and restoration diagram are shown on Plate 9. The continuous section towards the top is the intial interpretation and the underlying isolated panel is an alternative interpretation for a portion of the Juniata Culmination. The fracture array with numbered solid lines corresponds to the initial interpretation and the lettered dashed lines the alternative respectively.

The arrangement of the stiff layer thrust slices forms a hinterland dipping duplex as described by Boyer & Elliot (1982), and the cover layer represents a continuous folded layer. Both stiff layer interpretations contain seventeen 'break forward' or primary horses not counting the first and last thrust slices appearing within the section. The first slice towards the foreland is shown as a developing horse; the splay fault has not yet terminated in the upper detatchment. The last thrust slice appears incomplete on the section and therefore is not considered. The section may change in structural character at the Great Valley boundary so the position and character of this slice is questionable.

Differences in the two interpretations result from the formation of different length horses in the Juniata Culmination interval as shown in the restored fracture diagram (Plate 9). The two interpretations also differ in the number of 'secondary' splay faults occuring within this interval. For the initial section, ten splay faults are proposed and are represented on both the current and restored sections as unnumbered, broken lines. In contrast, the alternative interpretation has nine proposed splay faults. Splay faults segment the primary thrust slices into smaller horses and typically display anamolous trajectories in the restored state when compared to the primary fracture trajectories (Plate 9). Anamolous trajectories result because the splay faults form after the primary thrust slice has been folded.

The results of applying equations 2 through 5 (page 51) on the section interpretation are as follows:

L1 - 98.28 km.

Lo - 180.39 km.

S - 82.11 km.

H' - 6.24 km.

to - 3.41 km.

L1/Lo - .540

A - 614.22 sq. km.

Resulting values for B' (subsidiary fault angles) for both interpretations average 38.6 and range between 25 - 50 . Primary fracture angles for both interpretations average 27.5 and range from 20 - 38 . The length of the horses in the restored state averages 9.36 kms. and the range is from 5.0 to 19.7 kms. The largest fracture angles and horse lengths occur within the Juniata Culmination (Plate 9). The reason for this tendency is unclear, however, there is a tendency for the horse length to be relatively proportional to the size of the associated folds in the cover layer.

18. DISCUSSION

Topics of discussion in this section include possible breakdowns in the section construction constraints and assumptions, and the comparison between the section interpretations and a portion of cross section c-c' of the Pennsylvania Geologic Survey (1980).

18.1 Modeling constraints and assumptions

Examples occur in the section interpretation where some of the imposed modeling constraints and assumptions seemingly breakdown. For instance, what are the effects on the interpretation from having assumed plane strain when evidence shows minor extension along the fold axes? Also, not all thrust slices are aligned with their hinge regions underlying first and second anticlinoria as assumed. In addition, the variation of thickness displayed by the Reedsville formation in the current state suggests that the roof thrust interval is more complex than originally assumed for construction purposes. Finally, an original assumption for section balancing methods was for the initial lengths of the cover and stiff layers to be equal, yet the restored cover layer is 71.77 km. shorter than the stiff layer. What processes operate on the cover layer to account for this length difference?

18.1.1 Plane strain assumption

Hossack (1979) gives a review of the use of balanced cross sections for calculation of orogenic contraction. Briefly, he states that in nature, the area of section may have decreased by 15-45% from the combined processes of lithification and tectonic compaction, so the assumption of plane strain leads to a minimum estimate of shortening. To simplify calculations, Hossack (op. cit.) assumes that both kinds of a area decreases have isotropic symmetry and that reductions in length are the same in all directions in the section.

To estimate the effect on the interpretations from neglecting strike elongation and tectonic compaction, it is assumed that the sections have experienced a 5% strike elonation and 10% tectonic compaction. The 5% elongation is an estimate which approximates reported elongation values for local portions of the Central Appalachians (Nickelsen 1966 - 4.4%, Cloos 1947 - 6.4%). The 10% tectonic compaction value stems from calculated density increases as mudstones are deformed to form slates (Wood, 1974). According to Hossack (1979, Figure 5), these values of elongation and compaction result in an approximate area reduction of 10% for the section interpretation. Accordingly, this area decrease for the section results in too short of estimate for both the current and restored lengths and thicknesses. However, the values of strike elongation and tectonic compaction probably represent upper limit values. It follows that a 10% area reduction is probably an upper limit value.

18.1.2 Cover layer fold pattern

Four horses are considered which do not conform to the assumption that first and second order anticlinoria correspond to the hinge region of underlying thrust slices. Two correspond to the those located under the first order synclinoria, and the remaining two correspond to the horses bounded on the left by stratigraphic cutoffs 7-9 and 25-27, respectively (Plate 9).

The occurence of the horses underlying the first order synclinoria is inconsistent with the concept of synclines as remaining fixed in depth during deformation (Cloos, 1940). However, these synclinoria require underlying thrust slices due to the greater than (to) thickness existing between the enveloping surface and the sole thrust. Variations in the thickness between the eveloping surface and the sole thrust could allow a (to) thickness to be maintained, but then the character of either or both the the sole thrust and cover layer would be altered. Such alterations could include an undulating decollement which arches under the synclinoria, or a thickened cover layer in these vicinities. However, existing data contradicts such alterations. The original configurations are retained because the nature of the folds on the map pattern shows that the synclinoria are as deformed as the anticlinoria.

A second point which supports the existence of thrust slices underlying the synclinoria is that other first order synclinoria, such as the Anthracite Depression (Nickelsen 1974), can be shown to correspond to the point of no structural relief. If it is assumed that statigraphic thicknesses are consistent between the depression and it's margins, then the deeper level of erosion displayed at the margin of the Anthracite Depression results from structural relief associated with thrust faulting at depth.

The two remaining horses which do not correspond with anticlinoria traces (to the left of cuttoffs 7-7 and 25-27, Plate 9) are both positioned between two other slices which do conform. The positioning of these two horses is supported by a spatial consideration and fold patterns along strike.

The spatial consideration is that a horse of constant thickness simply fits in the respective positions and therefore maintains the constant thickness constraint. In addition, the resulting fracture array is acceptable. Perhaps a more convincing argument in support of the positioning of these two horses is the map pattern along strike. In both instances, a second order anticline attains it's maximum structural relief to the immediate southwest of the line of section along strike from the position of each horse (compare Plate 1 with Plate 9). The horses may therefore represent the lateral extension of these second order anticlines which achieve higher structural relief at some distance along strike. The cover layer immediately above these two horses may therefore simply reflect the termination of the larger folds existing along strike into smaller order folds above the anomalous slices.

18.1.3 Roof thrust

Field data and structural position places the roof thrust in the lower reedsville formation. The variable thickness of the roof thrust interval as interpreted in the current state suggests that the roof thrust is more complex than originally assumed. Field evidence also suggests that there is a much thicker interval involved in the translation motion occuring between the cover and stiff layers.

Abundant wedge faulting occurs within the lower portion of the Reedsville formation within the Juniata Culmination (see Part 1, Section 5.3). The wedges seem to increase in size and decrease in quantity away from this horizon. The larger wedge faults, occuring in Trenton-aged carbonates, resemble minor thrust slices and have displacements on the order of tens of feet. The consequences of ignoring these features may account for the variable thickening and thinning within the Reedsville horizon in the current section interpretations. A more even thickness distribution would result if the smaller details of thrusting were better developed in this area. Nevertheless, correcting this portion of the section would not alter the principle structural character of the interpretation and would serve only to complicate restoration procedures.

18.1.4 Layer balancing

The length disparity between the restored cover layer and stiff layer disagrees with the balancing assumption that the inital sedimentary wedge was of a uniform length. However, if the assumption is correct, then other processes must operate on the cover layer which result in a preferentially shortened cover layer. The following discussion presents some processes which may produce the length deficiency of the restored cover layer.

The folding in the Appalachian Plateau is documented as being a result of deformation within the Valley and Ridge province (Rodgers 1963, Gwinn 1964, 1970). The mechanics and structures resulting in the folds in Pennsylvania and New York have been well established by Woodward (1959a), Rodgers (1963), Gwinn (1964), Frey (1973), Wiltshko & Chapple (1977), Engelder & Engelder (1977), and Geiser (1984). The consensus of information is that the Plateau folds form as a result of translation of an upper Paleozoic rock sequence towards the northwest on decollements within the Silurian Salina group. The sole thrust is presented as stepping up from the Cambrian beneath the Valley and Ridge province to the Silurian horizon in the Appalachian Plateau. The foreland pinning point used for the section construction may only apply to the stiff layer due to the translation of the cover layer past this point onto the Appalachian Plateau. By referencing the restoration of the cover layer from the foreland pinning point, the translated cover layer has been excluded from balancing and therefore has contributed to a shortened cover layer restoration.

Two additional processes also contribute to a shortened cover layer; the processes of LPS penetrative strain and contraction folding and faulting. As shown in Part 1 and 2, LPS penetrative strain occurs in the cover layer for both the Appalachian Plateau and Valley and Ridge provinces. Estimates of integrated strain for the Plateau are given as

10% (Nickelsen 1963, Engelder & Engelder 1977, Geiser 1984), and suggested estimates within the Valley and Ridge province may approach 20% (Faill 1977, and Part 2, section 9.0).

Contraction folding and faulting within the cover layer rocks of the Valley and Ridge province has been documented by Cloos (1940, 1964, 1961), Cloos & Broedel (1943), and Faill (1973). Percentage estimates of shortening have not been specified but 10% layer-parallel shortening may be a reasonable first estimate (Cloos, 1964).

The combined processes of LPS penetrative strain, contraction faulting and folding, and cover layer translation may account for the length balancing disparity. Folding within the Appalachian Plateau requires approximately 6.0 km. translation as determined from sinuous bed- length measurements (Pennsylvania Geologic Survey cross section c-c'). An additional 15 km. translation would be required for the Plateau to accomodate a 10% LPS penetrative strain (Engelder and Engelder 1977, Geiser 1984). The combined strain processes for the Plateau thus result in an estimated 21.0 km. translation of the cover layer past the foreland pinning point. This value is approximately 12% of the length of the restored stiff layer (Plate 9).

The remaining length discrepency within the restored cover layer is 50.51 km. (28%) after accounting for Plateau translation. This remaining interval must then be partitioned between the layer-parallel shortening processes operating within the Valley and Ridge province. If the suggested value of 10% layer-parallel shortening strain associated with contraction faulting and folding is applied, then 18.04 km. more is accounted for. The remaining 32.47 km. is thus attributed to the LPS penetrative strain processes. The LPS penetrative strain processes thus represent approximately 18% shortening, which results from volume loss strain associated with pressure dissolution, and volume constant mechanical strains. This percentage is well within the range suggested from studies of strain.

The above estimates of strain partitioning are given on Plate 9. It should be emphasized that these strain partitioning values are only estimates and may vary considerably. Application of the different strain values was necessary because of the assumption that the cover and stiff layer lengths were initially equal. If this assumption is incorrect, then the application of the derived strain partitioning values would vary considerably. For instance, Geiser (1984, pers. commun.) suggests that the cover layer length may never have been equal to that of the stiff layer east of the Valley and Ridge province. An originally longer stiff layer may have been thrust under a shorter cover layer which would require less layer-parallel shortening processes in the cover layer than would be required if the two layers were of original equal lengths. Nevertheless, the manner in which the layers balance when acccounting for all of the documented processes suggests that this interpretation could very well represent physical reality.

18.2 Comparison of interpretations

Figure 10 is a current and restored portion of the Pennsylvania Geologic Survey cross section c-c'. The restored portion is restricted to that part of the section from the foreland pinning point to point Z. The major differences between the interpretations should first be pointed out. In contrast to a hinterland dipping duplex solution, c-c' more closely resembles an imbricate splay thrust system (Boyer & Elliot, 1982). In additon, the Juniata Culmination for this interpretation results from a doubling of the stiff layer for a distance of approximately 30 km..

Geiser (1984, pers. commun.) has termed this double stiff layer configuration a 'flat-on-flat' solution for thrust sytems. Important aspects concerning cover layer strain distributions should be emphasized when considering the validity of a 'flat-on-flat' solution. To result in this configuration, a disproportionate amount of strain must occur in the stratigraphic interval that has been replaced by the overiding thrust sheet. A more feasable interpretation for the thrust system would provide a more even strain distribution; such as afforded by a duplex thrust system.

Problems also arise in the restoration diagram for section c-c'. From Figure 10, it is seen that restoring the

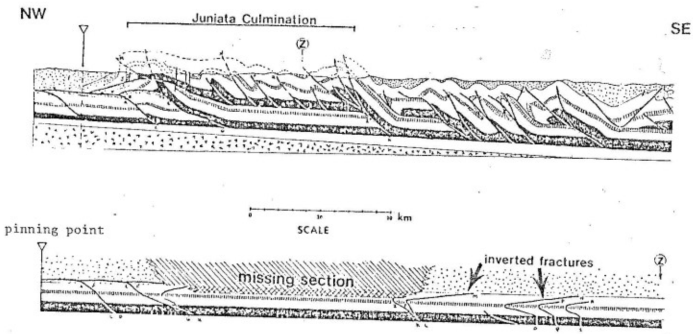


Figure 10. - Part of P.G.S. cross section c-c' - current and restored state

Note the 'flat-on-flat' solution for the Juniata Culmination in the current state and the inverted fracture array pattern and missing section in the restored diagram.

proposed section results in a restoration having inverted fractures and a missing portion of section. These problems emerge due to the lack of a designated roof thrust and because of the 'flat-on-flat solution'. The incorporation of a roof thrust in section c-c' combined with some minor adjustments in the current fault trajectories would allow a more feasable fracture restoration.

19. SUMMARY

Physical constraints which are derived from characteristic deformation responses in non-metamorphic terraine provide the needed tools for constructing more accurate and precise cross section interpretations. Such physical constraints are combined with assumed section boundary conditions for reinterpreting a portion of the Valley and Ridge province of Pennsylvania.

The section boundaries conditions for this interpretation include the foreland pinning point, a hindward boundary, the lower decollement (sole thrust), and an upper detatchment which separates two layers of differing mechanical response to deformation. The two layers are a lower stiff layer which is a thick sequence of Cambro-Ordovician carbonates, and the overlying cover layer which consists of interlayered clastics and thin carbonate horizons.

The foreland pinning point approximates the foreland limit of stiff layer thickening as is a reference for both the section construction and restoration procedures. The hindward reference corresponds to the Great Valley-Valley and Ridge province border. The stratigraphic position for the sole thrust and roof thrust are derived from a set of closely agreeing physical relations. The roof thrust is assumed to correspond to the lower Reedsville formation and the sole thrust to the upper Waynesboro formation.

The characteristic deformation responses include a break-forward sequence of developement for a fracture-thrusted stiff layer, the adherence to kink-domain geometry for stiff layer folds, and the cover layer fold map pattern reflects the position and geometry of underlying stiff layer thrust slices.

The cross section interpretation is developed with a computer aided drafting system (CAD). The construction procedures start by developing the section profile, which is the framework within which the stiff layer geometry is developed. The section profile consists of the stiff layer enveloping surface, the topographic surface along the line of section, a 'contracted wedge' diagram, and the remaining section boundaries. The cover layer was established in obtaining the enveloping surface, and is constructed from collected field data and geologic maps. The 'contracted wedge' is a thickness reference for the stiff layer during initial stages of interpretation.

The construction of the stiff layer relies upon well-constrained (outcropping) thrust slices, the physical constraints, and the developement of kink-domain geometry by the CAD system for the initial interpretations. Section restoration and balancing techniques cross check proposed solutions. Appropriate corrections are applied unitil the resulting interpretations for both the current and restored states uphold the imposed constraints and conform to the physical relations derived from field data.

The resulting cross section interpretations are hindward dipping duplex thrust systems which display a length difference between the restored cover and stiff layers. The difference in the lengths can be acounted for by strain processes occuring within the cover layer, which are apparently missing in the deformed stiff layer. These strain processes include the translation of the cover layer past the foreland pinning point onto the Appalachian Plateau and the combined processes of contraction fauting and folding and LPS penetrative strain.

Proposed strain values for the processes which result in a preferentially shortened cover layer are: 12% shortening (with respect to Lo) from Plateau translation, and 28% shortening from the LPS penetrative strains and contraction faulting and folding. A proposed partitioning of strain between the LPS penetrative strain and the contraction processes is 18% LPS penetrative strain and 10% faulting and folding.

The interpretation of this portion of the Valley and Ridge province is better represented as a duplex thrust system rather than an imbricate splay thrust system. The duplex system with an overlying, continuously folded cover layer is a more feasable interpretation under the given physical conditions. The occurence of a roof thrust allows a more uniform distribution of cover layer LPS strain than is provided by a previous interpretation which lacks such a mechanism. In addition, the proposed 'flat-on-flat' solution for the Juniata Culmination seems kinematically inappropriate in comparison to a duplex solution.

REFERENCES

Berg, T.M., 1980, Geologic Map of Pennsylvania. Pa. Geol. Survey, 4th ser., scale 1:250,000.

Berger, P.S., Perry, W.S., Jr., and Wheeler, R.R., 1979, Three stage model of brittle deformation in the Central Appalachians. Southeastern Geology, v.20, p. 59-67.

Boyer, S.E., and Elliot, D., 1982, Thrust Systems. Amer. Assoc. Petroleum Geologists Bull., v.86, p. 1196-1230.

Bucher, W.H., 1933, The Deformation of the Earth's Crust . Princeton Univ. Press., 518 p..

Butts, C., and Moore, E.S., 1936, Geology and mineral resources of the Bellefonte quadrangle, Pennsylvania. U.S. Geol. Survey Bull. 855, p. 1-111.

Chafetz, H.S., 1969, Carbonates of the Lower and Middle Ordovician in Central Pennsylvania. Pa. Geol. Survey, 4th ser., Report G 58, 39 p..

Chamberlain, R.T., 1910, The Appalachain folds of Central Pennsylvania. J. Geol. Chicago, v.18, p. 228-251.

Cleaves, A.B., 1939, Oriskany Group in Devonian of Pennsylvania. Pa. Geol. Survey, 4th ser., Rept. G-19, p. 29-130.

Cloos, Ernst, 1964, Wedging, bedding slips and gravity tectonics in the Appalachians. p. 237 in the Geologic Society of America, Abstracts for 1963: Geol. Soc. America Special Paper 76, 342 p..

___________, 1961, Bedding slips, wedges and folding in layered sequences. Geol. Soc. Finland Bull., v.33, p. 105-122.

___________, 1947, Oolite deformation in the South Mountain fold, Maryland. Geol. Soc. America Bull., v.58, p. 843-918.

___________, 1940, Crustal shortening and axial divergence in the Appalachians of South eatern Pennsylvania. Geol. Soc. America Bull., v.51, p. 841-872.

Cloos, E., and Broedel, C.H., 1943, Reverse faulting north of Harrisburg, Pa.. Geol. Soc. of America Bull., V. 54, pgs. 1375-1398

Conlin, R.R., and Hoskins, D.M., 1962, Geology and mineral resources of the Mifflintown quadrangle. Pa. Geol. Survey, 4th ser., Atlas 126, 46 p..

d'Invilliers. E.V., 1891, Report on the geology of the four counties Union, Snyder, Mifflin and Juniata. Pa. Geol. Survey, 2nd ser., Rept. F-3, 420 p..

Dahlstrom, C.D., 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains. Canadian Petro. Geol. Bull., v.18, p. 332-406.

Diegel, F.A.,Jr., 1984, A topologic approach to deciphering thrust complexes: The Mountain City Window as an example. (in-prep)

Dobelbower, R.R., 1953, Typical section, Bald Eagle Creek at Milesburg to Nittany Mountain at Pleasant Gap - Section, Whiterock quarry #1, Pleasant Gap. unpublished stratigraphic section on file at the University of Connecticut.

Dyson, J.L., 1967, Gology and mineral resources of the northern half of the New Bloomfield quadrangle. Pa. Geol. Survey, 4th ser., Atlas 137cd, 63 p..

__________, 1963, Geology and mineral resources of the southern half of the New Bloomfield quadrangle. Pa. Geol. Survey, 4th ser., Atlas 137ab, 86 p..

Engelder, T., 1979, Mechanisms for strain within the Upper Devonian clastic sequence of the Appalachian Plateau, Western New York. American Jour. Sci., v.279, p. 527-542.

Engelder, T., and Engelder, R., 1977, Fossil distortion and decollement tectonics of the Appalachian Plateau. Geology, v.5, p. 457-460.

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

Faill, R.T., 1977, Fossil distortion, Valley and Ridge province, Pennsylvania. Geol. Soc. America Abs. with Programs, v.9, p.262-263.

__________, 1973, Kink-band folding, Valley and Ridge province, Pennsylvania. Geol. Soc. America Bull., v.89, p. 1289-1314.

__________, 1969, Kink-band structures in the Valley and Ridge province, central Pennsylvania. Geol. Soc. America Bull., v.80, p. 2539-2550.

Faill, R.T., et. al., 1973, Structure and Silurian-Devonian stratigraphy of the Valley and Rodge province, central Pennsylvania. in Faill, R.T., ed., Guidebook for the 38th annual Field Conference of Pennsylvania Geologists Pa. Geol. Survey, 168 p.

Geiser, P.A., 1984, Mechanisms of thrust propagation: some examples and implications for the analysis of overthrust terrains. (submitted to Amer. Assoc. Petroleum Geologists Bull.)

__________, 1974, Cleavage in some sedimentary rocks of the central Valley and Ridge Province, Maryland. Geol. Soc. America Bull., v.85, p. 1399-1412.

Geiser, P.A., and Engelder, T., 1983, The distribution of layer-parallel shortening fabrics in the Appalachian forelan of New York and Pennsylvania: Evidence for two non-coaxial phases of the Allegheny orogeny. Geol. Soc. America Memoir 157, p. nn -nn.

Gough, W.R., 1977, The geology and water resources of the MilesburgSayers Dam area, Pa.. M.S. thesis - Pennsylvania State University (unpublished thesis)

Groshong, R.H., Jr, 1975, Strain, fracture, and pressure solution in natural single-layer folds. Geol. Soc. America Bull., v.86, p. 1363-1376.

Gwinn, V.E., 1964, Thin-skinned tectonics in the Plateau and southwestern Valley and Ridge provinces of the Central Appalachians. Geol. Soc. America Bull., v.69, no.9, p. 863-900.

__________, 1970, Kinematic patterns and estimates of lateral shortening Valley and Ridge and Great Valley provinces, central Appalachians, south-central Pennsylvania. in Fisher, G.W., and others, eds., Studies of Appalachian geology: central and southern. New York, Wiley-Intersci., p.127-146

Hayes, C.W., 1891, The overthrust faults of the Southern Appalachians. Geol. Soc. America Bull., v.2, p. 141-152.

Hossack, J.R., 1984, A cross section through the Scandanavian Caledonides constructed with the aid of branch-line maps. Jour. Struct. Geol., V.5, No.2, p. 103 to 111

_____________, 1979, The uses of balanced cross sections in the calculation of orogenic contraction: A review. Jour. Geol. Soc. London, v.136, p. 705-711.

Kay, G.M., 1944, Middle Ordovician of Central Pennsylvania. Jour. Geol., v.52, p. 1-23, 97-116.

_________, 1937, Stratigraphy of the Trenton Group. Geol. Soc. America Bull., v.48, p. 233-302.

Krohn, M.D., 1976, Relation of lineaments to sulfide deposits and fractured zones along Bald Eagle Mt.: Centre, Blair, and Huntingdon Counties, Pa.. M.S. thesis - Pennsylvania State University, 104 p. (unpublished thesis)

Lane, M.V., 1956, Geology of part of the Upper Lewistown Valley of Mifflin county, Pa.. M.S. thesis - Pennsylvania State University, 171 p. (unpublished thesis)

Meiser, E.W., Jr., 1971, The geology and water rsources of the Bellefonte-Mingoville area, Pa.. M.S. thesis - Pennsylvania State University. (unpublished thesis)

Miller, J.T., 1961, Geology and mineral resources of the Loysville quadrangle, Pa.. Geol. Survey, 4th ser., Atlas 127, 47 p..

Moebs, N.N., and Hoy, R.B., 1959, Thrust faulting in Sinking Valley, Blair and Huntingdon counties, Pennsylvania. Geol. Soc. America Bull., v.70, p. 1079-1088.

Nickelsen, R.P., 1979, Sequence of structural stages of the Allegheny Orogeny, at the Bear Valley Strip Mine, Shamokin, Pa.. Amer. Jour. Sci., v.279, p. 225-271.

_______________, 1972, Attributes of rock cleavage in some mudstones and limestones of the Valley and Ridge province of Pennsylvania. Proc. Pa. Acad. Sci., v.46, p. 107-112.

_______________, 1966, Fossil distortion and penetrative rock deformation in the Appalachian Plateau, Pennsylvania. Jour. Geology, v.74, p. 924-931.

Nickelsen, R.P., and Wagner, W.R., 1963, Fold patterns and continous deformation mechanisms of the central Pennsylvania folded Appalachians. in Cate, A., ed., Guidebook: Tectonics and Cambro-Ordovician Stratigraphy, central Appalachians of Pennsylvania Pittsburgh Geol. Society with the Appalachian Geol. Soc., p. 13-29.

Perry, W.J., Jr., 1978, Sequential deformation in the Central Appalachians. American Jour. Sci., v.278, p. 518-542.

Pierce, K.L., and Armstrong, R.L., 1966, Tuscarora Fault, and Acadian ? bedding-plane fault in Central Appalachian Valley and Ridge Province. Amer. Assoc. Petroleum Geologist Bull., v.50, p. 385-390.

Pohn, H.A., and Purdy, T.L., 198?, Disturbed zones: Indicators of deep-seated subsurface faults in the Valley and Ridge and Appalachian structural front of Pennsylvania. U.S. Geol Survey, Open file report 82-967.

Rodgers, H.D., 1858, The Geology of Pennsylvania; A Government Survey.

Rodgers, John, 1963, Mechanics of Appalachian foreland folding in Pennsylvania and West Virginia. Amer. Assoc. Petroleum Geologists Bull., v.47, p. 1527-1537.

_____________, 1949, Evolution of thought on structure of middle and southern Appalachians. Amer. Assoc. Petroleum Geologists Bull., v.33, p. 1643-1655

Rones, M. - Unpub. map on file at the Pennsylvania Geol. Survey.

Sherril, R.E., 1934, Symmetry of Northern Appalachian foreland folds. Jour. Geology, v.42, p. 225-247.

Suppe, J., 1983, Geometry and kinematics of Fault-bend Folding. American Jour. Sci., v.283, p. 684-721.

Swartz, F.M., 1973, Tenton and Sub-Trenton of Outcrop Areas in New York, Pennsylvania and Maryland. Pa. Geol. Survey, 4th ser., Rept. 22, p. 1493-1595.

___________, 1949, The Keyser limestone and Helderberg Group, in the Devonian of Pennsylvania. Pa. Geol. Survey, 4th ser., Rept 6.19, p. 29-72.

Thamm, J.K., Jr., 1956, Geology of part of the Seven Mts. district of Central Pa.. M.S. thesis - Pennsylvania State University, 169 p. (unpublished thesis)

Thompson, A.M., 1974, Lithostratigraphy of the Middle Ordovician Salona and Coburn formations in central Pennsylvania. Pa. Geol. Survey, 4th ser.,Report G 38, 154 p..

______________, 1970, Sedimentology and origin of Upper Ordovician clastic rocks, central Pennsylvania. Guidebook, Eastern Section, SEPM, April 25-26, 1970, 88 p..

Thompson, R.I., 1981, The nature and significance of large 'blind' thrusts within the northern Rocky Mountains of Canada. from Thrust and Nappe Tectonics The Geologic Society of London, p. 449-462.

Turner, F.J., and Weiss, L.E., 1963, Structural analysis of metamorphic tectonite , Mcgraw-Hill Book Co., New York, 554 p..

Willis, B., 1893, The mechanics of Appalachian Structure. U.S. Geol. Survey, 13th Ann. Rept., Pt. 2, p. 211-281.

Wiltschko, D.V., and Chapple,.W.M., 1977, Flow of weak rocks in the Appalachian Plateau folds. Amer. Assoc. Petroleum Geologists Bull., v.61, p. 653-671.

Wood, D.S., 1974, Current views of the developement of slaty cleavage. Ann. Rev. Earth Sci., v.2, p. 369-401.

Wood, G.H., Jr., and Bergin, M.J., 1970, Structural controls of the Anthracite region. in Fisher, et. al., eds., Studies of Appalachian geology: Central and Southern New York, Intersci. Pubs., p. 147-160.

Woodward, H.P., 1961, Repraisal of Appalachian Geology. Amer. Assoc. Petroleum Geologists Bull., v.45, p. 1625-1633.

______________, 1959, Structural interpretations of the Burning Springs Anticline. in Woodward, H.P., ed., A symposium on the Sandhill Deep Well, Hood County, West Virginia . West Virginia Geol. Survey Inv. Rept. 18, p. 159-168.

______________, 1957, Chronology of Appalachian Folding. Amer. Assoc. petroleum Geologists Bull., v.41, p. 2312-2327.

Wright, T.O., and Platt, L.B., 1982, Pressure dissolution and cleavage in the Martinsburg shale. Amer. Jour. Science., v.282, p. 122-135.

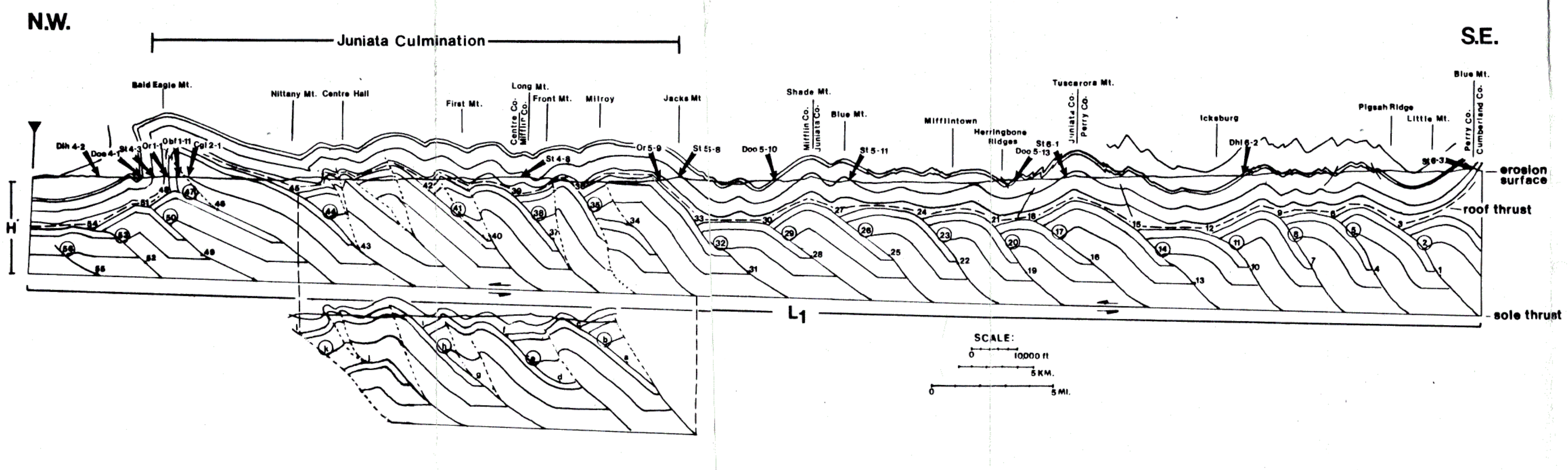
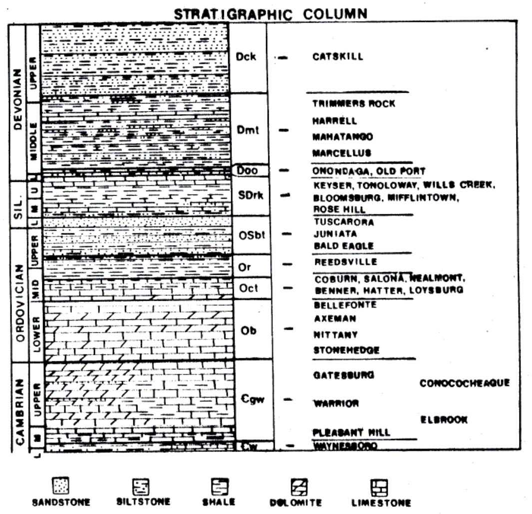
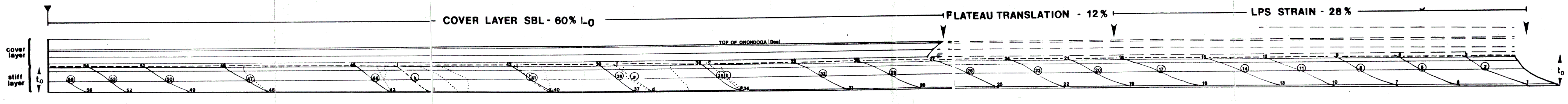


PLATE 9

Gregory Herman
5/30/84

STIFF LAYER (km):	
L_1	98.28
L_0	180.39
L_1 / L_0	.54
t_0 (N.W)	3.11
t_0 (S.E.)	3.70
H'	6.24
Sole thrust depth;	
N.W.	6.20
S.E.	9.70
Area (km^2)	614.22
COVER LAYER (km):	
Sinuous bed length (SBL)	108.62
Plateau translation (including penetrative LPS)	20.77
Layer parallel shortening:	
Contraction faulting and folding	18.04
Penetrative	32.47





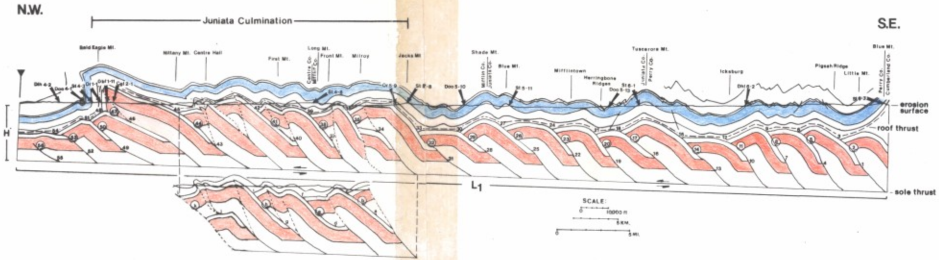


PLATE 9

Gregory Herman

5/30/84

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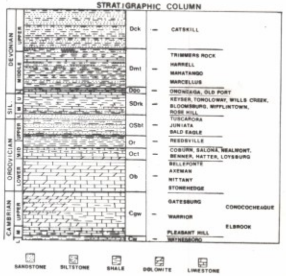

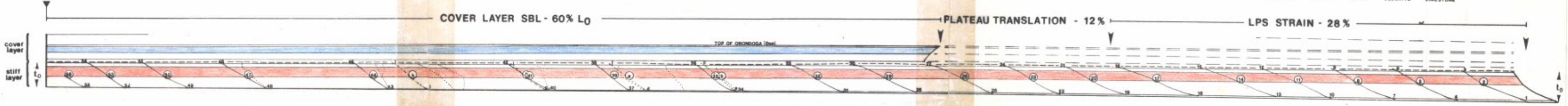

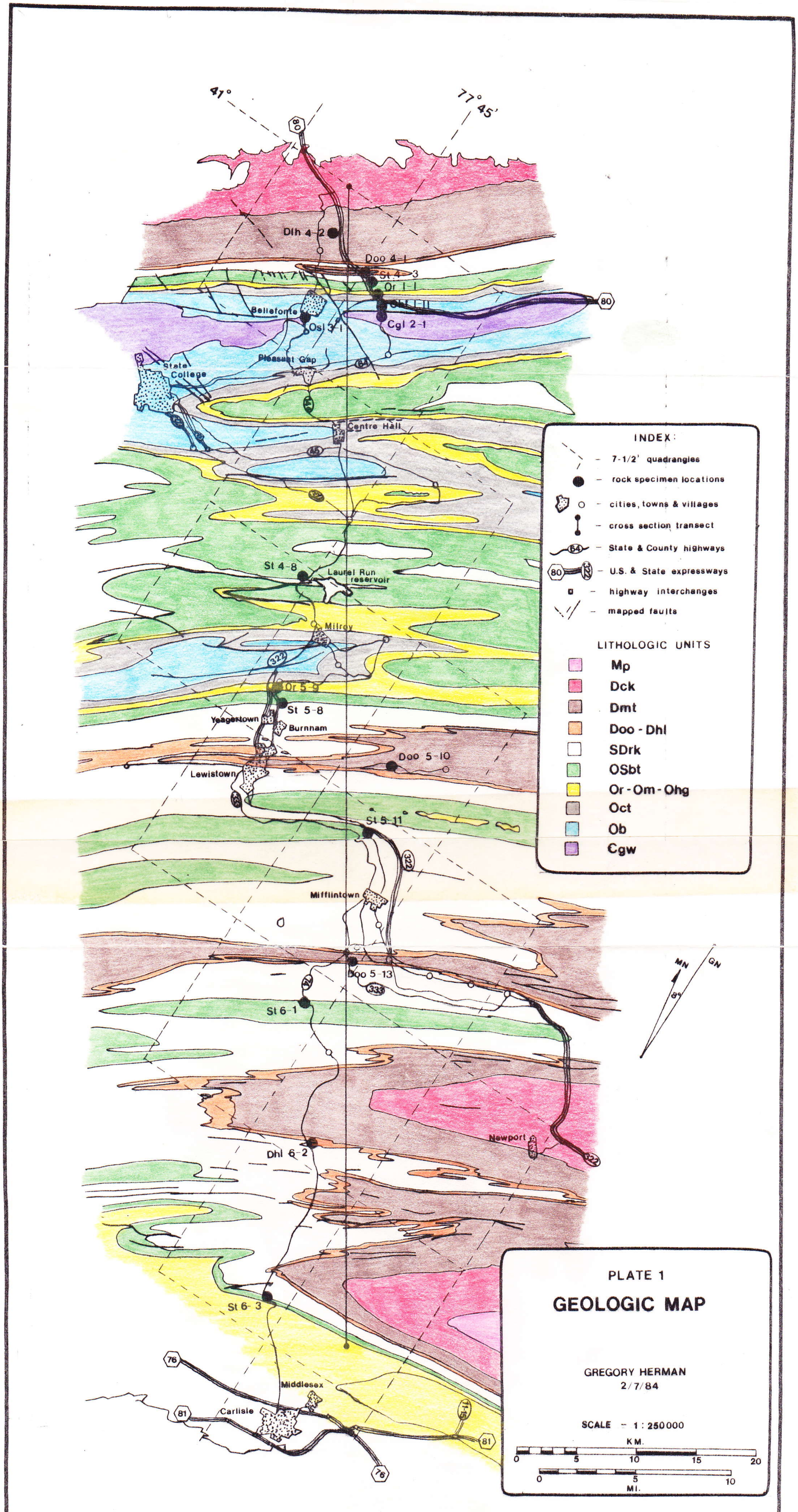

41°
77° 45'
INDEX:
- 7-1/2' quadrangles
- rock specimen locations
- cities, towns & villages
- cross section transect
- State & County highways
- U.S. & State expressways
- highway interchanges
- mapped faults
LITHOLOGIC UNITS
Mp
Dck
Dmt
Doo - Dhl
SDrk
OSbt
Or - Om - Ohg
Oct
Ob
Cgw
Dlh 4-2
Doo 4-1
St 4-3
Or 1-1
Obf 1-11
Cgl 2-1
Bellefonte
Osl 3-1
Pleasant Gap
State College
Centre Hall
St 4-8
Laurel Run reservoir
Milroy
Or 5-9
St 5-8
Yeagertown
Burnnam
Doo 5-10
Lewistown
St 5-11
Mifflintown
Doo 5-13
St 6-1
MN
GN
8°
Newport
Dhl 6-2
St 6-3
Middlesex
Carlisle
80
64
45
322
333
74
76
81
PLATE 1
GEOLOGIC MAP
GREGORY HERMAN
2/7/84
SCALE - 1 : 250000
KM.
0
5
10
15
20
0
5
10
MI.