Along-Axis Segmentation and Growth History of the Rome Trough in the Central Appalachian Basin[1]

Dengliang Gao,[2] Robert C. Shumaker,[3] and Thomas H. Wilson[3]

ABSTRACT

The Rome trough, a northeast-trending graben, is that part of the Cambrian interior rift system that extends into the central Appalachian foreland basin in eastern North America. On the basis of changes in graben polarity and rock thickness shown from exploration and production wells, seismic lines, and gravity and magnetic intensity maps, we divide the trough into the eastern Kentucky, southern West Virginia, and northern West Virginia segments. In eastern Kentucky, the master synthetic fault zone consists of several major faults on the northwestern side of the trough where the most significant thickness and facies changes occur. In southern West Virginia, however, a single master synthetic fault, called the East-Margin fault, is located on the southeastern side of the trough. Syndepositional motion along that fault controlled the concentrated deposition of both the rift and postrift sequences. The East-Margin fault continues northward into the northern West Virginia segment, apparently with less stratigraphic effect on postrift sequences, and a second major normal fault, the Interior fault, developed in the northern West Virginia segment. These three rift segments are separated by two basement structures interpreted as two accommodation zones extending approximately along the 38th parallel and Burning-Mann lineaments.

Computer-aided interpretation of seismic data and subsurface geologic mapping indicate that the Rome trough experienced several major phases of deformation throughout the Paleozoic. From the Early(?)–Middle Cambrian (pre-Copper Ridge deposition), rapid extension and rifting occurred in association with the opening of the Iapetus-Theic Ocean at the continental margin. The Late Cambrian–Middle Ordovician phase (Copper Ridge to Black River deposition) was dominated by slow differential subsidence, forming a successor sag basin that may have been caused by postrift thermal contraction on the passive continental margin. Faults of the Rome trough were less active from the Late Ordovician–Pennsylvanian (post-Trenton deposition), but low-relief inversion structures began to form as the Appalachian foreland started to develop. These three major phases of deformation are speculated to be responsible for the vertical stacking of different structural styles and depositional sequences that may have affected potential reservoir facies, trapping geometry, and hydrocarbon accumulation.

INTRODUCTION

The Rome trough (Woodward, 1961; McGuire and Howell, 1963) is one of the major rift elements of the interior rift system (Harris, 1978) that formed in eastern North America during the Early and Middle Cambrian in association with the opening and spreading of the Iapetus-Theic Ocean (Thomas, 1991) (Figure 1). The Rome trough extends across extensive areas of oil and gas production in the central Appalachian foreland basin. The Rome trough has aroused interest among structural geologists and petroleum geologists over the past 30 yr (e.g., Woodward, 1961; McGuire and Howell, 1963; Harris, 1975, 1978; Ammerman and Keller, 1979; Kulander and Dean, 1980, 1993; Shumaker, 1986a, b, 1993, 1996; Kulander et al., 1987; Thomas, 1991; Patchen et al., 1993; Drahovzal, 1994; Wilson et al., 1994a, b; Gao, 1994; Gao and Shumaker, 1996; Harris and Drahovzal, 1996; Shumaker and Wilson, 1996; Ryder et al., 1997a, b; Beardsley, 1997). Although the stratigraphy and

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[2] Marathon Oil Company, P.O. Box 3128, Computer-Aided Interpretation, Houston, Texas 77056; e-mail: DGao@MarathonOil.com

[3] Department of Geology and Geography, West Virginia University, Morgantown, West Virginia 26506.

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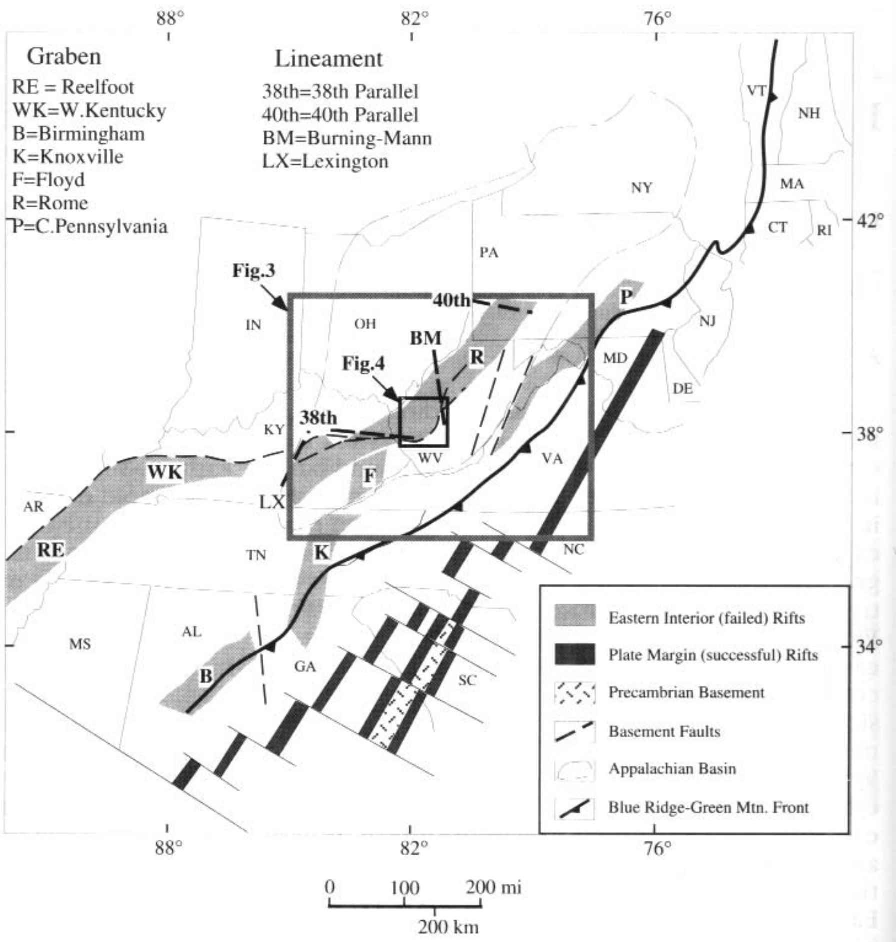


Figure 1—Tectonic map showing the Iapetian structure of southeastern North America and the Appalachian foreland basin (after Shumaker and Wilson, 1996; Shumaker, 1996). Rome trough and other grabens of the interior rift system are from Shumaker (1986a). Rifts and transform faults at the plate margin are from Thomas (1991). The 38th parallel lineament is based on Heyl (1972), and the Burning-Mann lineament is based on Shumaker (1986b). Also shown are the locations of areas shown in Figures 3 and 4.

structure of the Rome trough have been extensively discussed in previous studies, little has been published on the along-axis segmentation in trough geometry and its control on focused sedimentation and hydrocarbon accumulation. In this study, we compare and contrast the subsurface geology of different segments on the basis of well, seismic, magnetic, and gravity data. The results reveal complexities in the geometry and growth history of the trough that have enhanced our understanding of the mechanism for hydrocarbon entrapment and tectonic evolution of the pre-Appalachian and Appalachian foreland. That understanding, in turn, should provide the basis for a more accurate assessment of the hydrocarbon potential of both deeply buried and shallow Paleozoic reservoirs along the trough.

GEOLOGIC SETTING

The central Appalachian foreland basin is underlain by a series of continental grabens that are collectively part of a more extensive interior rift system (e.g., Shumaker, 1986a, 1996; Shumaker and Wilson, 1996). This system formed in association with the late-stage opening of the Iapetus-Theic Ocean at the plate margin during the Early and Middle Cambrian (Rankin, 1976; Thomas, 1977, 1991; Read, 1989; Ryder et al., 1997a, b). The crustal extension of the interior rift system produced a thick sequence of lower Paleozoic sedimentary rocks in several grabens (Shumaker, 1986a). The Rome trough (McGuire and Howell, 1963; Harris, 1975) is one of the elements of the interior rift system that extends into the Appalachian foreland in eastern Kentucky and western West Virginia where it follows the northeast-trending magnetic gradient named the New York-Alabama lineament (King and Zietz, 1978). Thousands of meters of sedimentary rocks are present within the trough, which consists of diverse lithologic units (Figure 2) (Schwietering and Roberts, 1988; Ryder, 1992). These sedimentary rocks can be divided into rift (Rome-Conasauga), passive-margin (Copper Ridge-Black River), and

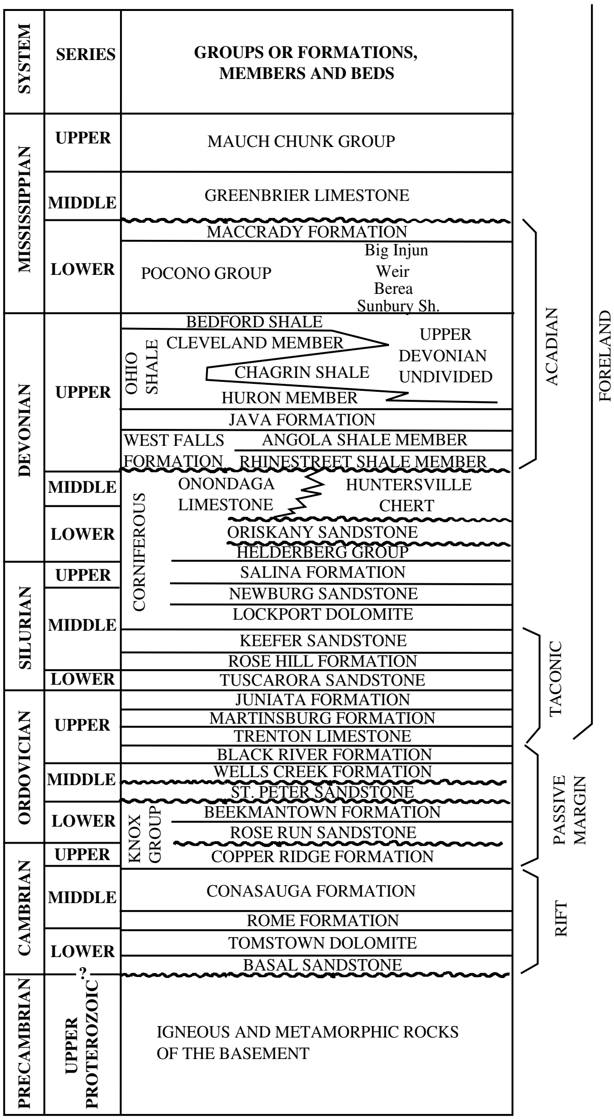


Figure 2—Generalized stratigraphic sequences of the study area (after Schwietering and Roberts, 1988; Shumaker and Wilson, 1996).

foreland (above Trenton) sequences (Shumaker and Wilson, 1996).

Gravity maps (Ammerman and Keller, 1979; Kulander et al., 1987) and a total magnetic intensity map (King and Zietz, 1978) indicate that the Rome trough shows significant along-axis variations in depth of the rift valley and thickness of overlying Paleozoic sediment infill. Superposition of the total magnetic intensity map with major basement structures of the Rome trough (Figure 3) indicates the spatial relationship between magnetic intensity variations and major basement lineaments. From south to north, the Rome trough is interrupted by a west-trending basement fault zone, named the 38th parallel lineament, that has been observed at the surface (Heyl, 1972) and by a north-trending magnetic gradient, named the Burning-Mann lineament, that extends from the Burning Springs to the Mann Mountain anticline developed at the surface (Shumaker, 1986b). These two basement lineaments (Figure 3) divide the Rome trough into the eastern Kentucky, southern West Virginia, and northern West Virginia segments.

Shumaker and Wilson (1996) discussed basement structures of the Appalachian foreland in West Virginia and their affect on sedimentation. They suggested that most of the larger basement faults in the Rome trough formed during the Precambrian Grenville orogeny. Subsequently, the trough experienced rifting during the Early(?) and Middle Cambrian, postrift subsidence (Ryder et al., 1997a), possibly forming a sag basin in the passive-margin sequence (Figure 2) during the Late Cambrian and Ordovician, and, finally, broad regional subsidence associated with a foreland basin stage during the middle and late Paleozoic.

Basement structures of the Rome trough in eastern Kentucky were discussed in previous studies (e.g., Black et al., 1976; Ammerman and Keller, 1979; Cable and Beardsley, 1984; Black, 1986; Drahovzal, 1994; Drahovzal and Noger, 1995; Shumaker, 1996). For example, Ammerman and Keller (1979) discussed the areal extent and geometry of the Rome trough in eastern Kentucky using gravity and deep drilling data. Their gravity modeling results indicate that basement faults controlled the graben geometry and thickness of the Paleozoic sedimentary rocks in this part of the Rome trough. Drahovzal and Noger (1995) and Shumaker (1996) mapped the extent of major subsurface faults in eastern Kentucky using existing geologic maps, deep well data, and a series of widespread regional seismic lines.

The fundamental geological work in West Virginia dates back to the early 1900s, when the West Virginia Geological and Economic Survey published a series of geologic reports and maps. This was followed by extensive discussions on the structural geology and stratigraphy in West Virginia (e.g., Neal and Price, 1986; Caramanica, 1988; Schwietering and Roberts, 1988; Zheng, 1990; Shumaker, 1993; Shumaker and Coolen, 1993; Wilson et al., 1994a, b; Gao, 1994; Gao and Shumaker, 1994, 1996). For example, Shumaker (1993) and Shumaker and Coolen (1993) reported on the studies on the East-Margin fault and the 38th parallel lineament. Wilson et al. (1994a, b) reported on the study of reflection seismic data across the Rome trough of northern West Virginia. Their seismic analyses indicated that basement faults and fault-bounded blocks have been intermittently active

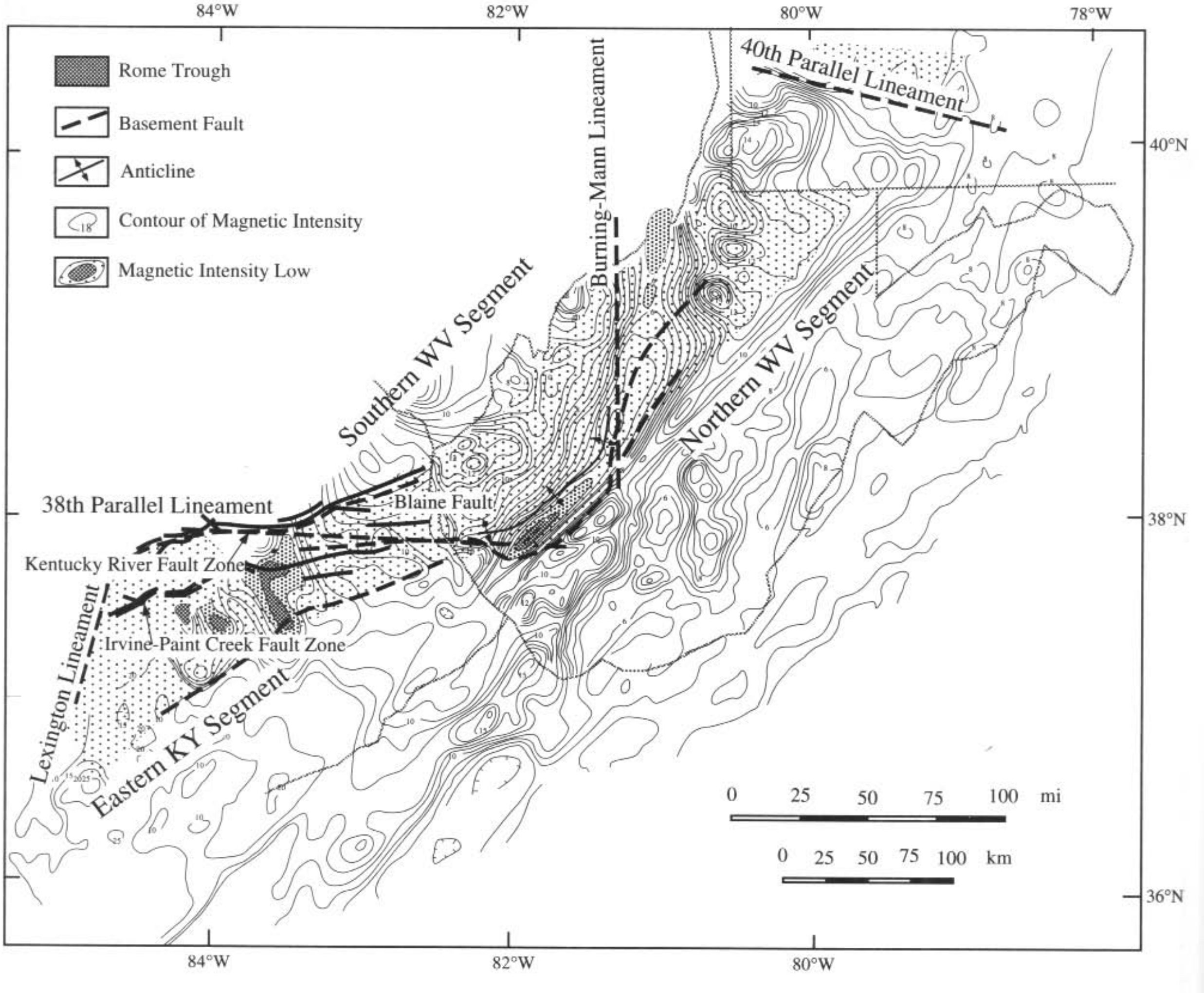


Figure 3—Superimposed magnetic and tectonic map showing the spatial relationship among the total magnetic intensity, areal extent of the three major segments of the Rome trough, and associated major basement fault systems. See Figure 1 for location. Magnetic intensity map is from King and Zietz (1978). Basement faults in eastern Kentucky are from Ammerman and Keller (1979). Basement faults in northern West Virginia are based on Shumaker and Wilson (1996). Note that the major magnetic intensity lows are spatially related to the three major segments of the trough, which are named the eastern Kentucky segment, the southern West Virginia segment, and the northern West Virginia segment.

during the Paleozoic and have significantly affected the deposition of the Paleozoic sedimentary rocks in the Rome trough of northern West Virginia.

Using more than 4000 shallow wells and several seismic lines, Gao (1994) and Gao and Shumaker (1996) mapped the subsurface geology in southwestern West Virginia and documented the geometric and kinematic relationship of shallow structures to the East-Margin fault and the 38th parallel and Burning-Mann lineaments. Based on their spatial and temporal relationship, Gao (1994) and Gao and Shumaker (1996) suggested that the 38th parallel and Burning-Mann lineaments represent a possible oblique (wedge-shape) transfer fault system that accommodated the complex deformation of the subsurface structures in southwestern West Virginia.

In this study, using new seismic data and interpretation and subsurface mapping techniques, we compare and contrast structures among the three rift segments to evaluate the along-axis variation in graben geometry. We propose that the 38th parallel and Burning-Mann lineaments are two possible accommodation zones to transfer extension from one graben segment to the next along the trough. We establish a structural model to emphasize along-rift segmentation and geometric and kinematic

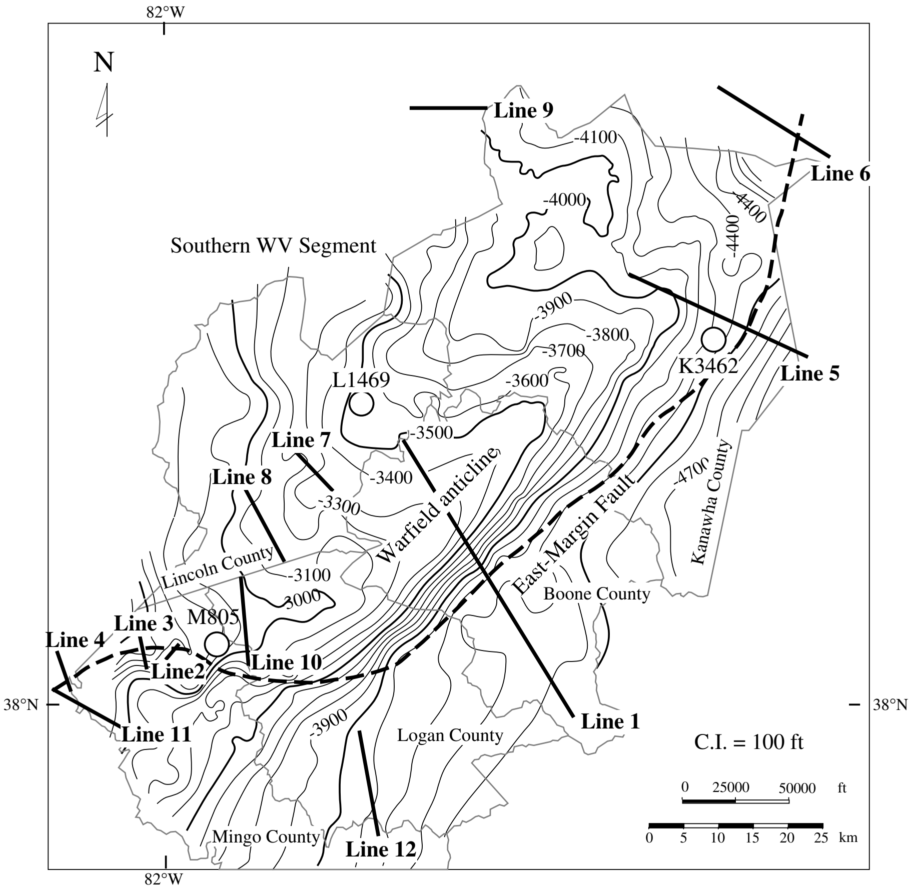


Figure 4—Index map showing the data set in the southern West Virginia segment of the Rome trough. See Figure 1 for location. The approximate locations of seismic lines are indicated by bold straight lines. The background structure contour map, which was constructed on the basis of more than 1000 shallow wells, shows the top of the Devonian Onondaga Limestone in southern West Virginia (from Gao and Shumaker, 1996). The Onondaga serves as a reference surface for extrapolating and interpolating deep structures via trend-surface analysis.

differences among the three rift segments, which may have important implications for hydrocarbon exploration along the Rome trough and other rift systems on a regional basis.

SOUTHERN WEST VIRGINIA SEGMENT

The southern West Virginia segment is defined between the 38th parallel and Burning-Mann lineaments (Figure 3). Because the southern West Virginia segment is bounded by the 38th parallel and Burning-Mann lineaments to the south and north, respectively, a detailed study of the geometry and growth history of that segment, using new seismic data and interpretation techniques, provides a key to understand the along-axis variation in graben geometry and growth history of the Rome trough.

Seismic Analysis

A total of 12 seismic lines were interpreted in the southern West Virginia segment (Figure 4). Sonic and density logs of three deep wells (Figure 4) were digitized. Impedance, reflection coefficients, and normal incidence synthetic seismograms were computed (Figure 5). The synthetic seismograms are derived from the convolution between reflection coefficients and a zero-phase wavelet. The stratigraphic positions of the major reflection events are shown in Figure 5. We identified stratigraphic intervals based on drillers' logs and lateral correlation with other log data (e.g., Ryder, 1992; Drahovzal and Noger, 1995), and the seismic event picks are based on synthetic seismic correlation with actual seismic lines (e.g., Figure 5c).

To better analyze and emphasize lateral and temporal variations in structural geometry, we digitized two-way traveltimes of major seismic events associated with several key horizons. The digitized reflections were vertically exaggerated by upward shifting of sequential horizons coupled with rescaling on the vertical axis (Wilson et al., 1994a, b; Shumaker and Wilson, 1996). Although vertical shifts of reflection events eliminate absolute values of arrival time, such shifts do not affect absolute differences in structural relief along individual

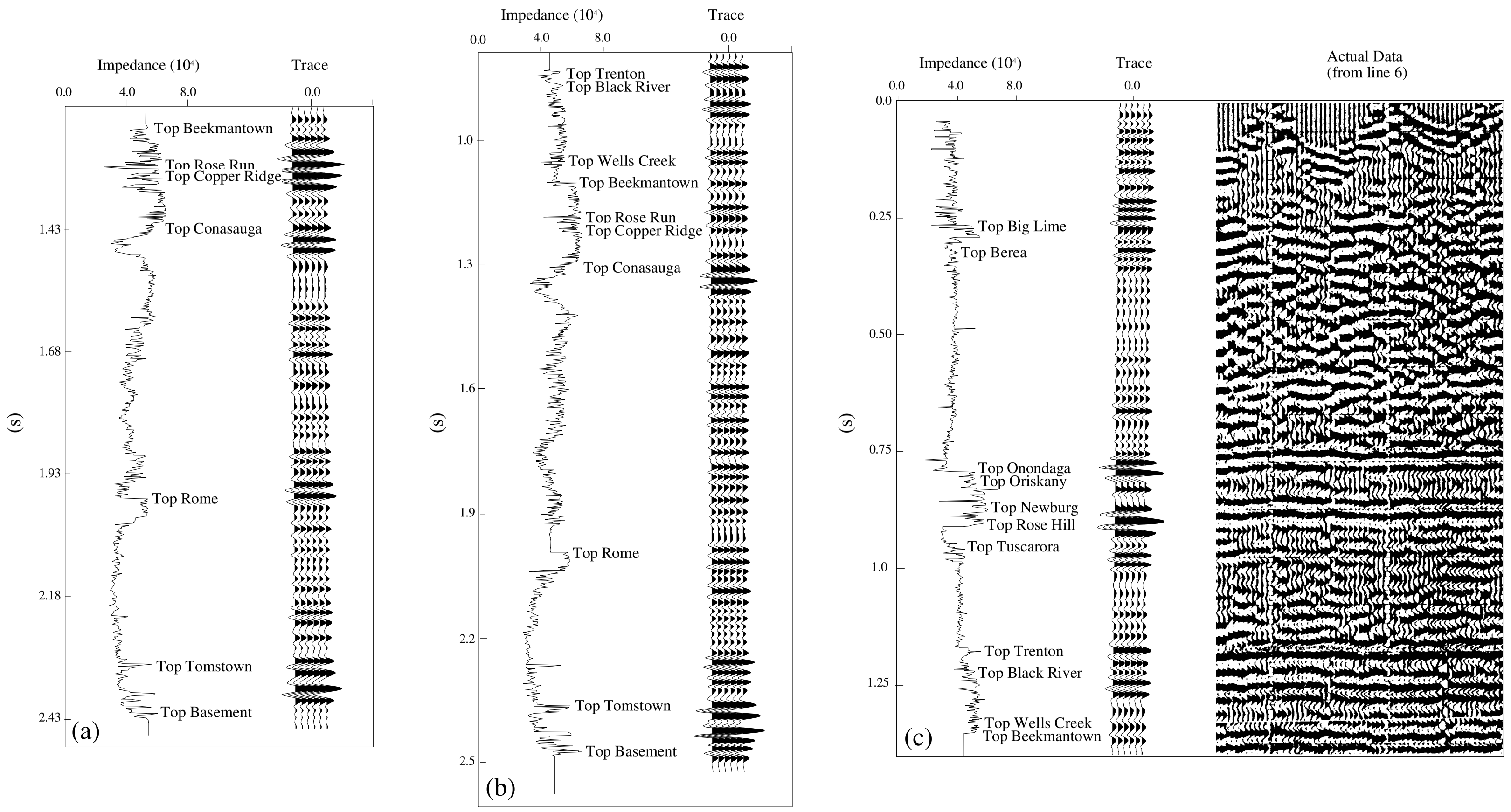


Figure 5—Impedance and synthetic seismograms for (a) well L1469 in Lincoln County, (b) well M805 in Mingo County, and (c) well K3462 in Kanawha County. Wells show their lateral correlation and similarity in interval velocity. Impedance is calculated by merging the sonic (velocity) and density logs. Note the similarity in velocity package within the same stratigraphic interval. The normal-incidence synthetic seismograms were computed from the convolution between the reflection coefficient (calculated from acoustic impedance profile) and zero-phase wavelet. Several major lithologic boundaries can be resolved as separate reflections. Example correlation between a synthetic seismogram and an actual seismic time section is shown in (c). Time is in seconds two-way traveltime.

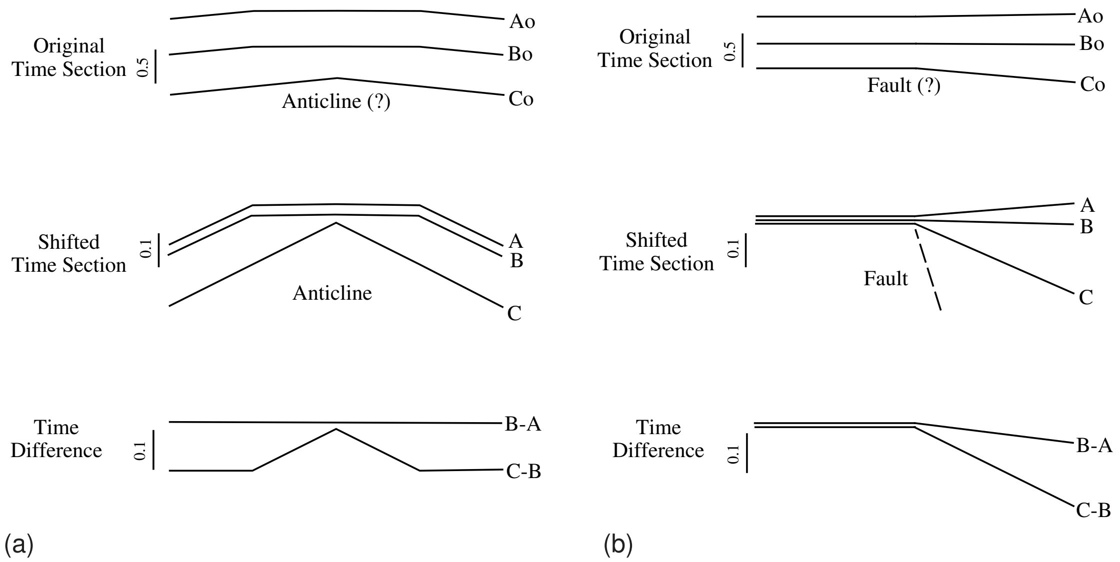


Figure 6—Two simplified examples showing the benefits of constructing shifted arrival times and time difference curves from the original time section. Subtle structural and stratigraphic features such as the (a) anticline and the (b) fault are difficult to recognize in the original time section. By shifting sequential reflections and increasing the vertical scale, the geometry of the anticline (a) and the location of the fault (b) are easily recognizable; furthermore, the time difference curves, calculated by sequentially subtracting shifted arrival times, remove the structural effect to emphasize the differential subsidence associated with the drape anticline (a) and the growth fault (b).

reflectors. Figure 6 demonstrates how vertical exaggeration is achieved via vertical shifts and rescaling of the sequential horizons. Original, unshifted reflections generally appear as widely spaced flat areas. The original plotting scale tends to mask or attenuate subtle structural and stratigraphic features. By upward shifting and rescaling on the vertical axis, subtle variations associated with the anticline (Figure 6a) and the fault (Figure 6b) that would otherwise be difficult to recognize are exaggerated. In the study area, we found no direct evidence that supports the presence of velocity anomalies, and both seismic lines and sonic logs indicate that major thickness changes within individual lines are restricted to the deepest, synrift reflections. Most of the shallow intervals show relatively minor changes in thickness; hence, in the absence of a satisfactory time-depth conversion table, major lateral variations in arrival time can be properly interpreted as related to structural relief. The distortion, if any, may occur at the basement structure level due to significant thickness variation of the overlying rift sequence.

To remove structural effects and to emphasize differential subsidence, we constructed a series of subsidence curves by calculating the differences in arrival times between the adjacent horizons, called time difference (Figure 6), that aid in identifying changes in the polarity of differential subsidence and the location of depocenters. Unlike arrival time, lateral variation in time difference is not affected by lateral variations in velocity of the overlying strata. Basically, lateral variations in time difference represent changes in rock thickness in the absence of significant lateral variation in interval velocity. After careful examination of sonic logs of several wells, and after making several test calculations, we note that average interval velocity is relatively constant based on sonic logs from the three deep wells; therefore, variations in time difference can be properly interpreted as related to thickness changes, and local depocenters can be better defined with the help of the differential subsidence curves.

Line 1 is located in the central part of the southern West Virginia segment, away from both the 38th parallel and Burning-Mann lineaments. The digitized and processed section (Figure 7a) suggests that this segment of the Rome trough is an asymmetric graben with a single East-Margin fault dipping toward the northwest on the southeastern side of the trough. Reflections, interpreted as tops of the Rome, Tomstown, and basement units, dip toward the East-Margin fault, suggesting that the hanging wall rotated clockwise into the footwall. We found more than 0.5 s of lateral variation in time difference (Figure 7b) across the East-Margin fault in the rift sequence (see Rome-Conasauga

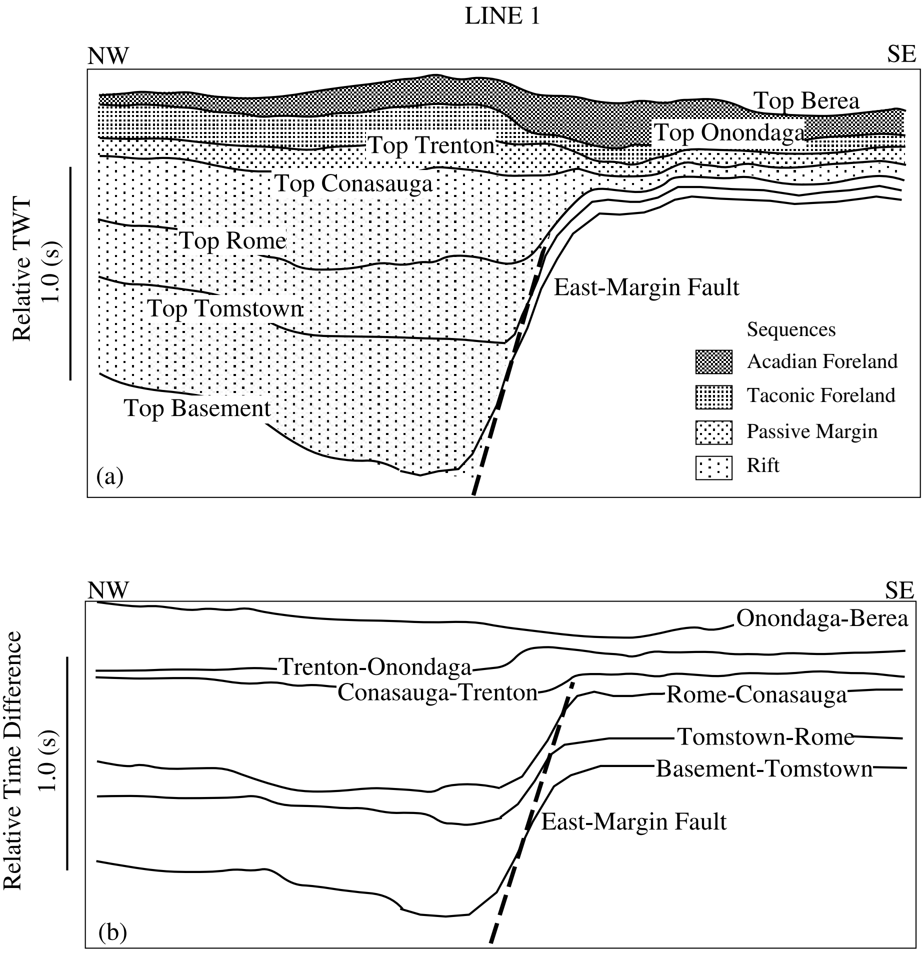


Figure 7—(a) Digitized and enhanced arrival times and (b) time difference curves of line 1 (see Figure 4 for location and scale) showing lateral variations in structure and differential subsidence, respectively. Note no absolute values are attached to the vertical axis because of vertical shift of the arrival times and time difference curves. See text for explanation. TWT = two-way traveltime.

time difference), but only 0.2 s difference in the passive-margin sequence (see Conasauga-Trenton time difference) and 0.1 s difference in the foreland sequence (see Trenton-Onondaga time difference), indicating that a major amount of differential subsidence and deposition across the East-Margin fault occurred during the Early(?) and Middle Cambrian. The thickest part of the Conasauga-Onondaga interval is located on the hanging wall just northwest of the East-Margin fault, but unlike the underlying rift sequence, deposition is not restricted within the trough but extends outside of the trough. The overlying Onondaga-Berea interval reveals a shift in the depocenter toward the southeast (Figure 7), which suggests inversion across the East-Margin fault following deposition of the Devonian Onondaga Limestone. The relative time difference plot (Figure 7b) indicates that normal displacement of the East-Margin fault occurred intermittently throughout the Paleozoic.

Near the 38th parallel lineament is a series of east-west–trending basement faults. At the border between the southern West Virginia and eastern Kentucky segments, lines 2, 3, and 4 show a well-defined basement fault that juxtaposes basement rocks on the south with sedimentary rocks of the trough on the north (Figure 8). The changes in both dip polarity (Lee, 1980) and strike of this basement fault (Gao, 1994; Gao and Shumaker, 1996) indicate the structural complexity at the border of the two rift segments.

Near the Burning-Mann lineament, internal structures of the trough are more complicated. Digitized reflections from line 5 (Figure 9a) reveal that reflectors above the Trenton Limestone dip to the east, whereas reflectors below the Trenton Limestone generally dip to the west. The East-Margin fault appears to be a high-angle normal fault dipping to the northwest with a large normal offset of units in the rift sequence below the top of the Conasauga Formation. The southeast-dipping reflections of the

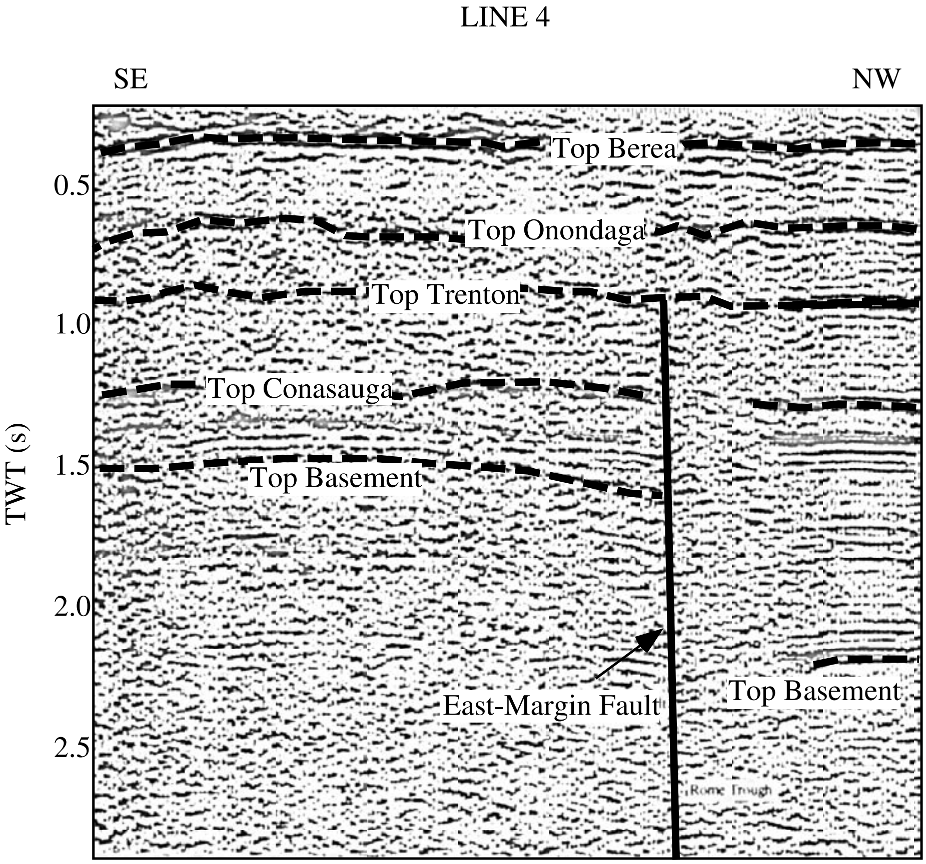


Figure 8—Seismic line 4 (see Figure 4 for location and scale) across the East-Margin fault in the southern West Virginia segment of the Rome trough. Note the East-Margin fault and the discontinuity of reflections across the fault. TWT = two-way traveltime.

Rome Formation and the Tomstown Dolomite near the East-Margin fault indicate a clockwise rotation of the fault block toward the East-Margin fault during the deposition of the rift sequence. Variations in the time differences (Figure 9b) from the basement to Tomstown, the Tomstown to Rome, and the Rome to Conasauga indicate southeastward thickening locally in the vicinity of the East-Margin fault. The Conasauga to Trenton interval shows a northwestward thickening into the Rome trough, which would be expected for a sag basin. The Trenton to Rose Hill and the Rose Hill to Onondaga intervals both show slight thickening toward the northwest. These observations suggest that the clockwise rotation of the basement block occurred mainly during the Early(?) and Middle Cambrian. The Onondaga to Huron interval, however, thickens toward the southeast across the East-Margin fault, indicating a shift in subsidence polarity toward the southeast after deposition of the Onondaga. This shift is accompanied by a change from carbonate to clastic sedimentary rocks of the Acadian sequence that is generally considered to mark the onset of an orogen in the growth history of the Appalachian foreland.

Farther to the north, line 6 is located at the border between the southern West Virginia and northern West Virginia segments. Here, the trough is complicated by a major basement fault in the interior of the trough, called the Interior fault (Figure 10). The extension, which occurs largely across the East-Margin fault to the south, probably is distributed between the two major faults toward the northern West Virginia segment north of the Burning-Mann lineament. The Interior fault shows a normal offset of more than 0.35 s, which is larger than that of the East-Margin fault (compare the Interior fault and the East-Margin fault in Figure 10a). The variations in interval time difference (Figure 10b) suggest a complex history of differential subsidence during the Paleozoic controlled by the Interior fault and the East-Margin fault. Interestingly, the Interior fault seems to have a longer history of deformation than the East-Margin fault; the Interior fault influenced the deposition from the Cambrian to Devonian with alternating polarity of differential subsidence, whereas the East-Margin fault had minor effect on sedimentary rocks deposited after the Conasauga was deposited. These observations indicate that line 6 shows different internal structure and

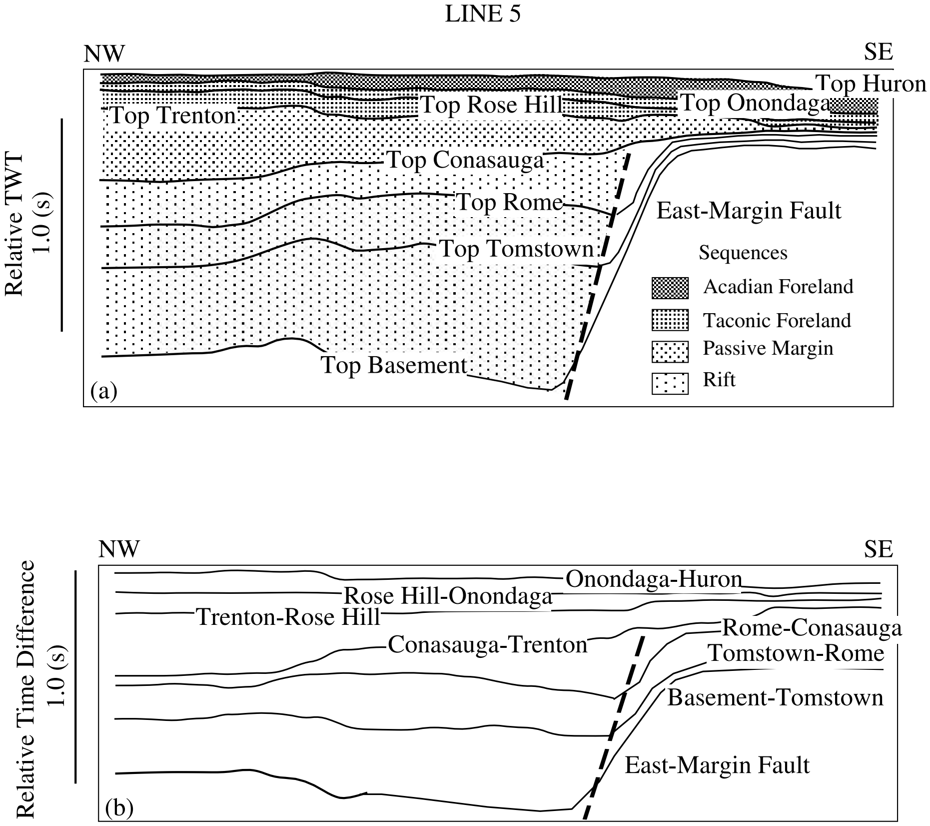


Figure 9—(a) Digitized and enhanced arrival times and (b) time difference curves of line 5 (see Figure 4 for location and scale) showing lateral variations in structure and differential subsidence, respectively. Note no absolute values are attached to the vertical axis because of vertical shift of the arrival times and time difference curves. See text for explanation. TWT = two-way traveltime.

growth history of the trough than line 5, which suggests that graben geometry and growth history may have changed from the southern West Virginia segment to the northern West Virginia segment.

On the northwestern side of the Rome trough (Figure 11), the top of basement dips gently eastward toward the East-Margin fault; the dip may be caused by the rotational subsidence at the western margin of the trough. Increasing dip of the reflections with depth indicates that rotational subsidence largely occurred during the rift stage, and that differential subsidence or clockwise rotation became less active after the formation of the rift basin.

In summary, several points regarding the southern West Virginia segment can be drawn from seismic analysis. (1) The strike, dip, and throw of the East-Margin fault change significantly along strike from south to north. Between the 38th parallel and Burning-Mann lineaments, the East-Margin fault strikes to the northeast and dips to the northwest. Toward the south at the segment border, the East-Margin fault swings abruptly to the west near the 38th parallel lineament. Toward the north at the segment border of the Burning-Mann lineament, the graben geometry is complicated by an Interior fault, and the influence of the East-Margin fault on deposition decreases from south to north relative to the Interior fault. (2) Three vertically stacked structural styles are associated with three vertically stacked rock sequences (Figure 2) that reflect changes in the structural history of the study area. These styles include a half graben associated with a rift sequence that abruptly appears at the eastern margin of the rift, a relatively broad sag basin associated with a passive-margin sequence that slightly thickens above the rift, and a foreland sequence that expands eastward toward the plate margin and is particularly apparent on the seismic expression of the Acadian clastic wedge.

Structure and Isopach Contouring

A total of 2221 control points were used to construct subsurface geologic maps. These data include depths to the top of the Devonian Onondaga Limestone extracted from the wells, depths to the top of the Precambrian basement digitized from an acoustic basement map (J. Lemon, 1993, personal communication), and depths to several intervening horizons of the Ordovician and Cambrian converted from seismic sections.

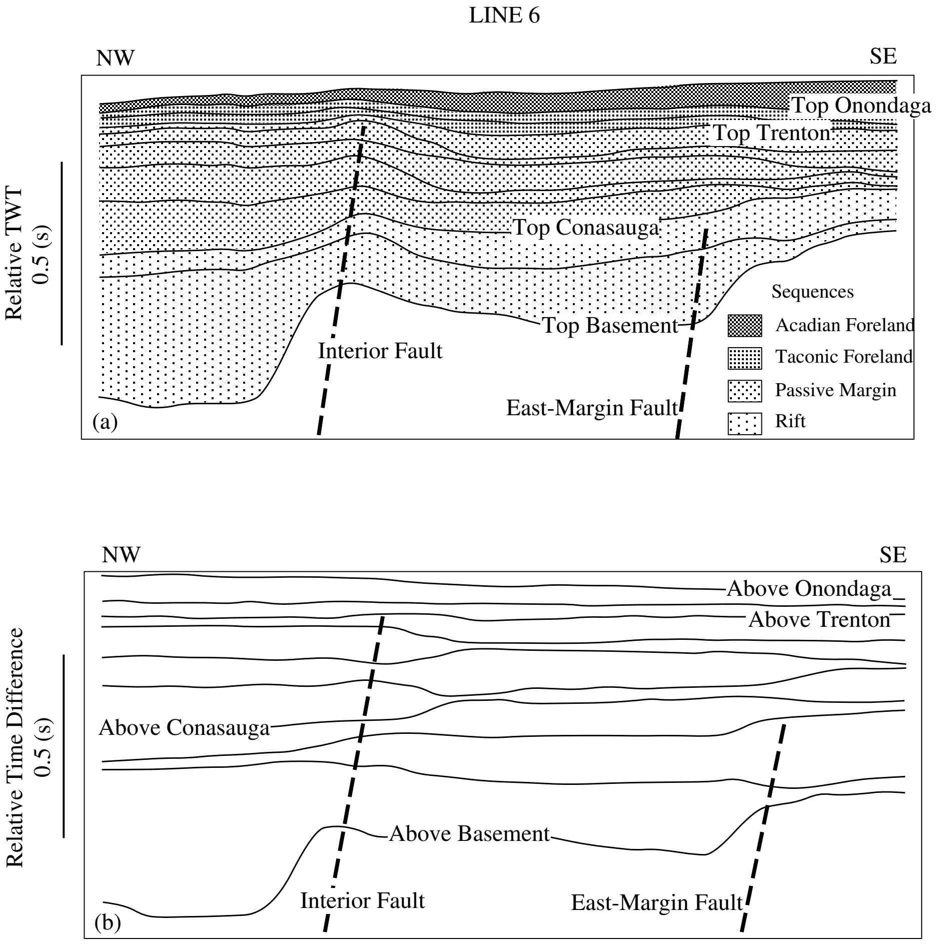


Figure 10—(a) Digitized and enhanced arrival times and (b) time difference curves of line 6 (see Figure 4 for location and scale) showing lateral variations in structure and differential subsidence, respectively. Note no absolute values are attached to the vertical axis because of vertical shift of the arrival times and time difference curves. See text for explanation. TWT = two-way traveltime.

To construct the structure and isopach contour maps at deep structure levels of the Cambrian and Ordovician, arrival times of the seismic sections were first converted to depth using interval velocities derived from sonic logs nearest to the seismic lines (e.g., Zheng, 1990). Following the time-depth conversion, we integrated the well data with the seismic data and performed multisurface extrapolation and interpolation via thickness trend analysis (Figure 12). This computation may introduce considerable error due to a lack of detailed three-dimensional velocity control and structural complexities across the whole area, and thus the resultant contour maps provide only low-resolution constraints on structures of deeply buried Cambrian and Ordovician formations. A comparison was made with published maps produced by well data at shallow structural levels to determine the reliability of the interval thickness trend analysis. The comparison demonstrated that maps made via trend analysis are similar to those made based only on well data.

Even allowing for the potential errors inherent in velocity and the sparse well control at depths below the Devonian Onondaga horizon, contour maps indicate that structural relief generally increases with depth, which is consistent with and obvious from seismic sections; however, the half graben that is visible below the Ordovician Trenton Limestone (Figure 12b, c) contrasts with the asymmetrical anticlines seen in the younger rocks (Figures 4, 12a) (Gao and Shumaker, 1996). This contrast probably relates to inversion of the trough. Basement structures are characterized by a structural depression that is bounded by basement faults on the southeastern margin of the trough. The asymmetry of the trough at the basement level is shown by a difference in steepness of dip between the northwestern and southeastern margins of the trough. In map view, the general trend of the graben is to the northeast, but adjacent to the 38th parallel and Burning-Mann lineaments, it swings to the west and north, respectively (Figure 12c).

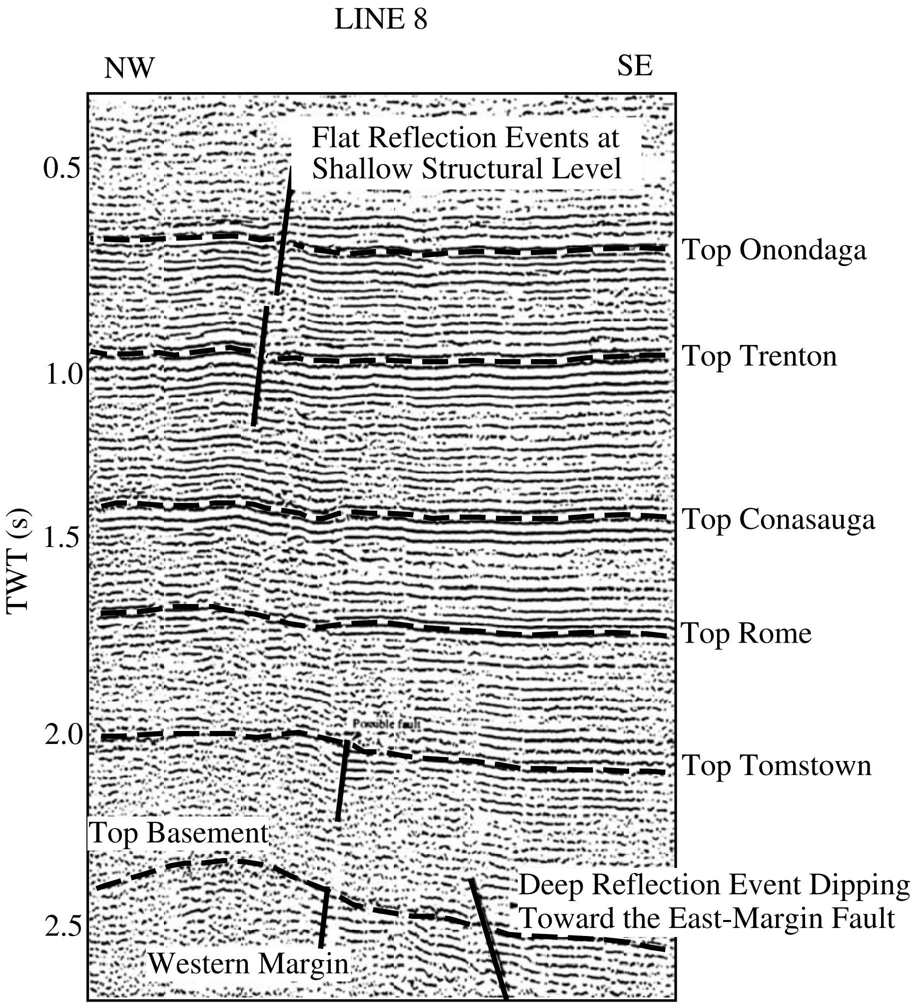


Figure 11—Seismic line 8 (see Figure 4 for location and scale) on the western flank in the southern West Virginia segment of the Rome trough. Note the basement top dips toward the East-Margin fault on the southeast, indicating rotation of basement fault block and asymmetric geometry of the trough. TWT = two-way traveltime.

Isopach maps indicate that both the rift sequence (Figure 12e, f) and the Taconic foreland sequence (Figure 12d) are affected not only by the limits of the trough itself but also by the 38th parallel lineament to the south and the Burning-Mann lineament to the north. A northeastward shift of depocenter along the trough is suggested by comparing the thickness patterns of the sequential isopach maps (Figure 12d–f). Vertical changes in rock thickness patterns and gradients from the oldest sedimentary rocks (Figure 12f) to the successively younger intervals (Figure 12d, e) probably reflect the transition from the rift to the sag basin stage.

In summary, subsurface structure and isopach maps indicate that the southern West Virginia segment of the trough is characterized by the East-Margin fault that developed along the southeastern side of the trough. Across the East-Margin fault, the early Paleozoic sediments thicken from 1000 ft (305 m) outside of the trough to more than 20,000 ft (6100 m) within the trough (Harris, 1975, 1978; Neal and Price, 1986; Schwietering and Roberts, 1988). The asymmetry of the trough cannot be extended along its axis into Kentucky. This change is spatially associated with the 38th parallel lineament and an increased structural complexity within the zone itself, as well as by the increased complexities in dip and strike of the East-Margin fault (Gao and Shumaker, 1996). We interpret this structural complexity as an indication of an accommodation zone that transfers extension between the southern West Virginia segment and the eastern Kentucky segment of the Rome trough.

EASTERN KENTUCKY SEGMENT

The eastern Kentucky segment is defined between the 38th parallel lineament and the

Lexington fault zone (Figure 3), which roughly coincides with the western overthrusted margin of the Grenville (1.0 Ga) basement (Drahovzal and Noger, 1995; Shumaker, 1996). Differing from the southern West Virginia segment, the eastern Kentucky segment shows an irregular and complicated anomaly pattern in both gravity (Ammerman and Keller, 1979; Kulander et al., 1987) and magnetic intensities (Figure 3) (King and Zietz, 1978), suggesting more complicated basement structures than in the southern West Virginia segment. Several basement faults extend to the surface along the northwestern margin of the trough. Computer modeling of gravity profiles of the Rome trough in eastern Kentucky by Ammerman and Keller (1979), using data from deep wells as constraints, indicates that the trough is bounded on the north by a major gravity gradient that corresponds to a major basement structure called the Kentucky River fault zone that has been mapped at the surface (Figure 3). A second fault zone called the Irvine-Paint Creek fault zone extends eastward within the trough from the Lexington fault zone (Figure 3).

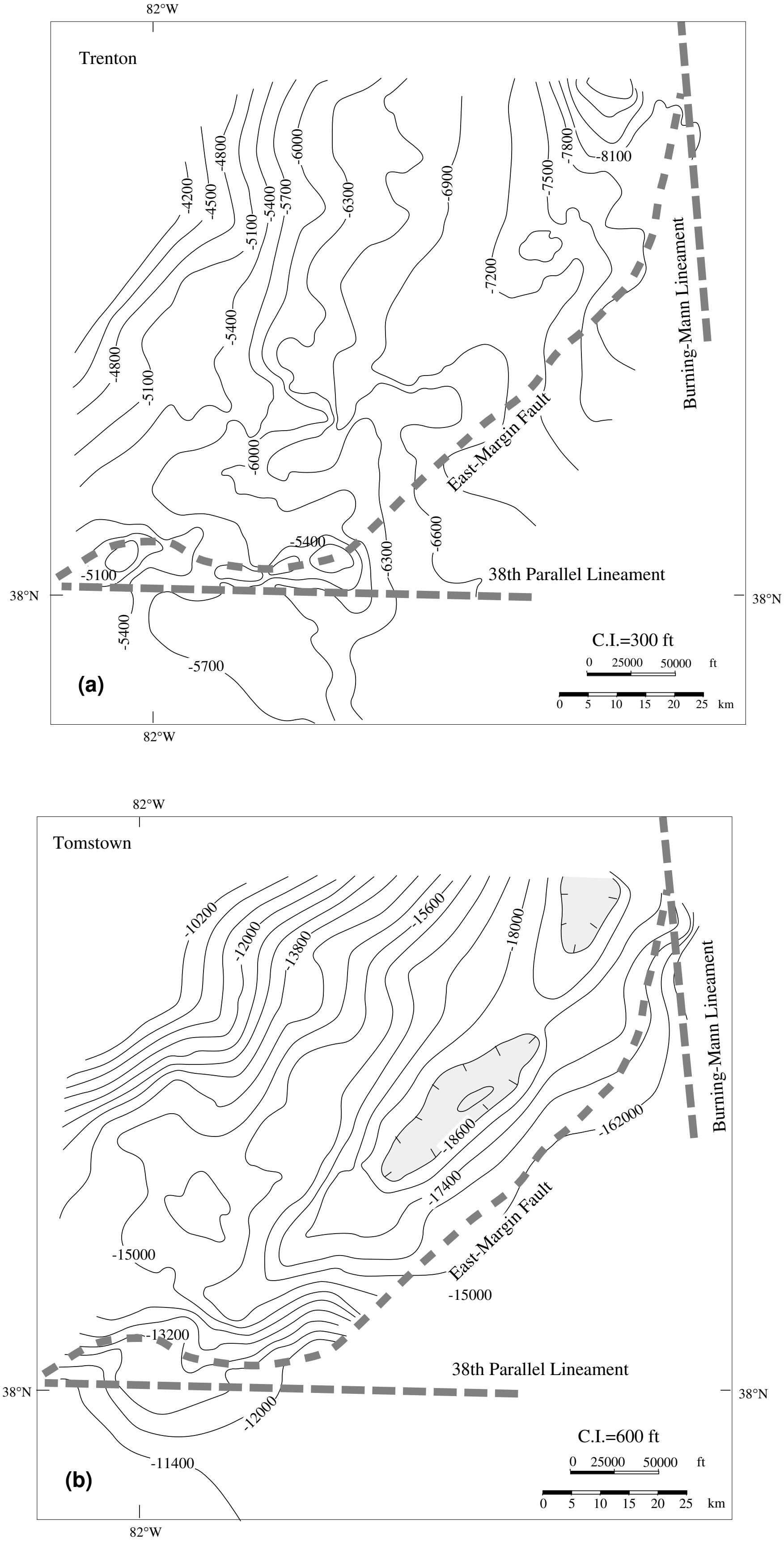
The Rome trough in eastern Kentucky has been identified since the early 1960s on the basis of stratigraphy and structure in the region. Woodward (1961) first described it as a Lower Cambrian coastal declivity, which may be a fault scarp or a steep coastwise cliff, that is responsible for an abrupt thickening of the Early Cambrian deposits. Along the northwestern boundary of the trough, sedimentary rocks of the Rome Formation thicken from approximately 270 ft (82 m) north of the trough to more than 4560 ft (1390 m) within the trough (Thomas, 1960; Ammerman and Keller, 1979). Harris and Drahovzal (1996) reported that the rift sequence (pre-Knox deposition) is 300–600 ft (91–183 m) thick in northernmost Kentucky, but abruptly thicken across a series of extensional growth faults (the Kentucky River fault system) into the trough where the rift sequence is as thick as 10,000 ft (3050 m) in some areas (e.g., Drahovzal and Noger, 1995). Rocks that may be Early Cambrian but largely are Middle Cambrian in age (Ryder et al., 1997b) in the trough have no equivalents to the north on the shelf of the rift basin, and the Cambrian depocenters are located along the northwestern margin of the trough in Kentucky (Harris and Drahovzal, 1996). Structure maps of the Precambrian basement surface in eastern Kentucky (Drahovzal and Noger, 1995; Shumaker, 1996) indicate that structural relief of the top of the Precambrian basement is greater than 13,000 ft (3965 m) from the northern boundary to the deepest part of the trough, whereas relief along the southern boundary is generally only 7000–8000 ft (2135–2440 m) and locally much less. Webb (1969) suggested that the trough was formed by growth faulting along a cratonic boundary with a fault scarp at its northern boundary. Silberman (1972) confirmed this interpretation by showing that throw along the northern boundary is approximately 5000 ft (1525 m) at the top of the Precambrian, decreasing to 3900 ft (1189 m) at the top of the basal sand and to 2060 ft (628 m) at the top of the Rome Formation. The Kentucky River fault zone swings toward the south to join the Lexington fault zone to delineate what appears to be the northwestern boundary of the Rome trough in Grenville basement of that area (Black et al., 1976; Black, 1986; Shumaker, 1996). A few faults extend westward in older basement to connect with major faults of the Western Kentucky graben (Figure 1); however, most of the Rome trough faults converge and apparently disappear as they swing southward.

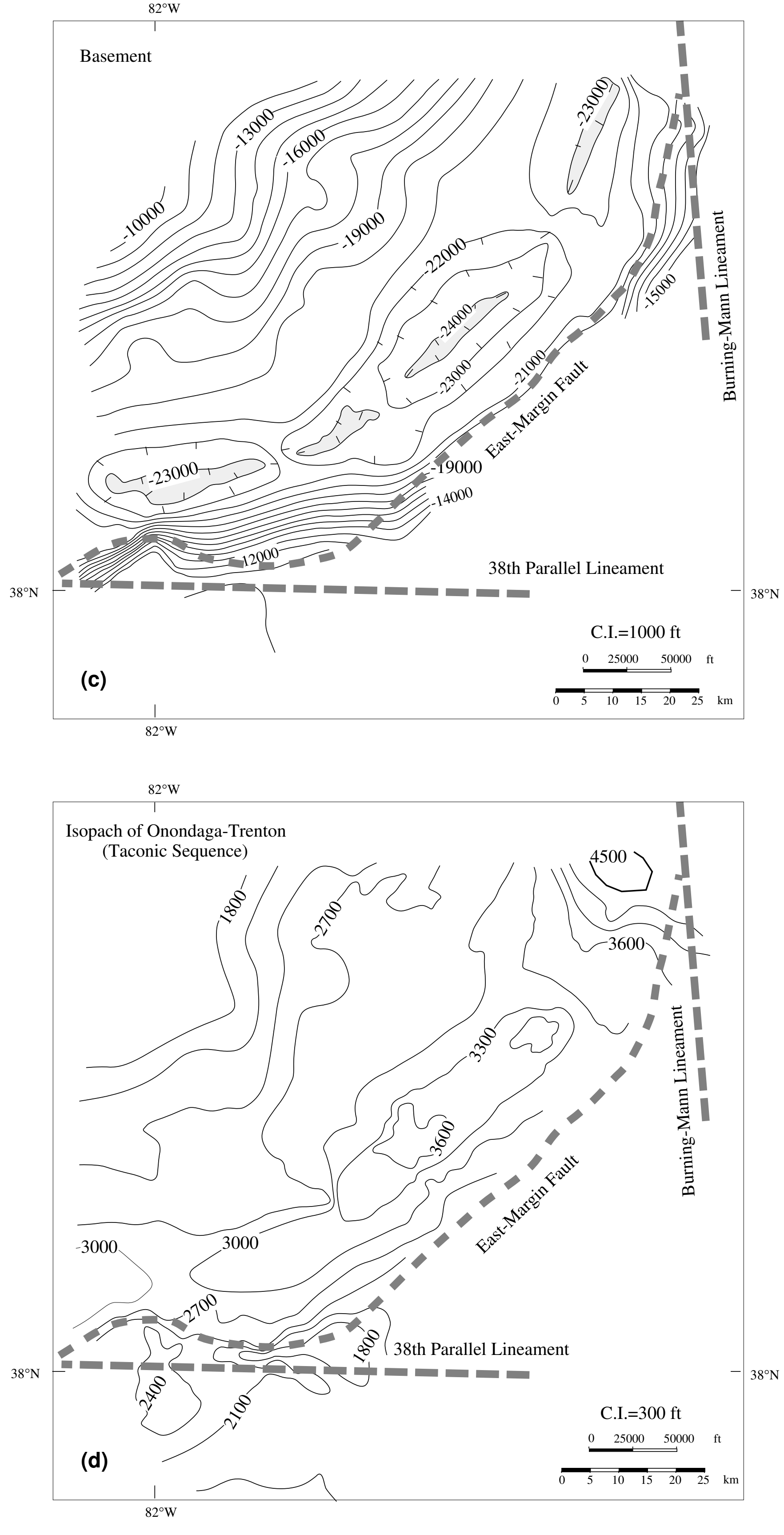
Drahovzal and Noger (1995) and Shumaker (1996) mapped the subsurface extent of faults in eastern Kentucky using proprietary seismic data to confirm that the surface faults in that area are part of the Cambrian rift system. The asymmetry and arcuate geometry of the fault system in eastern Kentucky indicate that the northwestern boundary of the Rome trough in eastern Kentucky is a convex-to-the-northwest fault system (Figure 13a) that includes several smaller half grabens with opposite polarity to the large fault-bounded graben of the southern West Virginia segment. The fault along the southeastern margin of the trough is diffuse and is generally of small magnitude (Figure 13b) (Ammerman and Keller, 1979; Drahovzal and Noger, 1995; Shumaker, 1996). These observations indicate that the graben polarity is reversed and that deposition in the eastern Kentucky segment was controlled by several faults along the northwestern side of the trough.

NORTHERN WEST VIRGINIA SEGMENT

The northern West Virginia segment refers to that part of the trough north of the Burning-Mann lineament. Its northern boundary is unknown because little subsurface data are published to define its northern extent. The total magnetic intensity map by King and Zietz (1978) shows a cross-strike magnetic intensity gradient at the latitude of 40° in southern Pennsylvania called the 40th parallel lineament (Shumaker and Wilson, 1996) (Figures 1, 3). In contrast to the southern West Virginia segment, this segment has a magnetic low on the western side of the trough, and it has several magnetic intensity highs in the middle and the east of the trough. In addition, the gradient of the magnetic intensity across the East-Margin fault is relatively low compared to the southern West Virginia segment.

Figure 12—Computer-generated subsurface structure and isopach maps. These maps indicate tectonic control by basement structures on deposition of the Cambrian and Ordovician in the southern West Virginia segment. Focused sedimentation was controlled by the East-Margin fault, the 38th parallel lineament, and the Burning-Mann lineament. The structural lows and thickness changes occur in the vicinity of the 38th parallel and Burning-Mann lineaments, which suggest transtensional deformation associated with the two oblique accommodation zones. (a) Trenton Limestone structure, (b) Tomstown Dolomite structure, (c) basement structure, (d) isopach between Onondaga Limestone and Trenton Limestone, (e) isopach between Rome Formation and Tomstown Dolomite, (f) isopach between Tomstown Dolomite and top of basement.





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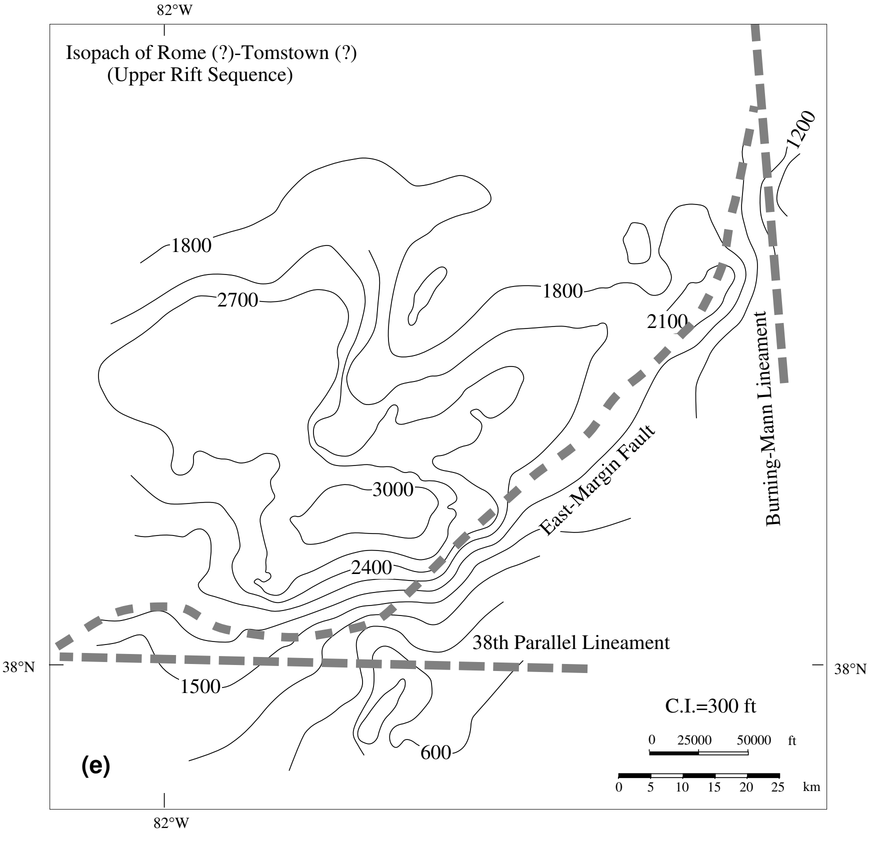

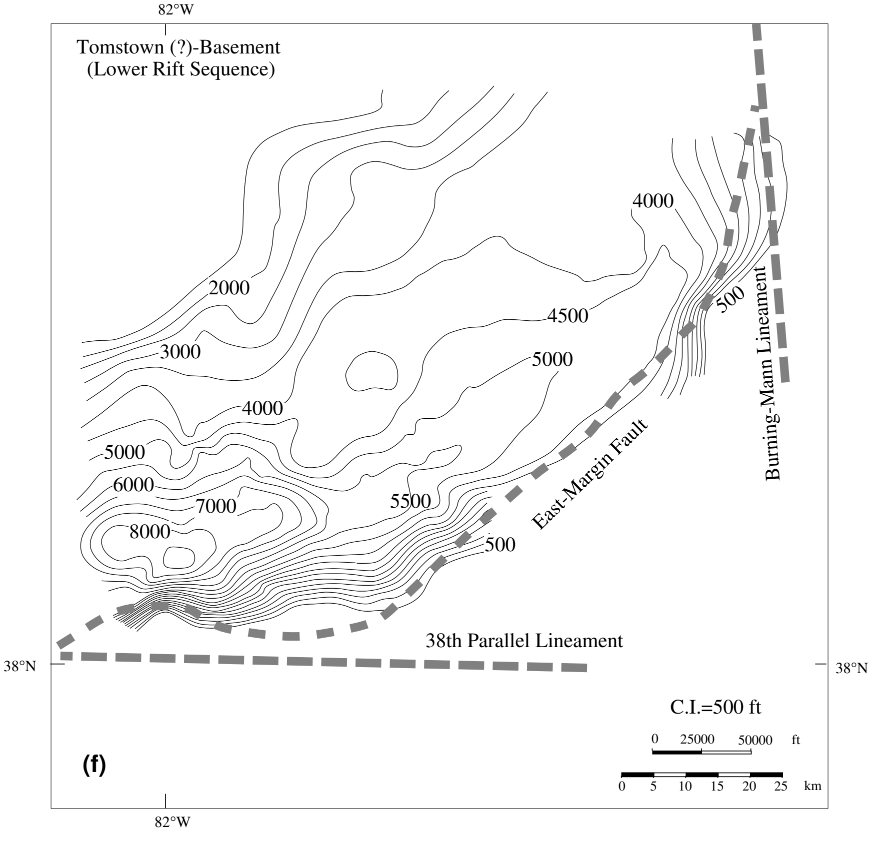

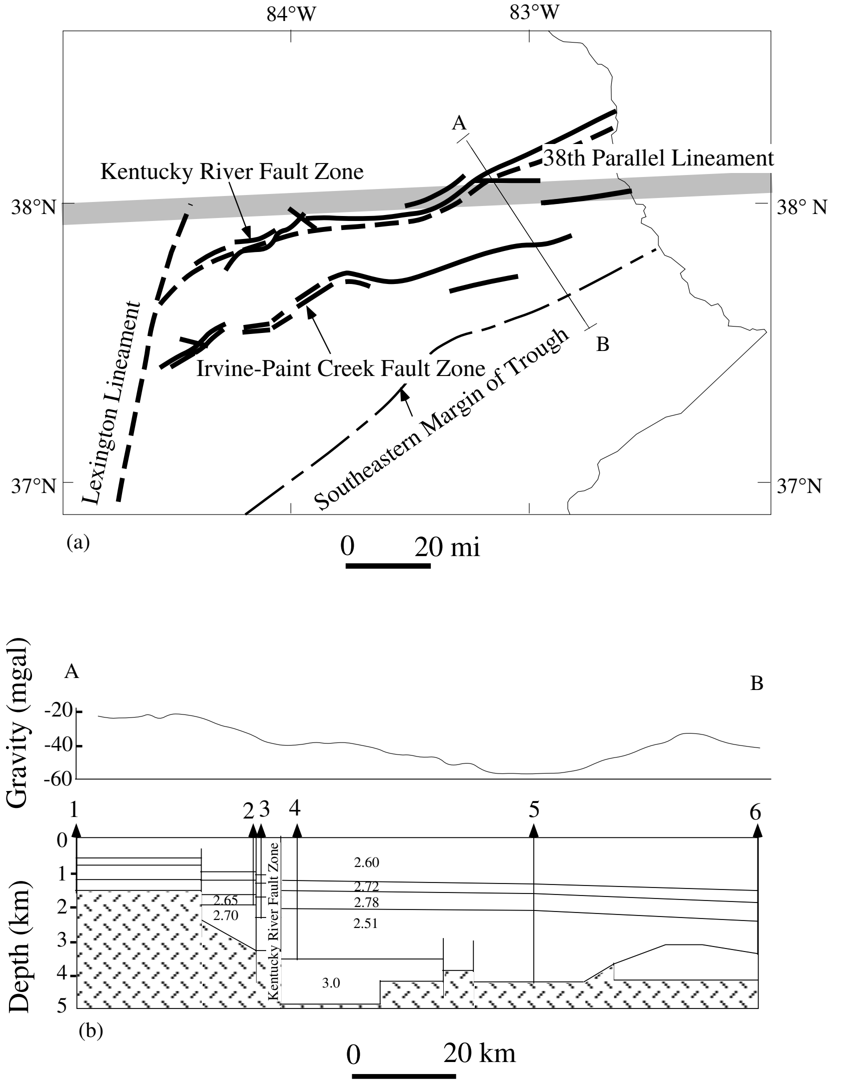

Figure 13—Structure map and computed cross sectional model based on gravity data along profile AB. Densities for each unit are given in grams/cubic centimeter. Wells used for control are 1 = U.S.S. Chemicals well (Scioto County, Ohio), 2 = Inland Gas 538 Coalton Fee, 3 = Inland Gas 533 Fee, 4 = Inland Gas 542 Young, 5 = Signal 1 Elkhorn Coal Company, 6 = Signal 1 Stratton. The master synthetic fault zone labeled as Kentucky River fault zone is located on the northwestern side of the trough (from Ammerman and Keller, 1979).

A regional contour map of the top of the Grenville basement (Shumaker, 1996) indicates that the trough geometry in the northern West Virginia segment is somewhat different from that of the southern West Virginia segment. The interior of the trough is broken by a large, tilted horst block that is bounded on the west by the Interior fault, and the trough becomes wider and the East-Margin fault is less well defined. These changes contrast with the comparatively unbroken and narrow graben of the southern West Virginia segment. Several isopach maps (Figure 14), such as that of the Devonian black shale (Harris et al., 1978), Mississippian Big Injun sandstone, and Mississippian Weir sandstone (Zou and Donaldson, 1994) indicate that the northern West Virginia segment has different lithofacies and rock thickness compared to those in the southern West Virginia segment, and the intervening Burning-Mann lineament is associated with a north-trending linear gradient of rock thickness shown inseveral published isopach maps (Harris et al., 1978; Zou and Donaldson, 1994; Shumaker and Wilson, 1996).

Comparison of seismic lines indicates that the East-Margin fault in this segment has different geometry, internal structure, and deformation history from those observed in the southern West Virginia segment. For example, a seismic line (Figure 15) across the northern West Virginia segment (T. H. Wilson, 1998, personal communication) indicates that the East-Margin fault controlled deposition and basin geometry during the rifting stage from the Early(?) to Middle Cambrian, but it was largely inactive during the passive-margin and foreland basin stages;

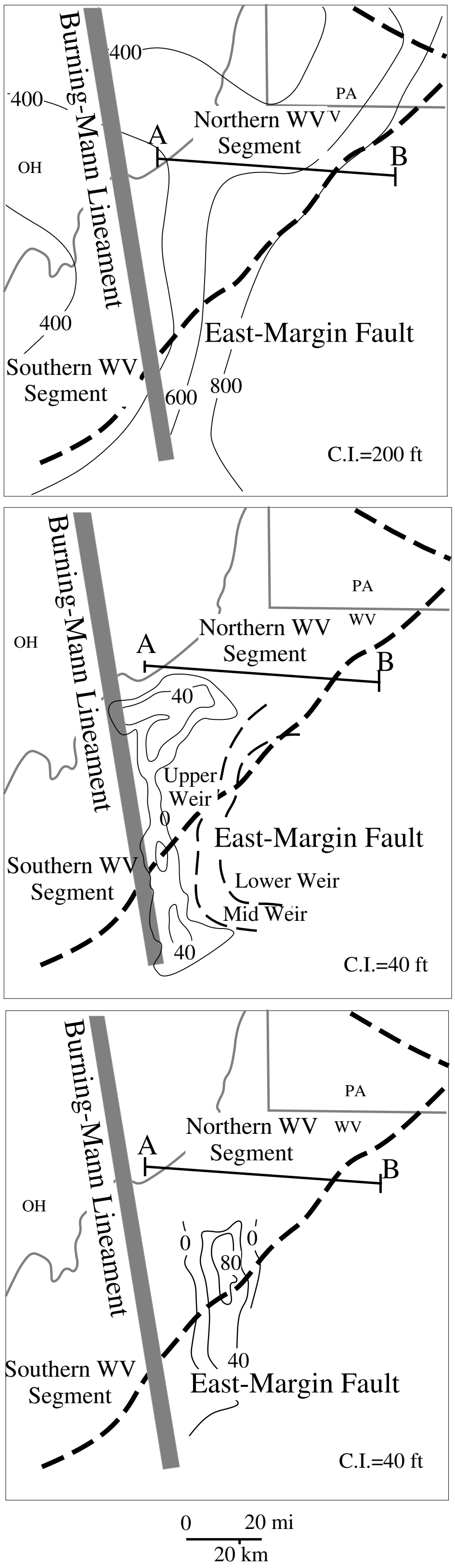

Figure 14—Selected isopach maps of the northern West Virginia segment (after Shumaker and Wilson, 1996). Note the relationship of the Burning-Mann lineament to changes in rock thickness and depositional environment. Line AB indicates a seismic line shown in Figure 15. (a) Devonian black shale (Harris et al., 1978), (b) Mississippian Big Injun sandstone and Weir sandstone subcrop (Zou and Donaldson, 1994), (c) Mississippian Weir sandstone (Zou and Donaldson, 1994).

however, substantial differential subsidence occurred along the northwestern margin of the trough during the passive-margin and foreland basin stages (Figure 15). Thus the northwestern margin in the northern West Virginia segment of the trough appears to have had a longer history of differential subsidence through the passive-margin phase than the Eastern-Margin fault. These observations imply that differential subsidence shifted from the eastern margin during the rift stage to the western margin during the passive-margin and possibly the foreland basin stages, which contrasts with the growth history of the southern West Virginia segment where the East-Margin fault continued to affect sedimentation through the passive-margin and foreland basin stages (see Figures 7, 9).

In addition to the deeply buried rift and sag basin, folds at shallow structural levels also show contrast in deformation intensity and asymmetry between the northern West Virginia and the southern West Virginia segments (compare Figures 7 and 15). In the northern West Virginia segment, asymmetry polarity of the anticlines at the Rose Hill and the Onondaga horizons is toward the northwest (Figure 15), whereas in the southern West Virginia segment, the asymmetry of an anticline at the same horizons is toward the southeast (Figure 7). These observations suggest that rift segmentation probably continued to impact shallow structures that formed during the foreland basin stage, and the three rift segments may have been overprinted to different extents by the crustal deformation during the foreland basin stage.

DISCUSSION

Accommodation Zones

Total magnetic intensity, Bouguer gravity anomaly, reflection seismic, and well data show that the eastern Kentucky, southern West Virginia, and northern West Virginia segments of the Rome trough are different in geometry and polarity of normal faulting, sedimentation, and folding. From south to north, these three rift segments are separated by the 38th parallel and Burning-Mann lineaments. A regional, comparative analysis supports

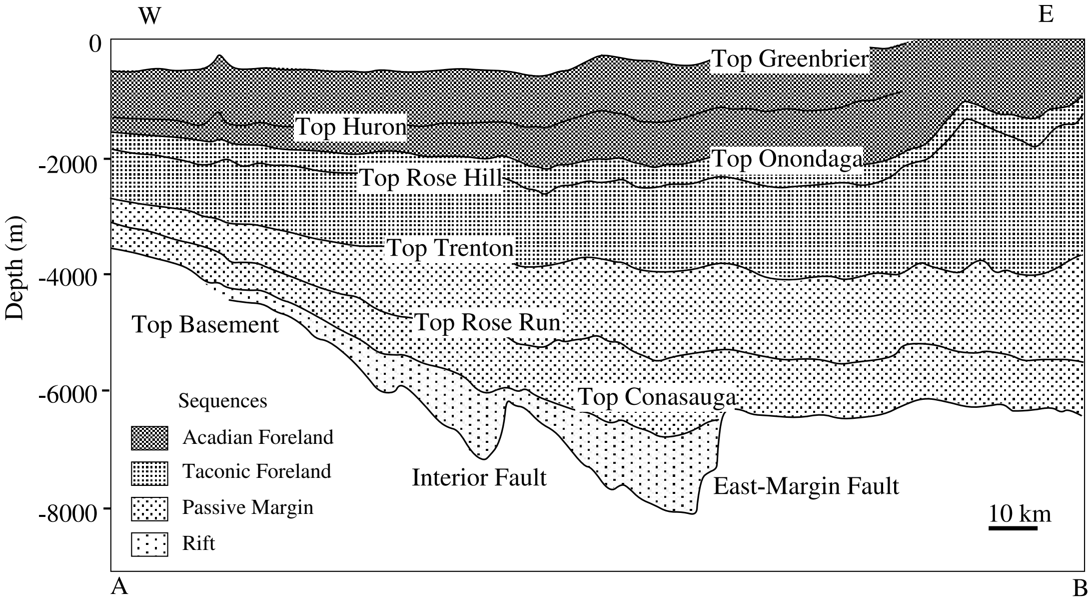

Figure 15—A depth-converted seismic line (see Figure 14 for location) across the northern West Virginia segment of the Rome trough (T. H. Wilson, 1998, personal communication). Note the East-Margin fault has little effect on postrift sedimentation after Conasauga deposition, contrasting with the East-Margin fault seen in the southern West Virginia segment (Figure 7). In contrast, the western margin of the trough experienced consistent differential subsidence throughout the early Paleozoic. Asymmetrical anticlines above the Devonian Rose Hill horizon with steeper western flanks than eastern flanks, contrast with those mapped in the southern West Virginia segment (Gao, 1994; Gao and Shumaker, 1996).

the suggestion that the two lineaments represent accommodation zones that transferred the along-axis reversal in geometry and polarity of the three segments of the Rome trough (Figures 3, 16).

The Burning-Mann lineament is a north-south-trending structure that separates the northern West Virginia segment from the southern West Virginia segment. Based on well, seismic, and magnetic intensity data, it was previously documented that this lineament had a strong effect on the subsurface geology in south-central West Virginia, and possibly represents a transfer fault system to accommodate the complex deformation in the subsurface of south-central West Virginia (Gao, 1994; Gao and Shumaker, 1996). Although direct evidence for throughgoing basement faults along the Burning-Mann lineament is equivocal, it is spatially associated with the detached Burning Springs (Rodgers, 1963) and the Mann Mountain anticlines (Perry, 1980). Total magnetic intensity maps suggest the presence of a basement fault zone underneath both the Burning Springs and the Mann Mountain anticlines. Presumably, the basement structure served in part as a locus for the formation of the overlying detached folds in the central Appalachian foreland basin. Seismic data (Shumaker, 1986b) shows a basement fault that affects Cambrian strata under the northern end of the Burning Springs anticline. Root (1996) interpreted strike-slip movement along a basement fault under the Cambridge arch, an extension of the Burning-Mann lineament in Ohio. The intensively deformed Burning Springs and the Mann Mountain anticlines in the Paleozoic cover rocks may be attributed in part to transcurrent movement of the underlying basement fault zones of the Burning-Mann lineament. The stacked changes in facies and rock thicknesses along the Burning Springs anticline, as described in this paper, and in other rock units (Shumaker and Wilson, 1996) (see Figure 14) also support the presence of active basement faults or a basement flexure under the lineament. Beaumont et al. (1988) suggested that the Burning-Mann lineament was a peripheral bulge, but the consistent position of facies and thickness changes in Phanerozoic rocks through time (Shumaker and Wilson, 1996) suggest the existence of a more fundamental change in crustal structure or thickness rather than an ephemeral bulge.

The 38th parallel lineament (Heyl, 1972), approximately following the 38th parallel of latitude for more than 800 mi (1280 km), is an east-trending zone of complex deformation and sedimentation. Along the lineament, mullions in fault

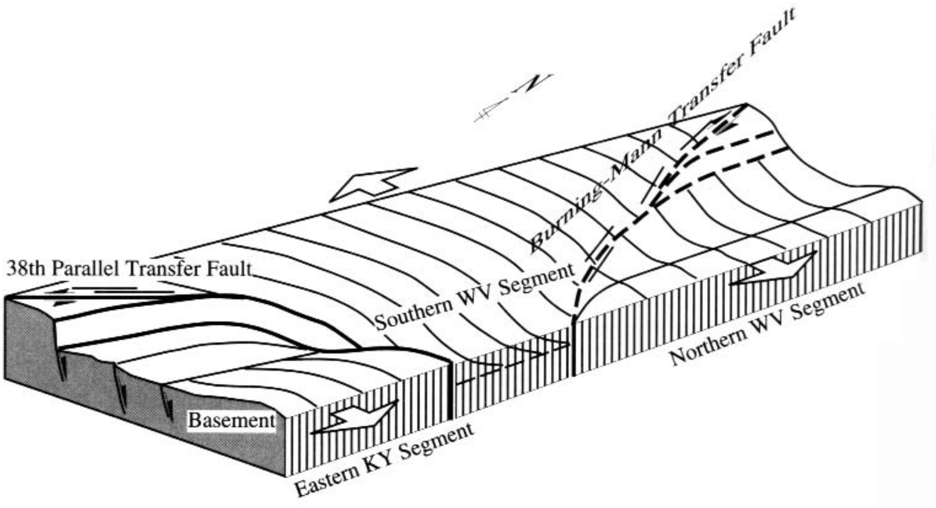

Figure 16—A conceptual model showing along-axis segmentation and variation in graben geometry and polarity of the Rome trough. Three segments, denoted as the eastern Kentucky, southern West Virginia, and northern West Virginia segments, respectively, are separated by the 38th parallel and Burning-Mann accommodation zones. Note how the differences in graben geometry and polarity of the three major segments are accommodated by the intervening accommodation zones along the axis of the Rome trough.

outcrops show that lateral displacement is a major component accompanied by scissors and dip-slip movements (Heyl, 1972). Shumaker (1993) and Shumaker and Coolen (1993) reported on the relationship of the 38th parallel lineament to the subsurface structures in West Virginia. On the basis of subsurface geologic mapping in southern West Virginia, Gao (1994) and Gao and Shumaker (1996) suggested that part of the 38th parallel lineament possibly represents another transfer fault system that was coupled with the Burning-Mann lineament to accommodate the complex deformation of the subsurface structures in south-central West Virginia. In eastern Kentucky and southern West Virginia, the lineament constitutes the boundary between the two rift segments with opposite graben polarity, which is typical of accommodation zones. Both surface and subsurface data in this limited section of the lineament indicate the presence of regional east-west–trending faults. The trend of the lineament is more complicated where it intersects the Rome trough in the border area of eastern Kentucky and West Virginia. There, a boxlike or rhom-graben (Shumaker, 1996) that is typical of an extensional, transfer zone suggests left-lateral offset between the two rift segments. Incoherent seismic reflections at the Kentucky–West Virginia border also indicate complex deformation of Cambrian sedimentary rocks within the accommodation zone. This increase in structural complexity coincides with the westward bending of the rift trend and the East-Margin fault (Gao, 1994; Gao and Shumaker, 1996) between the southern West Virginia and the eastern Kentucky segments.

Differing from other accommodation zones commonly observed along extensional systems that are orthogonal to the rift axis and parallel to each other, the east-west–trending 38th parallel and the north-south–trending Burning-Mann lineaments are both oblique to the northeast-trending rift axis of the Rome trough and converge toward the southeast. This relationship (Gao, 1994) requires that the 38th parallel and Burning-Mann accommodation zones experience transtensional rather than simple strike-slip displacement during the formation of the trough (Gao, 1994; Gao and Shumaker, 1996). The transtensional deformation is responsible for the normal displacement component, magnetic intensity gradient, structural lows (e.g., Figure 12c), and rock thickness changes (e.g., Figure 12e, f) in the vicinity of the accommodation zones. This transtensional deformation along oblique accommodation zones may be an important mechanism to accommodate the along-axis variation and segmentation of rift systems.

Growth History

The Rome trough formed as a result of the Early(?) and Middle Cambrian faulting associated with the late-stage opening of the Iapetus-Theic Ocean at the continental margin (Thomas, 1991; Shumaker, 1996; Shumaker and Wilson, 1996). A detailed study in southern West Virginia indicates that the trough has experienced a multiphased tectonic evolution and evolved during an episode of rapid extension in the early Paleozoic following the late Precambrian Grenville convergent orogeny (Shumaker, 1996; Shumaker and Wilson, 1996). The major extensional event is indicated by an abrupt change in thickness of the interval deposited before

Copper Ridge deposition (Lower and Middle Cambrian) across the southeastern margin of the trough (see Figures 7, 12e, f). A drill hole in southern West Virginia (Donaldson et al., 1975) and the recovered fossils from a cored sequence within the lower one-half of the Rome Formation indicate an age of Middle Cambrian and a possible Late Cambrian age (Donaldson et al., 1988). Based on the fossil data, Ryder et al. (1997b) considered the Rome Formation drilled in southern West Virginia to be Middle Cambrian in age, but a late Early Cambrian age for the lowermost part of the Rome Formation at that locality cannot be ruled out (Ryder et al., 1997b). They also suggested that the Rome Formation at the western margin of the Rome trough and in the adjoining area probably is entirely Middle Cambrian in age (Ryder et al., 1997b). This age is different from the ages of other grabens of the interior rift system to the southeast, such as in Alabama, Virginia, and Tennessee (see Figure 1) (W. A. Thomas, 1998, personal communication). In addition, radiometric dates at the plate margin (Bartholomew et al., 1991) from igneous rocks of the rift sequence that were deposited on Grenville basement provide an age of approximately 570 Ma, indicating that the major rift event in the Rome trough is slightly younger than the early spreading at the plate margin (Read, 1989; Shumaker, 1996), and that major extension associated with different grabens of the interior rift system was diachronous in association with different stages of the spreading at the plate margin. Thick infill of sediments with little igneous rocks within the Rome trough, indicated by data from deep well drilling in the southern West Virginia segment (Donaldson et al., 1988), suggests that the crustal extension was largely accommodated by mechanical extension and syntectonic sedimentation. This scenario contrasts with successful rifts farther east and south at the plate margin where continental crust completely broke up to form oceanic crust (Thomas, 1991). Although inconsistent stratigraphic nomenclature and ages of the Cambrian sedimentary rocks make it difficult to achieve a detailed and systematic lateral correlation on a regional basis, age differences among different grabens suggest that extension may have occurred at different times and rifting propagated in a systematic manner from spreading center toward the interior of the craton.

Following the Early(?) and Middle Cambrian rifting, a decrease in the rate of differential subsidence occurred during the time between deposition of the Cambrian Conasauga Formation and the Middle Ordovician Trenton Limestone, as indicated by analysis of arrival time differences of seismic reflections (Gao, 1994). This slow subsidence and reversal in direction of sedimentary thickening suggest that a relatively broad, shallow sag basin (Shumaker, 1986a, 1996) formed above the rift basin of the Rome trough. The mechanism for the formation of the sag basin may be attributable to the postrift thermal contraction at the passive continental margin (Shumaker, 1996; Shumaker and Wilson, 1996) and to decreased differential subsidence along the master synthetic fault and other basement faults that have been intermittently reactivated during the postrift broad subsidence.

Little differential subsidence had occurred during the Late Ordovician–Middle Devonian, but regional studies indicate a reversal and thickening of Middle Ordovician–Lower Silurian rocks into the developing Taconic foreland. Anticlines began to develop over the underlying half graben, but their geometry and intensity are different from one rift segment to the next (e.g., Figures 7, 12a, 15). We suggest that structural and depositional inversion probably could be attributed to Taconic and Acadian orogenies as the foreland developed, which, in turn, probably were associated with a major change in stress regime that emanated from the plate margin during the Middle Devonian–Pennsylvanian when the Iapetus-Theic Ocean closed during the Acadian and the Alleghanian orogenies.

Implications for Hydrocarbon Exploration

In the southern and northern West Virginia segments, and to a lesser extent in the eastern Kentucky segment, exploration has been limited largely to post-Ordovician rocks of the foreland sequence. Thus opportunity for exploration exists in the two older (rift and passive-margin) sequences. The role of accommodation zones in hydrocarbon accumulation lies in the enhanced porosity and complicated structure and stratigraphy at their intersection along the length of a composite graben. The paleotopographic complexity at accommodation zones favors the formation of stratigraphic traps due to facies and thickness changes at segment borders. Also, accommodation zones are responsible for variations in polarity of both half grabens and the overlying inversion structures. Differences in graben geometry, polarity, and magnitude of extension among the three rift segments may result in changes from one segment to the next in source rock thickness and distribution, reservoir lithofacies and thickness, fracture porosity and permeability, and geothermal gradient and thermal maturity of sediments. In addition, thickness and facies changes are common in the vicinity of the master synthetic fault along one side of a half graben. Generally, coarser grained facies, such as sand-rich fan deposits, are likely to exist in a narrow fairway and at point sources in proximity to

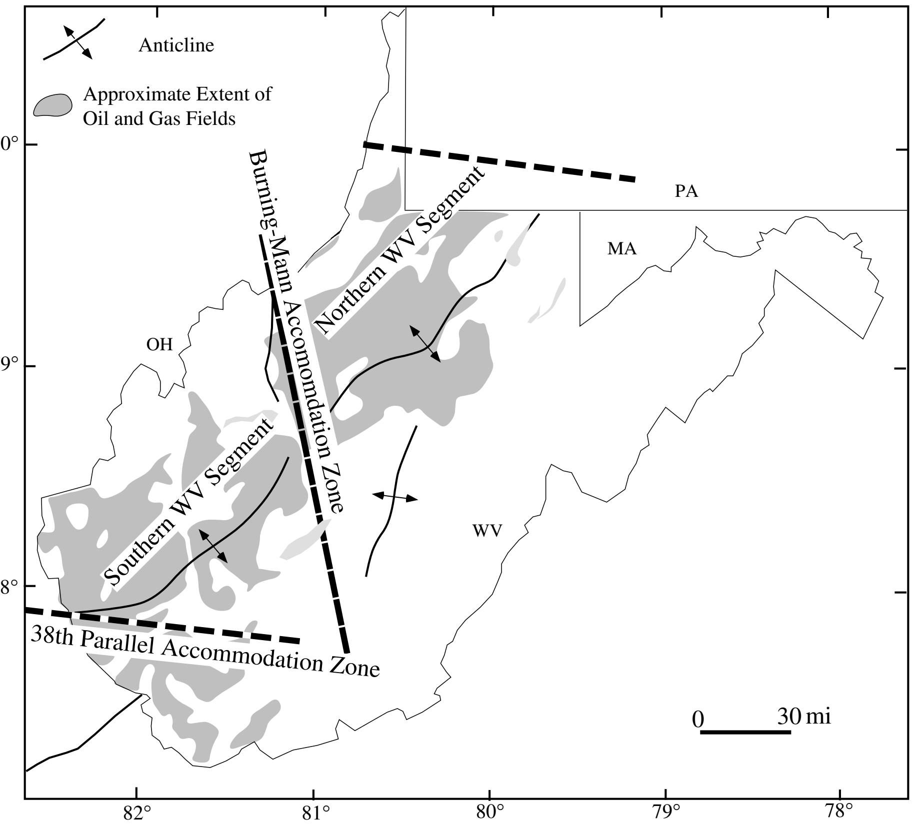

Figure 17—Areal extent of major oil and gas fields in West Virginia superimposed with the major structural elements, showing spatial relationships of hydrocarbon distribution to rift segments and accommodation zones along the Rome trough.

the master synthetic fault. Such potential reservoir facies, coupled with significant enhancement of fracture porosity and permeability, could result in significant hydrocarbon accumulation along the master synthetic fault. For example, fan-delta and basin-floor fan deposits have been documented in the vicinity of the master synthetic fault on the northwestern side of the trough in eastern Kentucky (Drahovzal, 1994; Harris and Drahovzal, 1996). Commercial gas wells that produce from a fractured interval of the Conasauga and Rome Formation also have been reported in eastern Kentucky (Harris and Drahovzal, 1996). The potential reservoir facies are near the northern bounding fault zones, and the fracturing is related to the faults along the northwestern margin of the trough in eastern Kentucky (Harris and Drahovzal, 1996). In addition, commonly associated with master synthetic faults are structural closures that can trap oil and gas at relatively shallow structural levels, such as in post-Ordovician rocks of the foreland sequence in the southern West Virginia segment of the Rome trough (Gao and Shumaker, 1996). These geometric and spatial relationships make trough margins favorable sites for the migration and accumulation of oil and gas. Polarity shifts along the Rome trough across accommodation zones probably have affected source rock thickness, reservoir lithofacies (Figure 14), and the potential distribution of oil and gas fields (Figure 17) in different segments of the Rome trough. This along-axis segmentation and associated accommodation zones may have important implications for assessing hydrocarbon potential of the deeply buried rift sequence, the intermediate passive-margin sequence, and the shallow foreland sequences along the Rome trough.

CONCLUSIONS

(1) The Rome trough can be divided into the eastern Kentucky, southern West Virginia, and northern West Virginia segments. The master synthetic faults in eastern Kentucky are located on the northwestern side of the trough. These master synthetic faults shift to the southeastern side of the trough and coalesce to a single East-Margin fault in southern West Virginia. The southern West Virginia segment is characterized by a deep, narrow rift valley, and the East-Margin fault controlled the concentrated sedimentation of the Early(?) and Middle Cambrian deposition. This East-Margin fault has been intermittently reactivated throughout the

Paleozoic. Northward in northern West Virginia, the trough is complicated by the major Interior fault, and the East-Margin fault has a different growth history than that in the southern West Virginia segment.

(2) The 38th parallel and Burning-Mann lineaments are associated with the boundaries of the three segments of the Rome trough and may represent two major accommodation zones that transfer different extensional polarity and geometry along the axis of the trough. Because of their oblique position to the trough axis, both are inferred to have experienced transtensional deformation in association with the formation of the trough during the Early(?) and Middle Cambrian.

(3) Basically, the Rome trough has experienced three major tectonic stages throughout the Paleozoic. Stage 1 was characterized by rapid extension and rifting during the Early(?) and Middle Cambrian in association with the late-stage opening of the Iapetus-Theic Ocean. Stage 2 featured a slow subsidence to form a successor sag basin from the Late Cambrian to Middle Ordovician, perhaps in association with postrift thermal contraction at the passive continental margin. Stage 3 was dominated by a major structural inversion from the Late Ordovician through the Pennsylvanian in association with the development of the Appalachian foreland basin.

(4) The along-axis segmentation of the Rome trough may have affected the along-axis variation in source rock thickness, thermal maturity, reservoir lithofacies, and trapping mechanism. Thus the segmentation model established for the trough may have important implications for hydrocarbon exploration on a regional basis.

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ABOUT THE AUTHORS

Dengliang Gao

Dengliang Gao received a B.S. degree (1983) and an M.S. degree (1986) in geology from Hefei University of Technology, People's Republic of China. From 1986 to 1991, he worked as a lecturer at Tongji University, People's Republic of China, where he won the National Science and Technology Progress award for his research project in 1991. In 1992, he went to the United States and received an M.S. degree in geology from West Virginia University (1994) and a Ph.D. in geology from Duke University (1997). After spending one year in the oil industry at Exxon Production Research Company, he joined Marathon as a geologist in 1998, focusing on three-dimensional seismic interpretation and visualization. His current interests include computer-aided structural and stratigraphic interpretation of three-dimensional seismic using attribute and visualization technologies.

Robert C. Shumaker

Robert C. Shumaker received an A.B. degree (1953) from Brown University and an M.S. degree and Ph.D. (1960) in geology from Cornell University. He worked for the Humble Oil and Refining and Exxon Companies in their research and exploration departments from 1960 to 1972. He joined the faculty in the Department of Geology and Geography at West Virginia University in 1972 where he was a professor and where he was associated chairperson of the department from 1984 to 1995. He retired in 1996 and presently is a professor emeritus at West Virginia University.

Thomas H. Wilson

Thomas H. Wilson received B.A. (1974) and M.S. (1977) degrees in physics, and a Ph.D. (1980) in geology from West Virginia University (WVU). He worked with Exxon Company USA (1981–1983) in the EDPC special seismic problems group and later in the Gulf Atlantic division seismic evaluation group. In 1983, he joined the WVU Department of Geology and Geography, where he is a professor. He teaches courses in applied geophysics and quantitative methods.