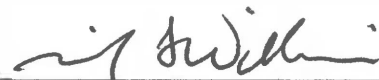


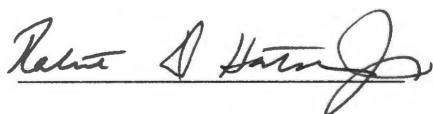
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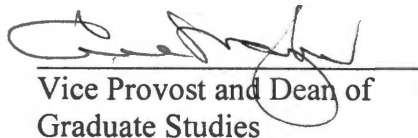


Richard T. Williams, Major Professor

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Acceptance for the Council:



Vice Provost and Dean of
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**Basement Faults in the East Tennessee Seismic Zone:
Observations From the Area of the Swan Creek Field**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Stephen A. Tavernier
May 2002

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ABSTRACT

Basement structures and their relationship to the Alleghanian thrust system in the vicinity of the New York – Alabama lineament are revealed by new seismic reflection and well data from the Swan Creek oil and gas field. A system of normal faults and monoclinial flexures, having an aggregate ~800 m of vertical offset down to the southeast, changes the depth to Precambrian crystalline basement here. Structural relationships between the basement offset and the overlying Pine Mountain and Wallen Valley thrust sheets show that the basement faults predate the Alleghanian orogeny, and possibly originated during Eocambrian rifting. A mushwad (ductile shale duplex) containing Rome and Conasauga rocks formed beneath the structurally stiff units during Alleghanian thrusting, and arched the overriding Wallen Valley thrust sheet. Decoupling of the Wallen Valley thrust near the base of the stiff Maynardville limestone allowed the duplex to form in the underlying weak Conasauga strata without internal shortening of the structurally stiff Maynardville and Knox Group. The Swan Creek anticline formed where the Knox carbonates in the Wallen Valley thrust sheet arched over the mushwad, but without the basement buttress that is an integral part of mushwad formation elsewhere in the southern Appalachians. Enhanced porosity and permeability, probably due to outer arc extension in the uppermost Knox and higher strata where they arch over the mushwad, are a major factor contributing to oil and gas production from the Swan Creek field.

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1. Seismic reflection data geometry and profiles

1. Introduction

Basement faults and the geometry of the basement surface play an important role in the geology of East Tennessee, impacting the seismicity, the development of structures in the fold and thrust belt, and oil and gas production. East Tennessee basement hosts one of the most active seismic zones in the eastern United States (Powell et al., 1994), providing direct evidence that faults exist in the basement, but years of study have thus far not led to a consensus about the kinds, locations, and orientations of basement seismogenic faults. For example, the NY–AL lineament (King and Zeitz, 1978) is a broad magnetic anomaly that may be associated with regional-scale strike-slip faults or a crustal-scale shear zone in East Tennessee (Watkins, 1964; King and Zeitz, 1978; Johnston et al., 1985; Culolotta et al., 1990; Powell et al., 1994) or as a boundary between major crustal blocks that exhibit different physical properties and styles of deformation. Basement faults are also known to occur elsewhere in the Appalachians, in Alabama (Thomas, 1985), West Virginia (Williams et al., 1999), and Pennsylvania (Shumaker et al., 1985), yet until recently basement faults were seldom depicted on cross sections for East Tennessee (e.g., Woodward and Gray, 1985; Hatcher et al., 1994). It is paradoxical that the greatest seismicity occurs where basement fault identification seems least certain.

Thomas (2001) identified a possible connection between basement faults and the development of hydrocarbon traps during the Pennsylvanian-Permian Alleghanian thrusting in the Appalachians. He found locations in northeastern Alabama where the Cambrian Rome Formation and Conasauga Group are thickened by duplexes due to a buttressing effect in the hanging wall of major basement normal faults, arching the

overlying Cambro-Ordovician Knox Group. Duplexes imbricating Conasauga Group rocks are also mapped in Tennessee (Rodgers, 1952; Smith, 1968) and are also believed to underlie the Swan Creek oil and gas field (Hatcher et al., 2001).

Seismic reflection profiles that might reveal basement faults have been recorded throughout East Tennessee for petroleum exploration, mostly in the late 1970's and early 1980's. Unfortunately, nearly all of these data remain proprietary and unavailable to the academic community, but new data from the Swan Creek oil and gas field are an exception. The Swan Creek field sits astride the NY-AL lineament in the northeast portion of the ETSZ (Figure 1) in a location that provides opportunities to study basement faults using seismic reflection profiles and well data for the purposes of determining: (1) their possible relationship to the magnetic lineament; (2) their influence on Alleghanian thrusting; and (3) their relevance to crustal block models for basement structure in East Tennessee..

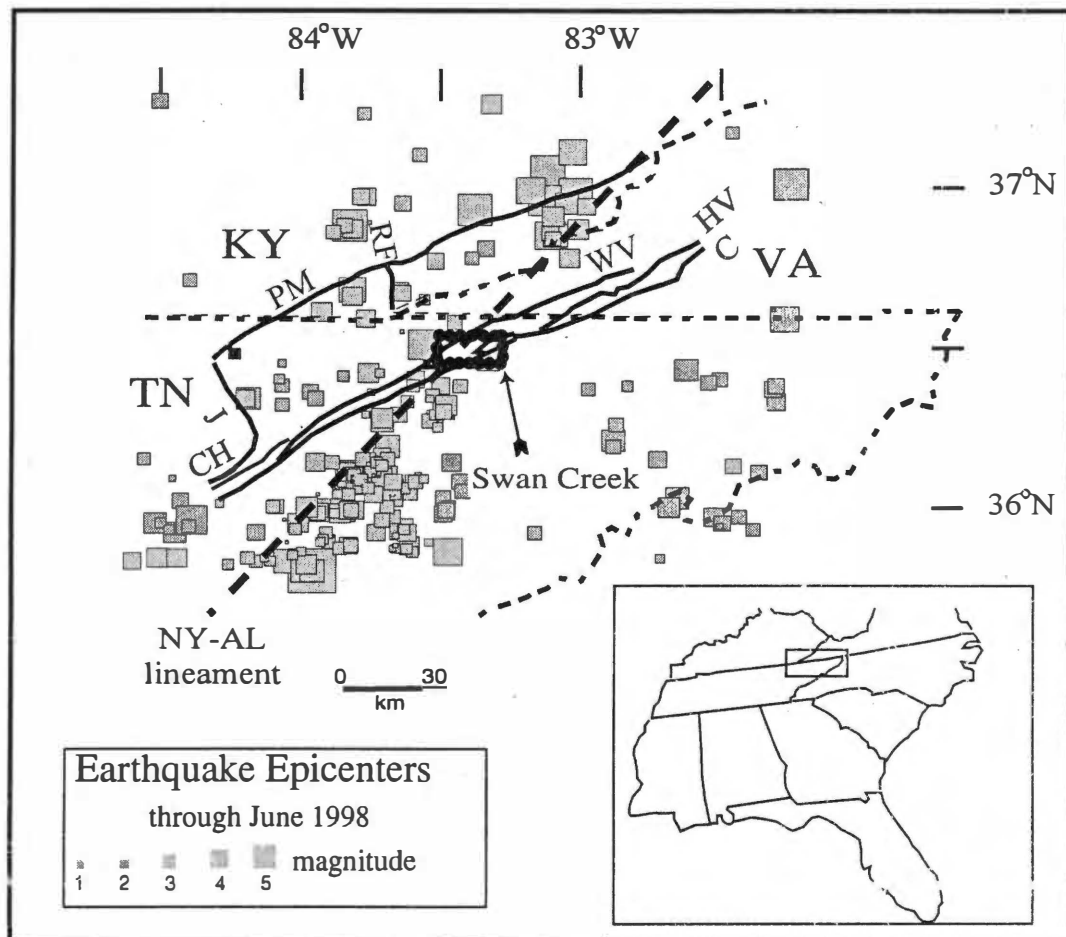


Figure 1. Location of Swan Creek (stippled box) in upper East Tennessee. Solid lines represent major thrusts in the region, except as noted: C - Clinchport; CH - Chattanooga; HV - Hunter Valley; J - Jacksboro (strike slip); PM - Pine Mountain; RF - Rocky Face (strike slip); WV - Wallen Valley.

2. The East Tennessee Seismic Zone

Earthquakes provide the most direct evidence that basement is faulted. The East Tennessee Seismic Zone (Bollinger, 1973) is a 300 km long by 50 km wide trend of seismicity, located mostly in the Appalachian Valley and Ridge province in Tennessee and northern Georgia (Powell et al., 1994). The long axis of the seismic zone parallels the southern Appalachian orogen, but the earthquakes are concentrated within the crystalline basement rocks at 5 – 25 km depth, below the regional decollement for Alleghanian orogenic structures. Relatively little is known about individual faults, or the physical properties and petrologic changes in the basement rocks where the earthquakes occur. Kaufmann and Long (1996) combined earthquake travel times and gravity data to produce a three-dimensional seismic velocity model for basement in the ETSZ. They found a velocity low associated with the greatest seismicity in the central portion of the seismic zone but were unable to connect the seismicity to individual faults or crustal blocks, preferring instead a broad zone of weakness in the crust, possibly related to increased fluid content (Long and Zelt, 1991). In contrast, Chapman et al. (1997) found evidence for a conjugate system of strike-slip faults in basement with dominant trends of N95°E and N50°E, which is parallel to the NY – AL lineament. Most recently, Vlahovic et al. (1998) produced a velocity model that shows alternating bands of high and low P- and S-wave velocities trending NE-SW. The bands have nearly vertical boundaries parallel to the trend of the seismic zone, which may be ancient faults that juxtapose rocks of different compositions.

3. NY-AL Lineament

The New York -Alabama lineament, first identified by King and Zeitz (1978), is an enigmatic feature, nearly 1,300 km long, extending the length of the Appalachian basin from southwestern Alabama to near Albany, NY. Between East Tennessee and New York, it is defined by a series local magnetic anomalies that have similar characteristics across the region (Culolotta et al., 1990). Presumably, the magnetic anomalies indicate changes in basement lithologies, as the Paleozoic sedimentary rocks of the Appalachian basin are magnetically transparent, and reasonable changes in the depths to crystalline basement rocks do not account for the observed anomalies (Watkins, 1964). Almost no samples of the relevant basement rocks are available, however, to confirm this interpretation. Regions of high magnetic values are truncated by the lineament with no sign of continuation to the other side, as would be expected if one side were down-dropped. Also, the areas of high magnetic values are not always found on the same side of the lineament, yet all are cut off sharply. These observations led King and Zeitz (1978) to conclude that the source of the anomaly may be a crustal scale, left-lateral strike-slip fault. Johnston et al. (1985) said the magnetic anomaly is the expression of a major boundary in basement, with more frequent earthquakes in the Ocoee crustal block southeast of the lineament. Powell et al. (1994) believed that seismicity is greater in the Ocoee block due to the presence of numerous, relatively small, preexisting faults, which may eventually evolve into a larger through-going strike-slip fault near the position of the NY-AL lineament. Kaufmann and Long (1996) expressed reservations about extending the NY-AL lineament as a linear feature through the ETSZ, because the lineament does

not obviously trace the same crustal feature or changes rock properties across the entire seismic zone. Culolotta et al. (1990) re-examined the magnetic nature of the eastern U.S. mid-continent (Committee for the Magnetic Anomaly Map of North America, 1987) and concluded that the magnetic anomaly might delineate a crustal-scale shear zone of considerable lateral extent within the Grenville province.

4. Basement Faults and Mushwads

Thomas (2001) coined the term “mushwad” to describe an internally deformed shale duplex produced in northeastern Alabama by Alleghanian thrusting where basement normal faults, downthrown toward the hinterland, behaved as buttresses to the motion of weak layers in the Conasauga Group. In a mushwad, disharmonic folding and faulting of the limestone beds, combined with ductile flow of the shale beds, tectonically thickens the Conasauga Group. The thickened Conasauga uplifts and distorts the layering at higher stratigraphic levels. According to Thomas (2001), the along-strike termination of mushwads can be gradual, marked by plunge of an anticline in the overlying Knox Group, or abrupt, if a transverse fault propagates through the roof.

Thomas believes that mushwads may be common in other parts of the Appalachian fold and thrust belt, including East Tennessee where the geologic setting is comparable to northeastern Alabama. The lithostratigraphies of the two regions exhibit a similar succession of carbonate shelf strata. The structurally stiff Knox Group, composed primarily of dolomite with subordinate amounts of limestone, overlies the weaker Conasauga Group in both regions (Woodward et al., 1988). While the lithostratigraphy is similar in both, the proportions of the units in the thrust sheets differ. The thickness of the Conasauga Group rocks is relatively greater in the thrust sheets of East Tennessee than in northeastern Alabama. Also, the thrust sheets in Tennessee commonly include nearly complete successions of Conasauga Group rocks attached to Knox Group rocks, with the decollement in the Rome Formation (Woodward and Gray, 1985). These

factors will affect the development of mushwads, which require the Knox to detach from the Conasauga during thrusting.

The basement structure also differs between the two regions. The basement surface in Alabama is offset by normal faults that have up to 3 km of vertical offset (Thomas, 1985). Basement faults with comparable offsets have not been identified in East Tennessee, although a map by Hatcher et al. (1998), based on widely spaced seismic reflection profiles, shows faults with smaller offsets (~500 m). The absence of large normal faults offsetting basement may alter the development of mushwads in East Tennessee.

5. Data and Analysis

Amoco acquired numerous seismic reflection profiles in East Tennessee during the late 1970's and early 1980's, including 5PM13, 5PM62, 5PM72, and 5PM74 in the Swan Creek area. They drilled a discovery gas well, the Paul Reed #1 in 1981, but did not subsequently develop the field (Hatcher et al., 2001). The Amoco seismic data remain proprietary and unpublished, but still contribute to knowledge about the structure of the field, including basement structure. Tengasco, a publicly traded company that conducts oil and gas exploration in Tennessee and Kansas, resumed development of the Swan Creek field in the 1990's. They recorded a number of new seismic profiles near the field, including TGC04, TGC06, TGC07, TGC08, TGC14, TGC15, and TGC16, from fall, 1999, to spring, 2001, and drilled additional wells. The new seismic data were obtained using vibroseis sources, 20-80 hz sweeps, 10 hz geophones, and either 35 or 70 m group intervals, similar to the acquisition parameters used earlier in East Tennessee by Amoco and other companies. The Tengasco seismic data and well descriptions were made available for this project, and the new seismic data were reprocessed using standard CDP stacking (Yilmaz, 1987) with dip move out (DMO), using ProMAXTM software.

5.1 The Rome-Basement Reflector

The Rome Formation at Swan Creek (Mixon and Harris, 1971) lies unconformably on crystalline basement, and is composed of relatively low velocity shale interbedded with acoustically fast dolomite and sandstone. The variations in acoustic

impedances within the Rome Formation give rise to a package of reflections 4-5 cycles long at 1.6-1.8 s, two-way time (Figure 2). Crystalline basement lacks internal reflections and the presumed top of basement reflection cannot be resolved from the package of Rome reflections, but it is interpreted to occur at the base of the package. The Rome Formation is relatively thin (~150 m) and contains the basal detachment for the fold-thrust belt (Harris, 1976). It may therefore contain numerous low-angle or subhorizontal Alleghanian thrust faults. Here, high-angle to subvertical displacement observed in the Rome are interpreted to be the result of offset in the uppermost portion of basement.

5.2 Knox-Conasauga Reflector

The top of the Knox Group is an unconformity that does not produce consistent reflections on seismic sections, and compositional changes within the uppermost portion of the Knox Group may give rise to additional reflections at some locations. Here, a more consistent reflection is used at the boundary between the base of the Knox Group and the top of the Conasauga Group (Figure 2). The basal member of the Knox Group is the Copper Ridge Dolomite, which is ~280 m thick. The top of the Conasauga includes dolomites and limestones of the Maynardville Formation, which is relatively thin (~70 m) and underlain by the thicker (~250 m) Nolichucky Shale (Harris and Mixon 1970). The presence of the Maynardville between the seismically transparent Copper Ridge and Nolichucky produces a package of reflections 4-5-cycles long, the top of which can be used to interpret the location of the Knox-Conasauga boundary.

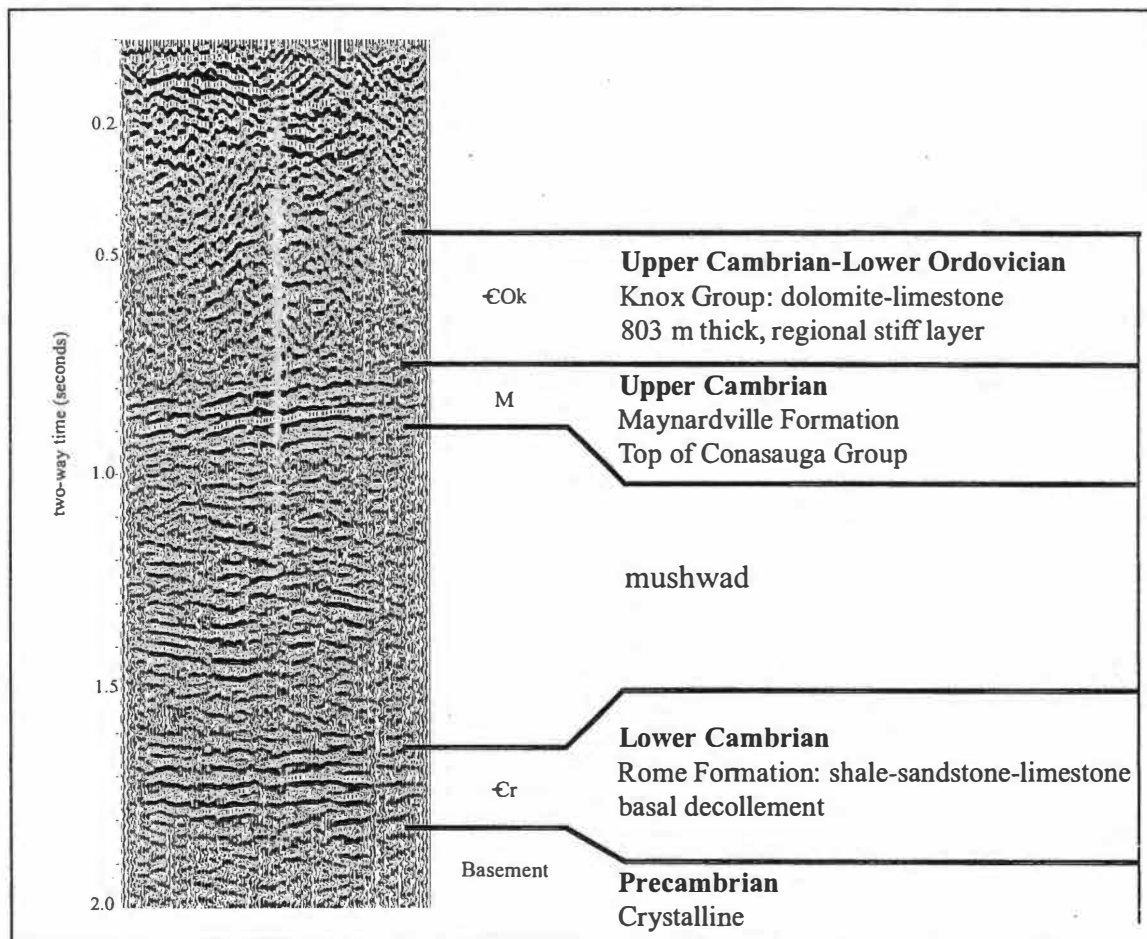


Figure 2. Marker reflections typical of the seismic reflection profiles used to construct cross sections and contour maps.

5.3 Well Data

The Knox-Conasauga reflection travel times were supplemented with estimated depths from 37 wells drilled into the Upper Knox Group, mostly located in a limited area near the center of the Swan Creek field, while the seismic profiles cover a larger area predominantly to the north and west. First, a total depth (D) to the base of the Knox Group was estimated for each well using the depth to the top of the Knox from Tengasco well reports plus an assumed and uniform thickness of 803 m for the Knox Group within the Swan Creek area. The Knox thickness is consistent with data from the Paul Reed #1 well, which penetrated the entire Knox Group, and with outcrop thicknesses reported on nearby geologic quadrangle maps (Harris and Mixon, 1970; Mixon and Harris, 1971). Second, the depth (D) was converted to seismic two-way travel time (t) according to the equation $t=2D/V$, where V represents the average P-wave velocity for the rocks between the surface and the base of the Knox Group. The equation was calibrated by using data from four wells that coincidentally lay on a seismic profile to determine the best average velocity (V). In this case, the depth (D) is estimated from the well log, the travel time (t) is known from the seismic profile, and the equation is solved for the velocity (V). The best average velocity was found to be 5600 m/s. The uncertainty in the procedure can be evaluated from the disagreement between the observed seismic travel times, and the times estimated from the depths for the four calibration wells. The disagreement for these four wells ranged from 2 ms to a maximum of 15 ms.

5.4 Contour Maps

The seismic travel time data were contoured to produce maps for the Rome-basement reflector (Figure 3) and the Knox-Conasauga reflector (Figure 4). The MapIt! contouring algorithm in SeisWorks 2D software from Landmark Graphics was used to produce initial, machine-contoured maps, which were smoothed by hand to remove obvious computer-generated artifacts. MapIt! provides options for contouring with or without faults. In all cases, the Swan Creek data were contoured without faults, except where a fault was clearly visible as it crossed one or more of the seismic reflection profiles.

5.4.1 Rome-Basement Map

The Rome-basement map (Figure 3) reveals a complex undulating surface at a reflection time of ~ 1.7 s over much of the Swan Creek area, with local highs and lows that amount to ~ 20 - 30 ms (~ 50 - 100 m). The most striking feature is an offset where basement rises in several southeast to northwest steps from ~ 1.72 s in the middle of the Swan Creek area to ~ 1.56 s beneath the strike line TGC16 (Figure 5), amounting to a depth change of ~ 450 m over a horizontal distance of ~ 2000 m. The nature of the depth change cannot be resolved in the Rome-basement reflections. We favor several small normal faults stepping down to the SE, but southeast-facing monoclinial basement flexures could instead be present. The steeper limbs of these folds would dip ~ 12 degrees to the SE. Basement rises more abruptly to the northwest of TGC16, near the end of

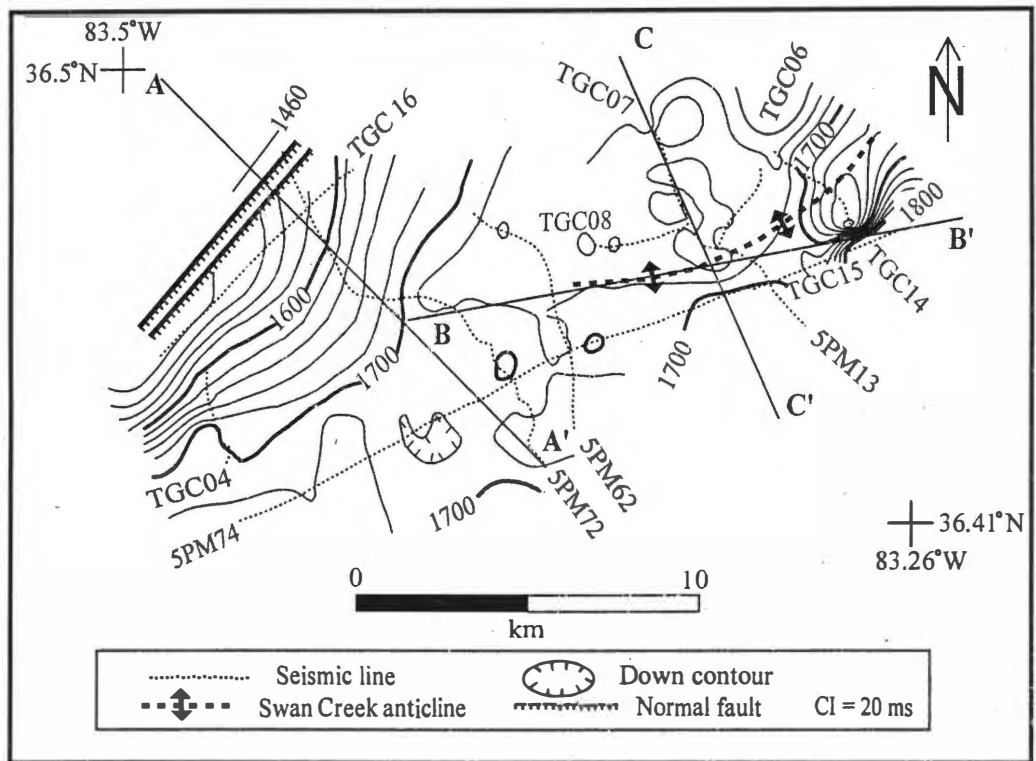


Figure 3. Contour map of the Rome-basement reflector. A-A' is the location of the cross section in Figure 6. B-B' is the location of the cross section in Figure 8. C-C' is the location of the cross section in Figure 7.

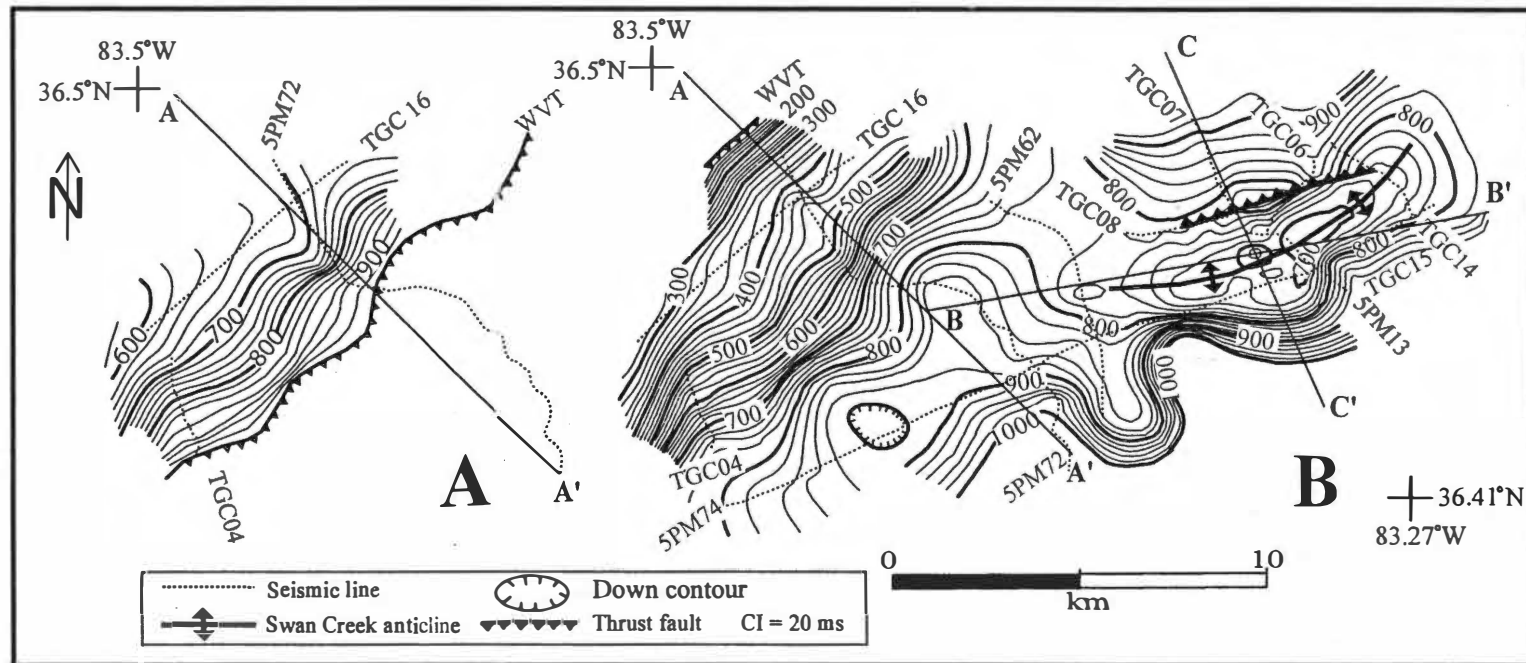


Figure 4. Contour map of the Knox-Conasauga reflector. 0 ms corresponds to a datum elevation of 350 m above sea level. A: Contours of the reflector in the Pine Mountain thrust sheet. B: Contours of the reflector in the Wallen Valley thrust sheet. Contours in B are positioned directly above contours in A. A-A' is the cross section in Figure 6. B-B' is the cross section in Figure 8. C-C' is the cross section in Figure 7. WVT - Wallen Valley Thrust. Wells in the Swan Creek oil and gas field used in addition to seismic profiles are shown on Figure 9.

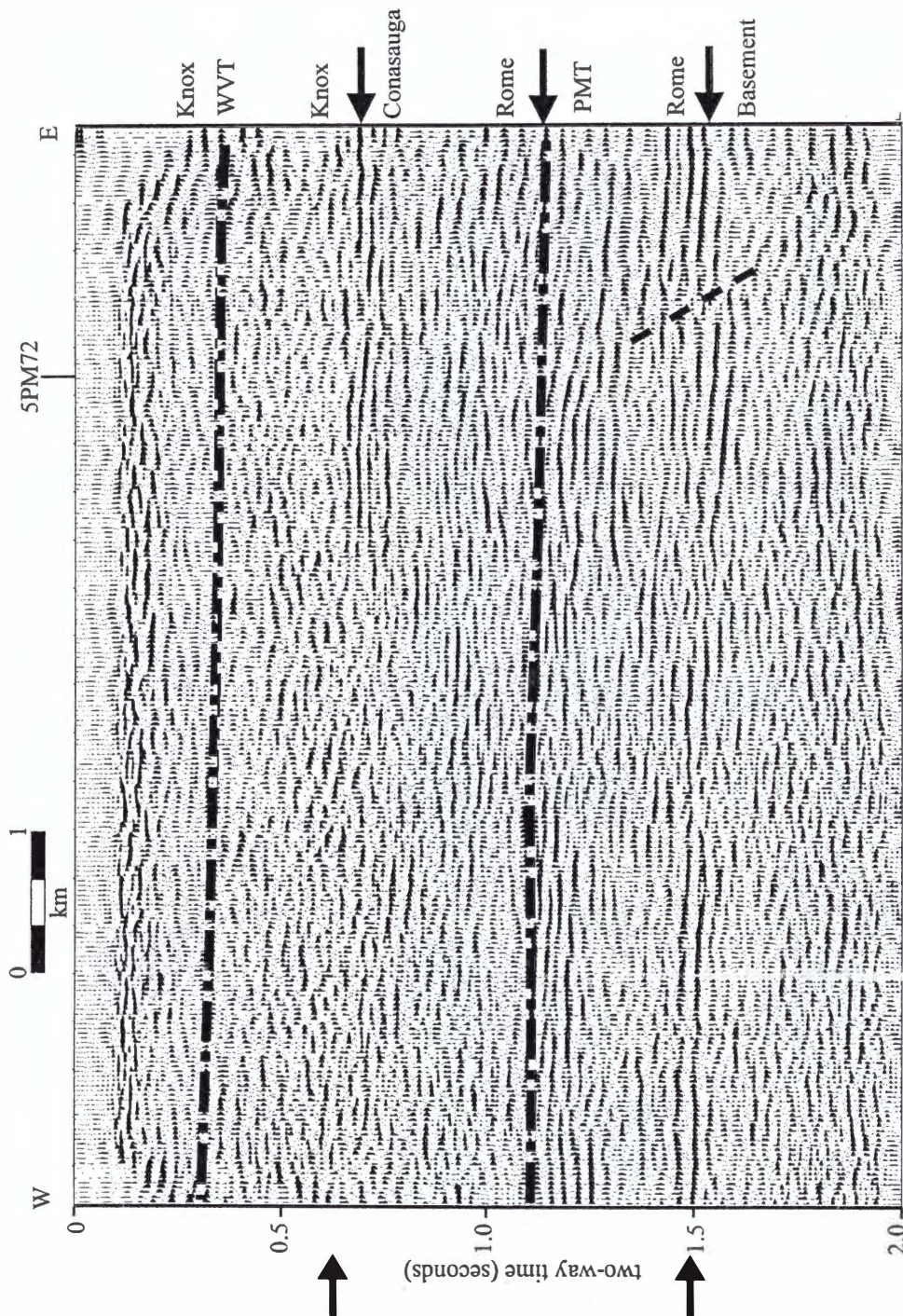


Figure 5. Seismic profile TGC16. Strike line. Rome-basement reflector in this profile (~1.5) is higher up in the section than in the profiles to the southeast. PMT - Pine Mountain thrust. WVT - Wallen Valley thrust.

5PM72, to the depths reported by Mitra (1988) for basement beneath the Powell Valley anticline. This change is depicted schematically by two parallel normal faults on the map (Figure 3), but the actual faults are not resolved in the existing seismic profiles, except that the change is abrupt. It could occur across a single fault rather than two. Overall, basement is ~800 m deeper beneath the Swan Creek area than the Pine Mountain footwall ramp (Figure 6).

In the southeastern corner of the Swan Creek area, closely spaced contours (Figure 3), stepping down to the south or east by ~100 ms (~300 m) are interpreted to be a manifestation of additional basement faults. Since no seismic lines cross this large change in slope, the exact position of the faults is not shown in the map. The control for this portion of the contour map derives from the basement reflections that can be seen in the southern or eastern ends of seismic profiles 5PM13, TGC14, and TGC15. The trajectory of this fault cannot be identified from the available data, except that it does not appear to cross 5PM13 southeast of Swan Creek, nor does it enter the area beneath the Swan Creek anticline.

5.4.2 Knox-Conasauga Maps

The Knox-Conasauga data were contoured separately for the Wallen Valley thrust sheet and the Pine Mountain thrust sheet (Figure 4). Contours of the reflector in the Pine Mountain thrust sheet were smooth and only the Wallen Valley thrust fault was included in the calculations. Likewise, the reflector in the Wallen Valley thrust sheet was contoured smoothly and the Wallen Valley thrust fault was included where it crops out.

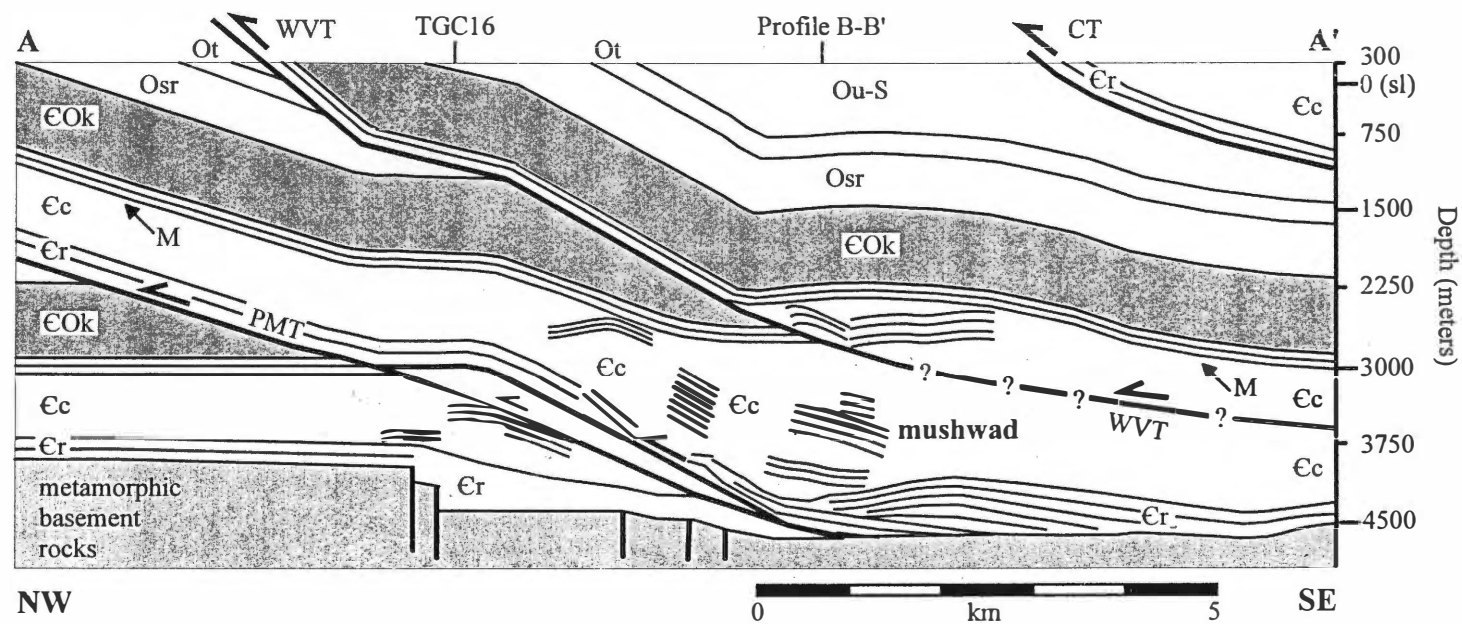


Figure 6. Relationships between basement faults and deformation in and beneath the Pine Mountain and Wallen Valley thrust sheets, in the area of the NY-AL lineament. Trajectory of the Wallen Valley thrust through the mushwad cannot be determined. Discontinuous lines within the mushwad represent reflector packages identified from proprietary seismic data. Cr - Cambrian Rome Formation. Ec - Cambrian Conasauga Group. EOK - Cambro-Ordovician Knox Group. Osr - Ordovician Stones River. Ot - Ordovician Trenton. Ou-S - Upper Ordovician to Silurian. M - Maynardville Formation (Conasauga Group). PMT - Pine Mountain thrust. WVT - Wallen Valley thrust. CT - Clinchport thrust. Mushwad - ductile duplex (Thomas, 2001).

Contours of the reflector in the Wallen Valley thrust sheet show the geometry of the Swan Creek anticline (Figure 4). The contours reveal a tightly folded and complex structure. The northwest and southeast limbs of the anticline dip steeply away from the crest of the structure. The crest of the anticline is a narrow, slightly bowed ridge. The anticline gently plunges out to the northeast and west-southwest, showing a gradual loss in structural relief.

6. Results and Discussion

6.1 Basement Offset at the NY–AL Lineament

The location of the basement faults depicted in the cross section (Figure 6) coincides with the NY-AL lineament. The magnetic anomaly is thought to be a consequence of the basement rocks having significantly greater magnetic susceptibilities to the northwest of the lineament, because the observed changes in depths to the top of basement due to the faults would not account for the observed magnetic gradient (Watkins, 1964). Thus, the faults in the cross section occur on the boundary between different crustal blocks, with the block to the southeast being the Ocoee block of Johnston et al. (1985).

The presence of basement normal faults along the NY-AL lineament at Swan Creek is different from the results obtained in the center of the ETSZ, where Hopkins (1995) reprocessed a number of seismic profiles to produce sections that cross the seismic zone and the lineament. Her sections revealed a west-dipping zone of higher reflectivity in the crust, which intersects the top of crystalline basement at the NY-AL lineament, but she did not find that the top of basement was offset. Culolotta et al. (1990) had previously reported a similar west-dipping zone of higher reflectivity in the COCORP seismic section TN4. The up-dip projection of their west-dipping zone is approximately coincident with the lineament beyond the southeastern end of TN4. It is not clear whether that the west-dipping zones observed by Culolotta et al. (1990) and Hopkins (1995) are faults, or whether they are related to the magnetic anomalies that

define the NY-AL lineament in East Tennessee. Yet Hopkins' (1995) section shows that the lineament is not always associated with faults that offset the basement surface.

The basement geometry in Figure 6 is consistent with the basement faults believed by Wheeler and Bollinger (1984) to be responsible for earthquakes in the Giles County, Virginia, seismic zone, where faults formed during Eocambrian rifting are thought to have been reactivated. The absence of continuation of these faults through the overlying Alleghanian duplex argues against crustal block models (e.g., Powell et al., 1994) that associate the NY-AL lineament with strike slip motion in the ETSZ. If the basement faults have not accumulated sufficient displacement to have propagated into the overlying rocks since the Alleghanian orogeny, they are unlikely to fail in a large earthquake in the near future.

6.2 Swan Creek Mushwad

The thickening of Conasauga Group strata at Swan Creek, and arching of the stiff Knox Group, is similar to the description of northeastern Alabama mushwads, but the size of the Swan Creek mushwad is small in comparison, and there are fewer observable faults in the overarching roof. Thomas (2001) emphasized the role of basement faults that impeded the forward movement of the weak (Conasauga Group) strata during Alleghanian thrusting. In contrast, basement beneath Swan Creek is relatively smooth. A cross section through the center of the mushwad, perpendicular to strike, is shown in Figure 7, which includes the central portion of the Swan Creek oil and gas field. The basement offsets present to the northwest of Swan Creek (Figure 3) are too distant to have played the role of the stress concentrator in Thomas' (2001) description of mushwad

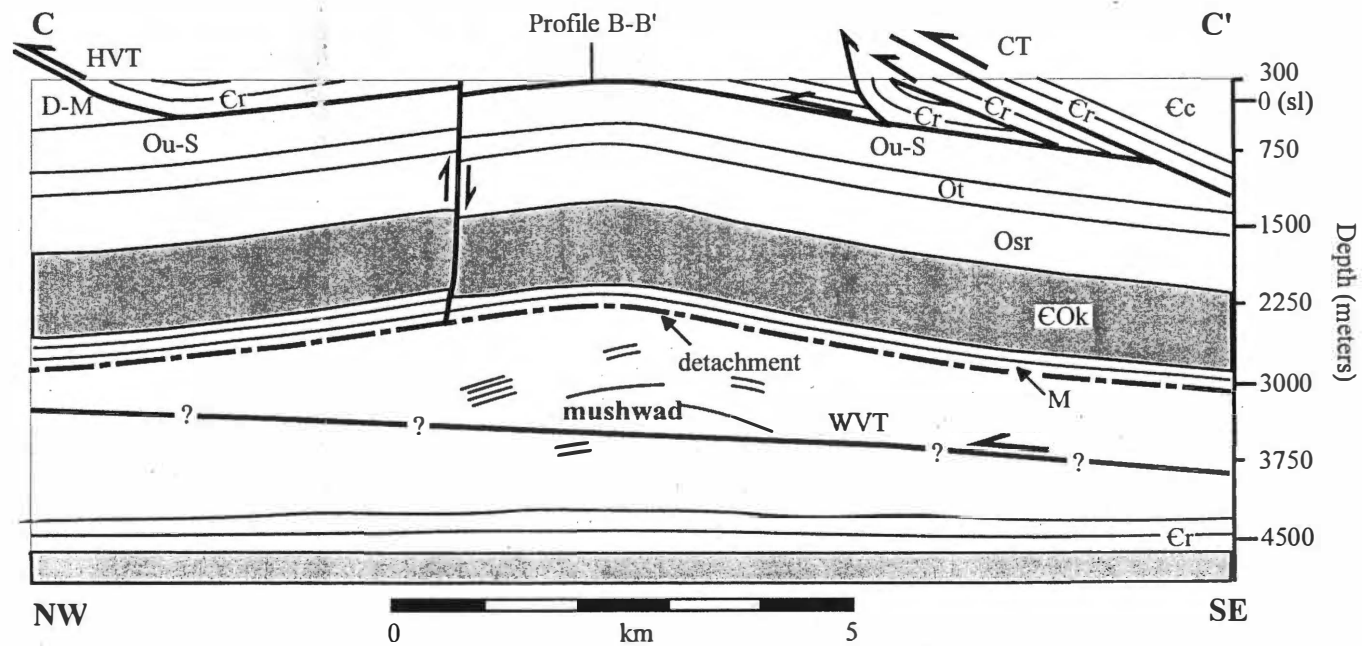


Figure 7. Cross-section of the Swan Creek anticline, perpendicular to strike. The mushwad reaches its maximum thickness beneath the crest. The trajectory of the Wallen Valley thrust (WVT) through the mushwad cannot be determined. D-M - Devonian to Mississippian. HVT - Hunter Valley thrust. All other symbols are the same as in Figure 7.

development. The southwestern end of the Swan Creek mushwad, shown in Figure 6, is nearest the basement offset, but remains ~5 km to the southeast of it, still too distant. The mushwad terminates gradually, as illustrated in the cross section parallel to strike (Figure 8). A relatively small (~300 m) basement offset, down to the east or south (Figure 3), is present in the cross section, but is not in position to have presented a buttress to thrusting during the formation of the mushwad.

The Wallen Valley thrust fault has a long, flat detachment at the base of the stiff Maynardville Limestone in the Swan Creek area (Figure 6), which is atypical for thrust faults in the southern Appalachian Valley and Ridge of Tennessee (Woodward and Gray, 1985). This detachment allowed the underlying weaker Conasauga strata to experience layer-parallel shortening, while the overlying stiff Maynardville-Knox Group was not internally shortened. Such an interpretation is consistent with the observation that where such a detachment is absent and the Conasauga Group is coupled to the Knox Group the thickness of the Conasauga only changes as a function of lithostratigraphic (Rankey et al., 1994) and not structural variations.

One possible internal geometry for this layer-parallel shortening is suggested by a duplex mapped in the Conasauga Group by Smith (1968, Plate 1) in the hanging wall of the Saltville thrust. This duplex has 150-300 m ramp spacing and horses extend laterally for 2 km or less; and steep bedding dips of 40-60° within horses. This geometry limits the structural details resolvable in a seismic profile because of the steeply dipping strata. On the other hand, this map scale geometry may not be applicable to layer-parallel shortening of these Conasauga sections in Figures 6, 7 and 8. Instead, as discussed by Thomas (2001) for mushwad formation, the thickening may be achieved by outcrop-scale and smaller structures that would not be resolvable from seismic reflection data sets. In either case, the thickened Conasauga section in the different profiles are structural features related to Alleghanian thrusting that produce anticlinal closure in the overlying younger Knox Group, such as the Swan Creek anticline.

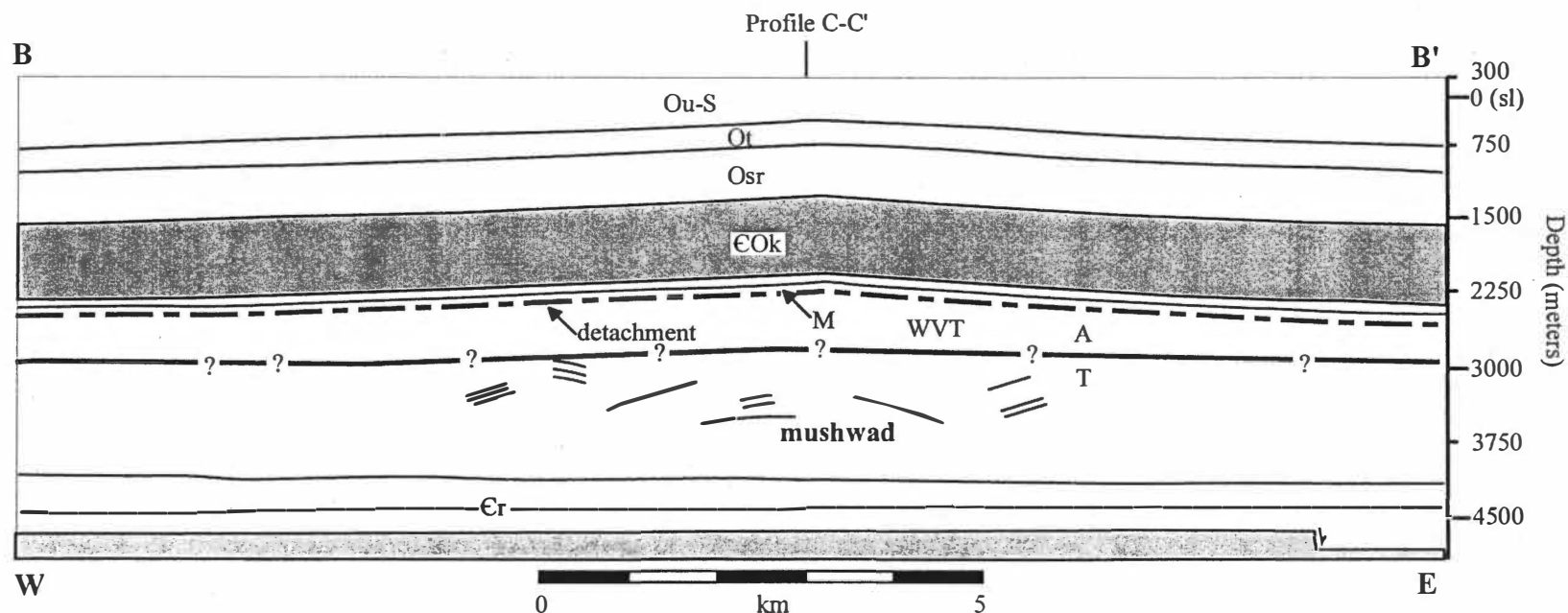


Figure 8. Cross section of the Swan Creek mushwad, parallel to strike. The Hunter Valley thrust (not shown) is thin, but present over most of the cross section at an elevation above 300 m. The trajectory of the Wallen Valley thrust through the mushwad cannot be resolved. The oil and gas production occurs above the thickest portion of the mushwad, which loses amplitude gradually along-strike. Symbols are the same as in Figure 7. T-toward, A-away.

6.3 Faults and Fractures in the Swan Creek Anticline

Thomas (2001) concluded mushwads have significant potential for oil and gas production, because a structural trap may form where the higher stratigraphy arches over the thickened Conasauga, and because of the probable greater number of fractures in the domed stiff layer. This interpretation appears to be applicable to Swan Creek oil and gas field. Gas production in the Swan Creek field is mainly associated with fracture-enhanced porosity in Ordovician rocks near the top of the Knox Group. The gas reservoir, indicated by the distribution of wells in Figure 9, is closely associated with the highest portion of the mushwad in Figures 7 and 8. Evidently, outer-arc extensional fractures in the upper portion of the Knox Group make an important contribution to the reservoir porosity and permeability. Oil is produced at higher stratigraphic levels in the Swan Creek field, above the Knox unconformity, and is also believed to be associated with fracture-enhanced porosity and permeability (Clendening and McCown, 1999; Hatcher et al. 2001).

6.3.1 Backthrust

A minor fault was found in the northwestern limb of the Swan Creek anticline (Figures 4 and 7). The fault cuts the Knox-Conasauga reflector in TGC14 (Figure 10), dipping steeply to the northwest. The sense of displacement is down to the southeast. Faults with the same sense of displacement in the Knox-Conasauga reflector can also be

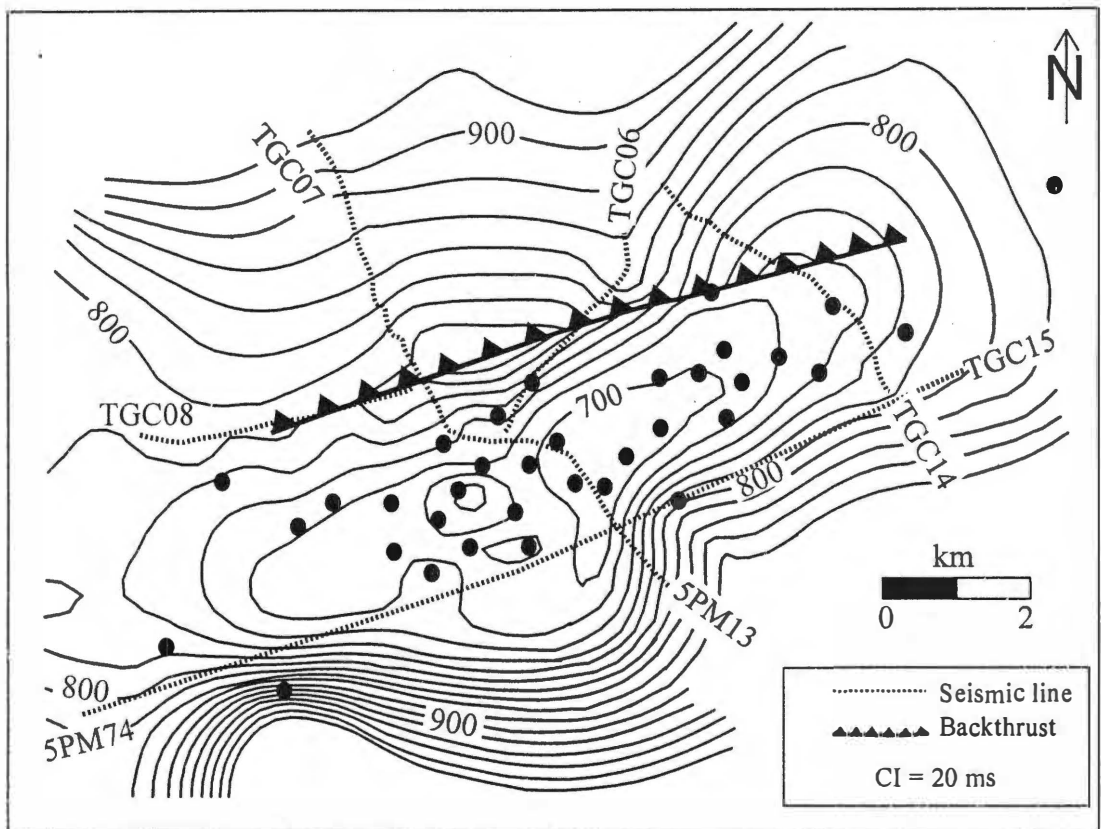


Figure 9. Details of the Knox-Conasauga reflection from the Swan Creek oil and gas field (Figure 4). Northwest limb contains a northwest-dipping backthrust, striking $N71^{\circ}E$. Black circles represent wells used to supplement the seismic data for the Knox-Conasauga reflector.

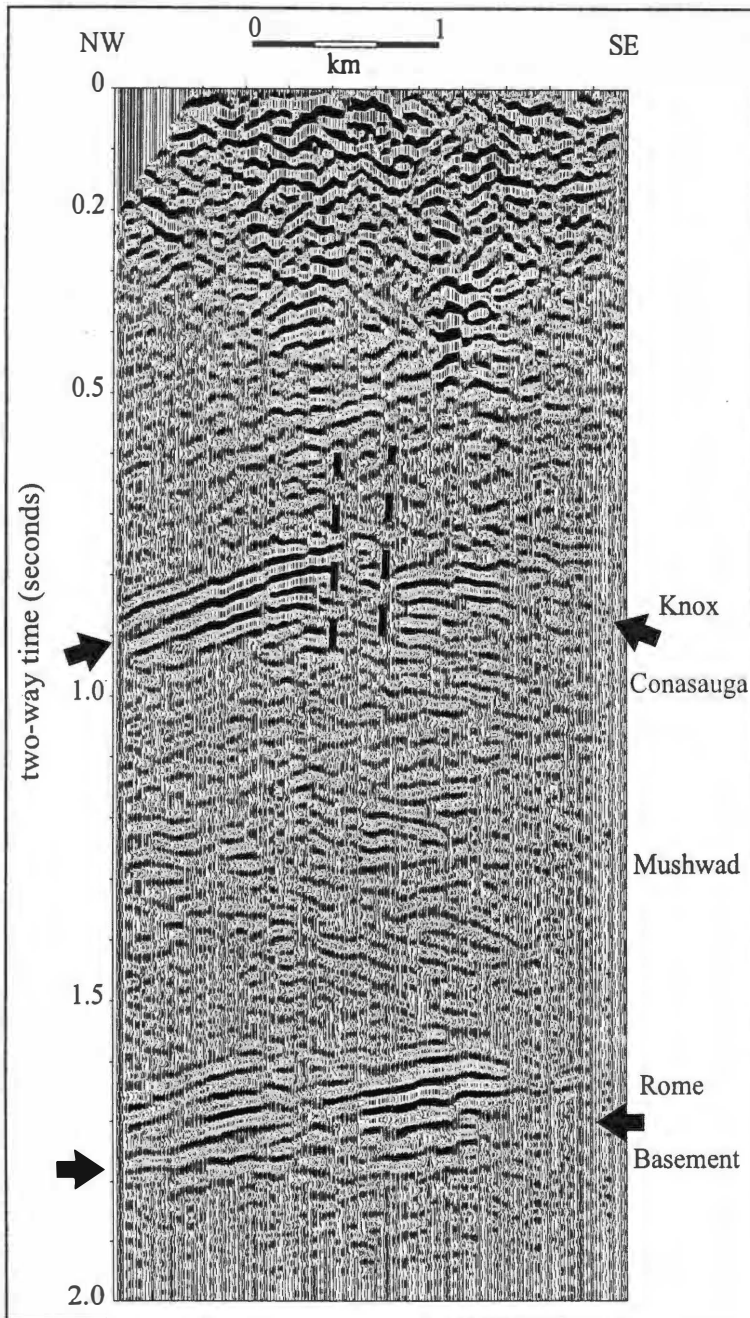


Figure 10. Seismic profile TGC14. Minor backthrust displaces the Knox-Conasauga reflector.

seen in seismic profiles 5PM13, TGC06 (Figure 11), TGC07, and TGC08. All of these lie on a straight line trending N71°E, and are depicted as a single fault in Figure 9. The downward continuation for the fault in the seismic profiles is lost in the Nolichucky Shale (Conasauga Group). Similarly, the fault cannot be seen at higher levels above the Knox Group in the seismic data. Although Mixon and Harris (1971) mapped a possible backthrust in a small window through the overarching Hunter Valley thrust sheet. The mapped fault has nearly the same location and orientation as the fault identified in the seismic profiles, but it is not possible to connect the two in the seismic profile (Figure 10).

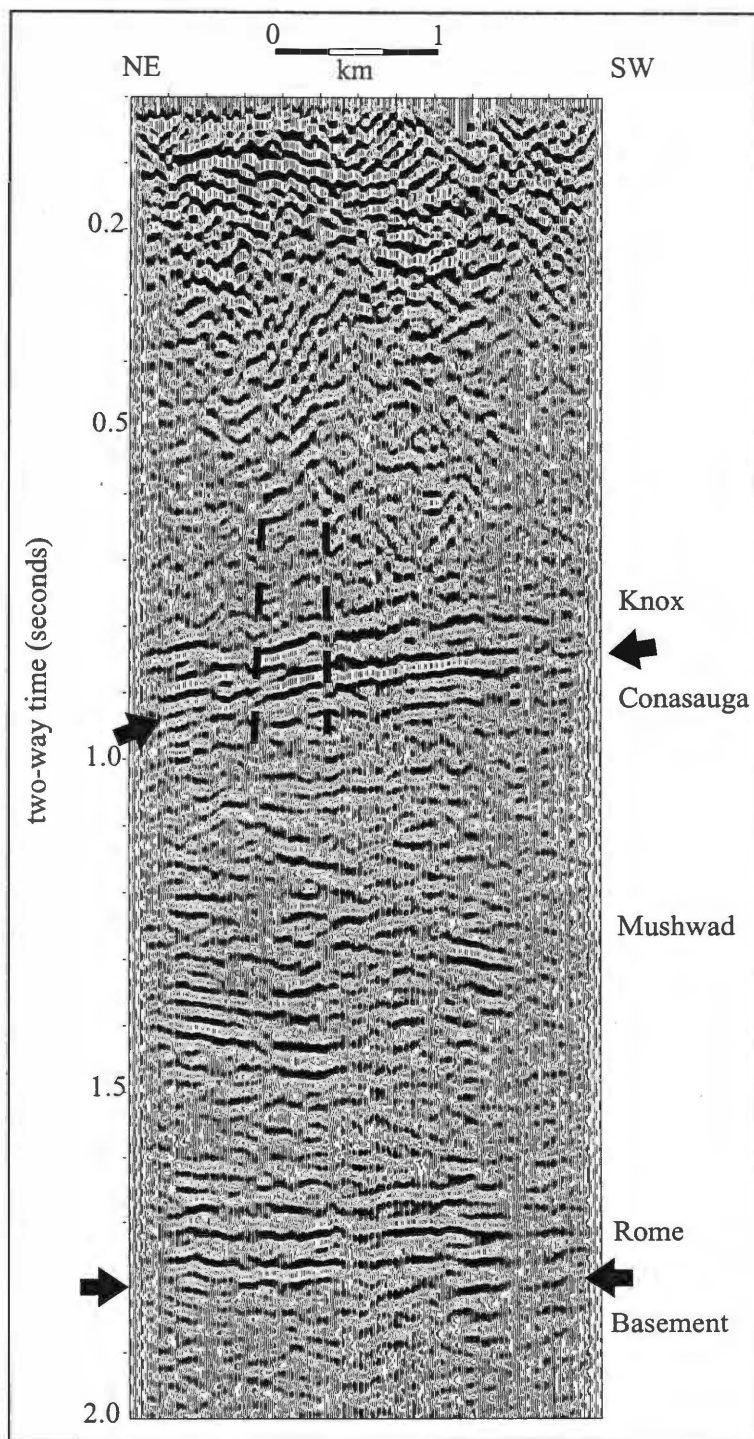


Figure 11. Seismic profile TGC06. Minor backthrust displaces the Knox-Conasauga reflector.

7. Conclusions

- (1) A system of normal faults and monoclinā flexures, having an aggregate ~800 m of vertical offset down to the southeast, changes the depth to Precambrian crystalline basement across the NY-AL lineament in the Swan Creek area of upper East Tennessee.
- (2) Structural relationships between the basement offset and the overlying Pine Mountain and Wallen Valley thrust sheets show that the basement faults are ancient, possibly related to Eocambrian rifting, and exhibit no observable displacement since the Alleghanian orogeny.
- (3) The faults associated with the NY-AL lineament and the northwestern boundary of the Ocoee block are not major contributors to seismicity in the East Tennessee seismic zone, and they are unlikely to be reactivated in a major earthquake in the near future, as some current crustal block models suggest.
- (4) A mushwad formed beneath the Wallen Valley thrust sheet in the Conasauga Group without the basement buttress that is an integral part the process in northeastern Alabama where they were first described. The mechanism involved a long detachment that developed at the base of the stiff Maynardville Limestone above the Nolichucky Shale during Alleghanian thrusting, atypical for thrust faults in the southern Appalachian Valley and Ridge.

- (5) Enhanced porosity and permeability, probably due to outer arc extensional fractures where the uppermost Knox carbonates and higher strata arch over the Conasauga mudstone, are a major factor contributing to oil and gas production from the Swan Creek field.

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Appendices

Appendix 1

Explanation of Data Processing

A.1.1 Explanation of Seismic Data Processing

A series of processing steps were applied to each data set in order to enhance the data to noise ratio as well as the coherency of reflection horizons. The first step in processing is the application of geometry to the shot files. Seismic data were checked for geometry quality by going through each shot to check for proper location of source flag at the top of each shot profile. Once this first step was complete and geometry was acceptable, each shot file was analyzed so that traces with unusually high amounts of noise were discarded. Velocities for common vibroseis noise sources were determined for proper attenuation. Initial velocities for use in normal moveout correction were also calculated at this step. Comparing velocity hyperbolae to hyperbolic reflection horizons identified velocities.

Data are grouped into common depth point (CDP) files during the initial step of applying geometry. Normal moveout correction is applied to the CDP files, which are then stacked together to make an initial stack image. The velocities used in the normal moveout step were best estimates calculated in the second step of processing. These files are later converted to more useful RMS velocity functions for more complex processing.

CDP files were then grouped into common offset files for use in partial-pre-stack migration or Dip Moveout (DMO). This level of processing is essential to begin correction for data scatter as a result of dipping reflection surfaces. Once DMO is applied to the data files, they are then regrouped into CDP files for normal moveout (using RMS

velocity) and stacking. The DMO processing step is also effective in removing steeply dipping noise, which often pollutes vibroseis seismic data.

In order to complete the data scatter correction the DMO-stacked seismic section is then processed as a post stack file. The final processing step of poststack migration was accomplished using Kirchhoff Time Migration. This particular style of migration was employed because of its ability to handle structurally complex data as well as lateral variations in RMS velocity across a dataset. The data were migrated in the time domain because of a lack of well control, which would have provided the proper depth conversion to the data. This processing step produced the final product used in the seismic interpretation phase of the study.

A.1.2 Explanation of Seismic Data Interpretation with SeisWorks

SeisWorks software was used to interpret the seismic data after it was processed in ProMAX software package, as described in Appendix 1-B. The processed data were exported into the SeisWorks project 'stthesis'. The seismic data and the UTM coordinates for the data are imported together into the project. Nine seismic profiles were exported from ProMAX into SeisWorks 2D. These profiles were used for interpretation of the faults and horizons used in contour mapping of the Swan Creek field. The interpretation of horizons and faults was done in the seismic view screen while contour mapping was done in the map view screen.

The name and interpretation color for the Rome-Basement horizon and Knox-

Conasauga horizon were first set using 'create horizon' command. The horizon for the Rome-Basement boundary was named Basement and set as red. The horizon for the Knox-Conasauga boundary was named Base of Knox and set as yellow. Each of the seismic reflection horizons was traced in the horizon interpretation application. Locations where faults were interpreted were left blank.

Faults were the next features interpreted in the seismic data. The name and style of fault(s) are first set. The only fault interpreted in this project is the N71°E fault on the northern limb of the Swan Creek anticline. This fault was named 'Swan Creek Anticline Fault' and was set as a strike-slip fault. This fault was then interpreted as a linear feature on the seismic sections.

Contours can now be drawn in the map view screen for the individual horizons using the Map It' contour algorithm. The horizon used in contouring is set from the list of available horizons for this project. A contour interval is set, in this case 20 ms is used. The 'Map It' command is applied and the software automatically calculates and draws the contours for the specified horizon. These contours are drawn without the influence of faults. In order to include faults in contour calculations, the faults must be converted to polygons.

The first step for converting faults to polygons is calculating heaves for the specified horizon. The software automatically calculates the heaves for the specified horizon. Once the heaves are calculated, the heaves are converted to polygons using the 'convert heaves to polygon' command. This calculation needs to be done for each horizon, regardless if it is the same fault.

The faults can now be included in the contour algorithm by toggling on the 'create

and use polygon' command in the Map It! window. This will automatically include fault polygons in the drawing of contours for the specified horizon. The contours will not cross the fault polygon when drawn. The contour algorithm on one side of the fault will not influence the algorithm for drawing the contours on the other side of the fault.

The contours created using the seismic data can be supplemented by control points, as used in the case of the base of Knox horizon. The location of the control points can be identified using the UTM coordinate read out at the base of the map view. The value for the control point was set for each point before adding them to the map. Once all control points are set, the 'convert horizon to map points' was toggled off in the Map It! window. The Map It! contour algorithm was applied and the software automatically includes the data from the control points in calculations. The 'convert horizon to map points' must be toggled off at all times or else the contours will be recalculated using only the seismic data and the control points will be lost.

The contours initially created by the software could not be manipulated. In order to do so, they were converted to manual contours by the 'convert computed to manual' command. The contours for this study were converted at a 20 ms contour interval and a spline value of 200. The calculated contours were toggled off in the 'map view contents' window and the manual contours were toggled on. The manual contours will be exactly the same as the calculated contours. The manual contours were then edited using the 'contour create/edit' command and contours that were drawn beyond the scope of the data were deleted. The contours were then manipulated in the cases where the contour algorithm made assumptions for missing data. Once the contours were in the proper locations, annotation was applied to the individual contours. Annotations were applied to

every 5th contour (100 ms).

When the contour map is complete, the map can be exported as a CGM file of any dimension. This file will be exported into the folder named for the SeisWorks project.

Appendix 2

Seismic Reflection Data Geometry and Profiles

A.2.1 Components of ProMAX Geometry Application

Included on CD: Geometry spreadsheets for data shot with a vibroseis gap and data shot without a vibroseis gap.

Receivers: Establishes UTM coordinate and elevation positions for each geophone in each geophone array used for the particular seismic profile.

Sets UTM x, UTM y, and Elevation (m) values in seismic data headers.

Sources: Establishes UTM coordinate and elevation positions for each source location.

Connects proper geophone array locations with source locations using 'Parameters' table.

Sets UTM x, UTM y, and Elevation (m) values in seismic data headers

It is essential, for this software, that every source location be accounted for in terms of UTM coordinates and elevation. If all locations are unknown, use Excel spreadsheet LMRKsource to estimate pad positions between known points.

Need to know for these calculations: A) number of shots between each known pad position B) UTM and elevation coordinates for end point pad positions.

Patterns: Each array of geophones is set to a pattern number. Each time a geophone is moved or a sequence is renumbered, a new pattern must be created.

Use the pattern numbers created in this table to correlate geophone arrays with proper source locations and file numbers.

Save the Excel files as space delimited tables with the set column widths. Import these files into the ProMAX geometry program with the import command in the pull down menu for each geometry table. Tune the geometry program to read the proper columns from these excel files.

A.2.2 Explanation of Contents on Attached CD ROM (plate 1)

The CD in the appendix is an archive for the seismic reflection data used in this study. Tables A-1 through A-7 are template examples to guide the use of ProMAX geometry application. Examples of seismic data acquired with and without a source gap are included in the templates. Table A-7 is used to calculate unknown source locations.

Tables A-8 through A-31 contain UTM coordinates for each seismic profile. Included for each profile is coordinate locations for each source, receiver and CDP. Each profile also includes a table of RMS velocities used in the processing of the data.

Table A-32 contains the UTM coordinates for control points used from seismic profile TGC15. Table A-33 contains UTM coordinates for the gas wells used as control points in this study.

The seismic profiles used in this study are also included on the CD. The files are in both SEG-Y format and Adobe Illustrator 9.0.

Guide to processing sequence for ProMAX 2D also included.

Vita

Steve Tavernier was born December 15, 1976 in Concord, MA. He was raised in Acton, MA. Following graduation from Acton-Boxborough Regional High School in 1995, Steve attended Franklin & Marshall College in Lancaster, PA. He received his B.A. in Geology in the spring of 1999 and began graduate studies the following fall at the University of Tennessee in Knoxville, TN. He received his M.S. in Geology in the spring of 2002.

Steve is currently at Anadarko Petroleum Co. in Houston, TX where he hopes to build a long and fruitful career in the petroleum industry.

