Final Report of Results for the Project "Geologic controls of hydrocarbon occurrence in the southern Appalachian basin in eastern Tennessee, southwestern Virginia, eastern Kentucky, and southern West Virginia"

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ABSTRACT

This report summarizes the accomplishments of a three-year program to investigate the geologic controls of hydrocarbon occurrence in the southern Appalachian basin in eastern Tennessee, southwestern Virginia, eastern Kentucky, and southern West Virginia. The project: (1) employed the petroleum system approach to understand the geologic controls of hydrocarbons; (2) attempted to characterize the P-T parameters driving petroleum evolution; (3) attempted to obtain more quantitative definitions of reservoir architecture and identify new traps; (4) is worked with USGS and industry partners to develop new play concepts and geophysical log standards for subsurface correlation; and (5) geochemically characterized the hydrocarbons (cooperatively with USGS).

Third-year results include: All project milestones have been met and addressed. We also have disseminated this research and related information through presentations at professional meetings, convening a major workshop in August 2003, and the publication of results. Our work in geophysical log correlation in the Middle Ordovician units is bearing fruit in recognition that the criteria developed locally in Tennessee and southern Kentucky are more extendible than anticipated earlier. We have identified a major 60 mi-long structure in the western part of the Valley and Ridge thrust belt that has been successfully tested by a local independent and is now producing commercial amounts of hydrocarbons. If this structure is productive along strike, it will be one of the largest producing structures in the Appalachians. We are completing a more quantitative structural reconstruction of the Valley and Ridge and Cumberland Plateau than has been made before. This should yield major dividends in future exploration in the southern Appalachian basin. Our work in mapping, retrodeformation, and modeling of the Sevier basin is a major component of the understanding of the Ordovician petroleum system in this region. Prior to our undertaking this project, this system was the least understood in the Appalachian basin.

This project, in contrast to many if not most programs undertaken in DOE laboratories, has a major educational component wherein three Ph.D. students have been partially supported by this grant, one M.S. student partially supported, and another M.S. student fully supported by the project. These students will be well prepared for professional careers in the oil and gas industry.

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INTRODUCTION

The purpose of this report is to summarize the activities and results of the project "Geologic controls of hydrocarbon occurrence in the southern Appalachian basin in eastern Tennessee, southwestern Virginia, eastern Kentucky, and southern West Virginia," DOE Contract Number DE-FC26-02NT15341, emphasizing activities related to the third year (Fig. 1).

The goals of this project, as originally stated, are: (1) to employ the petroleum system approach to help understand the geologic controls of hydrocarbon occurrence in the southeastern Appalachian basin; (2) to better characterize the P-T parameters for petroleum migration from the oil/gas window; (3) to obtain quantitative definitions of reservoir architecture and recognize new traps; (4) to work with the U.S. Geological Survey and industry partners to develop new play concepts; (5) to geochemically characterize hydrocarbons, mostly a U.S. Geological Survey effort; and (6) to disseminate results at professional meetings and in scientific journals.

Regarding the first goal, we have employed the petroleum system concept (Magoon and Dow, 1994) (Fig. 2) to better understand the interactive link between stratigraphy, structure, and hydrocarbon generation and migration at the oil-gas window to petroleum systems in this region as a result of our work and work by industry partners. These results reinforce many of the original data on the location of the oil/gas window derived from Ordovician rocks, and the limits to petroleum and natural gas occurrence in this area (e.g., Epstein et al., 1977; Orndorf et al., 1988), but forthcoming USGS conodont alteration index (CAI) data on the Ordovician and Mississippian rocks (Repetski, in progress) will permit better understanding of the thermal regime in three dimensions. We have recognized several new reservoir types and potential reservoirs in the region, and identified a major structure that may be productive in the western Valley and Ridge of Tennessee (Whisner and Hatcher, 2003). We also have identified a new fairway and plays beneath the Plateau of Tennessee and Kentucky, and possibly southern West Virginia. We have developed new play concepts based on data that have existed for several decades and new data that we have collected. We have made numerous presentations at professional meetings, including the Eastern Section of the American Association of Petroleum Geologists (Evenick and Hatcher, 2003, 2004; Whitmer et al., 2003; Bultman et al., 2004; Bailey et al., 2005; Hatcher et al., 2005), the Southeast-Northeast Sections meeting of the Geological Society of America (Evenick et al., 2004; Whisner et al., 2004; Hatcher et al., 2004; Evenick and Hatcher, 2005, 2006a, 2006c), American Association of Petroleum Geologists (Whisner and Hatcher, 2002; Evenick et al., 2005), and presentations at the Tennessee Oil and Gas Association annual meeting (no published abstracts). We have published one paper in the *Oil and Gas Journal* (Whisner and Hatcher, 2003), and have two more in press in *Oil and Gas Journal* to be published in fall of 2006 (Evenick and Hatcher, 2006b). We have also published another paper by the Tennessee Division of Geology (Evenick and Hatcher, 2006d).

EXECUTIVE SUMMARY

This report summarizes the activities and results of the project "Geologic controls of hydrocarbon occurrence in the southern Appalachian basin in eastern Tennessee, southwestern Virginia, eastern Kentucky, and southern West Virginia," DOE Contract Number DE-FC26-02NT15341, emphasizing third year activities and accomplishments. The goals of this project were: (1) to employ the petroleum system approach to help understand the geologic controls of hydrocarbon occurrence in the southeastern Appalachian basin; (2) to better characterize the P-T parameters for petroleum migration from the oil/gas window; (3) to obtain quantitative definitions of reservoir architecture and recognize new traps; (4) to work with the U.S.

Figure 1. Generalized geologic map of the southern Appalachian basin with some known fields producing from Ordovician strata. (Adapted from Schruben et al., 1998).

Figure 2. Ven diagrams showing the major components of the Ordovician and Devonian-Mississippian petroleum systems.

Geological Survey and industry partners to develop new play concepts; (5) to geochemically characterize hydrocarbons, mostly a U.S. Geological Survey effort; and (6) to disseminate results at professional meetings and in scientific journals.

The project structure consisted of several components and activities that were all directed by the PI, but were divided into responsibilities of the PI and several graduate students conducting applied and basic research. The Nashville (Trenton)-Stones River (Black River) geophysical log analysis component was conducted by Ph.D. student Jonathan C. Evenick. The pre-Chattanooga structure component was carried out by RDH and Ph.D. student Jonathan Evenick, and derived information from both surface geologic data and the log analysis component. *We have achieved a major breakthrough in both the identification of a new fairway and exploration model for exploration of the pre-Chattanooga Ordovician that should prove useful to the independent oil and gas companies for many years.* The structural reconstruction of foreland fold-thrust belt component, rapidly nearing completion by Ph.D. student Jennifer Whisner, intends to better understand curved segments of foreland fold-thrust belts, the structure of the Tennessee salient, and foreland fold-thrust belt deformation in the southern Appalachian basin. A major product of this component has been the rediscovery of a subsurface triangle zone called the Eureka structure (Whisner and Hatcher, 2003). The publication of this rediscovery in the *Oil and Gas Journal* article has created a large amount of interest in the structure, including drilling and new hydrocarbon production. Field studies and basin analysis in the Middle Ordovician Sevier basin component were conducted by RDH, Ph.D. student S. Christopher Whisner, and M.S. students John G. Bultman and Neil E. Whitmer. Chris Whisner has been responsible for mapping part of and compiling the geology of the southern Tellico-Sevier basin, whereas John Bultman and Neil Whitmer have completed detailed geologic maps to form a transect across the basin at its widest point in northeastern Tennessee. For the first time the Sevier Shale has been subdivided into three mappable units. This activity has enhanced our ability to understand the dynamics of the Tellico-Sevier basin and its relationship to the platform to the west. Collaboration and technology transfer have been an integral part of the study since its inception, with collaboration

with the U.S. Geological Survey (Eastern Mineral Resources). Since the first year of the project the oil and gas associations of Tennessee and Kentucky, along with several independent petroleum companies, have been involved in collaboration. We held a successful workshop on geophysical log correlation in the Ordovician section on August 7, 2003 in Knoxville attended by 38 people to enhance our technology transfer activities and to provide independent producers with our latest results. A recent collaboration was also begun with the Polish National Oil Company in May 2004 and 2005 when RDH visited their offices in Warsaw to review their exploration program in the Paleozoic rocks of the subsurface Lublin basin and to discuss the possibility of using Appalachian analogs to better understand the this structure.

All project milestones have been successfully met. We also have been disseminating this research through presentations at professional meetings, convening a major workshop in August 2003, and the publication of results. Our work in geophysical log correlations of Middle Ordovician stratigraphy is bearing fruit both in recognition that the criteria developed locally in Tennessee and southern Kentucky have much greater extensibility than anticipated earlier. We have identified a major 60 mi-long structure in the western part of the Valley and Ridge thrust belt that is generating considerable exploration interest, drilling, and new hydrocarbon production. We are completing a more quantitative structural reconstruction of the Valley and Ridge than has been made before. This should yield major dividends in future exploration in the southern Appalachian basin. Our work in mapping, retrodeformation, and modeling of the Sevier basin is a major component of the understanding of the Ordovician petroleum system in this region.

This project, in contrast to many if not most programs undertaken in DOE laboratories, has a major educational component wherein three Ph.D. students have been partially supported by this grant, one M.S. student partially supported, and another M.S. student fully supported by the project. These students will be well prepared for professional careers in the oil and gas industry.

RESULTS AND DISCUSSION

PROJECT COMPONENTS AND ACTIVITIES

NASHVILLE (TRENTON)-STONES RIVER (BLACK RIVER) GEOPHYSICAL LOG ANALYSIS. This component of the research was conducted largely by Ph.D. student Jonathan C. Evenick and produced numerous very positive results that have impacted the successful completion of several project milestones.

PRE-CHATTANOOGA STRUCTURE. This component of the project was conducted by RDH and Ph.D. student Jonathan Evenick and derived information from both surface geologic data and the log analysis component. We have achieved a major breakthrough in both the identification of a new fairway and model for exploration of the pre-Chattanooga Ordovician that should prove useful to the independent oil and gas companies. This exploration concept did not previously exist, and should enhance the success of future wildcat and development drilling above the very low reported current 17 percent (for both). We have recognized folds and faults in Ordovician and Silurian rocks that are truncated by the pre-Chattanooga (360 Ma) unconformity.

STRUCTURAL RECONSTRUCTION OF FORELAND FOLD-THRUST BELT. This component was conducted by Ph.D. student Jennifer Whisner. Her goal was to better understand curved segments of foreland fold-thrust belts, the structure of the Tennessee salient, and foreland

fold-thrust belt deformation in the southern Appalachian basin employing surface and industry seismic reflection data. A major product of this component has been the rediscovery of the subsurface Eureka structure (Whisner and Hatcher, 2003), which was probably known to several of the major oil companies when they explored this area in the 1980s, but was largely unknown to the independent oil companies that remain here today and explore this region. Publication of the *Oil and Gas Journal* article has created a large amount of interest in the Eureka structure. Refinement of models for curved foreland fold-thrust belts, and the application of these models to hydrocarbon exploration, will be a major product of her 3-D modeling.

FIELD STUDIES AND BASIN ANALYSES IN THE MIDDLE ORDOVICIAN SEVIER BASIN. This component was conducted by RDH, Ph.D. student S. Christopher Whisner, and M.S. students John G. Bultman and Neil E. Whitmer. Chris Whisner was responsible for mapping part of and compiling the geology of the southern Tellico-Sevier basin, whereas John Bultman and Neil Whitmer have completed a transect of detailed geologic maps across the basin at its widest point in northeastern Tennessee, producing the first stratigraphic subdivision of the Sevier Shale. Field-related activities and basin analysis have been completed. This activity has enhanced our ability to understand the dynamics of the Tellico-Sevier basin and its relationship to the platform to the west.

COLLABORATION AND TECHNOLOGY TRANSFER. This has been a collaborative project with the U.S. Geological Survey (Eastern Mineral Resources) since its inception, and since the first year of the project with the oil and gas associations of Tennessee and Kentucky, along with several independent petroleum companies. We held a workshop on geophysical log correlation in the Ordovician section on August 7, 2003 in Knoxville to increase our technology transfer activities and to provide independent producers with our latest results. This workshop was attended by 38 professionals from independent oil companies, the state geological surveys of Tennessee and Kentucky, service companies, and a few graduate students. We have continued to provide information to numerous companies and readily share the results of this project. To maximize the dissemination of knowledge about our rediscovery of the Eureka structure, we published the *Oil and Gas Journal* article in the place where it would appear rapidly and quickly reach the largest industry audience.

A recent collaboration was begun with the Polish National Oil Company in May 2004. RDH visited their offices in Warsaw (2004 and 2005) to review their exploration program in the subsurface Paleozoic rocks of the Lublin basin in eastern Poland (Hooper et al., 2002). The purpose was to discuss the possibility of using Appalachian basin and foreland fold-thrust belt analogs to better understand the this structure.

PRESENTATIONS AND PUBLICATIONS. Presentations at meetings have been outlined already in several places above and below, and our publications to date and in review also have been noted.

EDUCATIONAL ACCOMPLISHMENTS

Bultman, J. G., 2005, Structure, stratigraphy, and tectonics of the northwestern Bays Mountain synclinorium, Greene and Hawkins Counties, Northeast Tennessee [M.S. thesis]:

Knoxville, University of Tennessee, 163 p.

Evenick, J. C., 2006, Potential subsurface structures and hydrocarbon reservoirs in the southern

- Appalachian basin beneath the Cumberland Plateau and eastern Highland Rim, Tennessee, Kentucky, and southwestern Virginia [Ph.D. thesis]: Knoxville, University of Tennessee, 402 p.
- Whisner, S. C., 2004, The Middle Ordovician Tellico-Sevier syncline: A Stratigraphic, structural and paleoseismic investigation [Ph.D. thesis]: Knoxville, University of Tennessee, 230 p.
- Whitmer, E. N., 2005, Structural and stratigraphic investigations of the Bays Mountain synclinorium, Parrottsville and portion of Cedar Creek 7.5-minute quadrangles, East Tennessee [M.S. thesis]: Knoxville, University of Tennessee, 119 p.

2004-2005 MILESTONES

- (1) Thermal Models; (2) Reservoir Characterization; (3) 3-D Reconstruction; (4) Presentations; (5) Publications.

Completion of Milestone (1): We have better delineated the distribution of the thermal oil/gas window relationships in the Ordovician rocks in this region. U.S. Geological Survey, through new CAI studies of Mississippian rocks, is constructing a thermal regime array for the Mississippian to compare with the Ordovician thermal structure delineated previously. This will permit better understanding of the late Paleozoic thermal regime in 3-D. These data should be available before the end of our project for additional analysis.

Completion of Milestone (2): We have made major strides toward reservoir characterization in this region by identifying a large subsurface structure that has no surface expression and have made this information available to the community (Whisner and Hatcher, 2003). This structure is greater than 50 mi long, was drilled by ARCO during the 1980s, and there was both oil and gas in the Wright #1 hole. The prospect was abandoned when the major oil companies decided not to undertake additional exploration in the Appalachian region. Based on our work and rediscovery of this structure, there is a large amount of interest in exploration of this feature, including new drilling and hydrocarbon production. We have additionally identified a series of structures that may provide insight into the success or mainly lack of success that the independent oil companies have experienced in exploring the Ordovician "Trenton-Black River" (Nashville-Stones River groups) play in southern Kentucky and Tennessee.

Completion of Milestone (3): We also have made great progress in 3-D structural reconstruction of the Tennessee salient from Georgia to southwestern Virginia. A presentation of the preliminary results of this analysis was made at the Southeast-Northeast Section meeting of the Geological Society of America in March (Whisner et al., 2004), and a paper has been submitted for publication in a Geological Society of America Special Paper (Hatcher et al., in review).

Completion of Milestone (4): Our presentations at professional meetings have been numerous, including the Eastern Section of the American Association of Petroleum Geologists (Evenick and Hatcher, 2003, 2004; Whitmer et al., 2003; Bultman et al., 2004; Bailey et al., 2005; Hatcher et al., 2005), the Southeast-Northeast Sections meeting of the Geological Society of America (Evenick et al., 2004; Whisner et al., 2004; Hatcher et al., 2004; Evenick and Hatcher, 2005, 2006a, 2006c), American Association of Petroleum Geologists (Whisner and Hatcher, 2002;

Evenick et al., 2005), and presentations at the Tennessee Oil and Gas Association annual meeting (no published abstracts). We have published one paper in the *Oil and Gas Journal* (Whisner and Hatcher, 2003), and have two more in press to be published in fall of 2006. We have also published another paper by the Tennessee Division of Geology (Evenick and Hatcher, 2006d). We will also be submitting additional papers for publication in the near future. All abstracts and papers have been submitted as required to DOE.

Completion of Milestone (5): A paper was published in 2004 on thrust tectonics in an American Association of Petroleum Geologists Memoir.

SPECIFIC ACTIVITIES

Defined Milestone-Related Activities. In addition to analyses of existing thermal data modified by data from oil and gas occurrences and fields in the southern Appalachian basin, RDH accompanied Dr. John Repetski (USGS) to the field in July 2003 to collect additional samples from Ordovician rocks and to sample the Mississippian carbonate rocks from the Plateau across much of the Valley and Ridge to obtain new CAI data. These new data will be used to compare Ordovician and Mississippian thermal regimes and to determine thermal gradients that existed in the late Paleozoic between the Ordovician and Mississippian rocks. The results from the Mississippian sampling are not yet available but should be soon.

We have been successfully characterized many of the reservoirs that exist, particularly in the Ordovician of this region. We firmly believe at this point that the hydrocarbons that occur in Ordovician rocks were sourced in the carbonate rocks in which they occur based on structural and stratigraphic criteria, as well as the geochemical analyses conducted by Dr. Robert Burruss (USGS) on hydrocarbon samples from this area. Confirmation of the Ordovician carbonate source generates additional possibilities for hydrocarbon occurrences and reservoirs. We also have recognized specific new plays, one beneath the Chattanooga shale (Devonian-Mississippian boundary) unconformity where post Early Silurian–pre-Chattanooga deformation (folds and faults) exists throughout the region that has not been previously recognized (Fig. 3). This opens up a new fairway for plays beneath the Cumberland Plateau and Highland Rim in Tennessee, Kentucky, and northern Alabama. This discovery may also help explain the poor success that independent oil and gas companies have experienced in exploring Ordovician reservoirs. Until now there has been no viable exploration model for the Ordovician that has proved useful over the entire region.

3-D reconstruction has concentrated largely in the deformed parts of the Appalachian basin, and we are now putting together palinspastic sections and maps that provide superior information about the location of the platform margin during the Ordovician and the configurations of Ordovician and younger clastic wedges (Hatcher et al., in review).

Geophysical Log Analysis and Correlation. The geophysical log analysis and correlation that was outlined in the 2002-03 report (Evenick et al., 2003; Fig. 4) has been extended well beyond Tennessee and southern Kentucky into southwestern Virginia, and as far north as southern West Virginia and Ohio (Fig. 5). This permits us to construct very precise structure maps to locate plays in the southern Appalachian basin and conduct much more detailed analysis of pre-Chattanooga structures (Fig. 6) over a wider area than we had anticipated and that has ever been conducted before.

Figure 3. (a) Geologic map and cross section of part of the Columbia, Tennessee quadrangle showing the truncation of the Ordovician and Silurian rocks beneath the (Chattanooga Shale-) Ft. Payne Chert unconformity. (b) Geologic map of the Buffalo Valley quadrangle, Tennessee, and structure contours constructed on the (Chattanooga Shale-) Ft. Payne Chert unconformity (red) and on the base of the Catheys Formation. The red contours reflect eastward dip off the Nashville dome (see Fig. 1), whereas the black contours reveal a series of anticlines and synclines in the Ordovician rocks beneath the unconformity.

(b)

Figure 4. (a) Type logs for the Middle and Upper Ordovician rocks beneath the Highland Rim and Cumberland Plateau in Tennessee, Kentucky, and southwesternmost Virginia. (b) Composite section with several gamma ray logs from the subsurface of the Cumberland Plateau in Tennessee.

Figure 5. Regional geophysical log correlation of Stones River and Nashville Groups units across the study area with the Millbrig bentonite as the vertical datum. Tennessee stratigraphic names are used on the right and Kentucky terminology is to the left. The Camp Nelson Limestone correlates with the Ridley, Pierce, and Murfreesboro Limestones.

Figure 6. Structure contour map on top of the “pencil cave” (Deicke) bentonite (near the top of the Carters Limestone) based on 882 wells near Livingston, Tennessee. The bulls-eye highs are likely based on erroneous drillers’ picks in individual wells. Removal of these highs still leaves a large amount of structural relief in the Stones River Group.

Geologists with the small independent companies that do most of the exploration, drilling, and producing of hydrocarbons in Tennessee, southern Kentucky, and southwestern Virginia have traditionally recognized only the broad stratigraphic subdivisions used farther north in the Appalachian basin for the Ordovician and mostly thought in more general terms of the "Black River" and "Trenton" Groups of New York. The equivalent units, the Stones River and Nashville Groups, have long been subdivided in Central Tennessee from surface exposures (Wilson, 1949, 1962). Farmer and Holyday (1999) demonstrated that the lower Stones River Group in Central Tennessee is readily divisible using geophysical logs from water wells. We have now demonstrated that both the Stones River and Nashville Groups are divisible by making detailed comparisons of the characteristics and thicknesses of surface exposed units and their characteristics in geophysical logs (Fig. 4). The key is to locate the two distinctive K-bentonite layers (lower “pencil cave” or Deicke bentonite, and upper “mud cave” or Millbrig bentonite) at

the top of the Stones River Group, then work upward through the shaly limestone of the Hermitage Formation and massive Bibby-Cannon Limestone into the shaly Catheys-Leipers limestone interval; each unit has easily recognized geophysical log signatures (Fig. 5). The section downward from the bentonites is also equally divisible into the massive Carters Limestone (containing the bentonites at the top), the thin-bedded shaly Lebanon Limestone, the massive Ridley Limestone, the thin shaly Pierce Limestone, and the more massive Murfreesboro Limestone. The discontinuous Wells Creek (or Pond Springs, Blackford, or Douglas Dam Member) Dolomite, deposited on the Knox (Lower Ordovician) unconformity, also has a distinctive geophysical log signature. Some structural mapping of recognizable horizons has been carried out (Fig. 6), but wells are largely concentrated in small areas with less regional coverage making it more difficult for us to conduct structural analysis over large areas and resolve the detailed structure beneath the Cumberland Plateau.

Gamma-ray signatures of Nashville-Stones River Groups units are commonly diagnostic. The discontinuous Wells Creek Formation, if present, has irregular gamma-ray amplitudes over 80 API units. The Murfreesboro Limestone has an irregular gamma-ray signature that ranges in amplitude from 20 to 80 API units. The Pierce Limestone is around 30 ft thick and bounded by two prominent shaly limestone sections (Wilson, 1949) that have gamma-ray signatures with amplitudes of 60 to 70 API units. The massive Ridley Limestone has a low amplitude and an almost flat gamma-ray signature of 20 to 30 API units. Lebanon Limestone is around 100 ft thick (Wilson, 1949) and, because of its mixed massive to thin-bedded and shaly character, has a heterogeneous gamma-ray signature typically of 25 to 40 API units. The massive Carters Limestone generally has a flat gamma-ray signature of 20 to 30 API units (Evenick and Hatcher, 2006d).

The gamma-ray signature of the shaly-sandy limestone of the Hermitage Formation (basal Nashville Group) is irregular and has amplitudes ranging from 60 to 80 API units with occasional spikes approaching 200 API units. The overlying, clean medium-bedded Bibby-Cannon Limestone has a consistently flat and low amplitude gamma-ray signature of 20 to 30 API units. The gamma-ray signature of the Catheys Formation is higher in overall intensity (30 to 80 API units) and is very irregular, much like the Hermitage Formation (Evenick and Hatcher, 2006d).

Field Studies of the Middle Ordovician Tellico-Sevier Basin. Detailed geologic mapping of parts of the Tellico-Sevier basin in southeastern and northeastern Tennessee are largely complete, with current efforts directed toward basin reconstruction and analysis following retrodeformation of late Paleozoic structure. We are at present involved in reconstructing the basin with the knowledge (Hatcher et al., 2004) that this basin is not a foredeep as had been hypothesized by many geologists in the past (Walker et al., 1983; Mussman and Reed, 1986). We now recognize based on our work in this basin, and that by Kellberg and Grant (1956), that the Tellico-Sevier basin is not a classic foredeep but is more likely a basin developed ≥ 100 km into the platform. Kellberg and Grant (1956) recognized that pebbles in conglomerates are composed of platform, rifted margin, and Grenvillian basement lithologies, but dominated by limestone (Fig. 7). There is no vestige of early Paleozoic volcanic and distal margin sedimentary rock clasts, as would be expected if this were a foredeep basin in front of a thrust-loaded margin. The coarser clastic rocks disappear to the west, and the fine clastics thin and give way to carbonate platform rocks still farther west (Fig. 8). The Sevier basin could be a back-bulge basin (Hatcher et al., 2004) (Fig. 9), but the ~ 3 km accumulation may be too thick for a classic back-bulge like that in front

Figure 7. Sawed conglomerate samples from Fincastle, Virginia (upper left), South Holston Dam, Tennessee (upper right), and Cisco, Georgia (bottom) and clast counts (by Kellberg and Grant, 1956). Note the difference of limestone clasts.

Figure 8. Correlation of Middle Ordovician lithofacies from the Sevier basin to the carbonate platform (Modified from Walker et al., 1983).

Figure 9. Crustal model for formation of a foreland basin, forebulge, and a back-bulge basin in response to loading of a continental margin by thrust sheets.

of the Antler orogen in Nevada-Utah (Giles and Dickinson, 1995). This revision in basin architecture and basin concepts helps explain why there may be less organic-rich shale in this basin than was previously thought and that long-distance migration of hydrocarbons into reservoirs tens of kilometers to the northwest may not have occurred. Industry seismic reflection data (Fig. 10) indicate the structure at depth is much more complex than revealed by surface geologic data (e.g., Hardeman, 1966).

RELATED MILESTONES

Exploration and Geologic Models. All of our efforts to date in this project have focused downstream on the formulation of exploration models. We believe that we have been very successful to date in this undertaking: (1) We have developed a new exploration model and paradigm for the Ordovician and identified several plays and a fairway beneath the Plateau and Highland Rim in Tennessee, Kentucky, southwest Virginia, and southern West Virginia (Fig. 11). (2) We have identified a major structure in the western part of the foreland fold-thrust belt that, if proved productive, will justify the project by a factor of several tens or hundreds of its original cost. (3) We feel that formulation of a rigorous basin model for the Tellico-Sevier basin will become a springboard to refining future exploration models along the platform margin.

Exploration models historically have not been used in the southern Appalachian basin because the different petroleum systems and trapping styles have not been categorized. Successful wildcat drilling commonly has not led to the development of producing fields. It has been proposed that regionally there are three main types of fields (structural, stratigraphic and fracture-dominated plays) in the region that can be identified by a combination of seismic imaging, well data, trend surface residual anomaly mapping (Evenick et al., 2005), or soil gas anomalies (Fountain and Jacobi, 2000).

Regionally the Ordovician plays, such as the Nashville-Stones River (Trenton-Black River) are predominantly stratigraphic plays (Nuttall, 1996; Wickstrom, 1996). There may be small structural plays near the Nashville dome where small gentle folds caused by the migration of the Taconic peripheral bulge have been noted (Stearns and Reesman, 1986; Reesman and Stearns, 1989). The Cambrian-Ordovician Knox Group, the Mississippian Fort Payne reef, and the Pennsylvanian coal-bed methane plays are also considered stratigraphic, although they are mostly small and isolated traps (i.e., Baranoski et al., 1996). Sometimes associated with these stratigraphic traps are fracture-dominated plays, which are larger in size and are not associated with structural highs, but rather with regional joint patterns and deep-seated faults (Wickstrom, 1996). Secondary hydrothermal dolomitization is sometimes associated with fracture plays, particularly in the Stones (Black) River Group, but hydrothermal dolomite plays are difficult to

Figure 10. (a) Migrated seismic reflection line in Cocke County, Tennessee, across part of the syncline preserving Middle Ordovician rocks. (b) Cross section interpretation. (From Whitmer, 2005).

Figure 11. Schematic geologic model for hydrocarbon emplacement in Tennessee and southern Kentucky. Known hydrocarbon reservoir types and sources in the southern Appalachian basin in Tennessee and southern Kentucky in the petroleum systems that are currently recognized in the region.

initially prospect and delineate because they are represented by structural lows that may not indicate secondary dolomitization (Evenick and Hatcher, 2006b).

In the Ordovician section the shaly limestones, especially the Hermitage and Murfreesboro Limestones of the Nashville (Trenton) and Stones (Black) River Groups, are some of the probable source and reservoir horizons found within the groups. Other pay horizons have been identified throughout these groups and vary by geographic location (Butts, 1919; Born and Burwell, 1939; Clendening and McCown, 1999). Well, seismic and trend-surface residual anomaly data do not indicate that production from these groups is structurally related. This suggests these traps are mainly stratigraphic or fracture-dominated reservoirs (i.e., Wickstrom, 1996), but more data are needed. It is unlikely that the Knox and Trenton–Black River Groups are sourced from the Chattanooga Shale (e.g., Ryder et al., 1998), because hydrocarbons would have to migrate down-section or laterally (up-dip) and across stratigraphic contacts. This hypothesis also cannot adequately explain emplacement of shallow hydrocarbons in the Knox Group in the Central Basin.

We propose that the Mississippian plays are structural traps sourced from the underlying Chattanooga Shale. Trend-surface residual anomaly maps indicate that there are many small, linear highs that are oriented parallel to regional strike. All of the mapped Mississippian horizons, such as the Pennington Limestone, Bangor Limestone, and Fort Payne Formation, contain these features, although the number of linear highs increases and amplitudes of the residuals decrease down-section. Some of these linear highs are evident in the Chattanooga Shale horizon, but they are minor. Below the Chattanooga Shale this pattern is not noticeable, indicating that these features are related to Alleghanian deformation that is correlated with a blind décollement soled in the Chattanooga Shale. The deformation could both increase reservoir permeability and porosity, along with creating a linear trap.

Extending Middle Ordovician Correlations across the Southern Appalachian Basin.

Geophysically subdividing the Nashville-Stones River Groups into the known formations is readily achievable in the southern Appalachian basin (Evenick and Hatcher, 2006d; Fig. 6), and doing so enhances the success in identifying possible structures, potential pay horizons, and

traps. While large log suites exist for some of the deeper tests, the most commonly available log useful for stratigraphic correlation is the gamma-ray log.

Hydrothermal Dolomite (HTD) Traps. HTD structures in the Appalachian basin have a number of similarities, yet, the stratigraphic horizons where HTD structures have been found vary regionally: in the MVT mining districts of Tennessee HTD structures occur in the Kingsport Formation and Mascot Dolomite (upper Knox Group), and Murfreesboro Limestone (lower Stones River–Black River Group; Misra et al., 1996). In central New York, 300 feet of the upper Black River Group is pervasively hydrothermally dolomitized (Von Rudloff, personal communication). In Kentucky, HTD structures have been found only in the Lexington (Trenton) Group, but not in the upper High Bridge (Black River) Group (Black et al., 1981). A recent test core drilled by the Kentucky Geological Survey into the largest known outcropping HTD structure (sometimes called “light bulb” or “dolomite chimney” structures) indicates that dolomitization decreases with depth and does not appear to be directly related to the proximity of a fault zone thought to have served as the conduit for hydrothermal fluids (Harris et al., 2005). An exposed HTD structure in Kentucky suggests that dolomitizing basal fluids migrated up section (Fig. 12) through a small thrust fault and dolomited around the tip of the fault, creating the circular structure. It is likely that future prospecting in the region will identify additional HTD structures in Kentucky and Tennessee. It is also probable that producing fields have not been accurately identified as being related to HTD structures where a well or field with anomalously high porosity could exist on the flanks of an unknown structure. A small, productive HTD structure has recently been postulated, although unconfirmed, to exist in part of the Swan Creek field in the upper Carters Limestone (upper Stones River Group) (Fig. 13; Bailey et al., 2005). The thickness of this weakly dolomitized section is only a few feet, but may be responsible for the best oil production in the field (Bailey et al., 2005). Production data from this possible hydrothermal dolomite structure indicate that these plays can be significant (>300 barrels of oil per day), but like the Mississippian Walsortian reef reservoirs, production may last only days or months.

These typically small, but potentially high-yield reservoirs commonly have structural lows over the structures because the overlying stratigraphy subsides as dolomitization continues. These structures, therefore, should be differentiated from synclinal trends before being prospected. Drilling structural lows is not a widespread practice, although they may be identified in seismic reflection data. Identification of HTD structures requires the differentiation of dolomitization-related sags from synclines (Fig. 14). Dolomite sags: 1) will correspond to a thinned isopach map (for the unit that contains the dolomite), whereas folded stratigraphy typically does not thin or thicken near fold hinges, especially in synclinal hinges; 2) are characterized by localized, linear lows while synclines are typically broad and gentle linear lows; 3) will not commonly follow regional strike because they are generally controlled by basement faults and fractures; and 4) commonly do not have an anticlinal component.

Mississippian valley type (MVT) deposits typically have the highest concentration of economic minerals in the center where secondary porosity related to dolomitization and/or brecciation is cemented with gangue minerals (Misra et al., 1996). Conversely, drilling data indicate hydrocarbons typically occur on the flanks or “baked zone” halo of the MVT deposits (Smith, personal communication; Von Rudloff, personal communication) where the leached limestone/dolomite retains its secondary porosity (Fig. 15). Surface analog Ordovician HTD structures in Kentucky mimic this general pattern: thin sections from within a HTD structure

Figure 12. Hydrothermal dolomitization in the Lexington Limestone at the inferred fault tip of a minor thrust fault, Highway 627, south of Winchester, Kentucky. Regionally these features have been called “light bulb” or “dolomite chimney” structures. Hammer for scale, located next to two shaded areas located directly below the structure.

Figure 13. Structure contour maps from the Swan Creek field, Tennessee. Note the structural low superposed on the northwestern flank of an anticline. Hydrocarbon production from surrounding wells is from the top of the Stones River (Carters Limestone) Group. The structural low is evident from the top of the Lebanon Limestone downward into the Knox Group, but is not present in younger horizons.

Figure 14. Schematic map (top) and cross-sectional (bottom) views of a hydrothermal dolomite sag (left) and classic folds (right). Note the constant unit thickness and paired anticlines associated with the syncline, whereas the hydrothermal sag does not maintain thickness or have paired anticlines.

Figure 15. Thin sections on- and approximately 100 feet off-structure from the hydrothermal structure in Figure 12. Note the iron staining in both photos (yellow/brown) and increased porosity off-structure. (1.03 mm x 1.37 mm, blue light, plane polar).

typically have 0-10 percent porosity, 5-30 percent porosity within 100 feet of the structure, and 0-1 percent regional porosity in the surrounding carbonate rocks (Wilcox, 2005). This relationship has been confirmed by recent drilling in central New York, where wells in the center of a HTD structure are commonly dry and the best production occurs near the flanks of the structure (Von Rudloff, personal communication). Horizontal drilling also enhances recovery rates, because both sides of HTD structures are tested with one hole.

The temporal relationship between dolomitization (with or without brecciation) and mineral emplacement have been studied extensively by mining companies (Misra et al., 1996). Dolomitization commonly occurs first and is followed by precipitation of pyrite, calcite, sphalerite, galena, and fluorite, and then localization of hydrocarbons (Misra et al., 1996; Wilcox, 2005). This sequence can vary depending on the number of hydrothermal fluid pulses and the temperature and composition of the fluid (Wilcox, 2005). These relationships can be seen in thin- or polished-section to outcrop-scale exposures and have helped mining companies avoid hydrocarbons. The presence of oil is a hindrance to mining and processing, and can force a company to abandon a prospect (Smith, personal communication). Numerous test cores in Tennessee and HTD outcrops in Kentucky reveal that there commonly are not economic amounts of oil associated with these structures, making them difficult to identify or prospect in the subsurface. Most HTD outcrops in Kentucky have an aerial extent of 0.1 mi². If they were buried to a considerable depth, they would not be positively identifiable in seismic reflection data, because the associated sags and velocity contrasts would be too small.

The potential of other HTD plays is high in the Cumberland Plateau and eastern Highland Rim of southern Tennessee and northern Alabama, because prospecting and drilling in those areas have been very limited. Hydrothermal dolomite has recently been identified in the Catheys-Leipers Formation (Nashville Group) and impact breccias (Devonian) at the Flynn Creek impact structure, but the age, extent, and amount of hydrothermal dolomite is unclear (Evenick, 2006). Other known large and cursorily tested structures are present in the region (e.g., Whisner and Hatcher, 2003) that should be prospected.

Oil Migration into Hydrothermal Dolomite Traps. Comprehension of oil migration processes and timing of emplacement are fundamental to understanding how to prospect and develop potential hydrothermal dolomite plays. Since hydrocarbons are typically the last fluid to migrate into hydrothermal traps (Misra et al., 1996), it is plausible that hydrocarbons are generated in a “baked zone” surrounding the conduits accommodating hydrothermal fluid migration (Fig. 16). The increased temperature would facilitate the localized generation of oil that would be proportional to the temperature and amount of hydrothermal fluid, the organic content of surrounding host rocks, and the aperture and density of fracture zones. The generated hydrocarbons would then migrate into the fluid pathway and up-section into the highest suitable structural or stratigraphic trap. The inferred lag time between hydrocarbon sourcing and migration into the HTD traps would explain the presence of bitumen in vugs and the lack of oil inside Tennessee’s MVT deposits that have had early-stage quartz, pyrite or calcite cementation (Misra et al., 1996; Smith, personal communication).

Construction of Reservoir Probability Maps. The construction of reservoir probability maps is also a component toward which we have been working throughout the project, and with the breakthroughs in log correlation and defining structures beneath the Chattanooga unconformity,

Figure 16. Schematic cross section of a hydrothermal dolomite trap associated with a transpressional fault and timing of hydrocarbon migration.

we feel that construction of probability maps for exploration within the Ordovician petroleum system possible.

CONCLUSIONS

1. All current milestones have been met. We also have been effecting the ultimate goal of the project in the dissemination of information through presentations at professional meetings, convening a major workshop in August 2003, and publication of results.
2. Our work in geophysical log correlation in the Middle Ordovician units is bearing fruit both revealing that the criteria developed locally in Tennessee and southern Kentucky have much greater extensibility than anticipated earlier.
3. We have identified a major 60 mi-long structure in the western part of the Valley and Ridge thrust belt, the Eureka structure, which has been successfully tested by a local independent company and is now producing commercial quantities of hydrocarbons. If this structure is productive along strike, it will be one of the largest producing structures in the Appalachians.
4. We established a new exploration and geologic model of the Valley and Ridge, Cumberland Plateau, and eastern Highland Rim. This should yield major dividends in future exploration in the southern Appalachian basin.
5. Our work in mapping, retrodeformation, and modeling of the Sevier basin is a major component of the understanding of the Ordovician petroleum system in this region. Prior to our undertaking this project, this system was the least understood in the Appalachian basin.
6. We have made numerous presentations, convened a workshop, and are disseminating our results in scientific journals.
7. This project, in contrast to many if not most programs undertaken in DOE laboratories, has a major educational component wherein three Ph.D. students have been partially supported, one M.S. student partially supported, and another M.S. student fully supported by the grant. These students are well prepared for professional careers in the oil and gas industry.

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Employed by Humble Oil and Refining Company (now ExxonMobil). Served on the faculties of Clemson University, Florida State University, the University of South Carolina, and the University of Tennessee (joint appointment at the Oak Ridge National Laboratory, 1986–2000). More than 35 years of experience in research on the processes related to the formation of continental crust and mountain chains, concentrating on the southern Appalachians, but with considerable familiarity with the Alps, British and Scandinavian Caledonides, Canadian, and U.S. Cordillera, Argentine and Colombian Andes, and Moroccan Atlas and Meseta. Applied interests and research spinoff in petroleum exploration (South Louisiana, Appalachians), eastern U.S. intraplate seismology, hazardous and radioactive waste management, and engineering geology. Research requires collection of basic geologic data and ability to integrate, manipulate, and interpret geophysical and geochemical data. To date, 160 refereed papers, 8 books, and a tectonic map of the U.S. Appalachians have been published, and some 220 papers have been presented by RDH and coauthors at professional meetings. Serves and has served on numerous advisory committees: National Academy of Sciences (National Research Council) boards and committees; Geological Society of America committees and GSA Foundation Board of Trustees; and as a reviewer of federal, state, and university programs, papers for journals, and proposals for funding by several government agencies. Highest honors received to date include the Geological Society of America Distinguished Service Award (1988), serving as President of the Geological Society of America (1993), President of the American Geological Institute (1996), the I. C. White Foundation Award (1997), being made an honorary citizen by the governor of West Virginia (1998), the John T. Galey Award (2001), the Geological Society of America Penrose Medal (2006), and the American Geological Institute Ian Campbell Medal (2006).

EDUCATION

Vanderbilt University, Nashville, Tennessee

B.A.–1961, M.S.–1962

University of Tennessee, Knoxville, Tennessee

Ph.D.–1965

PROFESSIONAL EMPLOYMENT

Distinguished Scientist and Professor of Geology University of Tennessee Knoxville, Tennessee	2000–Present
Distinguished Scientist and Professor of Geology (Tenure Awarded, 1986) University of Tennessee/Oak Ridge National Laboratory Knoxville/Oak Ridge, Tennessee	1986–2000
Professor of Geology (Tenure Awarded, 1980) University of South Carolina, Columbia, South Carolina	1980–1986
Professor of Geology (Tenure Awarded, 1979) Florida State University, Tallahassee, Florida	1978–1980
North Carolina Geological Survey (Geologic mapping, Part Time)	1974–1980
Georgia Geological Survey (Geologic mapping, Part Time)	1970 (Summer)
South Carolina Division of Geology (Geologic mapping, Part Time)	1966–1982
Professor of Geology Associate Professor of Geology (Tenure Awarded, 1970) Assistant Professor of Geology Clemson University, Clemson, South Carolina	1976–1978 1970–1976 1966–1970
Humble Oil and Refining Company, New Orleans, Louisiana (Geologist, Southeastern Division Stratigraphic–Paleontological Group)	1965–1966
Teaching Assistant University of Tennessee, Knoxville	1962–1965
Tennessee Division of Geology (Geologic mapping, Part Time)	1961–1964 (Summers)

Teaching Assistant Vanderbilt University, Nashville, Tennessee	1960–1962
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HONORS AND APPOINTMENTS

President, Geoclub, University of Tennessee	1962–1963
Sigma Gamma Epsilon, University of Tennessee	Elected 1966
President, Carolina Geological Society	1975
Convenor of Geological Society of America, Penrose Research Conferences	1974, 1976, 1980
President, Clemson University Chapter, Society of Sigma Xi	1975–1976
Associate Editor, Geological Society of America Bulletin	1976–1981
Editor, George Swingle Memorial Issue of Southeastern Geology	1979
Chairman, Southeastern Section Geological Society of America	1978–1979
Geological Society of America Council	1980–1982
International Geological Correlation Program—Caledonide Orogen	1976–1985
Project 27 Secretary, U.S. Working Group and Member of International Working Group	
Editor, Geological Society of America Bulletin (with W. A. Thomas)	1981–1988
Geological Society of America Committees	
Chairman, Technical Program Committee and Technical Program co-Chairman (with C. E. Weaver) for the Atlanta National Meeting	1980
Program Review Committee	1979–1981
Joint Technical Program Committee	1979–1982
Audit Committee	1981–1982
Chairman, Committee on Publications	1981–1983
Committee on Publications	1981–1988
Chairman, Committee on the Arthur L. Day Medal	1982
Committee on the Penrose Medal	1987–1988
Chairman, Committee on Nominations	1988
Chairman, Committee on Committees	1991
Executive Committee and Council:	
Vice President	1991–1992
President	1992–1993
Past President	1993–1994
Executive Director Search Committee	1993–1994
Technical Program Chairman SE Section Meeting	1994–1995
Foundation Board of Trustees and Executive Committee	1999–2004
Honorary Fellows (Chairman, 2003–2005)	2002–2005
Technical Program Committee Chairman SE Section Meeting	2005–2006
Project Director and Chief Scientist, Appalachian Deep Core Hole (ADCOH) Project.	1983–1990
Involved management of \$2M NSF budget for site study and coordination of research efforts of 10 scientists from University of SC, Virginia Tech, Princeton, Stanford, and Columbia Universities.	
Geological Society of America Distinguished Service Award	1988
Elected Fellow, American Association for the Advancement of Science	1989
Chairman, American Geological Institute Committee to Investigate the Need for Accreditation of Geosciences Professional Degrees	1993–1999
National Academy of Sciences Board of Radioactive Waste Management	1990–1997
National Academy of Sciences Committee to Review the Ward Valley, California, LLRW Wilshire Group Objections to the Site	1994–1995
National Academy of Sciences Committee to Review the New York State Low-Level Radioactive Waste Siting Process	1994–1996
Nuclear Regulatory Commission Nuclear Reactor Safety Research Review Committee	1993–1996
National Academy of Sciences National Committee on Geology	1993–1996
American Geological Institute	
President Elect	1994–1995
President	1995–1996
Past President	1996–1997
National Cooperative Geologic Mapping Program Federal Advisory Committee	1996–2002
I.C. White Memorial Award for career contributions	1997
West Virginia honorary citizenship for career contributions	1998
Member, Geological Society of America Foundation Board of Trustees	1999–2003
John T. Gale Award by the Eastern Section of the AAPG	2001
Geological Society of America Penrose Medal	2006
American Geological Institute Ian Campbell Medal	2006

SCIENTIFIC PAPERS ACKNOWLEDGING DOE/NPTO SUPPORT*

- Evenick, J. C., and Hatcher, R. D., Jr., 2006, Geophysically subdividing the Nashville (Trenton) and Stones River (Black River) Groups beneath the eastern Highland Rim and southern Cumberland Plateau in Tennessee and southern Kentucky: Tennessee Division of Geology, Report of Investigations no. 52, 15 p.
- Evenick, J. C., and Hatcher, R. D., Jr., 2006, Differentiating the Nashville-Stones River (Trenton-Black River) Groups carbonate platform facies and hydrothermal dolomite traps: subsurface identification and hydrocarbon emplacement in the southern Appalachians: Oil and Gas Journal – in press as two articles.
- Evenick, J. C., Hatcher, R. D., Jr., and Potter, D. B., Jr., An exploration and geologic model for hydrocarbon emplacement in the southern Appalachian basin (in prep).
- Evenick, J. C., Hatcher, R. D., Jr., Whisner, S. C., Whitmer, N. E., and Bultman, J. G., A synthesis of the Middle Ordovician basin in the southern Appalachian basin (in prep).
- Evenick, J. C., Mei, S., Baker, G. S., and Hatcher, R. D., Jr., Trend surface residual anomaly mapping and well data: An underutilized combination? (in prep).
- Hatcher, R. D., Jr., 2004, Properties of thrusts and upper bounds for the size of thrust sheets *in* McClay, K. R., ed., Thrust tectonics: American Association of Petroleum Geologists Memoir.
- Hatcher, R. D., Jr., Lemiszki, P. J., and Whisner, J. B., in review, Boundaries and internal deformation in the curved southern Appalachian foreland fold-thrust belt: Geological Society of America Special Paper.
- Whisner, J. B., and Hatcher, R. D., Jr., 2003, Detachment folds and triangle zones —Unexplored hydrocarbon potential along the eastern Cumberland Escarpment, Tennessee: Oil and Gas Journal, July 28, 2003 issue, p. 38–44.

*Copies submitted to Mark P. Dvorscak, DOE, 9800 Cass Avenue, Argonne, IL 60439 behind Form NETL F 510.1-5.

PROJECT-RELATED PAPERS PRESENTED AT PROFESSIONAL MEETINGS

Whisner, J. B., and Hatcher, R. D., Jr., 2002, Developing a regional 3D model of deformation in the Valley And Ridge Province, East Tennessee: American Association of Petroleum Geologists, Abstracts with Programs, p. A42., v. 11, p. A-189.

The Tennessee salient is a foreland-convex map-scale curve in the southern Appalachians extending from southwest Virginia to northwest Georgia. Regional hydrocarbon exploration has focused on the fold-thrust belt portion of the salient since discovery of the Swan Creek oil and gas field in a subthrust structure in northeast Tennessee. The present understanding of regional stratigraphy/basin development as well as the kinematics of the salient result in part from construction and palinspastic restoration of serial, balanced 2D cross sections. Factors vital to understanding the development of structures such as the Swan Creek Field, but not always included in these 2D sections include the potential regional effects of basement faults, facies boundaries, and out-of-sequence thrusts. In addition, 2D cross sections cannot account for strike-parallel movement required by a regional radial thrusting model, which is suggested by both the orientation of map-scale folds and faults, and kinematic indicators such as small-scale fold geometry, cleavage, and calcite twin strain analyses. A 3D model of the salient can incorporate these complexities and address questions about the kinematic development of structural traps. New cross sections constructed with the aid of recently available industry 2D seismic reflection lines are combined to develop a 3D volume-balanced regional model for deformation. This model is then used to evaluate different kinematic models, proposed out-of-sequence thrusting, the possible timing and location of hydrocarbon generation and migration, and predict possible locations of complex structural plays in the fold-thrust belt.

Evenick, J. C., and Hatcher, R. D. Jr., 2003, Potential Ordovician hydrocarbon plays in the Cumberland Plateau of Tennessee and southern Kentucky: Finding a needle in a haystack?: American Association of Petroleum Geologists, Eastern Section Meeting Abstracts, v. 87, p. 23.

The hydrocarbon potential of the Cumberland Plateau has been explored for over a century with most discoveries to date being small oil or gas fields in Mississippian limestone reservoirs sourced by the Devonian-Mississippian Chattanooga Shale. The underlying Knox and Middle-Upper Ordovician (Stones River or Black River Group, and Nashville or Trenton Group) carbonate rocks, however, have only been cursorily explored, with only minimal success in Tennessee. The historic success of the Rose Hill field in southwest Virginia, other fields in Middle Ordovician rocks farther northeast, and the recent development of the Swan Creek field in the Knox and Middle Ordovician rocks in northeastern Tennessee indicate there is greater potential in the Middle and Upper Ordovician rocks beneath the Cumberland Plateau. The source of these hydrocarbons is the Ordovician rocks (gas chromatography by R. Burruss, USGS). Deformed zones related to previously unmapped blind faults and décollements may locally enhance an otherwise primarily porosity-dominated province. Research currently underway intends to identify markers (other than the known K-bentonites) in geophysical logs that will permit detailed resolution of units in the Stones River and Nashville Groups. These units have been mapped in surface exposures on the Nashville dome and in the western Valley and Ridge, as well as in the Sequatchie anticline that dissects the central and southern Plateau in Tennessee. Such resolution will provide new opportunities to better understand the structure and reservoir characteristics in the subsurface beneath the Plateau and Eastern Highland Rim of East Tennessee and southern Kentucky.

Whitmer, N. E., Hatcher, R. D., Jr., Whisner, S. C., Whisner, J. B., Thigpen, J. R., and Bultman, J. G., 2003, Middle Ordovician clastic wedges in East Tennessee: A new look at an old basin: American Association of Petroleum Geologists, Eastern Section Meeting Abstracts, v. 32.

Two Middle-Upper Ordovician (Taconian) clastic wedges formed in the southern and central Appalachians: the Blountian (Sevier, Middle Ordovician) and the Martinsburg-Tuscarora (Upper Ordovician to Early Silurian). Several depositional models have been proposed for each. We are constructing a 3-D model for the Blountian basin in Tennessee and adjacent states and reevaluating existing models. Development of a 3-D model of the Middle Ordovician clastic wedge in East Tennessee permits reexamination of current models of syn/post-Taconic orogenic basin dynamics. Within this basin major facies changes, both along and across strike, have been previously recognized but not examined in mapping context. Detailed geologic mapping, and stratigraphic and structural analysis are being conducted in selected areas where Blountian basin deposits are preserved in several Alleghanian synclines. 1:24,000- and 1:12,000-scale mapping facilitate more precise delineation of facies distributions and refined correlations of units in the Middle Ordovician Chickamauga Group. Two-dimensional industry seismic reflection data and detailed mapping permit a reevaluation of stratigraphic thickness estimates, previously considered as much as 10,000 ft. More quantitative estimates of Alleghanian structural geometries and stratigraphic thicknesses will yield viable palinspastic restorations of basin and facies geometries. Paleocurrent

indicators in carbonate bank and basin facies are being employed for the first time to determine sediment dispersal and sources. Facies distributions and source areas are particularly important if tectonic and thermal loading of Middle Ordovician black shales are a source of hydrocarbons in carbonate reservoirs farther west.

Bultman, J. G., Hatcher, R. D., Jr., and Whitmer, N. E., 2004, Reexamination of the Sevier-Blountian basin through detailed geologic mapping, structural and stratigraphic analysis: Bays Mountain synclinorium, northeastern Tennessee: American Association of Petroleum Geologists, Eastern Section Meeting Abstracts, p. 66.

One key to understanding the development of the Middle Ordovician southern Appalachian Sevier-Blountian basin lies in detailed geologic mapping. Key subdivisions have been identified that permit more accurate estimates for the thickness of the Sevier Shale. New detrital zircon and existing sedimentological data suggest the Sevier-Blountian basin is a back-bulge basin. Detrital zircon analyses from Ordovician to Pennsylvanian foreland clastics reveal few Paleozoic zircon cores until the Devonian and Carboniferous, indicating late Paleozoic unroofing of the southern and central Appalachians. Palinspastic reconstructions of the Alleghanian foreland fold-thrust belt require the Sevier-Blountian basin to be formed as much as 300 km inboard from the Middle Ordovician Laurentian margin. Furthermore, easterly derived conglomerate in the lower third of the section on the eastern flank of the basin is composed predominantly of Cambrian-Ordovician platform carbonates, and includes fewer 1.1 Ga basement and Cambrian rifted-margin and platform clasts. Regional isopachs and previously unidentified structural features in the basin may identify locations and migrations of the palinspastically restored forebulge and back-bulge basin. Isopach maps and 2-D backstripping curves would provide additional evidence for timing, possible depocenter migration, and subsidence rates for the basin. Facies and thickness information from new detailed geologic mapping helps define the role the back-bulge played in tectonic loading and deposition rates. A new model for Sevier-Blountian basin dynamics has been formulated based on our new data that better delineates thickness and facies variations.

Evenick, J. C., and Hatcher, R. D., Jr., 2004, Identifying possible Pre-Chattanooga structures in the Cumberland Plateau of Kentucky and Tennessee using trend-surface residual anomaly maps: American Association of Petroleum Geologists, Eastern Section Meeting Abstracts, v. 88, p. 77.

New maps have been constructed for the Cumberland Plateau of Kentucky and Tennessee to investigate the possibility of Pre-Chattanooga structures in the Ordovician rocks beneath the Plateau. The main horizons mapped include the tops of the Nashville (Trenton/Lexington), Stones River (Black River/High Bridge), and Knox Groups along with the Chattanooga Shale and the Millbrig (Mud Cave) and Deicke (Pencil Cave) bentonites. Other mapped units include the Wells Creek Dolomite, Copper Ridge Dolomite, Conasauga Group, Rome Formation, and top of basement, although limited data in the region limit the usefulness of these maps. Overall, trend-surface residual anomaly (TSRA) maps are a more accurate mapping technique/filter that enables subtle structures to be more accurately identified. The TSRA maps were constructed from standard structure contour maps and 1st- and 2nd-order trend surfaces. The maps identify numerous isolated small-scale structures across the Cumberland Plateau (that are probably not connected) that could be targets for future exploration. The western Valley and Ridge of Tennessee (west of the Whiteoak Mountain-Clinchport thrust) should also be explored further. We have shown that the existing Rose Hill and Swan Creek fields are producing from Ordovician reservoirs that have identical geophysical well log signatures as those subsurface Nashville-Stones River units beneath the Cumberland Plateau.

Evenick, J. C., Hatcher, R. D. Jr., and Whisner, J. B., 2004, Continuity of C. W. Wilson's Middle Ordovician stratigraphy from the Nashville dome to the footwall of Whiteoak Mountain-Clinchport thrust: Key to understanding the Middle Ordovician (Trenton-Black River) petroleum system: Geological Society of America Abstracts with Programs, v. 36, no. 2, p. 118.

The Middle Ordovician carbonate bank facies of C. W. Wilson (Nashville/Trenton and Stones River/Black River Groups) have been described in detail and mapped from the Nashville dome through the subsurface beneath the Cumberland Plateau, using well log geophysical signatures, to the western Valley and Ridge in TN, southern KY, and southwestern VA. The sequence above the Knox unconformity consists of the discontinuous Wells Creek (Blackford, Douglas Lake) Dolomite, massive Murfreesboro Limestone, thin-bedded Pierce Limestone, Massive Ridley Limestone, thin-bedded Lebanon Limestone, and massive Carters Limestone containing the Deicke and Millbrig bentonites near the top to comprise the Stones River Group. The silty/shaly Hermitage Formation, massive Bigby-Cannon Limestone, and shaly Catheys Formation comprise the Nashville Group. The Bigby-Cannon Limestone and the lower Stones River Group are known oil-producing intervals. These facies extend into the Valley and Ridge to the footwall of the Clinchport-Whiteoak Mountain thrust system from E of Chattanooga, TN into SW

VA. To the E, the thin platform carbonate bank facies changes to a thickened, more bank-edge facies then to a very thick siliclastic basin facies. The thickening carbonate facies marks the approximate western edge of the Taconic back-bulge (Middle Ordovician) and foreland (Upper Ordovician) basins. Palinspastically restored cross sections locate the eastern edge of the Ordovician carbonate bank 50-75 km E of the Clinchport–Whiteoak Mountain fault, at approximately today's TN-NC border. Recognition of the continuity in stratigraphy over this wide an area has both stratigraphic and tectonic implications, but also is important because the Stones River–Nashville Groups are known hydrocarbon producers and comprise a definable petroleum system. The region W of the Clinchport–Whiteoak Mountain fault system lies in the oil/gas window.

Hatcher, R. D., Jr., Whisner, S. C., Bream, B. R., Miller, C. F., Heath, M. A., II, 2004, Sediments derived from mountain chains do not always land in foredeeps: Southern Appalachian Sevier-Blountian basin dynamics: Geological Society of America Abstracts with Programs, v. 36, no. 2, p. 92.

The Middle Ordovician southern Appalachian Sevier–Blountian clastic wedge filled a basin that extended from GA to VA. From TN into VA the Late Ordovician Martinsburg basin, likely the central Appalachian foredeep, is a successor atop the Sevier–Blountian basin. Clastics in both were derived from the southern Appalachian-central Appalachian internides, earlier termed “tectonic land,” Taconian highlands, or obducted arc; both basins were called foredeeps. Clasts in conglomerates at the same stratigraphic level on the eastern flank of the basin are composed predominantly of Cambro-Ordovician platform carbonates, with some 1.1 Ga basement, and Lower Cambrian rifted-margin clastics. Twenty-four Middle Ordovician Sevier Shale detrital zircon ion microprobe analyses contain only pre-Paleozoic cores, duplicating ages from nearby rifted margin detrital zircon analyses. Detrital zircon analyses from Ordovician to Pennsylvanian clastics derived from the southern Appalachian and central Appalachian internides (Gray and Zeitler; Eriksson et al.; Becker et al.) reveal few Paleozoic cores until the Carboniferous, indicating late Paleozoic unroofing of the southern and central Appalachians. The easterly source must be an uplifted part of the Laurentian rifted margin—probably the peripheral bulge in front of the obducting Early to Middle Ordovician (480-460 Ma) volcanic arc-ocean crust. Palinspastic reconstructions of the Alleghanian foreland fold-thrust belt, Blue Ridge-Piedmont thrust sheet, and pre-Alleghanian terranes, require that the Sevier–Blountian basin formed as much as 300 km from the Middle Ordovician Laurentian margin, not adjacent to the obducted oceanic crust. The Sevier–Blountian basin is more likely a modified back-bulge basin, more similar to that NW of the Taranaki retroarc foredeep NW of New Zealand than to a classic foredeep. A better candidate for the southern Appalachian Middle Ordovician foredeep basin is the Mineral Bluff sequence preserved above an unconformity in the Murphy syncline in the Blue Ridge-Piedmont sheet in NC and GA. Paleozoic uplift of the Cincinnati arch peripheral bulge may have begun with Late Middle Ordovician to Late Ordovician uplift in response to formation of the Martinsburg foredeep.

Whisner, J. B., Hatcher, R. D., Jr., Merschat, A. J., Bultman, J. G., Evenick, J. C., Gatewood, M. P., Stahr, D. W. III, Thigpen, J. R., Whitmer, N. E., and Wilson, C. G., 2004, 3-D reconstruction of Alleghanian structure of the Appalachian foreland fold-thrust belt, NW Georgia to SW Virginia around the Tennessee salient: Geological Society of America Abstracts with Programs (SE-NE Section Meeting), v. 36, no. 2, p. 139.

New balanced serial cross sections have been constructed across the Appalachian foreland fold-thrust belt (FFTB) from the Cumberland Plateau into the western Blue Ridge (BR) around the TN salient from NW GA to SW VA. These sections are based on surface geology, well data, and seismic reflection data. The cross sections record the changing character of Alleghanian deformation both along and across the salient. Cross sections were imported into 3DMove to connect major structures and fault surfaces in a 3D reconstruction of the FFTB, and to attempt some 3D balancing. The number of major faults in the Valley and Ridge increases south into TN from VA to a maximum of ten at the narrowest part of the salient, near Knoxville, TN, then decreases again south into GA. The basal detachment through most of the FFTB lies in the Cambrian Rome Fm, though it ramps into shallower units on the west side of the FFTB, and downward into basement east of the Pulaski fault. Restorations suggest that total shortening in the FFTB is close to 60%, greater than the previously estimated 45-55%. From the Saltville fault west, deformation is dominated by imbricate faulting; south of Harriman, TN, a large subsurface detachment fold lies just west of and below the imbricate zone. East of the Saltville fault folding dominates surface deformation, but structure below the Middle Ordovician Tellico-Sevier syncline is much more complex than previously thought. Industry seismic reflection data reveal details of previously unknown imbricate and duplex geometries. The BR-Valley and Ridge transition is marked by a NE-trending set of en echelon duplexes of Cambro-Ordovician Valley and Ridge rocks arching the BR thrust sheet from the GA/TN border (Ducktown antiform) to the Foothills duplex to NE TN and SW VA (Mountain City window) and east into NC (Shooting Creek, Hot Springs, and Grandfather Mountain windows). In the Hot Springs window, an uninterrupted section of rocks from Middle Cambrian to Precambrian

Ocoee Supergroup is folded by underlying duplexes. Frontal duplexes are consistently oriented 10-20 degrees west of the trace of the frontal BR thrust. The occurrence and location of the sub-BR duplexes may be influenced by localization of the BR thrusts in basement and Chilhowee Group rocks to the north, versus Chilhowee Group and Ocoee Supergroup rocks to the south.

Bailey, J. R., Evenick, J. C., Hatcher, R. D., Jr., and Weyland, H. V., 2005, Possible hydrothermal dolomite reservoir(s) in the Swan Creek field, Tennessee: American Association of Petroleum Geologists, Eastern Section Meeting Abstracts, v. 89, p. 16.

A possible subsurface hydrothermal dolomite reservoir has recently been identified in the Swan Creek field, northeastern Tennessee. Swan Creek field is in a blind, faulted anticline located beneath the shallow-dipping Clinchport thrust wherein small displacement duplex imbricates partly localize production. A structural low is superposed on the northwestern flank of an anticline that contains a pronounced increase in dolomite in the lower and middle Stones River (Black River) Group, but hydrocarbon production from surrounding wells is from the top of the Stones River (Carters Limestone). The structural low is evident in maps contoured from top of the Lebanon Limestone downward into the Knox Group, but is not present in younger horizons. Dolomitization probably occurred prior to Alleghanian folding and faulting, but deformation may have localized the hydrothermal zone and hydrocarbons, and did not breach and drain the reservoir. Production probably results from secondary enhanced porosity not cemented by late-stage, pre-Alleghanian fluid migration and mineralization. Trends in hydrothermal fluid migration related dolomite porosity have long been recognized in the zinc districts in Tennessee. For hydrothermal dolomite plays, drilling off structure may be better than drilling on structure. Locating this structure in Swan Creek was as a result of secondary target development, with the Knox Group the original primary target. Oil shows are widespread in Swan Creek in the Stones River and Nashville Groups, but most oil production here is from these dolomites. Wells associated with this hydrothermal event and proximity to their off-structure locations, and disproportionate high cumulative volumes, warrant special economic considerations and investigation.

Evenick, J. C., and Hatcher, R. D., Jr., 2005, Evidence for a décollement soled in the Chattanooga Shale in the southern Appalachian Plateau: Geological Society of America, Southeastern Section, Abstracts with Programs, v. 37, no. 2, p. 34.

To the northwest of the Wartburg basin (a region historically known for hydrocarbon production in Tennessee and Kentucky), trend surface residual anomaly (TSRA) maps illustrate deformational changes with respect to depth that may be caused by a décollement soled in the Chattanooga Shale. Horizons above the Chattanooga Shale TRSA map show pronounced linear trends parallel to regional strike, possibly indicating blind deformation associated with Alleghanian faulting. Mapped horizons below the Chattanooga Shale do not have these linear trends, signifying the units are below a detachment or that the trends were not able to be represented due to smaller amounts of data. Other detachment structures with more associated deformation and larger displacements are known to exist in the region (i.e., the Pine Mountain thrust and Cumberland Plateau overthrust). Hence, it is possible that a lower décollement is associated with these structures (e.g., the Cumberland Plateau overthrust could be soled in the Chattanooga Shale and ramp up-section into Mississippian and Pennsylvanian strata in different areas). This hypothesis could explain the tectonic stylolites identified west of Sequatchie valley, in Mississippian strata and faults soled in the Pennington Group (Mississippian) at Short Mountain, Tennessee. Lastly, the region northwest of the Wartburg basin corresponds to a possible small rift basin (identified in a Knox Group – basement isopach map) that connects with the Rome trough to the northwest. It is uncertain what role, if any, this structure had on petroleum sourcing, migration, and later deformation in the area.

Evenick, J. C., Hatcher, R. D., Jr., Kah, L. C., Labotka, T. C., and Weyland, H. V., 2005, Hydrothermal dolomites in the southern Appalachian basin: Ideal reservoirs with inherent exploration difficulties: American Association of Petroleum Geologists, Abstracts with Programs, p. A42.

Hydrothermal dolomite plays have become a prominent exploration target in the Appalachian basin. Large known hydrothermal dolomite fields in the Michigan and Illinois basins (i.e., Albion-Scipio and Lima-Indiana trends) and smaller fields in the northern Appalachian basin (i.e., Glodes Corner field, NY) have illustrated that these are ideal reservoirs and petroleum targets. Consequently, interest has been growing in the southern Appalachian basin pertaining to the potential of similar hydrothermal dolomite plays. Occurrences of “light bulb or dolomite chimney structures” in eastern Kentucky and Tennessee indicate that these targets are also present within Ordovician strata, but reservoir size and quality have not been adequately addressed. Most of the documented hydrothermal dolomite structures are associated with the Rome trough fault system in Kentucky (mostly surface exposures) and subsurface Mississippi Valley type ore deposits in Tennessee (Gordonsville and Mascot-Jefferson

City mining districts). Exploration and development difficulties of these reservoirs include: 1) known semi-linear structures are typically small in horizontal extent (less than 0.2 km²); 2) their small size make them difficult to delineate in the subsurface because they are below the seismic imaging resolution; 3) larger structures are represented by sagging up-section reflectors that may get confused with synclines; 4) oil is not always associated with these structures; and 5) XRD and thin-section analyses from an exposed structure suggest that secondary dolomitization increased porosity of the immediate area within and around the structure, but also produced authigenic clays (smectite) and silica, which may hinder petroleum extraction.

Hatcher, R. D. Jr., Evenick, J. C., and Weyland, H. V., 2005, Pre-Chattanooga (Devonian-Mississippian black shale) structure and Nashville (Trenton) - Stones River (Black River) hydrocarbon production in Tennessee, Kentucky, and southwestern Virginia: American Association of Petroleum Geologists, Eastern Section Meeting Abstracts, v. 89, p. 24.

The Nashville (Trenton) and Stones (Black) River Groups comprise one of the major petroleum systems in the Appalachian basin, and have been productive for decades. Reservoirs in Tennessee, Kentucky, and southwestern Virginia are in limestones of variable porosity (both primary and secondary), with oil production most commonly from the lower and upper Stones River Group (Murfreesboro and Lebanon) and middle Nashville Group (Bigby-Cannon). A disconformity with variable amounts of erosion separates the two groups. Some areas that should be productive are not, while others for which geologic data exist that should not be productive turn out to be productive. An additional variable is compressional structures that formed prior to formation of the pre-Chattanooga (Devonian-Mississippian black shale) unconformity. These structures consist of folds and faults truncated by the unconformity, and are most easily documented on the surface. Numerous examples are published in Tennessee Division of Geology quadrangle geologic maps, and we have also mapped them in the subsurface beneath the eastern Highland Rim and Cumberland Plateau where adequate well control exists. These structures were tilted by subsequent uplift on the Nashville dome and Cincinnati arch, superposing a southeast regional dip that in some cases may cause spilling of potential traps, in others increasing the opportunities for survival of hydrocarbons. These structures should be considered as possible additional structural traps throughout the Appalachian basin.

Evenick, J. C., and Hatcher, R. D., Jr., 2006, A new geologic model for the southern Appalachian basin and the continuation of the Rome trough southward and Sequatchie Valley thrust northward into northern Tennessee: Geological Society of America, Southeastern Section, Abstracts with Programs, v. 38, no. 3, p. 10.

Hydrocarbon exploration in the Cumberland Plateau is difficult because there are inadequate data to generate new geologic models. Regional-scale subsurface structures that have been identified (such as the Eureka structure in the western Valley and Ridge) have not been systematically investigated, which reflects a general reluctance to test deeper targets. This is mainly due to most oil and gas production in Tennessee and Kentucky is from shallow Mississippian and Ordovician limestones. Well data and new regional cross sections, however, indicate there are also shallow targets in the region that have not been prospected. We propose that the Rome trough continues southward from East-central Kentucky into northern Tennessee, but the full extent of the structure cannot be resolved because of paucity of seismic and basement well data. The trough exhibits a pronounced thickening of the Rome and Conasauga Formations (up to 2,000 ft) and a linear low in Precambrian-Ordovician trend surface residual anomaly (TSRA) maps. It is also proposed that Sequatchie Valley (SV) thrust extends northward beneath part of the Wartburg basin, based on well data and cross-section interpretation. In the Wartburg basin the Knox Group is shallower than expected, when compared to its elevation West of the Pine Mountain thrust. It is possible the extrapolated SV fault has not been identified before because most wells stop in Knox Group and no wells have yet drilled through the repeated section. The SV thrust is projected to ramp up-section in the northern part of the Wartburg basin and sole into the Chattanooga Shale, because the unit is structurally weak and the Pennsylvanian strata are not folded at the surface. This would also help explain a series of northwest-trending TSRA trends above the Chattanooga Shale that may correlate with blind structures, the marked thickening of the Chattanooga Shale (up to 300 ft) northwest of the Pine Mountain thrust, and tectonic stylolites suggesting pressure solution in the Mississippian section west of Sequatchie anticline where there are no known structures below the Cumberland Plateau overthrust.

Evenick, J. C., and Hatcher, R. D., Jr., 2006, Exploration targets in the southern Appalachian basin: Geological Society of America, Southeastern Section, Abstracts with Programs, v. 38, no. 3, p. 11.

The southern Appalachian basin is separated into three provinces (Highland Rim, Cumberland Plateau, and Valley and Ridge). These provinces have been prospected for nearly two centuries with limited success because

regionally the reserves are small, limited basement data leading to an incomplete geologic model, and very sparse well and seismic coverage. In the Valley and Ridge, the few wells drilled primarily target gas in the Sevier Shale and oil in the Middle Ordovician carbonates (i.e., Swan Creek field and Eureka structure). Potentially shallow targets and low leasing costs make it desirable to test structures in this region, but very few have been tested. The Cumberland Plateau, however, has been heavily drilled, but most of the drilling is clustered in a few counties. Prospecting has usually been based on “feel” rather than on following a model. There are numerous drilling targets in the Plateau; some of the most common drilling targets are gas from Pennsylvanian coal seams, oil and gas from Mississippian limestones, gas from the Chattanooga Shale, oil from the Middle Ordovician carbonates, and gas from the Upper Knox Group. Few deep tests have been conducted in the area because of the large amount of shallower pay horizons. Deep potential gas (i.e., in the Rome trough in Kentucky and Tennessee) and possible hydrothermal plays are present in the region, but the paucity of seismic data makes difficult any justification for large-scale exploration of these plays. The absence of prospecting has also greatly hindered development of a geologic model for the southern Cumberland Plateau, especially west of the Sequatchie anticline. In the Highland Rim, most of the prospecting is focused on regionally large oil and gas reserves found in the Middle Ordovician carbonates; with drilling depth being around 1,500 ft, it is not surprising that most of the recent prospecting in the southern Appalachian basin is done in this region.