REGIONAL SEISMIC LINES ACROSS THE ROME TROUGH AND ALLEGHENY PLATEAU OF NORTHERN WEST VIRGINIA, WESTERN MARYLAND, AND SOUTHWESTERN PENNSYLVANIA

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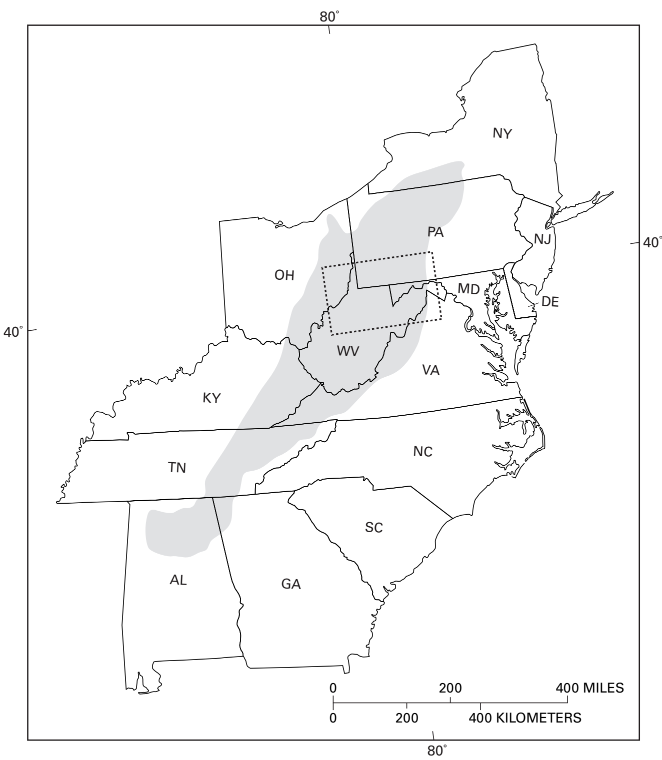
INTRODUCTION

The study area for this investigation is the central Appalachian basin (see index map below). The northern West Virginia, western Maryland, and southwestern Pennsylvania parts of the central Appalachian basin consist of complex structural geometries and a thick Paleozoic sequence. Here, the basin coincides with the Allegheny (Appalachian) Plateau province, a moderately deformed terrain characterized by thin-skinned structures of Alleghanian age (Gwinn, 1964) (fig. 1). In the easternmost part of the study area, the Allegheny Plateau abruptly changes to the Valley and Ridge province (fig. 1), a strongly deformed terrain having thin-skinned structures with greater tectonic shortening. These provinces meet at a physiographic and structural boundary called the Allegheny structural front. The Rome trough, a northeast-trending graben that involves basement, underlies the Allegheny Plateau (fig. 2). Commonly, basement rocks in the Rome trough are buried beneath at least 20,000 feet (ft) of Paleozoic strata (Shumaker, 1996).



Map of the Appalachian basin (combining the Appalachian Plateau and the Valley and Ridge provinces). Area of study shown by pattern.

Little has been published that is related to the deep structure of the Rome trough in northern West Virginia, western Maryland, and southwestern Pennsylvania. Wells drilled to basement are absent here and most of the multi-fold seismic data are proprietary. Although Ryder (1991) and Ryder and others (1992) constructed several detailed stratigraphic cross sections of Cambrian and Ordovician strata across parts of the Rome trough and Shumaker (1996) mapped basement structure along the entire Rome trough from central Kentucky to northeastern Pennsylvania, few interpreted, regional seismic-based geologic cross sections have been published in this area. The objective of this investigation is to interpret the structure and stratigraphy of the Rome trough and Allegheny Plateau of northern West Virginia, western Maryland, and southwestern Pennsylvania based on three multi-fold seismic lines acquired by Amoco in the early 1980s. Of major importance are geologic structures and stratigraphic intervals that may influence deep gas entrapment, crustal-scale fluid flow, and coal quality.

The U.S. Geological Survey (USGS) purchased the license for the digital data used in this investigation from Seismic Exchange Inc. (SEI). If further access to these data is needed, please contact SEI. These data display a wide variety of geological information that includes interbedded carbonates, evaporites, and siliciclastics, strong marker reflections, subtle unconformities, complex fault and fold geometries, and marked thickness changes of several stratigraphic intervals. The seismic sections were reprocessed and are displayed in the report both as interpreted and uninterpreted versions.

SEISMIC REPROCESSING

The processing steps described below were undertaken in order to properly prepare the data set for migration and for interpretation on a computer workstation. All processing was performed using the industry-standard ProMAX® seismic data processing system developed by Landmark Graphics®.

1. All three lines were completely reprocessed from the raw field data. The processing performed prior to stacking included editing of noisy data, amplitude scaling, spiking deconvolution, datum statics, normal moveout corrections using velocities determined by interactive velocity analysis, and residual static correc-

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tions calculated by a surface consistent residual statics routine.

2. The three lines were reconstructed from the individual stacked, unmigrated seismic data. This "post-stack" processing included amplitude scaling and frequency filtering, in order to create versions of the data that were relatively consistent in character from line to line.

3. For all the lines, the datum was adjusted to 2,800 ft of elevation, corresponding to the highest elevations encountered on the lines. The resulting top of the seismic data mimics the actual topographic profile.

4. The data were migrated using smoothed stacking velocities adjusted to the 2,800-ft datum.

5. After migration, post-stack predictive deconvolution (using the 2d zero crossing of the autocorrelation function as the predictive distance) was applied in order to increase the temporal resolution of the data. The software used for this deconvolution process was developed at the USGS in Denver, Colo., by Myung Lee and others.

6. After predictive deconvolution, a signature deconvolution process (sometimes referred to as wavelet deconvolution) was applied to compensate for changes in the source waveform between lines and to further increase the temporal resolution of the data. The software used was developed in-house from Gray's (1979) Variable Norm deconvolution method, adapted for post-stack data.

METHODOLOGY

In this report, the study area is divided for discussion into two different structural and stratigraphic realms: the "western" Allegheny Plateau ("low plateau" of Gwinn, 1964) and underlying Rome trough and the "eastern" Allegheny Plateau ("high plateau of Gwinn, 1964) up to the Allegheny structural front (figs. 1, 2). The high and low plateau provinces are separated by the "intra-plateau structural front" of Gwinn (1964). On section *A–A′*, the dividing line between the two regions is near the Ligonier syncline. Section *B–B′* is located mostly in the western Allegheny Plateau and Rome trough except for the easternmost part of the line. Most of section *C–C′* is located in the eastern Allegheny Plateau. The eastern part of section *C–C′* crosses the Allegheny structural front and extends just into the Valley and Ridge province. The low plateau includes the western parts of sections *A–A′* and *B–B′* and includes such structures as the Arches Fork and Wolf Summit anticlines. The Rome trough is located primarily beneath the low plateau but extends under the westernmost part of the high plateau. The high plateau includes compressional structures such as the Etam and Deer Park anticlines.

In the Allegheny Plateau province, individual fold axes are often impossible to trace near the surface, largely because of imaging problems related to complex static correction parameters. Entire anticlines and synclines are easier to image in the eastern Allegheny Plateau province, as they have considerably more relief than the regional folds in the western Allegheny Plateau and Rome trough.

Section *B–B′* consists of five smaller seismic lines. Collectively, these lines form a composite section that crosses section *C–C′* in Monongalia County, West Virginia. The black seams that occur between the components of section *B–B′* are caused by edge effects that processing cannot completely eliminate. However, these edge effects do not adversely affect interpretation except near the basement, and false structures (chevron-shaped folds) have not been interpreted as being real structures. Imaging of basement faulting, already made difficult by the depths involved, is further hindered both by these edge effects and the short gaps between the components of section *B–B′*.

Natural and manmade obstacles sometimes make continual seismic-reflection surveys impossible. This leads to areas where no data could be gathered and loss-of-fold problems that are seen occasionally on the seismic sections, particularly the easternmost part of section *A–A′*. In this area, the geometry of the apparent symmetric anticline is partially a result of loss-of-fold post-stacking problems.

The primary structural differences between the Rome trough and the Allegheny Plateau are related to regional tectonics. The Rome trough is characterized by normal faults of early Paleozoic age (albeit with some subsequent reactivation due to compression or transpression components on the western side), whereas the eastern Allegheny Plateau is characterized by complex folds and thrust faults of late Paleozoic age (Alleghanian orogenic episode). Western Allegheny Plateau strata above the Rome trough are largely undeformed except for broad tilting and large open folds. Although technically the Rome trough is filled with Early to Middle Cambrian syn-rift strata, in this report we include post-rift rocks as young as Middle Ordovician that have been thickened over the trough by post-rift subsidence. Younger strata above the trough are associated with the Allegheny Plateau. Faults on all the sections are shown in red. Dotted red lines show the three major décollement zones, mostly in the eastern Allegheny Plateau.

The stratigraphy and stratigraphic nomenclature of many formations in the Appalachians are very complex. Because these seismic lines cover hundreds of miles, an effort has been made to simplify the units across the study area. Stratigraphic differences between the eastern and western parts of the lines are indicated on the correlation chart (fig. 3). Lithologic descriptions of the stratigraphic column are shown in figure 4.

Seismic Sequence Stratigraphy

Due to the resolution limitations of the seismic data, not all formations can be resolved. Some formations are either too thin or do not provide enough acoustic contrast with the neighboring strata to cause an interpretable event. Therefore, between interpreted horizons, several formations have been grouped together into seismic stratigraphic packages and are shown by separate colors on the interpreted sections. The color intervals on the seismic sections, correlation chart, and stratigraphic column (figs. 3, 4) represent a group of related strata, usually topped by a strong regional reflector. The names given to these intervals on the seismic sections represent the thickest unit within the interval or the seismic marker bed on the top of the interval, or both (fig. 3). Regional reflectors that top these mapped seismic units are typically positive in polarity and generally result when sandstone or carbonate underlie a thick and relatively transparent shale sequence.

Two of the six regional unconformities shown in figure 3 have associated angular pinchouts. Progradation sequences within the individual formations or seismic stratigraphic packages, or both, are difficult to follow and generally cannot be used to help mark sequence boundaries or unconformities. Hence, the unconformities are mapped nearly entirely on the basis of well logs and surficial mapping data. In the Allegheny Plateau, these unconformities, over short stretches, can look like regular formation tops. In the Rome trough, the Middle Devonian unconformity and the Greenbrier Limestone unconformities have some subtle downlapping reflectors along their upper surfaces. The Middle Ordovician (Knox) unconformity is found over the Rome trough, but is not visible on the seismic sections.

Synthetic Seismograms and Well Data

Well control available for this study is sparse. Moreover, wells drilled deeper than the Upper Devonian and with sonic logs of intervals long enough to be useful for construction of synthetic seismograms are particularly rare. Sonic logs from the following wells were used for the seismograms: (1) Amoco Svetz No. 1 and (2) Occidental Petroleum Corporation Burley No. 1 (fig. 1). Although these were effective in correlating horizons to specific lithologic interfaces, their scarcity made time-to-depth conversions of the seismic lines difficult.

The synthetic seismogram from the Burley No. 1 well was superimposed on sections *A–A′* and *B–B′*. This well is located in southeastern Marshall County, West Virginia (fig. 1), roughly 35 mi (miles) north of section *A–A′* and 20 mi southwest of section *B–B′*. The sonic log in the Burley No. 1 well recorded continuous velocity data from the post-Pottsville rocks at the surface in the Pennsylvanian and lowermost Permian continuously down to the top of the Upper Cambrian Copper Ridge Dolomite of the Knox Group. The synthetic seismogram and the sonic log and velocity from which it was constructed are shown in figure 5. This is a very accurate record, showing not only tops of major regional reflectors, but also such local phenomena as individual Pennsylvanian coal beds in the post-Pottsville rocks and salt beds within the Salina Group. Despite the intervening distance between the well and the seismic sections, the correlations between the strong reflections on the seismic sections and those on the synthetic seismogram are very close. Together they accurately identify geologic formation tops on seismic sections *A–A′* and *B–B′* in the western Allegheny Plateau and Rome trough. This accuracy is made possible by the regionally extensive, flat-lying “layer cake” stratigraphy. The Burley No. 1 synthetic seismogram does not accurately match the Pottsville and post-Pottsville strata on sections *A–A′* and *B–B′* probably because of changing topography, slightly dipping beds, and inaccuracies in the static corrections during processing.

The subsurface stratigraphy of the eastern Allegheny Plateau, as identified in selected deep wells, is difficult to correlate with specific reflection events on the seismic sections. First, there are very few deep wells that have been drilled in the province. Second, continuous sonic logs that are necessary to generate a synthetic seismogram to tie the subsurface geology to a seismic section have not been acquired in most of the deep wells. Third, the wells commonly are offset from the seismic lines by tens of miles and the intervening structural geometries are very complex. Detailed geologic maps, when available, help identify reflection events in the near-surface parts of the seismic sections.

SEISMIC STRATIGRAPHIC PACKAGES

The regional stratigraphy varies widely across all lines, particularly between the eastern and western Allegheny Plateau and the underlying Rome trough. The correlation chart (fig. 3) attempts to reflect this.

Grenvillian Basement

The Grenvillian basement is identified on the seismic sections by a fairly continuous positive reflector near the base of the Rome Formation. The basement reflector separates the metamorphic and igneous rocks within the basement from the stratified rocks above.

Little internal structure can be imaged in the basement despite extensive reprocessing of the lines. Basement faults which mark the boundary of the Rome trough are only suggested by slight disruptions in the top one-half second of the basement. Internal texture of the basement that can be imaged, particularly in the Rome trough, is characterized by local discontinuous reflectors. In the eastern Allegheny Plateau part of the lines, no significant intra-basement features are discernable, nor is the geometry of the compressional structures of the overlying rocks related to structures in the basement.

Knox Group and Pre-Knox Rocks

The boundary between the upper sandstone member of the Copper Ridge Dolomite of the Knox Group and the overlying Beekmantown Group provides a strong positive reflector. The Conasauga Group and Rome Formation that underlie the Knox Group, although fairly indistinguishable on the seismic sections as a result of depth and internal homogeneity, form a thick sequence of limestone, shale, and local sandstone.

The Conasauga Group is fairly structurally competent, contributing to the typical harmonic folds. Limestone and shale in the lower part of the Rome Formation form an incompetent structural unit that is prone to bedding plane detachment along the Rome décollement. In the eastern Allegheny Plateau and Valley and Ridge provinces, the interbedded siliciclastics in the Conasauga Group and Rome Formation also appear to subtly contribute to disharmonic folding in the vicinity of the imbricate thrust faults on the basal Rome décollement.

An eastward-thickening wedge of Knox Group and pre-Knox rocks cut by basement-involved normal faults defines the Rome trough as an asymmetric graben or half graben (sections *A–A′*, *B–B′*, *C–C′*). As interpreted by Shumaker (1996), the east side of the trough (graben) is bounded by a major down-to-the-west normal fault across which abrupt westward thickening of Knox and pre-Knox rocks has occurred (sections *A–A′* and *C–C′*). Additional fault-controlled depocenters are shown in the central and eastern parts of the Rome trough where abrupt thickening of Knox and pre-Knox strata is recorded across down-to-the-west normal faults (section *A–A′* in the vicinity of the Arches Fork and Wolf Summit anticlines; section *B–B′* in the vicinity of the Fayette anticline). These depocenters mark the thickest accumulations of Knox and pre-Knox rocks in the study area. In contrast, the western part of the Rome trough consists of a westward-tapering wedge of Knox and pre-Knox rocks that is cut by minor down-to-the-east normal faults (sections *A–A′* and *B–B′*). Thus, the western part of the Rome trough is mildly deformed in comparison to the eastern part and the western margin of the trough appears to be defined by a hinge zone with accompanying minor, down-to-the-east normal faults (section *B–B′* in the vicinity of the Washington anticline).

Beekmantown Group

The Beekmantown Group consists of structurally competent, mostly dolomite, layers. The Beekmantown dolomites and the overlying Black River Limestone are not prone to disharmonic folding. In the region under the Allegheny Plateau, the Beekmantown contains a series of step-up faults and associated ramps. The Black River Limestone is largely indistinguishable on the seismic sections from the overlying Trenton Limestone and underlying Beekmantown Group.

Trenton Limestone

The top of the Trenton Limestone provides one of the strongest and most continuous positive reflectors across the seismic sections. The strong positive reflector marks the strong acoustic contrast between the top of the Trenton Limestone and the Utica Shale. The Utica Shale is the lowermost siliciclastic layer in the thick Ordovician sequence.

Reedsville Shale

The Reedsville Shale is a product of the Taconic orogeny (fig. 3). It is distinguished from the Juniata Formation on the seismic sections by a subtle but prevalent negative event visible across most of the Rome trough. The Reedsville is composed predominantly of gray shale with minor beds of siltstone and sandstone. In the more deformed sections of the eastern Allegheny plateau, the Reedsville interval is largely transparent, with fewer internal reflectors in the lower part, suggesting a coarsening-upward sequence.

Being mostly thin-bedded shale, the Reedsville is structurally incompetent and prone to flow as the Reedsville-cored Deer Park anticline illustrates on sections *A–A′* and *C–C′*. The thrust faulted core of this anticline is made up of Reedsville Shale that probably flowed in from the neighboring synclines.

In the eastern parts of sections *A–A′* and *B–B′*, the Oswego Sandstone part of the Juniata seismic stratigraphic package overlies the Reedsville Shale. The Oswego is over 1,000 ft thick in south-central Pennsylvania (Laughrey and Harper, 1996) and is considerably more structurally competent than the Reedsville.

Juniata Formation

The Juniata Formation, largely red shale and mudstone interbedded with siltstone and fine-grained sandstone, has a distinctive stratified seismic signature, typified by a series of moderately high amplitude peaks and troughs (see figure 5 and the western end of section *A–A′*). The contact between the Tuscarora Sandstone and the overlying Rose Hill Formation provides an intermittent positive regional reflector that marks the top of the Juniata Formation seismic stratigraphic package. Over the eastern Allegheny Plateau, the seismic signature of the Juniata Formation breaks up considerably, although the Juniata appears to thicken into the anticlines much like the surrounding Salina and Reedsville packages. The sediments that formed the Juniata resulted from uplift caused by the Taconic orogeny (fig. 3).

Salina Group

The top of the Upper Silurian Salina Group and overlying Lower Devonian Helderberg Group represents one of the greatest rheological contrasting horizons in the study area. Lithologically, the Salina Group is largely composed of dolomite and interbedded anhydrite and halite. Its seismic signature is distinct: alternating strong negative and positive parallel reflectors, similar to the overlying Hamilton Group seismic stratigraphic package. However, zones of the Salina appear to be transparent or blurred, particularly in the eastern Allegheny Plateau part of sections *A–A′* and *C–C′* where flowage has taken place. In the western Allegheny Plateau, the incompetent Salina does not flow and remains stratified like the adjoining rocks. Flowage in the Salina of the eastern Allegheny Plateau accounts for the majority of any disharmonic folding and flow that accompanies regional compression throughout the Reedsville-Martinsburg sheet.

The Salina Group seismic stratigraphic package consists, in ascending order, of the Silurian Rose Hill Formation, Keefer Sandstone, Lockport Dolomite/McKenzie Limestone, Wills Creek Formation, Tonoloway Limestone, and Salina Group. The highly competent Keefer/Lockport/McKenzie interval in contact with the underlying Rose Hill Formation and interbedded evaporite and dolomite beds in the Salina Group provide moderate to strong reflectors.

Hamilton Group

The Middle Devonian Tully and Onondaga Limestones and the intervening Marcellus Shale of the Hamilton Group provide strong positive reflectors across most of the three sections. A strong increase in both density and compressional velocity provides the strong positive-reflecting interface between the Marcellus Shale and the Onondaga Limestone. This thin but highly visible interval represents a period of relatively quiescent sedimentation in the Early and Middle Devonian that preceded the Acadian orogeny (fig. 3).

The Middle Devonian unconformity is difficult to identify on the seismic sections. It does not often display obvious reflection truncations and the regionally incongruous reflectors often associated with unconformities. The Tully Limestone is the youngest formation included in the Hamilton Group seismic stratigraphic package, and commonly it directly underlies the Middle Devonian unconformity. The Oriskany Sandstone is a major regional gas reservoir and is included in the Hamilton stratigraphic structural unit.

Elk, Bradford, and Venango Groups

The Upper Devonian Catskill delta complex is a thick siliciclastic wedge that consists of gray shale, siltstone, and sandstone of offshore marine and deltaic origin and red beds of subaerial and fluvial origin. As a result of east-to-west progradation across the study area, the Catskill delta deposits are progressively finer grained (sandstone to siltstone to shale) and progressively darker in color (red to gray to dark gray or black) in a westward direction. Upper Devonian stratigraphy follows the distribution of these major lithofacies and the complex intertonguing among them. In this region of the Appalachians, Upper Devonian strata are organized into three parts as follows: (1) an eastern (proximal) part that consists, in ascending order, of the Harrell Shale, Brallier Formation, Greenland Gap Group (Dennison, 1970), and Hampshire Formation; (2) a central part that consists, in ascending order, of the Elk, Bradford, and Venango Groups; and (3) a western (distal) part that consists, in ascending order, of the

Genesee Formation, Sonyea Formation, West Falls Formation, Java Formation, Huron Member of the Ohio Shale, and Chagrin Shale.

The Elk, Bradford, and Venango Groups, first mentioned as informal sand groups (see Wilmarth, 1938) and later formalized by Harper and others (1999), are applied to the Upper Devonian seismic stratigraphic packages named in this report (fig. 3). The stratigraphy of the Elk, Bradford, and Venango Groups as used by Harper and others (1999) is slightly modified in this report to conform with the boundaries of the Elk, Bradford, and Venango "plays" recognized by Boswell and others (1996). For example, the Elk Group as used in this report follows more closely the "Elk play" of Boswell and others (1996) that occupies an older stratigraphic position than the Elk Group as used by Harper and others (1999).

The Elk Group seismic stratigraphic package consists of the following units: (1) Elk Group in the central part, (2) the Harrell Shale, Brallier Formation, and Greenland Gap Group (part) on the east, and (3) the Genesee Formation, Sonyea Formation, West Falls Formation, and Java Formation on the west (fig. 3). Most of the Elk Group seismic stratigraphic package is characterized on the seismic sections by short, discontinuous reflections. The Benson sands of informal driller's usage in the Elk Group provide moderately continuous reflections.

In addition to the Bradford Group, the Bradford Group seismic stratigraphic package consists of the equivalent Greenland Gap Group (part) on the east and the equivalent Huron Member of the Ohio Shale and Chagrin Shale (part) on the west (fig. 3). The Bradford Group is generally characterized on the seismic section by short, discontinuous reflections; however, the Balltown sands of informal driller's usage in the Bradford Group provide moderately continuous reflections.

The lower part of the Venango Group seismic stratigraphic package consists of the Venango Group (Formation) and Riceville Formation, flanked on the east by the Hampshire Formation and on the west by the Chagrin Shale (part) (fig. 3). The upper part of the Venango Group seismic stratigraphic package consists, in ascending order, of the Upper Devonian-Lower Mississippian(?) Berea Sandstone, Lower Mississippian Sunbury Shale, and Lower Mississippian Price Formation (fig. 3). The Venango seismic stratigraphic package is characterized by weak, discontinuous reflections. However, the Gordon sands of informal driller's usage in the Venango Group (Formation) and the Weir and Big Injun sands of informal driller's usage in the Price Formation provide local, moderately continuous reflections.

Greenbrier Limestone

The Upper Mississippian Greenbrier Limestone and the thin overlying Mauch Chunk Group provide the most continuous of the shallow reflections across the seismic sections. Being a well-cemented, thick-bedded limestone, the Greenbrier is an excellent regional reflector on all the lines. Although the Greenbrier Limestone unconformably overlies the clastic sequences of the Price Formation (Boswell and others, 1996), no sign of angular truncations is seen on the seismic sections.

Pottsville Group and Post-Pottsville Rocks

Pennsylvanian strata are grouped together into the Pottsville Group and post-Pottsville rocks. The Late Pennsylvanian-Lower Permian Dunkard Group crops out in the study area but has been truncated during processing because of poor data quality. Because of poor quality shallow reflectors, the internal stratigraphy and structure of the lithologically complex Lower and Middle Pennsylvanian Pottsville Group have not been imaged on the seismic sections. Although the coal beds within the Middle and Upper Pennsylvanian post-Pottsville rocks are probably the source of strong negative reflectors, these are intermittent and impossible to associate with any particular coal seam. The unconformity between the Pottsville Group rocks and the underlying Greenbrier Limestone has not been imaged. Sandstone and shale in this package were derived from the Alleghanian orogeny (fig. 3).

TECTONICS

Extensional Tectonics of the Rome Trough

The Grenville orogeny (1,000 Ma) developed the basement under the Appalachian foreland. Shumaker and Wilson (1996) noted that the basement structure flooring the Appalachian foreland was formed by a combination of Grenville compression and eastern interior extension. Eastern interior deformation triggered symmetric extension in the basement, resulting in grabens filled with Cambrian and Lower to Middle Ordovician sediment, largely carbonates. The Rome trough is the largest of these grabens.

Although not detected in this study, thrust faults have been reported in the Grenvillian basement in the vicinity of the study area. For example, Beardsley and Cable (1983) and Shumaker and Wilson (1996) interpreted imbricated thrust faults in the basement south of the study area. Also, Kulander (2001) noted northeast-trending thrust faults on east-west-trending seismic lines in the deepest part of the Rome trough to the south. These basement-involved thrust faults were attributed to regional compression dating from between 0.8 and 1.0 billion years ago.

Normal movement along the Rome trough boundary faults occurred largely during the Middle Cambrian and then intermittently in the Early and Middle Ordovician. In addition to normal offset along the boundary faults, post-rift differential subsidence caused thickening of the Early and Middle Ordovician section in the Rome trough. No normal movement seems to have occurred after the Middle Ordovician; however, the basin boundary faults of the Rome trough display indications of later compressive reactivation. Following the Rome trough boundary faults upward through the stratigraphic section from the carbonates of the Knox Group, Beekmantown Group, and Trenton Limestone into the shale and sandstone of the Reedsville Shale and Juniata Formation, the structural geometry changes from extensional to compressional. Although the basement faults may disappear up section and thrust faulting is not evident, anticlines, such as the Chestnut Ridge extension and Arches Fork, indicate compressional structures have, in part, been controlled by Rome trough basement faults. It is likely the basement faults were reactivated by Alleghanian compression or transpression.

On section *A–A′*, the Rome trough is asymmetric, with the eastern side being bounded by a series of parallel west-dipping normal faults; in places, the greatest throw of basement is almost 4,500 ft (Shumaker and Wilson, 1996). These faults are fairly obvious on seismic sections, and the deepest parts of the basin always abut this west-dipping fault zone. Shumaker (1996) interpreted this eastern boundary fault as being a single fault in places, but these seismic data suggest that the main drop into the eastern (deepest) side of the basin occurred along a series of closely spaced parallel faults that form a fault zone. In contrast, the western side of the Rome trough is a ramp on sections *A–A′* and *B–B′* where the boundary faults show significantly less throw at the top of the basement. In some places, the east-dipping boundary faults are only suggested by flexure in the internal reflectors of the Knox Group and pre-Knox strata.

Thin-Skinned Tectonics of the Eastern Allegheny Plateau

The eastern halves of sections *A–A′* and *B–B′* reflect the "thin-skinned" structural geometries prevalent in the central and southern Appalachians (Rodgers, 1963; Gwinn, 1964, 1970). Thin-skinned geometries were caused by lateral compression and the accompanying detachment along incompetent bedding planes (décollement horizons). Increased resistance to movement within regional décollement horizons caused them to "step-up" across longitudinal ramps to shallower incompetent units. Competent units between décollement horizons were carried over the longitudinal ramps and folded into ramp anticlines. This mechanism has created compressional folds and associated thrust faults with miles of horizontal displacement. Complex duplex structures may occur near ramps where many thin thrust slices (imbricates) have formed in competent units between boundary thrust faults. McClay (1992) calls these structures an "antiformal stack." Although the top of the basement is in places difficult to image exactly below the structurally complex eastern Allegheny Plateau, Kulander and Dean (1986a) cite geophysical and geological data that suggest basement control of regional fold patterns and the width of the Valley and Ridge overthrust belt.

Kulander and Dean (1986b) recognized two major thrust sheets in the eastern Allegheny Plateau and adjoining Valley and Ridge provinces: the Waynesboro sheet and the overlying Martinsburg sheet. In this report, these sheets are referred to as the Rome-Waynesboro and Reedsville-Martinsburg sheets, respectively (fig. 3). A third thrust sheet, the Salina sheet (suggested by Gwinn, 1964, and considered to be the upper part of the Martinsburg sheet by Kulander and Dean, 1986b) is recognized here as the uppermost thrust sheet in the Allegheny Plateau. These three distinct thrust sheets were caused by Alleghanian compression (Dean and others, 1988), and their constituent strata define the structural geometries of sections *A–A′*, *B–B′*, and *C–C′*. Dean and others (1988) concluded that compressional deformation of the Valley and Ridge and eastern Allegheny Plateau occurred during Permian or Pennsylvanian time.

The Rome-Waynesboro sheet consists primarily of structurally competent carbonates of the Conasauga Group, Knox Group, Beekmantown Group, and Black River and Trenton Limestones, whereas the base of the sheet consists of structurally incompetent shale units of the Rome Formation (fig. 3). Residual gravity anomalies and surface geological information strongly suggest that the Rome-Waynesboro sheet is cut by step-up faults that sole in the décollement near the base of the Rome-Waynesboro sheet (Kulander and Dean, 1986b). These buried thrust faults generated broad anticlines in the overlying strata. Work by Perry (1964, 1978) and Roeder and others (1978) support this concept. The Rome-Waynesboro thrust ramps and related broad-wavelength folds are indicative of thick and competent carbonate units. The seismic data reveal that the underlying Rome-Waynesboro sheet appears to be continuous because of its high velocity, thick-bedded homogenous strata, but is, in fact, imbricated by thrust faults that have caused thickening of the strata in the ramp regions.

The Reedsville-Martinsburg sheet consists predominantly of short-wavelength folds that commonly are asymmetrical or overturned in the Valley and Ridge province to the east. Kulander and Dean (1986a) show that deformation of the Reedsville-Martinsburg sheet, at any given location, generally preceded imbrication of the underlying Rome-Waynesboro sheet. Shortening of the Rome-Waynesboro sheet caused additional deformation and rotation of previously developed structures in the Reedsville-Martinsburg sheet. These anticlines commonly contain forelimb and backlimb thrust faults. Disharmonic folding such as this indicates high ductility contrasts between thick shale, siltstone, and thin-bedded limestone and relatively thin but competent sandstone and quartzite units, like the Tuscarora Sandstone.

The Reedsville-Martinsburg sheet shows noticeable thickness changes related to compression, particularly in the fold axes of anticlines and synclines. Although the folds are parallel in the strata above the Reedsville-Martinsburg sheet, they are not parallel within the sheet because of thickening in anticlinal cores. For example, the Deer Park anticline (section *A–A′*) is largely parallel down to the Reedsville-Martinsburg sheet. Within the sheet, however, the Salina Group, Juniata Formation, and Reedsville Shale thicken within the core of the Deer Park anticline because of flowage from adjacent synclines. A similar situation is found for the Etam anticline (section *A–A′*). Westward transport on the Reedsville décollement preceded later, lower sheet (Rome-Waynesboro) ramping. The competent strata of the Rome-Waynesboro sheet and the incompetent strata of the Reedsville-Martinsburg sheet, on the eastern part of section *A–A′* show contrasting structural styles. For example, the Reedsville-Martinsburg sheet shows many thickness variations and numerous thrust faults, whereas the Rome-Waynesboro sheet shows uniform thickness and fewer thrust faults.

The Salina sheet includes Upper Silurian to Lower Permian-age rocks. The base of the Salina sheet is located within the Salina Group. The Salina Group contains halite layers that act as incompetent décollements. From these halite layers small thrust faults rise upward and die out either in the Marcellus Shale or Brallier Formation (see Laurel Hill and Negro Mountain anticlines on section *C–C′*). The throw on these small thrust faults is minimal; often they are only recognizable by flexure, rather than offset, of the reflectors. Westward movement of the Salina sheet is about the same as that for the Reedsville-Martinsburg sheet.

Orogenic Events

The Taconic and Acadian orogenies probably had little or no influence on the thin-skinned structures of the Allegheny Plateau but may have reactivated earlier Rome trough extensional structures.

Taconic orogeny

Deposition of the Reedsville Shale, Juniata Formation red beds, and Tuscarora Sandstone resulted from the Taconic orogeny (fig. 3). The oldest compressional event recorded in the Rome trough may be related to the Middle to Late Ordovician Taconic orogeny. Reactivated boundary faults on the eastern side of the Rome trough appear to be the most affected, showing transitions from early extension to later compression within the Beekmantown interval.

Acadian orogeny

In the central and eastern parts of sections *A–A′* and *B–B′* three distinct packages constitute the Devonian sequence. These are all part of the Acadian (Catskill) clastic wedge, which marks the sedimentary response to uplift caused by the Acadian orogeny to the east. This wedge consists of three prograding clastic units that thicken toward their source east of the Allegheny structural front. In ascending order, the Acadian clastic wedge is subdivided on the seismic section into the Elk, Bradford, and Venango Groups. The Venango Group seismic stratigraphic package includes the overlying Price-Rockwell delta complex of Boswell and others (1996).

Alleghanian orogeny

The effects of the Alleghanian orogeny on the Allegheny Plateau are recorded in the Salina, Reedsville-Martinsburg, and Rome-Waynesboro sheets as folds and associated thrust faults. The eastern ends of sections *A–A′* and *C–C′* extend to the Allegheny structural front. In the adjoining Valley and Ridge province, complex duplex structures are common, bounded by step-up ramp faults that rarely reach to the surface (Kulander and Dean, 1986b). These faults commonly show thousands of feet of displacement. In contrast, simple duplex structures that are bounded by ramping thrust faults, and have much less tectonic shortening, mark the Allegheny Plateau.

In the Valley and Ridge province, thrust faulting in the lower sheet is critical to the development of anticlines and synclines in the upper sheets (Kulander and Dean, 1986b). Where the lower Rome-Waynesboro is ramped up on thrust faults, the overlying Reedsville-Martinsburg and Salina sheets are directly affected. However, in the Allegheny Plateau, these ramps appear to have minimal effect on the overlying strata of the Reedsville-Martinsburg sheet. Although many thrust faults ramp up from the Rome-Waynesboro décollement in section *A–A′*, these generally serve to thicken the Rome-Waynesboro sheet slightly such as beneath the Deer Park anticline, in contrast to the doubling of thickness often seen in the Valley and Ridge province. However, the location of these abortive ramps in the Rome-Waynesboro sheet do appear to affect the geometry of the Negro Mountain and Deer Park anticlines in the overlying Reedsville-Martinsburg sheet. These anticlines directly overlie ramps whose thrust faults flatten and merge into incompetent units at the base of the Rome-Waynesboro sheet.

IMPLICATIONS FOR FOSSIL FUELS

This set of seismic and well data is located in proximity to important coal and natural gas reserves and resources. While the sparse density of data, such as coal maps or amplitude extraction ("bright spot") analysis in gas reservoirs, prohibits detailed analysis of the resources themselves, interpretation of regional petroleum migration and structural framework studies will benefit from this data set.

Coal and Coal-Bed Methane

Coal beds are not visible on these seismic sections because they are either below the limit of resolution or are obscured by poor static corrections. However, the seismic sections contain pertinent information about deeper structures and stratigraphy that may affect coal location, quantity, geochemistry, and fracture zones for coal-bed methane production. For example, an accurate depiction of the geometry of the Rome trough and neighboring structural provinces contributes to a more accurate assessment of coal in the region. Even if the actual coal seams are not resolvable on seismic data, simply understanding the location and geometry of nearby marker beds will help locate the nearby coal seam, provided the coal can be assumed to be relatively continuous.

Interest in coal quality has led to the recent concept that sulfur, arsenic, and other contaminant elements have been introduced into coal beds by basin-scale fluid flow. For example, at the southern end of the Appalachians, Goldhaber and others (1997) suggested that thrust-fault-controlled fluid flow is responsible for the high arsenic content of the Warrior coal field of Alabama. Conceivably, thrust faults and associated detachment horizons identified on the seismic sections may have introduced deep-basin fluids into coal-bearing strata of the study area. Although none of the imbricate faults in this study can be traced above the Upper Devonian Bradford Group (for example, see Wolf Summit anticline, section *A–A′*), very likely they continue into Pennsylvanian strata as small-displacement and possibly associated fractures that cannot be resolved by the seismic data. Moreover, Rome trough basement faults, such as the one that underlies the Washington anticline (section *B–B′*), also could have introduced deep-basin fluids into coal beds in the study area.

These seismic sections probably have little bearing on exploration for coal-bed methane except perhaps for locating structures such as the Washington and Amity anticlines and underlying basement faults, where increased fracture density may improve gas productivity.

Natural Gas

Much of the future natural gas potential in the Appalachian basin lies in deeper, relatively unexplored lower Paleozoic strata of the Rome trough. Potential deep gas from reservoirs such as the upper sandstone member of the Upper Cambrian Knox Group and the Middle Ordovician Trenton and Black River Limestones depend on basement faults of the Rome trough and associated anticlines for entrapment. Recent successes for natural gas in Trenton and Black River reservoirs of central West Virginia are characterized by highly fractured strata and possibly by dolomite replacement of limestone (Schwochow, 2000; Avary, 2001). Similar Trenton and Black River reservoir successes in south-central New York are characterized by thermal dolomite reservoirs that have replaced the limestone along narrow, basement-controlled fault zones (Sanford, 2001). The volume reduction in the Trenton and Black River Limestones, caused by dolomite replacement, commonly results in an overlying structural sag that is visible on seismic data (Clark and White, 1987). A strong positive-amplitude event clearly marks the top of the Trenton Limestone in the Rome trough and images many small anticlines and associated basement faults. Therefore, the Trenton and Black River and deeper horizons may be prospective for deep gas along all three sections. No hint of local structural sags at the top of the Trenton Limestone can be seen on any of the seismic lines.

Commonly, highly permeable fracture zones enhance gas recovery. Although strata throughout West Virginia exhibit systematic fracturing (Kulander and Dean, 1993), these fracture patterns are not visible on these seismic data. The data do not contain the higher frequencies that permit analysis of regional fracture trends.

Historically, Devonian sandstones have been the best reservoirs for oil and gas in the study area. For example, the Lower Devonian Oriskany Sandstone has been a major producer of natural gas in the faulted anticlines of the eastern (high) Allegheny Plateau. Most of the gas fields in the Oriskany Sandstone have already been discovered, but it is very likely that there are still some small, undiscovered fields. Imbricate thrust faults interpreted here for the Chestnut Ridge, Laurel Hill, Negro Mountain, and Deer Park anticlines, shown on the sections, may help to identify previously undrilled fault-block traps. Also, sandstone beds in the Upper Devonian Catskill delta complex are important gas reservoirs in the study area. Although densely drilled for gas in stratigraphic and structural traps in western Pennsylvania and northern West Virginia, these sandstone reservoirs have been sparsely drilled in southwestern Pennsylvania mainly because of their greater depth. The northwestern end of section *B–B′* extends into this sparsely drilled area and may define several anticlines and amplitude changes for future gas exploration in the Upper Devonian interval.

Natural gas is produced in the study area from Devonian black shale units such as the Marcellus Shale and Rhinestreet Shale Member (figs. 4, 5). The reservoirs consist of naturally fractured shale and the source of gas is organic matter in the shale (Milici, 1996). To date, gas production in the Rhinestreet Shale is limited to the western margin of the study area but potential for additional gas exists for another 25 to 50 mi further eastward. Presently the Marcellus Shale is only marginally productive but it has potential gas in most of the study area. Imbricate thrust faults on the seismic sections may identify potential areas of interconnected fractures having improved gas yields.

CONCLUSIONS

These regional seismic lines highlight contrasting compressional and extensional structural regimes across part of the central Appalachian basin. In addition, three thrust sheets are recognized that show contrasting styles of compressional deformation. Each of these three sheets has a basal décollement zone.

The breadth of the seismic data also relates the complex surface geology to its subsurface roots. The broad anticlines and synclines found in the eastern Allegheny Plateau are a result of the thick sheets below reacting to compressive stresses from the east. Imaging the geometry of the Rome-Waynesboro and Reedsville-Martinsburg sheets in the eastern Allegheny Plateau explains the location and shape of the overlying folds. In some places, faults of the Salina and Reedsville-Martinsburg décollements may reach the surface in thick shale belts but may not be readily discerned. Seismic data are necessary to image these faults.

Relating surface expression to subsurface structure also has implications for gas exploration. Several folds in the Trenton and Black River Limestones look perspective for gas exploration but are not related to surface structure. Similarly, folds on the surface in the western Allegheny Plateau cannot always be related to deep structure.

In summary, the data set will benefit structural framework and tectonic development studies in the Rome trough. This, in turn, will assist in answering migration and source rock questions related to exploration. For example, speculation as to the role of basement faulting in hydrocarbon migration and maturity in West Virginia has fueled previous studies of the framework and development of the Rome trough, primarily in central and southern West Virginia.

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