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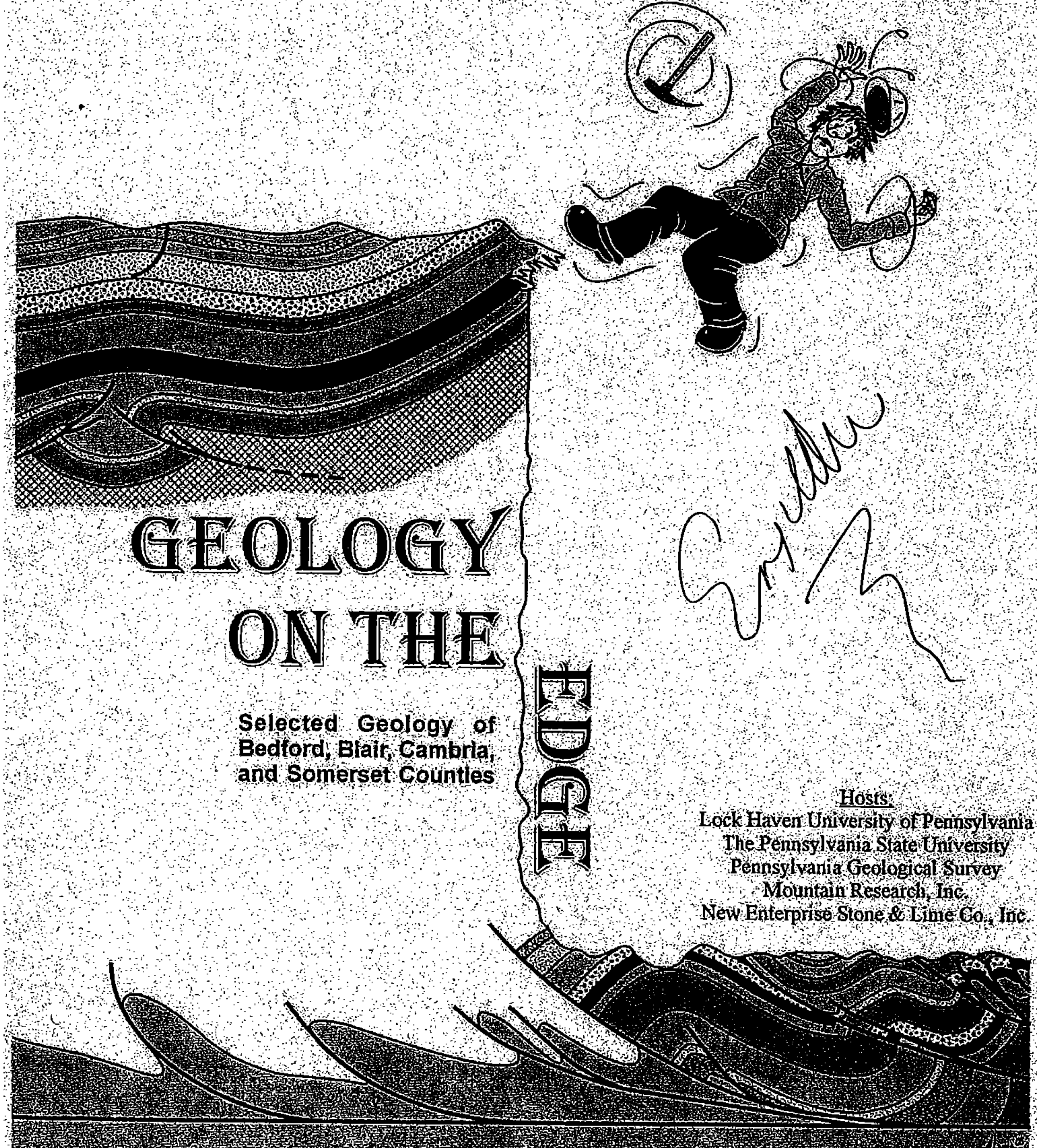

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THE PLATEAU CLIMB-OUT ZONE BENEATH THE ALLEGHENY FRONT AND DEER PARK ANTICLINE, SOUTHWESTERN PENNSYLVANIA: CHARACTERISTICS OF A GEOLOGIC SPEED BUMP

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ABSTRACT

The transition between the Appalachian Valley and Ridge and the Appalachian plateau in southwestern Pennsylvania is reflected in the hybrid architecture of three structures: the Allegheny structural front plus the Deer Park and Negro Mountain anticlines. This transition, the plateau climb-out zone, is characterized by the transfer of major detachment slip from the Waynesboro Shale in the Valley and Ridge upward to the Reedsville shale under Deer Park anticline and finally up to the Salina Group on the hinterland side of Laurel Hill anticline. At Deer Park and Negro Mountain, the Appalachian Plateau detachment sheet is passively folded above a roof thrust in the Salina Group. Further toward the foreland, the detachment sheet actively deforms in a three-tiered manner with the Salina Group acting as the major detachment surface. The Allegheny structural front is located above a 700-meter step in basement that disrupts tectonic transport between the Valley and Ridge and Plateau provinces, thus acting like a large geologic speed bump.

INTRODUCTION

A regional network of modern seismic data offers compelling evidence that the location and subsequent growth of anticlines on the Appalachian plateau of southwestern Pennsylvania is a direct consequence of deep-seated basement faults offsetting an otherwise flat décollement (Scanlin and Engelder, 2003). Because of this mechanical coupling between basement and Appalachian Plateau folding, it is reasonable to hypothesize that the Allegheny structural front, the boundary between the Appalachian Plateau province to the WNW and the Valley and Ridge province to the ESE, might also have a strong element of basement involvement. Specifically, the Allegheny "front" sits over a step in the basement with a down-thrown hinterland block, an idea that is present in the literature but somewhat vague (e.g., Cooper, 1964; Wagner, 1976; Beardsley and Cable, 1983; Beardsley et al., 1999; Harper et al., 1999). If such a step exists, it acts as a huge geologic speed bump against which and over which rocks of the Paleozoic from the Valley and Ridge were pushed during the Alleghanian orogeny. High-resolution seismic data are the best means of confirming the presence this geologic speed bump.

The geological analogy to the roadway speed bump is appropriate because the continent-continent convergence of Africa against North America during the Alleghanian Orogeny pushed the Appalachian foreland toward the northwest a distance well in excess of 100 km at the Blue Mountain structural front (Geiser, 1988). This lateral transport was accomplished with the development of high-amplitude, fault-related folds stacked across the Valley and Ridge terrane. Stacking of these first order folds comes to an abrupt halt at the Allegheny structural front. Tectonic transport across the Allegheny structural front was less than 25 km (Engelder, 1979). Assuming that motion of the Appalachian detachment sheets at both structural fronts was quasi-synchronous, the rate of tectonic transport at the Blue Mountain structural front was four times that at the Allegheny structural front. Aside from internal shortening, something else impeded the rate of tectonic transport across the Allegheny structural front. Our hypothesis is that faulted basement produced a significant offset at the basement-cover contact and that this step up of basement to the

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northwest was not only figuratively but literally a geologic speed bump over which the Allegheny structural front developed.

The Allegheny Front marks the boundary between two provinces of distinct structural styles (Figure 1). The differences arise primarily from transport on different detachment zones and differences in mechanical stratigraphy, mainly the presence of a significant thickness of Silurian salt in the Plateau region (Hatcher et al., 1989; Faill, 1998). As the result of the transfer of detachment up section near the Allegheny structural front, there are significant differences in the thickness of the detachment sheets on either side of the structural front. Northwest of the structural front the plateau detachment sheet consists primarily of a Silurian-Pennsylvanian sequence (Davis and Engelder, 1985). Southeast of the structural front the detachment sheet includes carbonates of the Cambrian-Ordovician section with Silurian-Devonian clastics uncoupled along a passive roof-thrust detachment (Onasch and Dunne, 1993). Lateral shortening of the detachment sheet, although an order of magnitude greater in the valley and ridge than the plateau province, has been accomplished by similar tectonic imbrication acting in the mechanically strong portions of the stratigraphic sequence (Scanlin and Engelder, 2003).

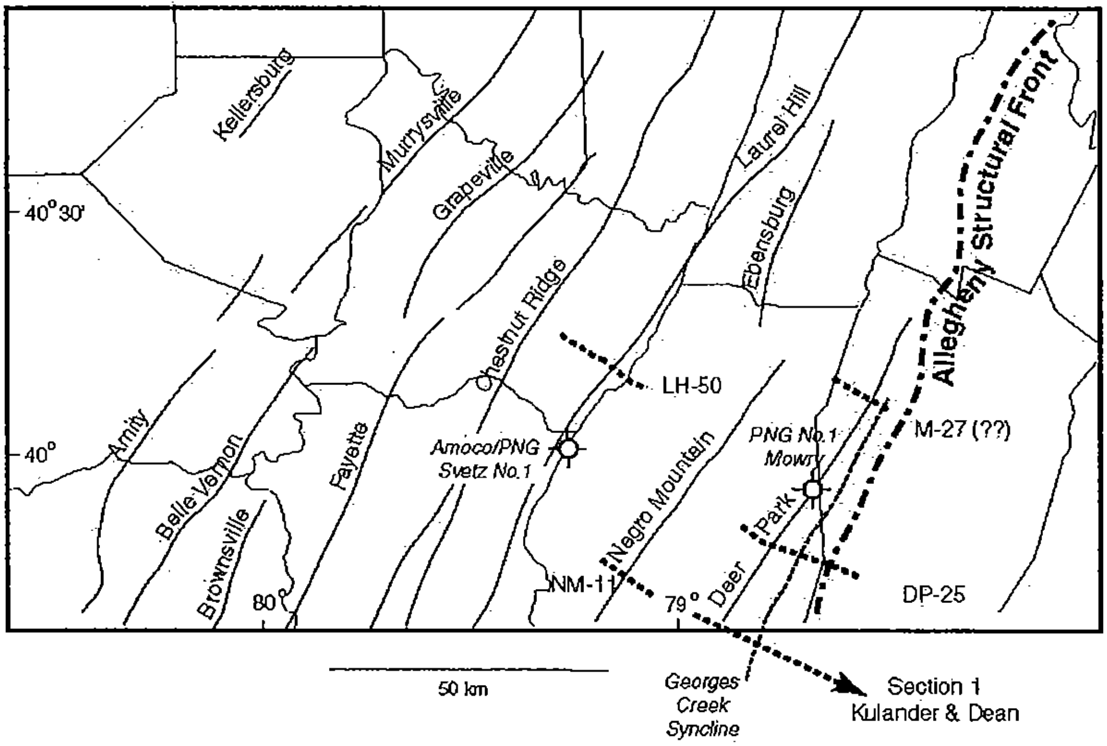

Figure 1. Structural geology of southwestern Pennsylvania. Important structural elements include: Allegheny structural front (thick dashed line), surface traces of Appalachian Plateau anticlines (solid lines), Georges Creek syncline (thin dashed line). Data elements include three key reflection seismic profiles and one schematic cross-section (adapted from Kulander and Dean, 1986) (thick dashed lines) plus location of two deep exploration wells used for stratigraphic correlation.

In the Pennsylvania salient, the Cambrian Waynesboro Shale facilitates detachment above the Precambrian basement complex southeast of the structural front and the detachment zone ramps upward stratigraphically to the northwest where the Silurian Vernon shale accommodates detachment above the topographically irregular Lockport Dolomite surface (Scanlin and Engelder, 2003). The rate of this climb from Waynesboro "shale" to Silurian Vernon "shale" is not as abrupt as may be assumed given the abrupt change in structural style at the structural front. The climb-up from the Waynesboro is accomplished throughout a zone including the two most proximal anticlines on the Appalachian Plateau, the Deer Park and Negro Mountain anticlines. This climb-out process is not apparent in recent cross-sections of the Allegheny Front (e.g., Beardsley et al., 1999; Harper et al., 1999).

When seen in map or plan view, Deer Park anticline is positioned immediately west of the Allegheny structural front. As a result of its geographic location on the foreland side of the Allegheny structural front, the Deer Park anticline is logically labeled as the easternmost and largest amplitude fold in the Appalachian Plateau province (e.g., Rogers, 1970). However, its position immediately west of the structural front permits the possibility of structural similarities to the Allegheny Front and structural differences relative to its sibling plateau anticlines farther WNW toward the foreland. Until now the nuances of its subsurface architecture as well as its tectonic relationship to both adjacent plateau anticlines and the Allegheny structural front to the east have yet to be accurately characterized.

With the support of high-resolution seismic data (see Appendix 1 for details concerning data source and resolution), the objective of this paper is to provide a unifying tectonic model that accommodates the interrelated structural elements of the adjacent Appalachian plateau structures, Deer Park anticline, and the Allegheny structural front in the vicinity of Somerset County, Pennsylvania. Advances made in this research include (1) improved delineation of the subsurface structural architecture of the Allegheny structural front and Deer Park anticline, (2) a clearer understanding of the mechanical stratigraphy and tectonic mechanisms within these structural elements, (3) improved understanding of the nature of the transition from the Valley and Ridge to the Plateau, and (4) explicit documentation of the spatial and kinematic relationship between all the Plateau province structures and the structural front.

THE APPALACHIAN PLATEAU DETACHMENT SHEET

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 (Scanlin and Engelder, 2003). The general architecture includes a basal detachment zone, a lower imbrication zone, and an upper wedge zone (Figure 2). The detachment zone is predominantly disturbed shale of the Silurian Vernon Formation. Salt horizons within the Syracuse Formation of the imbrication zone host secondary detachments 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, triangle zones form as a consequence of vergence from both sides toward the central core of the anticline. 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 (Scanlin and Engelder, 2003). 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

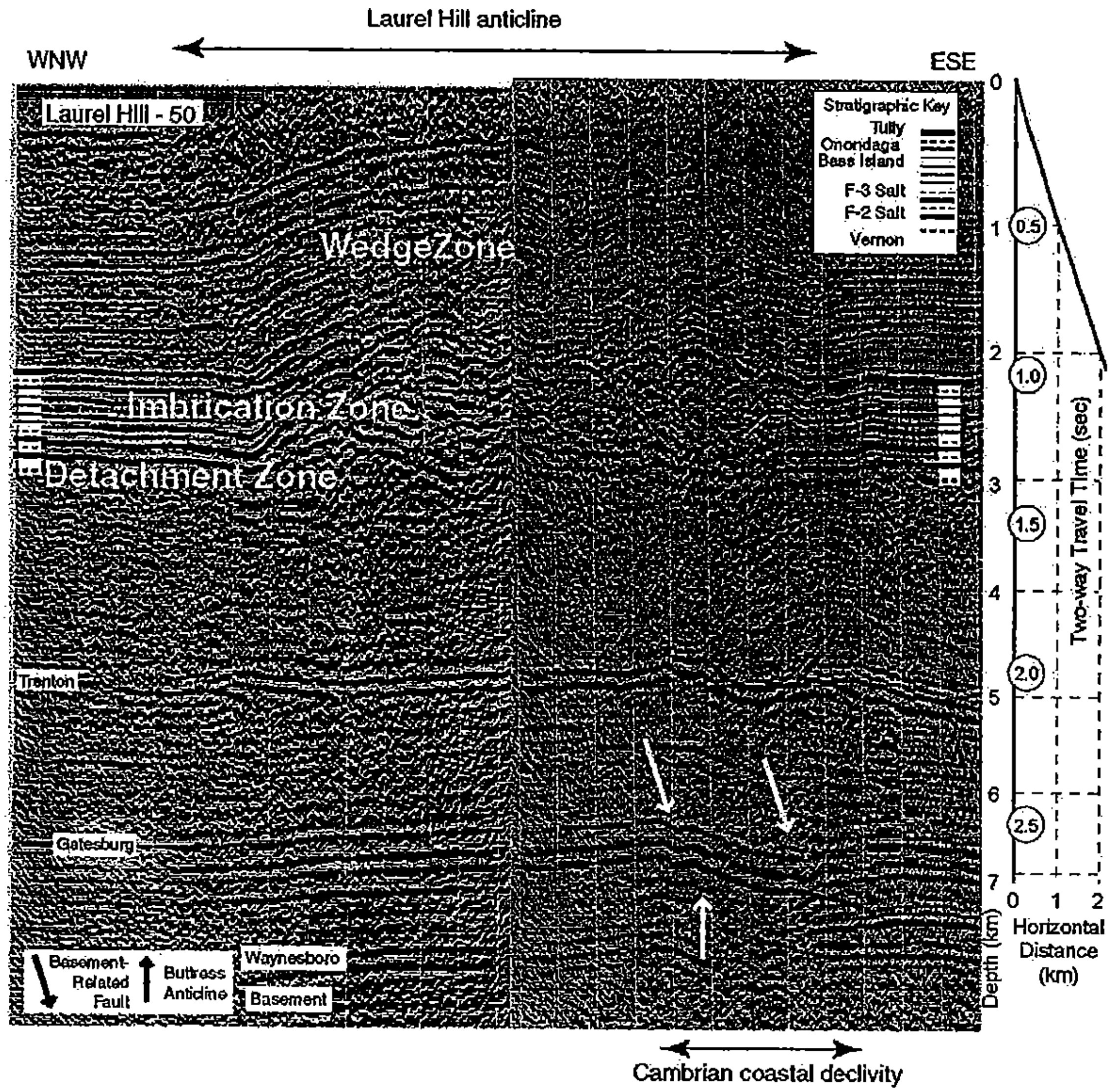

Figure 2. Interpretation of structural style within the detachment sheet as found in seismic profile LH-50 (migrated time section) through Laurel Hill anticline (see Figure 1 for location). The components of the three-tiered model annotated in their appropriate position on seismic profile (migrated time section). Approximately 3:1 vertical exaggeration.

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. In extrapolating this model toward the hinterland of the Appalachian Mountains, it permits the hypothesis that Deer Park anticline and the Allegheny structural front are both coupled to basement steps as well.

DEER PARK ANTICLINE

We focus first on the Deer Park anticline largely because it is, comparatively speaking, less structurally complicated than the Allegheny Front (Figure 3). The front contains more steeply dipping beds that are more difficult for the seismic reflection method to resolve and consequently offer a more challenging interpretation problem. Our strategy is to use the lessons learned from Deer Park as well as anticlines further toward the foreland to interpret the structures at the Allegheny structural front. Our premise in taking this approach is that the mechanical development of the structural front is as closely

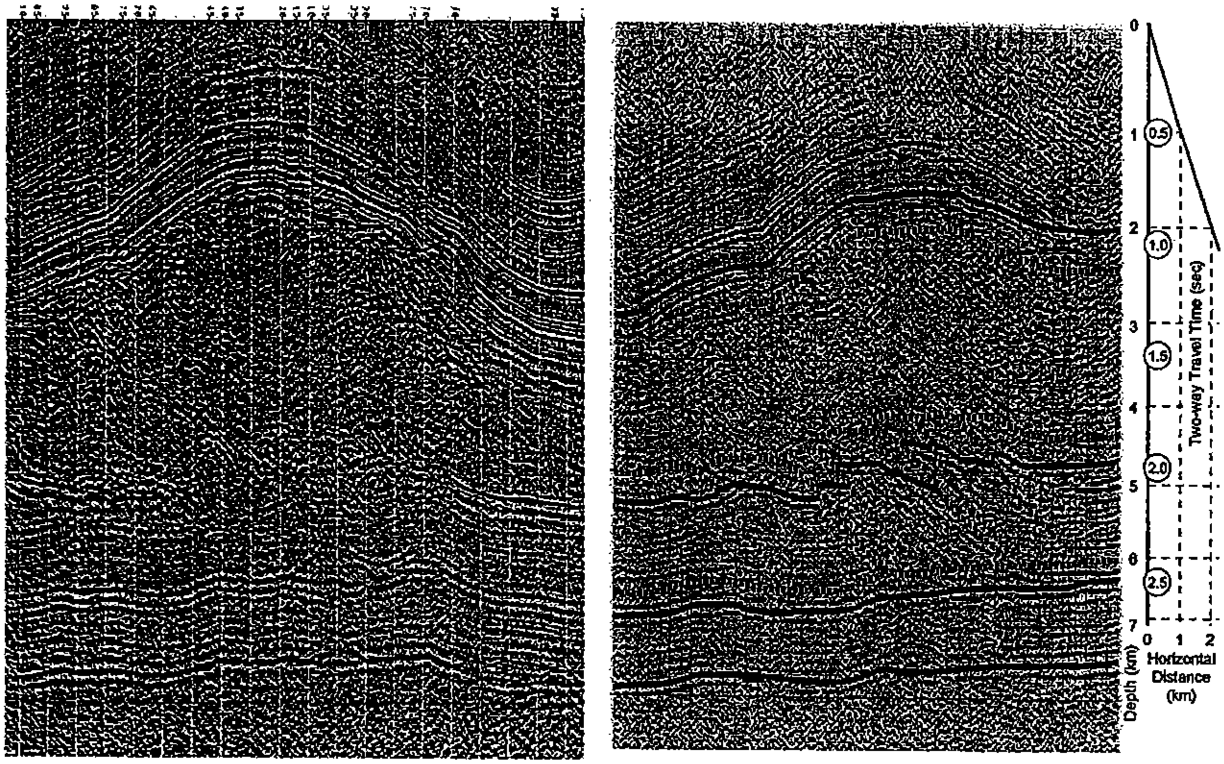

Figure 3. Two migrated-time seismic profiles across Deer Park anticline (see Figure 1 for locations). Seismic section DP-25 provided for academic research by Amoco Production Company and UGI Development Company. Seismic section M-27 (from Mitra, 1986).

related to the development of Appalachian Plateau anticlines as it is to the fault-related folding of the Valley and Ridge. This lesson is best illustrated using a cross-section drawn to the SSW of seismic sections DP-25 and M-27 (Figures 1 and 4). In this interpretation, both the Deer Park anticline and the structural front are drawn with splay faults ramping toward the foreland from a detachment in the Upper Ordovician Reedsville shale. The difference is that the Reedsville detachment at the structural front is fed by a master ramp from the Waynesboro shale under the Wills Mountain anticline (Kulander and Dean, 1986). The major structures that are missing from the Kulander-Dean interpretation of the Deer Park anticline are the stacked ramps from Waynesboro to the Reedsville as identified in the interpretation of seismic section M-27 (Figure 4 vs. Figure 3B). Only one blind thrust is shown in the Kulander-Dean interpretation.

Deer Park anticline is the first structure west of the Allegheny structural front (Figure 1). Based on seismic images (Figure 3), the Deer Park exhibits structural attributes characteristic of both the Plateau detachment sheet anticlines and the fault-related folds of the Valley and Ridge province. Valley and Ridge structures consist of a duplex thrust system developed in the Cambro-Ordovician section with a passive roof thrust developed in the overlying Siluro-Devonian section. In the Appalachian Plateau at Laurel Hill anticline duplex thrust systems are developed in the Siluro-Devonian section according to the three-tiered mechanical model (Scanlin and Engelder, 2003).

At Deer Park, the Siluro-Devonian section displays the passive roof thrust architecture characteristic of Valley and Ridge structures. The Lower Paleozoic section forms a stack of at least two and maybe more duplex thrust systems quasi-synchronously cutting the Lower Silurian Tuscarora, Ordovician Trenton, and the Cambrian Gatesburg sections (Figures 5-7). We interpret this partitioning of tectonic imbrication and duplex development to be a mechanical response to a dramatic difference in tectonic transport across the Allegheny structural front that necessitated detachment at multiple stratigraphic levels. Detachment and

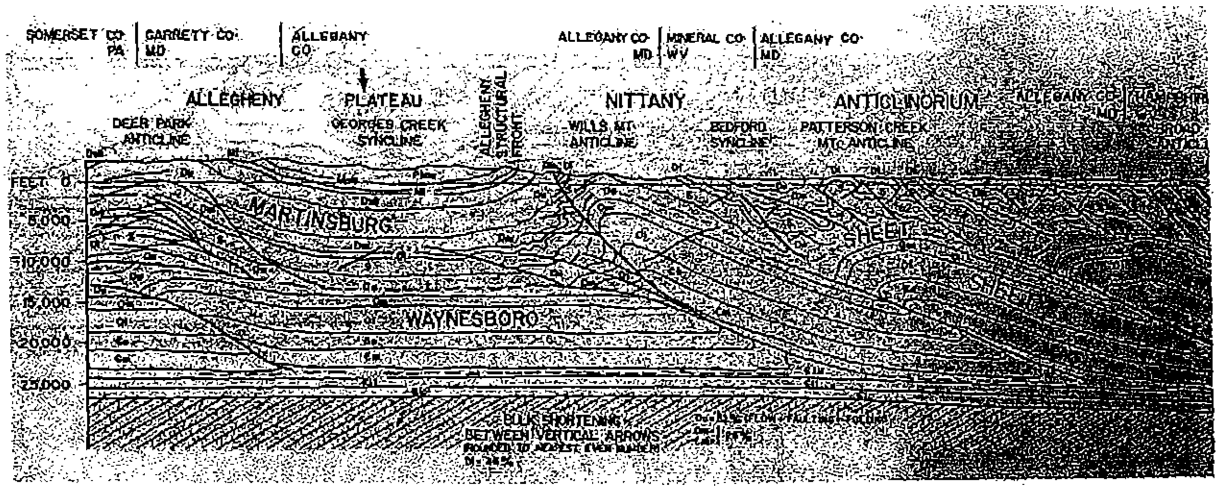

Figure 4. Structural cross section through Allegheny structural front (see Figure 1 for location) (from Kulander and Dean, 1986).

imbrication at multiple levels not only accommodated the large tectonic transport from the east but also facilitated the progressive stratigraphic climb of the basal detachment zone from the Waynesboro Shale in the Valley and Ridge to the Silurian Vernon Shale in the Plateau province. Deer Park anticline is part of the Plateau climb-out zone with slip being transferred upward from the Waynesboro Shale in the Valley and Ridge to Vernon Shale under the Appalachian detachment sheet at Laurel Hill anticline. Climb-out ramps through the Gatesburg, Trenton, and Tuscarora levels all possess a common vergence toward the foreland.

It is particularly noteworthy that Deer Park Anticline is situated in the immediate vicinity of and above ancient basement faults (Figure 7). The recurrence of this remarkable structural pattern is not only consistent with our tectonic model for adjacent plateau anticlines (i.e., a major ancient basement fault located at the trailing edge of each anticline) but also presents a reason for presuming that basement faulting is responsible for the structural front as well. Consistent with other Plateau detachment sheet structures, the surface trend of Deer Park appears to follow and be localized by these basement features. The basement fault at the trailing edge of Deer Park manifests a structural relief in excess of 500 m at both the Waynesboro and the Gatesburg levels.

Independent confirmation of the general structural architecture at Deer Park is derived from the interpretation of a seismic section (Mitra, 1986) traversing Deer Park approximately 30 km NE along strike (Figure 1: M-27). The position and orientation of the seismic line were not explicitly provided in the published paper; however, the position and dimensions of critical structural components within the subsurface landscape facilitated a fairly reliable line location and orientation with respect to the Deer Park structure. It is noteworthy that the surface expression of Deer Park anticline merges with the Allegheny structural front approximately 60 km along strike to the northeast. Side-by-side presentation of DP-25 and M-27 facilitates not only comparison of the structural elements displayed in each seismic image but also the imaging attributes of each seismic profile (Figure 3). M-27 contains interpretive markings on key stratigraphic horizons that could not be removed from the published image. DP-25 does not contain interpretive markings at this point to emphasize the presence of a sizable step in basement that was largely covered by a interpretation line in M-27. Also note that the southeastern side of DP-25 has been cropped horizontally to match the horizontal dimension of M-27, the cropped portion of the line is restored on all other Figures showing DP-25 (Figures 5-7).

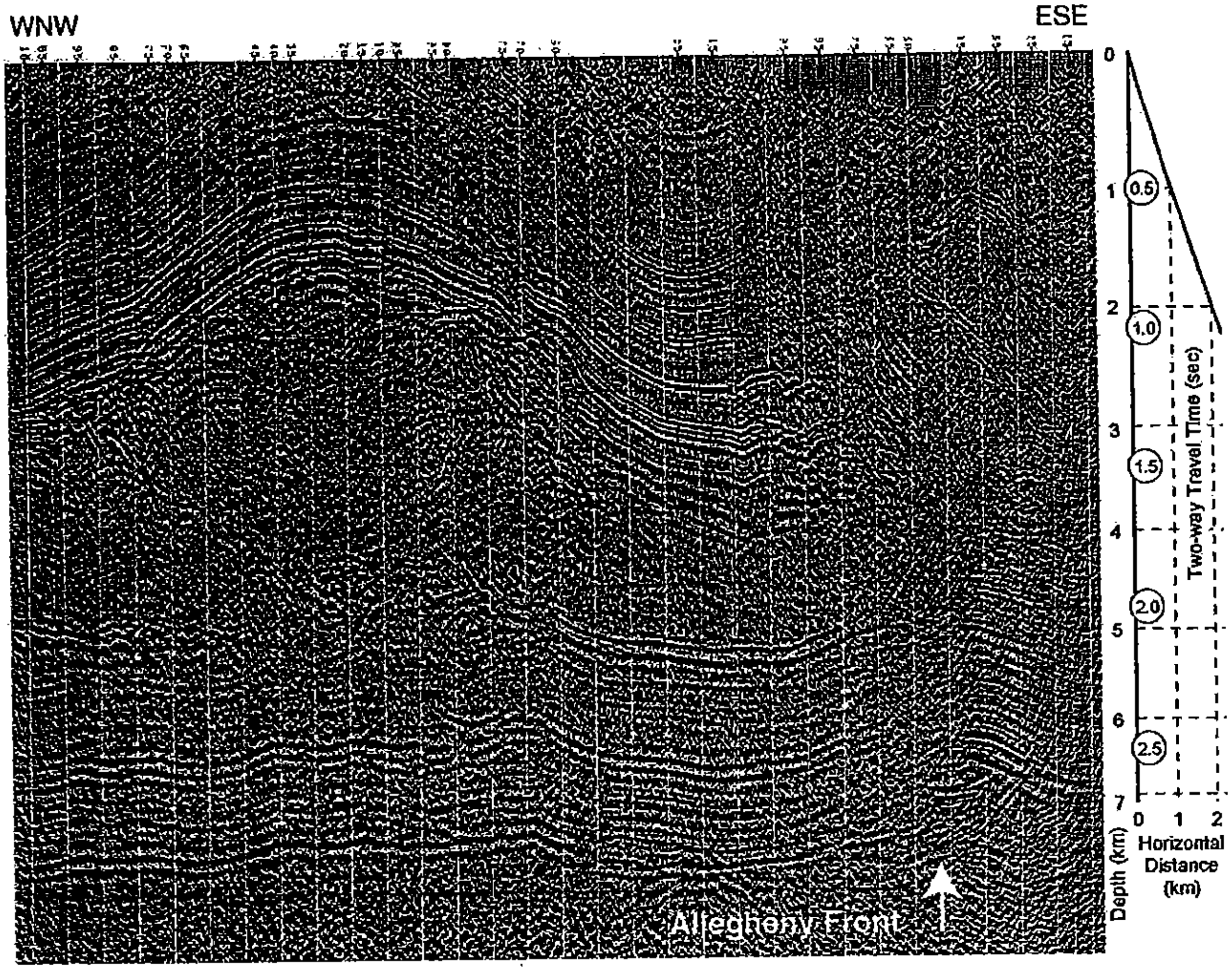

Figure 5. Seismic profile DP-25 showing the complete section cutting across the Allegheny structural front (migrated-time section).

Notable differences in the structural architecture portrayed in the two seismic lines from top to bottom include: (1) M-27 displays a Siluro-Devonian passive roof thrust section that appears to be substantially narrower toward the ESE than DP-25, (2) M-27 appears to exhibit a thicker mouth or tectonic feed zone between the Siluro-Devonian passive roof thrust and the top of the Trenton imbrication zone, and (3) the Gatesburg imbrication zone on M-27 seems to portray a diminished level of imbrication relative to our interpretation of DP-25 for this zone (Figure 7).

Closer examination of the seismic reflection events beneath the interpretive markings that have been superimposed reveals that the reflection picks beneath the Siluro-Devonian roof thrust are not consistent on the WNW and ESE flanks of the anticline. Our interpretation of M-27 would place the roof thrust boundary on the ESE side of Deer Park several hundred milliseconds below the level marked on the published section. This reinterpretation moves a portion of the roof thrust section to a zone of tectonic thickening in the core of Deer Park and erases significant differences between the sections. We also believe that the interpretive markings at the Gatesburg level have smoothed through seismic expressions of a much more intense level of imbrication in this zone that created the appearance of a difference where none exists.

Also at the Gatesburg and Waynesboro levels, the interpretive markings on M-27 have smoothed through unmistakable seismic signatures of major basement discontinuities including a major basement fault at the trailing edge of the anticline.

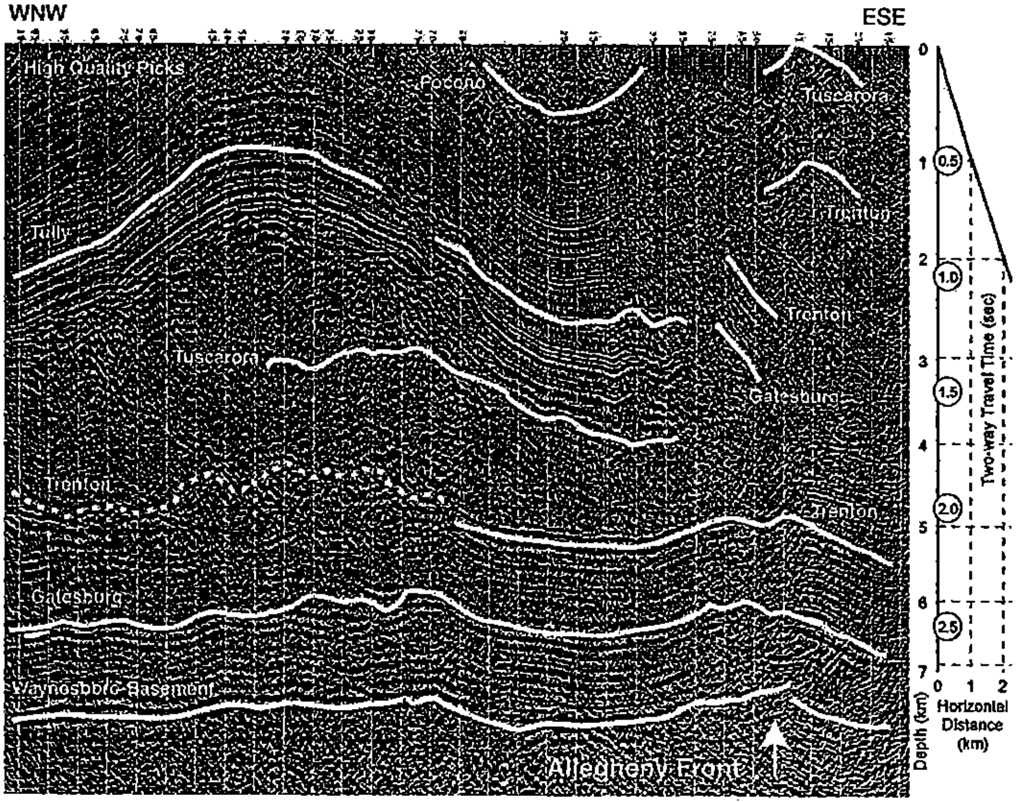

Figure 6. Prominent seismic reflections that correlate with key stratigraphic horizons on seismic profile DP-25 (migrated-time section).

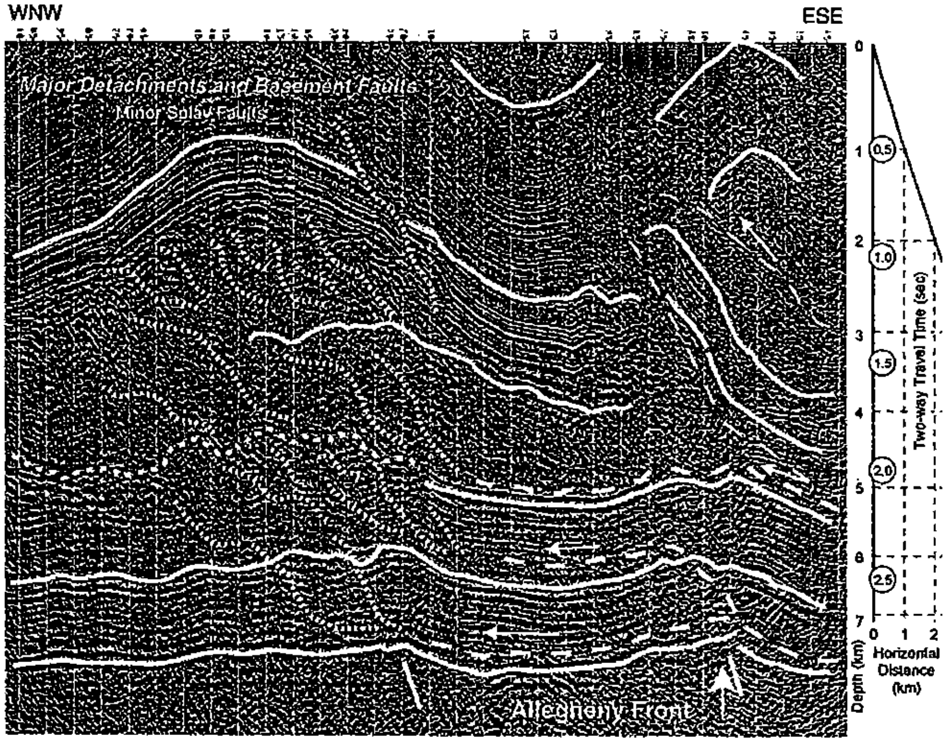

Figure 7. Final geological interpretation of the structural elements on seismic profile DP-25 (migrated-time section).

In summary, high-resolution seismic images confirm that Deer Park anticline exhibits an architecture that more closely resembles the Valley and Ridge structural pattern but differs in that tectonic imbrication and duplexes are stacked independently at the Tuscarora, Trenton, and Gatesburg levels as a result of a dramatic decrease in tectonic transport in moving from the structural front to the more foreland anticlines of the Appalachian Plateau. This architecture contains structural elements that reflect an initial transition from the fault-related folds of the Valley and Ridge to the three-tiered tectonic model of Plateau anticlines. A more mature transition is exhibited at Negro Mountain anticline, the Plateau anticline immediately west of Deer Park (Figures 1 and 8). Here the east flank of the anticline shares the architecture described above for Deer Park whereas the west flank of the anticline exhibits the three-tiered model architecture (Scanlin and Engelder, 2003) that is fully expressed beneath Laurel Hill anticline, the Plateau anticline immediately west of Negro Mountain (Figures 1 and 2).

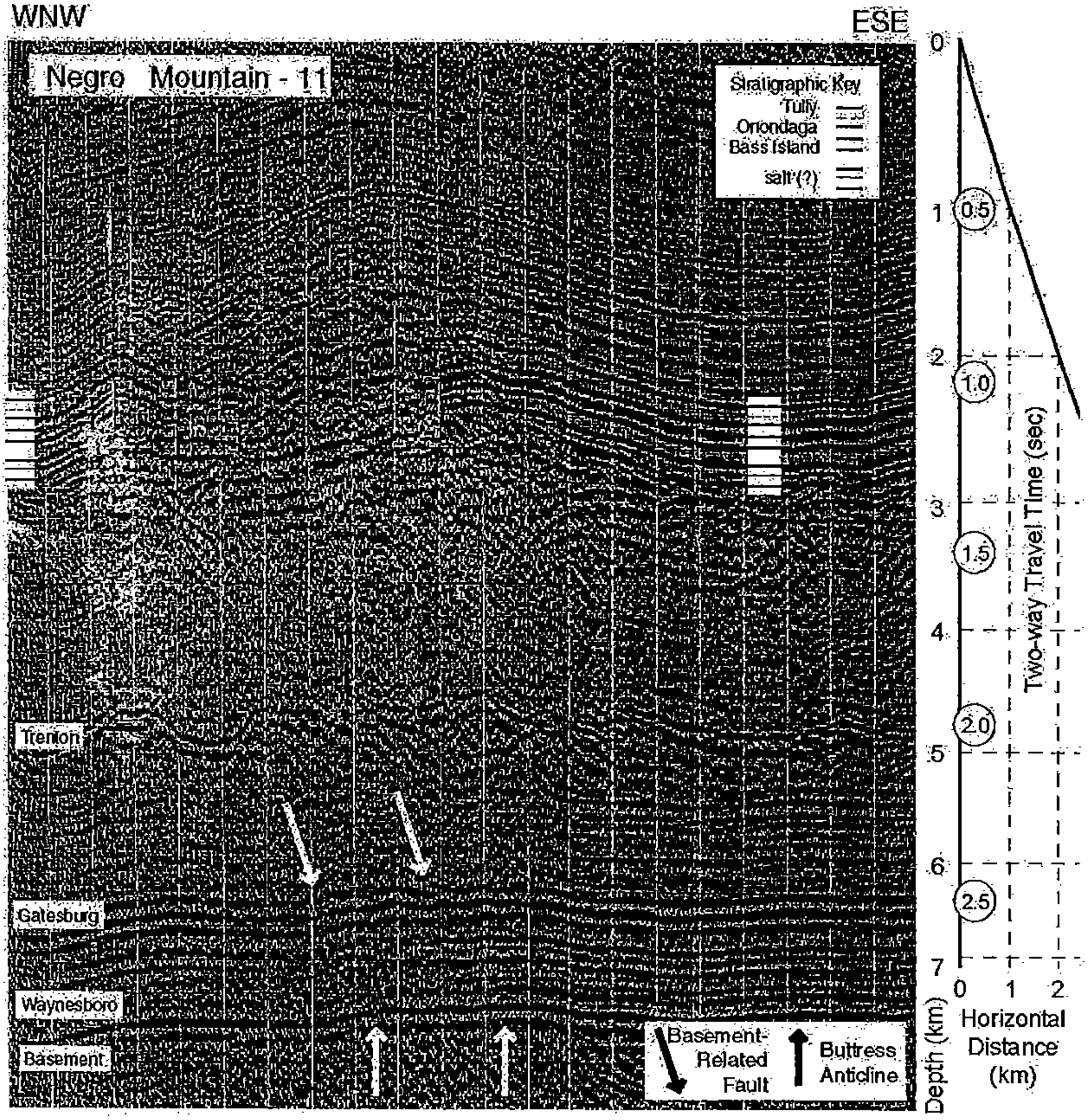

Figure 8. Thrust imbrications at the level of the Trenton horizon and basement-related faults on seismic profile NM-11 across Negro Mountain anticline (see Figure 1 for location). Approximately 3:1 vertical exaggeration.

ALLEGHENY STRUCTURAL FRONT

The east flank of Deer Park dips ESE into a broad relatively undeformed syncline, the Georges Creek syncline that strongly resembles other undeformed synclines between Plateau detachment sheet anticlines to the west. This recurrent structural feature between Plateau anticlines is the structural signature that ultimately led to the recognition of basement faults as the nucleation mechanism in the growth of detachment sheet anticlines (Scanlin and Engelder, 2003). Here, beneath the Allegheny structural front, we encounter perhaps the preeminent Appalachian basement fault with a structural relief in excess of 700 meters. Structural displacement that persists through the Trenton horizon suggests recurrent activity along this fault zone. Intense deformation of the overlying stratigraphic section is testimony to its potential as a nucleating mechanism for the development of tectonic imbrication of the overlying stratigraphic section.

The structural elements present above the fault-related disturbance at the Trenton level exhibit the classic architecture of a fault-propagation fold (Figure 4). Based on the seismic signature correlated with various stratigraphic marker horizons (Figure 6) and the dip of these units, we interpret the arrangement of stratigraphic units displayed to represent the upper portion of two stacked fault-propagation folds. Keeping in mind that the seismic sections are plotted with a 3:1 vertical to horizontal exaggeration, the dip on the beds portrayed in these fault-propagation structures is approximately 30 degrees. Therefore, the structural arrangement of the units and the dip of the beds are consistent with the mechanical constraints associated with fault-related structures. Our interpretation also suggests the strong possibility of the major detachment climbing from Cambrian Waynesboro Shale into the Ordovician Reedsville Shale, thereby facilitating the tectonic transport of the Upper Ordovician-Silurian section across the structural front and carried by imbrication systems into the core of Deer Park. Therefore, the first structure west of the Allegheny Front in the Plateau province displays architecture more akin to structures in the Valley and Ridge. Whereas the typical Valley and Ridge structures are duplexes that involve the entire Cambro-Ordovician carbonate section with a passive roof thrust, the first structure to the northwest of the Allegheny front shows considerable imbrication of the Upper Ordovician-Silurian section in the core of the anticline.

Consistent with our basement tectonic model for Plateau structures to the WNW, structures developed along the Allegheny Front appear to follow and be localized by basement features. The lack of structural continuity at all levels indicates foreland structural transport at all levels. In addition structures on either side of the Allegheny Structural Front exhibit some architecture characteristics consistent with sibling adjacent structures within both the Valley and Ridge and the Plateau.

CONCLUSIONS

Our model for the Allegheny front is consolidated and expressed most effectively by a schematic cross-sectional diagram through the region (Figure 9). Our cross-section begins in the WNW at the first three-tier model, detachment sheet anticline of the Plateau province, Laurel Hill anticline, and progresses ESE through the Plateau anticlines of Negro Mountain and Deer Park and ends at the Valley and Ridge structures of the Allegheny structural front. The two hinterland anticlines of the Plateau (i.e., Negro Mountain and Deer Park) together with the fault-related fold at the Allegheny structural front collectively constitute the Plateau climb-out zone (Figure 9).

Several significant and recurrent architectural themes emerge from an examination of these structures. First, the three structural features that comprise the Plateau climb-out zone are developed immediately above significant basement faults. These basement discontinuities exhibit structural relief that ranges from 300 m at Negro Mountain to > 700 m at the Allegheny structural front. Progressing from east to west the structural elements common to Valley and Ridge architecture evolve in phases through the development of structures across the Plateau climb-out zone into the architecture common to Plateau anticlines further toward the foreland. The passive Siluro-Devonian roof thrust of the climb-out zone evolves into the three-tier structural architecture on the west flank of Negro Mountain. The active Cambro-

Ordovician section common to the climb-out zone is left behind in the floor of Appalachian Plateau detachment sheet beneath Laurel Hill anticline and further to the foreland.

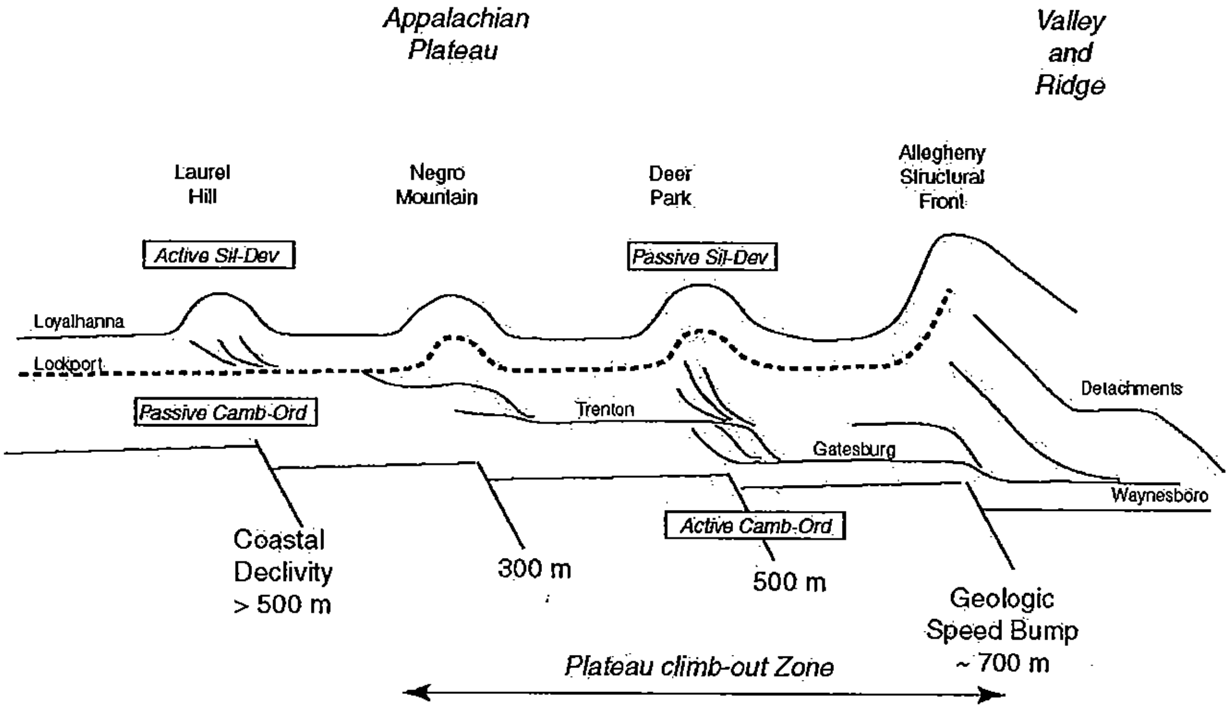

Figure 9. Model for the Plateau climb-out zone between the Allegheny structural front and the Laurel Hill anticline.

In summary, the evolution of the Plateau climb-out zone facilitated the reduction in tectonic transport across the Allegheny structural front relative to transport in the Valley and Ridge during the Allegheny orogeny. High-resolution seismic imagery accurately delineates the remarkable periodic occurrence of major basement faults or 'geologic speed bumps' that are, indeed, responsible for suppressing tectonic transport toward the foreland.

APPENDIX 1

Data Sources

Our analysis of the Deer Park anticline and Allegheny structural front is based on a high-resolution seismic reflection profile 26 km in length acquired by Amoco Production Company in the mid 1980's (Fig. 1). The seismic line traverses the structures being evaluated across strike from WNW to ESE. Geophysical well log information and a velocity survey from the P.N.G. Eberly and Snee, Mowery #1 exploration well, drilled to a depth of 2828 m, provided critical stratigraphic information for the correlation of seismic reflection data and stratigraphy. The seismic data utilized in this study are 24-fold CMP post-stack migrated time sections recording 4 sec of two-way travel-time that yields a penetration depth in excess of 8 km, well below the base of the Paleozoic strata. The data have a temporal sampling interval of 4 msec and a horizontal spatial sampling interval of 45.7 m. Recording instrumentation used in data acquisition was a 48 trace cable system deployed in a split spread configuration with a long offset of 2400 m. 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 an explosive source that consisted of single shot holes drilled to a depth of 15 m and detonated using 44 kg explosive charges. 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 m 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.

Well logs for our analysis are archived at the Oil and Gas Division of The Pennsylvania Topographic and Geologic Survey in Pittsburgh, Pennsylvania (e.g., 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.

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 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 m; the Lower Devonian interval is traversed by seismic wavelets in the 25-30 Hz range yielding resolution of 42 m; and the Cambro-Ordovician section is imaged by 20 Hz energy with a resolution of 56 m. Average velocities used for time to depth conversion can be calculated using the Depth-Horizontal Distance Chart (Figure 2). 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, whereas shallower 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 m 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.

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