Assessing Undiscovered Resources of the Barnett-Paleozoic Total Petroleum System, Bend Arch–Fort Worth Basin Province, Texas*

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ABSTRACT

Organic-rich Barnett Shale (Mississippian-Pennsylvanian) is the primary source rock for oil and gas that is produced from Paleozoic reservoir rocks in the Bend Arch–Fort Worth Basin Province. Areal distribution and geochemical typing of hydrocarbons in this mature petroleum province indicates generation and expulsion from the Barnett at a depocenter coincident with a paleoaxis of the Fort Worth Basin. Barnett-sourced hydrocarbons migrated westward into reservoir rocks of the Bend Arch and Eastern shelf; however, some oil and gas was possibly sourced by a composite Woodford-Barnett total petroleum system of the Midland Basin from the west.

Current U.S. Geological assessments of undiscovered oil and gas are performed using the total petroleum system (TPS) concept. The TPS is composed of mature source rock, known accumulations, and area(s) of undiscovered hydrocarbon potential. The TPS is subdivided into assessment units based on similar geologic characteristics, accumulation type (conventional or continuous), and hydrocarbon type (oil and (or) gas).

Assessment of the Barnett-Paleozoic TPS focuses on the continuous (unconventional) Barnett accumulation where gas and some oil are produced from organic-rich siliceous shale in the northeast portion of the Fort Worth Basin. Assessment units are also identified for mature conventional plays in Paleozoic carbonate and clastic reservoir rocks, such as the Chappel Limestone pinnacle reefs and Bend Group conglomerate, respectively. However, Barnett continuous gas is expected to add the greatest volume of undiscovered, technically recoverable resource. Undiscovered Barnett Shale gas will be assessed after mapping "sweet spots" and outlying areas of hydrocarbon potential, and by defining distributions of drainage (cell) size and cell estimated ultimate recovery. An example of a Barnett "sweet spot" is the Greater Newark East area where thick, siliceous Barnett has reached the gas window, and is overlain and underlain by impermeable limestones that contain fractures that are induced during completion.

INTRODUCTION AND BACKGROUND

Oil and gas in the Bend Arch–Fort Worth Basin Province (U.S. Geological Survey Province 045; see definition in a later section) of north-central Texas are produced from carbonate- and clastic-rock reservoirs ranging in age from Ordovician to Permian (Wolfcampian). The 1995 USGS

National Oil and Gas Assessment (1995 USGS Assessment) of undiscovered, technically recoverable oil and gas identified six conventional plays in the Bend Arch-Fort Worth Province (Ball and Perry, 1996) that are listed in Table 1. The cumulative mean undiscovered resource for the five conventional plays (Table 1) that were assessed was as follows: 381 million barrels of oil (MMBO), 103.6 million barrels of natural gas liquids (MMBNGL), 479 billion cubic feet (BCF) associated gas, and 1,029 BCF non-associated gas. In addition, an unconventional, continuous-type (Schmoker, 1996), hypothetical "Mississippian Barnett Shale" play was identified by Ball and Perry (1996) but not assessed due to lack of data.

1995 Play Number	1995 Play Designation	2003 Assessment Unit No. (see figure 4)	2003 Proposed Assessment (AU) Unit Designation
Conventional Plays and Assessment Units			
4501	Pre-Mississippian	1	Ordovician Carbonate Oil and Gas AU
4502	Mississippian Carbonate	2	Mississippian Pinnacle Reef Oil and Gas AU
		3	Pennsylvanian Carbonate Bank and Reef Limestone Oil and Gas AU
4504	Lower Pennsylvanian (Bend) Sandstone and Conglomerate	4	Pennsylvanian Fluvial-Deltaic Sandstone and Conglomerate Oil and Gas AU
4505	Strawn (Desmoinesian)		
4505	Post Desmoinesian	5	Upper Pennsylvanian/Permian Clastic Oil and Gas AU
Continuous-Type Plays and Assessment Units			
4503	Mississippian Barnett Shale (Hypothetical)	6	Greater Newark East Fractured Siliceous Shale Gas AU
		7	Ellenburger Subcrop Fractured Barnett Shale Gas AU
		8	North Basin and Arch Fractured Shale Gas and Oil AU

Table 1. Plays identified in the 1995 USGS National Oil and Gas Assessment (after Ball and Perry, 1996) and proposed assessment units (AU) for 2003 USGS National Oil and Gas Assessment of the Barnett-Paleozoic Total Petroleum System, Bend Arch-Fort Worth Basin Province. Assessment unit number also indicates time span of stratigraphic units shown on Figure 4.

Continuous-type accumulations include fractured shale and fractured chalk oil and gas, basin-centered gas, coal bed gas, and tight reservoir gas (Figure 1). Continuous-type accumulations typically cover large areas, have source rocks in close association with these unconventional reservoir rocks, and are mostly gas (and in some cases oil) charged throughout their extent (Schmoker, 1996). Continuous accumulations commonly have transition zones (Figure 1) that grade into more conventional accumulations (Schenk and Pollastro, 2001).

Subsequent to the 1995 USGS Assessment, Schmoker and others (1996) and Kuskraa and others (1998) estimated undiscovered (also referred to as undeveloped), technically recoverable gas for the continuous Barnett fractured shale play. Using a cell-based methodology Schmoker and others (1996) estimated a mean undiscovered gas of about 3.4 trillion cubic feet (TCF). Using a similar methodology, Kuskraa and others (1998) modified the input values using more recent estimated ultimate recovery (EUR) and cell-size (drainage area) data for Barnett wells and reported a mean undiscovered volume of about 10 TCF for the Barnett. Although these mean estimates of undiscovered gas for the continuous Barnett Shale play have been 'labeled' USGS assessments, they are not official USGS resource numbers. However, the results of these studies, and more recent studies (Bowker, 2002) indicate that the continuous fractured Barnett Shale may contain the greatest undiscovered resource in the Bend Arch-Fort Worth Basin Province.

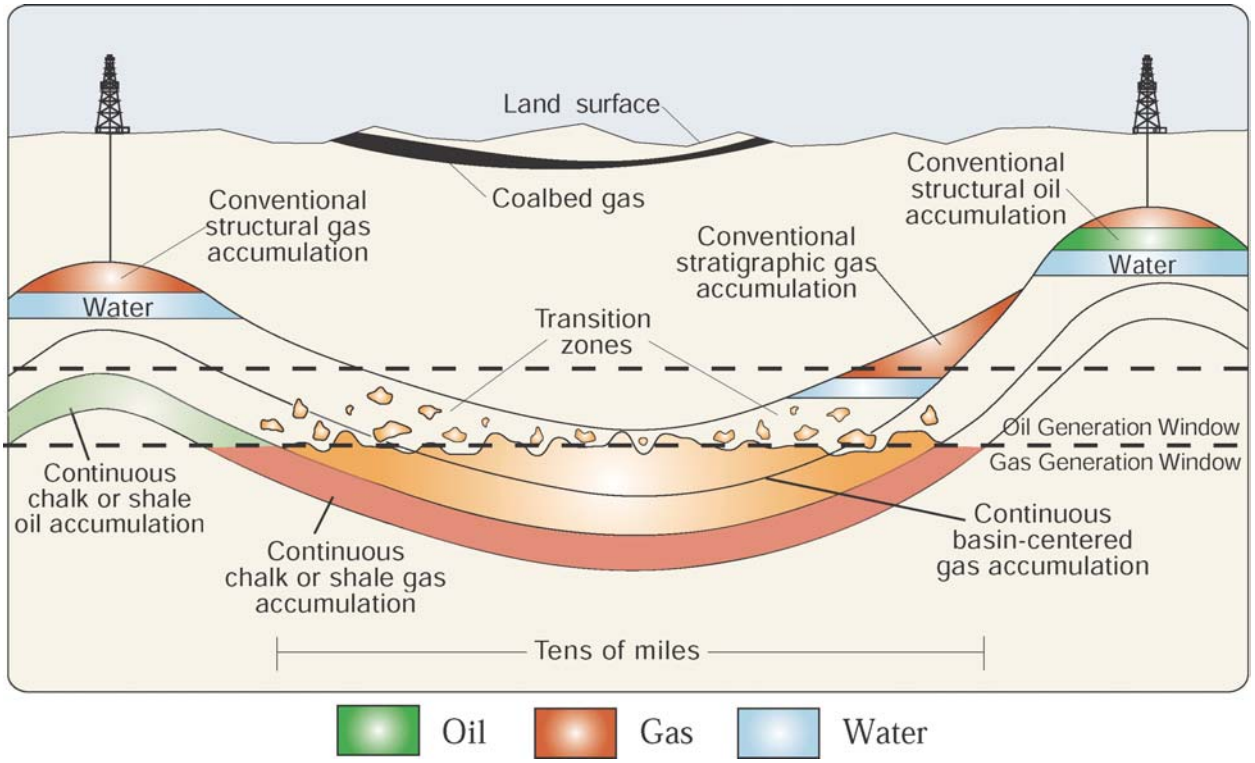

Figure 1. Generalized diagram showing categories of conventional and continous oil and gas accumulations. The continuous chalk or shale oil and gas accumulations in the diagram are representative of mature, fractured Barnett Shale in the Bend-Arch Fort Worth Basin Province. Modified from Schenk and Pollastro (2001).

Current USGS assessments incorporate the total petroleum systems–assessment unit (TPS-AU) method (Klett et al., 2000; Magoon and Schmoker, 2000) to estimate undiscovered oil and gas rather than the play concept method used in 1995 (Gautier et al., 1996). The total petroleum system (TPS) includes all of the elements of the petroleum system originally defined by Magoon and Dow (1996), but also incorporates those resources of the petroleum system that are yet to be discovered (Figure 2). The TPS-AU approach is preferred (USGS World Petroleum Assessment 2000) over the play-level approach because the former incorporates the assessment unit within a higher context level of the TPS. Moreover, the AU is based on similar geologic elements and hydrocarbon accumulation type and may also represent a play or group of plays. This allows for a greater understanding of the essential elements and processes within the TPS that relate to source, generation, migration, accumulation, and trapping of the undiscovered resource.

Petroleum geochemistry studies by Jarvie and others (2001), Jarvie and Claxton (2002), and in this report indicates that the organic-rich Barnett Shale is the primary source rock for oil and gas produced from reservoirs of Paleozoic age in the Bend Arch-Fort Worth Basin Province. Using the TPS methodology, a Barnett-Paleozoic TPS is defined here for the purpose of assessing undiscovered hydrocarbon resources of USGS Province 045 (Gautier et al., 1996); although the

Hardeman and Sherman (Marietta) Basins lie partly within the province, they are not included. Accordingly, it is the purpose of this report to briefly describe the geology, geochemistry, and methodology for assessing undiscovered oil and gas resources in both conventional and continuous accumulations of the Barnett-Paleozoic TPS of the Bend Arch-Fort Worth Basin Province. Although some hydrocarbon potential remains in conventional assessment units, assessment of this TPS focuses particularly on the Barnett Shale continuous accumulation, which is where the greatest undiscovered resource is expected within USGS Province 045.

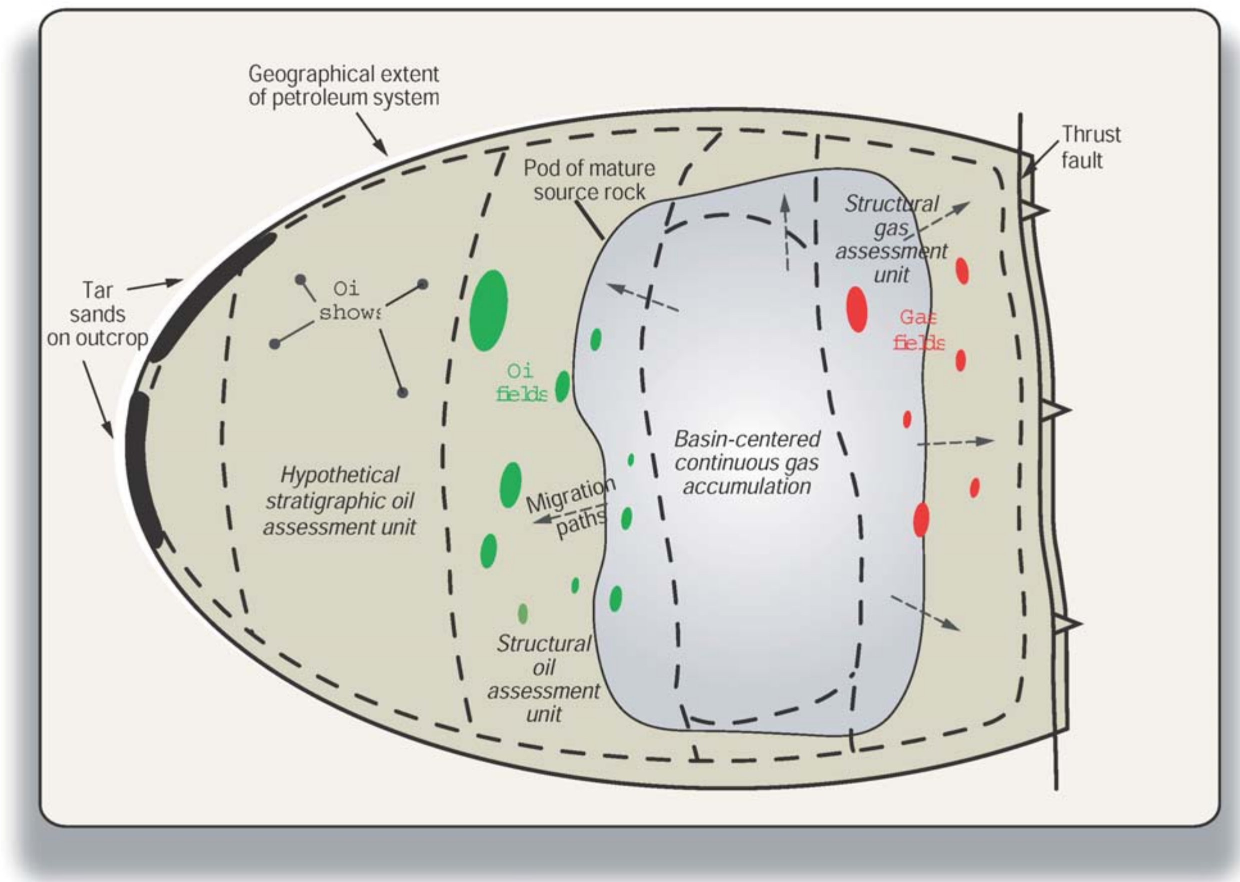

Figure 2. Schematic plan view of a Total Petroleum System showing pod of mature source rock, distribution of known petroleum occurrences, and boundaries of the conventional- and continuous-type assessment units.

PROVINCE BOUNDARY, STRUCTURAL ELEMENTS, AND TECTONIC HISTORY

The boundary of USGS Province 045, Bend Arch-Fort Worth Basin, is defined by State and county lines that closely follow U.S. Congressional Districts, rather than by geologic elements. However, the Province boundary generally follows the Ouachita structural front to the east and southeast, the Llano Uplift to the south, and the Texas-Oklahoma State line (the Red River) to the north (Figure 3). The western boundary trends north-south along county lines that define the junction with the Permian Basin Province (USGS Province 044) where part of the eastern shelf of the Permian Basin is included in the Bend Arch-Fort Worth Basin Province (Figure 3).

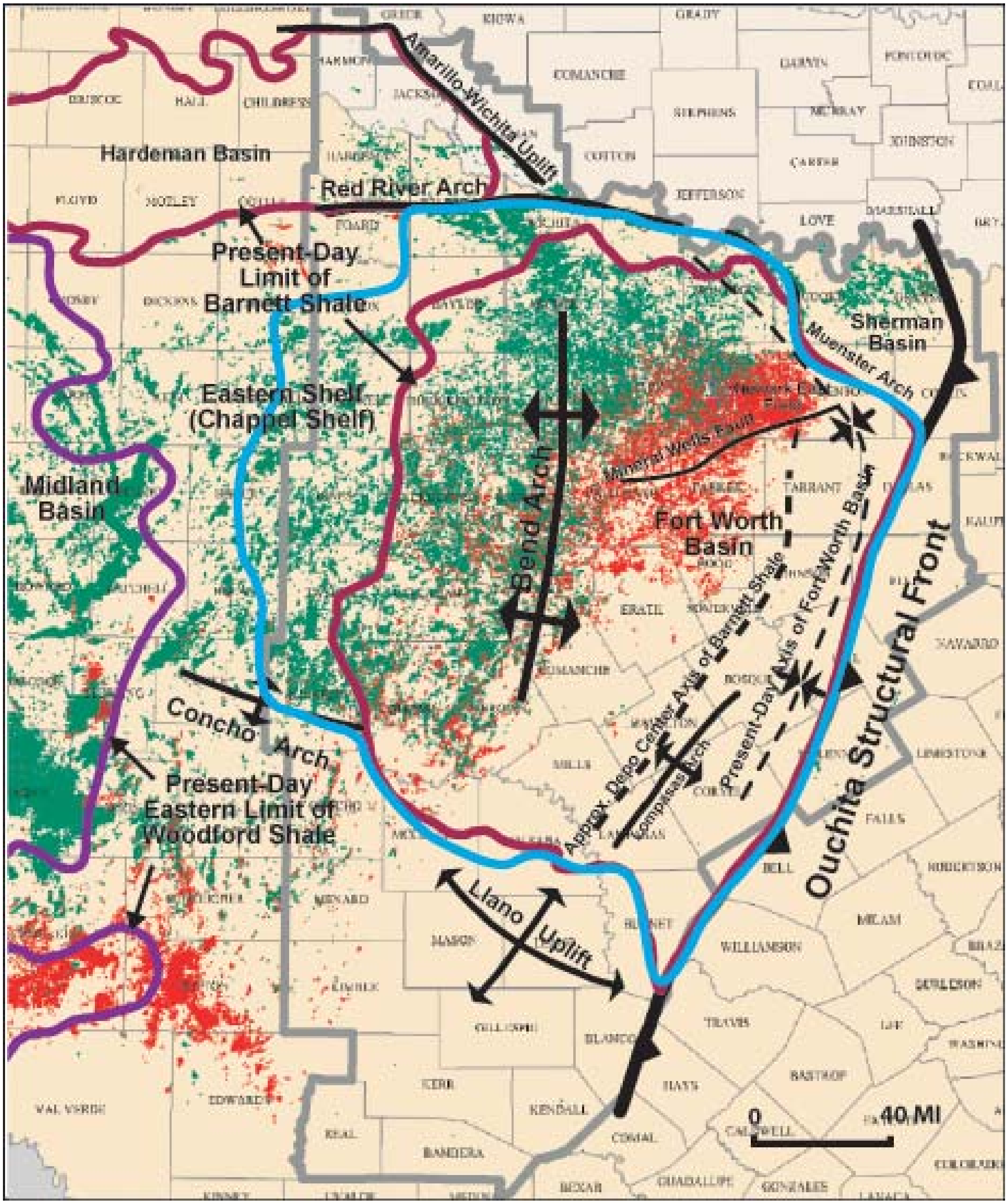

Figure 3. Map showing major structural elements (black lines), oil (green dots) and gas (red dots) well production, location of Newark East Field, and boundary of USGS Bend Arch-Fort Worth Basin Province (gray line). Red lines show present-day limit of Barnett Shale (Mapel et al., 1979) and purple lines are eastern limit of Woodford Shale (Comer, 1991). Blue line approximates the boundary of the Barnett-Paleozoic Total Petroleum System.

Major structural features of USGS Province 045 include the Muenster and Red River Arches to the north, and the Bend and Lompasas Arches along the central part of the Province. Along the eastern portion of the province is an area that includes the Eastern and Chappel Shelves and Concho Arch, collectively also known as the Concho Platform (Figure 3). The Mineral Wells fault runs northeast-southwest through Palo Pinto, Parker, Wise, Denton Counties and joins with the Newark East fault system. The fault system bisects the Newark East Field to create a zone of poor production in Barnett Shale gas reservoirs (Figure 3). Several faults that cut basement and lower Paleozoic rocks in the southern part of the province have been identified at the Ordovican Ellenburger Group stratigraphic level. These faults and associated structures formed during the development of the Llano Uplift and Fort Worth Basin with faulting ending by early Missourian time (Browning and Martin, 1982: Flippen, 1982).

The evolution of the Fort Worth Basin and Bend Arch structures are critical to understanding burial histories and hydrocarbon generation of the Barnett-Paleozoic TPS. The asymmetrical, wedge-shaped Fort Worth Basin is a peripheral Paleozoic foreland basin with about 12,000 ft of strata preserved in its deepest northeast portion and adjacent to the Muenster Arch and Ouachita structural belt; the approximate location of its present-day axis is shown in Figure 3. The basin is similar to other basins of the Ouachita structural belt, such as the Black Warrior, Arkoma, Val Verde, and Marfa Basins that formed in front of the advancing Ouachita structural belt as it was thrust onto the margin of North America. Thrusting occurred during a late Paleozoic (Late Mississippian and Early Pennsylvanian time) episode of plate convergence (Flippen, 1982).

The Bend Arch extends northward from the Llano Uplift; it is a broad subsurface, north-plunging, positive structure. The arch formed as a hingeline by (1) down-warping of its eastern flank due to subsidence of the Fort Worth Basin during early stages of development of the Ouachita structural belt in the Late Mississippian, and (2) westward tilting in the late Paleozoic, which formed the Midland Basin. There is some disagreement on the structural history of the Bend Arch. Flippen, (1982) suggested that it acted as a fulcrum and is a flexure and structural high and that only minor uplift occurred in the area to form the unconformable surface above the Comyn Limestone. In contrast, Cloud and Barnes (1942) suggested that periodic upwarp of the Bend flexure from mid-Ordovician through Early Pennsylvanian time resulted in several erosional unconformities. The Red River Arch and the Muenster Arch also became dominant structural features during Late Mississippian and Early Pennsylvanian time (Flippen, 1982).

GENERAL STRATIGRAPHY AND PETROLEUM PRODUCTION HISTORY

The stratigraphic section of the Bend Arch–Fort Worth Basin Province is generalized in Figure 4. Producing intervals, vertical distribution of total petroleum system elements, and proposed assessment units for the Barnett-Paleozoic TPS are also shown in Figure 4. Oil and gas production from rocks of Ordovician, Mississippian, and Early Pennsylvanian age in the TPS is mostly from carbonate rock reservoirs, whereas production in the Middle Pennsylvanian through Lower Permian part is mostly from clastic rock reservoirs (Figure 4).

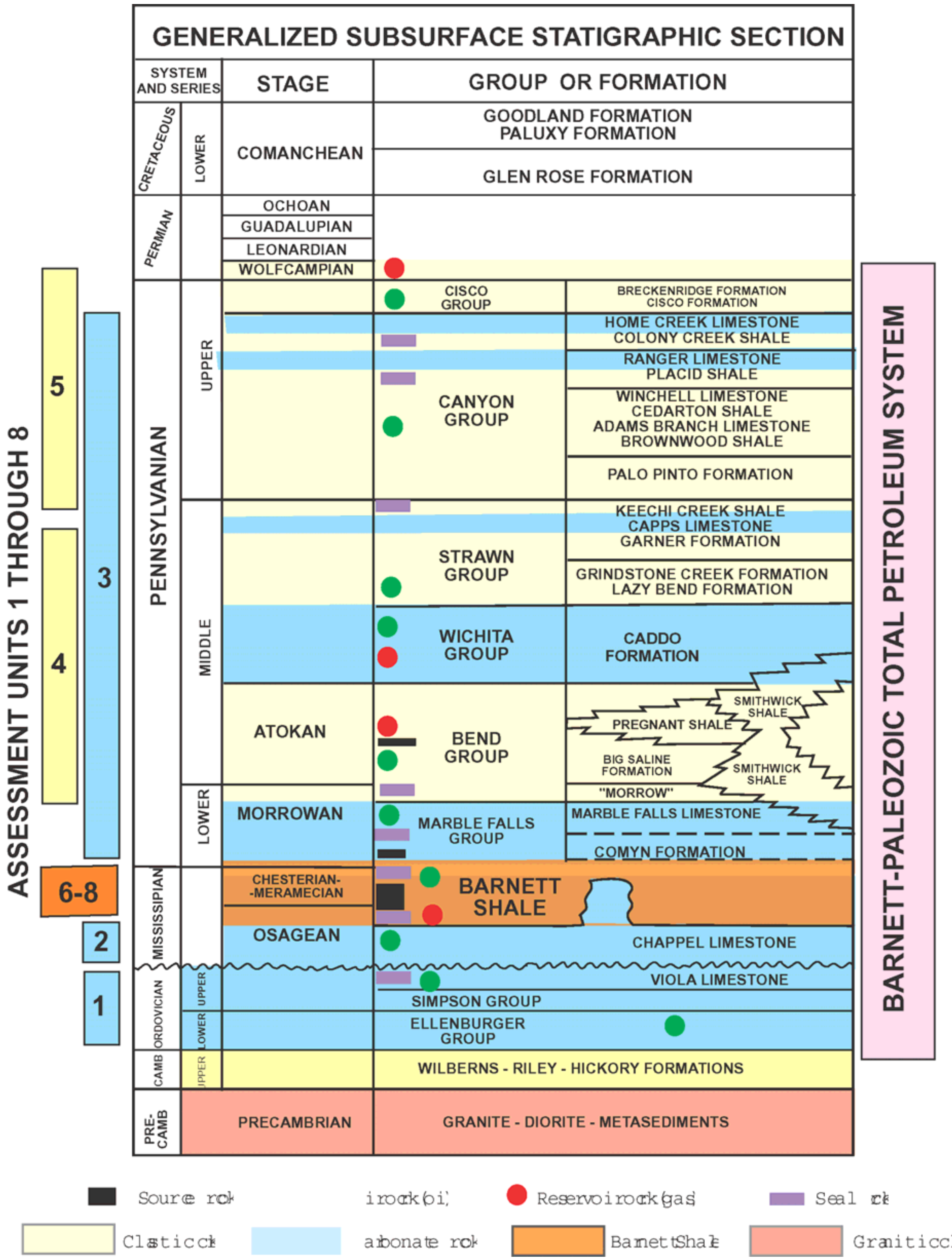

Figure 4. Generalized stratigraphic subsurface section of USGS Bend Arch-Fort Worth Basin Province showing stratigraphic extent of Barnett-Paleozoic Total Petroleum System, source rocks, producing oil and gas reservoir units, seal rocks, and proposed assessment units. Assessment unit numbers refer to those listed in Table 1.

The sedimentary section in the Fort Worth Basin is underlain by Precambrian granite and diorite. Cambrian rocks include granite conglomerate, sandstones, and shale that are overlain by marine carbonate rocks and shale (Flippen, 1982). No production has been reported from Cambrian rocks. The Silurian, Devonian, Permian, Jurassic, and Triassic are absent in the Fort Worth Basin (Flippen, 1982).

From Cambrian to Mississippian time, the area that is now the Fort Worth Basin was part of a stable cratonic shelf with deposition dominated by carbonates (Burgess, 1976). Ellenburger Group carbonate rocks represent a broad epeiric carbonate platform that covered virtually all of Texas during the Early Ordovician. A pronounced drop in sea level at the end of Ellenburger deposition resulted in prolonged platform exposure and development of extensive karst features in the upper part of the carbonate rock sequence (Sloss, 1976; Kerans, 1988). Moreover, a later major erosional event removed any Silurian and Devonian rocks (Figure 4; post Viola Limestone unconformity) that may have been present in that area (Henry, 1982).

The Barnett Shale was deposited over the resulting unconformity. Provenance of the terrigenous material that constitutes the Barnett Shale was from Ouchita thrust sheets and the reactivation of older structures such as the Muenster Arch. Clastic rocks of similar provenance dominate the Pennsylvanian part of the stratigraphic section in the Bend Arch-Forth Worth Basin. With progressive subsidence of the basin during the Pennsylvanian, the western basin hinge line and carbonate shelf, represented by carbonate rocks of the Comyn, Marble Falls, Big Saline, and Caddo Formations, continued to migrate westward. Deposition of the thick basinal clastic rocks of the Atoka, Strawn, and Canyon Formations occurred at this time (Walper, 1982). These Middle and Late Pennsylvanian age rocks consist mostly of sandstones and conglomerates with fewer and thinner limestone beds (Figure 4). Wolfcampian age sandstones also produce oil and gas along the western portion of the USGS Province 50 and on the Bend Arch, Eastern Shelf, and Concho platform.

Shows of oil and gas were first encountered within Bend Arch-Fort Worth Basin Province during the mid-nineteenth century while drilling water wells. Some petroleum exploration began at the end of the Civil War, and the first commercial oil discoveries occurred in the early 1900's (Ball and Perry, 1996). By 1960, USGS Province 045 reached a mature stage of exploration and development, as demonstrated by the high density and distribution of well penetrations (see Ball and Perry, 1996), and production wells (Figure 3).

Cumulative production in USGS Province 045 from conventional reservoirs prior to the 1995 USGS Assessment was about 2 billion barrels of oil (BBO) and 7 trillion cubic feet of gas (TCFG). Cumulative gas production through 2001 from the continuous Barnett fractured shale play in Wise and Denton counties was about 440 BCF (Swindell, 2002). Cumulative gas production from the Barnett Shale for the first half of 2002 was 94 BCF (Texas Railroad Commission, 2202); annual production for 2002 is estimated to be about 200 BCF. Currently, more than 2.5 TCF of proven gas reserves are assessed for Newark East Field (Bowker, 2002). These recent production and proven reserve numbers for the Barnett play, combined with the estimates of undeveloped Barnett resources in the studies by Schmoker and others (1996) and Kuuskraa and others (1998), indicate that technically recoverable continuous gas, and to a lesser extent oil, from fractured Barnett Shale will provide the greatest additions to near-future reserves in the Bend Arch-Fort Worth Basin Province.

BARNETT-PALEOZOIC TOTAL PETROLEUM SYSTEM

General

Oil and gas is produced from reservoirs rocks of Paleozoic age within USGS Province 045. Organic geochemical analyses of samples of oil and gas from the Fort Worth Basin from this study and those reported by Jarvie and others (2001), indicate that these hydrocarbons were derived from a single source rock, the Barnett Shale. Thus, we have designated a Barnett-Paleozoic Total Petroleum System for USGS Province 50. An approximate boundary of the Barnett-Paleozoic TPS of the Bend Arch-Fort Worth Basin Province is shown in Figure 3. Because the Woodford Shale is also a major source rock in the Midland Basin to the west (Figure 3), we suspect that a composite Woodford-Barnett TPS is present in that area. Therefore, additional geochemical analysis of hyrocarbons from reservoirs on the Eastern Shelf and Concho Platform are needed to refine the western boundary of the Barnett-Paleozoic TPS. Total petroleum system elements (source, reservoir, traps, seals, maturation, thermal and burial histories) of the Barnett-Paleozoic TPS are discussed below and summarized in Figures 4 and 5.

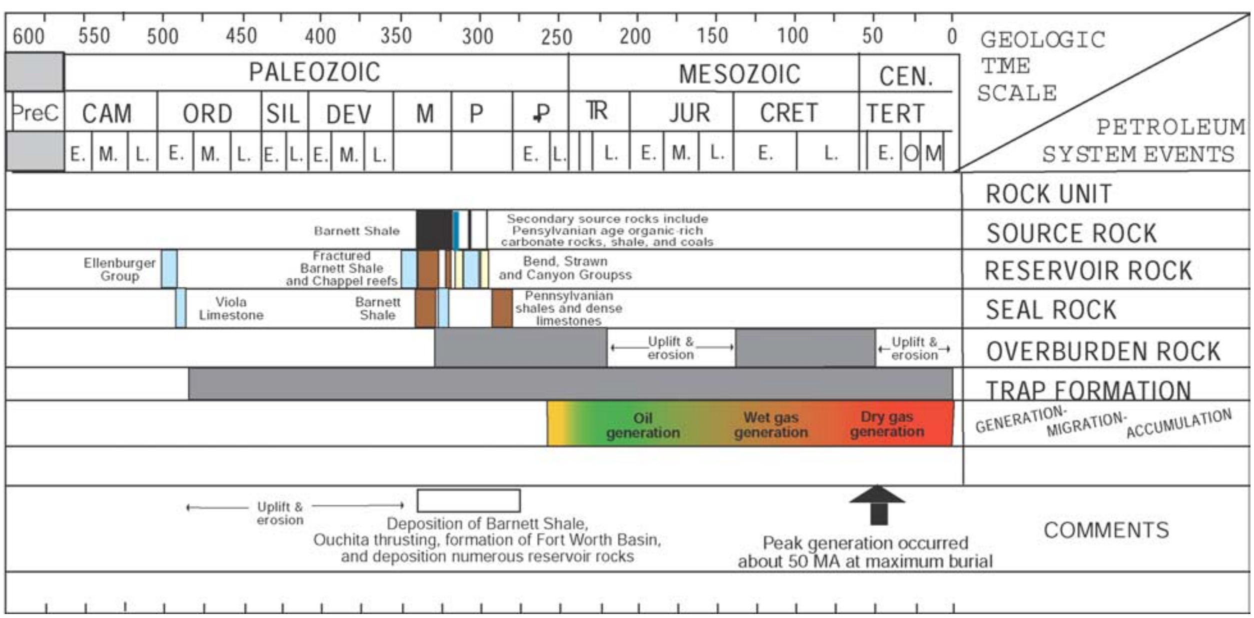

Figure 5. Events chart for Mississippian-Pennsylvanian Barnett-Paleozoic Total Petroleum System (TPS) of the Bend Arch-Fort Worth Basin Province, Texas, showing TPS elements and timing of trap formation and hydrocarbon generation. Also see stratigraphic chart of Figure 4. Hydrocarbon generation models were summarized and modified from Jarvie et al. (2001).

Source Rock, Thermal Maturity, and Hydrocarbon Generation

The primary source rock of the Bend Arch-Fort Worth Basin is the Mississippian-Pennsylvanian Barnett Shale. The Barnett Shale commonly exhibits high gamma-ray log response at the base of the unit (or basal “hot shale”). Other potential source rocks of secondary importance (Figure 4) are of Early Pennsylvanian age and include (1) dark fine-grained carbonate rock and shale units within the Marble Falls Limestone, (2) black shale facies of the Smithwick Shale (Walper, 1982;

Grayson et al., 1991), and (3) several thin Pennsylvanian age coal beds in Wise, Jack, Young, Parker, Palo Pinto, and McCulloch Counties (Mapel et al., 1979).

The Barnett Shale source rock was deposited over a large part of North-Central Texas; however, because of post-depositional erosion the present distribution of the Barnett is limited to the Bend Arch-Forth Worth Basin Province (Maple et al., 1979). The Barnett Shale is more than 1,000 ft thick along the southwest flank of the Muenster Arch (Maple et al., 1979; Henry, 1982). The Barnett Shale is present within the Midland, Delaware, and Palo Duro Basins to the west and the Hardeman Basin to the north (Figure 3). A smaller Barnett total petroleum system is probably present in the Hardeman Basin to the north (Figure 3). The Barnett Shale is eroded in areas (1) along the Red River-Electra and Muenster Arches to the north, (2) along the Llano uplift to the south where it outcrops, and (3) along the easternmost portion of USGS Province 045 where the Barnett laps onto the Eastern Shelf-Concho Platform (Figure 3). Small isolated remnants of Barnett Shale have been identified on the unconformity surface of the Ordovician Ellenburger Group carbonate rocks in the western most part of the USGS Province 045). The Barnett is absent in the Sherman Basin to the northeast, and absent east of the Ouachita Thrust Belt (Figure 3).

Average total organic carbon (TOC) content in the Barnett Shale is about 4% (by weight) and TOC is as high as about 12% in samples from outcrops along the Llano uplift on the south flank of the Fort Worth Basin (Henk et al., 2000; Jarvie et al., 2001). The highest average TOC for the Barnett Shale appears to follow a depocenter that is coincident with a paleo-axis of the Fort Worth Basin (Figure 3).

The Barnett Shale has geochemical characteristics similar to other Devonian-Mississippian black shales found elsewhere in the U. S. (e.g., Woodford, Bakken, New Albany, and Chattanooga Formations). These black shales all contain oil-prone organic matter (Type II kerogen) based on hydrogen indices greater than 350milligrams of hydrocarbons per gram of TOC and generate a similar type of high quality oil (low sulfur, >30 API gravity). Oils found in the far western and northern portions of USGS Province 50 are all typed as Barnett-sourced oils. Although decomposition of kerogen cracking is a source of oil and gas from the Barnett Shale, the principal source of gas in the Newark East Field is from cracking of oil and bitumen (Jarvie et al., 2001).

Low levels of maturation in the Barnett Shale at vitrinite reflectance (R_o), estimated at 0.6-0.7%, yields oils of 38^o API gravity in Brown County. The oils found in Shackelford, Throckmorton, and Callahan Counties as well, as in Montague County (Figure 3), are derived from the Barnett Shale at the middle of the zone of oil generation (oil window) thermal maturities levels (about 0.9% R_o). Although condensate is associated with gas production in Wise County, the Barnett source rock maturity is generally 1.1% R_o or greater. The zone of wet gas generation (condensate or wet gas window) is in the 1.1-1.4% R_o range, whereas the primary zone of dry gas generation (main gas window) begins at a R_o of 1.4%.

Thermal maturity of Barnett Shale can also be derived from TOC and Rock-Eval (T_{max}) measurements. Although T_{max} is not very reliable for high maturity kerogens due to poor pyrolysis peak yields and peak shape, the extent of kerogen transformation can be utilized. For example, Barnett Shale having a 4.5% TOC and a hydrogen index of less than 100 is in the wet or dry gas windows with equivalent R_o values greater than 1.1% TOC

Little or no data are available on the variability of the Barnett Shale organic matter content and type outside of Newark East Field (Figure 6). Average values for low maturity Barnett Shale ($T_{max} < 435^oC$) are about 3.26% TOC using well cuttings. This same set of samples has initial hydrocarbon potentials of about 172 barrels of oil per acre feet (BO/AF), which are dramatically lower than expected for the Barnett Shale. This is probably due to a mixing of terrestrial plant organic matter on the edges of the basin with marine organic matter common to the Barnett.

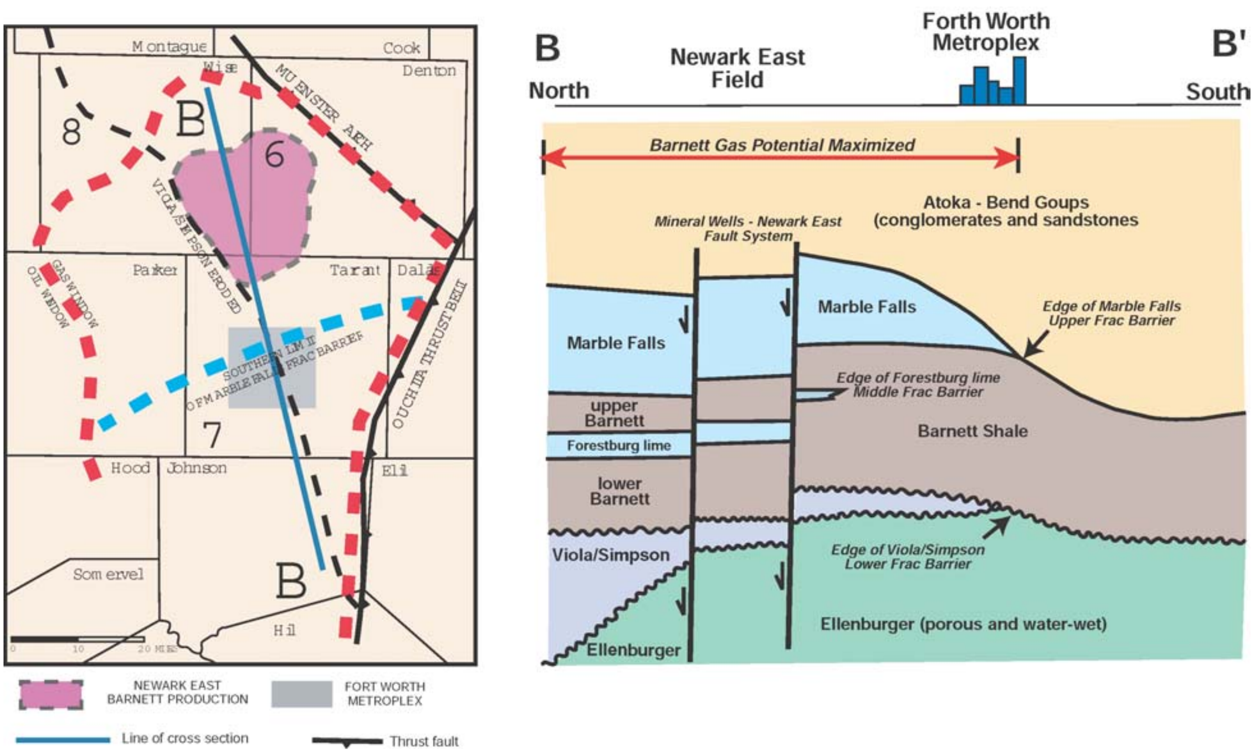

Figure 6. (A) Location map and (B) generalized cross section AA' of north Fort Worth Basin area showing main gas- producing area of continuous Barnett Shale accumulation at Newark East field and the various geologic conditions. Large bold numbers in (A) relate to the proposed continuous Barnett Shale assessment units of Table 1. Gas window in (A) approximates zone of gas generation, and oil window approximates zone of oil generation. Modified from Hall (2002) and Bowker (2002).

In contrast, low maturity Barnett Shale from outcrops in Lampasas County have initial TOC values averaging about 12% with hydrocarbon potentials averaging 1035 BO/AF. A good average value for the Barnett Shale is derived from the Mitcham #1 well in Brown County in which TOC is measured at 4.2% and the hydrocarbon potential is 354 BO/AF. Using these data we can determine that the TOC values will decrease 36% during maturation from the immature stage to the gas-generation window. Samples from the T. P. Simms well in the Newark East gas-producing area have average TOC values of 4.5%, but greater than 90% of the organic matter is converted to hydrocarbons. Thus, its original TOC was about 7.0% with an initial estimated potential of 593 BO/AF. Any oil generated would be (1) expelled into shallow (or deeper) horizons as in the west and north, or (2) cracked to gas where measured vitrinite reflectance is greater than 1.1% R_o.

This study found a poor correlation between measured R_o and present-day burial depth for the Barnett Shale, as did Bowker (2002). Vitrinite iso-reflectance contours commonly cross-cut both basin structure and structure contours on the top of the Barnett Shale. Similarly, samples of Barnett Shale in the deepest part of the Fort Worth Basin along the southwest flank of the Muenster Arch in Denton County, record lower R_o than the shales at shallower depths to the east and in Newark East Field. Also, north of Lampasas County, rock samples along the Ouchita thrust front have higher R_o than those from greater present-day depths. Thus in many areas of the Bent Arch-Fort Worth Basin Province, thermal maturity of the Barnett Shale determined from R_o appears to be influenced strongly by heat-flow regimes generated from Ouchita thrusting.

The Barnett Shale is thermally mature for hydrocarbon generation over most of its area within USGS Province 045 (Figure 3). The Barnett source rock is presently in the oil-generation window along the north and west parts of the province, and in the gas window on the east half of the Barnett-Paleozoic TPS (Figure 6). Expulsion of high-quality oil from the Barnett was episodic and began at low (R_o = 0.6%) thermal maturity (Jarvie et al., 2001). Thirty-two oils from Wise and Jack Counties were sampled and analyzed to determine the characteristics of the generating source rock. API gravity and sulfur content were integrated with high-resolution gas chromatography (GC) and gas chromatography mass spectrometry (GCMS) analyses. The API gravity of the oils ranges from 35° to 62° and sulfur contents are low (<0.2%), which is characteristic of high thermal maturity oils. Biomarkers from GCMS analyses show that the oils were sourced from marine shale, based on sterane distribution and the presence of diasteranes. Carbon isotopic analyses of the saturated and aromatic hydrocarbon fractions support hydrocarbon generation from a single-source unit. Although more work is required on oils of lower thermal maturity, the hydrocarbons in Wise and Jack Counties were most likely sourced from the Barnett Shale.

In the main gas-producing area of fractured Barnett Shale, the gas generation window is along a trend that is sub-parallel to the Ouchita thrust front (Bowker, 2002). Jarvie and others (2001) and Bowker (2002) reported that the British Thermal Unit (BTU) content of Barnett gas is directly proportional to R_o levels. Oil and gas windows for the Barnett source rock in proximity to Newark East Field are shown in Figure 6.

Reservoir Rocks

Reservoir rocks of the Barnett-Paleozoic TPS include both clastic and carbonate rocks ranging in age from Ordovician to Early Permian (Wolfcampian); they are listed in the stratigraphic section and total petroleum system distribution chart of Figure 4. Most production from conventional reservoirs is from rocks of Pennsylvanian age, whereas the only recognized production from an unconventional (continuous) accumulation is from the Mississippian-Pennsylvanian fractured Barnett Shale. Conglomerate of the Pennsylvanian Bend Group is the main producing reservoir at giant Boonsville Field of Wise and Jack Counties with cumulative production through 2001 of more than 3 TCFG (Swindell, 2002). Jarvie and others (2001) reported that oil sourced from the Barnett Shale is produced from numerous reservoir rocks in the Bend Arch-Fort Worth Basin, including Barnett Shale, Caddo Formation, Canyon Group, Chappel Limestone, Bend Group,and Ellenburger Group (Figure 4). Additional reservoir rocks of the Barnett-Paleozoic TPS considered in this report are in the Viola Limestone, Marble Falls Limestone, Atoka Formation, Strawn Group, and Cisco Group (Figure 4). Historical production summaries for many of these reservoirs are given in Ball and Perry (1996).

Seal Rocks

Seal rocks in the Barnett-Paleozoic TPS are mostly shale units and dense, low permeability carbonate rock (Figure 4) that are distributed on both regional and local scales. The Barnett Shale is a major regional seal for older reservoirs, mostly porous carbonate rock reservoirs of the Ellenburger Group. Production from the Barnett Shale is largely dependent on the presence or absence of Marble Falls and Viola limestones (Figure 4). Although these formations are not considered seal rocks in areas where they are tight and not water wet, they serve as barriers (Figure 6) to confine hydraulic-induced fracturing (referred to as frac barriers) and help retain formation pressures during well stimulation (Bowker, 2002; Shirley, 2002).

Traps

Traps for conventional hydrcocarbon accumulations are mostly stratigraphic for carbonate rock reservoirs and both structural and stratigraphic in clastic-rock reservoirs. Combination structural and stratigraphic traps are also common in Pennsylvanian sandstone reservoirs. Stratigraphic traps in carbonate rocks result from (1) a combination of facies and depositional topography, (2) erosion, (3) updip pinchout of facies, and (4) diagenetically controlled enhanced-permeability and porosity zones. A good example of a carbonate stratigraphic trap is the pinnacle reef traps of the Chappel Limestone (Figure 4), in which local porous grainstone and packstone are restricted to isolated buildups or reef clusters on low-relief paleotopography of the eroded Ellenburger Group. Chappel pinnacle reefs are draped and sealed by the overlying Barnett Shale. Stratigraphic traps in Atoka Formation sandstones and conglomerates are mainly pinch outs related to facies changes or erosional truncation. Structural traps for Pennsylvanian-age sandstones and conglomerate reservoir rocks are mainly simple anticlines and fault-bounded anticlines.

PROPOSED ASSESSMENT UNITS FOR THE BARNETT-PALEOZOIC TPS

The USGS assesses conventional accumulations using distributions of size and number of oil and gas fields. In contrast, continuous-type accumulations are assessed using a distribution of both well-cell size (drainage area) and well EURs (Schmoker et al., 1996). Five conventional assessment units are initially proposed for the Barnett-Paleozoic TPS in the Bend Arch-Fort Worth Basin Province and are listed in Table1; these assessment units are also compared with plays defined for the 1995 USGS Assessment. Most historical production in USGS Province 045 has been from extensively explored conventional clastic reservoirs of Pennsylvanian age, particularly the conglomerates and sandstones of the Bend Group (Morrowan and Atokan) and fluvial-deltaic sandstones of the Strawn Group (Desmoinesian) (Figure 3).

Continuous accumulations commonly cover large geographic areas. Thus, multiple assessment units are commonly defined for a particular continuous accumulation, such as the Barnett Shale, which commonly are based on differences primarily with regard to (1) geologic facies, thickness, structure; (2) hydrocarbon type; (3) organic geochemistry; (4) thermal maturation (oil- and gas-generation windows); (5) drainage area; and (6) well production (EUR). For example, assessment units that define "sweet spots" commonly have greater near-future resource volume potential because drainage areas are commonly smaller and have higher mean well EUR than other areas of lesser potential. The Greater Newark East Field is a Barnett continuous gas "sweet spot." Preliminary proposed assessment units for continuous Barnett Shale gas and oil are listed in Table 1.

FRACTURED BARNETT SHALE CONTINUOUS OIL AND GAS

Oil and gas are produced from fractured Barnett Shale in the Bend Arch-Forth Worth Province. High-quality (35-40° API gravity, low sulfur) oil is produced from the Barnett Shale in northern and western portions of the province where the Barnett exhibits low thermal maturity (R_o about 0.6%). Oils of similar quality (40-50° API gravity), and condensates associated with gas are produced in Wise County where the Barnett is of higher thermal maturity. Gas production is from hydraulically-fractured black siliceous shale. Calorific values of gases from Newark East Field are commonly in the range of 1,050-1,300 BTU (Jarvie and Claxton, 2002).

The main producing facies of the Barnett is a black, organic-rich siliceous shale with a mean composition, by weight, of about 45% quartz, 27% clay (mostly illite/smectite, and illite), 10% carbonate (calcite, dolomite, and siderite), 5% feldspar, 5% pyrite, and 5% TOC (Lancaster et al., 1993; Henk et al., 2000; Bowker, 2002). Average porosity in the productive portions of the Barnett is about 6% and matrix permeability is measured in nanodarcies (Lancaster et al., 1993; Bowker, 2002).

The lithology and petrophysical characteristics of units above and below the Barnett Shale are critical to gas production within the Barnett continuous accumulation. The Newark East Field "sweet spot" (Figure 6) is defined by having dense, impermeable (tight) carbonate rock units above and below the Barnett, which act as barriers to contain hydraulic-induced fractures during well stimulation. Viola and Simpson carbonate rocks are more favorable barriers than the more porous, water-wet Ellenburger Group carbonate rocks (Figure 6).

A minimum of three assessment units (Table 1) is proposed for the Barnett Shale continuous accumulations, each with different geologic and production characteristics: (1) a Newark East Field gas sweet spot where the Barnett is siliceous, thick, within the gas generation window, slightly overpressured, and enclosed by dense, tight overlying Marble Falls Limestone and underlying Viola Limestone and Simpson Group as frac barriers; (2) an outlying area where the Barnett is within the gas-generation window but the subcrop is the porous Ellenburger and the overlying Marble Falls Limestone barrier may be absent; and (3) an area of lesser potential where overlying and underlying barriers may be absent and production includes both oil and gas from fractured Barnett Shale (Figure 6).

The siliceous nature of the Barnett Shale, and its relation to fracture enhancement in the area of Newark East Field, has been noted by Lancaster et al. (1993) and Henk and others (2000). Thus, the geographic extent of the organic-rich siliceous facies of the Barnett Shale is of particular interest in this study for defining sweet spots. Also, the second assessment unit, where the Barnett Shale subcrop is Ellenburger Group carbonate rocks, is currently being tested by several operators. The resource potential of this unit will be guided, in part, by the near-future results of current testing with directional wells and various completion methods to determine optimum completion techniques for gas recovery (Bowker, 2002; Shirley, 2002.

Historically, typical EURs for Barnett gas wells at Newark East Field have increased with time, as follows: (1) 0.3-0.5 BCFG before 1990; (2) 0.6-1.0 BCFG between 1990 and 1997; and (3) 0.8-1.2 BCFG between 1998 and 2000 (Reeves. 2002). Recently, Devon Energy reported that the mean EUR for Newark East Barnett gas wells is 1.25 BCFG (Devon Energy Corporation, 2002; Bowker, 2002; Shirley, 2002). The progressive increase in EUR in Barnett wells is the result of improved geologic and engineering concepts that guide development of the Barnett continuous gas play (Reeves, 2002; Bowker, 2002). Moreover, recompletion of wells after about 5 years of production commonly adds 0.75 BCF to its EUR (Bowker, 2002; Shirley, 2002).

SUMMARY

A Barnett-Paleozoic Total Petroleum System has been defined for the Bend Arch-Fort Worth Basin Province, USGS Province 045. Distribution and geochemical typing of hydrocarbons produced from Paleozoic reservoirs rocks indicate generation, expulsion and emplacement from the organic-rich, Mississippian-Pennsylvanian Barnett Shale. Reservoir rocks of the Barnett-Paleozoic TPS are carbonate and clastic rocks that range in age from Ordovician to Permian (Wolfcampian). Reservoirs are sealed by thick shale or dense, impermeable carbonate rocks. The boundaries for the Barnett-Paleozoic TPS are major geologic structures to the north, south, and east. However, the western boundary of the Barnett-Paleozoic TPS is poorly defined, and therefore only tentative at this time. The western Barnett-Paleozoic TPS boundary splits the area of the Eastern Shelf and Concho Platform where reservoir rocks containing Barnett-sourced hydrocarbons are likely mixed with hydrocarbons generated from source rocks of the Midland Basin to the west. Further oil and gas geochemical analysis is needed to further define the common boundary with the adjacent Midland Basin TPS.

TOC content in the Barnett Shale averages 4% and consists of oil-prone Type II kerogen. Oils were initially generated from the decomposition of organic matter in the Barnett Shale at low levels of thermal maturities, whereas gas produced from the greater Newark East Field area probably formed from secondary cracking of oil and bitumen. Variable lateral variation in thermal maturity of the Barnett determined from vitrinite reflectance measurements indicates that heat flow regimes resulting from Ouchita thrusting probably influenced hydrocarbon generation within the Fort Worth Basin.

Preliminary analysis of the Bend Arch-Fort Worth Basin Province has identified five conventional and three continuous assessment units for assessing undiscovered, technically recoverable resources of the Barnett-Paleozoic TPS. The three continuous assessment units are areas of potential Barnett Shale production that are defined by both geologic conditions and geochemical and thermal maturity parameters. The greatest volume of undiscovered resource in the Barnett-Paleozoic TPS is expected from continuous gas accumulations within the Barnett Shale.

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