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THE BASEMENT VERSUS THE NO-BASEMENT HYPOTHESES FOR FOLDING WITHIN THE APPALACHIAN PLATEAU DETACHMENT SHEET

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ABSTRACT. Within the Appalachian plateau detachment sheet of southwestern Pennsylvania tectonic thickening is a central element to the growth of anticlines in a Silurian-Devonian section containing a three-tiered mechanical stratigraphy (that is, a basal detachment zone, a lower imbrication zone, and an upper wedge zone). The detachment zone is predominantly within disturbed shale of the Silurian Vernon Formation which sits above a disturbed surface on the Lockport dolomite. Large-scale anticline growth is, in part, a consequence of small-scale blind imbrication of the more competent mechanical layers in the lower portion of the detachment sheet (the imbrication zone). Here, salt within the Silurian Syracuse Formation hosts secondary detachment responsible for imbrication and the development of triangle zones in the core of the anticlines. Some fold amplification is also accomplished by extensive, smaller-scale thrust wedging and concomitant tectonic thickening of the less competent Devonian section in the upper portion of the detachment sheet (the wedge zone). These spatially periodic anticlines are separated by horizontally bedded synclines characterized by the absence of thrust wedging and fault imbrication across all three zones. Tectonic thickening continued behind the foreland propagation of the detachment-tip line within the Vernon shale as indicated by a systematic hinterland increase in the cross-sectional width and amplitude of the anticlines.

On the basis of seismic images, each detachment sheet anticline is situated above prominent, periodically-spaced, pre-Alleghanian structures in the footwall of the detachment sheet. These footwall structures arise from a combination of thrust imbrication at the depth of the Ordovician Trenton Group and high-angle, basement-involved faulting at the depth of the Cambrian Gatesburg Formation. Some of the high-angle fault displacement is a consequence of Alleghanian inversion on faults associated with the extensional Rome Trough and other basement structures developed during the Late Proterozoic rifting of the eastern margin of Laurentia. Evidence for tectonic inversion is present in seismic reflection images that show buttress anticlines in the Cambro-Ordovician carbonate section.

The superposition of detachment-sheet anticlines above footwall structures strongly suggests that the foreland transport was disrupted by topographic bumps on the base of the detachment zone. Bending of the detachment sheet over these irregularities may have promoted the spatially periodic collapse and concomitant tectonic thickening in the over-riding sheet as it was pushed laterally toward the foreland. A strain hardening of the detachment zone part of the detachment sheet at the topographic irregularities permitted the growth of double-sided tapered wedges (that is, each anticline). The overall structural profile of the detachment sheet is consistent with the growth of a Coulomb wedge whose low basal friction is interrupted by patches of strain hardening.

INTRODUCTION

Concerning the basement and the no-basement hypotheses for folding within the Appalachian Mountains, John Rodgers (1964) wrote that the present forms of the hypotheses:

> *"are perhaps somewhat extreme, and presumably after we are all dead, future generations of geologists will decide what compromise to make between them. Let me just characterize them in terms of the homely analogy of a pile of rugs lying on a floor. According to one hypothesis, the pile of rugs is being pushed from one side over*

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> *the floor; the rugs are somewhat rotten and they tear a bit as they slide and wrinkle, but the floor doesn't seem to be affected much nor to affect them, except by providing a stable base. According to the other hypothesis, the different floorboards beneath the rugs shift separately up and down and maybe to some extent sideways as well, folding and tearing the rugs above them. The question why the rugs are being pushed from the side in the one hypothesis or why the boards are shifting in the other we must postpone; it is more important I think to find out first which did happen. Certainly we ought at least to be able to find that out within the next 50 years."*

In lecturing to graduate students at Yale during the 1960s, Rodgers (1949, 1953, 1964) emphasized the view that the Appalachians were best characterized by thin-skinned tectonics. His protagonist in this debate was Byron Cooper (1964) who argued that local changes in stratigraphic thickness pointed to a role for basement-involved tectonics during the development of Appalachian folds. Supported by a regional network of modern seismic lines, we revisit the Rodgers-Cooper debate in search of the compromise that Rodgers (1964) sought regarding the basement versus the no-basement hypotheses for Appalachian tectonics.

Chestnut Ridge, Laurel Hill, and Negro Mountain, the most prominent of the anticlines in the Appalachian plateau detachment sheet in southwestern Pennsylvania, are characterized by their lateral continuity, periodic spacing, and common orientation (Gwinn, 1964). The classic model for folding of the Appalachian plateau detachment sheet involves a periodic buckling above a detachment in salt (Rodgers, 1963; Gwinn, 1964; Sherwin, ms, 1972; Davis and Engelder, 1985, 1987). This buckling theory prescribes that the detachment sheet consists of a thick competent section of rocks that fold concentrically (Wiltschko and Chapple, 1977). Uplift during concentric folding creates a volume (beneath anticlinal cores) that must be filled by lateral flow of a more ductile formation from adjacent synclines. Although the general architecture inherent in the classic model is well established and widely accepted, the internal geometry of these periodic anticlines and their kinematic relationships at all stratigraphic levels is neither well documented nor completely understood. In addition, the literature contains hints that the mechanism for generation of these periodic anticlines is tied to footwall structures (for example, Reeves and Morris, 1988; Towey, 1988; Beardsley and others, 1999).

The objective of this paper is to present a unifying tectonic model of the Appalachian plateau detachment sheet. Advances made in this paper include: (1) a better delineation of the internal structures within the detachment sheet anticlines, (2) a reevaluation of the lithology hosting the plateau detachment surface, (3) a clearer understanding of the mechanical stratigraphy within the detachment sheet, and (4) an explicit documentation of the spatial and kinematic relationship between structures in the footwall of the Silurian detachment zone and superimposed structures in the detachment sheet. Our interpretation is based on a regional network of high quality seismic reflection data acquired by Amoco Production Company during the middle to late 1970's as part of a very successful natural gas exploration program in the region (fig. 1).

General Characteristics of the Appalachian Plateau Detachment Sheet

The Central Appalachian Mountains consist of a series of arcuate longitudinal belts characterized by different structural styles and deformational histories (Rodgers, 1963, 1982, 1987; Berg and others, 1980; Wiltschko and Geiser, 1989; Hatcher, 1989; Faill, 1997a, 1997b, 1998). The Appalachian plateau is the most external province and constitutes a foreland belt of blind thrust faults and fault-related folds that are a consequence of the shortening of a thin platform cover of Paleozoic sedimentary rocks (fig. 1). The upper portion of this Paleozoic cover was detached on a décollement surface that propagated northwestward along mechanically weak stratigraphic intervals, primarily salt and shale of the Silurian Salina Group (Rodgers, 1970). This is the Appalachian plateau detachment sheet. Its lateral boundaries are approximately

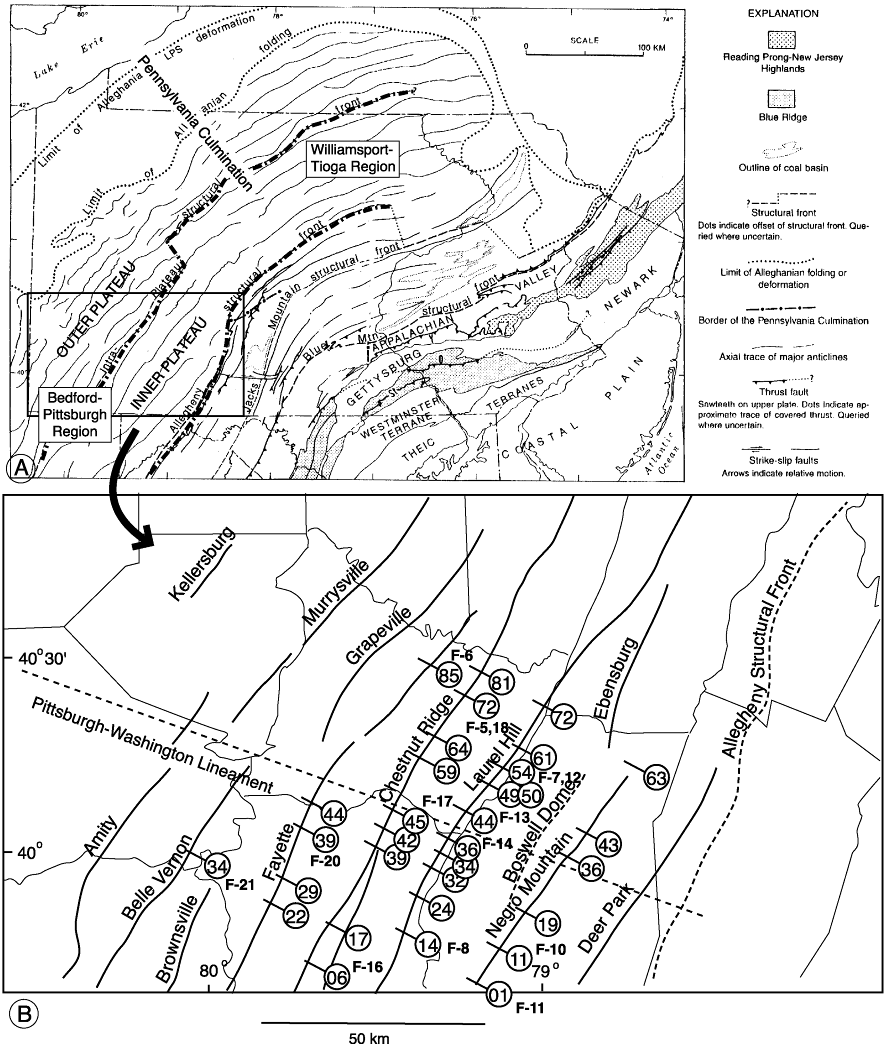


Fig. 1. Appalachian structural provinces in Pennsylvania. A. Location of tectonic elements in the Appalachian plateau detachment sheet (adapted from Faill, 1998). B. Base map of research area showing anticlinal traces, approximate location of seismic profiles, and corresponding figures (F-5, et cetera).

coincident with the aerial extent of the Silurian Salina salt basin (Davis and Engelder, 1985, 1987). Many of the detachment sheet anticlines are slightly over-steepened on their southeastern limbs, in a sense, opposite the prevailing direction of tectonic transport (Gwinn, 1964). Detachment and westward translation of the former continental platform cover took place during the Pennsylvanian-Permian Alleghanian Orogeny (Rodgers, 1970, 1982). Although the underlying Proterozoic basement was not involved in the shortening, seismic records in this paper demonstrate that faulted basement blocks exert a major influence on the growth of subsequent Alleghanian structures.

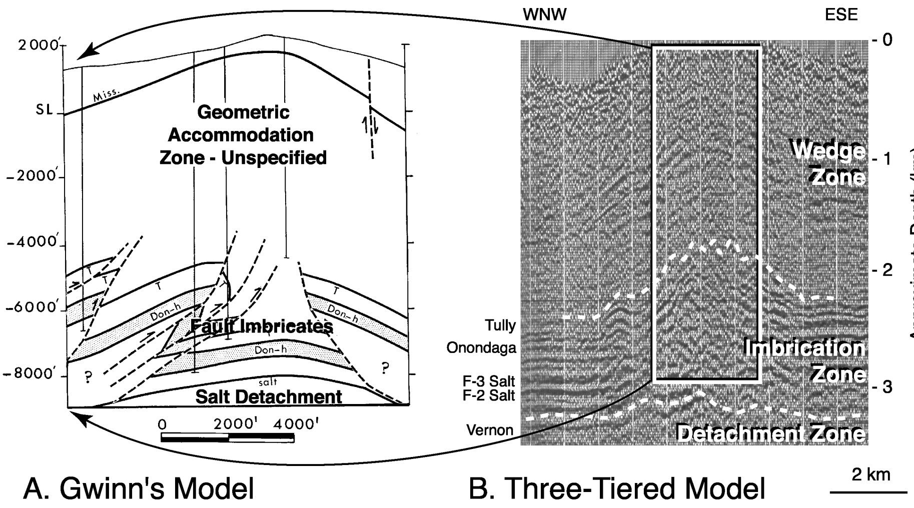
The distribution of shortening in foreland fold-thrust belts involves a variety of mechanisms including some combination of slip on detachment surfaces, localized imbrication, and pervasive layer-parallel shortening. Styles of slip dissipation across a detachment sheet vary depending on whether the décollement is emergent or blind as is the case for the Appalachian plateau detachment sheet (Geiser, 1988a, 1988b). Blind thrust fronts are characterized by either broad zones of layer-parallel shortening or a rather abrupt halt in slip beneath a steeply dipping forelimb of a fold (Morley, 1986). The Appalachian Plateau is commonly cited as the type example of a broad zone of layer-parallel shortening with subordinate splay faults in the hanging wall of the detachment sheet (Gwinn, 1964; Engelder and Engelder, 1977). The Sulaiman and Kirthar ranges of Pakistan have thrust fronts with narrow zones of layer-parallel shortening that accompany the development of passive-roof duplexes (Boyer and Elliott, 1982; Banks and Warburton, 1986).

There is a moderate increase in the width of the Appalachian plateau detachment sheet along strike in Pennsylvania from 165 kilometers in the southwest to over 175 kilometers in the northeast (Fettke, 1954; Gwinn, 1964; Faill, 1998). These two portions of the detachment sheet (that is, the Bedford-Pittsburgh region to the southwest and the Williamsport-Tioga region to the northeast) are separated by the Pennsylvania Culmination (fig. 1). One distinction between the two regions is that in the Williamsport-Tioga region and to the north in New York State, the Middle and Lower Devonian section is organized into more closely spaced, irregular anticlines (Bradley and Pepper, 1938; Van Tyne and Foster, 1979). In addition, the Silurian salt beds are considerably thicker and more continuous in the Williamsport-Tioga region (Fergusson and Prather, 1968). In the Bedford-Pittsburgh region, there is also a significant decrease in structural relief going toward the foreland leading Gwinn (1964) to identify an intra-plateau structural front separating the Inner plateau and the Outer plateau (fig. 1).

Early Paleozoic structural and stratigraphic development in the footwall of the Appalachian plateau detachment sheet is attributed to extensional faulting in the basement complex (Cooper, 1964; Beardsley and Cable, 1983; Harper, 1989). Growth faults in both the Cambrian and Ordovician intervals allowed the development of an intra-plateau basin, the Cambrian-Ordovician Olin Basin (Wagner, 1976). A Cambrian basin bounded by these growth faults is coincident with the projected boundaries of the Rome Trough (Harris, 1978). A second Cambrian extensional margin is located in the inner plateau. It is observed on the seismic data presented here as a remarkably steep escarpment, the Cambrian coastal declivity (Woodward, 1961). All these faults are traced to the development of a continental margin in the Late Proterozoic (Thomas, 1977).

Tectonic Issues Concerning the Appalachian Plateau Detachment Sheet

A classic cross-sectional view of the Chestnut Ridge anticline shows a thickened Upper Silurian section and doubly vergent blind thrusts at the level of the Lower/Middle Devonian section (fig. 2). The detachment that feeds slip to these blind thrusts is located in salt at the very top of the Silurian Salina Group. An implicit element of this cross-section is the passive behavior of the Upper Devonian section concentrically folded over blind splay thrusts cutting through the Lower/Middle Devonian section. This is the 'Gwinn model' for anticline growth in the detachment sheet. One interpretation of the Gwinn model is that shortening from imbrication of the Lower/Middle Devonian section is substantially greater than the arc-length shortening suggested for the Upper Devonian section. Differential shortening between the Lower/Middle section (large, obvious shortening in imbricate overlaps) and Upper Devonian section (little visual shortening) requires a nearly complete decoupling of the upper from the lower section. Complete decoupling is also a component of the 'Wiltschko-Chapple flow model' that calls upon flow of salt from the synclines toward the anticlines to fill the fold volume caused by upfolding during buckling (Wiltschko



A. Gwinn's Model

B. Three-Tiered Model

Fig. 2. Cross sections through Chestnut Ridge anticline. A. Gwinn model for anticlines of the Appalachian plateau detachment sheet (adapted from Gwinn, 1964). Depth in feet is given relative to sea level (SL). Vertical exaggeration 1:1. Stratigraphic units include the Tully Limestone (T), the Onondaga and Helderberg Groups (Don-h) and the top of the Syracuse Formation (salt). [see table 1 for a more complete stratigraphic column for the Appalachian Plateau. Stratigraphic units are compiled from Fergusson and Prather (1968), Colton (1970), Heyman (1977), and Lindberg (1985)]. B. Three-tiered mechanical-stratigraphy model for the anticlines of the Appalachian plateau detachment sheet. Vertical exaggeration is approximately 3:1 with the cross section of Gwinn's model shown as the solid white box overprinted on the seismic section. Fundamental advances in understanding the tectonic development of the detachment sheet anticlines include a detailed structural interpretation for both Gwinn's unspecified geometric accommodation zone and fault imbricates. These are called the wedge zone and the imbrication zone, respectively, in the new three-tier model. The three-tier model also redefines the level of the detachment sheet décollement by moving it down into the Vernon shale with the major salt beds acting as secondary detachments in the imbrication zone.

and Chapple, 1977). However, differential shortening is not necessary if layer-parallel shortening (LPS) takes place in the Upper Devonian section (that is, the Wiltschko-Chapple competent layer) along with thrust imbrication in the Lower/Middle Devonian section. This latter possibility is investigated in this paper.

Pervasive, uniform LPS in the form of disjunctive cleavage, crystal-plastic strain, the preferred orientation of chlorite, and an anisotropy of magnetic susceptibility is well documented throughout the Appalachian plateau detachment sheet (Nickelsen, 1966; Engelder and Engelder, 1977; Engelder, 1979a, 1979b; Geiser and Engelder, 1983; Geiser, 1988b; Evans and others, 1989; Oertel and others, 1989; Hirt and others, 1995). Penetrative strain took place during the earliest stage of tectonic deformation and is independent of structural position (that is, Nickelsen, 1979; Gray and Mitra, 1993). Since early LPS strain is uniform throughout the entire Devonian section, regardless of structural position, an additional shortening mechanism, as will be demonstrated later in this paper, must be present only in the anticlines of the detachment sheet to reconcile the differential shortening paradox inherent in the Gwinn and Wiktschko-Chapple flow models.

Variations in subsurface structural style and structural relief within the plateau in Pennsylvania were attributed to proximity to the Allegheny structural front and regional variations in the thickness of the salt detachment along strike (Wiltschko and Chapple, 1977). On the basis of salt thickness and deformational mechanics, there are two distinct regions of structural development within the detachment sheet (fig. 1). To the northeast in the Williamsport-Tioga region fold relief appears to develop by lateral movement of salt-bearing rocks into anticlinal cores (Frey, 1973). To the southwest in the Bedford-Pittsburgh region the movement of salt alone is insufficient to account for full fold amplitude so that an additional mechanism is required for anticlinal growth within the detachment sheet.

The periodic spacing of folds such as those in the Bedford-Pittsburgh region, is often attributed to a buckle mechanism for fold growth (for example, Biot, 1961; Sherwin, ms, 1972). However, a field criterion for buckle folds is that they have a relatively modest length to spacing ratio (Sattarzadeh and others, 2000). The long, continuous nature of the detachment sheet anticlines gives them aspect ratios outside the norm for buckle folds. Rather, such large aspect ratio anticlines are characteristic of forced folds, particularly those centered on basement-involved faulting (Sattarzadeh and others, 2000). This strengthens the notion that the structural development in the footwall contributes to the laterally extensive character of anticlinal growth in the Appalachian plateau detachment sheet (that is, Reeves and Morris, 1988; Towey, 1988).

DATA SOURCES

Our analysis of the Appalachian plateau detachment sheet is based on a network of 32 seismic reflection profiles with an average length of 20 kilometers from Amoco Production Company (fig. 1). Geophysical well log information and velocity surveys from 40 strategically located deep exploration or development wells provided critical stratigraphic information for the region. Sonic and density logs from select wells were utilized to generate synthetic seismograms that facilitated the correlation of seismic reflection data and stratigraphy for almost the entire Paleozoic section. The seismic data utilized in this study are 24-fold CMP post-stack migrated time sections recording 4 seconds of two-way travel-time that yields a penetration depth in excess of 8 kilometers, well below the base of the Paleozoic strata. The data have a temporal sampling interval of 4 milliseconds and a horizontal spatial sampling interval of 45.7 meters. Recording instrumentation used in data acquisition was a 48 trace cable system deployed in a split spread configuration with a long offset of 2400 meters. Record filters had a low frequency cutoff of 18 Hz and a high frequency cutoff of 90 Hz. The energy source used in acquisition was either vibroseis or explosives dependent upon terrain, access limitations, and nature and extent of surface development. In cases where an explosive source was utilized, single shot holes were drilled to a depth of 15 meters and detonated using 44 kilograms explosive charges. Vibroseis data were recorded using four vibrators in line, inputting a 4 second sweep with a frequency range of 8-56 Hz and recording for 9 seconds.

The processing stream has maximized signal to noise and migration image quality through pre-stack deconvolution, refraction statics, surface consistent reflection statics, velocity analysis/normal moveout correction, residual statics corrections, residual normal moveout corrections, CMP stacking, time-variant band pass filtering, and wave equation migration. Final data are presented as standard seismic profiles displaying horizontal distance and vertical two-way reflector time corrected to a horizontal datum 485 meters above sea level. The seismic profile display scale shows a vertical to horizontal exaggeration of approximately 3:1 to facilitate visual perception of the very broad, low relief structures characteristic of the plateau. Stratigraphic interval thickness was calculated using interval velocities that were specific to individual stratigraphic units. These interval velocities were derived from a combination of sonic logs and velocity analysis software.

The research area, southwestern Pennsylvania, is a geologic province where salt is not only anticipated but also the essential mechanism facilitating fracture-enhanced porosity in the overlying reservoir rocks. This expectation results in design specifications that are built into the seismic data processing component of the seismic imaging

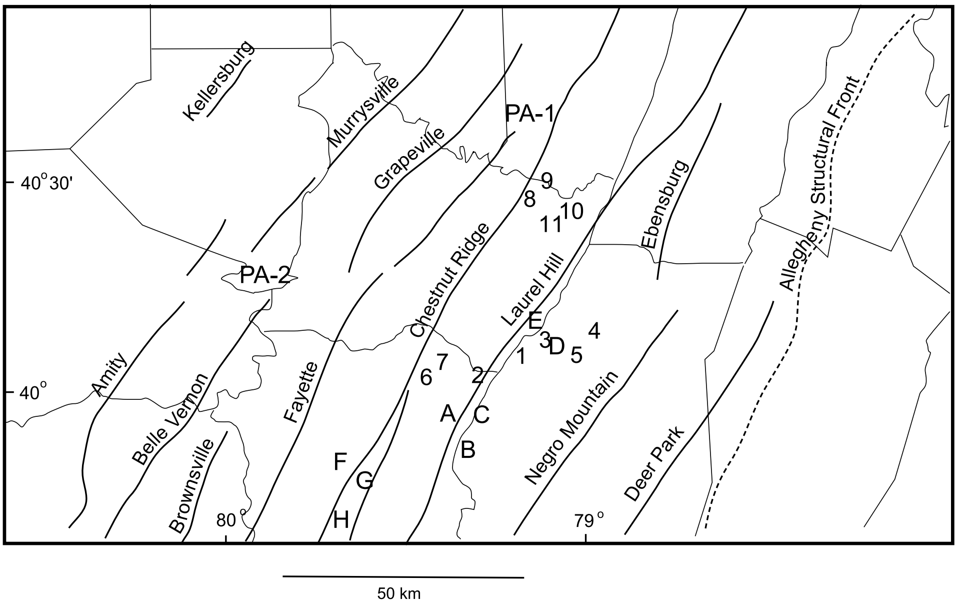


Fig. 3. Base map of research area showing well locations. Capital letters show the approximate location of deep wells utilized for velocity control and synthetic seismogram construction. Well names are: A. Maude Mountain #1; B. Tract III-A; C. Svetz #1; D. Hottle #1; E. Clark #1; F. Heyn #1; G. Ricks #1; H. C.B. Smith #2. Numbers show the approximate location of eleven other wells utilized to document tectonic thickening in the Upper Devonian section across Laurel Hill and Chestnut Ridge anticlines (see table 2 for well names).

process. Velocity profiles that reflect these lateral velocity changes (including the anticipation of salt in the section) are appropriately modified both vertically with depth and horizontally along the seismic line to mitigate the velocity pull-up phenomenon, a concern raised by reviewers of this manuscript. As a result, a structural anomaly beneath a suspected salt zone is not a processing artifact when the appropriate velocity analysis and processing precautions have been implemented.

Well logs for our analysis are archived at the Oil and Gas Division of The Pennsylvania Topographic and Geologic Survey in Pittsburgh, Pennsylvania (for example, Heyman, 1977). Several key geophysical well logs for each well were utilized for stratigraphic correlation and seismic interpretation. The gamma ray log is primarily used to correlate lithology between individual boreholes. Sonic and density logs define an impedance record from which the synthetic seismograms are calculated.

SEISMIC STRATIGRAPHY OF THE DETACHMENT SHEET

The Paleozoic stratigraphy of the Appalachian plateau reflects three orogenic cycles consisting of carbonates and clastics (Colton, 1970). Correlation of regional stratigraphy to distinctive seismic reflections in the network of regional seismic lines was achieved using synthetic seismograms. Eight synthetic seismograms were utilized to establish the regional seismic correlations (for example, fig. 3). Strategic wells used in this process include: five Oriskany/Huntersville wells with an average total depth of 3 kilometers, two Salina Group wells with an average total depth of approximately 4 kilometers, and the deepest test in the Appalachian plateau that reached a total depth of 7 kilometers in the Gatesburg Formation.

Seismic Marker Horizons

Synthetic seismograms are derived from sonic and density logs (fig. 4). These data allow the construction of an impedance log that, when convolved with an assumed signal wavelet, gives a theoretical seismic trace that facilitates correlation of stratigraphic position to reflection events. Strong seismic reflectors appear throughout the Paleozoic section. There are four very strong reflections that correlate with the Cambrian Gatesburg Formation, the Ordovician Trenton Formation, the Silurian Salina Group and the Devonian Tully Limestone (fig. 4). Aside from these prominent reflectors there are several characteristic reflection sets that represent distinctive intervals. For reference purposes within the seismic profiles that follow, we will briefly discuss the prominent characteristic reflection sets from bottom to top of the Paleozoic section.

Although no wells penetrated to basement, two strong impedance contrasts are found below the Gatesburg. The deepest reflection set is interpreted to include the shale of the Cambrian Waynesboro Formation and the basement-cover contact. Depth to basement beneath Laurel Hill Anticline is estimated to be about 8 kilometers below the surface. Aeolian sandstones within the Cambrian Gatesburg Formation are responsible for the marker seismic reflection at the top of the Gatesburg Formation. Moving up the section, the next strong impedance contrast correlates with the contact between the Ordovician Reedsville Shale and the underlying Trenton carbonates.

The Lockport reflector marks the basal portion of the Appalachian plateau detachment sheet and is the basal member of a characteristic reflection set found at depths of 2 to 3 kilometers. The top of this characteristic reflection set is found where a strong acoustic impedance contrast signifies the contact between the Middle Devonian Tully limestone and the overlying shales of the Upper Devonian Burket Shale (fig. 4). The second reflection below the Tully, about 150 meters deeper, represents the transition between the overlying shale of the Middle Devonian Hamilton Group and the Onondaga Limestone. Shale-carbonate transition within the Bass Island Formation constitutes a third strong reflector. The next strong reflector down is the transition between dolomite of the Silurian Syracuse Formation and the encapsulated F-3 salt about 500 meters below the Tully limestone. A strong reflector is also found at the depth of the F-2 salt another 100 meters down section. 850 meters below the Tully limestone is a reflector at the transition from carbonate to shale within the Vernon Formation. These reflectors permit a detailed analysis of the detachment surfaces of the Appalachian plateau detachment sheet. A transition from shale to the Silurian Lockport dolomite, about 970 meters below the Tully, produces a fair to poor seismic reflection in most areas.

Seismic reflections in the Upper Devonian are numerous but laterally discontinuous (fig. 4). A noteworthy reflection emanates from the base of the Braillier sandstone. The Mississippian Loyalhanna limestone also provides a good seismic reflection and is the upper boundary for the Catskill Delta complex. The latter two reflectors are best mapped by means of well logs.

Resolution Limit in the Seismic Data

Seismic resolution of structural features is dictated by the signal-to-noise level and frequency of the seismic data combined with the knowledge and experience of the interpreter. Vertical resolution is controlled by the frequency of the seismic signal that decreases with depth, resulting in a depth variant decrease in resolution. Horizontal resolution is more difficult to quantify but is strongly affected by the signal-to-noise level of the data and the horizontal sampling interval. Conventional limitations on seismic resolution can be overcome to some extent when a structural model, consistent

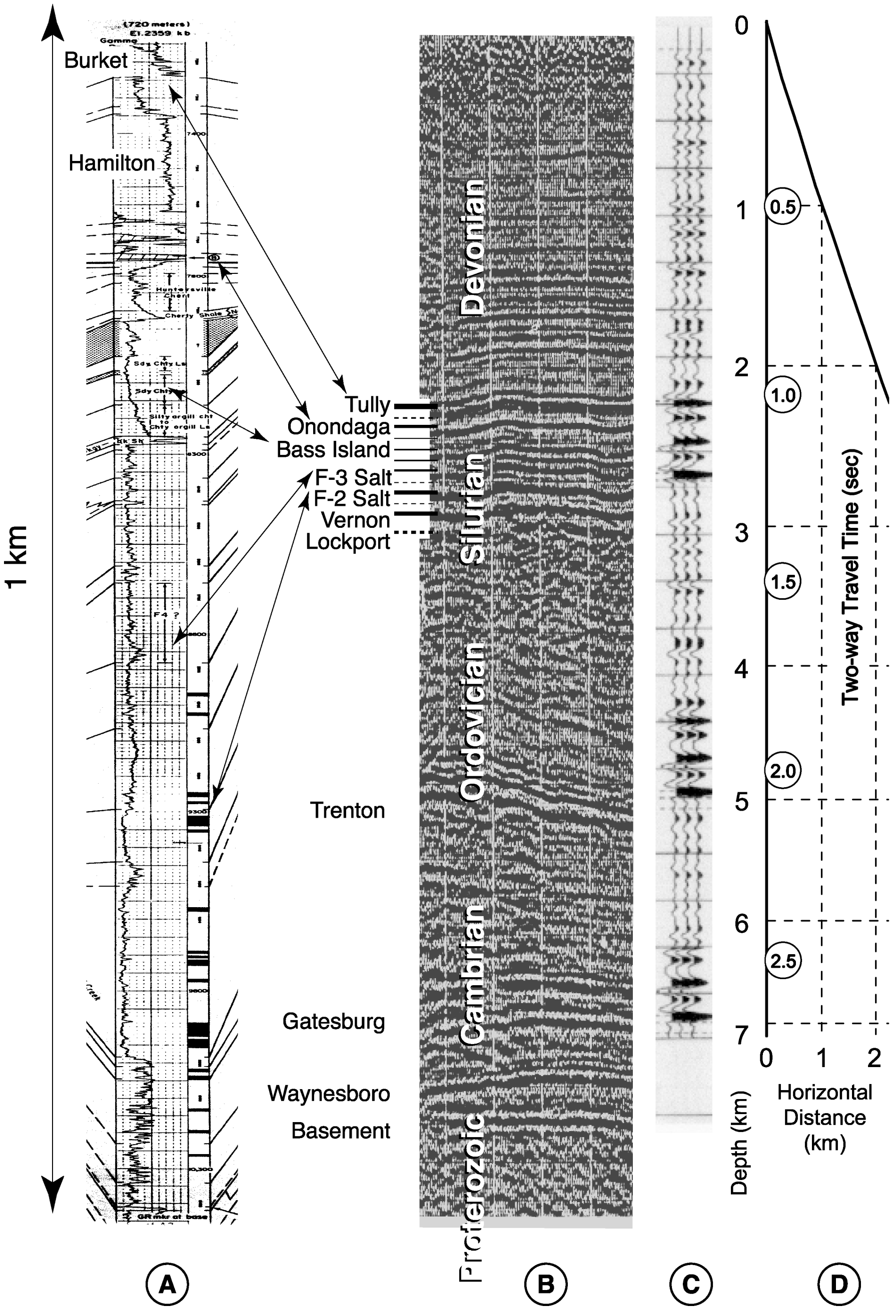


Fig. 4. Geophysical correlation suite: A. Portion of a gamma-ray well log from the Ricks No. 1 well between the Tully limestone and the Lockport dolomite about 960 m below (see table 1 for a more complete stratigraphic column). B. Seismic profile LH-50 (migrated time section) with geological time scale and major stratigraphic layers responsible for marker reflections on seismic lines. Horizontal trace spacing depends on vintage of seismic recording with the most common spacing at 45.7 m (that is, 50 yards) with 914 m (that is, 1000 yards) between vertical index lines. Approximately 3:1 vertical exaggeration. C. Synthetic seismogram derived from Amoco Svetz #1. D. Depth-horizontal distance chart with depth scaled to two-way seismic travel time. This diagram allows calculation of average velocities within the seismic profiles.

Table 1

Stratigraphic column for the Appalachian Plateau

System	Unit	Thickness (m)
Carboniferous	Mauch Chunk Fm.	135-142
	Loyalhanna Fm.	12
	Burgoon Fm.	49
	Rockwell Fm.	115
Devonian	Catskill Fm.	515
	Lock Haven Fm.	150
	Brallier Fm.	697-1060
	Genesee Fm.	49
	Tully Limestone	20
	Hamilton Gp.	110
	Onondaga Gp.	42-46
	Oriskany Sandstone	42-57
	Helderberg Gp.	13
Silurian	Bass Island Gp.	15-39
	Salina Gp.	330-600
	Lockport Dolomite	1-100
	Clinton Gp.	100-223
	Tuscarora Fm.	45-133
Ordovician	Juniata/Bald Eagle Fms.	291
	Reedsville Shale	287-515
	Trenton/Black River Gp.	312-396
	Beekmantown Gp.	726-1206
Cambrian	Gatesburg Fm.	348-954
	Warrior Fm.	134-909
	Waynesboro	>100

Unit	Formation	lithology	Thickness (m)
	Burket Memb.	shale	3-30
G	Camillus	shale	50
F		evaporite beds	240
E	Syracuse	evaporite beds	160
D		evaporite beds	
C		shale	150
B	Vernon	evaporite beds	
A		shale	

data from Lindberg (1985)
CSD NO. 160 Col. 17 & 18

with the mechanical behavior of the stratigraphy, is used to guide the seismic interpretation process.

The majority of the seismic signal in the Upper Devonian interval is 35 Hz providing a conventional vertical resolution of 33 meters; the Lower Devonian interval is traversed by seismic wavelets in the 25 to 30 Hz range yielding resolution of 42 meters; and the Cambro-Ordovician section is imaged by 20 Hz energy with a resolution of 56 meters. Average velocities used for time to depth conversion can be calculated using the Depth-Horizontal Distance Chart (fig. 4). The conventional limits set forth above pertain to the vertical resolution of stratigraphic layering. Vertical faults offsetting flat-lying strata can be detected at one-half of the above interval, while dipping faults have somewhat lower resolution. The necessary and sufficient condition for recognition of features in the horizontal domain is two samples per apparent wavelength. The majority of this seismic data set has a subsurface sample interval of 50 meters and therefore represents the smallest feature resolvable in the conventional sense. Even though many smaller structures in the Upper Silurian and Lower Devonian are below the conventional limits of resolution, our experience from drilling and outcrops of similar structure guides our interpretation.

The Upper Devonian section consists of alternating thin sands and shales with moderate physical property contrasts between adjacent beds that produce lower amplitude reflections. In general, the undeformed Upper Devonian section produces a seismic signature showing a layered sequence of weaker reflections that have few distinguishing features. Well-developed layering is found in the flat synclinal areas of the detachment sheet (fig. 4). With the development of subtle, smaller scale structures in detachment sheet anticlines, the Upper Devonian interval loses the clear continuity of its layered signature. In the absence of well-control points, it is extremely difficult to track individual reflections from the undeformed synclinal areas into the detachment sheet anticlines. Even with well control it is difficult to track individual reflections when the reflections (that is, layers) are discontinuous.

There are greater acoustic impedance contrasts between adjacent layers of the Upper Silurian through Lower/Middle Devonian section that produce stronger reflections. This sequence of reflectors is also horizontally layered in the flat synclines of the detachment sheet. The Upper Silurian through Lower/Middle Devonian section shows a disruption of layers within the anticlines but the distinctive seismic signature of this reflector package can generally be correlated with sufficient confidence to define distinct structures in the anticlinal zone.

Stratigraphic Interval Thicknesses from Gamma-ray Logs

The Upper Devonian interval is a thick section of alternating sands and shales typically with a sand at the top and a black shale at the bottom of each sequence (Piotrowski and Harper, 1979; Ettensohn, 1985). The seismic signature, characteristic of lower impedance contrasts, is weak and of less value in confidently measuring tectonically induced thickness changes within the section (fig. 4). In well data, however, several events within the Upper Devonian sequence can be tracked using distinctive gamma ray well log signatures. These can be used to measure thickness changes within the Upper Devonian interval at 11 locations in the region. Markers at the top of the Burket Shale and the Mississippian Loyalhanna Limestone give a range of thickness that are listed in table 2.

A THREE-TIERED MECHANICAL STRATIGRAPHY WITHIN THE APPALACHIAN PLATEAU DETACHMENT SHEET

During slip toward the foreland, the Appalachian plateau detachment sheet folded into a series of periodically spaced anticlines (fig. 1). Seismic sections reveal patterns that can be interpreted to characterize a three-tiered mechanical stratigraphy for these anticlines located within the Upper Silurian through Upper Devonian section. From bottom to top these mechanical layers are: a thin basal detachment zone of Upper Silurian strata, an Upper Silurian through Lower/Middle Devonian imbrication zone, and an upper most wedge zone consisting of the Upper Devonian through Mississippian rocks. A sharp contrast exists in the seismic reflection pattern: wavy, segmented, and thickened within the anticlines and smooth, flat, and thinner within the synclines. This pattern will be demonstrated later. Structural complexity passes continuously from anticline to syncline only within the basal detachment zone. The following sections of our paper describe the internal structures within each tier of the detachment sheet.

The Detachment Zone

It is commonly assumed that the Silurian Salina Group is the host of the décollement upon which the Appalachian plateau detachment sheet was transported toward the foreland (Gwinn, 1964; Prucha, 1968; Frey, 1973). In southwestern Pennsylvania, the two thickest formations of the Salina Group are the Vernon, a unit of red and green shale, and the Syracuse, an interbedded dolomite, anhydrate, and salt (Cotter and Inners, 1986). These two plus the Camillus and Bertie Formations give the Salina Group an overall thickness of 650 meters (Heyman, 1977). The F-2 and F-3 salts of the Syracuse Formation can exceed 50 meters locally but are not regionally continuous and, therefore, cannot account for the regional extent of the plateau décollement, particularly in southwestern Pennsylvania (Fergusson and Prather, 1968; Heyman, 1977). However, the Vernon Formation does provide such a regional continuity.

The definition of the position and the extent of the décollement within the Salina Group are best expressed referring to a section through Chestnut Ridge (for example,

Table 2

Tectonic thickening results

Laurel Hill Anticline

			←Depth below Kb(m) →					Interval ← Difference→	
Well No.	**Well Name (State Permit No.)**	**Structural Position**	**KB**	**Mlh**	**Dbh**	**Dbr**	**Don**	**(Dbr-Mlh)**	**Percent Thickening Between Wells**
1	Fee #1 (20018)	ON	864	107	1278	2430	2645	2323	1 & 4 = 13% 1 & 5 = 15%
2	Seven Springs #1 (20495)	ON	584	0	1225	2288	2543	2288	1 & 6 = 22% 1 & 7 = 23%
3	Hay's #1 (20131)	ON	860	178	1341	2413	2694	2234	2 & 4 = 11% 2 & 6 = 19%
4	Berkey #1 (20037)	OFF	620	314	1369	2369	2649	2055	2 & 7 = 20%
5	Barron #1 (20038)	OFF	639	332	1354	2357	2634	2024	3 & 7 = 17%
6	Detweiler #1 (20030)	OFF	630	274	1316	2168	2491	1924	3 & 6 = 15%
7	Barger #1 (20169)	OFF	639	236	1300	2160	2466	1893	3 & 4 = 8% 3 & 5 =10%

Chestnut Ridge Anticline

			←Depth below Kb(m) →					Interval ← Difference→	
Well No.	**Well Name (State Permit No.)**	**Structural Position**	**KB**	**Mlh**	**Dbh**	**Dbr**	**Don**	**(Dbr-Mlh)**	**Percent Thickening Between Wells**
11	Felmont Trt 42	OFF	590	191	1470	1857	2337	1666	8 & 9 = 15% 8 &10 = 21%
10	Burrel #1	OFF	601	213	1483	1902	2360	1689	8 & 11 = 23%
8	McKelvey #1	ON	634	98	1285	2152	2370	2055	9 &10 = 10% 9 &11 = 9%
9	Smith #5	ON	590	125	1221	1918	2169	1793	

Wells used to document tectonic thickening across Laurel Hill and Chestnut Ridge Anticlines. Well numbers correspond to figure 3.

Note: Formation abbreviations used in the above tables: KB = Kelly Bushing; Mlh = Loyalhanna Limestone; Dbh = Brailler Sandstone; Dbr = Burket Shale; Don = Onondaga Limestone.

CR-64, fig. 1). Within the upfolded detachment sheet we identify coherent folding within a section that includes the Tully, Onondaga, Bass Island, F-2 salt and F-3 salt (fig. 5). Most of the fold volume is occupied by a footwall ramp cutting to the level of the F-2 salt within the Syracuse Formation. The ramp dips at an angle of about 25°, which is not as steep as many splays depicted in the Gwinn model (fig. 2). The hinterland (that is, ESE) limb of the anticline is over steepened as is characteristic of Appalachian plateau folds. In the footwall, we recognize reflectors of the Lockport passing under Chestnut Ridge disrupted by a few minor, high-angle faults having < 50 meters of slip. A minor amount of Vernon shale may have been thickened by thrusting to fill the fold

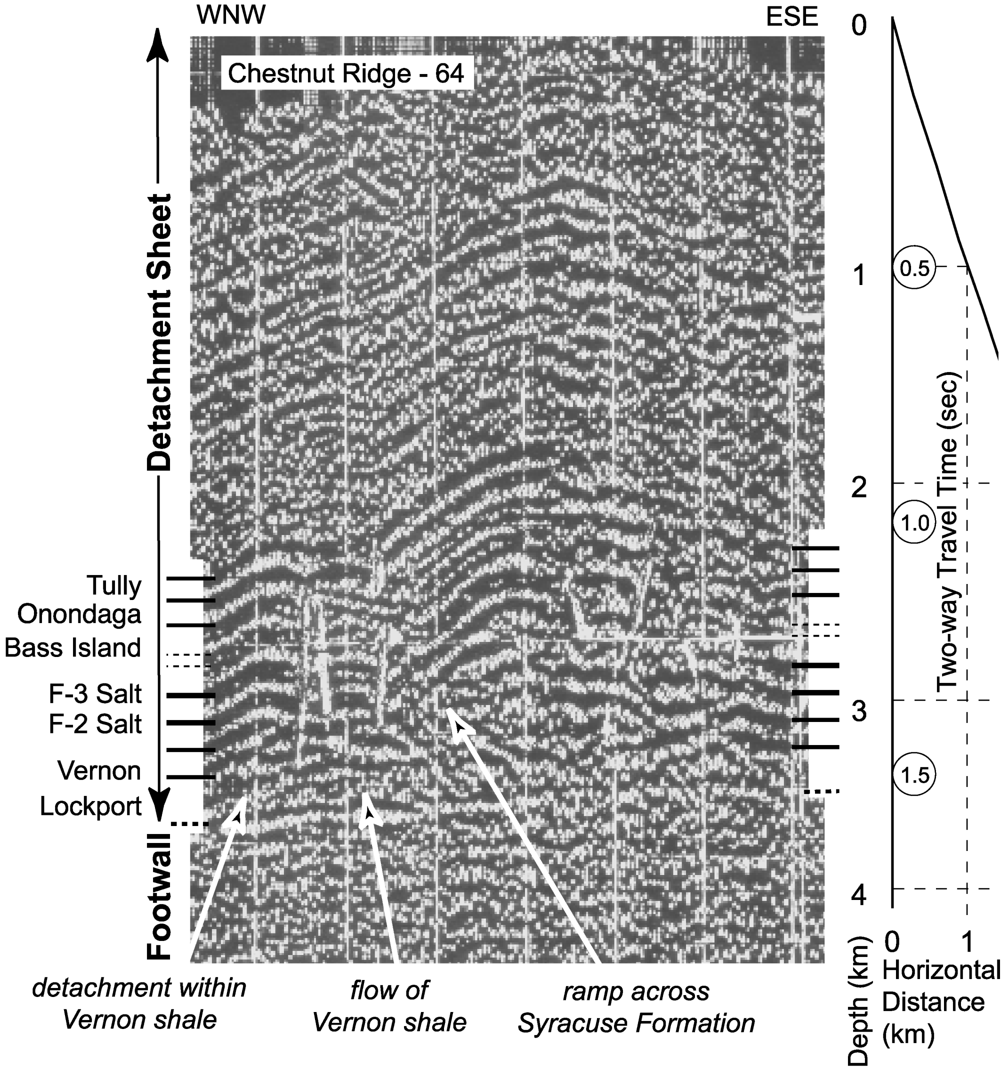


Fig. 5. Boundary between the detachment sheet and footwall annotated on seismic profile CR-64 (migrated time section) across Chestnut Ridge Hill anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

volume created by the upfolding of the detachment sheet. This view is consistent with the Wiltschko-Chapple flow model for detachment sheet folding except that the filling lithology is the Vernon shale rather than salt from the Syracuse Formation. While the Upper Silurian through Lower/Middle Devonian section is unusually coherent in CR-64, this cross-section clearly demonstrates that salt and encasing carbonate beds of the Syracuse Formation act as a single mechanical package lifting off from the Vernon shale and then folding concentrically. Detachment from the underlying Lockport dolomite appears to be complete.

A cross section through the Fayette Anticline shows two hinterland verging folds detaching at the level of the Vernon shale (fig. 6). These folds merge disharmonically

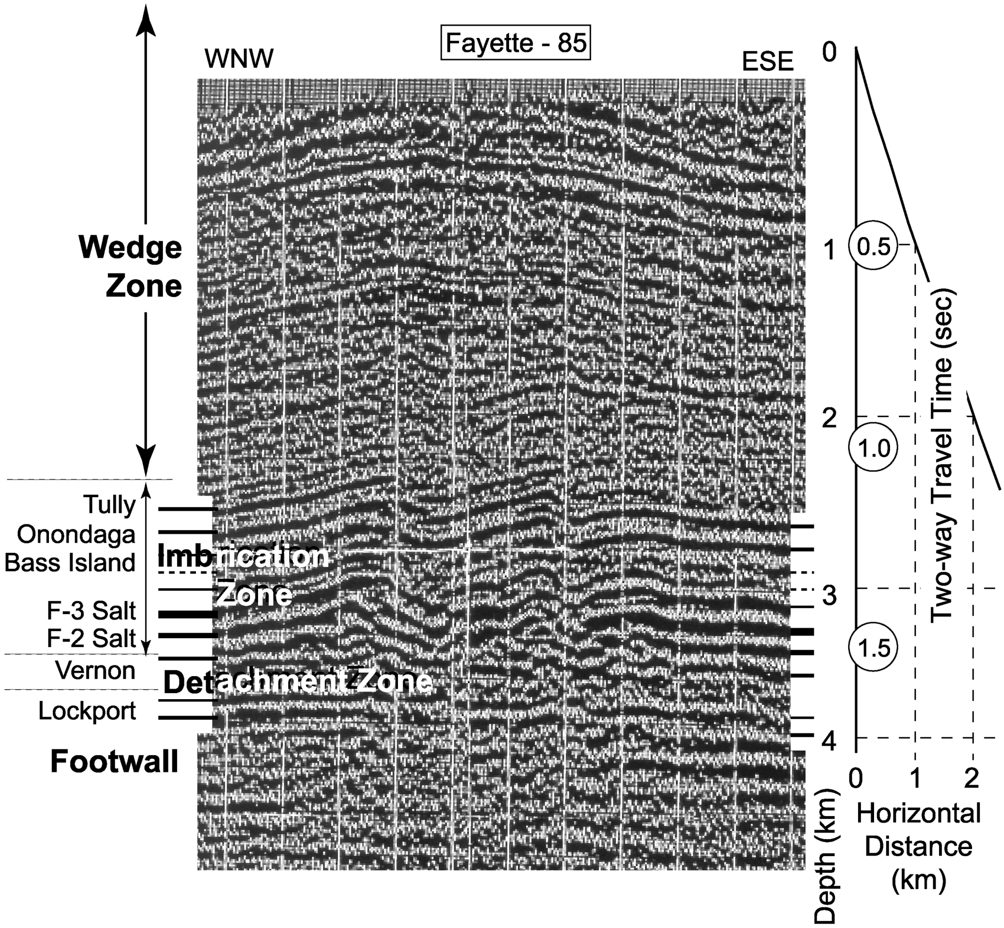


Fig. 6. The components of the three-tiered model annotated in their appropriate position on seismic profile F-85 (migrated time section) across Fayette anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

upward to become one anticline within the Upper Devonian section. The Lockport dolomite constitutes the un-deformed footwall bed along which the detachment sheet rides. Here again, the F-2 and F-3 layers gradually lift off the bed of Lockport dolomite to give the impression that ramps on thickening wedges in the Vernon shale fill the fold volume under each fault-related fold. Behavior of the detachment surface under both Chestnut Ridge and Fayette anticlines show that the top of the major décollement horizon is the Vernon shale rather than the salt units of the Syracuse Formation. Hence, we regard the Vernon shale as the *detachment zone* and the bottom tier of a three-tiered mechanical stratigraphy within the Appalachian plateau detachment sheet. These seismic profiles revise the historical interpretation that the thicker Silurian salt is the principal Appalachian detachment surface (for example, Gwinn, 1964; Wiltschko and Chapple, 1977; Davis and Engelder, 1985).

The seismic signature within the detachment zone displays panels of stratification that bear a strong resemblance to the formation of horses with long flats much like those found in the larger-scale Pine Mountain thrust (Kilsdonk and Wiltschko, 1988).

This suggests that the Vernon shale may consist of several thin salt layers with very little mechanical strength while its internal arrangement provides sufficient competence to permit thickening by thrust imbrication. Such a structural fabric differs from the standard seismic expression of intervals composed predominantly of salt that typically display an unorganized appearance commonly referred to as 'oatmeal' (Jenyon, 1986).

In summary, rather than the entire Salina Group or even the thickest salts of the Syracuse Formation, it is the Vernon shale that hosts the primary décollement surface at the base of the Appalachian plateau detachment sheet in the Bedford-Pittsburgh region. Thrust ramps transfer some of the lateral décollement slip into the F-2 and F-3 salts of the Syracuse Formation. The Vernon shale interval manifests a seismic expression that indicates a relative stratigraphic disorganization beneath both the undeformed synclines and the detachment sheet anticlines (figs. 5 and 6). We note that the Vernon shale thickens somewhat in the core of the anticlines.

The Imbrication Zone

The structural style of thrust-related repetition of stratigraphy in the Lower/Middle Devonian litho-stratigraphic unit of the Appalachian plateau detachment sheet, as expressed in the Gwinn model, is well-established and widely accepted (Gwinn 1964; Harper and Laurghry, 1987). The Lower/Middle Devonian section contains several carbonate beds (Tully, Onondaga, and Helderberg limestones) with interbedded clastics (Marcellus shale and Oriskany sandstone). This section on the seismic data exhibits several distinguishing features including fewer total folds, but larger amplitude folds relative to the detachment zone of the Vernon shale (figs. 5 and 6). In a departure from the previous literature, we include the upper part of the Upper Silurian Salina Group in the same structural/mechanical layer as the Lower/Middle Devonian section (figs. 5 and 6). Thus, it is common to find that the entire lithostratigraphic package, from the Syracuse Formation through the Tully limestone, deforms above a common network of splay faults ramping from the Vernon detachment zone. From the seismic images we infer that some of these thrust ramps tip out in weaker units, mainly within the salts of the Syracuse Formation or shales within the upper portion of the Lower/Middle Devonian section. Many of these fault-related folds exhibit shapes that resemble either fault-propagation folds or fault-bend folds depending on whether the fault tip finds an upper level detachment surface (Suppe, 1983, 1985).

Some of the fault-related folds do not extend throughout the entire Upper Silurian and Lower/Middle Devonian section. These smaller-scale fault-related folds and splay faults appear as intra-stratal bounded by upper and lower detachments within the salt of the Silurian Syracuse Group. A cross section through Laurel Hill (that is, LH-50) interprets fault-related folds emerging from a layer above the F-3 salt to explain the wormy seismic image (fig. 7). A duplex of at least four horses shows a foreland vergence. Here, fault-related folding is coherent through 450 meters of section from the Upper Silurian through the Tully limestone. The hinterland-most horse has the classic fault-bend fold shape with the forelimb panel dipping more steeply than the backlimb (fig. 7). The southeast limb of Laurel Hill at LH-50 most closely resembles the Gwinn model with a detachment in an upper salt feeding slip into a series of blind thrusts.

Individual fault-related folds also involve mechanically stiff struts less than 100 meters thick. The forelimb of cross section LH-50 also contains panels of Tully limestone that detach as individual struts with a hinterland vergence (fig. 7). Another cross section through Laurel Hill (that is, LH-14) shows fault-related folds emerging from both the F-2 and F-3 salt (fig. 8). Fault-related folds at the level of the Onondaga and Tully limestones also emerge from Lower Devonian detachments in shale. We believe that the seismic image arises from the dolomite layers of the Syracuse

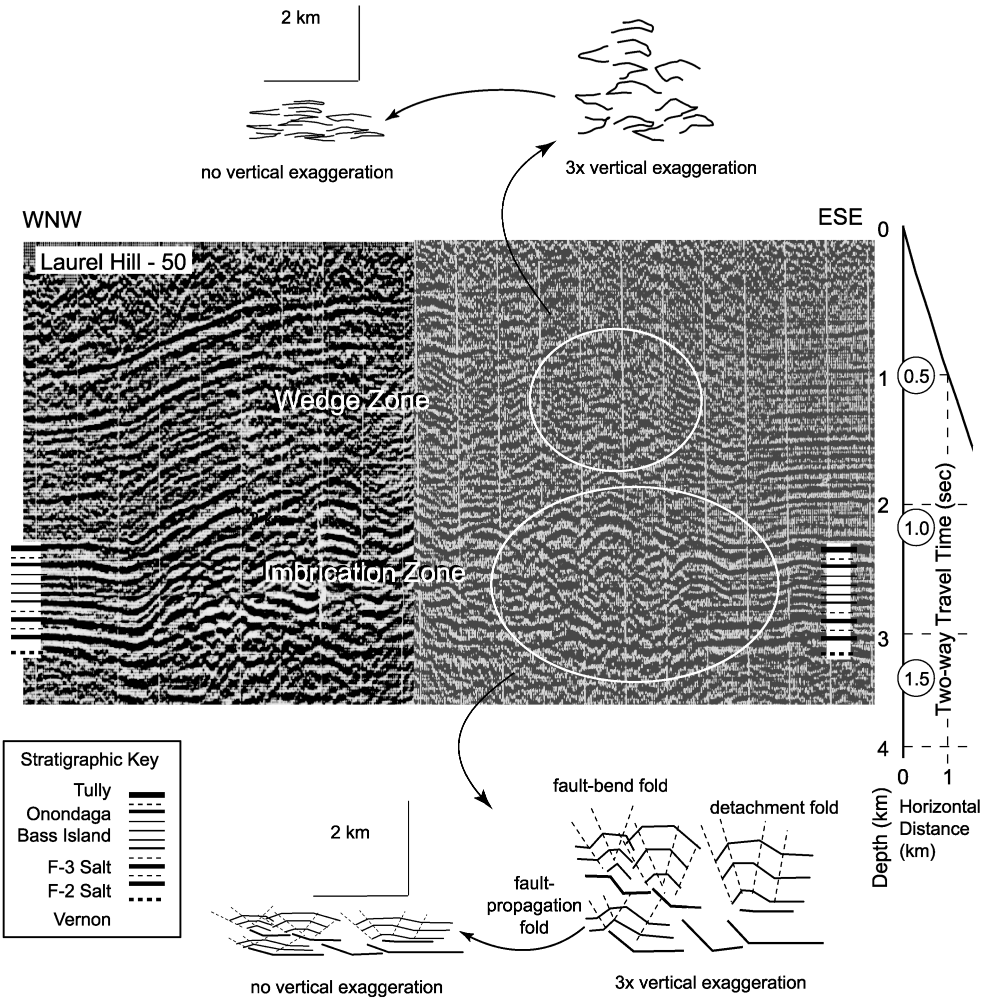


Fig. 7. Interpretation of structural style within the wedge and imbrication zones of the detachment sheet as found in seismic profile LH-50 (migrated time section) through Laurel Hill anticline (see fig. 1 for location). Schematic line drawings are shown at 3:1 vertical exaggeration, as portrayed in seismic sections, and with no vertical exaggeration.

Formation acting as thick, stiff struts in a manner similar to the carbonates of the Lower/Middle Devonian section (fig. 8). Structures in the Upper Silurian through Lower/Middle Devonian section are consistent with a stratigraphic interval containing thick competent units, mainly carbonates, that detach on thin weaker units, mainly salt and shale that act as both roof and floor thrusts.

Relatively more organized reflection patterns are interpreted to arise from the thicker, more competent units of the Upper Silurian through Lower/Middle Devonian section (figs. 5 - 8). These folds commonly stack in an imbricated pile with the affiliated detachment faults cutting unidirectionally up through the stratigraphic section in the form of a blind imbricate complex (McClay, 1992). Because low-angle faults within the Upper Silurian through Lower/Middle Devonian section are stacked with ramps dipping in one direction in a duplex, we draw a distinction between them

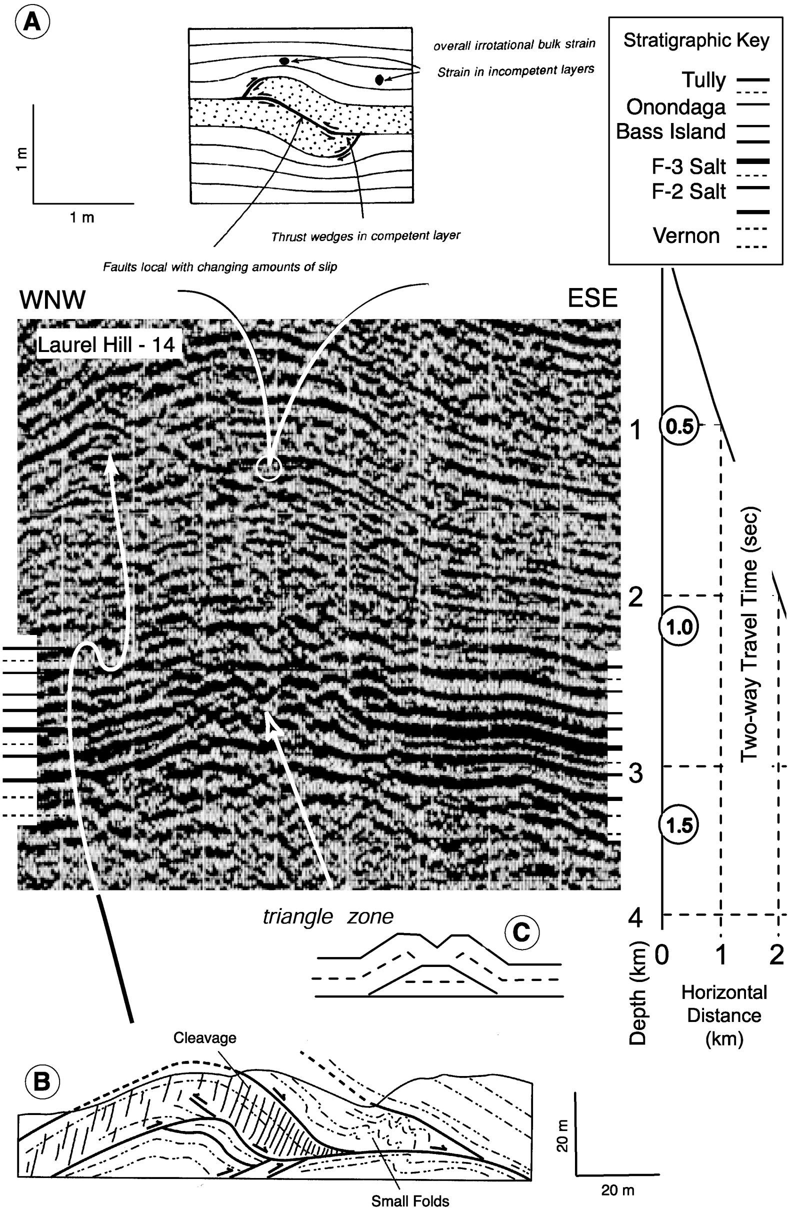


Fig. 8. Thrust wedges on seismic profile LH-14 (migrated time section) through Laurel Hill anticline (see fig. 1 for location). A. A thrust wedge similar to those found in the Wills Creek Formation at Round Top railroad cut, Maryland, represents our interpretation of subseismic-scale structures in the wedge zone of the detachment sheet (adapted from Ramsay, 1992). B. A thrust wedge from the Helderburg Group of the Hudson Valley fold-thrust belt represents our interpretation of seismic structures in the wedge zone of the detachment sheet (adapted from Marshak and Engelder, 1985). C. Line drawing of a triangle zone (adapted from MacKay, and others, 1996). Seismic profile shown at 3:1 vertical exaggeration whereas the line drawings show no vertical exaggeration.

and the underlying detachment zone. This second tier of the Appalachian plateau detachment sheet is called the *imbrication zone.* Unfortunately, resolution does not permit an analysis of the manner in which slip is transferred from the basal décollement in the Vernon shale to the upper detachment horizons in the salt in the Syracuse Formation and shale in the Lower/Middle Devonian section.

Central triangle zones.—Some detachment sheet anticlines tend to be oversteepened on the hinterland side (figs. 5 and 6). These are often cored with an imbrication zone stacked with ramps dipping in one direction. Other anticlines show two stacked sections with opposite vergence on either side of a central depressed block (figs. 7 and 8). This latter geometry is that of a triangle zone as is well documented in the foothills of the Canadian Rockies of Alberta, Canada (Gordy and others, 1977). The Canadian foothill triangle zone is found at the leading edge of a foreland fold-thrust belts and is, then, a single anticline that extends for considerable distance along strike (that is, Jones, 1996) or an en echelon arrangement of triangle zone (that is, Mackay and others, 1996). In contrast, these Appalachian plateau triangle zones are found in the cores of several of the detachment sheet anticlines. Hence, several of the triangle zones are incorporated within the detachment sheet as the detachment tip-line advances and the sheet is gradually transported toward the foreland. These deep triangle zones represent a stark contrast to the shallow triangle zone found in the Canadian Rockies.

Stacking of several secondary imbrication zones can occur when detachment takes place at multiple levels (fig. 7). When secondary stacking is accompanied by two-sided vergence toward the crest of the anticline, there can be a stacking of several triangle zones (fig. 8). Laurel Hill anticline, in particular, is characterized by vergence of the fault-related folding toward the crest of the anticline and stacked triangle zone (figs. 7 and 8).

In summary, the Upper Silurian through Lower/Middle Devonian lithostratigraphic unit may act as a thick, competent strut that deforms in unison or it may detach into several layers, some as thin as 100 meters. When acting as a series of thinner struts, each mechanical unit detaches along both roof and floor thrusts in a structural style described as a passive-roof duplex (Cooper, 1996). Regardless of the thickness of the mechanical struts, when they verge from both sides toward the central core of the anticline, triangle zones are found.

The Wedge Zone

The Upper Devonian section breaks into many small fault-related folds above low-angle faults within the crests of the detachment sheet anticlines (fig. 8). Although many of the structures beneath the surface anticlines of the detachment sheet are sub-seismic and difficult to resolve, some of the larger scale structures (that is, > 100 m) can be detected in the Upper Devonian section (figs. 6 - 8). Because these small fault-related folds approach the limit of seismic resolution, any interpretation has a subjective element and certainly our interpretation of Upper Devonian section in seismic line LH-50 is not the only possible interpretation (fig. 7). However, it is beyond doubt that smaller-scale structures within the Upper Devonian section exhibit a combination of hinterland and foreland thrusting directions with individual structures appearing more like wedges than kink folds (fig. 8). Wedge thrusts or wedges are commonly not stacked unidirectionally (van der Pluijm and Marshak, 1997). Hence, this zone of thrust wedging in the upper tier of the detachment sheet anticlines is herein called the *wedge zone.*

The Upper Devonian-Mississippian parts of the detachment sheet anticlines can be divided into three dip panels: 1. east-dipping panel (east limb), 2. flat-lying panel (crest), and 3. west-dipping panel (west limb). Section LH-50 has a relatively wide (4-6 km) flat-lying central panel with narrower (3 km) flanking panels (fig. 7). The dip of the flanking compartments as well as the fold amplitude of the entire Upper Devonian section mirrors the dip and amplitude of the underlying Upper Silurian through Lower/Middle Devonian interval. The flanks and central panel are lifted into place by imbrication (that is, local section repeats) of the more competent Upper-Silurian through Lower/Middle Devonian section. Within the central panel, which is in a strict sense, the wedge zone, structures should exhibit both foreland and hinterland vergence with evidence of wedge thrusts in both hanging walls and footwalls as is seen in outcrops within the Appalachian Mountains (that is, Geiser, 1974). Because the largest structures within the central panel are at the detection threshold and explain only part of the observed areal shortening we suggest that there are many structures below the limit of detection. A mottled seismic signature, common to the Upper Devonian section in all anticlines in the detachment sheet, is characteristic of the extreme breakup of bedding.

Expectations arising from the Wedge Zone Hypothesis.—There are a number of tests to verify the existence of thrust wedging in the Upper Devonian section. First, wedges occur at larger scales as well (Marshak and Engelder, 1985). Second, wedges are typically restricted to competent beds between incompetent units with back-thrusting common along the roof of the competent bed (Cloos, 1964). The Upper Devonian section is interlayered with competent sandstones and incompetent shale. Most of the sandstone beds are intraformational units below seismic resolution. Third, wedges may occur at several scales depending on the thickness of the mechanically competent unit (Alvarez and others, 1978). If they are present in the Upper Devonian section of the detachment sheet, they should also be present throughout the Appalachian Mountains. Larger examples of wedged sequences include the Silurian Bloomsburg Formation at Cacapon Anticline (Geiser, 1974) and the Devonian Helderberg Group along the Route 23 road cut at Catskill (Marshak and Engelder, 1985). Fourth, bedding-plane slip is associated with low-angle thrusting in sections that contain wedge thrusts. When single beds are involved in wedging, the footwall bed is just as likely to be down-folded as the hanging wall bed is to be up-folded and both bedding surfaces should exhibit bedding-plane slip (Ramsey, 1992). These slip surfaces are seen in well core from plateau anticlines (Cliffs Minerals, 1982). Fifth, wedging is a mechanism that tectonically thickens a section. Thickening can be measured using both well logs and seismic sections.

Ground truth concerning the Wedge Zone Hypothesis.—A test of the wedge zone hypothesis starts with a search for bedding-plane slip in the Upper Devonian section using well core recovered during the DOE Eastern Gas Shales Program of the late 1970's. Wells drilled in the Bedford-Pittsburgh region include 'PA-4' near Indiana, PA and 'PA-2' near Monongahela, PA (fig. 3A). 'PA-4' was drilled on the western flank of Chestnut Ridge Anticline and recovered 271 meters of core from the Upper Devonian (Cliffs Minerals, 1982). In the core, slip surfaces include both bedding planes with slickensides (24) and faults (31) with the majority of these brittle structures occurring in the Upper Devonian section and the Lower/Middle Devonian section. PA-2 was drilled at the northern tip of the Belle Vernon Anticline where 162 meters of core was recovered from the Lower/Middle Devonian section (Cliffs Minerals, 1982; Evans, 1994). 128 faults have been logged in this core distributed mainly in black shale. In both wells the orientation of the slickenside lineations clusters around WNW (300°). This is compatible with the WNW transport direction for the Appalachian Plateau detachment sheet in the Bedford-Pittsburgh region.

Other core was taken in the Williamsport-Tioga region where the cross-strike lateral flow of salt is a likely mechanism for anticline growth. In this region, none of the EGSP wells sit in the proximity of the crest of an anticline. The best recovery record for the Upper Devonian came from EGSP well 'NY-1' (Allegheny county, NY). In 473 meters of core, 44 joints appear but no faults or bedding plane slickensides are found (Cliffs Minerals, 1982). 40 meters of core from a sub-Tully black shale taken in EGSP well NY-4 is heavily faulted as might be expected for fault-related folding at the level of the Tully.

In summary, faulting in core taken within the anticlines of the Bedford-Pittsburgh region is consistent with localized deformation in the wedge zones in the Upper Devonian. Post-Tully core from the Upper Devonian north of the Williamsport-Tioga section are free of faulting, a situation consistent with the undeformed synclines in the Bedford-Pittsburgh region.

Tectonic thickening within the wedge zones: Well logs.—Thrust wedging observed in the seismic sections should manifest itself as tectonic thickening of the anticlinal wedge zone. In order to test the tectonic thickening hypothesis using well logs, the following elements were required: (1) a group of wells that penetrated the entire Upper Devonian section (defined as the Loyalhanna Limestone-Burkett Shale interval), (2) wells that sample the folds in critical locations both on (anticlinal crests) and off (synclinal troughs) structure as well as on opposite flanks of the structure, (3) wells that possess a gamma-ray log suitable for lithologic correlation, and (4) wells that are in close proximity to a seismic line in order to verify the structural position of the well locations. Adjacent wells that provide sampling on and off structure and that meet the remaining criteria are scarce. Nevertheless, two areas met these criteria, one on Laurel Hill and one on Chestnut Ridge (fig. 3).

Tectonic thickening of the Upper Devonian section was calculated by measuring the thickness of the stratigraphic interval between the base of the Loyalhanna Limestone and the top of the Burket Shale (table 2). Regionally these units span across the upper and lower boundaries of the Upper Devonian. The results document thickening in the Upper Devonian wedge zones that varies from 7 percent to 23 percent depending upon the structural position of the wells being compared. In general, the greatest thickening was found between wells at the highest and lowest structural position. Lesser amounts of thickening were determined for wells in closer structural proximity. Despite the strong evidence for symmetrical and progressive thickening with increasing structural elevation demonstrated by the above result, there remained the remote possibility that depositional thickening might be mistaken for tectonic thickening. This was tested using regional isopach maps and no evidence was found for depositional patterns that could be responsible for the pattern of symmetrical thickening discovered on the crests of the anticlines and conspicuously absent in the intervening synclines (Scanlin, ms, 2000).

Tectonic thickening within the wedge zones: Seismic cross sections.—On the seismic sections, the contiguous, prominent reflection at the top of the Upper Devonian Tully partitions the detachment sheet anticlines into two layers. From digitized sections, the increase in thickness and cross-sectional area can be measured. For this purpose, reflectors of the Vernon, Tully, and the Mississippian Loyalhanna are traced (fig. 9). To illustrate anticlinal thickening in a qualitative manner, a square is drawn to the full thickness of both the wedge and imbrication zones of the detachment sheet. A square of the same size is placed over the central portion of the anticline. As expected, imbrication of the Silurian through the Lower/Middle Devonian section results in a thickening of that section. However, it is clear that a concomitant thickening of the Upper Devonian section took place, thus confirming the extent to which subseismic wedging affects anticlinal development.

In brief, to anticipate the discussion of additional seismic profiles in the next section of this paper, all detachment sheet anticlines are composed of the same three-tiered mechanical stratigraphy. From top to bottom, these tiers are the wedge zone, the imbri-

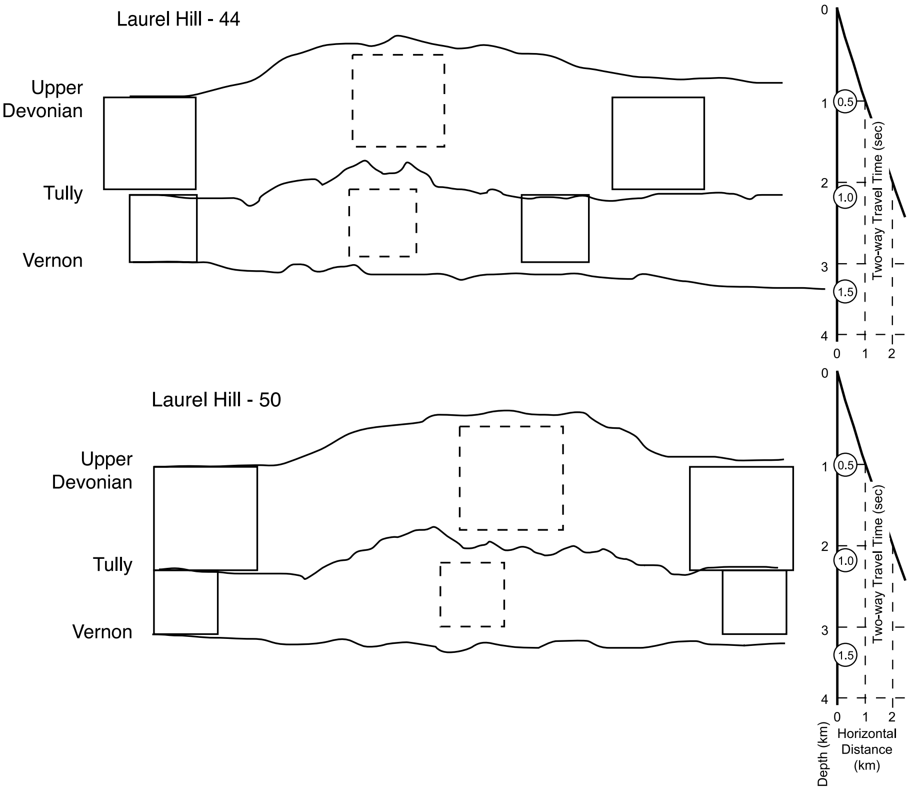


Fig. 9. Estimate of section shortening using a simple cross sectional area balance technique through Laurel Hill anticline at the level of the Tully Limestone. Section interpreted from seismic sections LH-44 and LH-50.

cation zone, and the detachment zone. Later we will also show that the anticlines vary in width and net cross-sectional area as a function of distance from the Allegheny Front.

THE COUPLING BETWEEN FOLDS IN THE DETACHMENT SHEET AND STRUCTURES IN ITS FOOTWALL

Rodgers's (1964) view of the Appalachian plateau was that of a thin-skinnned tectonic province. However, Rodgers (1964) did consider the possibility of "uplifts and downwarps of floorboards underneath the rugs; three have to rise up particularly strongly, at least relative to those beside them and they must be very long but roughly parallel floorboards". Seismic profiles from other thrust belts indicate a coupling between normal faults that cut the basement-sediment contact and younger thrust ramps (Schedl and Wiltschko, 1987). Evidence for this association in the Appalachian Mountains is found in southern Quebec (St. Julian and others, 1983), the Broadtop synclinorium (Jacobeen and Kanes, 1974), the Birmingham anticlinorium, Alabama (Thomas, 1982), and along the Appalachian-Ouachita trend (Lille, 1984).

Following Rodgers's lead geologists have also implied that there is a genetic link between the periodic anticlines of the detachment sheet and structures within the footwall (for example, Reeves and Morris, 1988; Towey, 1988; Beardsley and others, 1999). Our interpretation of seismic profiles supports this view point by documenting the structural style in both the hanging wall and footwall of the five most prominent structures of the detachment sheet in southwestern Pennsylvania: Negro Mountain, Laurel Hill, Chestnut Ridge, Fayette, and Belle Vernon anticlines. In addition, we note changes in structural style of the detachment sheet anticlines along their strike that also relate to the basement patterns.

Before a link can be established, evidence of the footwall structural patterns is required. Footwall structural patterns can be inferred from: 1. patterns in geophysical data from potential fields (that is, gravity and magnetics) and 2. deep seismic images of faulting or flexural bending in the Lower Paleozoic/basement. Analysis of footwall structures consists of tracking the geometry of the three most prominent reflectors in the Lower Paleozoic section of the Appalachian Plateau (fig. 4): 1. top of the Ordovician Trenton Formation (the Trenton reflector), 2. the middle of the Cambrian Gatesburg Formation (the Gatesburg reflector), and 3. a pair of reflectors including the Waynesboro Formation and the top of the Precambrian crystalline basement (basement reflection doublet). The latter two reflectors are inferred due to an absence of deep well ties. The style of structures indicated by these reflectors is different from structures found within the detachment sheet.

Coupling of structures across the Silurian décollement may, in part, depend on the thickness and lithological character of the Salina Group. In southwestern Pennsylvania, the depocenter of the Salina Basin was the Rome trough where the Salina Group is more than 580 meters thick (Fergusson and Prather, 1968). This is the Cambrian-Ordovician Olin Basin (Wagner, 1976). Here, in the vicinity of Chestnut Ridge, the F-2 salt is more than 50 meters thick. To the east under Negro Mountain, the Salina Group has thinned to about 360 meters and there is considerably less salt in the section (Heyman, 1977).

Negro Mountain

The Upper Devonian section at Negro Mountain is folded into a gentle anticline at least 16 kilometers in width (that is, seismic profile NM-11; fig. 10). Seismic-scale wedge thrusting is seen in the form of overlapping seismic reflections throughout the core of the anticline whereas the flanks contain largely undisturbed but gently dipping reflections. This wedge zone is nearly identical to that earlier described for Laurel Hill anticline (figs. 7 and 8). The Upper Silurian through Lower/Middle Devonian imbrication zone displays reverse faults with about 400 meters of structural relief at the Onondaga level with fault-related folds emerging from several detachment levels. Structural relief in the imbrication zone is developed by the stacking of horse blocks rather than as one coherent fault-related fold. Like Laurel Hill, the central portion of Negro Mountain imbrication zone is depressed and vergence is consistent with the development of one or more triangle zones in the central portion of the imbrication zone. There is disharmony between reflection patterns in the imbrication zone and the wedge zone.

The Vernon shale is nearly 200 meters thick in a well near Negro Mountain versus 125 meters in the anticlinal core beneath Chestnut Ridge (Heyman, 1977). Because the Lockport reflector cannot be identified with certainty in seismic profile NM-11, the contribution to overall structural relief developed by lateral flow of the Vernon shale cannot be determined. Never the less, Negro Mountain is different from other major anticlines further toward the foreland where the Lockport appears less disturbed and acts as the bed of the plateau detachment sheet. Here, topography at the Lockport horizon is interpreted to be a manifestation imbrication at the Trenton level. The mottled seismic texture over the imbricated Trenton also suggests a tectonic wedging within the section between the Trenton and the Lockport (fig. 10).

At the depth of the Trenton reflector there are imbricated structures with a basal detachment that resembles the Appalachian plateau detachment sheet above (fig. 10). A major difference is that this Lower Paleozoic carbonate imbrication zone possesses a

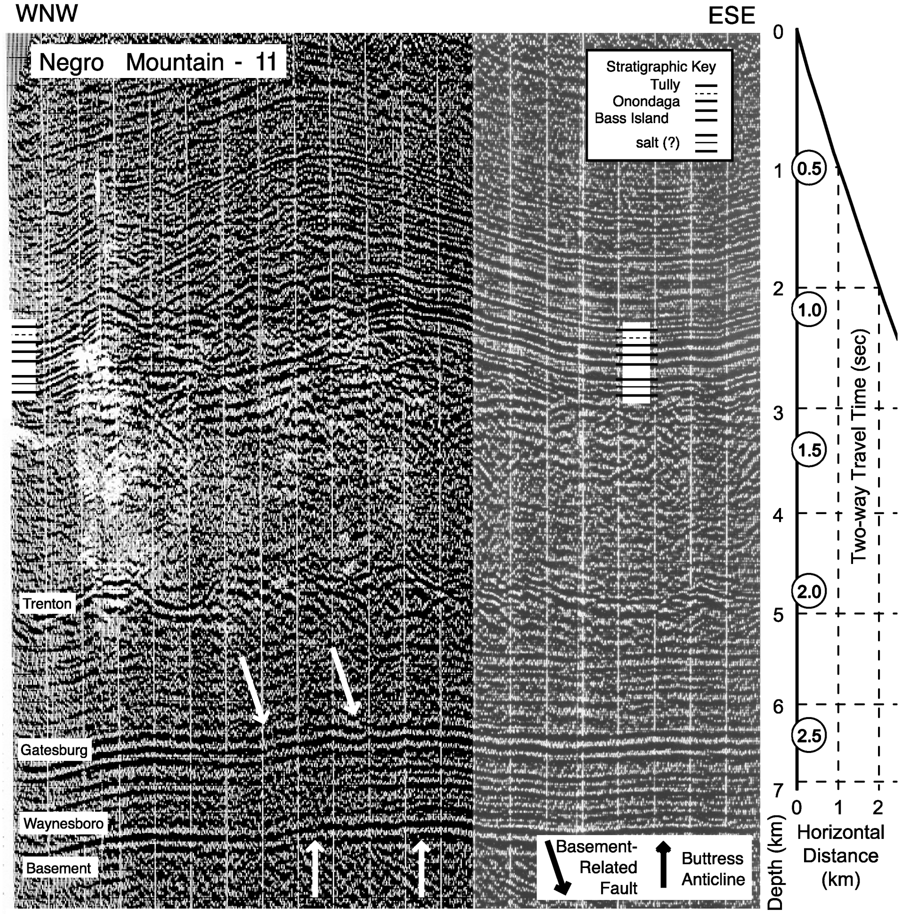


Fig. 10. Thrust imbrications at the level of the Trenton horizon and basement-related faults on seismic profile NM-11 across Negro Mountain anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

common vergence toward the foreland with no triangle zone. The layer-parallel shortening by thrust imbrication and folding is about 22 percent or slightly larger than layer-parallel shortening for the Appalachian plateau detachment sheet in western New York (that is, Engelder and Engelder, 1977). The structural relief is as much as 600 meters with several fault-related folds that are larger than many of their counterparts in the Upper Silurian through Lower/Middle Devonian section. The style of deformation of the lower Paleozoic does not produce a similar deformation pattern at the level of the Lockport. Seismic section NM-11 demonstrates that the structural relief within the plateau detachment sheet appears to come from the detachment zone rather than being passively lifted from thickening of the Trenton reflector (fig. 10). The core of the detachment sheet anticline at Negro Mountain has been pushed toward the foreland relative to the toe of the zone of Trenton structural relief (fig. 10). In style, if not magnitude, the detachment structures within the Trenton zone resemble those seen at the same level southeast of the Allegheny Front where they are believed to be evidence of a roof thrust above the massive Cambrian-Ordovician

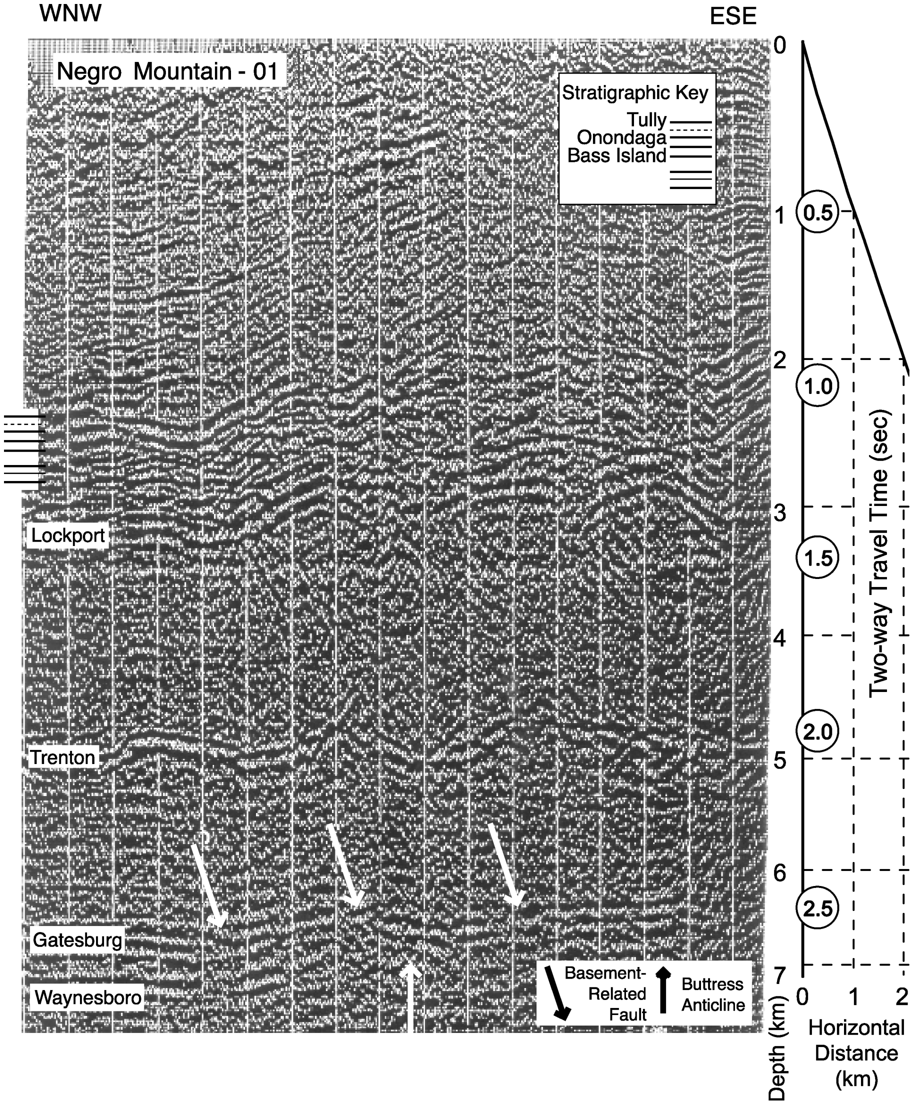


Fig. 11. Thrust imbrications at the level of the Trenton horizon and basement-related faults on seismic profile NM-01 across Negro Mountain anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

carbonate fault-related folds of the Valley and Ridge (Geiser, 1988a; Nickelsen and Engelder, 1989).

In contrast to seismic section NM-11, the Lockport is recognizable on seismic section NM-01 10 km SSW in the direction of the culmination of the Negro Mountain anticline (fig. 11). Here, unlike the section through the Fayette anticline (that is, F-85, fig. 6), the Lockport reflector, ordinarily the bed of the detachment zone, is disturbed from below. In NM-01, the Lockport reflector appears to deform conformably with structures below the floor thrust of the detachment sheet. The source of these fault-related folds at the level of the Lockport is unresolved. The style of the fault-related folding at the level of the Trenton is also variable with less apparent imbrication than 10 kilometers to the NNE.

At the Gatesburg reflector, structural relief is on the order of 350 meters as a consequence of the development of broad-open folds. Such open folding is strikingly different from the sharply developed detachment-like folds within the Trenton reflector. The lack of structural continuity between the Trenton and Gatesburg indicates foreland structural transport at the Trenton level relative to the Gatesburg level (that is, a detachment between the two). Bed length at the Trenton reflector is 22 percent longer than at the Gatesburg level in a 13 kilometer wide cross section (fig. 10). This requires an approximate 3 kilometers of westward transport of post-Trenton rocks at Negro Mountain above a sub-Trenton detachment. Slip on the Vernon detachment adds more shortening to the Appalachian plateau detachment sheet. This Trenton-level foreland transport probably roots into a basal detachment from the Cambrian Waynesboro shale in the Valley and Ridge Province. Into the Appalachian detachment sheet west of Negro Mountain the Trenton level shortening adds displacement to the detachment at the level of the Vernon shale.

In summary, what we will demonstrate is that, like Negro Mountain, the structures to the WNW in the direction of tectonic transport exhibit large-scale Silurian-Devonian folds that overlie locally developed smaller folds in the Ordovician Trenton. These in turn overlie perturbations in the basement reflector that may indicate basement-involved structures. The surface trends of these Appalachian plateau structures appear to follow and be localized by these basement features.

Laurel Hill

At Laurel Hill, the structures of the Appalachian Plateau detachment sheet are grouped into three tiers: an Upper Devonian wedge zone, a Silurian through Lower/Middle Devonian imbrication zone with central triangle structures, and a Silurian detachment zone (figs. 7 and 8). The structural tiers at Laurel Hill and Negro Mountain are similar but the individual thrust wedges within imbrication zone at Laurel Hill display more structural relief (that is, 450 m vs. 200 m) and have a wider cross section (compare figs. 12 and 13 with figs. 10 and 11). This larger structural relief in the imbrication zone is a consequence of the thickening dolomites of the Syracuse Formation as the depocenter of the Salina basin is approached.

Like its counterpart under Negro Mountain, structural relief at the level of the Trenton reflector under Laurel Hill mirrors that seen in the Silurian through Lower/Middle Devonian section (0.13 sec or 450 m). Detachment-related folding at the Trenton level is not as complex as that found under Negro Mountain nor do the detachments represent as much foreland transport. In some instances, more than a half dozen WNW verging thrust ramps are visible at the level of the Trenton (figs. 12 - 14) in a WNW distance of 22 kilometers. The most complex reverse faulting is found at the east side of the detachment sheet at Laurel Hill anticline. Although not visible, we infer that considerable detachment slip has been transferred up into the Vernon shale in the vicinity of Negro mountain and, hence, there is less thrust imbrication at the level of the Trenton.

The amplitude of a monoclinal bend at the level of the Gatesburg is about 250 meters (that is, figs. 12 - 14). In all sections of Laurel Hill this step-up to the west in the Gatesburg reflection shows little indication of detachment faulting (that is, it appears basement involved). High-angle basement-related faults appear in the vicinity of the monoclinal bend at the level of the Gatesburg. Vergence on these normal faults is generally but not always toward the WNW and is believed to be a manifestation of inversion of basement normal faults during the Alleghanian shortening of the Appalachian Plateau detachment sheets.

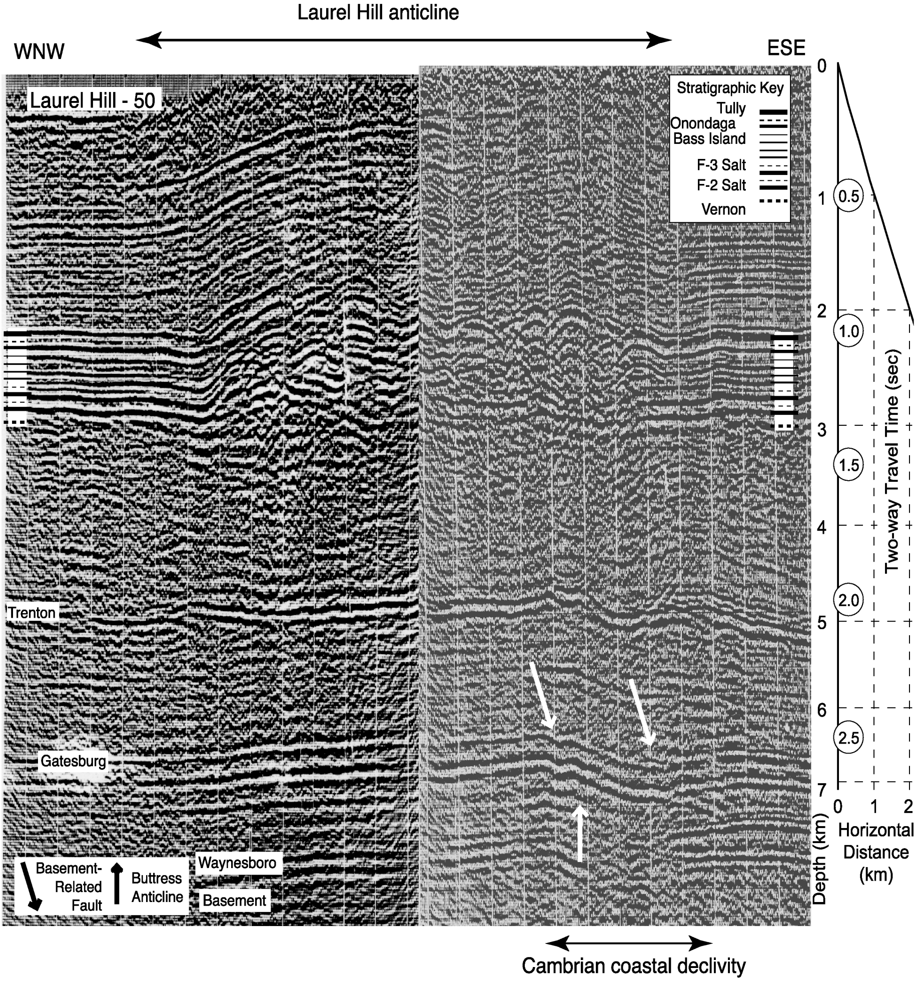


Fig. 12. Cambrian coastal declivity on seismic profile LH-50 across Laurel Hill anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

The monoclinal bend at the level of the Gatesburg is a uniformly developed structure in all seismic profiles through the Lower Paleozoic section under Laurel Hill (fig. 15). This is the crest of the Cambrian coastal declivity as imprinted on the Gatesburg reflector (Woodward, 1961). The edge of the declivity is an abrupt down faulting of basement by a few hundred meters. The crest of the declivity appears as a sharp bend with beds in the Gatesburg dipping more steeply to the east than to the west.

Chestnut Ridge

The detachment sheet at the Chestnut Ridge anticline displays a markedly different structural style when moving along the axis of the fold from SSW to NNE. The southwestern portion of the Chestnut Ridge anticline is narrower (that is, 8 km vs. 13 km) than Laurel Hill but displays the same three tier structure in cross section (figs. 16 and 17). To the northeast, the detachment sheet anticline has a less well-developed

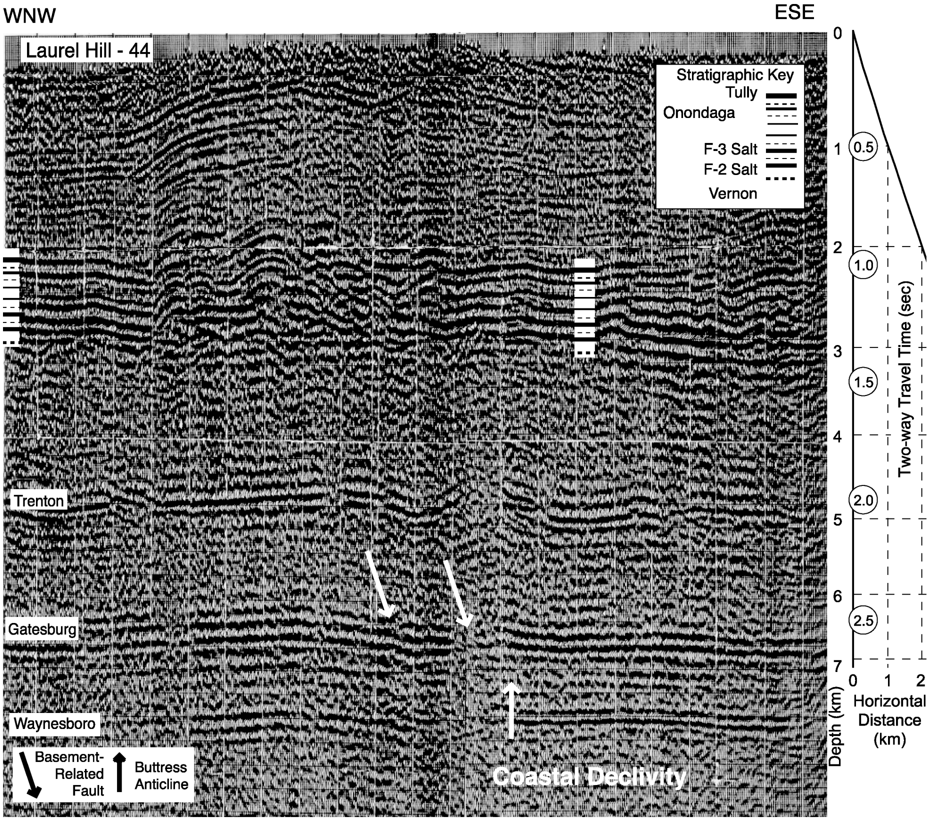


Fig. 13. Cambrian coastal declivity and associated basement-related faulting on seismic profile LH-44 across Laurel Hill anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

wedge zone and larger scale imbrication in the imbrication zone. The scale of fault-related folding in the imbrication zone leads to a more coherent fold throughout the Devonian section (fig. 18). Along the northeast section of Chestnut Ridge, the fault-related fold over a back thrust is the most coherent structure in the entire Appalachian Plateau detachment.

This change in structural style in the detachment sheet from wedge thrusting to coherent folding correlates with a remarkable change in the configuration of the sub-Salina section. At the level of the Trenton reflector, forward verging reverse faults are found (that is, CR-06; fig. 16). In seismic profile CR-06, it appears that the Trenton reflector has been pushed off a ledge. Here structural relief on fault-related folding is more than 100 meters but then the reflector spills down to the west. Further to the northeast, faulting in the Trenton reflector is more subdued than elsewhere (that is, CR-64; fig. 18). Although not completely flat, the Trenton reflector is only mildly undulating as it passes under Chestnut Ridge.

The most significant change in structural style along the trend of Chestnut Ridge anticline is seen at the level of the Gatesburg reflector. In seismic section CR-06 to the southwest, structural relief at the Gatesburg horizon is approximately 350 meters and this marks the ESE edge of the Rome Trough (fig. 16). Down-to-the-west throw of the northwest block stands in opposition to the throw on other faults at this level (for example, the coastal declivity under Laurel Hill). In general, the Chestnut Ridge

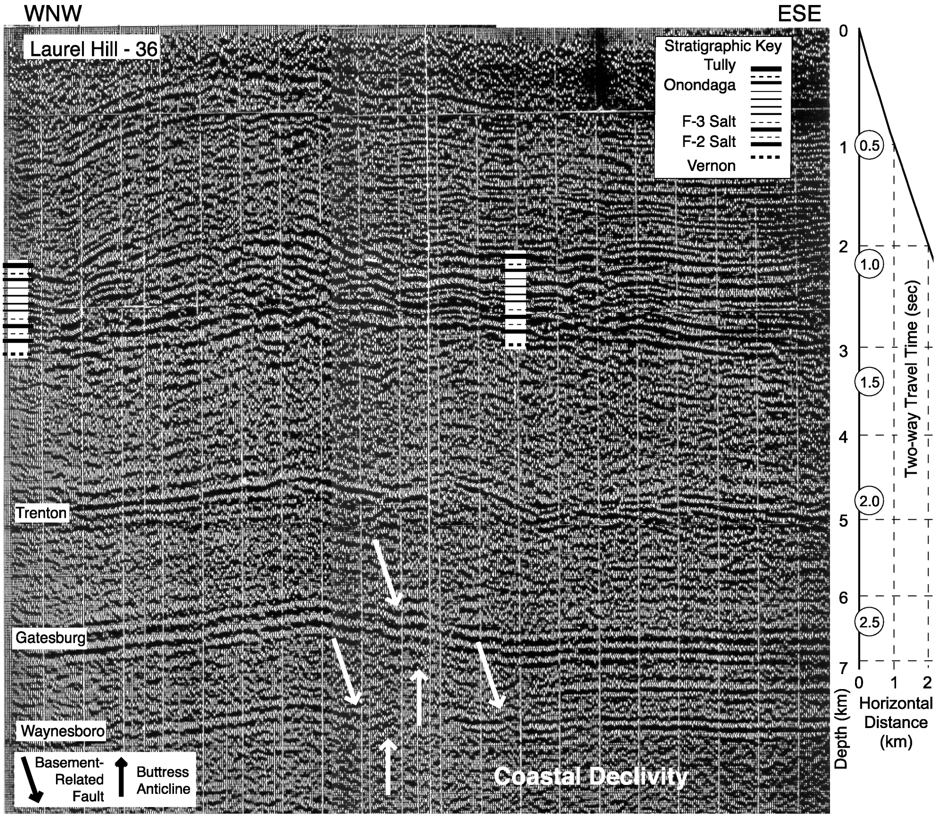


Fig. 14. Cambrian coastal declivity and associated basement-related faulting on seismic profile LH-36 across Laurel Hill anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

anticline is positioned so that its eastern or trailing edge is coincident with the eastern horst block of the Rome Trough.

To the northeast along Chestnut Ridge, evidence for a down-dropped western block in the Rome Trough is lost (that is, CR-64; fig. 18). In fact, this is the section of Chestnut Ridge where the structural style in the detachment sheet changes from a wedge zone in the Upper Devonian section to more classic concentric folding. Unlike the Coastal Declivity, a northeastern terminus of the Rome Trough is readily apparent in the eastern horst block of the Rome Trough (fig. 19). This is clear evidence that fold style in the detachment sheet is linked directly to a major Proterozoic structure and the thinning of the Olin Basin to the northeast (Wagner, 1976).

Fayette Anticline

Like its sibling anticlines to the southeast, the post-Salina section of the Fayette anticline is a three tiered structure but wedge faulting in the upper tier is more subdued and structural relief at the level of the Tully Limestone is on the order of 150 meters. Fault-related folding is incoherent between the Lockport reflector under the detachment zone and the imbrication zone (that is, F-39; fig. 20). In some instances the Lockport reflector passes rather smoothly beneath the detachment zone (fig. 6). In other instances there is evidence for minor transfer of detachment slip into the Vernon shale from below the Lockport dolomite (fig. 20).

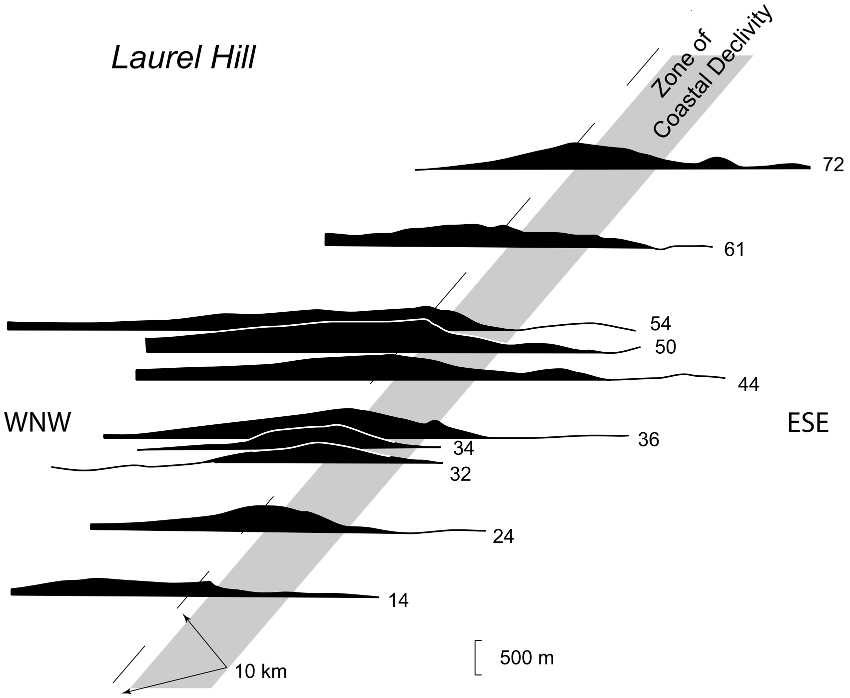


Fig. 15. Suite of seismic profiles across Laurel Hill anticline illustrating the structural expression of the Cambrian coastal declivity at the Gatesburg level. Refer to Scanlin (ms, 2000) for additional detailed seismic sections.

In general, there is little coherency between the structures in the footwall and the detachment sheet. In F-39, it may be argued that two major structures at the level of the Lockport reflector receive their structural relief from two major structures within the Trenton reflector (fig. 20). However, thrusting is low angle (about 25°) and cannot be directly extrapolated up through 1.5 kilometers of section. Furthermore, structural development at the Trenton and Gatesburg reflectors seems as coherent here as anywhere on the Appalachian plateau (fig. 20). If this coherency is fault controlled and the dip angle of these faults in the Gatesburg is relatively steep, these footwall structures must be consistent with basement-related faulting rather than detachment-related ramp thrusts extending back to the Valley and Ridge.

Belle Vernon Anticline

The structural relief and cross section area of the Belle Vernon anticline are even further reduced relative to its sibling anticlines to the southeast (BV-34; fig. 21). Yet, in the absence of seismic evidence, we infer that the detachment sheet still exhibits hints of the three tier development typical of the Appalachian plateau.

The Belle Vernon anticline is positioned over the up-thrown block that marks the northwestern boundary of the Rome Trough. Structural expression at the Trenton and Gatesburg levels is conformable and manifests a flexure characteristic of a normal fault down-thrown to the east. Seismic profile BV-34 is clear evidence for active faulting along the boundaries of the Rome Trough at least through middle Silurian time. This is also the WNW edge of the Olin Basin of Cambrian-Ordovician age (Wagner, 1976). Unlike its siblings toward the hinterland, major thrusting at the Tully to Lockport

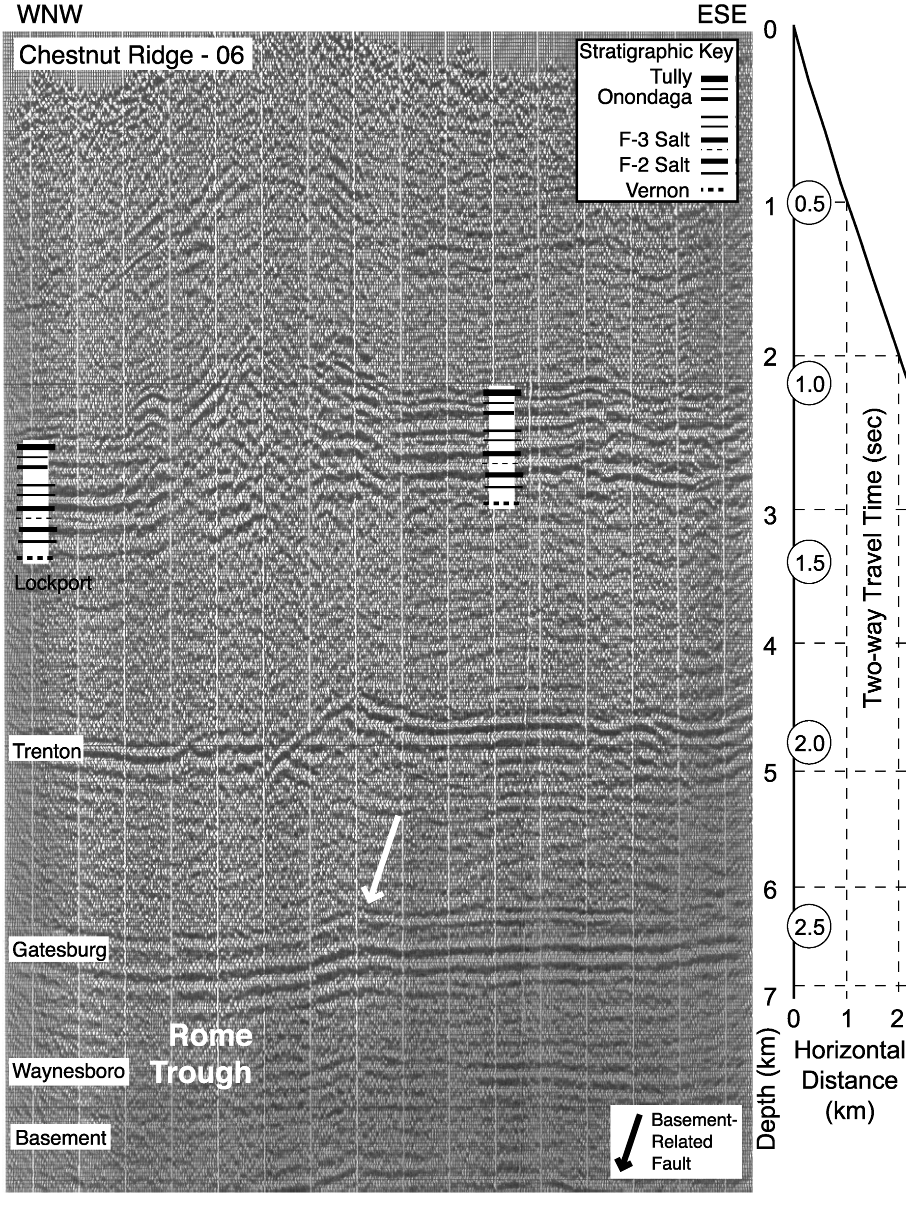


Fig. 16. Eastern boundary of the Rome Trough on seismic profile CR-06 across Chestnut Ridge anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

levels is situated to the east of the major upthrow footwall structure. Here, it may be argued that the WNW edge of the Rome Tough at the level of the Lockport reflector acted as a barrier impeding foreland transport of the detachment sheet.

Composite Section through the Coastal Declivity and the Rome Trough

Evidence now suggests that there is a genetic linkage between growth of detachment sheet structures and the presence of major basement-related faulting. The

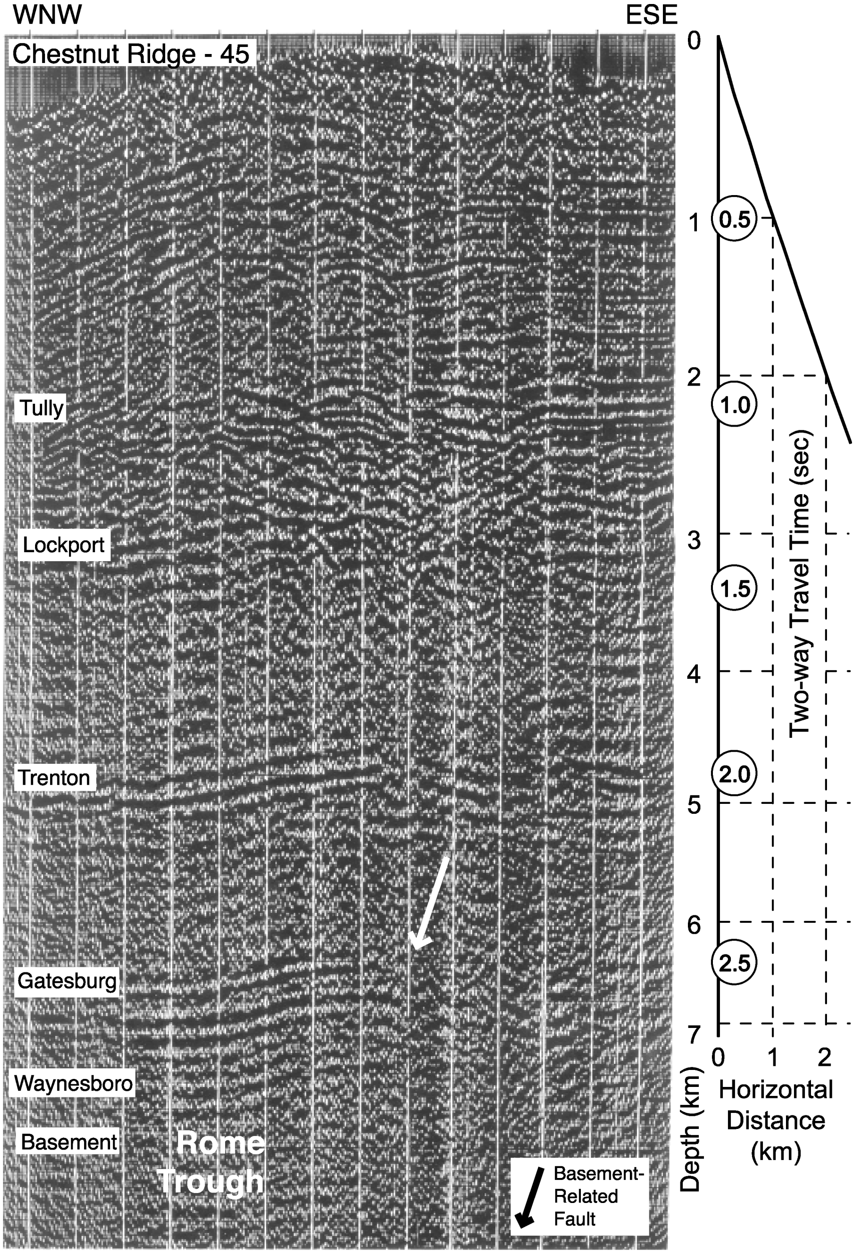


Fig. 17. Eastern boundary of the Rome Trough on seismic profile CR-45 across Chestnut Ridge anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

mechanical coupling between the anticlines of the detachment sheet and the occurrence of sub-adjacent footwall structures is best demonstrated in a composite seismic section from the Negro Mountain to the Belle Vernon anticlines (fig. 22). Basement structural relief is a consequence of several hundred meters of throw on the Lower Cambrian coastal declivity (~300 m) and the two boundaries of the Rome Trough

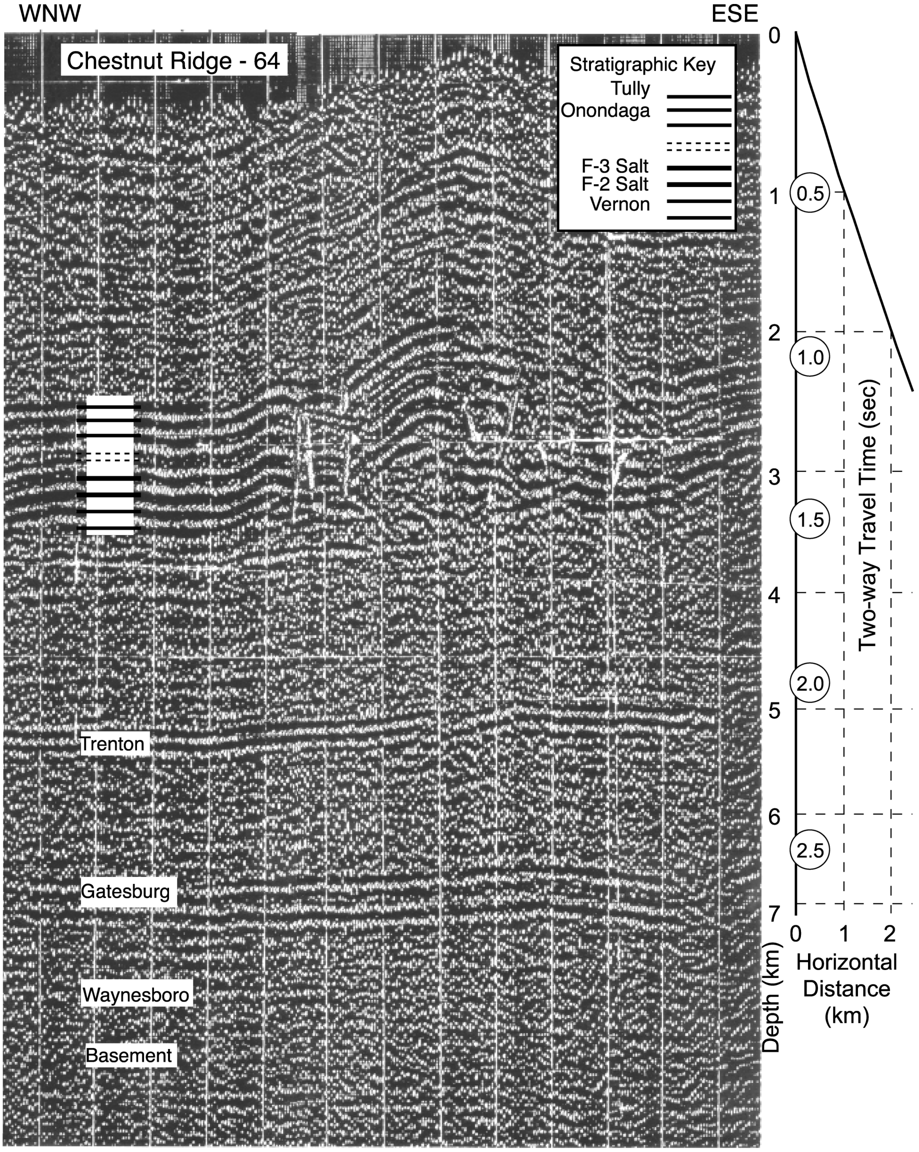


Fig. 18. Chestnut Ridge anticline north of the termination of the Rome Trough on seismic profile CR-64 (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

(~ 200 m). A small west-facing flexural step in reflections of basement occurs under Negro Mountain anticline and high angle faults are seen under Fayette anticline. Indeed, each of the five anticlines of the detachment sheet is associated with the five most prominent basement structures. If synclines are associated with basement structures, they are minor. Laurel Hill, Chestnut Ridge and Belle Vernon anticlines are located either on or immediately to the west of major basement structures.

Structural relief at the level of the Trenton reflector matches the Gatesburg in position and magnitude and is therefore associated with these same basement faults. At Negro Mountain, the Trenton is detached in a foreland verging, hinterland dipping

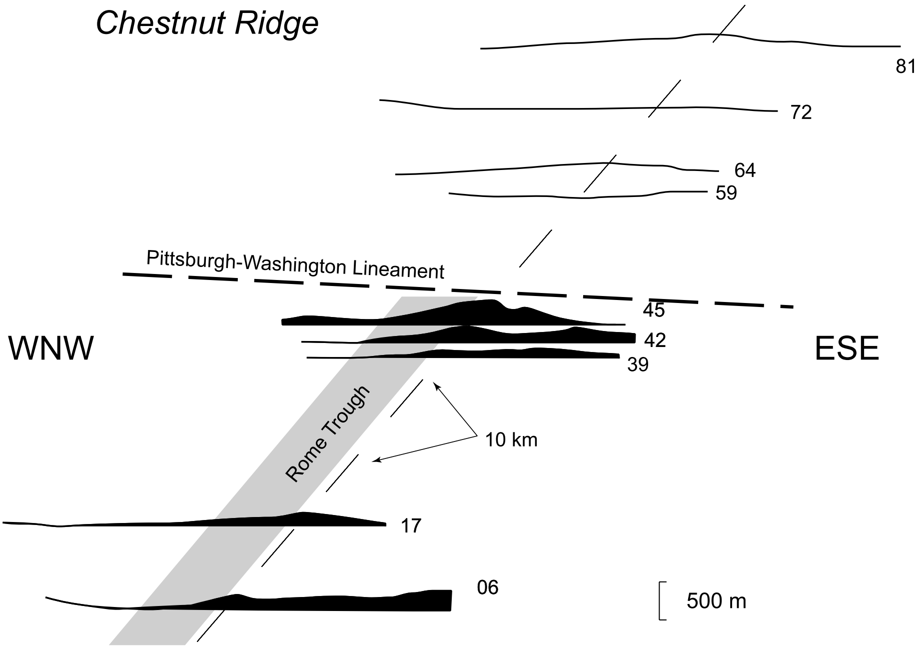


Fig. 19. Suite of seismic profiles across Chestnut Ridge anticline showing the southeastern edge of the Rome Trough at the level of the Gatesburg. Refer to Scanlin (ms, 2000) for additional detailed seismic sections.

duplex. Further west, structures at the Trenton level exhibit much less shortening but still display a foreland vergence. These basement faults have been interpreted as syn-sedimentary growth faults of Cambro-Ordovician age (Woodward, 1961; Wagner, 1976). One interpretation of the systematic vertical offset of Lower Paleozoic seismic reflectors is that some syn-sedimentary growth continued at least through deposition of the Silurian Lockport dolomite as is best displayed in BV-34 (fig. 21). Furthermore, the Lockport dolomite contains a reef complex that controlled the lateral extent of the Salina Group deposition as well as the topographic surface upon which it was deposited (Fergusson and Prather, 1968).

The implication is that the anticlines of southwest Pennsylvania were produced by detached contraction localized over buried early Paleozoic growth faults. Small inversion of these normal faults in the late Paleozoic deformed the mid-Paleozoic enough to create nucleation sites for thrust ramps. This nucleation eventually focused the lateral flow of salt or shale as envisioned in the Wiltschko-Chapple flow model.

Width of the Zone of Tectonic Thickening

The décollement tip-line for forward translation of the detachment sheet should have crossed basement faults at Negro Mountain first and gradually worked its way to the west, first cause LPS shortening and then periodic anticlinal growth. It is reasonable to hypothesize that anticlinal growth continued synchronously with advance of the tip-line. Progressive anticlinal growth should be seen in a general decrease in anticline amplitude and wave length moving in the direction of the foreland.

Based on surface expression at the Pennsylvanian-Mississippian level, the ampli-

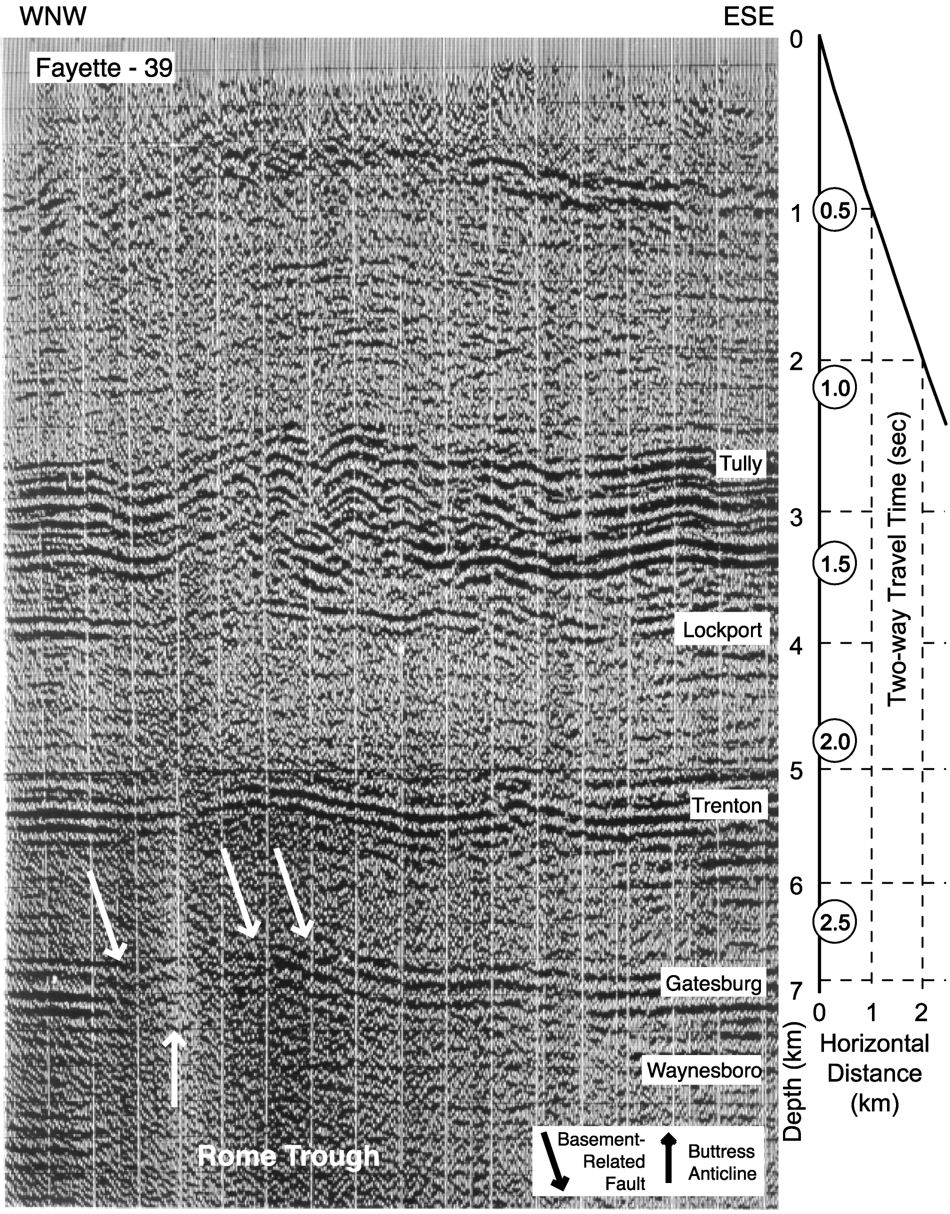


Fig. 20. Basement-related faulting and concurrent development of buttress anticlines in the middle of the Rome Trough on seismic profile F-36 across Fayette anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

tude of Plateau anticlines does, in fact, systematically decrease from the Allegheny Structural Front to the western terminus of the Salina Basin (Faill, 1998). Localized tectonic thickening in the basal detachment, imbrication, and wedge zones constitutes the primary mechanism responsible for structural relief. Seismic profiles provide the means to measure the width of the zone of tectonic thickening in each anticline

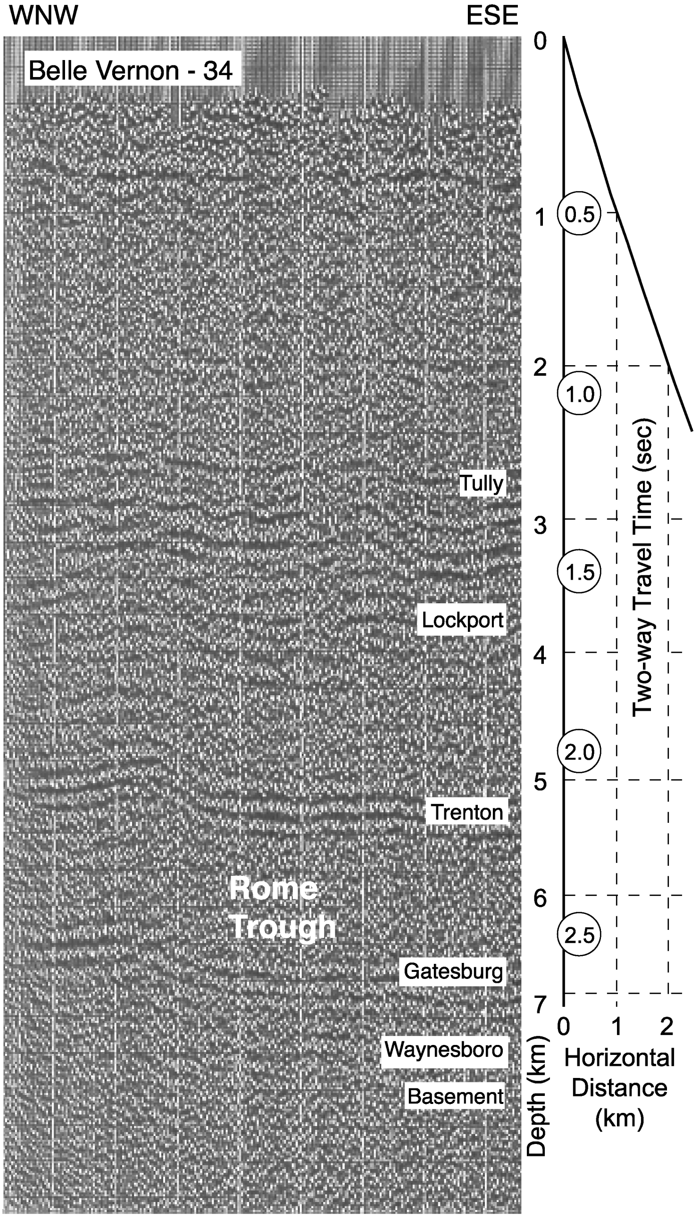


Fig. 21. Western boundary of the Rome Trough on seismic profile BV-34 across Belle Vernon anticline (see fig. 1 for location). Approximately 3:1 vertical exaggeration.

traveling westward across strike in the Bedford-Pittsburgh region. The width at the top of the Upper Devonian Burket shale was measured in all seismic profiles crossing each anticline (fig. 22). Growth of the tectonically thickened zone decreases toward the foreland, a result consistent with continued anticlinal growth as the detachment sheet tip-line migrates toward the foreland.

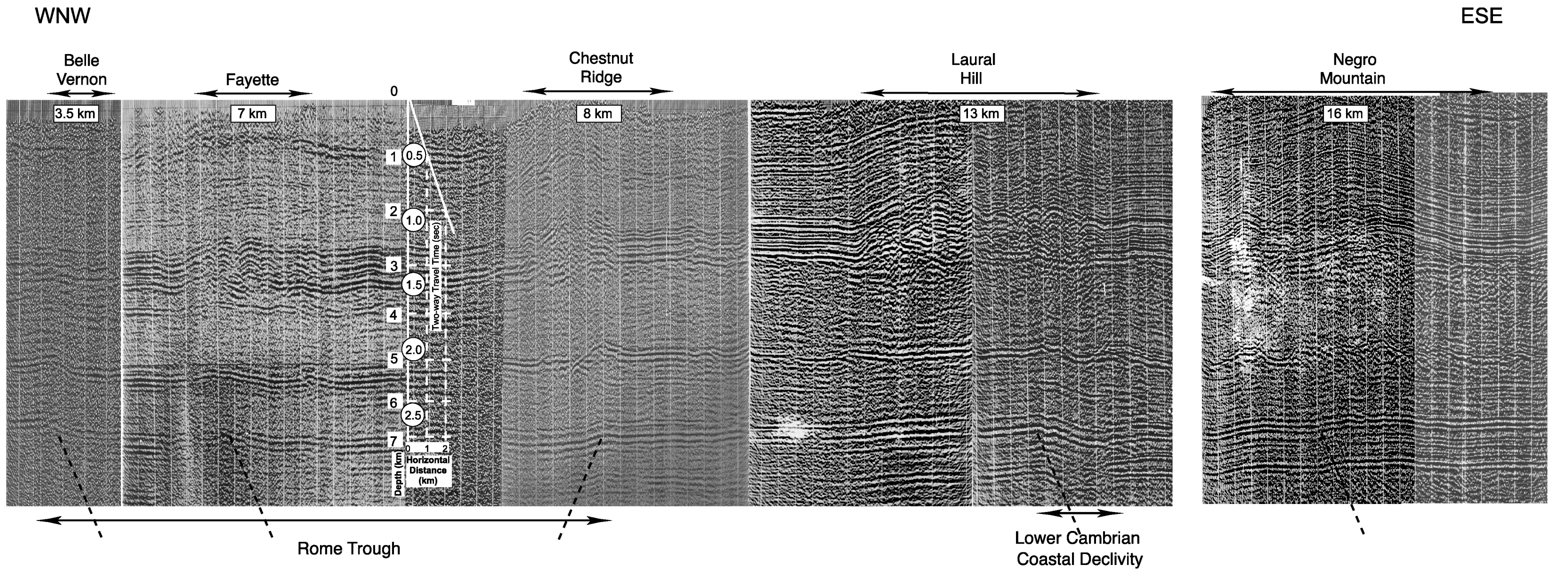


Fig. 22. Regional composite seismic profile. Important features include the position of the detachment sheet anticlines over major basement faults and the systematic decrease in horizontal and vertical dimension of Appalachian Plateau Detachment sheet anticlines from hinterland to foreland.

ROLE OF BASEMENT FAULTS IN CONTROLLING THE STRUCTURAL DEVELOPMENT OF THE FOOTWALL OF THE DETACHMENT SHEET

At this point we wish to reinforce two conclusions that have been drawn from seismic profiles of the Appalachian plateau detachment sheet. First, we conclude that basement was involved in the development of structures in the footwall of the detachment sheet. The best record of basement is found in CH-06 where basement has been offset in the same manner as the stratigraphy at the Gatesburg reflector (fig. 16). In the previous section of this paper, the presence of basement faults was largely inferred from the shape of the Gatesburg reflector. The similar structural relief in the Waynsboro-basement reflections argues strongly for basement involvement. The basement fault hypothesis can also be tested using the dip angle of faults cutting the Gatesburg reflector. In other words, we use a logical fault trajectory on seismic profiles to explain the localized structural relief (that is, reflection steps) that we see in the Waynesboro, Gatesburg, and sometimes Trenton reflections.

Second, we conclude that the growth of detachment sheet anticlines and thrust imbrication at the level of the Trenton are Alleghanian processes linked to reactivation of basement-related faults. This conclusion resolves the conundrum faced by Rodgers (1964) in considering the role of basement in Appalachian tectonics. However, the hypothesis that basement faults were active during the Alleghanian can be inferred from sense of slip on high-angle faults at the Gatesburg level.

Dip Angle on Gatesburg Faults

Negro Mountain.—The Gatesburg structural surface is gently undulating and sub-Gatesburg reflectors take this same shape down to basement (figs. 10 and 11). If this structural surface is a consequence of detachment near the basement-cover contact, concomitant ramp thrusting might also be expected. In fact, there is abundant evidence for reverse faulting at the Gatesburg level with foreland vergence. If the detachment hypothesis is valid, the dip angle of these reverse faults should be about 25° to 30° which is the common angle for fracture under foreland compression (for example, Handin and Hager, 1957; Suppe, 1983). If these Gatesburg faults emerge from basement, they should display a higher angle depending on whether they initiate as Laramide-type reverse faults [dip angles = 30° to 45°, (for example, Schmidt and others, 1993)] or basin-bounding normal faults [dip angle ~60° (for example, Coward, 1994)].

The Gatesburg faults trajectories were traced on the vertically exaggerated seismic profiles (figs. 10 and 11). Then the faults were restored to their attitude in a 1:1 cross section. Six foreland verging reverse faults with dip angles between 40° and 59° were detected in four sub-Gatesburg sections through Negro Mountain (fig. 1). The faults through the Gatesburg reflector under Negro Mountain are high angle (> 40°) and, thus, consistent with faults emerging from basement. These are all major faults with reverse slip in excess of 50 meters and therefore could be seismically resolved.

Laurel Hill.—Here, as at Negro Mountain, dip angle on reverse faults through the Gatesburg reflector are used to indicate whether or not basement was involved (that is, figs. 12 - 14). Twenty faults cut downward from the Gatesburg reflector in various sections through Laurel Hill. The median dip angle of this data set is 60° (fig. 23). As at Negro Mountain, a high-angle dip is inconsistent with splay faults ramping up section from a basal detachment and is thus taken as evidence that faults through the Gatesburg reflector cut down into basement.

Three anticlines of the Rome Trough.—Chestnut Ridge and the Belle Vernon anticlines sit above the southeastern and northwestern boundaries of the Rome Trough, respectively. At the level of the Gatesburg reflector, the southeast edge of the Rome trough is visible with its down thrown WNW block (that is, figs. 16 and 17). Here, the trailing or eastern edge of the anticline is located at the major fault marking the edge

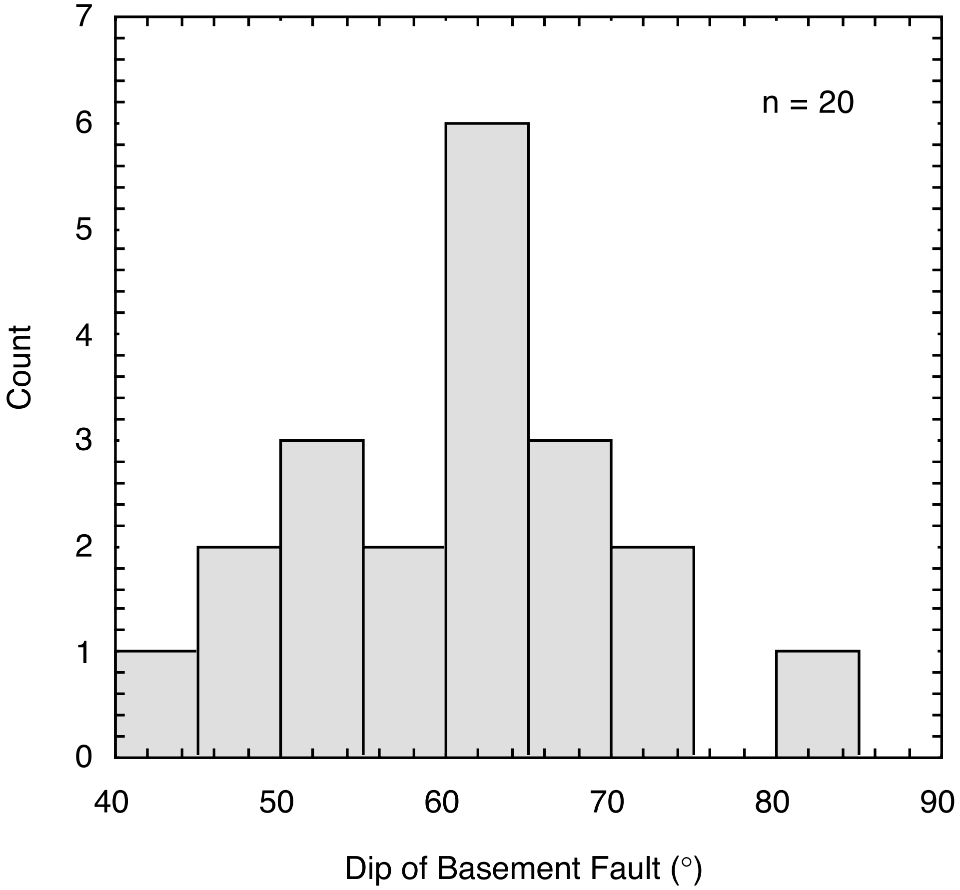


Fig. 23. Histogram illustrating the dip of high angle faults in the Lower Paleozoic section along Laurel Hill anticline. Dips are depth-converted values from interpreted fault trajectories on the seismic data.

of the Rome Trough. This is similar to the situation at Laurel Hill with the Coastal Declivity. The central portion of the Rome Trough beneath the Fayette anticline also includes several reverse faults that must emerge from basement (fig. 20).

Evidence for Inversion Tectonics During the Alleghanian Orogeny

Negro Mountain.—Six foreland verging reverse faults emerge from basement in four seismic sections through Negro Mountain (for example, figs. 10 and 11). There is a strong probability that these are east-dipping, Proterozoic normal faults that were reversed during Alleghanian compression. The highest structural position on the reflector at or near the cover-basement contact is found east of the axis of Negro Mountain (for example, fig. 10). This structural high is a bowing upward of the basement-cover contact just east of a reverse fault cutting to basement. Upfolding of the hanging-wall block of a reversed normal fault is the seminal characteristic of a buttress anticline, a structure common in other mountain belts where inversion tectonics has taken place (Cooper and Williams, 1989; Nemcok and others, 1995). Hence, it is reasonable to infer that the bending of the basement-cover contact under Negro Mountain is a manifestation of a tectonic inversion during Alleghanian compression. Other examples of tectonic inversion of Proterozoic basement faults during

Alleghanian compression are found in the Blue Ridge province, Virginia (Bailey and others, 2000).

Each of the four seismic sections through Negro Mountain show structures at the cover-basement contact, that are consistent with tectonic inversion and the formation of buttress anticlines. These structures carry upward at least 1.5 kilometers to the level of the Gatesburg reflector and then further up to the base of the Trenton detachment (for example, fig. 10). Higher amplitude fault-related folding at the Trenton level sits above the reversed faults responsible for buttress anticlines. Moving further up section, there also seems to be a correlation between the development of Negro Mountain in the post-Salina section and the position of buttress anticlines at the Gatesburg level and the higher amplitude structures at the Trenton level.

Laurel Hill.—Evidence also points to an inversion hypothesis for structural development in the section between the Gatesburg reflector and basement under the Laurel Hill anticline (fig. 12). First, the dip angle on reverse faults in the sub-Gatesburg section of cover rocks is consistent with the reactivation of normal faults (for example, fig. 23). Second, the hanging wall of the Gatesburg and basement is up-thrown (for example, figs. 12 and 14). Third, the Gatesburg reflectors in the hanging wall are upfolded in a manner consistent with the development of a buttress anticline reflecting inversion tectonic (for example, fig. 12). The structural relief on the buttress anticline east of the coastal declivity is about 100 meters. Fourth, there is the hint of more than one buttress anticline in some sections (for example, fig. 14).

Foreland verging fault-related folding at the Trenton level is located over the buttress anticlines at the Gatesburg level (for example, figs. 12 - 14). The structural complexity at the Trenton level, however, is disharmonic with the structural patterns from below and above. The eastern edge of the Laurel Hill anticline in the Lower/ Middle Devonian section coincides with the largest of the reversed normal faults in basement. Perhaps, because of foreland transport of the Appalachian plateau detachment sheet, the imbrication zone appears to have developed as a consequence of being carried toward the WNW across this basement high. This is a different situation from Negro Mountain where the center of mass of the imbrication and wedge zones of the Appalachian Plateau detachment sheet are centered upon a series of smaller basement faults.

Three anticlines of the Rome Trough.—Inversion of the normal fault boundaries of the Rome Trough appears to be lacking. Nevertheless, the Chestnut Ridge and Belle Vernon anticlines are localized above the Rome Trough margins. Evidence for the Rome Trough disappears to the northeast of CH-45 at the intersection of the Rome Trough with the Washington-Pittsburgh lineament (fig. 1B). Basement passes smoothly under the Chestnut Ridge northeast of the Pittsburgh-Washington lineament (fig. 19). The central portion of the Rome Trough appears to be inverted with a monoclinal bend in the eastern, hanging wall of two high angle reverse faults (fig. 20). In the only section through Belle Vernon anticline, the western margin of the Rome Trough is visible but there is no indication of Paleozoic inversion (fig. 21).

The Position of Footwall Structures Relative to Detachment Sheet Anticlines

Each of the five major anticlines in the Appalachian plateau detachment sheet is situated near the position of significant structural steps in the basement complex. The anticlines, like their basement counterparts are reasonably linear and, in fact, follow basement faults in plan view. Each of the basement faults appears to have been a product of the evolving continental margin during the rifting of a Late Proterozoic supercontinent. The fundamental implication is that the anticlines of the Appalachian plateau were produced by westward translation of the detachment sheet over these syn-sedimentary growth faults that propagated vertically by recurrent tectonic activity including Alleghanian inversion. The tie between anticlinal growth in the detachment sheet and basement faulting is compelling. The mechanism for the link is tied to the growth of a dual tapered Coulomb wedge (Scanlin, ms, 2000).

DISCUSSION

The Spatially Periodic Collapse of the Detachment Sheet

It was previously believed that anticlines within the Appalachian plateau detachment sheet were spaced at regular intervals due to instabilities in the salt (Frey, 1973) or a buckle folding mechanism (Wiltschko and Chapple, 1977). Now, it is clear that the regular spacing of these anticlines is a manifestation of pre-contraction spacing of Proterozoic normal faults that localized sites of lateral collapse in anticlines within the detachment sheet. Anticlinal growth, a direct consequence of periodic tectonic thickening, follows directly from the spatially periodic lateral collapse of the detachment sheet.

At an early stage of the Alleghanian Orogeny, deformation by layer-parallel shortening was remarkably uniform throughout the Appalachian plateau detachment sheet (for example, Nickelsen, 1966; Geiser, 1988a). This uniform deformation indicates that early in the orogenic cycle neither the rheological properties of the detachment sheet nor the stress state within the sheet varied appreciably across the plateau. Periodic collapse of the detachment sheet by local thrust imbrication and wedge faulting within the detachment sheet anticlines reflects the onset of a different deformation mechanism later in the orogenic cycle.

Any dynamic model of the Appalachian Plateau detachment sheet must account for the switch in deformation mechanisms from a pervasive strain to a spatially periodic collapse. In the search for the root cause of this spatially periodic collapse, it is noteworthy that all five major detachment sheet anticlines in the Bedford-Pittsburgh region are situated in the immediate vicinity above old basement faults (fig. 22). Only the margins of the Rome Trough are not visibly reversed normal faults. The location of basement faults at the trailing edge of the Laurel Hill and Chestnut Ridge anticlines is remarkable (figs. 12, 13, 14, 16 and 17). These basement faults are manifest in a structural relief of as much as 500 meters at the level of the Gatesburg reflector. In a few instances, this structural topography may have been enhanced by detachment faulting in the footwall block at the level of the Trenton reflector. This structural relief carries up section to the bed of the detachment zone, the Lockport dolomite (for example, figs. 11 and 16).

Because the initial strength of the detachment sheet is assumed to have been uniform, a lateral variation in local stress appears to be the root cause of spatially periodic collapse. The link between periodic collapse of the detachment sheet and footwall faulting is compelling. One plausible explanation for a periodically higher differential stress is the disruption of the foreland translation of the detachment sheet by fault-generated steps along the bed of the detachment sheet. A detachment bed with steps can certainly lead to large bending stresses where the detachment sheet passes laterally over an irregular surface. Indeed, large bending stresses can generate fracture (for example, Friedman and others, 1976; Handin and others, 1976).

As will be discussed in a companion paper, the detachment sheet is close to a critical state throughout, so that just a small perturbation by bending will push the sheet into a critical state and generate fracture. The response of the detachment sheet to periodic collapse is the growth of a Coulomb wedge that gives rise to a local tectonic thickening within the weakened section. Each anticline flank of the Appalachian plateau detachment sheet is a local Coulomb wedge that grows to a steeper angle than the overall taper of the detachment sheet. The disruption of salt stringers by thrust imbrication under anticlines leads to a strain hardening by frictional strengthening within the detachment zone and this strengthening supports the growth of detachment sheet anticlines with steeper limb dips by a Coulomb wedge mechanism.

Strike-parallel Variations in Structural Style of the Detachment Sheet

Thus far we have established that tectonic growth by a periodic collapse mechanism offers the best explanation for the origin and evolution of the anticlines in the detachment sheet of the Bedford-Pittsburgh region. However, the areal distribution of Alleghanian folding is wider by more than 10 kilometers in the Williamsport-Tioga region reaching nearly to Syracuse (Wedel, 1932). Since there is no marked displacement discontinuity in the adjacent Valley and Ridge province, it is assumed that lateral transport across the Allegheny Structural Front from the adjacent Valley and Ridge province did not vary significantly along strike from Williamsport to Bedford. Furthermore, both regions experienced a uniform layer parallel shortening of approximately 10 percent (Nickelsen, 1966; Engelder and Engelder, 1977). Why does the displacement across the Allegheny Front reach 5 to 10 percent further into the foreland in the Williamsport-Tioga region relative to the Pittsburgh-Bedford region?

We suggest that the cross-strike dimension of the folded area in the Bedford-Pittsburgh region is less because wedge thrusting absorbs some of the foreland displacement as the section passed over prominent basement faults. By contrast, the absence of basement breaks of that magnitude in the Williamsport-Tioga region enabled greater foreland transport. The lower structural relief of anticlines in the Williamsport-Tioga region can be accounted for by salt thickening alone (Frey, 1973). Tectonic thickening by thrust wedging of the Devonian section in the Bedford-Pittsburgh region supplies the missing deformational mechanism required by the Wiltschko-Chapple model of the detachment sheet. This mechanism also enables the anticlines in this region to achieve greater structural relief. The lower relief of the anticlines in the far western portion of the Bedford-Pittsburgh region is simply a function of the taper of a Coulomb wedge in the foreland direction from the Allegheny Front (Davis and Engelder, 1985).

CONCLUSIONS

The growth of detachment sheet anticlines in the Bedford-Pittsburgh region of the Appalachian plateau is a direct consequence of tectonic thickening of a three-tiered mechanical stratigraphy that comprises the Siluro-Devonian interval. The general architecture includes a basal detachment zone, a lower imbrication zone, and an upper wedge zone. The detachment zone is predominantly disturbed shale of the Silurian Vernon Formation. Salt horizons within the Syracuse Formation of the imbrication zone host secondary detachment responsible for imbrication and the development of triangle zones in the core of the anticlines. The Upper Silurian through Lower/Middle Devonian constitutes a tectono-stratigraphic layer thickened by imbrication. This stratal package acts as a thick competent strut that deforms in unison. Locally it breaks into multiple layers of imbrication along several detachment surfaces. In these cases, each mechanical unit detaches along both roof and floor thrusts as in a passive-roof duplex. Regardless of the thickness of the mechanical struts, when they verge from both sides toward the central core of the anticline they form triangle zones. Some fold amplification is also achieved by extensive, smaller-scale wedge thrusting and concomitant tectonic thickening of the less competent Upper Devonian wedge zone.

Each detachment sheet anticline is situated above prominent, periodically spaced structures in the footwall of the detachment sheet. Footwall structures are principally reactivated Late Proterozoic extensional normal faults. Most show structural inversion. Beneath Negro Mountain, a zone of thrust imbrication at the Ordovician Trenton level underlies the Siluro-Devonian and overlies the inverted normal faults. Tectonic inversion is seen in the development of buttress anticlines in the Cambro-Ordovician section. The superposition of hanging wall anticlines on footwall structures strongly suggests that these anticlines were produced by westward translation of the detachment sheet over syn-sedimentary basement growth faults that propagated vertically by recurrent tectonic activity including Alleghanian inversion.

The regular spacing of these anticlines is a direct consequence of periodic fracturing and concomitant lateral collapse at deformed steps in the detachment sheet. Evidence suggests that basement faults not only controlled the distribution of Lower Paleozoic stratigraphy but also provided the localized stress concentration that generated the periodic collapse and fold growth in the over-riding detachment sheet. The response of the detachment sheet to periodic collapse is the growth of a Coulomb wedge that gives rise to a local tectonic thickening within the weakened section. Thus, a compromise has been found in the long-standing Rodgers-Cooper debate over the basement versus no-basement hypotheses for deformational style of the Appalachian plateau detachment sheet.

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