STRUCTURAL GEOLOGY OF THE SOUTHWESTERN SECTION OF THE APPALACHIAN PLATEAU

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Introduction

The Appalachian plateau is the westernmost province of the Appalachian mountain belt and stretches from Alabama to New York. The Appalachian plateau is characterized by broad, low, open folds with dips ranging from 20° to less than 5°. Wavelengths of the folds range from 5 to 20 miles and the structural relief can be a few hundred to greater than 3,500 feet. The structural trends show fold amplitudes that decrease from the eastern margin to the western margin. Various structural lineaments, or cross-strike structural discontinuities, cross-cut the Appalachian plateau generally perpendicular to fold axes. The structural development of the Appalachian plateau ranges from Precambrian age, with Grenvillian basement structural features influencing lower stratigraphic levels, to Permian age with Allegheny orogeny development of décollement slip and folds. Much debate has occurred to determine the timing of fold development and the influence of the basement of the Appalachian plateau. This paper will focus on the key structural features of the Appalachian plateau in southwestern Pennsylvania.

General Geology

The Pennsylvania state portion of the Appalachian Plateau can be broken up into several sub-provinces or sections (Figure 1-1). This brief structural geology summary will focus on literature covering the Pittsburgh Low Plateau Section and the Alleghany Mountain Section. The plateau province comprises almost entirely sedimentary rocks in gentle folds with large wavelengths and amplitudes that decrease to the northwest. Most folds are asymmetrical with the steep flank dipping to the southeast. Anticlines commonly have dips ranging from 3° to 12° on their northwestern flanks and from 4° to 20° on their southeastern flanks, however, larger dips have been measured throughout the plateau at scattered localities (Hickok and Moyer, 1971; Harper, 1989; Beardsley et al., 1999). Fold axes are generally arcuate and remain parallel to sub-parallel to the arcuate trend of the Appalachian mountain range seen in central Pennsylvania. Folds generally trend northeast to southwest and plunge 1° to 2° to the northeast (Iranpanah and Wonsettler, 1989). Overall the plateau is characterized by generally level surface with some rolling hills which are at an altitude great enough to permit erosion of deep valleys by streams.

The general stratigraphy is Pennsylvanian through Cambrian sedimentary units deposited on a metamorphic Precambrian basement. Most models of the plateau show anticlines and synclines extending down to a décollement surface within salts of the Silurian Salina Group. The Appalachian plateau is often cited as the type example of broad zone, layer-parallel shortening with subordinate splay faults in the hanging wall of the detachment sheet (Gwinn, 1964; Rodgers, 1964; Scanlin and Engelder, 2003). Layers of rock above the décollement are referred to as the Appalachian plateau detachment sheet and were folded above the décollement by a variety of mechanisms. Using seismic reflection data Scanlin and Engelder (2003) were able to discern the following three-tiered mechanical stratigraphy: a thin basal detachment zone in Upper Silurian strata, an imbrication zone within Upper Silurian through Lower/Middle Devonian strata, and a wedge zone within Upper Devonian and Mississippian strata.

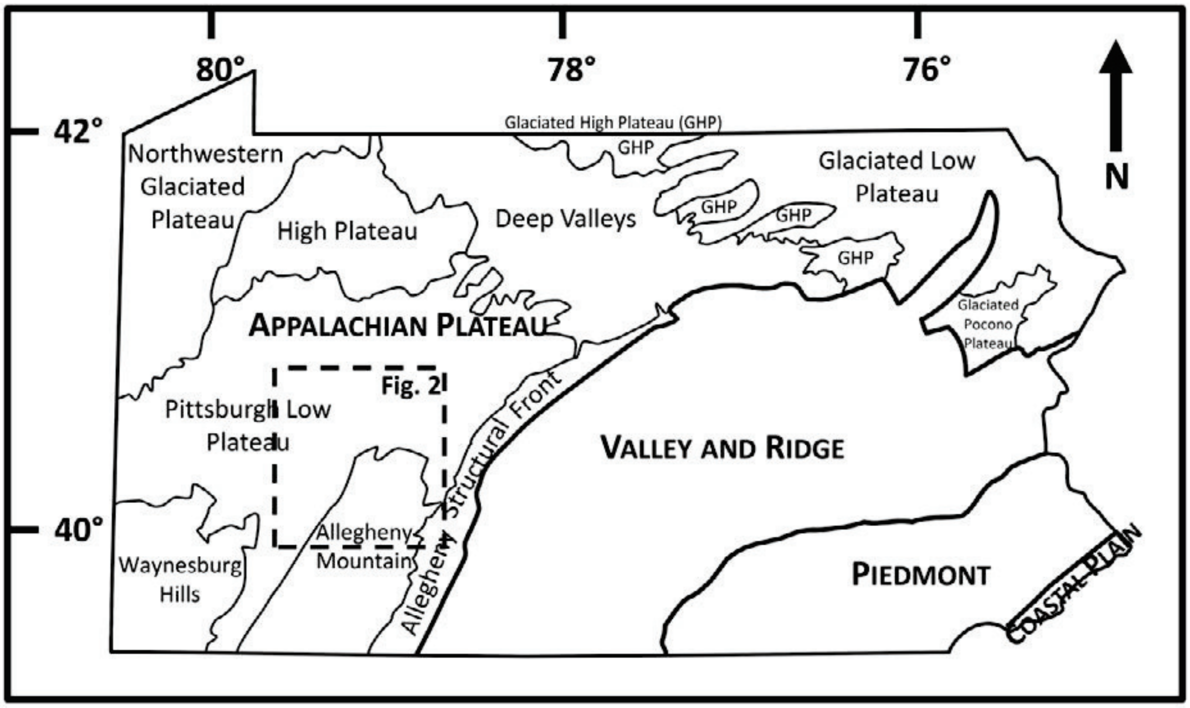

Figure1-1. Generalized physiographic provinces of Pennsylvania with province sections for the Appalachian Plateau (Berg et al., 1980)

Above the detachment zone, at the core of plateau anticlines, seismic data support the presence of imbricated thrusts of splay faults that exhibit fault-propagation folds, fault-bend folds, and kink banding morphology (Scanlin and Engelder, 2003; Gillespie et al., 2015). These imbrications are observed to cut the Lower/Middle Devonian units which are composed of carbonates (Tully, Onondaga, and Helderberg limestones) and interbedded clastics (Marcellus shale and Oriskany sandstone). Above the imbrication zone is an area that exhibits wedge thrusts with a combination of foreland and hinterland thrust directions (Scanlin and Engelder, 2003).

Proximity to the Allegheny structural front and variation of thickness of the salt detachment appears to control the variation of subsurface structural style and structural relief (Wiltschko and Chapple, 1977). Detachment and translation occurred during the Pennsylvanian-Permian Alleghenian Orogeny. Mount (2014) estimated the shortening necessary to create observed structural is approximately 1-2%. However, Scanlin and Engelder (2003) note that movement along the salt décollement alone is insufficient to account for the fold amplitude in the Bedford-Pittsburgh region and that additional mechanisms are required for full anticlinal growth. It is postulated that some salt doming within the Salinas Group has contributed to folding (Wiltschko and Chapple, 1977). When examining the folds within the context of buckle fold mechanisms, relatively modest length to spacing ratios are predicted (Biot, 1961). However, the anticlines of the Allegheny plateau have large aspect ratios which are more akin to forced folds centered on basement involved faulting indicating that there are important footwall structures involved in fold development (Scanlin and Engelder, 2003). Evidence appears to suggest that the evolution of the Appalachian plateau folds are a complex intermingling of mechanisms including:

décollement slip and buckling; hanging wall thrusts, imbrications, and wedging; kink banding; salt doming; pervasive layer-parallel shortening; and footwall faulting in basement rocks.

Formation

The classic model for the Appalachian plateau detachment sheet involves periodic buckling above a detachment in salt (Wiltschko and Chapple, 1977). There are two hypotheses for the formation of the large-scale folds of the Allegheny Plateau: folds are the result of thin-skinned tectonics which deformed the upper layers without basement deformation (Rodgers, 1949, 1953, 1964; Gwinn, 1964); folds are the result of deep basement faulting that passively folded the upper layers (Cooper, 1964).

The Grenvillian basement in the plateau has various décollement ramps, tear faults, and transform faults from the Grenville orogeny (~1 Ga) that were later reactivated to influence folding throughout the plateau (Beardsley et al., 1999). These Grenvillian structures initiated a large graben (the Rome Trough) and growth faults within the overlying Cambrian strata during tensional stress related to rifting in the Cambrian. The Appalachian plateau region was primarily a sedimentary basin during much of the Paleozoic which facilitated deposition of thick sedimentary sequences that were shed from the eastward Taconic and Acadian mountain belts. The Paleozoic sedimentary sequence is occasionally punctuated by limestone units. Throughout the Taconic orogeny (480-440 Ma) the plateau underwent compression stresses which created a series of monoclinal flexures across the old growth-faulted terrane (Beardsley et al., 1999). During the Acadian/Caledonian orogenies (~390 Ma) down-warping of monoclinal flexures occurred. Stresses imposed by the Alleghenian orogeny (~260-340 Ma) pushed strata along a basal detachment creating the Appalachian Plateau detachment sheet and induced thrusting and folding within the detachment sheet creating much of the structure present in the plateau today.

Examination of several types of strain indicators (e.g., deformed fossils, solution cleavage, and mechanically twinned calcite grains), studies have been able to show that there has been approximately 10% layer-parallel shortening throughout the Appalachian plateau (Nickelsen, 1966; Engelder and Engelder, 1977; and Engelder, 1979). Strain indicators are oriented at right angles to the northwestward movement of the orogenic front and suggest that layer-parallel shortening occurred prior to folding (Gillespie et al., 2015). Recent estimates of the shortening needed to create the folding present in the Appalachian plateau are approximately 1-2% (Mount, 2014).

Asymmetry of folds (i.e., shallow northwesterly limbs and over-steepened southeasterly limbs) in the Appalachian plateau has been the source of much debate. This asymmetry in the folds of the plateau is the exact opposite trend seen in the Valley and Ridge province to the east. Sherrill (1934) proposed that the asymmetry was caused by an overall southeasterly regional dip at the time of deformation and the southeasterly thickening of the folded sequence. Others have suggested that the asymmetry was developed by basement-driven, deep-seated underthrusting of northwest limbs by the southeast limbs (Cathcart and Myers, 1934). Gwinn (1964) developed a complex model of splay faulting shearing off the décollement and translating wedges of material northwest into the northwesterly limbs of the folds reducing the northwestern limb dips and over-steepening the southeasterly limbs. Seismic interpretations conducted by Mount (2014) suggest that fold asymmetry is created by mechanically pinched out salt at synclinal locations at the décollement level buttressing the folds and accentuating asymmetry.

Intra-Plateau Structural Front

Gwinn (1964) identified significant decrease in structural relief going toward the foreland which he subdivided into the Inner plateau, to the east, and the Outer plateau, to the west, along an intra-plateau structural front (Figure 1-2). The Intra-Plateau Structural Front is a demarcation within the plateau where a change in the character of folding is apparent. The Intra-Plateau Structural Front is present on the west side strike parallel to the Chestnut Ridge anticline and separates the relatively more intense folding of the southeastern portion of the plateau from the gentler, less intense folding of the northwestern portion of the plateau (Gwinn, 1964). The broad gentle folds of the Outer plateau region commonly have dips less than 5° on their limbs whereas the Inner plateau often has dips from 5° to 20° on their limbs.

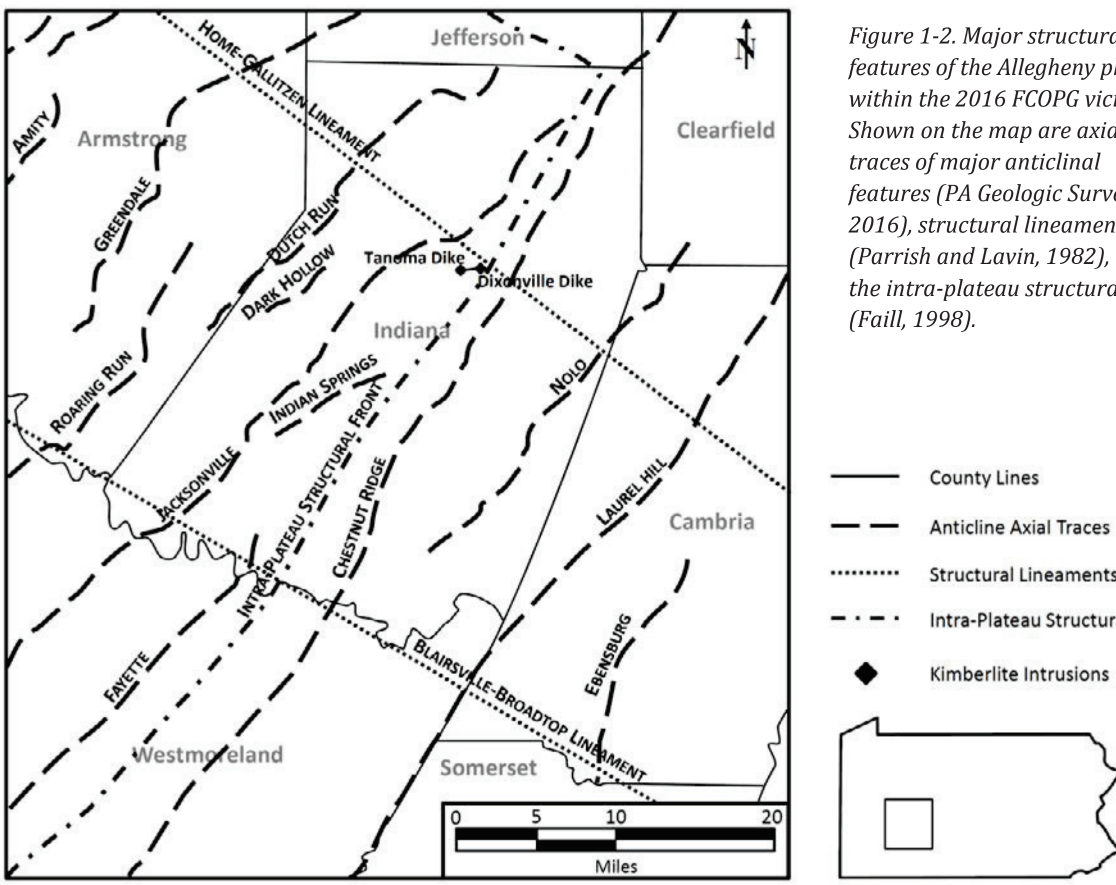

Figure 1-2. Major structural features of the Allegheny plateau within the 2016 FCOPG vicinity. Shown on the map are axial traces of major anticlinal features (PA Geologic Survey, 2016), structural lineaments (Parrish and Lavin, 1982), and the intra-plateau structural front (Faill, 1998).

Silurian Salina Group

Most models for the plateau folds suggest detachment along the Silurian Salina salts with overlying imbrication zones within the incompetent Devonian shales punctuated by limestones, folding the units above. In southwestern Pennsylvania the Salina Group generally consists of: the Vernon formation, a unit of red and green shale, and the Syracuse formation, an interbedded dolomite, anhydrate, and salt. Along with two other minor formations, the Camillus and Bertie formations, the overall thickness of the Salina Group is approximately 650 meters (Heyman, 1977). There are at least six major salt units within the Salina Group designated “A” through “F”. Two notable salt layers within the Syracuse formation, the F-2 and F-3 salts have been measured to exceed 50 meters in thickness. However, the F-2 and F-3 salts are not regionally continuous and therefore are unable to accommodate the full décollement of the plateau (Heyman, 1977). It believed that the Vernon shales must accommodate some of the detachment (Scanlin and Engelder, 2003). In northwestern Pennsylvania the folds die out, this is attributed to a reduction of stress but also the pinching out of the Salina salts (Frey, 1973).

Folds

Numerous folds transect the plateau region (Figure 2) and two major folds within this region, the Laurel Hill anticline and the Chestnut Ridge anticline, are further examined. Both folds are broad, open, slightly asymmetric folds with accurate axial trends that are approximately 030°. The folds plunge 1° to 2° to the northeast and both folds extend for over 125 miles. The Laurel Hill and Chestnut Ridge anticlines lie within the Inner plateau region of the Appalachian plateau with the northwestern margin of the Chestnut Ridge anticline serving as the limits of the Inner plateau region.

Laurel Hill anticline

The Laurel Hill anticline is an open, slightly asymmetrical fold with dip on southeastern limb ranging from 10° to 15° and 8° to 10° on the northwestern limb (Iranpanah and Wonsettler, 1989). The anticline, on average, is 8 miles wide and generally has a flat broad top that can be up to 2 miles wide. The amplitude of the Laurel Hill anticline to the adjacent synclines, the Ligonier syncline to the northwest and the Johnstown syncline to the southeast, is as much as 1,800 ft (Hickok and Moyer, 1971). However, the northwest limb of the Laurel Hill anticline has been uplifted slightly more than the southeast limb giving the northwest limb slightly less structural relief (Hickok and Moyer, 1971).

The Conemaugh River cuts through the Laurel Hill anticline just west of Johnstown creating the Conemaugh Gorge. The creation of the Conemaugh Gorge is thought to be from an antecedent river that existed before the surface expression of the Laurel Hill anticline (Iranpanah and Wonsettler, 1989). The Conemaugh Gorge is approximately 1,500 ft in relief, trends 330° and provides a well exposed cross-section of Pennsylvanian, Mississippian, and Devonian strata (Iranpanah and Wonsettler, 1989).

Scanlin and Engelder (2003) subdivide the subsurface of the Laurel Hill anticline 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. Thrust wedges within the wedge zone of the Laurel Hill anticline have been measured to be approximately 1,400 ft thick (Scalin and Engelder, 2003). There is evidence for basement involved faulting beneath the Laurel Hill anticline in the form of monoclinal bends that show little indication of detachment in seismic reflection, however, the seismic data show some deep high angle faults (Scalin and Engelder, 2003).

Chestnut Ridge anticline

The Chestnut Ridge anticline is an open, slightly asymmetrical fold with dip on southeastern limb are up to 15° to 20° and on the narrower northwestern limb approximately 10° or less (Shumaker, 2002). The anticline is about 8-10 miles wide with a generally flat broad top. Unlike the Laurel Hill anticline, the southeast limb of the Chestnut Ridge anticline has been uplifted slightly more than the northwest limb (Hickok and Moyer, 1971). The asymmetry of uplift provides varied structural relief with respect to the adjacent synclines. On the northwest limb of the Chestnut Ridge anticline, adjacent to the Uniontown syncline, structural relief is as much as 3,400 ft. The southeast limb of the Chestnut Ridge anticline, adjacent to the Ligonier syncline, structural relief is as much as 1,700 ft (Hickok and Moyer, 1971). Approximately 25 miles northeast of Indiana, near Johnsonburg, the Jacksonville anticline (also referenced as the Grapeville-Kinter Hill anticline) merges with the Chestnut Ridge anticline forming a broader Chestnut Ridge anticline which continues another 35 miles northeast.

Subsurface structure of the Chestnut Hill anticline displays the same three tier structure as Laurel Hill anticline as reported by Scanlin and Engelder (2003). Seismic reflection data shows that the Chestnut Ridge anticline has a thickened Upper Silurian section with doubly vergent blind thrusts at the level of the Lower/Middle Devonian section (Scanlin and Engelder, 2003). Passive concentric folding is accommodated above the blind splay faults in the Upper Devonian unit above the Lower/Middle Devonian faulted units. The footwall ramp can be seen in the reflection data cutting the F-2 and F-3 salt of the Syracuse formation at an angle of 25°. Additionally, thickening of the Vernon shale is seen by Scanlin and Engelder (2003) which fills some of the fold volume.

The change in structural styles between the southwest and northeast portions of the Chestnut Ridge anticline correlates to sub-detachment structures. Scanlin and Engelder (2003) used seismic data to suggest that, along the axis, changes in structural styles of the Chestnut Ridge anticline are due to the presence of the Rome Trough in the southwest portion which appears absent in the northeast portion of the Chestnut Ridge anticline. The southwestern portion of the Chestnut Ridge anticline subsurface exhibits extensive wedge thrusting at depth (Scalin and Engelder, 2003). Using a combination of well logs and seismic profiles along the southwest portion Shumaker (2002) identified subsurface structure that is more akin to faulted folds rather than traditional imbrications. The northeast portion of the Chestnut Ridge anticline seismic reflections indicate larger-scale imbrication in the imbrication zone leading to more coherent concentric folding throughout the Devonian section (Scanlin and Engelder, 2003).

Lineaments

Structural lineaments in this area have been identified using gravity, magnetic, structural, and Landsat data and represent fracture zones which penetrate deeply into the crust (Lavin et al., 1982). Using these data sets, several structural lineaments have been identified by observing the following: terminations and displacements in gravity and magnetic surveys; terminations of fold axes; high fracture densities; linear topographic depressions; zones of anomalous hydrocarbon leakage; and valley and stream alignments on Landsat images (Gold, 1999). Additionally, these fracture zones are occasionally visible in the field with the presence of: 0.3 to 1.2 miles wide zones of increased fracture density, geometrically related faulting and jointing, and Pb-Zn and Cu mineralization (Lavin et al., 1982). Where the lineaments intersect plateau folds there is often a rapid decrease in the amplitude of folding, as much as 900 ft in some locations (Parrish and Lavin, 1982). The lineaments may represent fossil transform faults that have been later reactivated (Gold, 1999).

The Allegheny plateau is thought to be part of the Lake Erie-Maryland crustal block. This rectangular crustal block is thought to be approximately 60 miles wide and 350 miles in length and bound in the plateau region by the Tyrone-Mt. Union lineament to the northeast and the Pittsburgh-Washington lineament to the southwest (both trending approximately 320-330°). These two larger lineaments are considered to extend at least into the Precambrian basement, if not into the mantle (Lavin et al., 1982). Displacement along the Pittsburgh-Washington and Tyrone-Mt. Union lineaments has been identified and is thought to be as much as 35 miles left-lateral movement on the Pittsburgh-Washington lineament and 60 miles right-lateral movement on the Tyrone-Mt. Union lineament resulting in northwest translation of the Lake Erie-Maryland block during continental collisions (Lavin et al., 1982).

Two structural lineaments, the Blairsville-Broad Top and Home Gallitzin lineaments (Figure 2), are present within the 2016 Field conference vicinity and are considered to be within the Lake Erie-Maryland crustal block. Gravity and magnetic data for the Blairsville-Broad Top and Home Gallitzin lineament lack strong reflectance which compelled Parrish (1978) to suggest that they are confined to the sedimentary section and upper basement. Additionally, Parrish (1978) found no apparent evidence of major displacement suggesting that they are undisturbed within the block but interrupted or terminated along the deep crustal fractures beneath the bounding lineaments (i.e., the Pittsburgh-Washington and Tyrone-Mt. Union lineaments).

Summary

The structural geology of the Appalachian plateau can be deceptively complex when examining only the subtle features expressed at grounds surface. Debate about the exact mechanisms of deformation has engaged geologists for over a century. The recent wealth of seismic profiles related to increased petroleum hydrocarbon exploration in the plateau is providing the opportunity for more detailed research of subsurface features responsible for the architecture of the Appalachian plateau. As more data becomes available, it is apparent that this region will spur debate for years to come.

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