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Sequential development of the Gassaway structure in Braxton County, West Virginia

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**SEQUENTIAL DEVELOPMENT OF THE GASSAWAY STRUCTURE
IN BRAXTON COUNTY, WEST VIRGINIA**

Richard F. Viso

Thesis

Submitted to the Eberly College of Arts and Sciences

Department of Geology and Geography

of West Virginia University

In Partial Fulfillment of the Requirements for

The Degree of Master of Science

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Alan Donaldson
Robert Shumaker
Thomas Wilson, Chair

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Sequential Development of the Gassaway Structure in Braxton County, West Virginia

Richard F. Viso

ABSTRACT

In central Appalachia, tracing the sequential development of geological structures is often a challenging task due to the activity of multiple tectonic events throughout its geologic history. Original structures often have been reconfigured during the Paleozoic, leaving long and complex growth histories. In order to unravel the development of these structures, analysis of a variety of data sets must be considered.

The following study was undertaken in an effort to reconstruct the development history of the Gassaway dome in Braxton county, West Virginia. Several different analyses were performed to answer questions regarding the timing of the growth of the structure, and the mechanisms responsible for the location and shape of the structure.

General interpretations of several seismic lines provided information about the location and trend of a basement level fault that exists directly beneath the Gassaway structure. These interpretations were also used to construct reactivation history diagrams, which chronicle the growth of the structure. Detailed interpretation of seismic line CNR-G1 (the only line that crosses the structure) reveals a fan-like distribution of faults (in cross-section), characteristic of strike-slip geometry typically associated with positive flower structures. 2D seismic models were constructed with geophysical computer software to further define possibilities for structures that could provide the responses seen in line CNR-G1. Structure and isopach maps constructed from several hundred wells throughout the study area help to constrain the aerial extent of the Gassaway structures, defining them as a series of domes rather than an anticline. Well log data were used in construction of stratigraphic cross-sections in an attempt to identify growth related thinning which could be correlated with features seen in the seismic data.

Results of the above analyses demonstrate that the Gassaway structure has a long growth history, beginning as early as Cambrian time, and continuing through the Early and Middle Paleozoic. The structure has also been identified as part of a larger cross-strike system that could be related to differential

spreading along the east margin of the Rome trough, or as an antithetic fault to the proposed ancient strike-slip system known as the New York – Alabama geophysical lineament.

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CHAPTER 1

INTRODUCTION

General Geological History of the Appalachian Basin

The Appalachian basin, now located adjacent to the Atlantic passive margin, has been affected by a complete set of tectonic events (ie: rift-drift-compression) throughout its development. It is one of many continental Paleozoic basins in which basement structures, associated with basin formation continued to be active and to influence younger sedimentation and structure trends. Even though the Appalachian basin contains structures representing a “full cycle” of plate tectonic processes, many of the structures are poorly understood. The term full cycle refers to the series of events including rift – continental drift/basin sag (collapse)- and compression, which are believed to be events responsible for the formation of many interior continental basins in North America.

Beginning in the Precambrian, and continuing into the Cambrian, extensional forces, associated with Iapetan rifting, tore apart the crystalline basement rocks that were formed earlier, during the Grenville orogeny (Shumaker, 1996). A major failed interior rift, the Rome trough, began forming at this time throughout western West Virginia, western Pennsylvania, and eastern Kentucky. Bounded on the east by a well defined, steeply dipping normal fault system and on the west by a rotational hinge, this asymmetric graben was active throughout the deposition of the Paleozoic cover, and has influenced development of structures therein (Beardsley and Cable, 1983; Shumaker and Wilson, 1996).

A period of post rift quiescence allowed for build-up of a carbonate shelf before the onset of subduction in the Middle Ordovician. Orogenic episodes in the

Appalachians are associated with three distinct orogenic pulses, which tended to affect different regions at different times. In the central Appalachian basin, several structures for example, the Warfield anticline, were affected by more than one tectonic event (Gao, 1994), resulting in a complex growth history. Such is also the case with the Gassaway structure.

Background Information

The Gassaway dome is located in Braxton county, West Virginia near the geographical center of the state (Figure 1-1). Originally mapped as an anticline extending from central Clay county north through central Braxton county (Rice, 1964), this study shows the structure to be more domal in shape and possibly confined completely to the Gassaway 7.5 minute quadrangle (Figure 1-2). Several oil and gas fields are located in close proximity to the Gassaway structure. The structure has significant closure, however wells drilled near the crest encountered only water. Hence, it is important to understand the growth history of the dome and how hydrocarbon entrapment may have been affected.

Seismic data (Figure 1-3) reveal what at a first glance has the appearance of a thrust detached cylindrical fold (Figure 1-4). Construction of isopach and structure maps of several subsurface intervals and horizons presented later in Chapter 4 (for example, see Figure 4-3) show that the structure has limited lateral extent, and more of a dome shape. The structure exists in Devonian aged strata of the Oriskany-Onondaga interval, and appears to be cored by Lower Devonian and Upper-middle Silurian intervals. In general, thin skinned plateau structures are believed to be products of the Permian aged Alleghany orogenesis (Gwinn, 1964; Rodgers, 1963). Thinning of Devonian-Pennsylvanian

Figure 1-1. Location map showing Braxton County and the study area. USGS 7.5 minute quadrangles covering the area are also shown. The anticlinal structure shown on the map is taken from Rice, 1964.

Figure 1-3. Selected portion of seismic line CNR-G1 showing the Gassaway structure.

Figure 1-4. Surface expression and seismic expression of an idealized Appalachian fold resulting from subsurface detachment.

aged units over the crest of the structure however, suggest a growth history that is not coincident with timing of the Allegheny orogeny. It is likely that the thinning seen in units shallower than the Oriskany is growth related rather than mechanical in nature. If thinning of units across the crest of the structure resulted from flexural flow, much larger amounts of mechanical thinning should be observed in larger structures such as the Deer Park anticline (Figures 1-5, 1-6). The Deer Park anticline however does not appear to thin at all in Devonian shale interval.

Also noteworthy in line CNR-G1 (Figure 1-7) is the appearance of at least two normal faults at the basement level, located directly below the crest of the Gassaway dome, stepping down to the east. These faults cut into Middle and possibly Upper Cambrian formation of the Cambrian-Ordovician carbonate sequence. Several structures in the Appalachian basin have been shown to be involved with reactivation of basement structures (Shumaker, 1986). Reactivation of the basement faults throughout the tectonic evolution of the Appalachian basin suggests that basement faults played an active role in the location of the Gassaway dome.

Purpose and Scope

Analyses of seismic and well log data across the Gassaway dome and surrounding area will be used to chronicle the events that led to the present configuration of the structure. Understanding of the geometry of the structure may also provide information relative to selection of alternate drilling locations.

The sequential development of the Gassaway dome is documented to increase our understanding of the development of the high plateau area of the Appalachian basin, adjacent to the Rome trough, in central West Virginia (Figure 1-8). Other significant

Figure 1-5. Seismic image of Deer Park anticline. No thinning (mechanical or stratigraphic) can be seen in the Huron - Oriskany interval across the crest of the structure. (from Wilson, in press)

Figure 1-6 Depth compressed representation of Deer Park seismic data. (from Wilson, in press)

Figure 1-7. Selected deep portion of seismic line CNR-G1 beneath the Gassaway structure. Basement begins at ~2.15 seconds (two-way travel time).

Figure 1-8. Map of Appalachian basin showing basic structural architecture, and location of study area relative to basin. (Modified from Shumaker, 1997)

structures in or near the study area include the East Margin fault, Burning-Mann lineament, and 38th parallel lineament (see Figure 4-1). All of these structures are located in an area that is a structural (Figure 1-8, 4-1) and stratigraphic (Figure 1-9) cross-roads. Understanding the growth histories of such structures will also contribute towards the understanding of larger scale tectonic processes associated with the development of the Appalachian basin.

The Gassaway structure is unique in that it is located, geographically, in an area where similar positive relief structures are interpreted to be thin skinned detached folds of the Permo-Pennsylvanian aged Alleghanian orogenesis (Gwinn, 1964; Rodgers, 1963). The possibility of syndepositional growth is suggested by seismic line CNR-G1 (Figure 1-3). Thinning across the Gassaway structure, if syndepositional, suggests that the structure began to develop long before the Alleghanian orogeny.

This study will evaluate the possibility that the Gassaway dome began to develop more than 100 My prior to the onset of Alleghanian orogenesis. Structural origins of the feature within the context of well based structure contours and isopach maps will also be considered, along with forward 2D modeling of the feature in seismic response.

Previous Study

The Gassaway anticline (Braxton county, West Virginia) is located geographically in the center of the state (Figure 1-1), and geologically in the central part of the Appalachian basin (Figure 1-8 & 1-9). In recent years, the influence of reactivated basement structure on the development of shallower structures has been recognized (e.g. Shumaker and Wilson 1996). This relationship between basement and surface structure is more common in the western portion of the basin over the Rome trough where

Figure 1-9. The extent and stratigraphic level of the major decollement zones of the folded Appalachians are shown. (After Shumaker, 1996)

recurrent basement activity is significant (Shumaker and Wilson, 1996). The dominant basement structure in this area is the Rome trough, which is a failed rift that developed initially during the Early and Middle Cambrian (Harris, 1978). Approximately one kilometer of displacement in basement blocks, in the Gassaway area (approximately 5 mi. (8 km) west of the Gassaway dome), is associated with this early to middle Paleozoic rifting episode. Subsidence along the Rome trough and associated structures continued in some cases into the Silurian and Devonian with several instances during which inversion occurred (Wilson, 1994; Shumaker and Wilson, 1996). Episodes of subsequent reactivation of basement structure are documented by thickening or thinning of sedimentary packages that overlie the hanging walls of normal basement faults (Shumaker and Wilson, 1996). Although most offset associated with basement faults is of Cambrian age, smaller amounts of thickening and thinning of sedimentary sequences across trough structures from the late Cambrian on up through the Pennsylvanian reveal continued reactivation of these basement structures. The folds of the central Appalachian plateau (east of the Rome trough) are generally believed to be detached predominantly in the Martinsburg shale (Figure 1-3) and the Silurian Salina salt (Gwinn, 1964; Rodgers, 1963). On regional structure maps, the major folds have an overall northeast to southwest surface trend.

Shumaker and Wilson (1996) have shown that some surface structures in central and western West Virginia are the product of subsequent reactivation of basement faults, and later thrusting. Shumaker (1986) demonstrated the effect of basement structure on sedimentation and surface structure trends by discussing the evolution of the Burning Springs anticline in western West Virginia. Reactivation of basement faults is verified by

noting facies and thickness changes in several different units. The Silurian Salina salt, Devonian Helderberg Limestone, Devonian Huntersville Chert and Onondaga Limestone, Mississippian Greenbrier Limestone, and Pennsylvanian Pittsburgh coal all show thickness changes across the anticline and along its eastern flank (Shumaker, 1986).

When studying the geology of central West Virginia, many possibilities exist for sequential development of geologic structures. The developmental history of the Rome trough provides evidence for several of the different geologic events that have occurred in the Appalachian basin. The Rome trough is a failed interior rift, which developed in response to tensional stresses associated with the opening of the Iapetus Ocean. After the initial phase of Cambrian rifting, sediments began to fill the basin during a passive margin phase in the early Paleozoic. Orogenic events, later in the Paleozoic, associated with the docking of Africa and North America resulted in reactivation of high plateau rift related structures. In some cases structural inversion has been documented. Compressed depth sections made from digitized seismic reflectors (Shumaker and Wilson, 1996) clearly represent this series of events, in addition to demonstrating the complex development history of geological structures in the study area.

In the central Appalachian foreland, it is important to understand that the evolution of present day basin structures is a product of three major tectonic events: 1) Precambrian Grenville orogeny (~1 Ga) which formed the metacrystalline basement underlying the Paleozoic sedimentary cover; 2) Iapetan rifting (~560 Ma) which resulted in the Eastern Interior Rift System including the Rome trough; and 3) the Appalachian orogenic events which span the time period from Middle Ordovician (Taconic episode) through the Permo-Pennsylvanian (Alleghanian episode). Several recent studies have

made great progress in understanding how combinations of at least the latter two of these three structural episodes provide major influences on development of younger structures and exert noticeable control on sedimentation.

A comprehensive basin analysis performed by Yang (1998) over most of south central West Virginia demonstrates how early structures influenced Carboniferous sedimentation and structural development. Sequence stratigraphic techniques and cross-section construction from hundreds of well logs document thickness changes across this study area which often coincide with basement structures produced during early Paleozoic rifting.

Through well log and quantitative seismic analyses, Gao (1994) showed how basement involved structures including the 38th Parallel lineament, the Burning – Mann lineament, and the East Margin fault of the Rome trough influenced the formation of the Warfield structure. This structure had significant effects on sediment distribution over south central West Virginia during the late Paleozoic.

Zou's analysis (1993) of the Lower Mississippian sequence also demonstrated how several syndepositional, basement involved structures including the West Virginia dome, Rome trough, Warfield anticline, and Burning – Mann lineament controlled sedimentation patterns in western West Virginia.

Li Zheng (1990) demonstrated through quantitative seismic analysis how the Griffithsville basement high provided control over the location of younger detached structures. Thinning of younger sediments over the Griffithsville fault provide evidence that the Griffithsville basement high was growing throughout Paleozoic time. Dip reversal caused by growth of shallow detachment structures in the sediments overlying

the Griffithsville high offer proof of basement structures reactivating as recently as the Permo-Pennsylvanian Alleghanian orogeny.

METHODOLOGY

Data Sets

Data were obtained from multiple sources in order to proceed with this study. Stratigraphic cross-sections were made from gamma ray and density logs taken from eighteen wells (Figure 1-2) either provided by Columbia Natural Resources or obtained from the West Virginia Geologic and Economic Survey (WVGES). Structure and isopach maps were created from a well database maintained by West Virginia University's Basin Analysis and Geophysics Lab (BAGL) in the Department of Geology and Geography. Seismic data were provided by Columbia Natural Resources in the form of pre and post migrated, final stack time profiles. Digitized travel times for major reflection events on two lines (CNR-G1 and CNR-G2) were converted to depth using velocities derived from a sonic log in a well located out of the study area. Validity of these velocities was confirmed by comparison of the depth converted seismic data with a gamma ray log from a well located in the center of the study area (well #1126, Figure 1-10) about 1000 meters from line CNR-G1 (Figure 1-2).

All data for cross-section construction and seismic analysis were digitized either at WVGES or in the BAGL for computer program analysis.

Preliminary Description of Seismic Lines

Seismic lines CNR-G1 and G2 were collected in June 1989 in Braxton county, West Virginia. The seismic source consisted of three Y-1100 Vibrators, with a source spacing of 220 feet (67 meters). The input signal consisted of linear upsweep with a

Figure 1-10 Depth converted shallow reflectors plotted with gamma-ray log from well #1126 in Braxton county. This display gives confidence to the accuracy of the velocities used in depth converting the shallow intervals from the time section.

frequency range of 20 – 110 Hz over a duration of 7 seconds. Mark Products 30 Hz geophones combined in 24 phone groups spaced 110 feet (34 meters) apart were used as receivers. The recording instrument was a DFS-V 120 channel recorder with a 12 second record length, and a 2 millisecond sample interval.

The most feature with the greatest relief in line CNR-G1 (Figure 1-11) appears in a reflection event at approximately one-half second, associated with Lower to Middle Devonian intervals. These reflection events define a distinct anticlinal structure between shot points 320 and 250. The seismic data appears to reveal a cross-sectional view of a thrust-detached anticline. Around shot point 310, the Lower to Middle Devonian reflector appears to be repeated across a low angle thrust fault.

Seismic line CNR-G1 provides a fairly representative look at a cross-sectional view of the Gassaway structure. The lateral extent along strike of the structure can not be inferred from the seismic profile alone, but relief and width of the structure can be estimated from line CNR-G1.

Two normal faults are interpreted to cut the basement and extend upward at least through the level of the Elbrook Limestone (Figure 1-7, 1-11). The basement faults lie beneath the east limb of the structure at shot points 271-260 and 2.1 seconds two way travel time (Figure 1-11). Their relationship to the shallower structure is also investigated. One problem with relating activity of the normal faults to growth of the anticline lies in determining the strike of the faults. These faults are only imaged on line CNR-G1. Their absence on line G2 (Figure 1-12) suggests that the fault system either dies out to the south/southwest, or has possible orientations between north-south and northwest-southeast.

Figure 1-11. Seismic line CNR-G1 showing major structural features.

Figure 1-12. Seismic line CNR-G2.

Line CNR-G2 is located to the south of line CNR-G1 (Figure 1-2). The antiform and basement faults imaged in line CNR-G1 are not seen in line CNR-G2. The two lines are sub-parallel, and approximately equal in length. Quantitative analysis of line CNR-G2 is undertaken to determine if thickness changes are present and if so, what structural implications they may have.

Lack of deep subsurface data (such as well logs and extensive seismic coverage) in the study area make it difficult to resolve the growth history of the Gassaway structure. The seismic appearance of the structure on line CNR-G1 however, was the initial motivation for this study. Thinned intervals across the antiform, seen in the seismic data between Devonian and Pennsylvanian units, raise questions regarding thinning mechanism (syndepositional growth versus flexural flow), and timing of growth. Basement faults beneath the east-end of the shallower structure offer the possibility that reactivation of these faults subsequently influenced the location and shape of the dome.

CHAPTER 2

SEISMIC ANALYSIS AND LOCAL STRUCTURAL INTERPRETATION

Introduction

Seismic lines CNR-G1 and CNR-G2 provide images that can be used to extract information about the historical development of the dome. Seismic line G1 provides a 2D glimpse of the Gassaway structure. The seismic profile across the structure provided the basis for geological interpretations as well as quantitative analyses of the Gassaway dome.

Thickness changes observed in the seismic data are used to construct reactivation history diagrams (RHD's) which quantify growth phases. This technique was especially important for gaining information about structural development of intervals beneath the Lower Devonian Onondaga Limestone for which little or no well bore data exists. The RHD's were then used to aid in the development of structural models, and to help identify possible structural interpretations that are not well represented by the cross-sections and contour maps.

Reactivation History Diagrams (RHD's)

Reactivation history diagrams were created based on thickness changes seen in depth shifted seismic displays (Figure 2-1, 2-2). These diagrams quantify the amounts of structural displacement that occurred at various stages of the growth history of a structure. Construction of RHD's follows procedures developed by Wilson et al. (1994). After digitizing ten fairly coherent reflectors found on seismic lines CNR-G1 and CNR-G2, the digitized data were re-sampled at one shot point increments, and plotted as line drawing representations of the time sections (Figure 2-3, 2-4). Plotted horizons were

Figure 2-1. Shifted depth plot of Line CNR-G1 from which thickness differences were calculated for construction of RHD's.

Figure 2-2. Shifted depth plot of Line CNR-G2 from which thickness differences were calculated for construction of RHD's.

Figure 2-3. Line drawings of reflectors digitized from seismic line CNR-G1.

Figure 2-4. Line drawings of reflectors digitized from seismic line CNR-G2.

time compressed in order to emphasize areas of significant thickness change (Figure 2-5, 2-6). This was accomplished by subtracting a suitable time constant from each reflection event in order to bring the line drawings of the reflectors as close together as possible. Stratigraphic order and relative travel time differences are retained in the shifted format.

Next, thickness differences were calculated from the depth converted digitized data (Figure 2-7, 2-8), and compared across active structural features revealed by the shifted time displays (Figure 2-5, 2-6). For example, Figure 2-5 shows significant time differences between shot points 285 and 255. These time differences translate to significant thickness changes upon conversion to depth.

Thickness differences (Δd_n) for each depth interval were calculated between the selected shot point pairs. This was accomplished by subtracting (for example) the depth to the Pennsylvanian aged reflector (d_P) from the depth Greenbrier reflector (d_G) at shot points 285 and 255:

$$d_{P285} - d_{G285} = \Delta d_{285P-G}$$

$$d_{P255} - d_{G255} = \Delta d_{255P-G}$$

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This calculation was repeated for all intervals at each shot point in the pairs shown in figures 2-5 and 2-6.

Then, the differences in thickness between shot point locations (ΔT) (identified by brackets on figures 2-5, 2-6) were calculated. For example:

$$\Delta d_{285P-G} - \Delta d_{255P-G} = \Delta T_1$$

Figure 2-5. Time compressed line drawing of CNR line G1. The reflectors have been compressed as close together as possible in order to emphasize thickness changes. Shot point pairs used in construction of RHDs are identified by brackets. Arrows indicate an example of one interval over which thickness differences were calculated between SP 285 and 255.

Figure 2-6 Time compressed line drawing of CNR line G2. The reflectors have been compressed as close together as possible in order to emphasize thickness changes. Shot point pairs used in construction of RHDs are indicated with brackets.

Figure 2-7. Line drawing of seismic line CNR-G1, depths converted, and corrected to sea level. Reflectors have been identified by formation name or age.

Figure 2-8. Line drawing of seismic line CNR-G2, depth converted, and corrected to sea level. Reflectors have been identified by formation name or age.

$$\Delta d_{285G-H} - \Delta d_{255G-H} = \Delta T_2$$

The thickness differences were then plotted cumulatively, against time (see Figure 2-9 B) to reveal amounts of thickening and directions in which thickening occurred throughout the Paleozoic (Figure 2-9, 2-10, 2-11).

Interpretation of Reactivation History Diagrams

Reactivation history diagrams present a record through time of systematic changes in interval thickness across major structural features. This information can be interpreted as structural reactivation. Most prior analysis of deformation chronologies in the Appalachian foreland area is limited to the Rome trough. For example, Wilson (in press) used reactivation history diagrams to show that vertical displacement along the east margin of the Rome trough occurring through the early and middle Paleozoic can be modeled using an exponential decay process. The Gassaway structure is in close proximity to the Rome trough, approximately four miles (6.4 km) east of the East Margin fault. While the RHD's constructed from seismic lines CNR-G1 and CNR-G2 do not give obvious indications of exponential motion of fault blocks, some interesting aspects were revealed about the growth of the Gassaway structure.

Line CNR-G1

The most obvious changes on the RHD's for line CNR-G1 appear between the Huron Member shale (reflector 3) and the Wills Creek formation of the Silurian Cayugan Series (reflector 5, Figure 2-5), between shot points 255 and 330 (Figure 2-9 B, D). In Figure 2-9 B, negative slope indicates westward thickening, while positive slope represents eastward thickening. Between shot points 255 and 285, significant westward

Figure 2-9. Reactivation history diagrams (RHD's) for seismic line CNR-G1. Amounts of motion are plotted against time throughout the Paleozoic. Figure B has been inverted to match Figure D.

Figure 2-10. Reactivation history diagrams (RHD's) for seismic line CNR-G2. Amounts of motion are plotted against time throughout the Paleozoic.

thickening (into the core of the structure) occurs between the Onondaga/Oriskany (reflector 4) and the Wills Creek formation. Figure 2-9 B was inverted in order to facilitate comparison with similar thickness changes during the Devonian also seen in 2-9 D. In Figure 2-9 D, negative changes in slope indicate eastward thickening. About the same amount of thickening occurs, this time to the east, between the Onondaga/Oriskany, and the Wills Creek from shot points 285 – 320. Together, these two figures indicate that about 400-500 feet of structural growth occurred gradually from Middle Devonian to at least Middle Mississippian time. The thickening between the Wills Creek and Onondaga may be tectonic in origin, resulting from material that was transported into the core of the dome.

The corresponding thinning (in diagrams B and D) between the Huron Member and the Onodaga/Oriskany is interpreted to indicate that the major growth of the dome occurred, as overlying sediments of the Upper Devonian, and Mississippian systems were being deposited. Figure 2-9 D demonstrates that significant growth after the early Pennsylvanian did not take place. This time constraint is placed on the growth period of the structure based on the fact that thickening of the core of the structure (between the Wills Creek and the Onodaga reflectors) equals vertical relief gained during the growth phase. Figure 2-9 B, D demonstrate the equality between amount of core thickening and vertical relief.

Constant eastward thickening starting in the Ordovician, and continuing throughout the rest of the Paleozoic as observed on the eastern section of line CNR-G1 (Figure 2-7 A). Eastward thickening can be explained by at least two mechanisms. Both require that the east block move independent of the rest of the section. Independent

motion of the east and west ends of line G1 indicates that basement block rotation is hinged about the two basement level faults (see Figure 1-5).

The first mechanism is crustal loading from the east. After the development of the deep normal faults (probably associated with an early continental margin collapse and extension phase), the Appalachian orogenic episodes culminated with the docking of Africa and North America during the Permian. During the final Alleghany orogeny, crustal thickening took place rapidly, as imbricated thrust sheets shortened the Paleozoic cover, and created the foreland fold-thrust belt (Gwinn, 1964). Tectonic forces associated with this crustal thickening episode may have contributed to down-to-the-east rotation of the eastern section of line G1 during the most recent development phase of the Appalachians.

The most rapid eastward thickening however is documented (in Figure 2-9) as early as late Ordovician time during which the Taconic orogenic pulse was active. During this time, differential subsidence among fault blocks could be attributed to sediment loading (by such units as the Juniata and Tuscarora) from the Taconic island arc to the east, which was colliding with North America.

The second possible mechanism that could contribute to the rotation of the east block is differential uplift under the Gassaway dome associated with a deep magmatic upwelling. The two normal faults that lie under the dome provide a hinge area about which independent motion of the east and west fault blocks occurred. It is possible that an intrusive event from sub-basement depth could have started the down to the east rotation of the eastern end of seismic line G1. Magnetic models constructed in a concurrent study (Sattler, 1999) suggest a deep crustal heterogeneity. This magnetic

anomaly marks a prominent linear feature running through the center of the Appalachian basin known as the New York - Alabama magnetic lineament.

The RHD for the western section of line CNR-G1 shows only small amounts of fault block activity throughout most of the early Paleozoic, aside from down to the east rotation during the late Cambrian (Figure 2-7 C). Starting in the Devonian, and on into the Mississippian, however, significant eastward thickening can be seen. During the Mississippian, a reversal in the direction of thickening occurs, and rapid westward thickening takes place into the Pennsylvanian.

The mechanisms for motion of the western fault block are unclear, however, it can be assumed that jostling of independent blocks occurred constantly throughout the Paleozoic. Wilson (1993, 1994) constructed RHD's across the Granny Creek oil field, a few miles southwest of the Gassaway area, which documented normal basement fault displacement along the East Margin fault of the Rome trough. Basement level faults beneath the Gassaway structure were active due to changes in tectonic stresses and sediment source areas from Cambrian through Pennsylvanian periods.

Line CNR-G2

Line G2 (Figure 1-10) does not contain as many prominent structural features as can be seen in Line G1, however, thickness changes are again ongoing throughout the Paleozoic (Figure 2-10). Thickness changes on both the east and west ends of Line G2 do not exhibit exponential behavior, but instead are random. Depth conversions of Line CNR-G2, at first glance, seem relatively uneventful (Figure 2-8). The compressed time representation (Figure 2-6) however, reveals a few features that warrant further discussion. The most notable feature in the time compressed section lies between shot

points 120 and 240. A gentle up warping of the lower units is evident with rapid westward thickening occurring during the Ordovician followed by a reversal in rotation (down to the east) from the Ordovician to the Pennsylvanian (Figure 2-10).

Once again, mechanisms for these features do not readily present themselves, however, it is known that tectonic stresses were changing early in the Paleozoic. Wilson and Shumaker (1994) have shown that significant displacement along the East Margin of the Rome trough occurred through the Ordovician, which is when the largest thickness change in Line G2 occurs. Seismic Line CNR-G2 lies less than 1.5 miles (~2000 meters) from the East Margin of the Rome trough (Figure 3-2). It is likely that East Margin fault motions influenced the rotations seen in line G2. Line 1 of Shumaker and Wilson (1996) ~1 mile north of Gassaway, WV shows that the footwall of the East Margin fault of the Rome trough underwent down to the west rotation during the late Cambrian and through the Ordovician. This phase of rotation was followed by a period of down to the east rotation beginning in the Silurian and continuing to the Middle Mississippian. Similar behavior is documented by line CNR-G2 in this study (Figure 2-10). The Rome trough has significant influence on the high plateau structures of the Appalachian basin. Thus the basement structure under the Gassaway structure it is likely to have had a similar history to the adjacent East Margin fault.

Thickness changes seen in the east end of line CNR-G2 follow a similar trend to the thickness changes seen in the west end of the line (Figure 2-10). Though the amounts of displacement are much less at the east end of the line, the directions of rotation are the same. Once again, these block rotations appear to be associated with the rotations of the

footwall of the East Margin fault of the Rome trough which were documented by Wilson (in press) on line 2 about 5 miles east of the study area.

Interline RHD's

In addition to the thickness changes documented over lines CNR-G1 and G2, RHD's (Figure 2-11) were constructed across the area between the two seismic lines (Figure 1-2) in an effort to provide a three dimensional view of relative fault block motion. On these interline RHD's, a negative slope indicates thickening to the south.

During the early Paleozoic, the eastern interline reactivation history diagrams suggests southward thickening, while the western interline RHD suggests northward thickening. Contours showing depths to acoustic basement (Wilson, in press) show that the footwall of the East Margin fault becomes deeper to the north. The northward thickening between lines CNR-G1 and G2 is probably associated with early Paleozoic down to the northwest rotation of the footwall block of the Rome trough. Southward thickening seen in the eastern interline RHD is probably associated with southeastward rotation of a basement block, broken by the normal faults imaged in line G1.

Together these diagrams indicate that the Gassaway study area sits on the footwall block of the east margin of the Rome trough. In order to accommodate the southeastward thickening demonstrated by figures 2-9 A and 2-11 B, the footwall block must be broken by a normal fault. Possible strike of this fault is uncertain because it is not imaged in seismic line G2.

Summary of RHD's

Reactivation history diagrams show direction of rotation and timing of displacement on faults that are located beneath the Gassaway structure. These diagrams

offer evidence that fault block rotation began as early as the Cambrian and continued through the Pennsylvanian. Fault block rotations are shown in some cases to have coincided with motions defined by Wilson (in press) of the footwall block of the Rome trough. The RHD's indicate that fault motions possibly related to the development of the Gassaway structure have a long and complex history.

CHAPTER 3

STRATIGRAPHY AND TIMING OF STRUCTURAL GROWTH

Stratigraphy and Producing Horizons

In central West Virginia, lower Paleozoic sedimentary rocks cover the Grenville crystalline basement (Figure 3-1). Seismic line CNR-G1 reveals coherent reflections as deep as the Middle Cambrian Elbrook Limestone, and as shallow as the Gas and Salt sands of the Pennsylvanian system. Hydrocarbon producing beds are present, and fields (such as the Rouzer, Rosedale, and Granny Creek) have been developed in Braxton and Clay counties. The area's largest producing formation is the Upper Mississippian Greenbrier Limestone (Haught, 1964). This formation consists largely of sandy limestones and calcareous sands that overlie the sub-Greenbrier unconformity in the study area. Most of the production in Braxton and Clay counties is from the 'Big Lime' and 'Big Injun'. The upper Mississippian Greenbrier Formation consists of light gray limestone (the Greenbrier Limestone), varying in thickness from approximately 100-200 feet (Figure 3-2). This interval is often referred to by drillers as the 'Big Lime'. Overlying the Greenbrier Formation is the Mauch Chunk Group, also of the upper Mississippian age (Figure 3-1). This interval (in western Braxton and Clay counties) consists of, from bottom to top respectively, the Blue Monday sandstone, the thin but extensive 'Little Lime' limestone, and then mostly shales (commonly red shales and mudstones) and sandstones. The Mauch Chunk Group is overlain by the New River Formation, a quartz rich sandstone of Lower Pennsylvanian age (Figure 3-1), and this contact represents a major unconformity.

Figure 3-1. Stratigraphic sequences from the Granny Creek field presented in the form of a generalized velocity log and stratigraphic column. Velocities are plotted relative to depth and two-way travel time (after Shumaker and Wilson, 1996).

Figure 3-2 Isopach map of Middle Mississippian Big Line.

Other stratigraphic units are useful, perhaps not as hydrocarbon producers, but as marker beds when interpreting well log data. For example, the Sunbury shale is a highly radioactive bed relative to surrounding lithologies. This makes the Sunbury a suitable datum for cross-section construction due to its easily identifiable ‘kick to the right’ on gamma ray logs (Zou, 1993).

Stratigraphic Cross-Sections

To construct the cross-sections, wells were selected over a six-quadrangle area around the Gassaway dome (Figure 1-2). Once the well locations were selected, gamma-ray and density logs (if present) were digitized from well log records. The digitized logs were then imported into Surfer. Individual stratigraphic intervals were then correlated from well to well (using both gamma-ray and density logs) following the previous work of Yang, 1998 and Zou, 1993.

The most prominent stratigraphic markers were selected for correlation. This resulted in a smaller number of relatively thick (200 – 400 feet) intervals, which more accurately represented thickness changes resulting from syndepositional or mechanical thickening and thinning rather than local processes such as scouring. For example, the Mississippian Greenbrier Formation was chosen for correlation because of its distinctive signatures on gamma ray and density logs.

Stratigraphic cross-sections were constructed through the study area mainly in an effort to suggest occurrence of Mississippian age thickness changes across the Gassaway structure and to evaluate the possibility that these changes are associated with syndepositional growth of the structure. A grid of cross-sections was constructed through

the study area (Figure 1-2). Only gamma-ray logs are displayed on the cross-sections. The density of the lines in the grid was restricted by available well control.

Thinning of intervals across the structure are interpreted to be associated with periods of structural growth. Mechanical thinning (from flexural flow) could possibly accommodate some of the thinning, however, cycle truncations observed in seismic line CNR-G1 are interpreted to result from structural growth during deposition (see Figure 3-3). Ideally, wells used in cross-section construction would contain logs that display the entire sedimentary cover in the study area. In many wells however, the rocks were not continuously recorded on the logs. Unfortunately, most wells are limited in depth, therefore, the cross-sections contain only shallower intervals, and in some cases, only the Greenbrier Formation. Many of the lithologies in the study area are not ‘clean’ sandstones or pure limestones, and their differentiation was difficult to discern on the wireline logs. To combat this problem, both gamma ray and density tracks (where available) were used to interpret sandstones, shales, and carbonates that comprise the stratigraphy. The most reliable pick on these logs is the basal contact of the Mississippian aged Greenbrier Formation. When the logging tool encounters the bottom of this formation, the gamma ray response deflects sharply to the left (decreasing API units) while the density response deflects sharply to the right (increasing density). Figure 3-4 demonstrates the typical signature of Mississippian aged units present in the study area.

Cross-section Interpretation

Cross-section EE’ (Figure 3-5) is an east-west section that crosses the Gassaway dome. This section is interpreted to suggest that the Greenbrier Formation thins almost

Figure 3-3. Exaggerated interval between Mississippian and Pennsylvanian aged reflectors. Several cycle truncations can be seen.

Figure I-4. Comparison of gamma-ray and density logs from well #1126 in Seaton county. The Greenhorn formation is well defined by the box shape (indicated by the dashed line) produced by the opposite deflections of the two curves.

Figure 3-5. Stratigraphic cross-section EE' showing the Upper Mississippian Greenbrier Formation thinning across the Gassaway structure.

50% from approximately 350 feet along the flanks to 180 feet at the center of the structure, and the thinning was gradual rather than abrupt, suggesting that the structure was growing during the deposition of the Greenbrier Limestone.

Thinning is also suggested along the north-south oriented cross-section CB' (Figure 3-6). Cross-section CB' also implies thinning in the (Upper) Mississippian Mauch Chunk Group on the order of 50-100 feet (over the structure) out of a total thickness of 550 – 600 feet, indicating that the structure was active throughout the remainder of the Mississippian and into the Pennsylvanian. Up to 300 feet of growth (33% thinning) over a 900 foot interval are indicated by these cross-sections to have occurred during the Mississippian.

While cross-sections EE' (Figure 3-5) and CB' (Figure 3-6) suggest the continued structural growth through the Mississippian, the scattered distribution of wells does not uniquely define the geometry of the structure. In a preliminary effort to better define the extents of the structure, several other cross-sections were constructed in north-south and east-west orientations throughout the study area. These cross-sections, for the most part, were difficult to construct due to the lack of well log data through the same intervals.

Cross-section AD (Figure 3-7) profiles the Upper Mississippian sections just north of the structure. Neither the Mauch Chunk, nor the Greenbrier are interpreted to show significant thickness change suggesting absence of the structure along strike to the north.

To the south, cross-section A'D' (Figure 3-8) shows an overall eastward thinning of the Greenbrier Limestone, but once again, the Gassaway structure is not present along strike to the south.

Figure 3-6 Stratigraphic cross-section CB' showing Mississippian Greenbrier Formation and Mauch Chunk Group.

Figure 3-7. Stratigraphic section AD showing the Upper Mississippian.

Figure 3-8. Cross-section A'D' showing Mississippian Greenbrier Formation. No expression of the Gassaway structure is present.

Figure 3-9. Cross-section AA' showing the Mississippian Greenbrier Limestone. No expression of the Gassaway structure is present.

Cross-section AA' (Figure 3-9) was constructed to the west of the structure. Minor amounts of thinning to the north are interpreted in this section, however the Gassaway structure is not present.

Finally, to the east of the Gassaway structure, cross-section DD' (Figure 3-10) shows Upper Mississippian groups changing thickness through the study area, however these changes do not appear to be associated with the growth of the Gassaway structure.

East-west section EE' and north-south section CB' both suggest significant thinning during the Mississippian in well #1126 which is close to the crest of the structure. Section CB' also shows minor amounts of thinning in well #1425 that appear to be related to the edge of the Gassaway structure. The amounts of thinning shown with these cross-sections are subject to argument based on each individual interpreter's formation picks from the well logs, however comparable amounts of thinning have been observed over the same intervals measured from seismic line CNR-G1 (Figure 3-3).

Detailed interpretation of the upper 400 milliseconds of line G1 reveal onlap cycles that are interpreted to be a product of growth of the Gassaway dome. For example, one cycle shown on the seismic interpretation (Figure 3-3 B) appears to be a depositional event that laps onto the surface of the Greenbrier unconformity. While apparent onlap cycles could be related flexural flow, the magnitude of thinning seen in the seismic data and cross-sections (more than 300 feet) is not commonly associated with mechanical thinning in Appalachian structures.

These cross-sections help to define the Gassaway structure as a dome rather than a cylindrical fold. In addition to roughly outlining the geometry of the structure, these cross-sections offer evidence for a growth history of the Gassaway dome that continues

Figure I-18. Cross-section DD' showing ~~Waucho Chunk~~ Greentriker and ~~Waucho Chunk~~ Waucho Chunk groups. No indication of the Gasaway structure is present.

from the Devonian through the Mississippian. Thin skinned detached structures in the high plateau are typically considered a product of the Permo-Pennsylvanian Allegheny orogeny, however growth periods suggested by the cross-sections and the seismic interpretation clearly indicate that the dome may have been growing rapidly well in advance of the Permian.

CHAPTER 4

STRUCTURAL CLASSIFICATION

Introduction

The Gassaway structure is located west of the Allegheny structural front, and a few miles east of the east margin of the Rome trough in central West Virginia. This area is a structural cross-roads, marked by the termination of the hinge of the West Virginia Dome from the north, the location of the Mid Foreland Hinge, and the 'gap' which links the northwest-southeast trending Burning Springs and Mann Mountain structures (Figure 4-1). Due to the absence of sufficient data coverage in this area, defining a mechanism for the formation of the Gassaway structure is difficult. The first steps in moving closer to an answer for this problem lie in defining the associated geometrical and temporal issues. Construction of structure and isopach maps was undertaken in an effort to better resolve the aerial extents of the structure, and the extent of thinning that occurs in overlying stratigraphic units.

Isopach and Structure Maps

Depths to formation tops from several wells were entered into Microsoft Excel, a spreadsheet program. The spreadsheets then provided data sets, which were readable by Surfer, a contouring program by Golden Software. Data were first contoured based on depths to structural tops of selected subsurface lithologies with 600 meter grid spacing (50 x 50 grid nodes). Then, using the grid math module in Surfer, intervals between horizons were calculated by subtracting grids on which the structure maps were contoured. The calculated thicknesses were then contoured to form isopach maps.

Figure 4-1. Map showing major structural features of the Appalachian basin. The Gassaway structure is located in a structural cross-roads amidst the Mid-Foreland Hinge, Burning-Mann Lineament, and the axis of the West Virginia (Pocono) Dome. (after Shumaker, 1996)

Several sets of maps were constructed over different scales in an effort to characterize the Gassaway dome and surrounding structures.

All data were contoured on identical grids, using Surfer's kriging option. The kriging method of grid construction was chosen based on the small amount of data and spatial distribution of the data. Data points were often located in clusters, or distributed at random with areas of uncertainty between control points. The kriging method provides a statistical basis for contour construction through areas in which data points are not present. Subsurface structural tops are constructed based on depths relative to sea level. Depth to a horizon is referred to in statistics as a regionalized variable. The degree of spatial continuity of the regionalized variable can be expressed as a semivariogram. Once constructed, the semivariogram is used to estimate depth to the horizon in question at a point where no real data exists (Davis, 1986). Several other gridding methods were tested (Figure. 4-2) during the construction of these maps, but the kriging method was employed based on the author's belief that this method provided the most accurate contours.

Defining the Gassaway Structure with Contour Maps

In the study area, well bore coverage of a detail suitable for construction of structure or isopach maps is often limited to the Mississippian system. The Upper Mississippian Greenbrier formation is the major hydrocarbon producer in the area. Not only are the depths limited, but well control also varies with each mapped horizon. Some units (for example Figure 4-3, 4-4) are penetrated by more than 1000 wells in Braxton and Clay counties, while other units have only a few control points. Therefore, structure

Inverted distance to a power

k/g/b

Hillshade

Nearest neighbor

Triangle to the nearest triangle

Shepard's method

Figure 4-2 Greenbrier structure map constructed with several different gridding methods. Study area is shown in a box on each map.

Figure 4-J. Regional structure map of the Big Bend area through Gassaway and Clay Courses. The location of the Gassaway dome is shown.

Figure 4.4. Regional structure map of the Big Line (Greenbrier Limestone) through Braxton and Clay Counties.

maps are limited to the shallower horizons, and seismic data provides the most comprehensive view of deeper structures in the area.

On seismic line CNR-G1 (Figure 1-9), the Gassaway structure appears to be a thrust-detached fold. Earlier, more regionalized mapping projects (Haught and Overbey, 1964) represented the structure as a cylindrical fold with significant expression along strike. Smaller scale contouring undertaken in this study (Figure 4-3, 4-4) however reveals that the Gassaway structure has a domal geometry, in agreement with conclusions drawn from the stratigraphic cross-sections.

Several obvious features can be immediately noticed through construction of the contour maps (Figure 4-3, 4-4). Regionally, the structure dips northwest, yet many smaller scale structures are superimposed on this regional dip. The Gassaway dome is prominent in the north-central area of the maps. A series of domal structures form a northwest-southeast trending zone that incorporates the Gassaway dome.

In the southeast part of the map (Figure 4-3), dip of the Big Injun increases rapidly. This area is interpreted to be a normal fault, possibly associated with a splay of the East Margin fault of the Rome trough.

The geometric arrangement of the Gassaway structure, and other similar structures (Figure 4-5 A, B, C; 4-6 A, B, C) are well defined on the Big Injun structure map (Figure 4-3). This alignment of domes is interpreted to be part of a larger scale northwest-southeast trending cross-strike discontinuity. The Gassaway dome and associated cross-strike structures are again readily seen on the Big Lime structural top (Figure 4-4).

Significant growth of the Gassaway structure occurred throughout the Mississippian (Figures 4-5 and 4-6). At least 100 feet of thinning can be seen across the dome during the deposition of the Mauch Chunk Group (Figure 4-5), which is consistent with the local study reported earlier (Figure 3-5). Comparable amounts of thinning are seen in other dome shaped structures located throughout the area at the same time (Figure 4-5 A,B,C; 4-6 A,B,C). An isopach of the Greenbrier Formation also shows significant thinning across the Gassaway dome and similar structures. These isopach maps agree with findings offered by the stratigraphic cross-sections in Chapter 3. Together, these pieces of evidence suggest that a whole series of structures extend across the Upland horst and were indeed being formed during the Middle to Upper Mississippian.

Figure 4.5 Isopach of the lower Murchie Group. Growth of the Gassaway structure is indicated by thinning across the structure.

Figure 4-6 Isopach of the Greenbrier (Big Horn - Blue Monday sand) Formation.

CHAPTER 5

STRUCTURAL INTERPRETATIONS

Block Diagrams

A set of block diagrams was constructed based on the stratigraphic intervals over which the largest thickness changes have occurred (Figure 5-2). The block diagrams were constructed assuming that the Lister, Etheridge, and Symonds (1986) model (after Wernicke, 1982) for continental extension (Figure 5-1 B) best describes the structural setting in the early Cambrian when the failed interior rift, known as the Rome trough, was formed. Figure 5-1A shows compartment, or tear faulting, in the sedimentary rocks that cover the rifted basement. The tear faults possibly result from compressional forces reactivating previously formed strike slip faults at basement depth. These diagrams illustrate one possible interpretation for the sequential development of the Gassaway dome.

Figure 5-2A, shows Precambrian crystalline basement rocks with a strike-slip fault developing. Throughout the Early Cambrian, tectonic stresses were extensional, associated with the opening of the Iapetus Ocean (Shumaker, 1996). It is likely that tectonic stresses were not evenly distributed over the entire continental margin. If present, significant variation of extensional stresses may have resulted in differential spreading along structures such as the Rome trough. To accommodate differential spreading, transfer faults (Figure 5-1) may have developed, roughly perpendicular to strike. Such a transcurrent fault zone may exist through central West Virginia.

Figure 5-1. A) Schematic diagram of compartmentalized faulting. One large thrust sheet is cut by several tear faults perpendicular to strike. (after Davis and Reynolds, 1996) B) Wernicke model for extension. (after Lister, Ethridge, and Symonds, 1986)

Figure 5-2. Sequential development block diagram showing various phases of structural development as defined by RHD's constructed over lines CNR-G1 & G2, and between lines.

Transcurrent Fault Zone Mechanism

Figure 5-3 shows a more detailed representation of a possible tear fault zone associated with the opening of the Rome trough during the Cambrian. Since the proposed tear fault is part of a system, several faults could be present with slightly varying orientations. Reactivation history diagrams (Chapter 2) document changing directions of rotation and fluctuating levels of fault activity starting in the Cambrian and continuing on through the middle Paleozoic. Figure 5-4 demonstrates one way that basement rocks could, if reactivated, be configured to provide a deep disturbance that could influence location and geometry of shallower detached structure. It has been well documented by Shumaker and Wilson (1996) that basement block geometry has a significant effect on the location of shallower structures in areas of the Appalachian basin.

Several regional profiles were extracted from the Big Injun (Figure 5-5) and Big Lime (Figure 5-7) structure maps. These profiles were then plotted and measured in order to compare amounts of apparent shortening along each profile (Figure 5-6, 5-8). Shortening results are reported in Table 1:

Table 1. Percent shortening along regional profiles

Profile	A	B	C
Big Injun	26.3%	47.5%	11.0%
Big Lime	34.5%	44.3%	29.1%

The largest amounts of measured shortening have occurred in the area within the proposed cross-strike fault zone. The Gassaway dome and similar structures along trend

Figure 5-3. Proposed tear fault along the east margin fault of the Rome trough through western Braxton County.

Figure 5-4. Close-up drawing of proposed cross-strike fault zone, originally formed as a result of early Cambrian extension, with independent blocks repositioned throughout subsequent tectonic episodes.

Figure 5-5 Regional structure map of the Big Horn sandstone through Brayton and Clay Counties. The location of the Gassaway dome is shown.

Figure 5-6. Regional cross-strike structural profiles of the top of the Big Injun structure map. Amounts of shortening are reported as percent values next to each profile.

Figure 5-7. Regional structure map of the Big Line through Braxton and Clay Counties.

Figure 5-8 Regional cross-strike structural profiles of the top of the Big Line structure map. Amounts of shortening are reported as percent values next to each profile.

appear to be accommodating more deformation than structures to the north and south. There is possibly a series of tear faults in this area to allow for such drastic differences in amounts of shortening over such a small area.

Strike-slip Antithetic Fault Mechanism

The existence of the New York – Alabama magnetic lineament is clearly defined in the study area by magnetic data (Figure 5-9). This lineament has been interpreted as a post-Grenville strike-slip fault (Gay, 1997; Shumaker, personal communication, 1999). It is possible that the basement fault responsible for the appearance of the Gassaway dome formed in association with the New York – Alabama fault. A possible mechanism (aside from the above mentioned transfer zone mechanism) is that the Gassaway dome lies over a reactivated antithetic fault to a larger scale strike-slip fault.

The Gassaway dome lies above a basement fault that is oriented 60° to the New York – Alabama magnetic lineament. The Gassaway fault could be a reactivated antithetic shear formed in response to much earlier right lateral offset along the New York – Alabama magnetic lineament (Figure 5-10).

2D Ray Trace Modeling of the Gassaway Dome

Ray trace modeling was undertaken in an effort to evaluate the viability of different structural interpretations for the origin of the Gassaway dome. A detached structure resulting from a strike-slip fault zone, accommodating abrupt shortening changes along strike, would have a different geometry than a structure resulting from a thrust detachment zone. For example, the strike-slip style produces flower structures, while a thrust style produces low angle detachment faults. Results from ray trace models

Figure 5-9. Magnetic data through West Virginia showing the New York - Alabama Magnetic Lineament and the location of the Gassaway Fault. (modified from Sattler, work in progress)

Figure 5-10. Strain ellipse showing wrench fault mechanics applied to the Gassaway study area.

of various structures provide a better understanding of which structural mechanism that could have formed the dome. Dome shape of the Gassaway structure at the Oriskany level does not fit the usual linear thrust fold shape of other foreland structures.

Ray trace modeling was performed with computer software provided by Geophysical Micro-Computer Applications (GMAplus). The first structure to be tested is a positive flower structure resulting from a transpressional stress (Figure 5-9). In this study, actual seismic data was first digitized, and then entered into the modeling software as distance (X) and depth (Y) coordinates. After entering ten digitized reflectors, and manually adjusting some characteristics of the structure (such as where it is detached, and how deep the detachment runs), interval velocities were entered into the program to complete the model. After the model was created, GMAplus was used to simulate travel times along normal incidence ray paths through the model.

A simple Ricker wavelet was convolved with the horizon reflectivities to yield a generalized variable area wiggly trace display of the model's seismic response. The synthetic seismic response of the model was then compared to the original seismic data. The models which best simulate the reflections seen on the seismic data are considered to be the most accurate representations of the Gassaway dome's structure.

MODELING RESULTS

Positive Flower Structure

After a thorough investigation of timing issues (suggesting a growth history from the Devonian through the Pennsylvanian) associated with the Gassaway dome was completed, a detailed interpretation of the shallower intervals in seismic line CNR-G1

was undertaken to help construct seismic models. Reflection events from the Devonian through the Mississippian were focused on for this evaluation.

Digitized results of this interpretation are shown in Figure 5-11. This interpretation identifies several faults through the shallower intervals of the seismic section. These faults appear to converge, with depth, on a high angle, narrow fault system located beneath the crest of the structure, and possibly related to the offsets seen below the structure at basement level. This configuration is typical of positive flower structures resulting from transpressional stresses along a strike-slip fault system.

The first model constructed (Figure 5-12) was designed to represent a positive flower structure that would result from strike-slip fault displacement. The proposed strike-slip zone trends northwest through the Gassaway dome (Figure 5-2). To model this structure, the dome was drawn with steep faults bounding a 'pop-up' type structure (Figure 5-12). This type of feature forms as transpressional stresses are applied to a high angle fault.

The resulting seismic response to this model (Figure 5-13) reveals repetition of strata on the west end of the structure. Reflections across the crest of the dome, which are discontinuous in seismic line CNR-G1, are present in the flower structure model. Repetition of the reflection event on the west edge of the structure is also present in this model. Absence of repetition of strata on the east end of the structure is also accounted for by this model, leading to the interpretation that the flower structure is asymmetric. It is possible that the fault bounding the east side of the structure is steeper than the fault on the west side. Therefore, the east limb of the structure is broken, and offset, but strata are not repeated. Inconsistencies in amplitudes across the crest of the structure are also

Figure 5-11. Digitized detailed interpretation of seismic line CNR-G1 (Figure 1-9). This interpretation shows the Gassaway dome as a positive flower structure with growth phases between the Devonian and Mississippian reconfirmed by truncations of stratigraphic units on the flanks against uninterrupted reflections across the crest of the dome.

Figure 5-12. Model developed in GMAplus to test positive flower structure hypothesis

Figure 5-13. Normal incidence seismic response to positive flower structure model.

simulated in this model by cutting the reflector across the crest of the dome with several faults.

Figure 5-14 shows the results of the positive flower structure model compared to part of the unmigrated seismic line CNR-G1. The normal incidence response generated in GMAplus is an unmigrated result, therefore it is best compared to unmigrated seismic data. The unmigrated data shows a disruption on the east limb of the structure. This disruption is likely a response to a diffraction point associated with fault offset. The positive flower structure model was designed to simulate faults on both limbs of the structure, leaving the crest of the structure as an independent fault block. Model response provides a fairly accurate representation of the broken east limb of the structure seen in the unmigrated portion of seismic line CNR-G1.

A regional map (Figure 5-15) shows the location of the New York – Alabama magnetic lineament (coinciding with the East Margin of the Rome trough), locations of regional seismic lines Juggernaut V, N45D-1 and N45B-5 are also shown. These lines were examined for fault offset that might be associated with the Gassaway dome. A fault observed on line N45D-1 and Juggernaut V can be correlated with the basement fault interpreted on line G1 yielding a possible strike slip fault with a N20°W orientation.

The angle between the New York – Alabama magnetic lineament and the interpreted fault zone through the Gassaway study area was measured and found to be 120°.

Theoretically, that is the angle at which first order wrenches develop with respect to larger scale strike-slip systems. The New York – Alabama lineament has been interpreted as a Precambrian strike-slip system (Gay, 1997; King and Zietz, 1978). It is

Figure 5-14. Flower structure model (top) compared to the actual unmigrated seismic data.

Figure 5-25. Base map showing locations of seismic lines used to constrain the orientation of the cross-strike system which gave rise to the Gassaway dome and similar structures.

possible that the Gassaway structure is a positive flower structure associated with a first order right lateral wrench fault of the New York – Alabama magnetic lineament.

Figure 5-11 also shows several stratigraphic truncations (represented by short sub-horizontal line segments) over the crest of the structure. These terminations are interpreted from the seismic data as onlap cycles. Presence of onlap cycles indicates that the structure grew as sediments were being deposited, rather than forming after deposition and thinning the overlying units via flexural flow. This observation helps to support the interpretation that the structure was growing as recently as the Mississippian.

Identifying a mechanism for the development of the Gassaway dome is a difficult problem for which an unquestionable solution may never be offered. The explanation presented in this study is the result of interpretations made with the limited data available during the research process. New data, in the future, will almost certainly provide grounds for new or reinterpretations.

Thrust Detached Structure

The next model was designed to simulate a thrust-detached structure with westward tectonic transport (Figure 5-16). A thrust detached model was constructed with a low angle fault, dipping to the east, which detaches and repeats the Onondaga on the west limb of the structure. The break in the east limb of the structure is simulated with a high angle back thrust.

Though it is difficult to justify a thrust detached geometry for the Gassaway dome based its geometrical arrangement in three dimensions, this scenario still must be modeled to gain further information about the structure. If the model were to yield

Figure 5-16. Model developed in GMaplus to test thrust detachment structure hypothesis.

Figure 5-17. Seismic response to thrust detachment model.

results very similar to line CNR-G1, then the possibility that the structure is a detached structure could not be ruled out.

Minor repetition of the Onondaga on the west limb of the structure is duplicated in this model. Back-thrusting in the Onondaga on the east side of the structure is shown as well. The differences in the amplitudes of the reflections over the crest of the structure between the model and the seismic line are not comparable.

Modeling Effort Summary

The models are very general representations of the interpretation of line G1. There are however, some features in the simulated seismic response of the flower structure model (Figure 5-12) that are consistent with features seen on line CNR-G1. The simulated seismic response of the thrust-detached model is less consistent. Minor adjustments however, could be continually made to the models in order to produce more accurate results. A combination of structure maps, cross-sections, and seismic modeling help to strengthen the case for a strike slip fault in the basement, with possible tear faults in the sedimentary cover. While the flower structure model seems to more accurately duplicate the seismic data, the thrust model can not be ruled out as a valid interpretation.

CHAPTER 6

CONCLUSIONS

This investigation into the sequential development of the Gassaway structure was motivated by the striking appearance of the structure observed in seismic line CNR-G1 (Figure 1-9). Line CNR-G1 profiles the structure which, at first glance, appears to be a thrust-detached anticline. However, thinning of shallower intervals across the structure (Figure 3-3) suggest the influence of a complex growth history that may predate the Permo-Pennsylvanian Alleghany orogenic episode.

Structures of the Appalachian high plateau are often interpreted to have developed largely in response to the Appalachian orogeny. This study was undertaken in an effort to investigate implications of the more complex growth history of the Gassaway dome suggested by the appearance in seismic profile. Evidence for a growth history that predates the Alleghany orogeny may lead to different strategies in the hunt for hydrocarbons in the area of the Appalachian foreland. In order to better define growth phases of the Gassaway dome, several analyses were employed.

Reactivation history diagrams (RHD's) were constructed to quantify basement and subsequent deformation phases (see Chapter 2). The RHD's unraveled a history of basement block motions that began as early as Cambrian time, and continued through the Paleozoic as recently as the Pennsylvanian (Figures 2-9, 2-10, 2-11). The Gassaway structure lies east (about 4 miles or 6.4 kilometers) of the East Margin fault of the Rome trough. Formation of the trough probably produced minor movements on the nearby basement faults beneath the Gassaway dome. Certain phases of basement block rotation (from the Cambrian to the Silurian) associated with displacement along the East Margin

fault of the Rome trough as illustrated and discussed by Shumaker and Wilson (1996) are also observed in Line CNR-G2. Though basement block activity is documented by the RHD's, these diagrams alone do not offer sufficient evidence that the development of the Gassaway dome extended from the Devonian through the Pennsylvanian. They do, however, graphically illustrate that there is significant thinning of the Middle to Upper Devonian sedimentary rocks over the domes.

In an effort to evaluate whether the Gassaway dome was growing as recently as Mississippian – Pennsylvanian time, well log analysis was performed. Several gamma-ray and density logs were correlated in order to construct cross-sections in several orientations across the study area (Figure 1-2). Two of these cross-sections (Figures 3-5, and 3-6) show thinning of the Greenbrier and Mauch Chunk Formations of the Middle to Upper Mississippian across the dome. The interpreted thinning is seen largely in Braxton county well #1126 (which was drilled by Consolidated Gas Supply), and offers a suggestion that growth of the Gassaway dome was active during this time. Thinning observed in the Mississippian – Pennsylvanian interval on seismic line CNR-G1 help to substantiate the well log interpretations. Caution should be exercised when examining these cross-sections , and it is important to realize that they merely offer a suggestion of as they are based on a few widely spread wells. Other cases of Mississippian – Pennsylvanian growth however have also been identified. One example is the Gauley Mountain anticline in southern Clay county, West Virginia (Yang, 1998). This structure is in close proximity to the Gassaway dome and is shown in Yang's study to have undergone a growth phase during Greenbrier (Mississippian) through Mauch Chunk (Pennsylvanian) time. Growth of the Gauley Mountain anticline is quantified in Yang's

study based on thinning and truncations of stratigraphic units across the structure (Figure 6-1).

While the seismic profile of the Gassaway structure provides a fairly clear image of the structure in cross-section, structural mapping based on well bore data is needed to determine the aerial extent and geometry of the dome. Contour maps were constructed on several subsurface horizons (see Chapter 4). These maps represent the structure as a dome. The Gassaway dome is approximately 3 miles (4.8 kilometers) in diameter, with about 1000 feet (305 meters) of vertical relief. The dome is well represented on the Big Injun and Big Lime structure maps (Figures 4-3, 4-4).

In addition to structure maps, isopach maps were constructed through several intervals to help define areas of thinning that may be attributed to structural growth (Chapter 4). Thickness changes occur across the Gassaway dome on Mauch Chunk isopach map (Figure 4-5) where approximately 100 feet (30.5 meters) of thinning can be observed.

While timing issues and some geometrical constraints can be placed on the Gassaway dome through use of RHD's, well logs, structure, and isopach maps, further information is necessary to define the mechanism responsible for the location and shape of the structure. Construction of block diagrams based on RHD results and seismic modeling were completed in order to help define a structural mechanism (Chapter 5). The shape of the Gassaway dome, and its WNW alignment with similar structures (ie: Figure 4-3) leads to the interpretation that these structures are part of a cross-strike fault zone. The domal shape of the Gassaway structure is difficult to explain with a thrust

detachment mechanism. Therefore, tear faults and strike-slip faults were investigated as possible structural styles that could produce the Gassaway dome.

After investigations of these two mechanisms, the strike-slip interpretation appears to satisfy the criteria of a strike-slip system. A tear fault would require a compressional force to fold the sedimentary rocks above a basement level structure (Figure 5-1).

Minor reactivation by a transpressional strike-slip system provides fault mechanics that are capable of forming a dome, and a trend of basement faults compatible with regional interpretation (Gay, 1990; Shumaker, personal communication) that the New York – Alabama magnetic lineament formed a strike-slip system (Figure 5-9, 5-10, 5-12). The cross-strike alignment of domes (Figures 4-3, 4-4), along with orientation of the cross-strike alignment of domes and the Gassaway basement fault (Figure 5-12) suggest that the trend of these domes is related to a series of en-echelon faults that often accompany strike-slip systems (Figure 6-2).

This interpretation indicates that the Gassaway basement fault may be part of a shear system which formed in response to activity along the New York – Alabama lineament between Grenville time (~900 ma) and Iapetan rifting (~570 ma). It is the subsequent reactivation of this basement pattern however, which may have provided the structural control responsible for the development of the Gassaway dome.

Figure 6-2. Fault system interpretation for the Gassaway dome, and similar cross-strike structures.

REFERENCES

1. Beardsley, R. W., and Mark S. Cable, 1983, Overview of the Evolution of the Appalachian Basin, *Northeastern Geology*, v. 5, no. ¾, p. 137-145.
2. Davis, J. C., 1973, *Statistics and Data Analysis in Geology*, John Wiley and Sons, p.239-240.
3. Davis, George H., and Stephen J. Reynolds, 1996, *Structural Geology of Rocks and Regions*, John Wiley and Sons, Inc., p.334-358.
4. Gao, D., 1994, *Surface Geometry and Growth History of the Warfield in South-Central West Virginia, Central Appalachian Basin: Morgantown, WV, West Virginia University, Master's Thesis.*
5. Gay, Parker, 1996, *The Configuration of the Buried Southern Extension of the Grenville Province in the United States as Deduced from Aeromagnetic Data (How Else?): Goose Bay, Labrador, Canada, COPENA and ECSOOT.*
6. Gwinn, V. E., 1964, Thin-skinned tectonics in the Plateau and northwestern Valley and Ridge provinces of the central Appalachians: *Geological Society of America Bulletin*, v. 75, p. 863-900.
7. Haught, O. L., 1964, *Oil and Gas Report on Braxton and Clay Counties, West Virginia: Bulletin 29, West Virginia Geological and Economic Survey.*
8. Lister, G. S., M. A. Etheridge, and P. A. Symonds, 1986, Detachment Faulting and the Evolution of Passive Continental Margins: *Geology*, v. 14, p. 246-250.
9. Shumaker, R. C., 1986, *Structural Development of Paleozoic, Continental Basins of Eastern North America: Conference on Basement Tectonics*, p.82-95.

10. Shumaker, R. C., 1986, The Effect of Basement Structure on Sedimentation and Detached Structural Trends Within the Appalachian Basin: The Lowry Volume, p.67-81.
11. Shumaker, R. C., 1998, Geological Structure of the Appalachian Basin: Unpublished Paper.
12. Shumaker, R. C., and Wilson, T. H. 1996, Basement Structure of the Appalachian Foreland in West Virginia: Its Style and Effect on Sedimentation: GSA Paper 308, p. 139-155.
13. Wilson, T. H., and R. C. Shumaker, 1988, Three-Dimensional Structural Interrelationships Within Cambrian-Ordovician Lithotectonic Unit of Central Appalachians: AAPG Bulletin, v. 72, p. 600-614.
14. Wilson, T. H., and R. C. Shumaker, 1992, Broad Top Thrust Sheet: An Extensive Blind Thrust in the Central Appalachians: AAPG Bulletin, v. 76, p. 1310-1324.
15. Wilson, T. H., Defining Reactivation Histories of Basin Structures and their Potential Role in Reservoir Localization Using Seismic Analysis.
16. Wilson, Thomas H., Robert C. Shumaker, and Li Zheng, 1994, Sequential Development of Structural Heterogeneity and its Relationship to Oil Production: Granny Creek, West Virginia: Virginia Division of Mineral Resources, publication 132, p. 20-25.
17. Yang, C., 1998, High-Resolution Sequence Stratigraphic Approach to Basin Analysis of the Carboniferous Strata in Central and Southern West Virginia: Morgantown, WV, West Virginia University, Ph.D. Dissertation.

18. Yeilding, C. A., and J. M. Dennison, 1986, Sedimentary Response to Mississippian Tectonic Activity at the East End of the 38th Parallel Fracture Zone: *Geology*, v. 14, p. 621-624.
19. Zheng, L., 1990, Seismic evaluation of the Mississippian Greenbrier Limestone and Devonian Ohio Shale in the Big Ugly Area, Southwestern West Virginia: Morgantown, WV, West Virginia University, Ph.D. Dissertation.
20. Zou, X., 1993, Sequence Stratigraphy of the Lower Mississippian in Western West Virginia: Correlation, Depositional Environments, Controls on Sedimentation and Related Reservoir Heterogeneities: Morgantown, WV, West Virginia University, Ph.D. Dissertation.

APPENDIX A

CONSTRUCTION OF SYNTHETICS

Statistical Estimation of Sonic (ITT) From Gamma-Ray and Density

In the Appalachian basin, many wells have been drilled for purposes of hydrocarbon exploration and production, and many well logs of various types have been collected. Operators rarely collect sonic logs, hence interval velocity data needed to construct synthetic seismograms is generally not available. Without synthetic seismograms, it is difficult to tie the seismic response to subsurface geology.

To compensate for a lack of sonic data, statistical approaches have been used in attempts to simulate sonic response from other logs. Gamma ray and density logs, for example, are often collected in the wells drilled in this basin. The possibility that sonic data can be constructed from gamma ray and density logs using a multiple linear regression approach is evaluated for a well from the Granny Creek field 15 miles southwest of the Gassaway dome.

If such a relationship can be established, it may be possible to apply the relationship to gamma ray and density logs from the Gassaway area to obtain a synthetic tie between the seismic lines through the area and nearby borehole data. A statistical computer package, PROSTAT, was used to solve for the coefficients (A, B, and C) which satisfy the regression equation of the following form:

$$\text{Sonic Response} = A(d) + B * \text{Gamma Ray}(d) + (C * \text{Density}(d))$$

where d is depth

The three tracks (gamma ray, density, and sonic) were digitized and resampled at one foot depth intervals. Least square fitting of sonic to density and gamma ray response

yields the coefficients A, B, and C in the above equation. A correlation coefficient of 0.75 was reported.

Bivariate linear regression was also derived between sonic and gamma ray and sonic and density. These individual relationships yielded correlation coefficients (0.39 and 0.55 respectively) much lower than that obtained from the multiple regression.

Results

Figure A-1 shows the actual versus the predicted sonic response obtained from multiple linear regression. The general character of the curve is maintained in the predicted response, though in some intervals the values are off by a constant factor. Correction factors could be derived on a site-specific basis to minimize the difference. Different correction factors could be derived for different depth intervals to optimize the match between the predicted and actual sonic responses. For example, in Figure A-1B, the carbonate interval from 1750 – 2000 feet looks much like the corresponding interval in Figure A-1A, however this section is shifted by constant factor which yields higher readings. A different correction factor may be required to properly adjust the predicted response through this interval than may be required for other parts of the log.

Another deep well (#21775) containing sonic data was selected from Upshur county, WV. Several attempts were made to predict sonic response in this well using the above technique, but these attempts were unsuccessful. After digitizing the well, the first multiple regression was applied to the entire interval covered by all three types of logs. The correlation coefficient for this process was extremely low. Other attempts were then made through smaller intervals in the log, all resulting in correlation coefficients of less than 0.40.

Figure A-1. A) Actual sonic log data, digitized from a well log. B) Sonic log, for the same well, as predicted by the multiple regression.

The multiple linear regression equation was applied to Braxton county well #1126 near the crest of the Gassaway dome, in an effort to create a sonic log, which could be used to construct a synthetic seismogram that could be tied to line CNR-G1. The synthetic seismogram constructed using the coefficients derived from the Upshur county well did not tie in with line G1.