Chapter 8

Petroleum Assessment of the Ferron/Wasatch Plateau Total Petroleum System, Upper Cretaceous Strata, Wasatch Plateau and Castle Valley, Utah

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Volume Title Page

By Mitchell E. Henry *and* Thomas M. Finn

Chapter 8 *of*

Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta-Piceance Province, Utah and Colorado

By USGS Uinta-Piceance Assessment Team

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Contents

Plates

Figures

Petroleum Assessment of the Ferron/Wasatch Plateau Total Petroleum System, Upper Cretaceous Strata, Wasatch Plateau and Castle Valley, Utah

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Abstract

The total petroleum system approach was used to estimate the undiscovered petroleum potential of the Ferron/Wasatch Plateau Total Petroleum System, located in the Wasatch Plateau and Castle Valley, central Utah. The Ferron/Wasatch Plateau Total Petroleum System was geologically defined and subdivided into seven assessment units, six of which were formally evaluated. Geologic data considered in defining the assessment unit boundaries included thermal maturity, coal presence and thickness, overburden thickness, and faulting intensity. Historical production data were also used to estimate volumes of gas from undrilled areas.

The one conventional assessment unit (Conventional Ferron Sandstone Gas Assessment Unit) includes the area of nearly the entire total petroleum system and is characterized by known accumulations of gas that occur in structural or combination traps in sandstone reservoirs. The estimated undiscovered conventional producible gas that may be added to reserves of this unit ranges from a low (at least a 95 percent chance) of 10.43 billion cubic feet of gas (BCFG) to a high (at least a 5 percent chance) of 81.23 BCFG and a mean value of about 39.75 BCFG.

Continuous gas accumulations are those in which the entire assessment unit is considered to be gas charged. Within these assessment units, there will almost certainly be wells drilled that are not economic successes but all are expected to contain gas. Coalbed gas is included in this continuous category.

Mean estimates of undiscovered gas for the five formally evaluated continuous assessment units are: (1) Northern Coal Fairway/Drunkards Wash, 752.33 BCFG; (2) Central Coal Fairway/Buzzard Bench, 536.73 BCFG; (3) Southern Coal Fairway, 152.59 BCFG; (4) Deep (6,000 feet plus) Coal and Sandstone, 59.10 BCFG; and (5) Southern Coal Outcrop, 10.56 BCFG; the Joes Valley and Musinia Grabens Assessment Unit was not assessed.

The mean estimate of undiscovered gas for the entire total petroleum system is 1,551.06 BCFG. There is a 95 percent chance that at least 851.64 BCF of undiscovered producible gas remain in the total petroleum system, and a 5 percent chance of at least 2,503.45 BCFG.

Introduction

Gas-prone coal source rocks and coal and sandstone reservoir intervals occur in the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale in the Wasatch Plateau, central Utah. These were combined into the Ferron/Wasatch Plateau Total Petroleum System (TPS) within the broader Uinta-Piceance Province as a part of this assessment by the U.S. Geological Survey (USGS). Several factors led to a separate assessment for this TPS: (1) a detailed study of Ferron coalbed gas accumulations was recently completed prior to the province-scale assessment, (2) adequate production data were available for engineering analysis, and (3) coalbed gas has recently been recognized as an important contributor to the gas supply of the U.S.A.

For complete details of the petroleum system concept see Magoon and Dow (1994); for details on the modification of the petroleum system, the broader total petroleum system used for this assessment, see Magoon and Schmoker (2000). Briefly, this latter approach consists of identifying and mapping the extent of the effective hydrocarbon source rock, known hydrocarbon production and shows that are attributed to that source, known or expected migration pathways, and reservoir and trap distribution. Based on other considerations, such as trap type, preservation variability, or petroleum type, the TPS may be subdivided into smaller assessment units (AU).

The purpose of this report is to review the geology of the Wasatch Plateau area, describe the Ferron/Wasatch Plateau TPS, present the rationale for the boundaries of the TPS and its associated AUs, and present the results of the assessment.

Major Data Sources

Extensive use was made of display and analysis functions of a geographic information system (GIS) and computer-based surface modeling software during this project. The source of digital well data and field boundaries used in this report was the Utah office of the U.S. Bureau of Land Management. Digital shapefiles (og_wells.shp and fields.shp) were downloaded in 1999. The well data and field data files are currently available (as of May 2002) at http:/

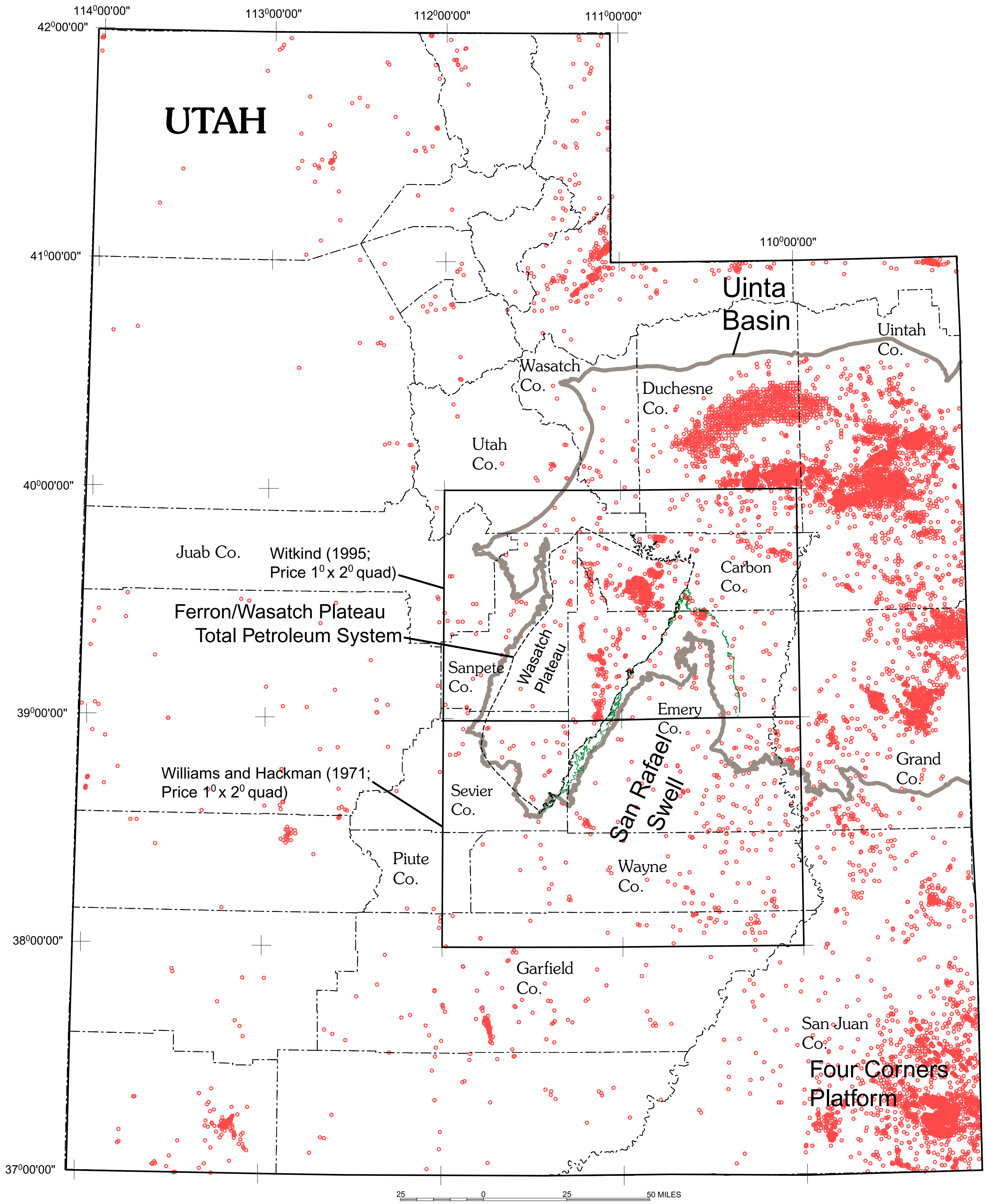


Figure 1. Location of Ferron/Wasatch Plateau Total Petroleum System, Utah. Well locations shown by red circles (well data set from the Utah office of the U.S. Bureau of Land Management). Green line represents outcrop of Ferron Sandstone Member of Mancos Shale (compiled from Bennett, 1955a, b; Detterman, 1955; Orkild, 1956; Williams and Hackman, 1971; and Witkind, 1995). Gray line shows Utah part of Uinta-Piceance Province.

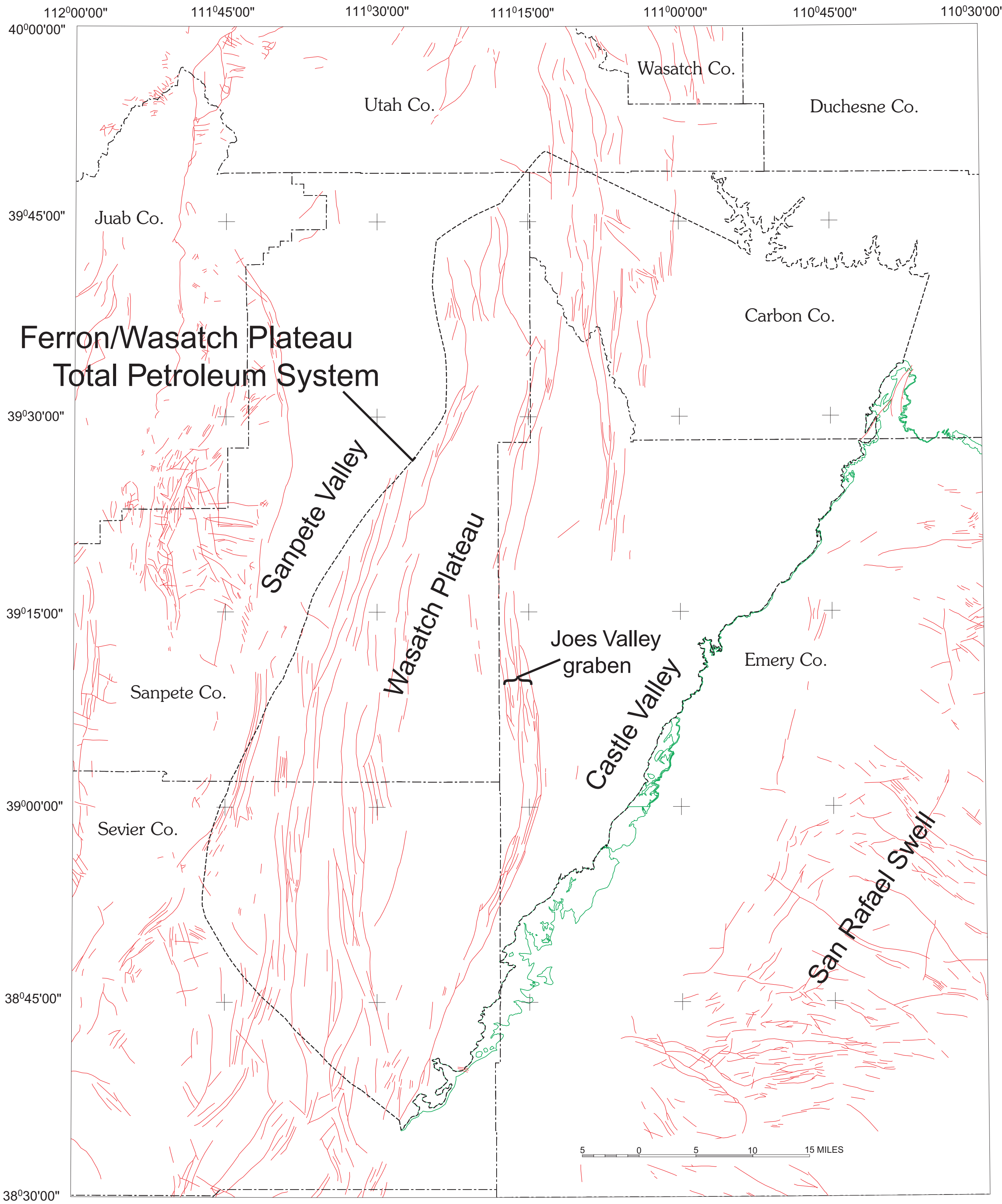


Figure 2. Distribution of faults (red lines) in area of Ferron/Wasatch Plateau Total Petroleum System (from Williams and Hackman, 1971; and Witkind, 1995). Green line shows Ferron Sandstone Member outcrop pattern.

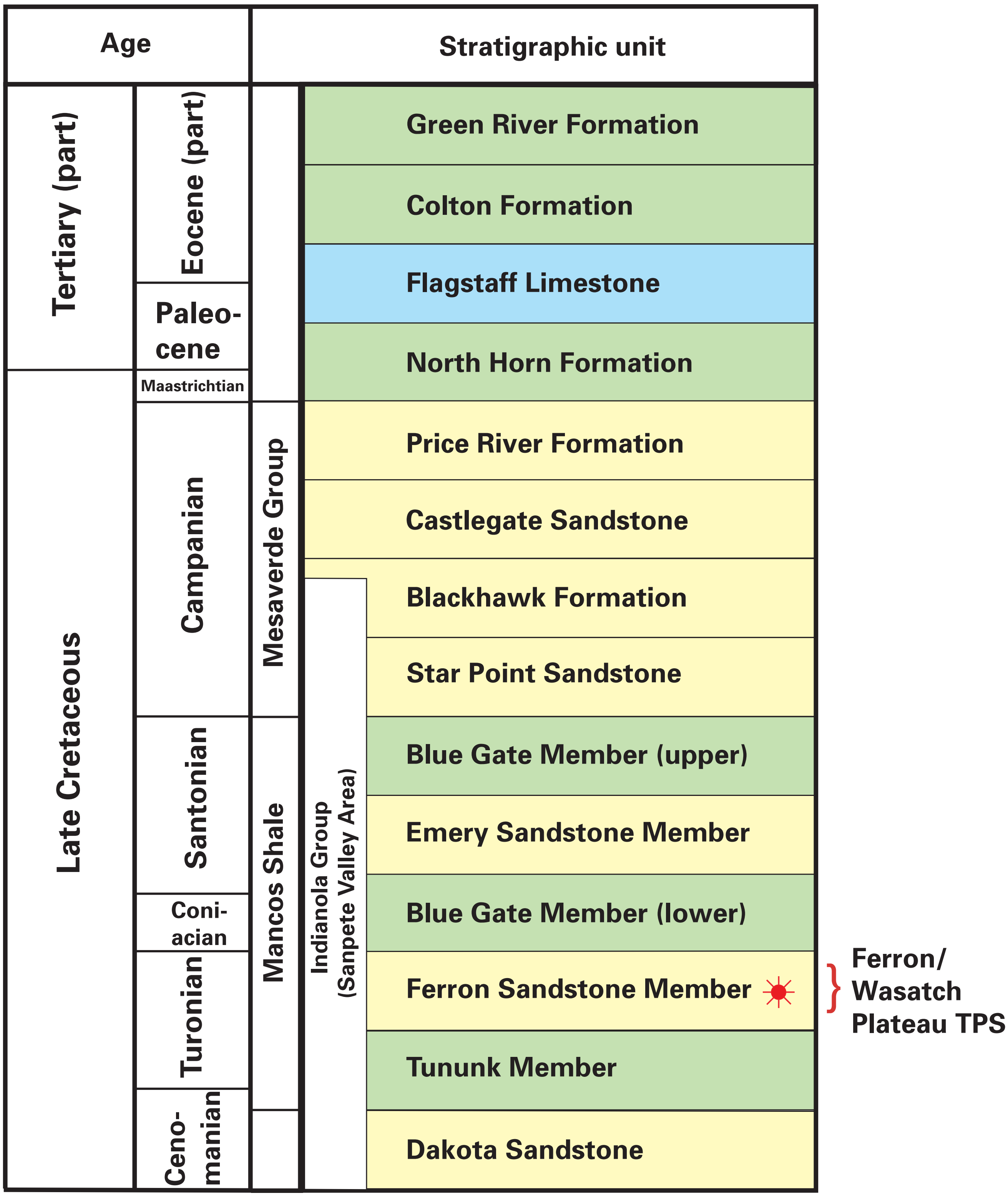


Figure 3. Generalized stratigraphic section of Cretaceous and Tertiary sedimentary rocks in Wasatch Plateau area. Section modified from Doelling (1972b), Fouch and others (1992), and Witkind (1995). Yellow color represents sandstone units, green indicates shale units, and blue indicates limestone. Volcanic rocks shown in figure 14 are generally younger (late Miocene to middle Oligocene in age) than Green River Formation and are not shown here.

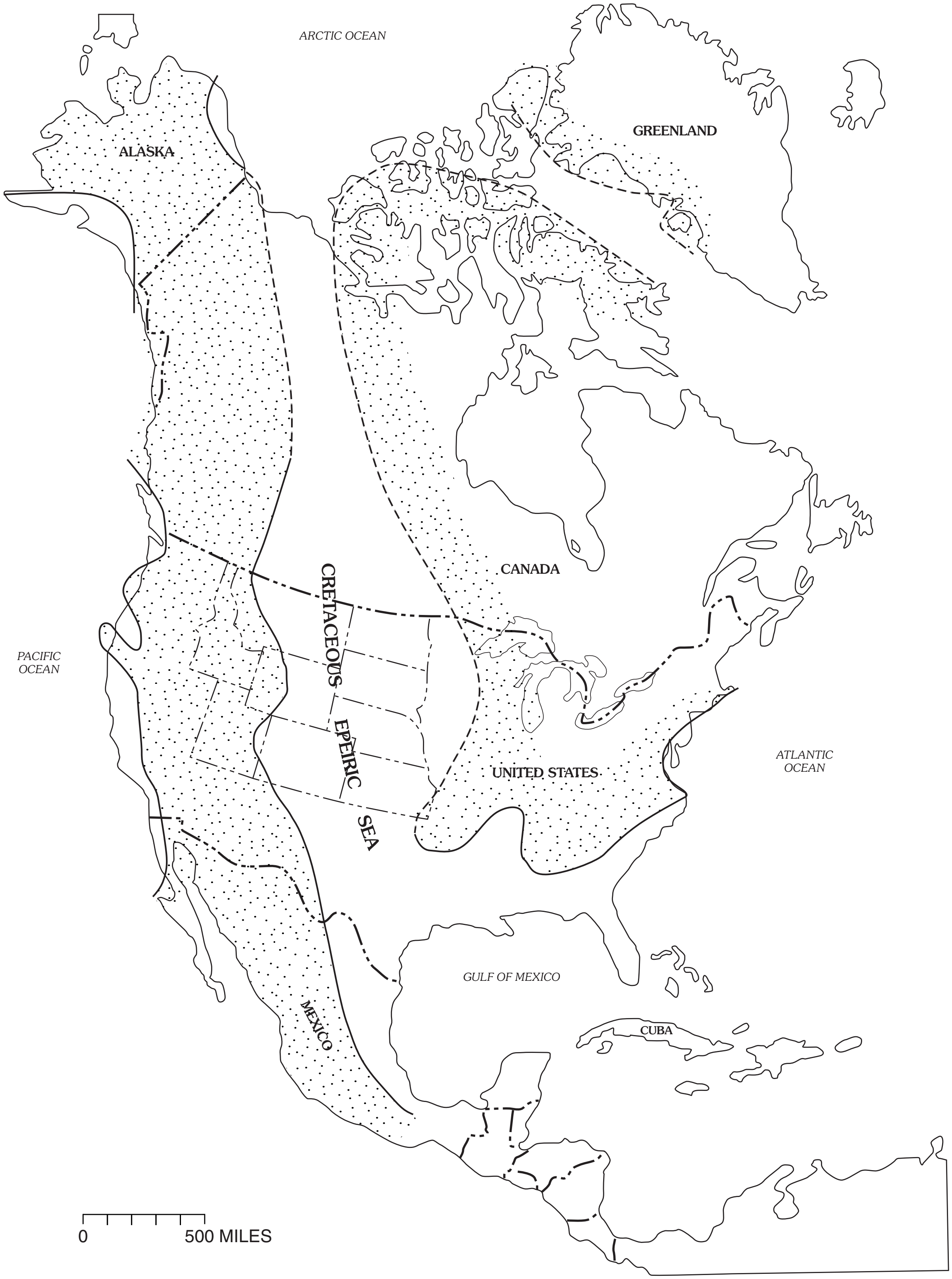


Figure 4. Extent of Western Interior seaway during Late Cretaceous time. Seaway boundary dashed where inferred. Stippled pattern indicates land areas. (Modified from Gill and Cobban, 1973.)

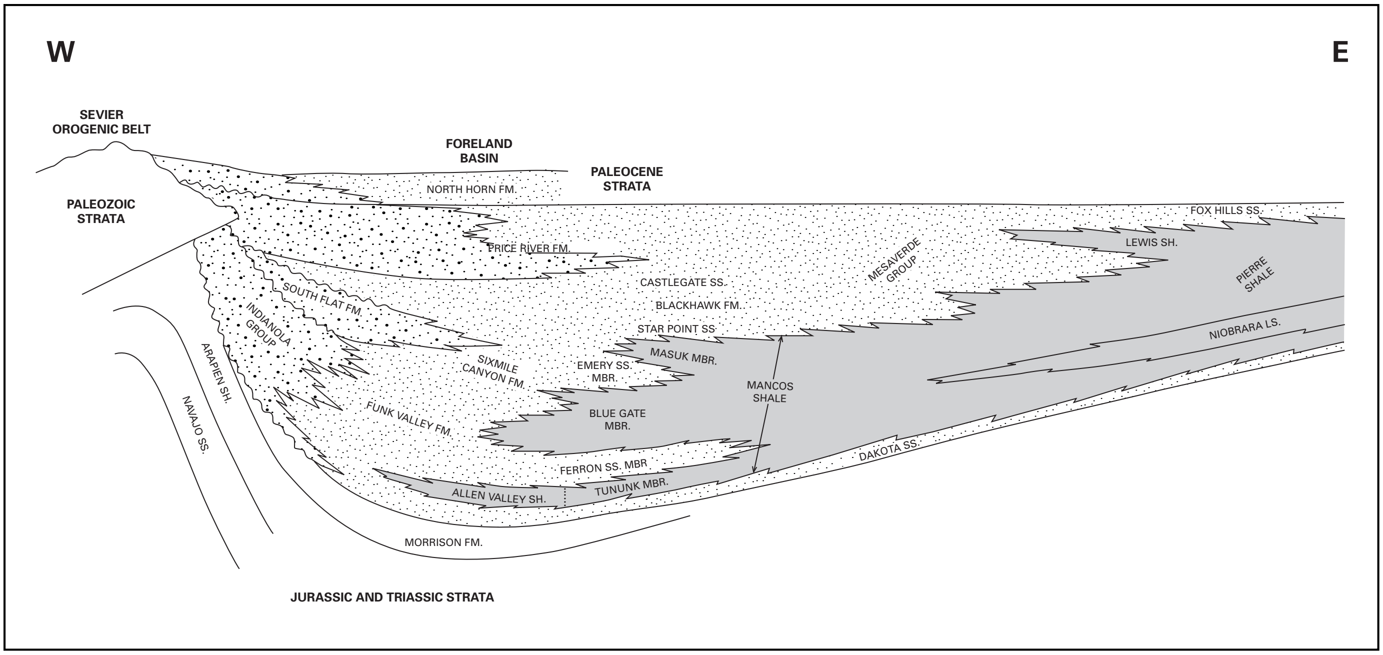


Figure 5. Regional stratigraphic cross section of Cretaceous strata extending from western Utah to western Colorado. Cross section shows intertonguing relationship between marine (shaded) and nonmarine (stippled) deposits. (Modified from Armstrong, 1968.)

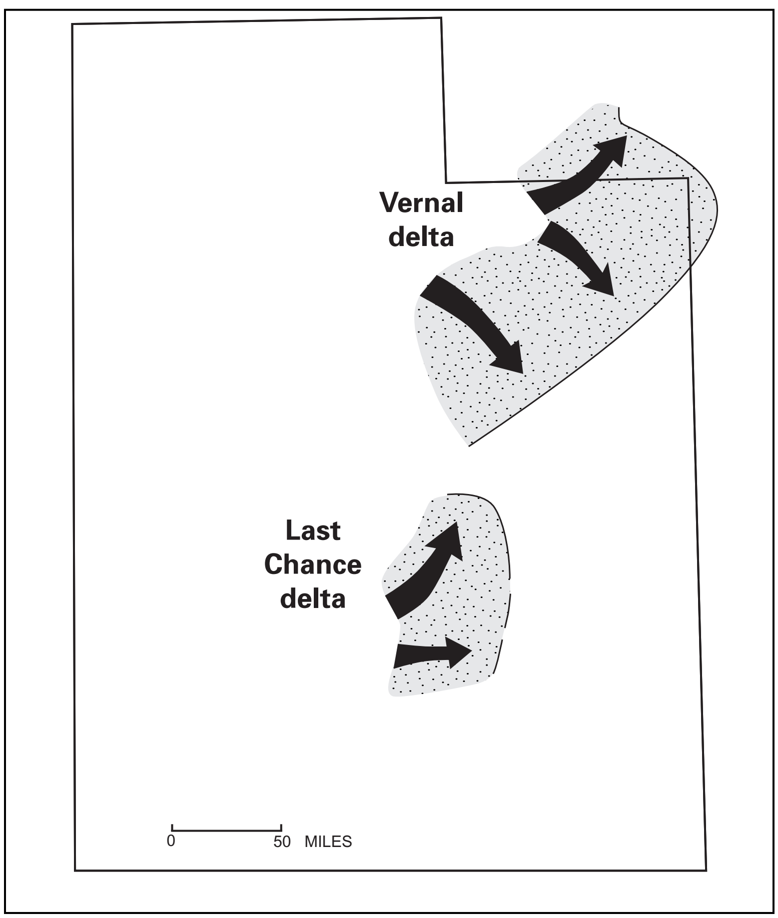


Figure 6. General locations of Last Chance and Vernal deltas (extent shown by dashed line where less certain). Arrows indicate inferred direction of sediment transport. (Modified from Cotter, 1976.)

/dogm.nr.state.ut.us/oilgas/DOWNLOAD/downpage.htm and the well data file is included in Sprinkle (1999). The well data set used contained almost 12,000 wells.

Geophysical logs from about 300 wells in the study area were collected for subsurface geologic mapping. Information from these logs was used to construct cross sections, isopach maps, and structure maps of selected units within the TPS. Digital well locations were generated for these wells by hand drawing the positions reported on well logs and optically scanning that map.

Vitrinite reflectance (Ro) data used in this study consist of measurements of samples from 82 locations. These data were compiled from 52 coal samples analyzed by the USGS, and an additional 30 samples from Tabet and others (1995).

Production data are from IHS Energy Group (1999). These production data were current as of September 1999. Locations of leases that began production after September 1999 are from IHS Energy Group (2000).

Digital surface elevation data (90-m spacing) used in this study were obtained from a website operated by Utah State University. [A higher resolution (30-m spacing) data set is now available at http://www.gis.usu.edu/gap-data/ut-gap/asdd in the file asdddem.e00.Z]. Surface elevation data (at 90-m spacing) were used in conjunction with elevation data, representing the top of the Ferron, to determine the areas where Ferron overburden thickness exceeds 6,000 ft.

Digital geologic map data for Utah were obtained from a data set compiled by Utah State University in 1994 from the original work of Hintze (1980), and for selected areas of the Wasatch Plateau from compilations made during this study using published geologic maps by Bennett (1955a, b), Detterman (1955), Orkild (1956), Williams and Hackman (1971), and Witkind (1995).

Land ownership in the TPS is from Biewick and Green (1999). This digital data set is available in Arc/Info export file format from ftp://geology.cr.usgs.gov/pub/open-file-reports/ofr-99-0553-b/neutown.e00.

General Geology of the Study Area

Nearly 12,000 oil and gas wells have been drilled in Utah, mostly in the eastern part of the State (fig. 1). Drilling is concentrated in the Uinta Basin, Four Corners Platform, and Wasatch Plateau.

Most of the Wasatch Plateau, central Utah, is underlain by coal beds in the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale. Ferron coals crop out in the southern part of Castle Valley and are at depths greater than 6,000 ft in the western part of the TPS.

Rocks within the Ferron/Wasatch Plateau TPS generally dip toward the northwest at about 2° (Lamarre and Burns, 1997). The plateau is highly faulted (Williams and Hackman, 1971; Witkind, 1995) and has a pronounced north-south structural grain (fig. 2). The north-trending Joes Valley graben extends over nearly the entire length of the plateau and is located in the central part of the study area (fig. 2). It separates the TPS into an eastern area that contains most of the petroleum wells and a western area that is sparsely drilled.

Sedimentary rocks exposed at the surface within the TPS range in age from middle Cretaceous to middle Tertiary (fig. 3). Pre-Cretaceous rocks are exposed east of the TPS; within the TPS, surface rocks become younger westward. Igneous rocks occur at the surface south of the TPS and obscure the sedimentary section. Few petroleum wells have been drilled there.

Generally unconsolidated or loosely consolidated Quaternary and Tertiary deposits are extensively developed within the TPS in Castle Valley. Elevations within the TPS range from about 5,500 ft in Castle Valley to more than 10,000 ft on the Wasatch Plateau.

Depositional Setting

During Late Cretaceous time, a broad epicontinental sea extended from the Arctic Ocean to the Gulf of Mexico (fig. 4). In the study area, the sea was bordered on the west by tectonically active highlands of the Sevier orogenic belt, which supplied sediment to eastward-flowing streams. The eastern shore was on the stable craton, which was topographically low and supplied little sediment (Molenaar and Rice, 1988; Williams and Stelck, 1975). During much of Late Cretaceous time, the sea repeatedly advanced and retreated across the western part of the basin resulting in a complex pattern of intertonguing marine and nonmarine deposits (fig. 5). The marine deposits are represented by westward-thinning tongues of marine shales and siltstones. The nonmarine deposits are represented by eastward-thinning clastic wedges of sandstone, siltstone, shale, and coal. The earliest of these clastic wedges in central Utah is the Ferron Sandstone Member of the Mancos Shale, which was deposited during a widespread regression of the shoreline (Anderson and others, 1997; Ryer and McPhillips, 1983; Gardner, 1995a). Early workers recognized a deltaic origin for the Ferron (Katich, 1953, 1954; Hale and Van De Graaff, 1964; Hale, 1972; Cotter, 1975, 1976) and divided it into two separate depositional systems, one being derived from the north and west and the other from the southwest (fig. 6). The northern system was named the Vernal delta by Hale and Van De Graaff (1964) for "an eastward bulging deltalike feature in the northern Uinta Basin." The southern system was named the Last Chance delta by Hale (1972) for sediments that "built a thick lobate, delta-like feature in the Last Chance area south of Emery, Utah." Subsequent work by Ryer and McPhillips (1983), Ryer and Lovekin (1986), and Tripp (1989) found little evidence to support the existence of the Last Chance and Vernal deltas as separate systems, but they believed the Ferron was deposited by a system of rivers that flowed eastward from the Sevier orogenic belt and formed numerous small lobate deltas

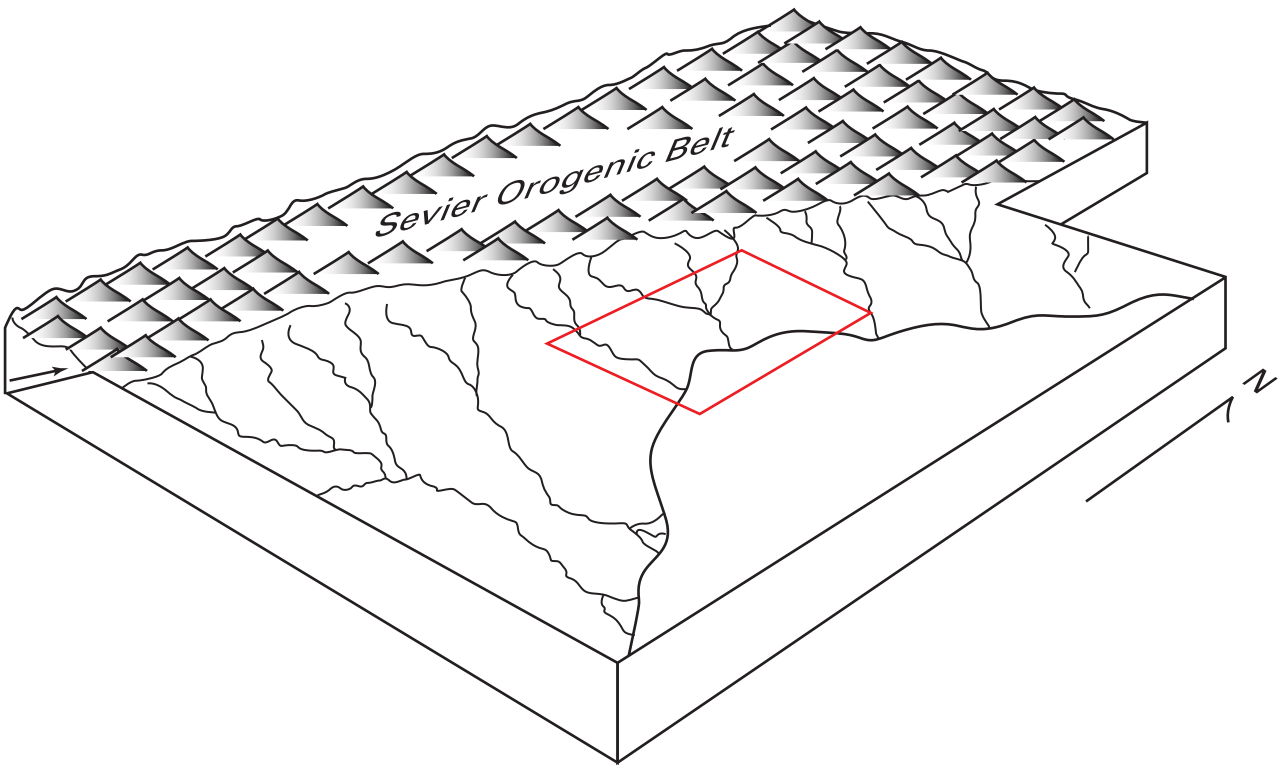


Figure 7. Paleogeographic reconstruction of Utah during late Turonian time, showing relationship between Sevier orogenic belt and Cretaceous shoreline. Study area outlined in red. (Modified from Ryer and McPhillips, 1983.)

along the western margin of the Cretaceous seaway (fig. 7). According to Ryer and McPhillips (1983), as the shoreline prograded, these deltas coalesced laterally to produce the laterally continuous sheets of delta-front sandstone. Ryer and Lovekin (1986) suggested that the pronounced bend in the shoreline was caused by differential subsidence that varied sediment supply and rates of progradation during the Ferron regression. The Ferron is conformable and interfingers with marine deposits of both the underlying Tununk and overlying Blue Gate Members of the Mancos Shale (Gardner, 1995a; Molenaar and Cobban, 1991; Ryer and McPhillips, 1983).

Stratigraphy

Tununk Member of the Mancos Shale

The Tununk Member of the Mancos Shale was named by Gilbert (1877) for the marine shales between the underlying Dakota Sandstone and overlying Ferron Sandstone Member of the Mancos Shale in the Henry Mountains region. Lupton (1914) applied the name Tununk to exposures in the southern part of Castle Valley. The Tununk is late Cenomanian to middle or late Turonian in age and represents deposition during a marine transgression (Ryer and McPhillips, 1983; Gardner, 1995a, b). The base of the Tununk is sharp and represents a transgressional disconformity that formed as the Cretaceous sea advanced westward into central Utah (Ryer and McPhillips, 1983; Molenaar and Cobban, 1991; Gardner, 1995a). The upper contact with the Ferron is gradational and conformable, and displays little interfingering. The Tununk Member is composed of shale, mudstone, siltstone, bentonite, and minor amounts of sandstone, which were deposited in an offshore marine environment. The Tununk ranges in thickness from more than 900 ft in the southwestern part of the study area to less than 300 ft in the northeastern part (fig. 8).

Ferron Sandstone Member of the Mancos Shale

The Ferron Sandstone Member of the Mancos Shale was named by Lupton (1914) for exposures in the Emery coal field in the southern Castle Valley on the west side of the San Rafael Swell (also referred to as the San Rafael uplift) (fig. 2). The Ferron Member consists of interbedded sandstones, siltstones, shales, carbonaceous shales, and coal, which accumulated along the western shore of the Cretaceous sea as an eastward-prograding fluvial-deltaic complex (Ryer and McPhillips, 1983). Biostratigraphic evidence from Gardner (1995b) and Molenaar and Cobban (1991) indicates a middle or late Turonian to Coniacian age. The Ferron ranges in thickness from about 1,100 ft in the western part of the study area to less than 100 ft near Farnham Dome at the north end of the San Rafael Swell (fig. 9). Ryer (1981a), Gardner (1995a), and Cotter (1975, 1976) recognized and described a variety of depositional facies in the Ferron, including alluvial-plain, delta-plain, delta-front, and prodelta deposits.

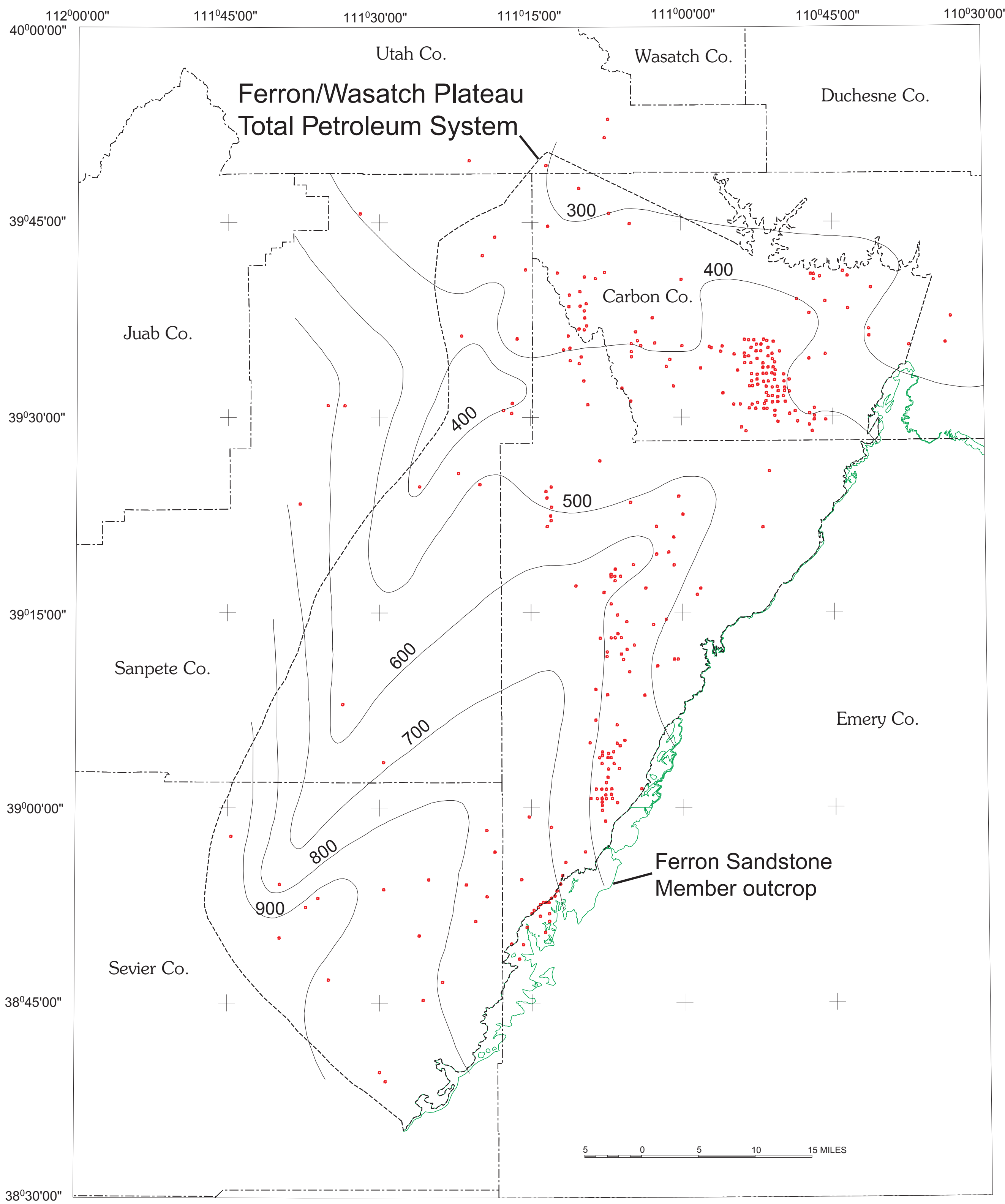


Figure 8. Isopach map of Tununk Member of Mancos Shale, central Utah. Contour interval 100 ft. Well locations shown by red dots.

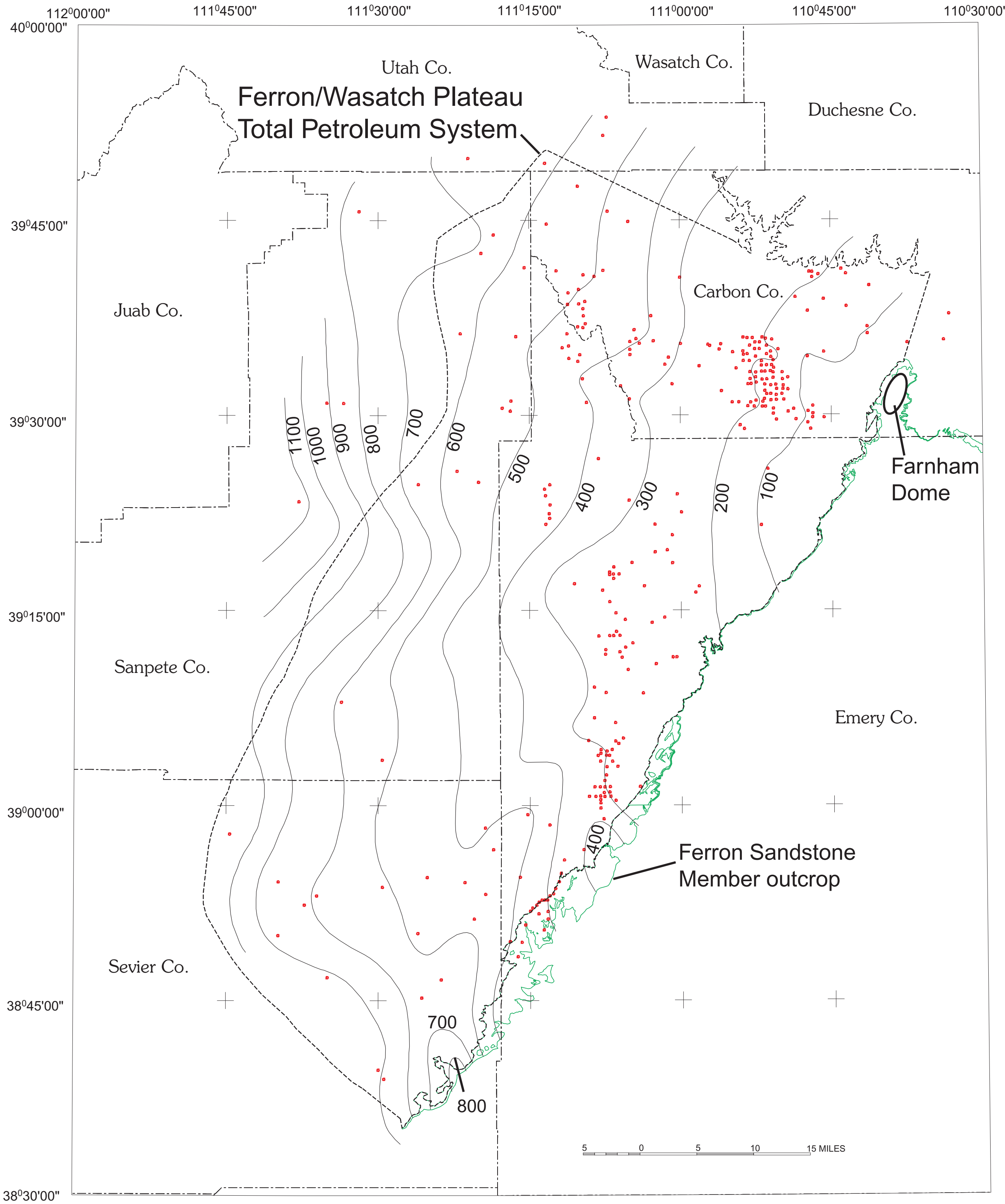


Figure 9. Isopach map of Ferron Sandstone Member of Mancos Shale, central Utah. Contour interval 100 ft. Red dots indicate location of wells.

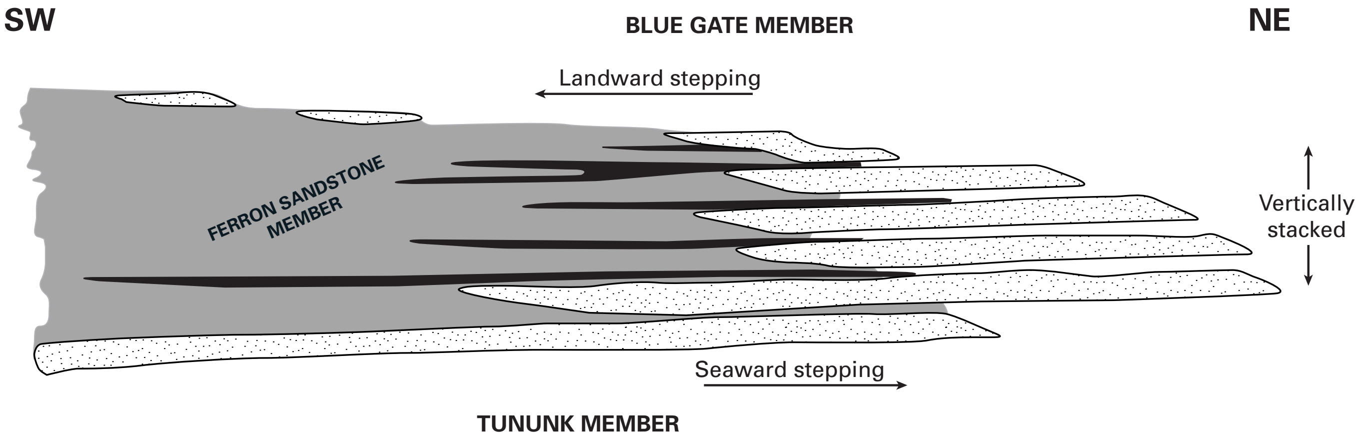


Figure 10. Generalized cross section of Ferron Sandstone Member, central Utah, showing stacking of delta-front sandstones, sequence stratigraphic relationships, and relationship between delta-front sandstones and associated coal deposits. Shading indicates delta-plain/alluvial-plain deposits; stipple indicates delta-front sandstone; coal beds shown in black; and marine shales unpatterned. (Modified from Ryer, 1981a.)

The alluvial-plain facies is represented by interbedded sandstone, siltstone, and shale. The sandstones are composed of fining-upward, very fine grained to coarse-grained deposits that accumulated as point bars in meandering streams (Ryer, 1981a; Cotter, 1976). Individual point bar sandstones are as much as 36 ft thick. Some sandstone bodies are as thick as 100 ft. According to Ryer (1981a), these thicker fluvial sandstone bodies are the result of vertical stacking of point bars. Coal beds are also present in the alluvial-plain facies but they are typically thin, laterally discontinuous, and insignificant in volume (Ryer, 1981a).

The delta-plain facies consists of interbedded sandstone, siltstone, shale, carbonaceous shale, and coal. The sandstones were deposited in distributary channels, and as crevasse splays. The siltstones and shales represent the most abundant rock types in the delta-plain facies, and were deposited in brackish water bays and swamps adjacent to the shoreline. The most extensive and economically important coal beds occur in the delta-plain facies.

The delta-front facies consists of laterally continuous coarsening-upward sequences of interbedded, very fine grained to medium-grained sandstone and siltstone. The grain size and thickness of individual sandstone beds increase upward, and individual sandstone beds become more massive as the amount of siltstone decreases (Cotter, 1976). The lower contact is gradational with the interbedded sandstones and shales in the upper part of the underlying prodelta facies, and the placement of the contact is somewhat arbitrary within this transitional zone. The prodelta deposits represent a transitional zone between the underlying marine shales and the overlying delta-front sandstones. Prodelta deposits consist of thin beds of interbedded shale and fine-grained sandstone. The thickness of the sandstone beds gradually increases upward.

Studies by Ryer (1981a, b) demonstrated that the Ferron was deposited during numerous transgressive-regressive cycles, each represented by one laterally continuous delta-front sandstone (fig. 10). Each deltaic cycle is separated by a marine flooding surface and is considered a parasequence or parasequence set (Anderson and others, 1997; Ryer and Anderson, 1995; van den Bergh and Garrison, 1996; Van Wagoner and others, 1990). The stacking pattern of parasequences and parasequence sets changed through time from seaward stepping (progradational), to vertically stacked (aggradational), to landward stepping (retrogradational) as shown in figure 10.

Significant coal deposits occur in the Ferron and were first described by Lupton (1916) in the southern part of Castle Valley. According to Lupton (1916), as many as 14 important coal beds and associated rider beds range in thickness from <1 ft to 20 ft. Subsequent work by Ryer (1981b) and Bunnell and Hollberg (1991) has shown that individual coal seams may reach a thickness of nearly 30 ft. Major coal beds in the Ferron accumulated as peat in coastal mires associated with delta-plain deposits. Some minor coal beds are associated with the alluvial-plain deposits, but these beds are typically thin and laterally discontinuous (Ryer, 1981a). Outcrop and subsurface studies conducted by Ryer (1981a) in southern Castle Valley demonstrate a clear relationship between the geometries of the delta-front sandstones and their associated coal beds. Ryer (1981a) showed that the coal deposits occur on top of, and landward of, the associated delta-front sandstones (fig. 10). According to Ryer (1981a) the thickest coals within each delta cycle occur in a 6-mi-wide belt located landward of the landward pinch out of the associated delta-front sandstone. Subsurface studies in the the northern part of Castle Valley by Bunnell and Hollberg (1991) confirm Ryer's (1981a) model. Although coals are associated with all of the delta cycles, Ryer (1984), Cross (1988), and Bohacs and Suter (1997) have shown that the most significant volume of coal is associated with the vertically stacked (aggradational) parasequence sets.

Blue Gate Member of the Mancos Shale

The Blue Gate Member of the Mancos Shale conformably overlies and extensively interfingers with the Ferron Member in the study area. It is composed of siltstone and shale that were deposited in a marine setting. Lupton (1916) reported a thickness of 3,000 ft for the Blue Gate northeast of Emery, Spieker (1931) indicated that it reaches 2,400 ft near Price, and according to Ryer and McPhillips (1983) it thins to a wedge edge west of the Wasatch Plateau. Biostratigraphic work by Cobban (1976) indicated an early Coniacian to Santonian age for the Blue Gate Member.

Structure

The study area is located in the southwestern part of the Uinta Basin (fig. 1) and is confined to the areas known as Castle Valley and the Wasatch Plateau (fig. 2). Castle Valley occupies the eastern part of the area and extends westward from the Ferron outcrops along the northwest flank of the San Rafael Swell to the east-facing scarp that forms the eastern edge of the Wasatch Plateau (fig. 11). The Wasatch Plateau forms the western part of the study area and lies between Castle Valley on the east and the Sanpete Valley on the west. Structurally, the Wasatch Plateau is considered to occupy the transition zone between the Colorado Plateaus Province and the Basin and Range Province (Stokes, 1986; Spieker, 1931; Witkind and others, 1987). The boundary between the Wasatch Plateau and Castle Valley is formed by prominent cliffs that are erosional remnants of resistant sandstones and limestones that make up the crest of the plateau (fig. 11). This escarpment is not fault related, but is a southwestern extension of the Book Cliffs, which form the southern margin of the Uinta Basin (Stokes, 1986). Along the western margin of the plateau, strata flex down sharply into Sanpete Valley to form the Wasatch monocline.

Castle Valley lies on the northwest flank of the San Rafael Swell, a large asymmetric basement-cored dome-like structure of Laramide age. The Swell trends about N. 30° E., and is characterized by steeply dipping sedimentary strata on the southeast flank and gently dipping strata on the northwest flank. Stucturally, Castle Valley is an extension of the northwestern monoclinal dip (5°–15°) of the San Rafael Swell (fig. 12). As shown on structure maps (fig. 13), several anticlinal folds are evident. The trend of the folds is north-northeast and generally parallels that of the San Rafael Swell. The southernmost of these anticlinal structures, known as the Ferron anticline (see fig. 13), has produced gas from the Ferron Sandstone Member and oil from Permian reservoirs (Tripp, 1991). Northeast-striking reverse faults have been described by Lamarre and Burns (1997) and Tripp (1989) along the southeast flank of the anticlinal feature in the Drunkards Wash field area (see fig. 13) These faults are southeast directed and dip to the northwest, and have as much as 150 ft of displacement (Lamarre and Burns, 1997). Using Consortium for Continental Reflection Profiling (COCORP) and unpublished industry seismic data, Neuhauser (1988) described a previously unmapped thrust fault (not shown on structure maps in this report) located along the east flank of the Huntington anticline in the central part of Castle Valley (see fig. 13). Neuhauser (1988) described this fault as a low-angle, ramp-style thrust that dips west underneath the Huntington anticline. The thrust fault is east directed, originates in Jurassic age strata, and terminates in the overlying Mancos Shale. Peterson (1954) identified several reverse faults that offset the Ferron at Farnham dome (T. 15 S., R. 11 E.). Like the faults at Price and Huntington anticlines, these faults are east directed and dip at low angles to the west-northwest. The origin of the faults and folds in Castle Valley is unknown, but Tripp (1991) and Montgomery and others (2001) suggested a Laramide origin for some structures, whereas Neuhauser (1988) and Willis (1999) provided evidence to extend Sevier-style deformation east into Castle Valley.

The Wasatch Plateau is an extension of the monoclinal structure that is related to the northwest flank of the San Rafael Swell. It is about 80 mi long and 20–25 mi wide, trends approximately N. 20° E., and is characterized by flat-lying to westward-dipping Cretaceous and Tertiary strata. The northern end is arched upward to form the Monument Peak uplift (Stokes, 1956; Walton, 1954), a large regional uplift that has several anticlinal folds superimposed on it. The largest of these structures, the Clear Creek anticline (see fig. 13), has produced significant amounts of natural gas from the Ferron Member (Laine and Staley, 1991). The crest and western margin of the Wasatch Plateau are greatly disrupted by a system of high-angle normal faults that trend from nearly north-south to about N. 20° E. The fault system extends the full length and width of the plateau, but does not appear to extend east into Castle Valley (fig. 13). Witkind and others (1987) described some of these faults as “scissors faults” that show opposite displacement along the length of the fault. Figure 13 shows that many of these normal faults are paired to form grabens, the most prominent of which is Joes Valley graben, which extends north-south for nearly 60 mi. The displacement varies among the grabens with minimum displacements of several hundred feet (Witkind and others, 1987). Spieker (1931) suggested that displacement in the Joes Valley graben ranges from 1,500 to 2,500 ft. In some cases the grabens consist of a simple downdropped prism of sedimentary rock that may be relatively undisturbed or cut locally by internal subsidiary faults. In contrast Spieker (1931) described the rocks in the Joes Valley graben as being highly shattered, and Doelling (1972a) stated that the coals in many of the grabens are so disrupted that they could not be mined. The origin of these normal faults on the Wasatch Plateau is uncertain; however, Stokes (1952, 1956) and Stokes and Holmes (1954) implied that the faults do not extend below the salt-bearing Jurassic beds, suggesting that the faults and grabens are collapse features related to the dissolution and withdrawal of salt in the Jurassic section. Witkind and Page (1984), Witkind and others (1987), and Montgomery and

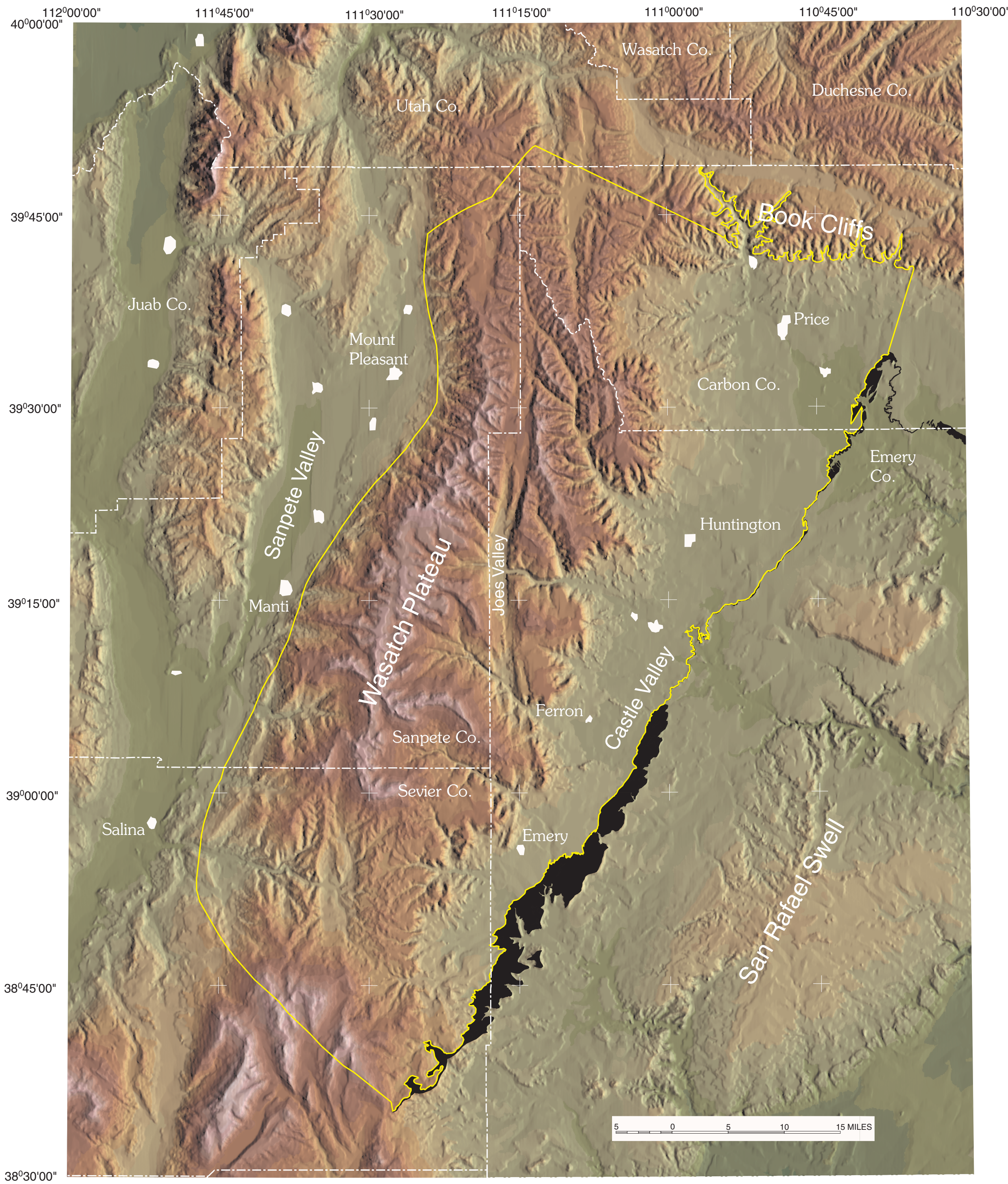


Figure 11. Shaded relief map of study area, central Utah. Black area represents Ferron Sandstone Member outcrop. Dark-green colors represent lowest lying areas; lighter green through yellow, brown, red-brown, to off-white colors reflect increasing surface elevation; white areas represent towns. Yellow line represents Ferron/Wasatch Plateau Total Petroleum System boundary.

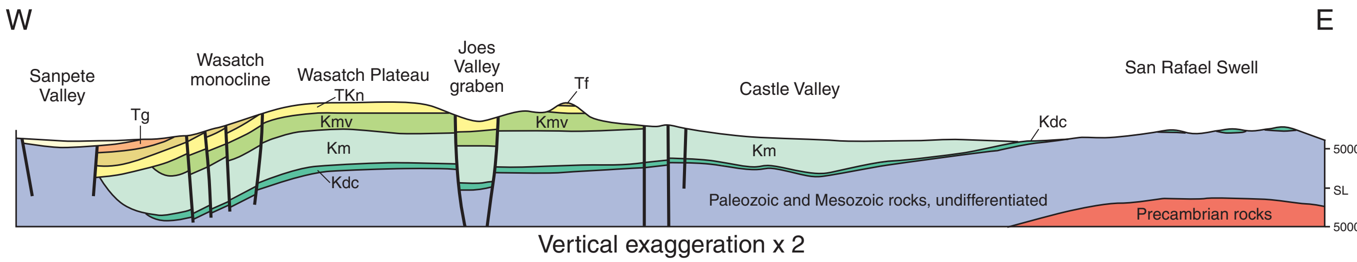


Figure 12. Generalized west-east cross section extending from Sanpete Valley to San Rafael Swell, showing structural configuration of study area. Abbreviations: Kdc, Dakota Sandstone and Cedar Mountain Formation; Km, Mancos Shale; Kmv, Mesaverde Group; TKn, North Horn Formation; Tf, Flagstaff Formation; Tg, Green River Formation. Ferron Sandstone Member occurs in lower part of Mancos Shale. (Modified from Hintze, 1980.) Location of cross section shown in figure 13.

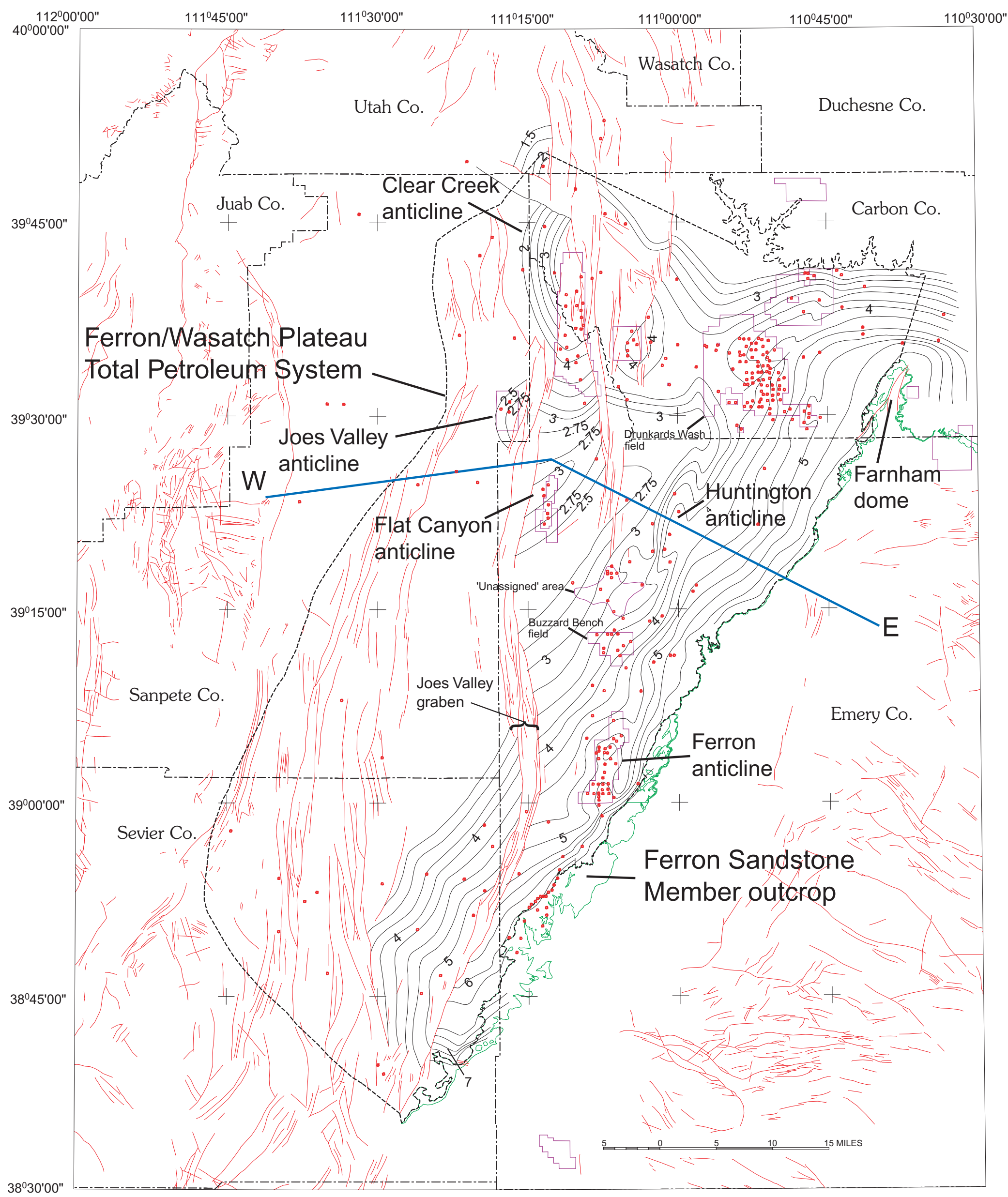


Figure 13. Structure contour map drawn on top of Ferron Sandstone Member in study area. Contour interval 250 ft. Contour labels show elevation X 1,000 ft. In western part of Ferron/Wasatch Plateau Total Petroleum system drilling is too sparse for a detailed, reliable mapping of this surface. Red dots represent locations of well control; red lines are faults; and purple lines represent petroleum field boundaries. Blue line shows approximate location of cross section shown in figure 12.

others (2001) suggested that some of the normal faults are related to Basin and Range extension, which has been active in the Western United States since Miocene time.

Ferron/Wasatch Plateau Total Petroleum System

Extent

The Ferron/Wasatch Plateau TPS boundary (fig. 14) was drawn as the result of several geologic considerations. The most definite part of that boundary is along the eastern side of the TPS. East of the outcrop of the Ferron there is no source and no reservoir rock for this system.

The western boundary was drawn to include that area where Ferron coals are known or are expected to exist, and generally coincides with the Wasatch monocline. The Ferron is generally deeply buried here and sparsely drilled. This western boundary was placed east of outcrops of the Indianola Group, which consists, in part, of rocks similar in age to the Ferron but composed of conglomerates rather than sandstones. These conglomerates were deposited landward of the area where coal deposition occurred. The western boundary is positioned west of the westernmost surface reports of coal in the Ferron, and west of the westernmost wells that record evidence of Ferron coals. In areas where geologic data are sparse, the western boundary of the TPS generally follows a marked topographic break between the Wasatch Plateau and the Sanpete Valley.

The southern boundary follows the known southern extent of the Ferron. South and southwest of the southern boundary, volcanic rocks cover the surface and there has been virtually no drilling.

The northern boundary generally follows a significant topographic break near the base of the Book Cliffs and continues northwest to connect with the western boundary. The northern boundary closely coincides with a northward deepening of Upper Cretaceous rocks into the Uinta Basin.

Source Rock

The principal source rock for this TPS is believed to be coal beds within the Ferron Sandstone Member of the Mancos Shale. Coal is generally considered a good source for gas. Ferron coals were deposited in various nearshore environments related to the Cretaceous Western Interior sea (fig. 4). Thickness of individual coal beds and net coal thickness are generally greater in the eastern part of the TPS (fig. 15). Localized areas of increased net coal thickness occur along the eastern edge of the TPS, generally parallel to the Ferron outcrop.

Ferron coals are generally subbituminous to bituminous in rank. Doelling (1972b) reported analyses of coals from the Emery coal field (fig. 15), apparently all from Ferron coals, in the range of 7,823–12,970 Btu/lb, with an average of 11,450 Btu/lb (proximate analysis, as received basis). Lamarre and Burns (1997) described the Ferron coals at Drunkards Wash field as high volatile B bituminous coal based on vitrinite reflectance and proximate analysis data.

Vitrinite reflectance (Ro) values for Ferron coals from this study and from Tabet and others (1995) range from about 0.4 to 1.25 percent. The isoreflectance map of combined Ro data from Tabet and others (1995), and this study, shown in figure 16 indicates a probable westward increase in thermal maturity, although control is poor toward the west.

In some cases, Ro values may underestimate the actual level of thermal maturity (Price and Barker, 1985). No correction for vitrinite reflectance suppression was applied; thus contours on figure 16 represent a minimum thermal maturity for these coals.

Geochemical studies of produced gases indicate a significant component of biogenic gas in the northern part of the Ferron coal fairway (Lamarre and Burns, 1997; T.S. Collett, USGS, oral commun., 2000); therefore, low Ro values may not relate to generation of low gas volumes.

The shale sequences that enclose the Ferron, the Blue Gate Member, and the Tununk Member were not considered to be significant source rocks for this TPS. The Blue Gate Member should be less thermally mature than the Ferron, and the Tununk is, at best, a lean source rock. Total organic carbon (TOC) values from the Tununk west of the San Rafael Swell range from 0.22 to 0.5 weight percent (Sprinkle and others, 1997).

Reservoir Rock

Coal beds are both source and reservoir rocks for much of the produced natural gas in this TPS. Four conventional gas fields in the TPS produce or have produced sizeable volumes of gas. The principal reservoir rocks for these conventional accumulations are fluvial and deltaic sandstones in the Ferron, and the probable source of the gas produced from these conventional accumulations is the intraformational coal beds. Key factors used in the assignment of fields to conventional accumulations were (1) presence of conventional traps, mostly structural in this area, (2) presence of gas-water contacts, and (3) production data that generally show high initial gas rates which decrease with time, and that have low initial water rates which often increase with time.

Generation and Migration

We assume that the primary source of gas in the TPS is Ferron coal. The gas appears to be both thermogenic and biogenic in origin. However, Lamarre (2000) has suggested

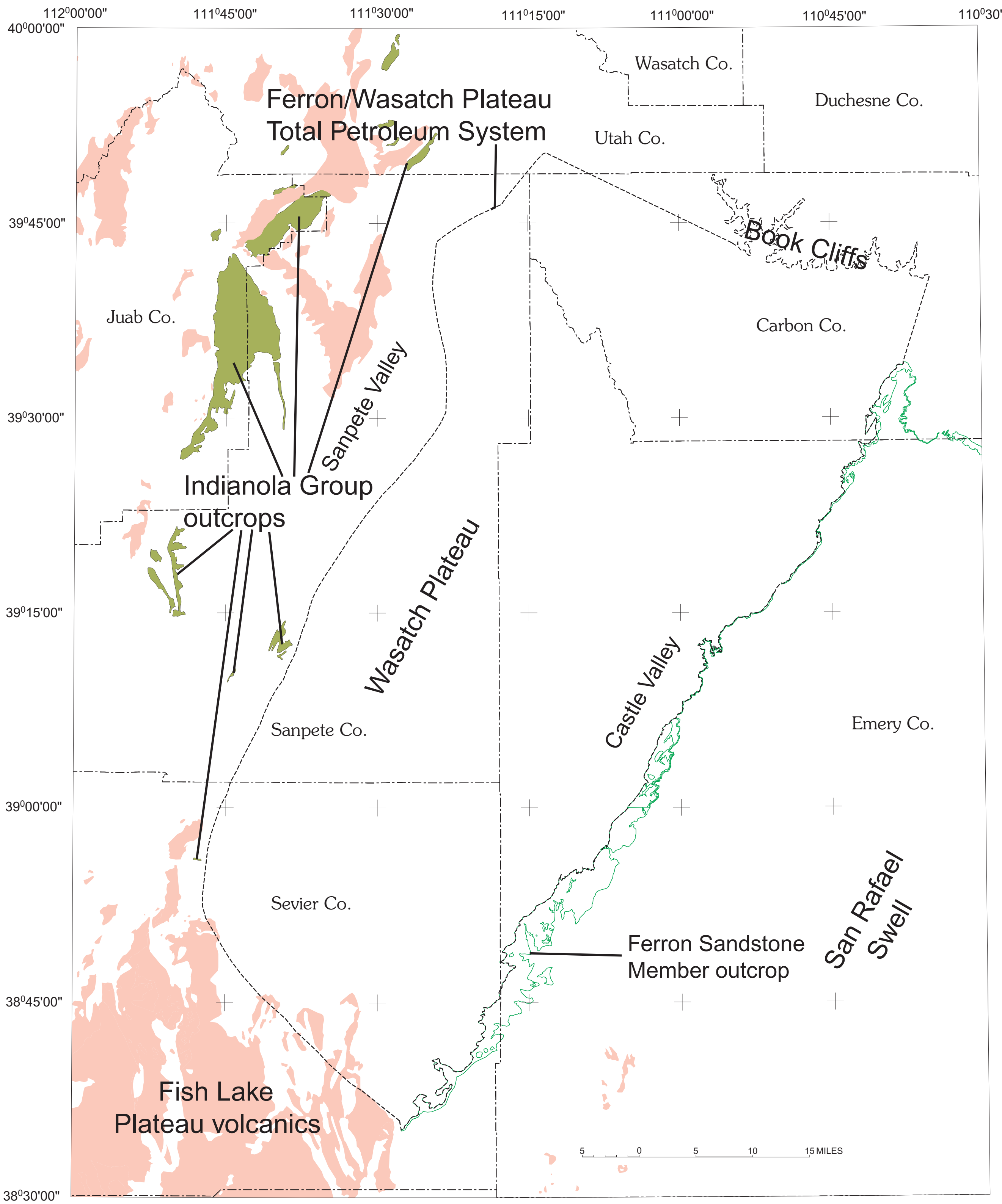


Figure 14. Ferron/Wasatch Plateau Total Petroleum System boundary and some of the geologic criteria used in its definition. Pink color represents Tertiary igneous rocks; green color represents Upper Cretaceous Indianola Group outcrops. Outcrop data for volcanics from Hintze (1980); Indianola outcrop data from Williams and Hackman (1971) and Witkind (1995).

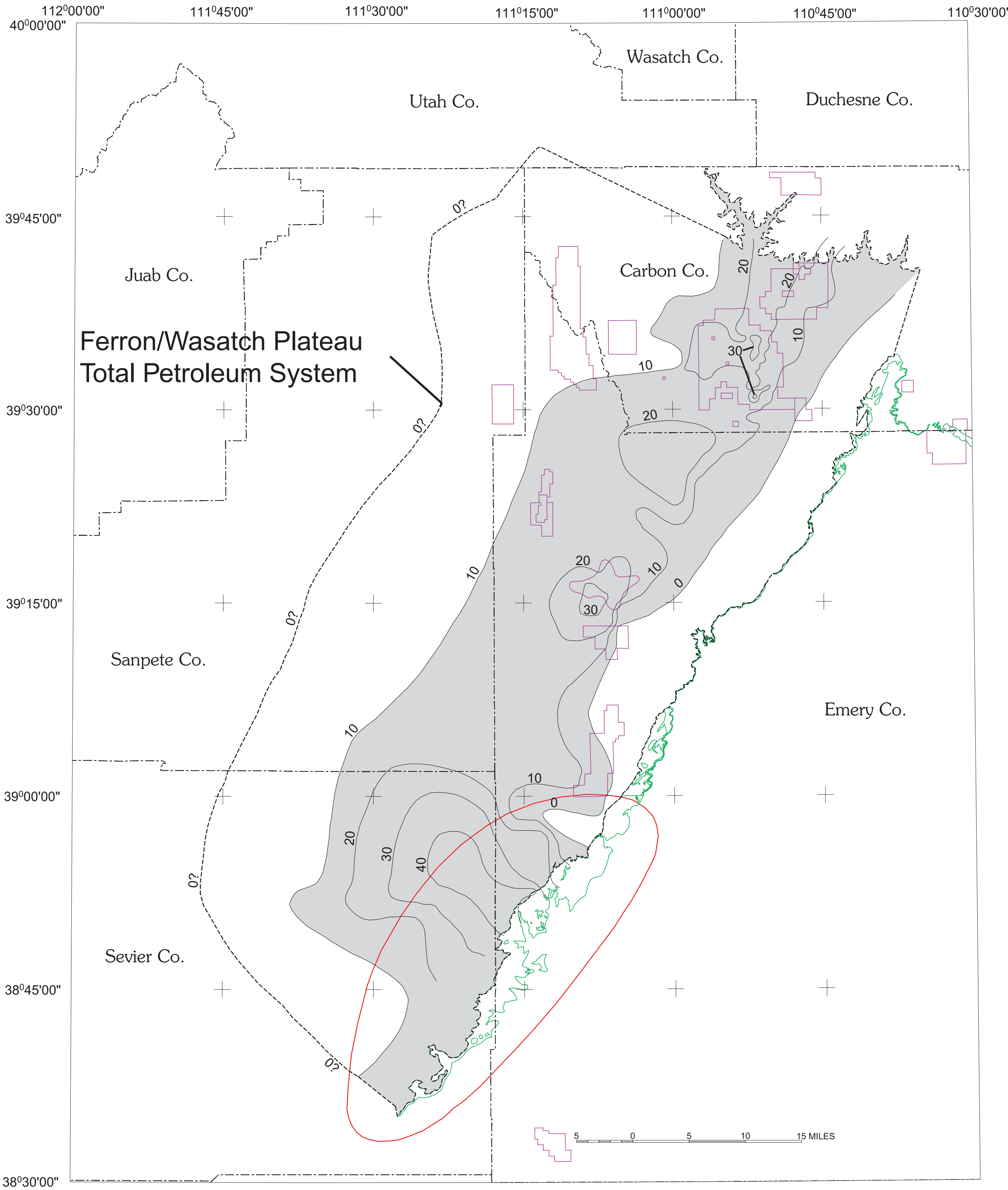


Figure 15. Ferron coal fairway (gray shading) and net coal thickness contours in central Utah; contour interval 10 ft. Coal fairway is defined by zero coal isopach line on the northeast, Ferron Sandstone Member outcrop to the southeast, and 10-ft coal isopach line to the west. Green line represents Ferron Sandstone Member outcrop pattern. Red line encloses Emery coalfield (from Doelling, 1972b). Purple lines show petroleum field boundaries.

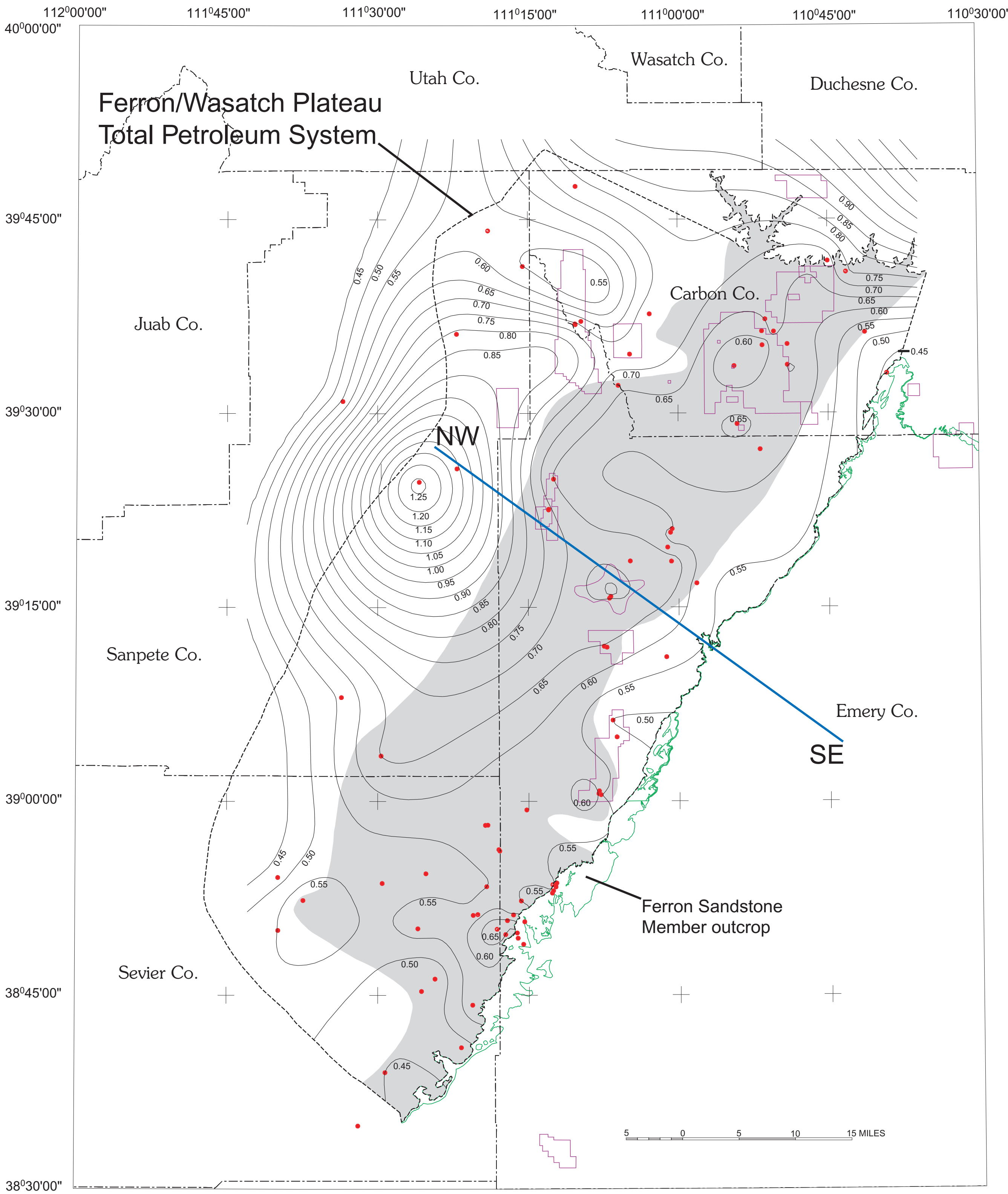


Figure 16. Mean vitrinite reflectance (Ro) contours from Ferron coal samples. Contour interval 0.05 percent Ro. Gray area represents Ferron coal fairway. Blue line shows approximate location of cross section shown in figure 17. Red dots show sample localities. Purple lines show approximate petroleum field boundaries. Vitrinite reflectance data from Tabet and others (1995), and this study.

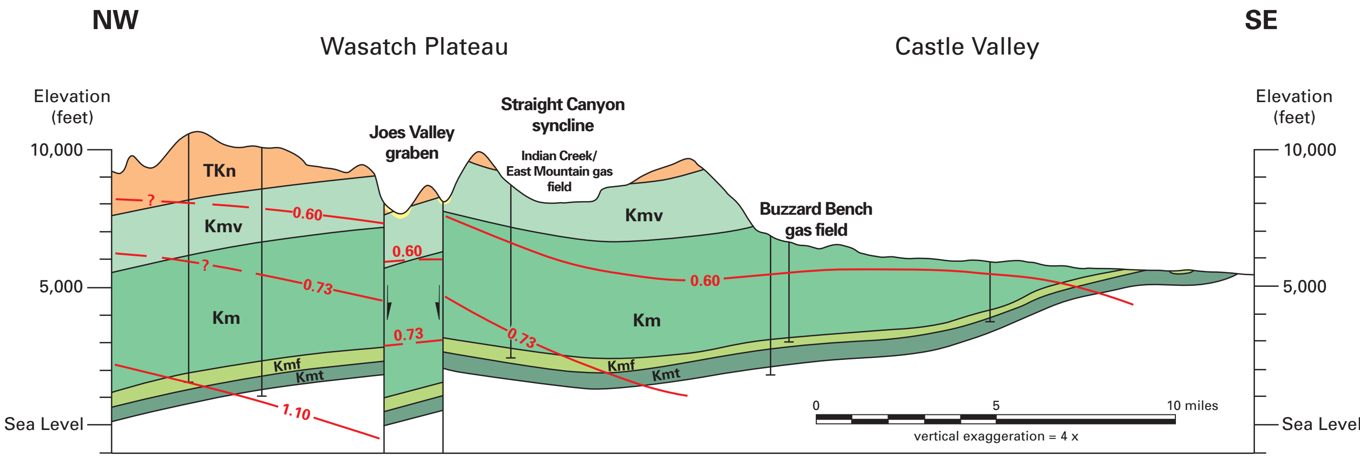


Figure 17. Generalized northwest-southeast cross section across central part of Utah study area illustrating relationship between structure, stratigraphy, and levels of thermal maturity (Ro in percent, red lines). The generally accepted boundary between biogenic and thermogenic gas generation is 0.60 percent Ro. The onset of significant thermogenic gas generation is at 0.73 percent Ro and the onset of maximum thermogenic gas generation is at 1.10 percent Ro. Abbreviations: Kmt, Tununk Member; Kmf, Ferron Sandstone Member; Km, upper part of Mancos Shale; Kmv, Mesaverde Group; TKn, North Horn Formation.

that part of the gas migrated from deeper more mature sources in the Uinta Basin. We cannot rule out that possibility, but extensive lateral migration does not appear necessary to explain gas in this TPS (T.S. Collett, USGS, oral commun., 2000). Limited vitrinite reflectance measurements in the western part of the TPS (fig. 16) indicate a relatively high thermal maturity with average Ro values as high as 1.25 percent. Evidence for igneous activity is common in the vicinity of the TPS (fig. 14) but whether the thermal maturity anomaly resulted from this or other factors was not determined. A cross section (fig. 17) from the central part of the TPS shows the relationship among structure, stratigraphy, and thermal maturity.

This TPS appears to be well isolated stratigraphically. Shale of the Tununk Member underlies the Ferron and ranges from 400 to 750 ft in thickness (Doelling, 1972b). Shale of the Blue Gate Member overlies the Ferron and ranges from 1,500 to 2,400 ft in thickness (Doelling, 1972b).

Traps

Traps for conventional gas accumulations, both discovered and undiscovered, as previously mentioned, are structural and combination types. The plateau area is highly faulted (fig. 2), and because of the relative lack of exploratory drilling west of Joes Valley (figs. 1, 2) more conventional accumulations could exist in that area.

In true coalbed gas accumulations (those accumulations where coal beds form the principal reservoir), hydrostatic pressure exerted on the adsorbed gas is a primary trapping mechanism. Lamarre and Burns (1997), however, presented arguments for a stratigraphic trapping component in the Drunkards Wash field shown on figure 13. Structure may play a role in localization of these coalbed gas accumulations, but based on the character of the contour lines at Buzzard Bench (fig. 13) structural closure is not necessary. Charts showing the timing of geologic events related to this TPS are shown in figures 18*A* and 18*B*.

Exploration History

The earliest date shown for a completed well in the TPS from the well database is 1899. From 1899 through January 1999, at least 534 wells have been drilled here, about one-half of which have been drilled since 1992, the approximate time that production of coalbed gas began. Four conventional gas fields (Clear Creek, Ferron, Flat Canyon/Indian Creek, and Joes Valley) within the TPS have produced commercial quantities of gas (fig. 19). These fields were discovered during the mid 1950's; three of the four were found by surface geologic study.

The greatest concentration of recently drilled (post-1992) wells has been in the Drunkards Wash/Helper area (fig. 19), the area of the most volumetrically significant recent gas production. Other areas that have undergone recent drilling activity are Buzzard Bench, and an unnamed area about 2 mi north of Buzzard Bench (fig. 19). To date, produced water to gas volume ratios in the Buzzard Bench area are higher than those of the Drunkards Wash/Helper area.

Production History

As of September 1999, cumulative gas production for the entire TPS was reported to be about 284 billion cubic feet of gas (BCFG) (IHS Energy Group, 1999). Of this total, about 159 BCFG were produced over an interval of more than 40 years from the four conventional fields. For these four fields,

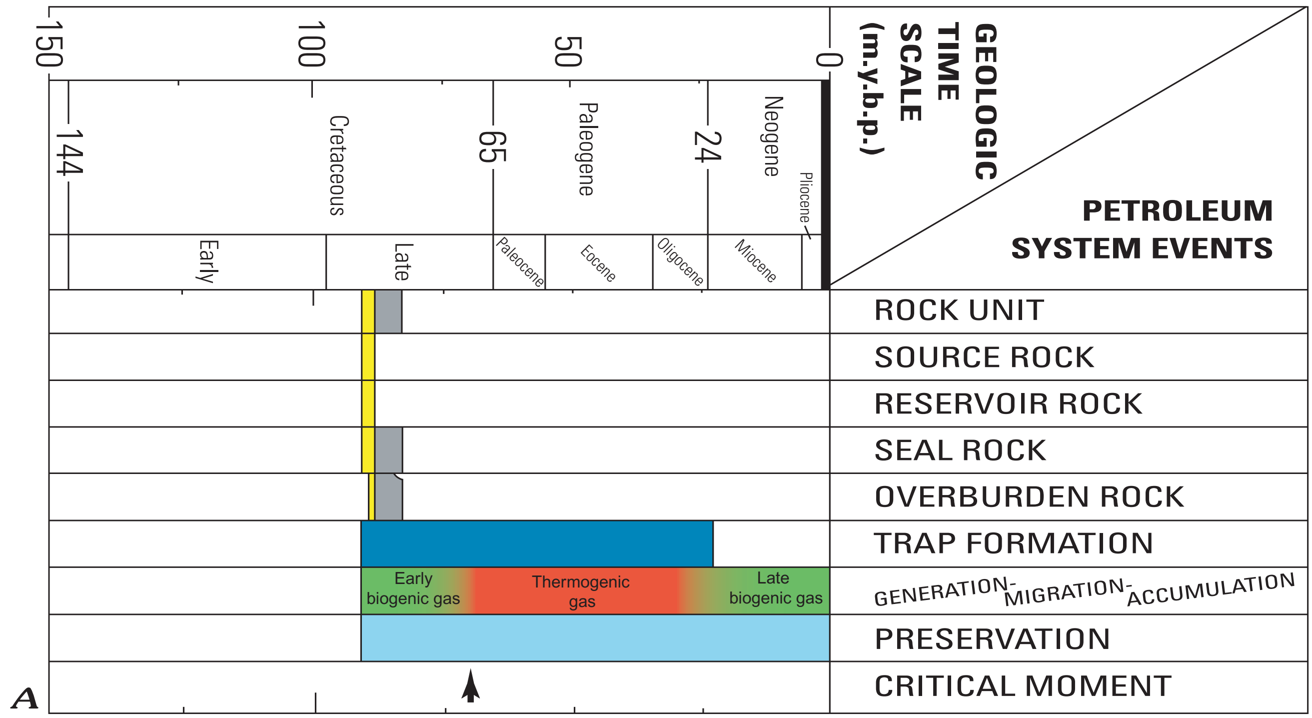


Figure 18*A*. Petroleum system events chart for eastern part of Ferron/Wasatch Plateau Total Petroleum System.

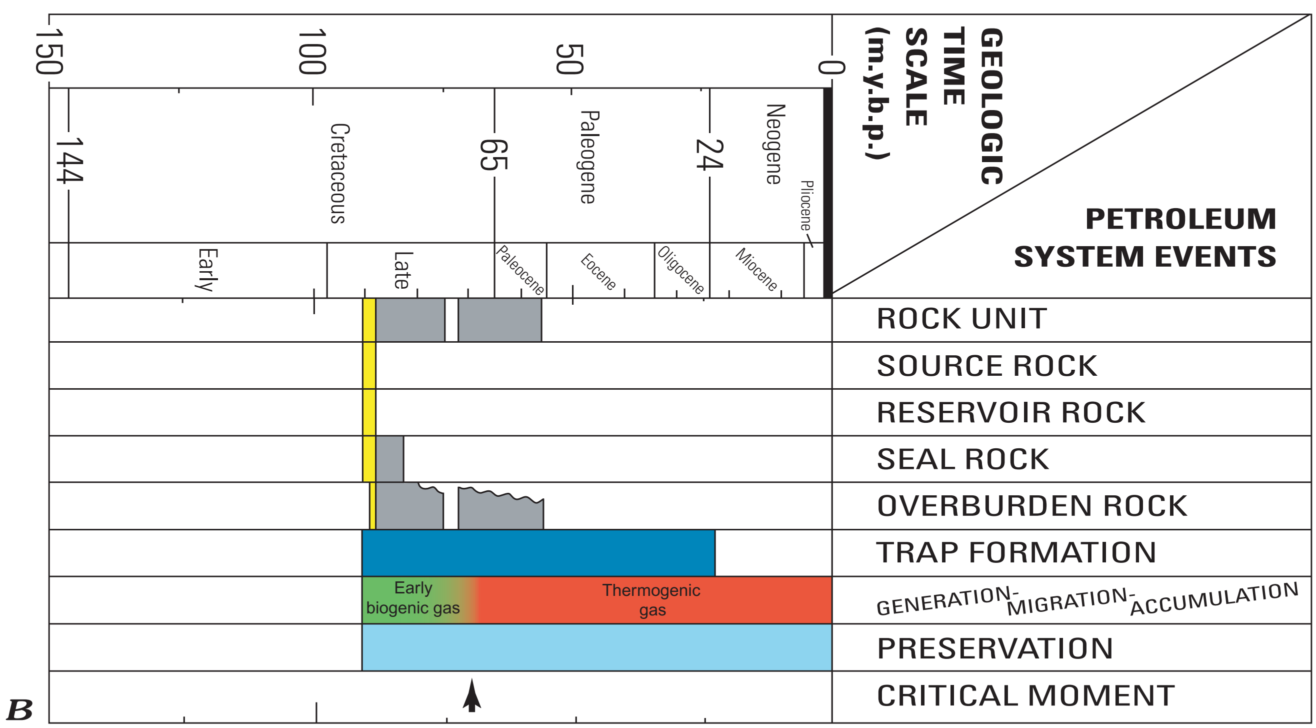


Figure 18*B*. Petroleum system events chart for western part of Ferron/Wasatch Plateau Total Petroleum System.

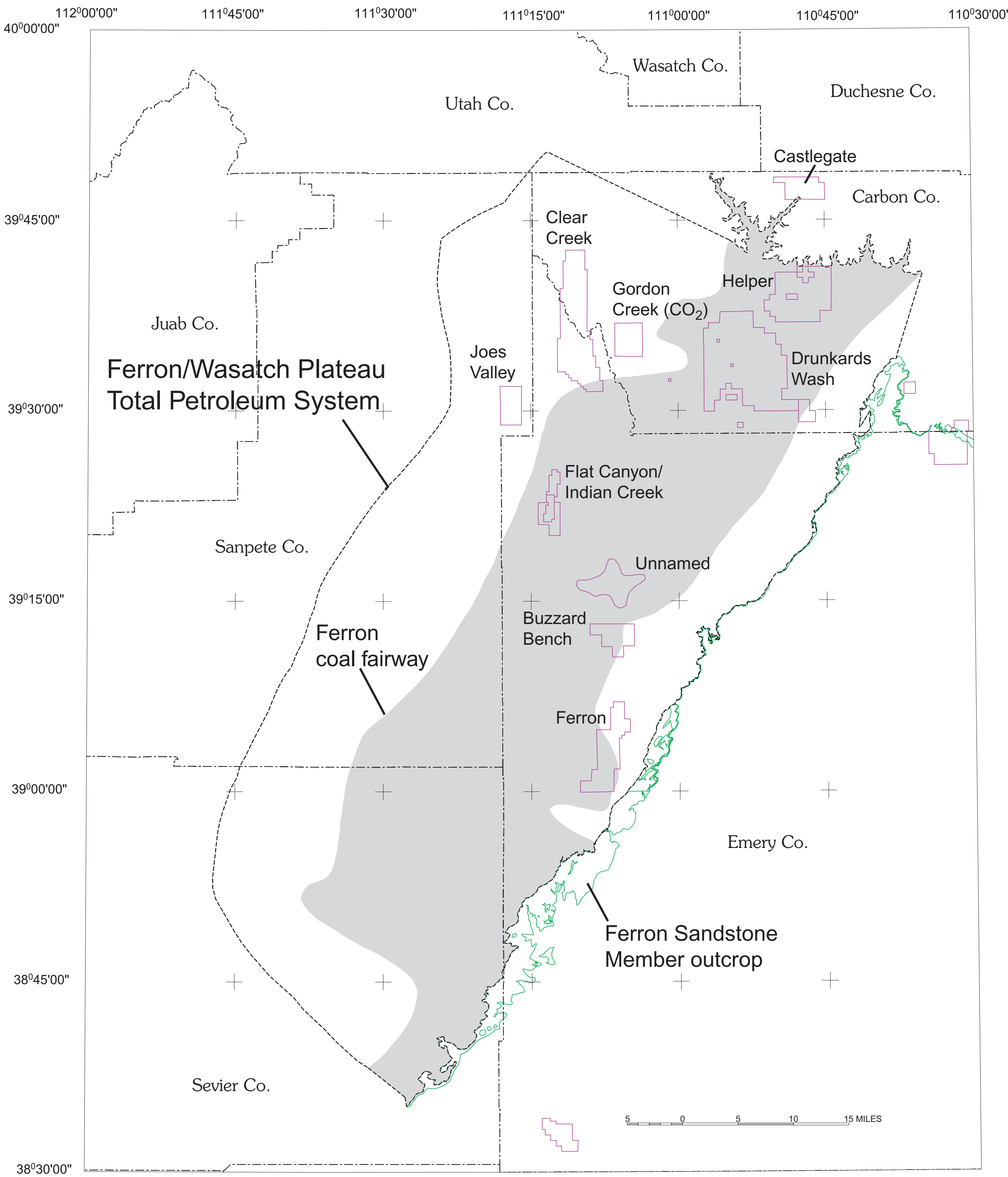


Figure 19. Location of petroleum fields (purple lines) within and near Ferron/Wasatch Plateau Total Petroleum System.

Clear Creek (discovered in 1951) has a cumulative production of about 136.3 BCFG; Flat Canyon/Indian Creek (discovered in 1953) has a cumulative production of about 8.3 BCFG; Joes Valley (discovered in 1955) has a cumulative production of about 2.5 BCFG; and Ferron (discovered in 1957) has a cumulative production of about 11.6 BCFG. Cumulative production from the coalbed gas areas is about 125 BCFG and has been increasing yearly; prior to 1992, cumulative production was reported at about 1.7 BCFG. From January through September 1999, production from the four conventional fields totaled about 0.3 BCFG and that from the coalbed gas areas totaled almost 36 BCFG.

Small volumes of oil (approximately 133,000 barrels) have been produced from the conventional fields, generally from Permian and Triassic age reservoirs (IHS Energy Group, 1999; Tripp, 1991). Total cumulative liquid production from wells within or near coalbed gas areas is about 200 barrels of oil.

Assessment Units

Overview

An assessment unit (AU) is a mappable volume of rock in which a particular set of similar geologic and geochemical characteristics is present. These defining geologic characteristics include trap type, reservoir type, and structural setting. Defining geochemical characteristics include presence of oil, heavy oil, or tar deposits and gas, gas condensate, biogenic gas, or combinations of these and other characteristics. AUs are linked to the principal source rock identified for the TPS and are located within the TPS boundary.

Seven AUs were defined for the Ferron/Wasatch Plateau TPS and considered for evaluation (fig. 20). The area to the northeast, where coal was not identified in the subsurface, and the western part of the TPS, where net coal thickness is less than 10 ft (fig. 15), were ultimately combined with the Ferron coal fairway area for assessment of conventional sandstone reservoir accumulations.

Several factors (discussed in the following sections) were considered in defining the boundaries for the AUs. The AUs contain one of two general types of accumulation, conventional or continuous. Those AUs in which coal beds form the principal reservoir rock are in the continuous category, and the AU in which sandstone forms the principal reservoir rock is in the conventional category. One conventional and five continuous AUs were formally assessed. One continuous AU (Joes Valley and Musinia Grabens AU) was not assessed because of low expectations for the presence of undiscovered gas accumulations. The assessed continuous AUs are located within a northeast-trending area where the net Ferron coal thickness lies between the zero coal isopach line to the east and the 10-ft coal isopach line in the western part of the TPS, an area referred to here as the Ferron coal fairway (figs. 15, 20).

Northern Coal Fairway/Drunkards Wash Assessment Unit (AU 50200181)

This continuous AU is currently the most significant gas-producing unit in the TPS. It consists of two major areas of coalbed gas production, Drunkards Wash and Helper (fig. 21). The western boundary of the AU is the 10-ft net coal thickness contour line which is also the western boundary of the Ferron coal fairway. To the east, the boundary is the zero coal thickness isopleth in the subsurface. The northern boundary is the topographic break at the base of the Book Cliffs. The southern boundary includes known production that is an extension of Drunkards Wash production. This southern AU boundary separates the highly productive wells in the north from less productive wells within the Central Coal Fairway/Buzzard Bench AU.

The Northern Coal Fairway/Drunkards Wash AU is currently undergoing rapid development. The oldest well in this AU was completed in 1927. Exploration and production data show that the coalbed gas potential of the area was recognized by 1991. In 1998, the number of new wells per year had reached 70. Perforation depths in the Ferron for this AU range from about 1,400 to 4,500 ft at Helper, and from about 1,000 to 3,600 ft at Drunkards Wash.

Most leases are single well leases and well spacing is typically 160 acres. Drunkards Wash is located on the eastern side of a structural saddle (fig. 19), in the northern part of the Wasatch Plateau. The gas-productive area generally coincides with one of the thicker pods of coal in the fairway; however, individual wells show only a moderate correlation between the estimated ultimate recovery (EUR) and net coal thickness (fig. 22). Net coal thickness ranges from about 10 to 30 ft in most of the Drunkards Wash area, and from about 10 to 20 ft in the Helper area (fig. 16). Wells in the Helper area often produce less gas and more water than those in the Drunkards Wash area.

Current drilling patterns indicate that the Drunkards Wash field is expanding in nearly every direction although the greatest growth is to the south and west of the present field boundary. Cumulative gas production from the Drunkards Wash/Helper area was about 121.5 BCFG through September 1999 and cumulative water production was about 56.2 million barrels (MMB) (IHS Energy Group, 1999). Estimated potential additions to reserves for this AU are 752.33 BCFG at the mean.

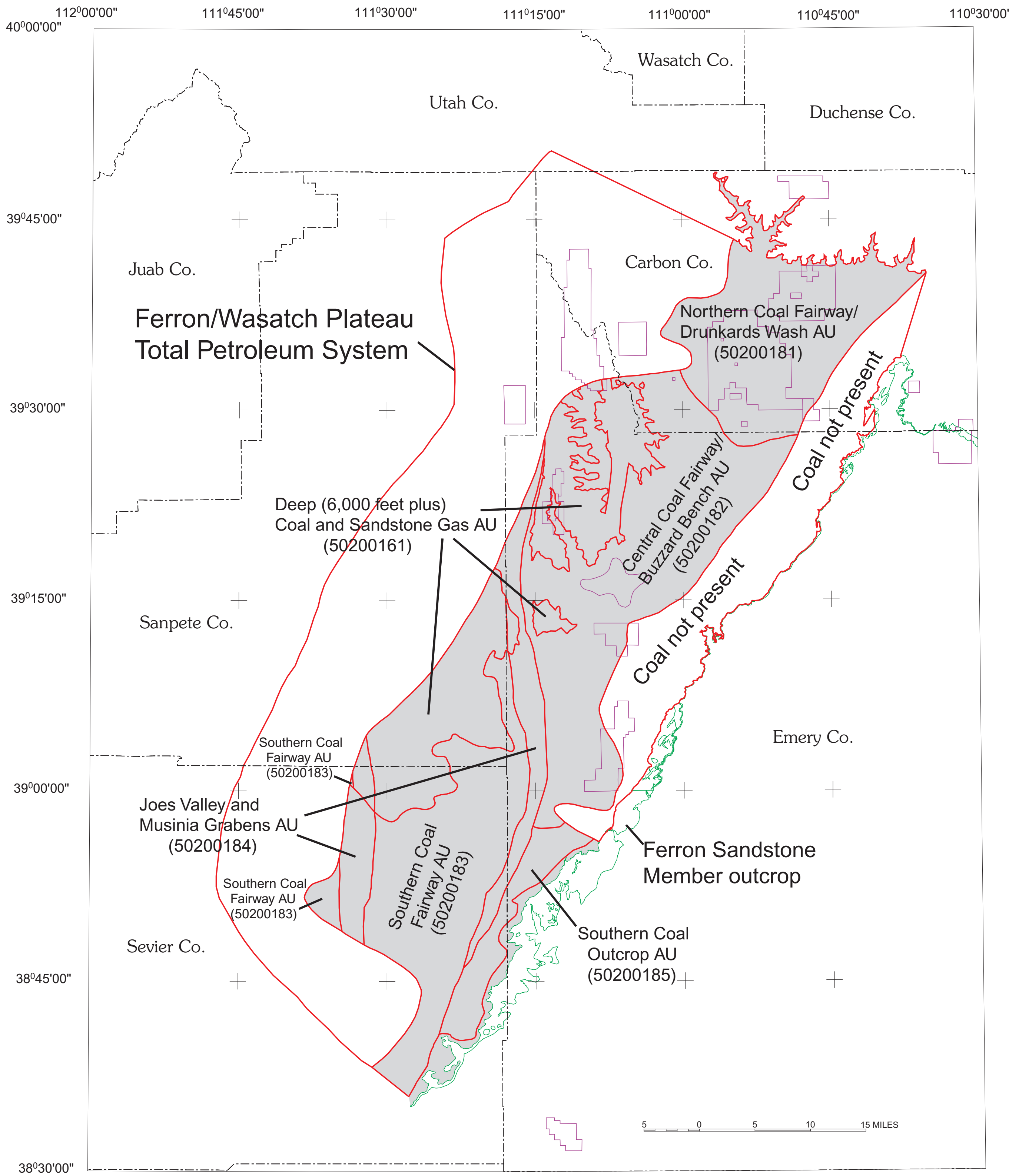


Figure 20. Boundaries of the six continuous gas assessment units (AU) in Ferron/Wasatch Plateau Total Petroleum System. Gray shaded area represents Ferron coal fairway. Nonshaded area to the northeast has no coal; large area to the west has coal in thicknesses of less than 10 ft.

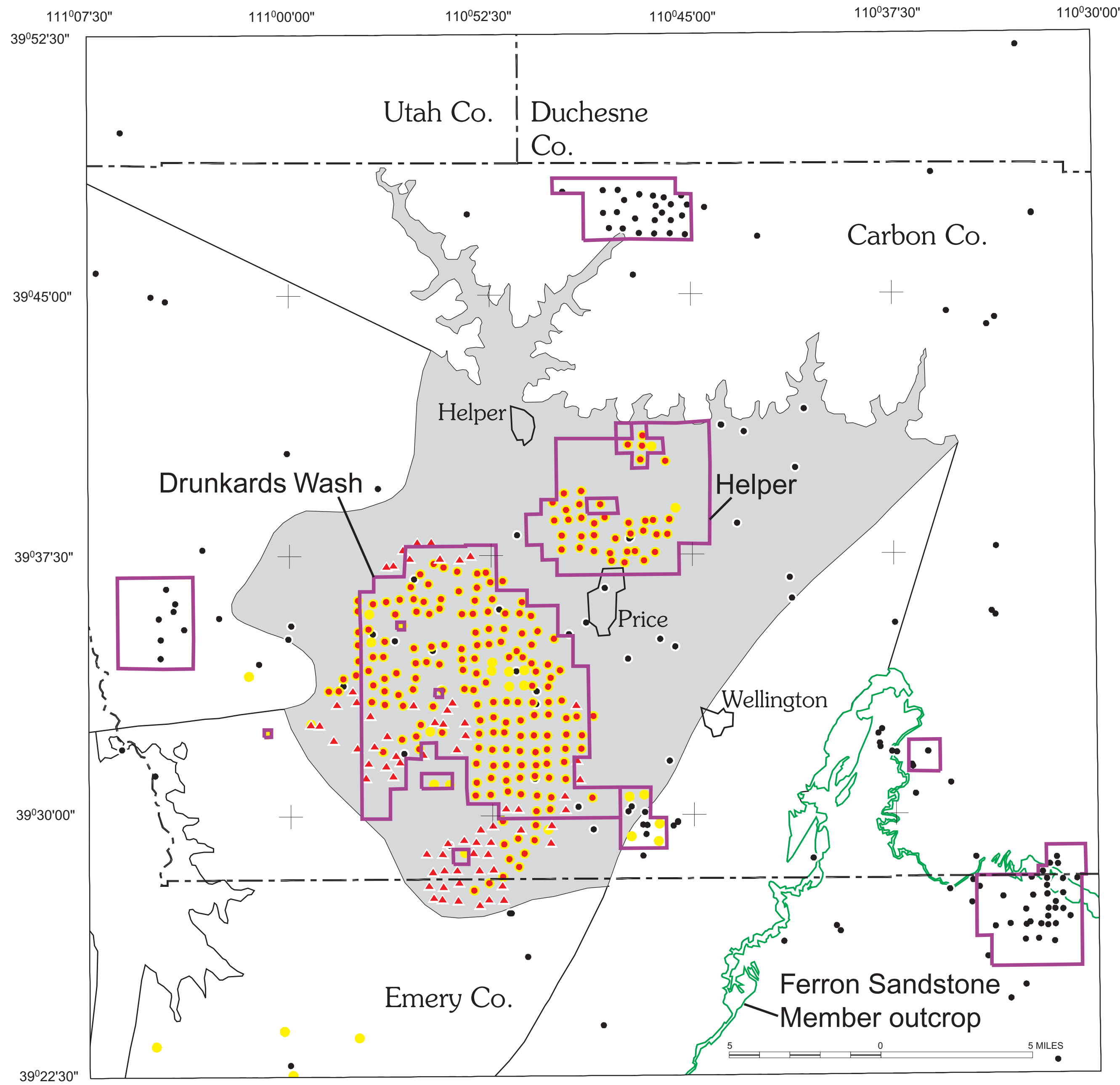


Figure 21. Northern Coal Fairway/Drunkards Wash Assessment Unit (gray shading) of Ferron/Wasatch Plateau Total Petroleum System. Yellow dots represent wells that report Ferron Sandstone Member as producing unit; smaller red dots represent wells reported as current gas-producing wells; black dots represent other wells. Wells represented by dots are from the well data file, og_wells.shp, which was downloaded in 1999 from Utah office of U.S. Bureau of Land Management. Red triangles represent wells that began gas production after November 1999, and are from IHS Energy Group (2000). Purple lines show petroleum field boundaries.

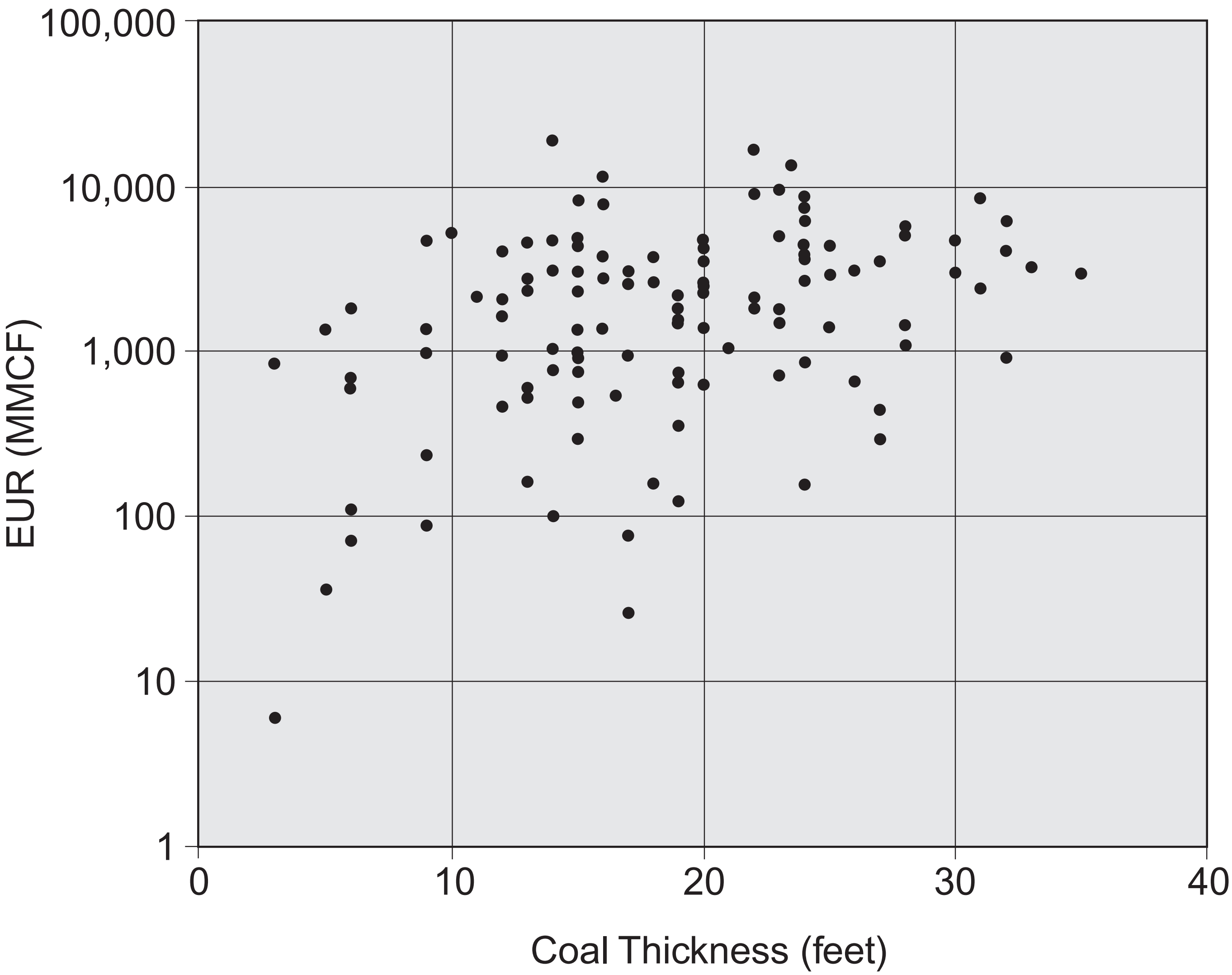


Figure 22. Relationship between coal thickness and estimated ultimate recovery (EUR) of gas for individual wells in Drunkards Wash field area.

Central Coal Fairway/Buzzard Bench Assessment Unit (AU 50200182)

The northern boundary for this continuous AU is the southern boundary of the Northern Coal Fairway/Drunkards Wash AU (figs. 23, 21). The eastern boundary is the zero coal isopach line, and the western boundary follows the trend of major faults along the eastern side of Joes Valley. Areas within the Ferron coal fairway where the coal is covered by more than 6,000 ft of overburden are placed in a separate AU because poorer reservoir quality is expected within coal beds buried deeper than 6,000 ft. The northwestern boundary of this AU is the10-ft net coal isopach line.

As with the Northern Coal Fairway/Drunkards Wash AU, this AU also produces coalbed gas. Production is present in and just north of the Buzzard Bench field. Recent wells drilled to the north of Buzzard Bench have “unassigned” as the field name in the database, but in the concept of a continuous accumulation these are viewed as part of a larger accumulation that includes Buzzard Bench—perhaps a “sweet spot”. Coal is thicker in the area to the north than at Buzzard Bench. Structural features present in the Ferron at the Buzzard Bench/“unassigned” area (fig. 13) are more subtle than those at Drunkards Wash.

From our analysis of production data from this central area and from the known north to south decrease in coal gas content (Lamarre, 2000), we concluded that estimated ultimate recovery data from the Northern Coal Fairway/Drunkards Wash AU would not be representative of new producing wells drilled in the Central Coal Fairway/Buzzard Bench AU. In the Buzzard Bench/“unassigned” area, wells generally produce less gas and more water than wells in the Drunkards Wash/Helper area. Estimates of ultimate gas recoveries from producing coalbed gas wells in the Buzzard Bench/“unassigned” area were used as an analog for the assessment of undiscovered gas within this AU. Part of the Ferron gas field, a conventional accumulation discovered in 1957, is also located within the boundary of this AU. Cumulative gas production from the Ferron field was reported at about 11.6 BCFG, and cumulative production from Buzzard Bench field and the unnamed area to the north, within this AU, is reported at about 3.4 BCFG through September 1999 (IHS Energy Group, 1999). Cumulative water production from the Buzzard Bench and unnamed areas was reported to be about 7.2 MMB (IHS Energy Group, 1999). Estimated potential additions to reserves, at the mean, are 536.73 BCFG for this continuous AU.

Drilling activity is high in this AU, although lower than in the Drunkards Wash/Helper area. The oldest well in this AU was completed in 1921. Drilling activity increased significantly in 1995 in the Buzzard Bench area when 23 wells were completed. Wells in this area have been producing for a relatively short period of time, and that may be one of the more important reasons for the lower production from this area compared to the Drunkards Wash/Helper area.

Southern Coal Fairway Assessment Unit (AU 50200183)

This continuous AU is bounded on the northeast by a major fault trend along the western flank of Joes Valley (fig. 24). The northwestern boundary generally follows a present-day Ferron burial depth of >6,000 ft. The southwestern boundary is the 10-ft net coal thickness isopach, and the southern boundary is the TPS boundary (fig. 15). This AU was separated from the Central Coal Fairway/Buzzard Bench AU primarily because of the southerly decrease in gas content within the coal beds reported by Lamarre (2000). This decrease suggests that using the estimated ultimate recovery data from the Central Coal Fairway/Buzzard Bench AU would overestimate the undiscovered potential of this AU. There has been minimal exploration in or sampling from this AU and low coal gas contents are expected. Within this AU, net coal thickness ranges from 10 to more than 40 ft (fig. 15). Any significant future gas discoveries are expected to be found within coal reservoirs. Potential additions to reserves in this AU were estimated to be 152.59 BCFG at the mean.

In this AU the oldest well was completed in 1956; only 16 wells have been drilled and no production is reported. One well listed Ferron as the producing stratigraphic unit but no production volumes for the well were given.

Deep (6,000 feet plus) Coal and Sandstone Gas Assessment Unit (AU 50200161)

This continuous AU is located within the Ferron coal fairway (figs. 25, 15). The northern and western boundary of the AU is that of the Ferron coal fairway (10-ft net coal thickness line); other boundaries include areas with 6,000 ft or more of overburden. Overburden thickness is a primary consideration in evaluation of coalbed gas AUs. Coalbed gas production generally occurs at depths less than 6,000 ft (Rice and others, 1996). McKee and others (1986) showed that reservoir permeability in the coals from several other basins decreases to values less than 1 millidarcy (mD) at burial depths greater than about 6,000 ft. No data were obtained relating reservoir properties to depth in this AU; however, coals buried deeper than 6,000 ft are likely to have poorer reservoir properties. This AU was assessed as a continuous-type accumulation even though these coals may not be as productive as coal reservoirs at shallower depths. Ten wells are reported in the AU, five within the conventional Flat Canyon/Indian Creek field. One producing gas well is within this AU, 0.5 mi west of the Flat Canyon/Indian Creek field. Potential additions to reserves are estimated to be 59.10 BCFG at the mean.

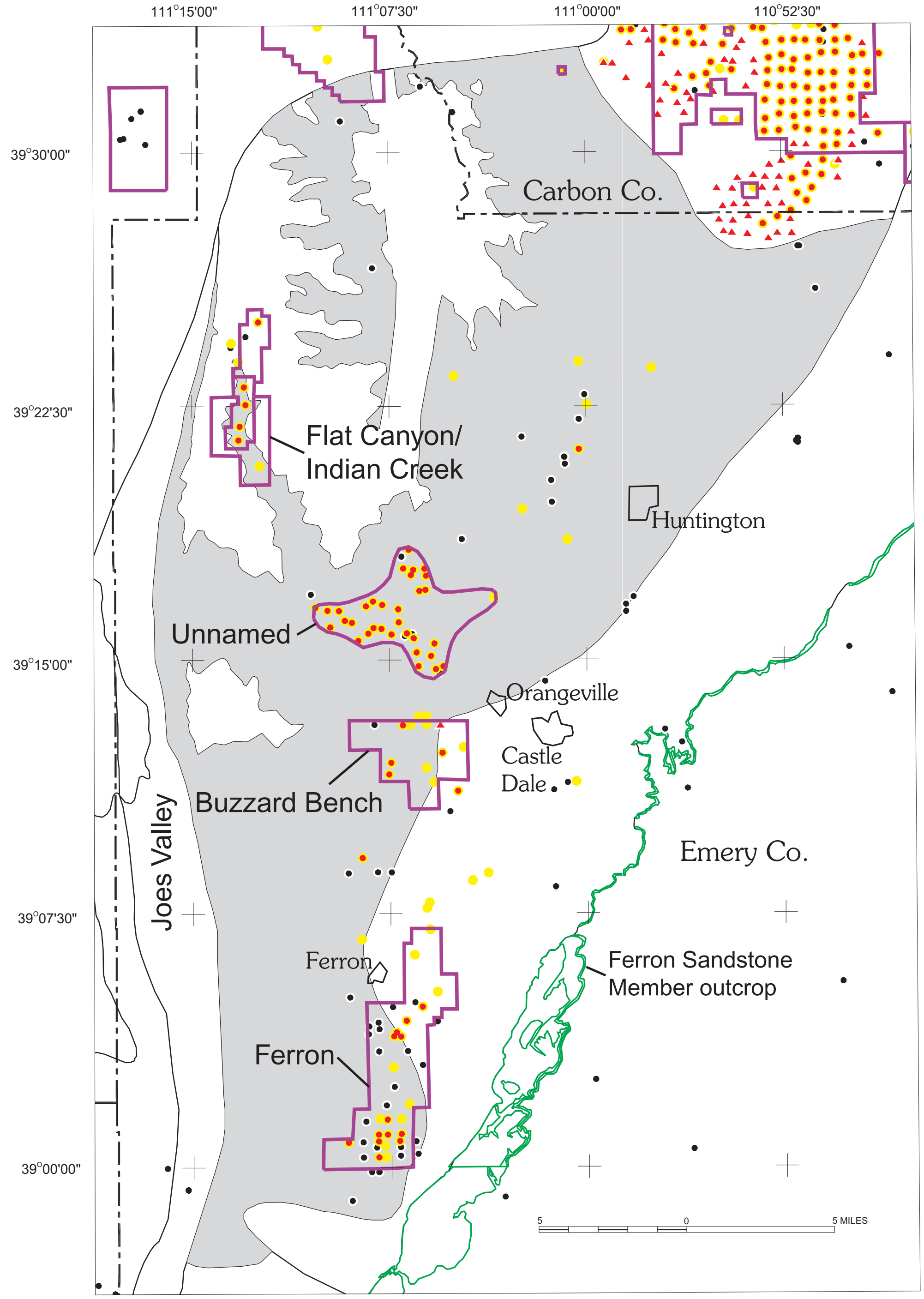


Figure 23. Central Coal Fairway/Buzzard Bench Assessment Unit (gray shading) of Ferron/Wasatch Plateau Total Petroleum System. Yellow dots represent wells that report Ferron Sandstone Member as producing unit; smaller red dots represent wells reported as gas-producing wells; black dots represent other wells. Wells represented by dots are from the well data file, og_wells.shp, which was downloaded in 1999 from Utah office of U.S. Bureau of Land Management. Red triangles represent wells that began gas production after November 1999, and are from IHS Energy Group (2000). Purple lines show petroleum field boundaries.

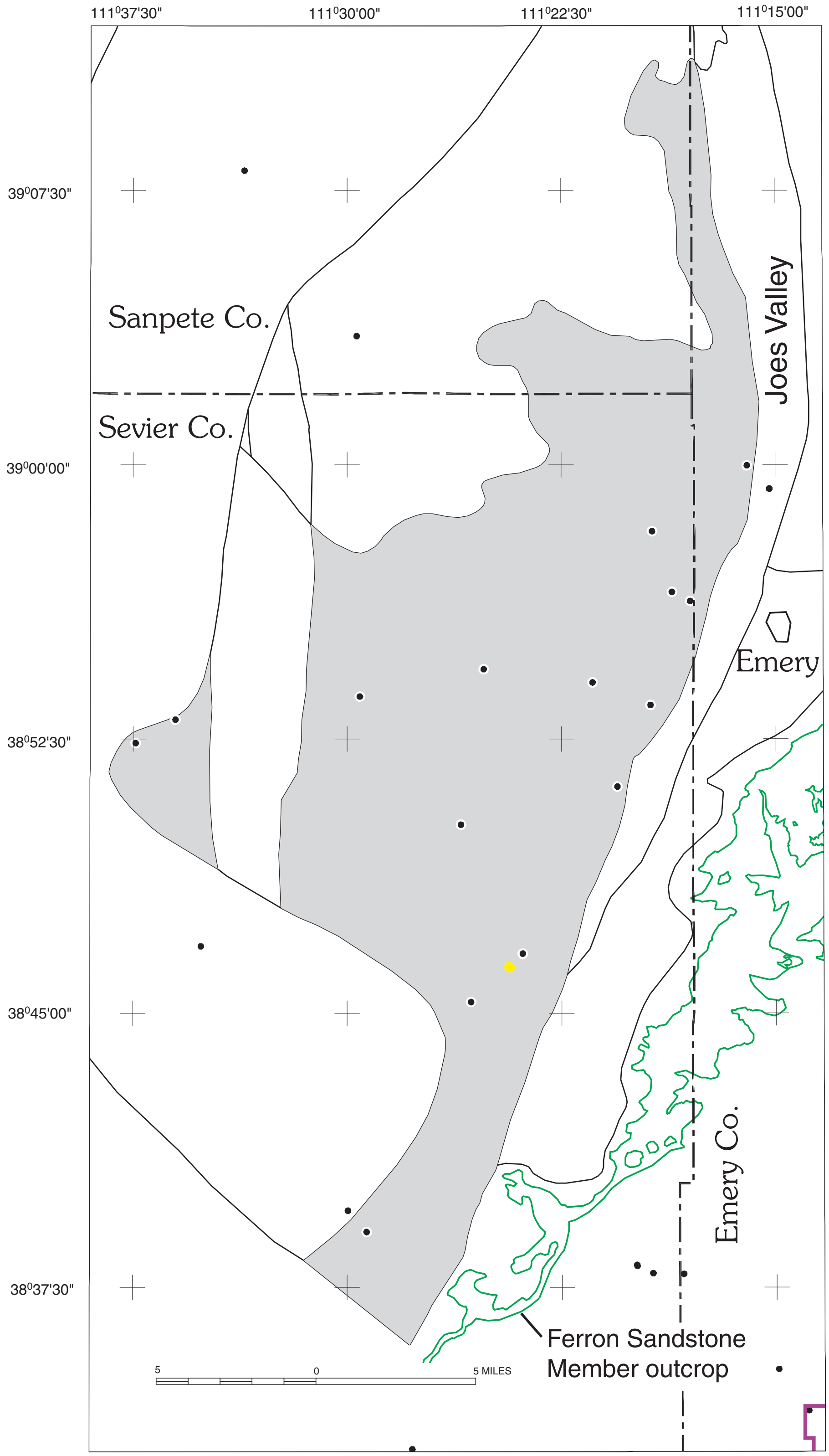


Figure 24. Southern Coal Fairway Assessment Unit (gray shading) of Ferron/Wasatch Plateau Total Petroleum System. Yellow dots represent wells that report Ferron Sandstone Member as producing unit; black dots represent other wells. Wells are from the well data file, og_wells.shp, which was downloaded in 1999 from Utah office of U.S. Bureau of Land Management. Purple lines show petroleum field boundaries.

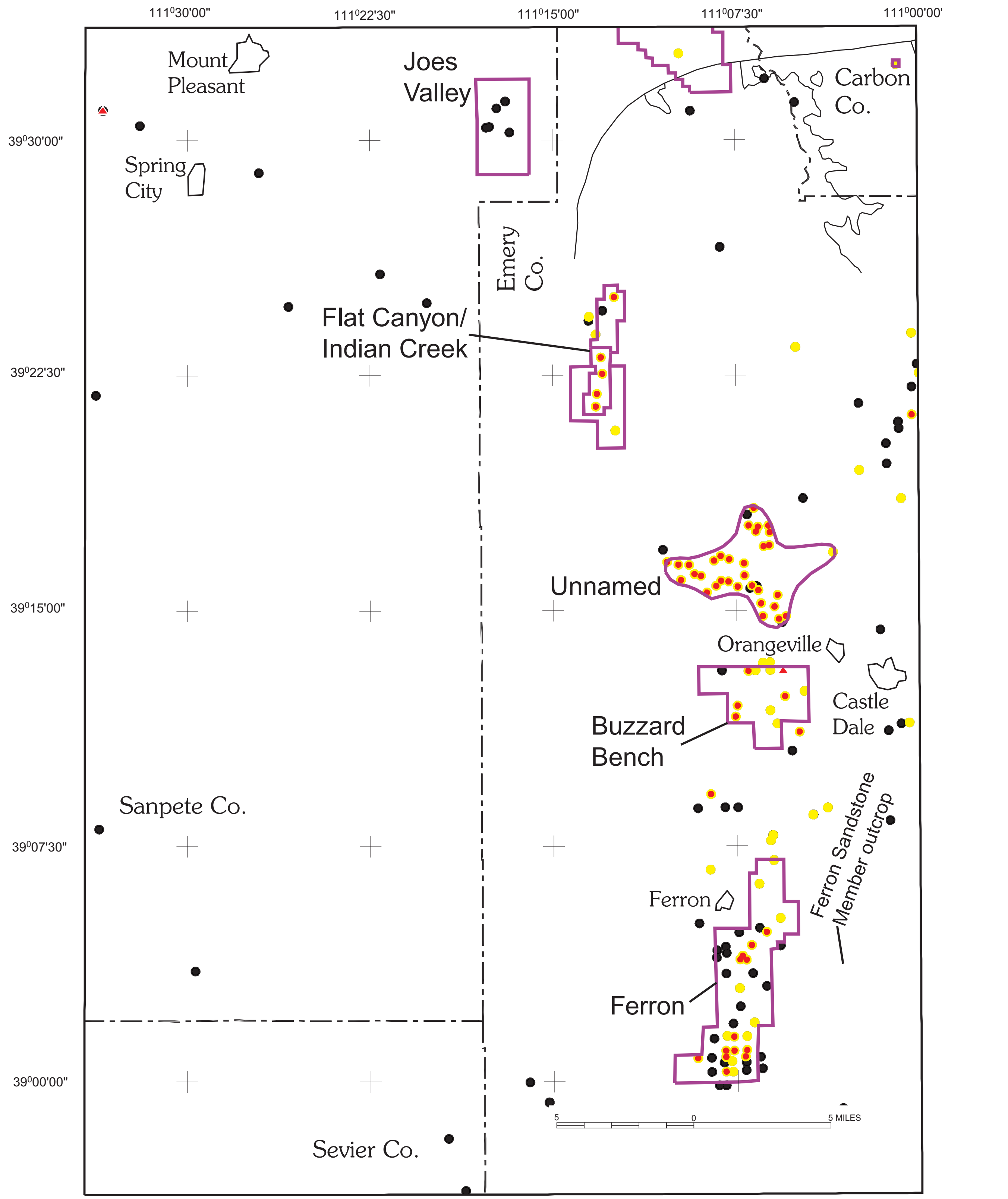


Figure 25. Deep (6,000 feet plus) Coal and Sandstone Gas Assessment Unit (gray shading) of Ferron/Wasatch Plateau Total Petroleum System. Yellow dots represent wells that report Ferron Sandstone Member as producing unit; smaller red dots represent wells that are reported as current gas-producing wells; black dots represent other wells. Wells are from the well data file, og_wells.shp, which was downloaded in 1999 from Utah office of U.S. Bureau of Land Management. Red triangles represent wells that began gas production after November 1999, and are from IHS Energy Group (2000). Purple lines show petroleum field boundaries.

Joes Valley and Musinia Grabens Assessment Unit (AU 50200184)

The database used contained only one well within this continuous AU. Joes Valley gas field is located along the western edge of Joes Valley, not within the graben (figs. 13, 19). The Joes Valley and Musinia Grabens AU (fig. 26), although within the Ferron coal fairway, was not assessed as a continuous-type accumulation. Narrow grabens and numerous faults in this AU suggest that it may be difficult to dewater the coals, a necessary step in producing coalbed gas (Spieker, 1931; Doelling, 1972a). No production is reported from this AU and no quantitative assessment was made.

Southern Coal Outcrop Assessment Unit (AU 50200185)

This continuous AU occupies a small area located within the Ferron coal fairway (fig. 27) and is expected to have a lower potential for additions to gas reserves than the other formally assessed AUs within the coal fairway based on: (1) small area, (2) coal beds cropping out to the east, (3) proximity to Joes Valley graben on the west, and (4) the known trend, within the TPS, of lower gas content in coal to the south. The eastern boundary of the AU approximates 250 ft of present-day overburden. The 250-ft overburden thickness represents the estimated minimum required for coalbed gas trapping. The western boundary of the AU approximates a line of major faults bounding the eastern margin of Joes Valley graben. Numerous coal evaluation wells have been drilled (Ryer, 1981c) along the eastern edge of the AU and near the Ferron outcrop; however, no oil or gas exploration wells have been reported. Lines and Morrissey (1983), however, reported some gas from water wells within the area. Potential for additions to reserves in this AU is estimated, at the mean, to be 10.56 BCFG.

Conventional Ferron Sandstone Gas Assessment Unit (AU 50200101)

This conventional AU (fig. 28) encompasses the entire Ferron/Wasatch Plateau TPS except for that small part of the Southern Coal Outcrop AU that has an overburden thickness of less than 250 ft. This AU was established for the assessment of undiscovered conventional gas fields. Four conventional hydrocarbon gas fields and one carbon dioxide field have been discovered in the AU and all are related to structure (fig. 13). Undiscovered fields within this AU are expected to produce gas from sandstone reservoirs and display conventional gas production characteristics (high initial gas and low initial water production rates followed by decreasing gas and increasing water production rates). Early exploratory wells drilled in this AU were probably drilled on the basis of surface geology and were targeting conventional accumulations. Even though Clear Creek field, the largest accumulation in the TPS (in terms of cumulative production) is conventional, new reserves from this AU are expected to be small compared to the estimated potential reserves of coalbed gas. Completion depths in Ferron sands range from ≈3,700 to ≈6,200 ft at Clear Creek field, ≈5,500 to ≈7,200 ft at Flat Canyon field, and ≈600 to ≈1,300 ft at Ferron field. Net coal thickness is generally 10 ft or less within the field boundaries for these conventional accumulations. Undiscovered gas in this AU is estimated to be 39.75 BCFG at the mean.

Land Ownership

Plates 1 and 2 show the distribution of these land categories and give the reader a qualitative idea of the surface and mineral ownership categories in each AU.

Assessment Results

The results of the assessment of undiscovered recoverable gas in the Ferron/Wasatch Plateau TPS are shown in Appendixes 1 and 2. Expectations of the performance of future wells are based on a few hundred producing wells with a limited production history. Many are still in the initial production phase (see Cook, chapter 23, this CD-ROM, for a description of well production profile sections). Because this initial phase of production may last from a few months to several years, and because the coalbed gas wells in this TPS are all relatively young, the long-term accuracy of the modeling approach used here is difficult to evaluate.

Our analysis resulted in estimated volumes of potential additions to reserves within this TPS of at least 851.64 BCFG at the 95 percent certainty level, at least 2,503.45 BCFG at the 5 percent certainty level, and a mean value of 1,551.06 BCFG (Appendix 1).

Summary and Conclusions

The Ferron/Wasatch Plateau TPS is primarily a gas system and most of the estimated undiscovered recoverable gas resources are expected to exist within the Ferron coal fairway in a continuous-type accumulation. The principal source rock for all gas accumulations in the system is believed to be the Ferron coal, which also forms the principal reservoirs. Gas was generated by thermal maturation of coal and by microbial processes. Migration of gas from deeper parts of the Uinta Basin to the north cannot be ruled out;

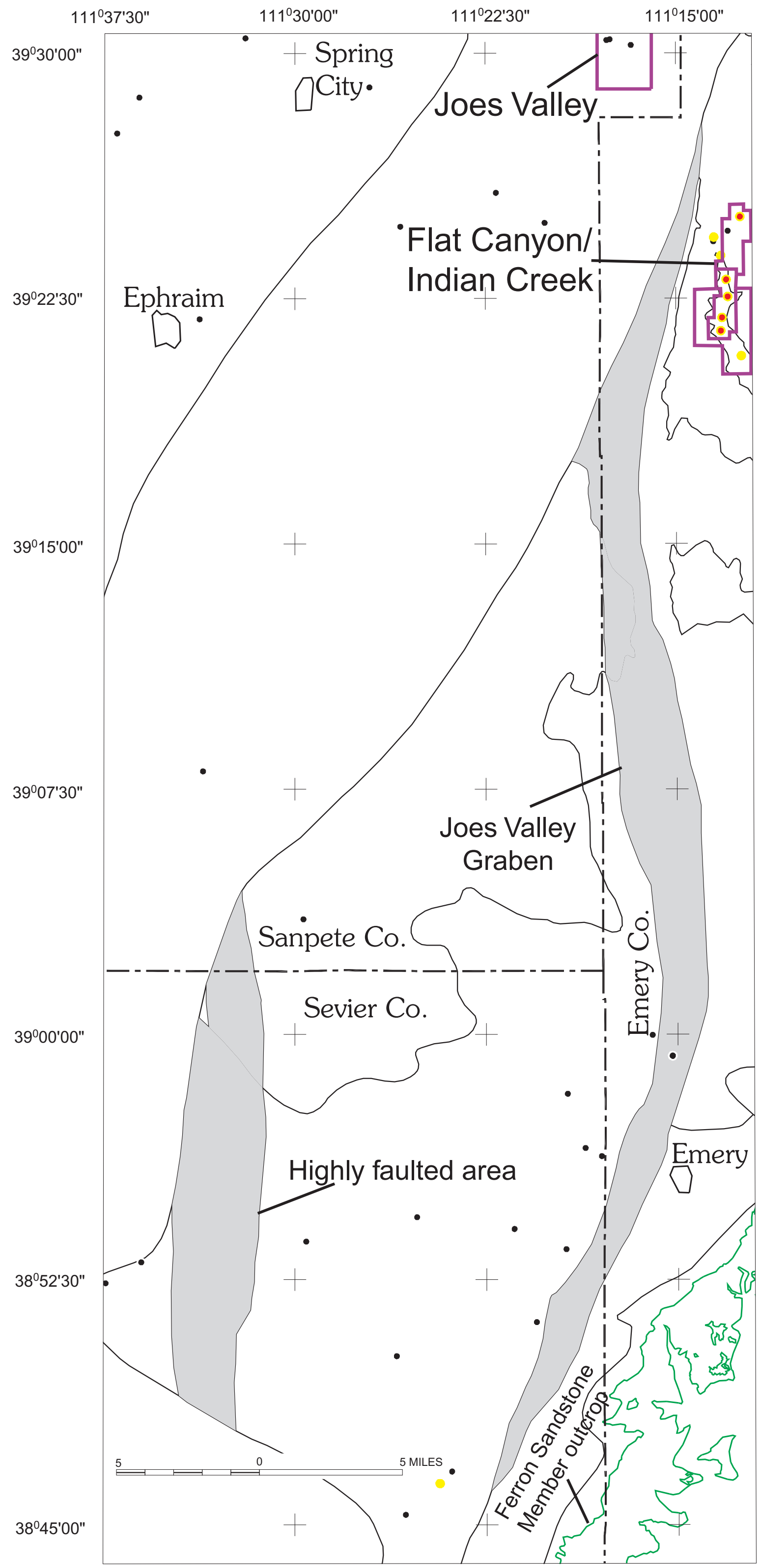


Figure 26. Joes Valley and Musinia Grabens Assessment Unit (gray shading) of Ferron/Wasatch Plateau Total Petroleum System . Yellow dots represent wells that report Ferron Sandstone Member as producing unit; smaller red dots represent wells reported as gas-producing wells; black dots represent other wells. Wells are from the well data file, og_wells.shp, which was downloaded in 1999 from Utah office of U.S. Bureau of Land Management. Purple lines show petroleum field boundaries.

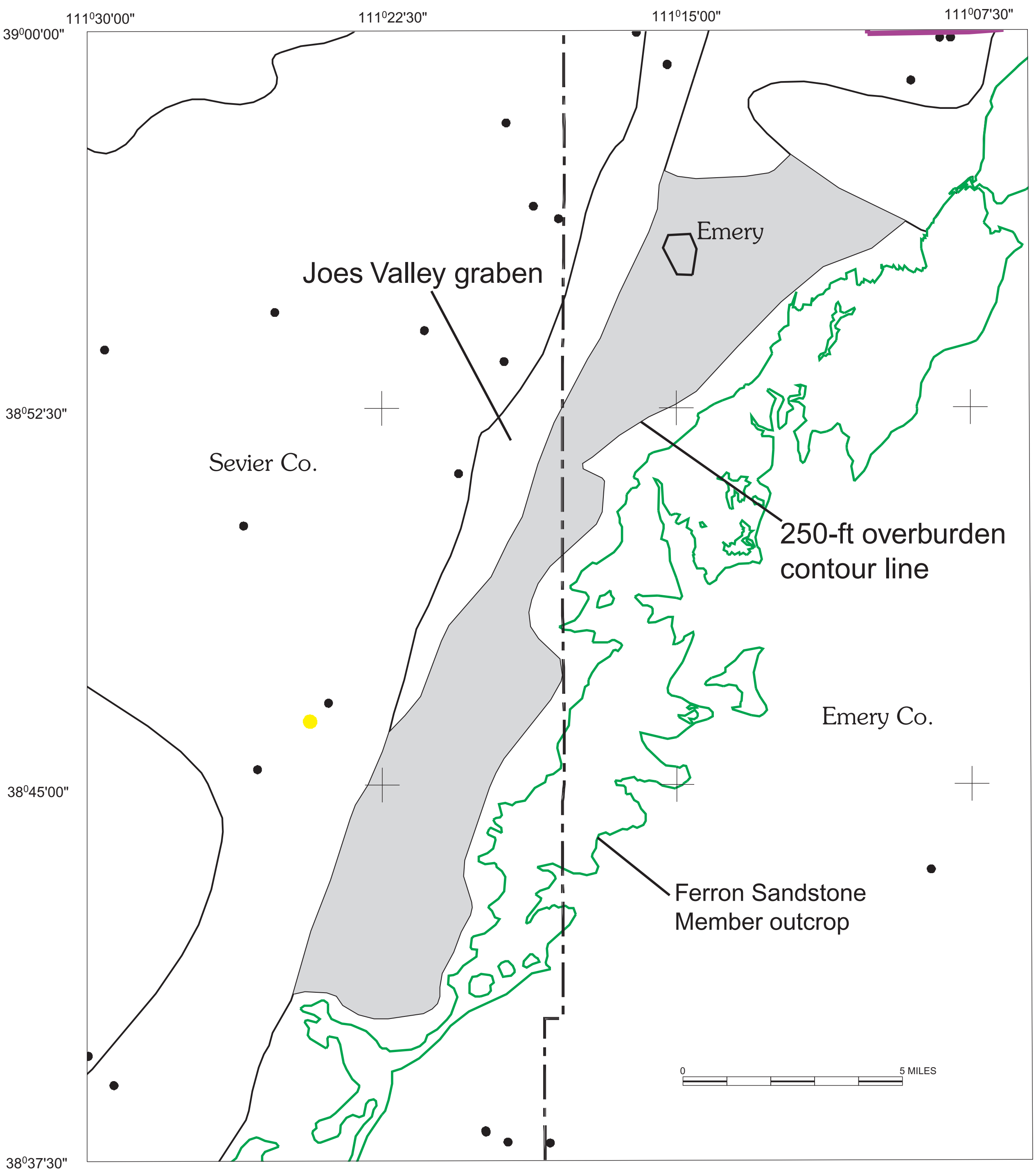


Figure 27. Southern Coal Outcrop Assessment Unit (gray shading) of Ferron/Wasatch Plateau Total Petroleum System. Yellow dots represent wells that report Ferron Sandstone Member as producing unit; black dots represent other wells. Wells shown are from the well data file, og_wells.shp, which was downloaded in 1999 from Utah office of U.S. Bureau of Land Management. Purple lines (northeastern part of area of figure) show petroleum field boundaries.

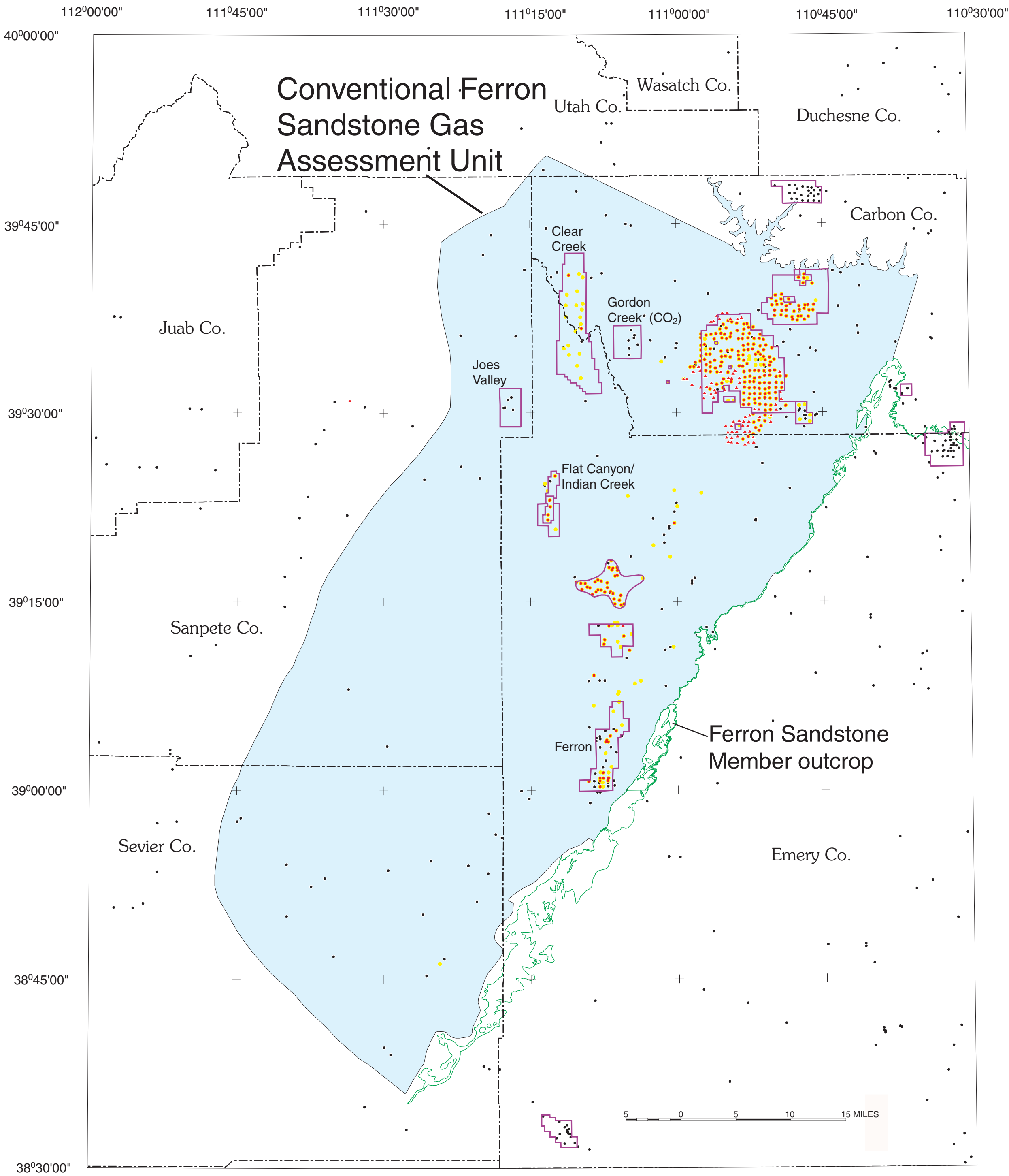


Figure 28. Conventional Ferron Sandstone Gas Assessment Unit (blue shading) of Ferron/Wasatch Plateau Total Petroleum System. It includes entire area of total petroleum system except for southeastern part where Ferron Sandstone Member is less than 250 ft from surface. Yellow dots represent wells that report Ferron Sandstone Member as producing unit; smaller red dots represent wells reported as current gas-producing wells; black dots represent other wells. Wells represented by dots are from the well data file, og_wells.shp, which was downloaded in 1999 from Utah office of U.S Bureau of Land Management. Red triangles represent wells that began gas production after November 1999, and are from IHS Energy Group (2000). Purple lines show petroleum field boundaries. Known conventional gas fields associated with this total petroleum system are labeled.

however, local generation and trapping of gas within the coal appears more likely. The Northern Coal Fairway/Drunkards Wash AU is estimated to contain the largest volumes of undiscovered recoverable gas in the TPS. Within the coal fairway, a general decrease in well productivity is predicted, from north to south, as a result of the trend of decreasing gas content in that direction. On an individual well basis, no relationship is evident between well productivity and coal thickness or thermal maturity, although the best production is generally found in areas of thicker coal.

With increased exploration within the coal fairway, much of the area between Drunkards Wash and Buzzard Bench is expected to produce gas. Expansion of production will likely extend south of Buzzard Bench if, over time, well productivity in that area improves. Based on limited gas content data, we estimate that the Southern Coal Fairway AU contains the least undiscovered, recoverable gas volumes of the three major coal fairway AUs, even though some of the thickest coals in the fairway are present in this southern unit. Lower expected gas contents in the Southern Coal Outcrop AU, as well as the possibility that gas may have been naturally desorbed and flushed from the coal, resulted in a low estimate for volumes of undiscovered gas in the AU The probability of poor reservoir quality and relatively thin coals resulted in a low estimate for future gas discoveries in the Deep (6,000 feet plus) Coal and Sandstone Gas AU. The Joes Valley and Musinia Grabens AU was not assessed because the highly fractured nature of the area may prevent efficient dewatering.

The Conventional Ferron Sandstone Gas AU probably contains undiscovered gas accumulations related to structural or combination-type traps and reservoirs in sandstone. Future drilling in the western part of the AU may add new reserves; however, no significant volumes of new gas are expected.

References Cited

Anderson, P.B., Chidsey, T.C., Jr., and Ryer, T.A., 1997, Fluvial-deltaic sedimentation and stratigraphy of the Ferron Sandstone, *in* Link, P.K., and Kowallis, B.J., eds., Mesozoic to Recent geology of Utah: Brigham Young University Geology Studies, v. 42, pt. 2, p. 135–154.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429–458.

Bennett, H.S., 1955a, Photogeologic map of the Emery-7 quadrangle Emery County, Utah: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–10, scale 1:24,000.

———1955b, Photogeologic map of the Emery-10 quadrangle Emery County, Utah: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–11, scale 1:24,000.

Biewick, L.R.H., and Green, G.A., 1999, Land and mineral ownership coverage for the Uinta Basin, Wasatch Plateau and surrounding areas, northeastern Utah: U.S. Geological Survey Open-File Report 99–553–B, Version 1.0. [Available at URL http://geology.cr.usgs.gov/pub/open-file-reports/ofr-99-0553-b/]

Bohacs, K.M., and Suter, J.R., 1997, Sequence stratigraphic distribution of coaly rocks—Fundamental controls and paralic examples: American Association of Petroleum Geologists Bulletin, v. 81, no. 10, p. 1612–1639.

Bunnell, M.D., and Hollberg, R.J., 1991, Coal beds of the Ferron Sandstone Member in northern Castle Valley, east-central Utah, *in* Chidsey, T.C., Jr., ed., Geology of east-central Utah: Utah Geological Association Publication 19, p. 157–172.

Cobban, W.A., 1976, Ammonite record from the Mancos Shale of the Castle Valley–Price–Woodside area, east-central Utah: Brigham Young University Geology Studies, v. 22, pt. 3, p. 117–126.

Cotter, E., 1975, Deltaic deposits in the Upper Cretaceous Ferron Sandstone, Utah, *in* Broussard, M.L., ed., Deltas, models for exploration: Houston Geological Society, p. 471–484.

———1976, The role of deltas in the evolution of the Ferron Sandstone and its coals, Castle Valley, Utah: Brigham Young University Geology Studies, v. 22, pt. 3, p. 15–41.

Cross, T.A., 1988, Controls on coal distribution in transgressive-regressive cycles, Upper Cretaceous, Western Interior U.S.A., *in* Wilgus, C.K., and others, eds., Sea-level changes; an integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 371–380.

Detterman, J.S., 1955, Photogeologic map of the Emery-2 quadrangle Emery County, Utah: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–9, scale 1:24,000.

Doelling, H.H., 1972a, Coal in the Sevier-Sanpete region, *in* Baer, J.L., and Callaghan, E., eds., Plateau–Basin and Range transition zone, central Utah, 1972: Utah Geological Association Publication 2, p. 81–89.

———1972b, Central Utah coal fields—Sevier-Sanpete, Wasatch Plateau, Book Cliffs and Emery: Utah Geological and Mineralogical Survey Monograph Series No. 3, 571 p.

Fouch, T.D., Nuccio, V.F., Osmond, J.C., MacMillan, L., Cashion, W.B., and Wandrey, C.J., 1992, Oil and gas in uppermost Cretaceous and Tertiary rock, Uinta Basin, Utah, *in* Fouch, T.D., Nuccio, V.F., and Chidsey, T.C., Jr., eds., Hydrocarbon and mineral resources of the Uinta Basin, Utah and Colorado: Utah Geological Association Guidebook 20, p. 9–47.

Gardner, M.H., 1995a, The stratigraphic hierarchy and tectonic history of the mid-Cretaceous foreland basin of central Utah, *in* Dorobek, S.L., and Ross, G.M., eds., Stratigraphic evolution of foreland basins: Society of Economic Paleontologists and Mineralogists (Society of Sedimentary Geology) Special Publication 52, p. 283–303.

———1995b, Tectonic and eustatic controls on the stratal architecture of mid-Cretaceous stratigraphic sequences, central western interior foreland basin of North America, *in* Dorobek, S.L., and Ross, G.M., eds., Stratigraphic evolution of foreland basins: Society of Economic Paleontologists and Mineralogists (Society of Sedimentary Geology) Special Publication 52, p. 242–281.

Gilbert, G.K., 1877, Report on the geology of the Henry Mountains: U.S. Geographic and Geologic Survey, Rocky Mountain Region Report, 160 p.

Gill, J.R., and Cobban, W.A., 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: U.S. Geological Survey Professional Paper 766, 37 p.

Hale, L.A., 1972, Depositional history of the Ferron Formation, Central Utah, *in* Baer, J.L., and Callaghan, E., eds., Plateau–Basin and Range transition zone, central Utah: Utah Geological Association Publication 2, p. 29–40.

Hale, L.A., and Van De Graaff, F.R., 1964, Cretaceous stratigraphy and facies patterns—Northeastern Utah and adjacent areas, *in* Sabatka, E.F., ed., Guidebook to the geology and mineral resources of the Uinta Basin: Intermountain Association of Petroleum Geologists 13th Annual Field Conference, p. 115–138.

Hintze, L.F., 1980, Geologic map of Utah: Utah Geological and Mineral Survey, 2 plates, scale 1:500,000. [The Arc/Info coverage used in our report was created by workers at Utah State University in 1994 from this original work of Hintze]

IHS Energy Group, 1999, Petroleum Information/Dwights petroROM Rocky Mountain Region Production Data on CD-ROM: IHS Energy Group, 15 Inverness Way East, D205, Englewood, CO 80112 U.S.A.

———2000, Petroleum Information/Dwights petroROM Rocky Mountain Region Production Data on CD-ROM: IHS Energy Group, 15 Inverness Way East, D205, Englewood, CO 80112 U.S.A.

Katich, P.J., Jr., 1953, Source direction of Ferron Sandstone in Utah: American Association of Petroleum Geologists Bulletin, v. 37, no. 4, p. 858–862.

———1954, Cretaceous and Early Tertiary stratigraphy of central and south-central Utah with emphasis on the Wasatch Plateau area, *in* Grier, B., ed., Geology of portions of the High Plateaus and adjacent Canyon Lands, central and south-central Utah: Intermountain Association of Petroleum Geologists, p. 42–54.

Laine, M.D., and Staley, D., 1991, Summary of oil and gas exploration and production in Carbon, Emery and Sanpete Counties, east-central Utah, *in* Chidsey, T.C., ed., Geology of east-central Utah: Utah Geological Association Field Symposium, p. 227–235.

Lamarre, R.A., 2000, Exploring for large coalbed methane stratigraphic traps in Ferron coals of east-central Utah, *in* Coalbed methane in the Rocky Mountains—2000 RMAG coalbed methane symposium, June 20–21, 2000: Rocky Mountain Association of Geologists, unpaginated.

Lamarre, R.A., and Burns, T.D., 1997, Drunkard's Wash unit—Coalbed methane production from Ferron coals in east-central Utah, *in* Coalson, E.B., Osmond, J.C., and Williams, E.T., eds., Innovative applications of petroleum technology in the Rocky Mountain area: Rocky Mountain Association of Geologists Guidebook, p. 47–59.

Lines, G.C., and Morrissey, D.J., 1983, Hydrology of the Ferron Sandstone aquifer and effects of proposed surface-coal mining in Castle Valley, Utah: U.S. Geological Survey Water-Supply Paper, 40 p.

Lupton, C.T., 1914, Oil and gas near Green River, Grand County, Utah: U.S. Geological Survey Bulletin 541, p. 115–133.

———1916, Geology and coal resources of Castle Valley, Carbon, Emery, and Sevier Counties, Utah: U.S. Geological Survey Bulletin 628, 88 p.

Magoon, L.B., and Dow, W.G., 1994, The petroleum system, *in* Magoon, L.B., and Dow, W.G., eds., The petroleum system—From source to trap: American Association of Petroleum Geologists Memoir 60, p. 3–24.

Magoon, L.B., and Schmoker, J.W., 2000, The total petroleum system—The natural network that constrains the assessment unit, *in* U.S. Geological Survey World Petroleum Assessment 2000—Description and results: U.S. Geological Survey Digital-Data Series DDS–60, 4 CD-ROMs.

McKee, C.R., Bumb, A.C., Way, R.A., Koenig, J.M., Reverand, J.M., and Brandenburg, C.F., 1986, Using permeability-vs-depth correlations to assess the potential for producing gas from coal seams: Gas Research Institute, Quarterly Review of Methane from Coal Seams Technology, v. 4, no. 1, p. 15–26.

Molenaar, C.M., and Cobban, W.A., 1991, Middle Cretaceous stratigraphy on the south and east sides of the Uinta Basin, northeastern Utah and northwestern Colorado: U.S. Geological Survey Bulletin 1787–P, 34 p.

Molenaar, C.M., and Rice, D.D., 1988, Cretaceous rocks of the Western Interion Basin, *in* Sloss, L.L., ed., Sedimentary cover—North American Craton, U.S.: Geological Society of America, The Geology of North America, v. D-2, p. 77–82.

Montgomery, S.L., Tabet, D.E., and Barker, C.E., 2001, Upper Cretaceous Ferron Sandstone—Major coalbed methane play in central Utah: American Association of Petroleum Geologists, v. 85, no. 2, p. 199–219.

Neuhauser, K.R., 1988, Sevier-age ramp-style thrust fault at Cedar Mountain, northwestern San Rafael Swell (Colorado Plateau), Emery County, Utah: Geology, v. 16, no. 4, p. 299–302.

Orkild, P.P., 1956, Photogeologic map of the Emery-1 quadrangle Emery County, Utah: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–166, scale 1:24,000.

Peterson, V.E., 1954, The Mounds and Farnham area of the northern San Rafael Swell, *in* Grier, D., ed., Geology of portions of the High Plateaus and adjacent Canyon Lands, central and south-central Utah: Intermountain Association of Petroleum Geologists, p. 86–88.

Price, L.C., and Barker, C.E., 1985, Suppression of vitrinite reflectance in amorphous rich kerogen—A major unrecognized problem: Journal of Petroleum Geology, v. 8, p. 59–84.

Rice, D.D., Young, G.B.C., and Paul, G.W., 1996, Methodology for assessment of technically recoverable resources of coalbed gas, *in* Beeman, W.R., Obuch, R.O., and Brewton, J.D., comps., Tabular data, text, and graphical images in support of the 1995 National Assessment of United States Oil and Gas Resources: U.S. Geological Survey Digital-Data Series DDS–35, 1 CD-ROM.

Ryer, T.A., 1981a, Deltaic coals of Ferron Sandstone Member of Mancos Shale—Predictive model for Cretaceous coal-bearing strata of western interior: American Association of Petroleum Geologists Bulletin, v. 65, no. 11, p. 2323–2340.

———1981b, Cross section of the Ferron Sandstone Member of the Mancos Shale in the Emery coal field, Emery and Sevier Counties, central Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF–1357, 1 sheet.

———1981c, The Muddy and Quitchupah projects—A progress report with descriptions of cores of the I, J, and C coal beds from the Emery coal field, central Utah: U.S. Geological Survey Open-File Report, 34 p.

———1984, Transgressive-regressive cycles and the occurrence of coal in some Upper Cretaceous strata of Utah, U.S.A., *in* Rahmani, R.A., and Flores, R.M., eds., Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists Special Publication 7, p. 217–227.

Ryer, T.A., and Anderson, P.B., 1995, Parasequence sets, parasequences, facies distributions, and depositional history of the Upper Cretaceous Ferron deltaic clastic wedge, central Utah [abs.]: American Association of Petroleum Geologists Bulletin, v. 79, no. 6, p. 924.

Ryer, T.A., and Lovekin, J.R., 1986, The Upper Cretaceous Vernal Delta of Utah—Depositional or paleotectonic feature?, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 497–510.

Ryer, T.A., and McPhillips, M., 1983, Early Late Cretaceous paleogeography of east-central Utah, *in* Reynolds, M.W., and Dolly, E.D., eds., Mesozoic paleogeography of the west-central United States: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Rocky Mountain Paleogeography Symposium 2, p. 253–271.

Spieker, E.M., 1931, The Wasatch Plateau coal field, Utah: U.S. Geological Survey Bulletin 819, 210 p.

Sprinkle, D.A., 1999, Digital geologic resources atlas of Utah: Utah Geological Survey Bulletin 129DF, 1 CD-ROM.

Sprinkle, D.A., Castaño, J.R., and Roth, G.W., 1997, Emerging plays in central Utah based on regional geochemical, structural, and stratigraphic evaluation [abs.]: American Association of Petroleum Geologists Official Program, v. 6, p. A110.

Stokes, W.L., 1952, Salt-generated structures of the Colorado Plateau and possible analogies [abs.]: American Association of Petroleum Geologists Bulletin, v. 36, no. 5, p. 961.

———1956, Tectonics of Wasatch Plateau and near-by areas [abs.]: American Association of Petroleum Geologists Bulletin, v. 40, no. 4, p. 790.

———1986, Geology of Utah: Utah Museum of Natural History, Occasional Paper Number 6, 280 p.

Stokes, W.L., and Holmes, C.N., 1954, Jurassic rocks of south-central Utah, *in* Grier, D., ed., Geology of portions of the High Plateaus and adjacent Canyon Lands, central and south-central Utah: Intermountain Association of Petroleum Geologists, p. 34–40.

Tabet, D.E., Hucka, B.P., and Sommer, S.N., 1995, Depth, vitrinite reflectance, and coal thickness maps, Ferron sandstone, central Utah: Utah Geological Survey Open-File Report 329, scale 1:250,000, 3 plates.

Tripp, C.N., 1989, A hydrocarbon exploration model for the Cretaceous Ferron Sandstone Member of the Mancos Shale, and the Dakota Group in the Wasatch Plateau and Castle Valley of east-central Utah, with emphasis on post-1980 subsurface data: Utah Geological and Mineral Survey Open File Report 160, 81 p.

———1991, Ferron oil and gas field, Emery County, Utah, *in* Chidsey, T.C., ed., Geology of east-central Utah: Utah Geological Association Field Symposium, p. 265–272.

van den Bergh, T.C.V., and Garrison, J.R., Jr., 1996, Channel belt architecture and geometry—A function of depositional parasequence set stacking pattern, Ferron Sandstone, east-central Utah: American Association of Petroleum Geologists Rocky Mountain Section Meeting, Billings, Mont., Expanded Abstracts Volume, p. 37–42.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: American Association of Petroleum Geologists Methods in Exploration Series No. 7, 55 p.

Walton, P.T., 1954, Wasatch Plateau gas fields, Utah, *in* Grier, D., ed., Geology of portions of the High Plateaus and adjacent Canyon Lands, central and south-central Utah: Intermountain Association of Petroleum Geologists, p. 79–85.

Williams, G.D., and Stelck, C.R., 1975, Speculations on the Cretaceous paleogeography of North America, *in* Caldwell, W.G.E., ed., The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Paper 13, p. 1–20.

Williams, P.E., and Hackman, R.J., 1971, Geologic map of the Salina quadrangle, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I–1591–A, scale 1:250,000.

Willis, G.C., 1999, The Utah thrust system—An overview, in Spangler, L.E., ed., Geology of northern Utah and vicinity: Utah Geological Association Publication 17, p. 1–9.

Witkind, I.J., 1995, Geologic map of the Price 1° x 2° quadrangle, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I–2462, scale 1:250,000.

Witkind, I.J., and Page, W.R., 1984, Origin and significance of the Wasatch and Valley Mountains monoclines, Sanpete–Sevier Valley area, central Utah: The Mountain Geologist, v. 21, no. 4, p. 143–156.

Witkind, I.J., Weiss, M.P., and Brown, T.L., 1987, Geologic map of the Manti 30′ x 60′ quadrangle, Carbon, Emery, Juab, and Sevier Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I–1631, scale 1:100,000.

Appendix 1. Ferron/Wasatch Plateau Total Petroleum System, Assessment Unit Results Summary

MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Minimum, for conventional resources this is the minimum field size assessed (MMBO or BCFG); for continuous-type resources this is the minimum estimated ultimate recovery assessed per cell. Prob., probability (including both geologic and accessibility probabilities) of at least one field (or, for continuous-type resources, cell) equal to or greater than the minimum. Results shown include geological and access risk. For gas fields, all liquids are included under the natural gas liquids category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

Field	Minimum	Prob. (0-1)	Undiscovered Resources											
			Oil (MMBO)				Gas (BCFG)				Natural Gas Liquids (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Ferron/Wasatch Plateau Total Petroleum System- Conventional Resource Assessment Unit Summary														
Conventional Ferron Sandstone Gas Assessment Unit (AU 50200101)														
Oil Fields	0.5		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas Fields	3	1.00					10.73	35.91	81.23	39.75	0.02	0.07	0.19	0.08
Total		1.00	0.00	0.00	0.00	0.00	10.73	35.91	81.23	39.75	0.02	0.07	0.19	0.08
Ferron/Wasatch Plateau Total Petroleum System- Continuous Resource Assessment Unit Summary														
Deep (6,000 feet plus) Coal and Sandstone Gas Assessment Unit (AU 50200161)														
Gas	0.02	1.00					0.00	52.04	136.43	59.09	0.00	0.00	0.00	0.00
Northern Coal Fairway/Drunkards Wash Assessment Unit (AU 50200181)														
Gas	0.02	1.00					451.14	722.18	1,156.05	752.33	0.00	0.00	0.00	0.00
Central Coal Fairway/Buzzard Bench Assessment Unit (AU 50200182)														
Gas	0.02	1.00					311.61	512.69	843.54	536.73	0.00	0.00	0.00	0.00
Southern Coal Fairway Assessment Unit (AU 50200183)														
Gas	0.02	1.00					78.16	145.81	255.49	152.59	0.00	0.00	0.00	0.00
Joes Valley and Musinia Grabens Assessment Unit (AU 50200184)														
	(NOT QUANTITATIVELY ASSESSED)													
Southern Coal Outcrop Assessment Unit (AU 50200185)														
Gas	0.02	1.00					0.00	9.95	30.71	10.56	0.00	0.00	0.00	0.00

Appendix 2. Ferron/Wasatch Plateau Total Petroleum System, Results Summary

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Minimum, for conventional resources this is the minimum field size assessed (MMBO or BCFG); for continuous-type resources this is the minimum estimated ultimate recovery assessed per cell. Prob., probability (including both geologic and accessibility probabilities) of at least one field (or, for continuous-type resources, cell) equal to or greater than the minimum. Results shown include geological and access risk. For gas fields, all liquids are included under the natural gas liquids category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the

Field	Minimum	Prob. (0-1)	Undiscovered Resources											
			Oil (MMBO)				Gas (BCFG)				Natural Gas Liquids (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Conventional resources														
Oil Fields			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas Fields		1.00					10.73	35.91	81.23	39.75	0.03	0.07	0.19	0.08
Total		1.00	0.00	0.00	0.00	0.00	10.73	35.91	81.23	39.75	0.03	0.07	0.19	0.08
Continuous-type resources														
Oil			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas		1.00					840.91	1,442.67	2,422.22	1,511.31	0.00	0.00	0.00	0.00
Total		1.00	0.00	0.00	0.00	0.00	840.91	1,442.67	2,422.22	1,511.31	0.00	0.00	0.00	0.00
Total resources														
Total		1.00	0.00	0.00	0.00	0.00	851.64	1,478.58	2,503.45	1,551.06	0.03	0.07	0.19	0.08

Click on image below to bring up high-resolution image of plate 1.

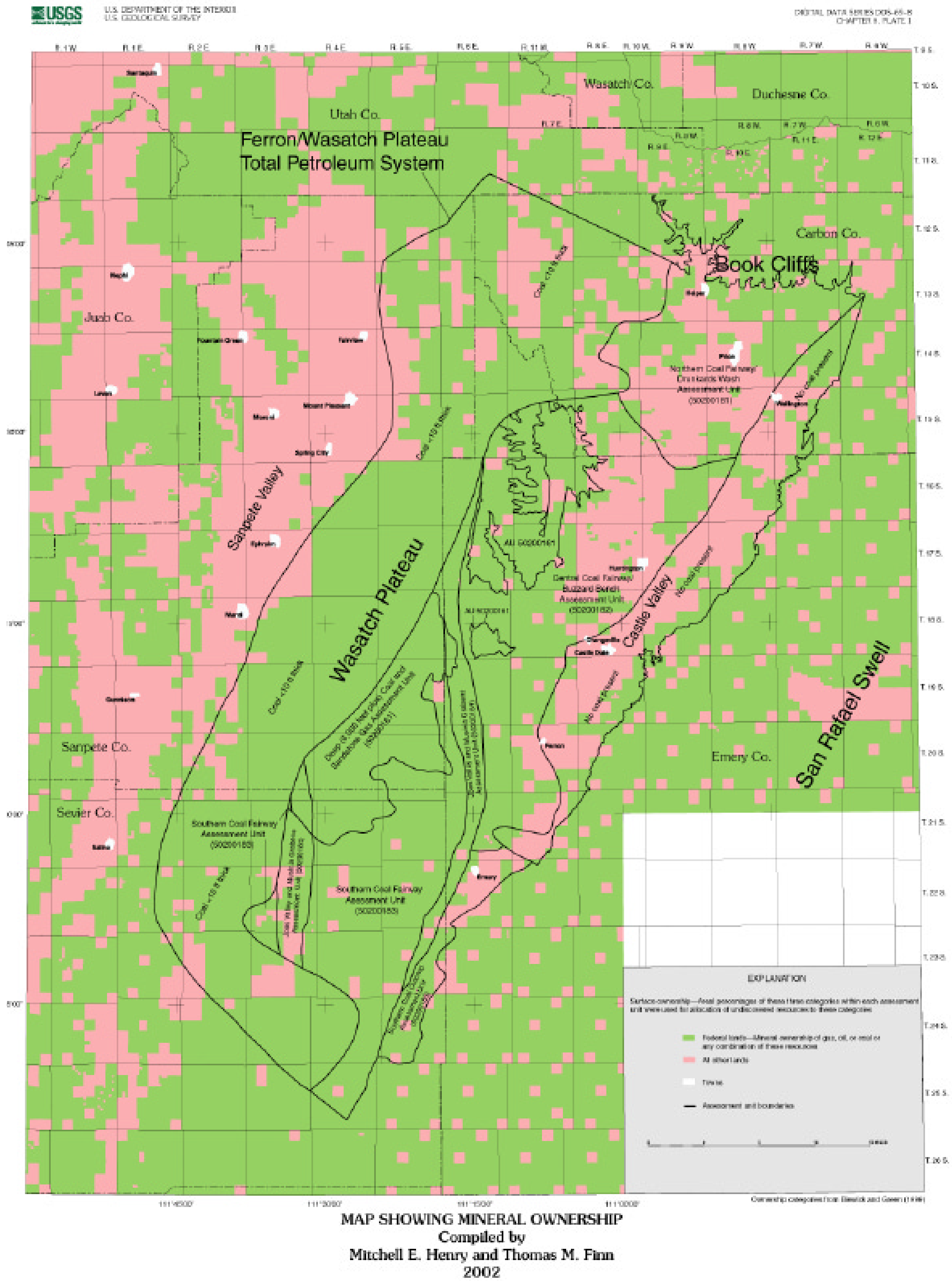


Plate 1. Map showing mineral ownership.

Click on image below to bring up high-resolution image of plate 2.

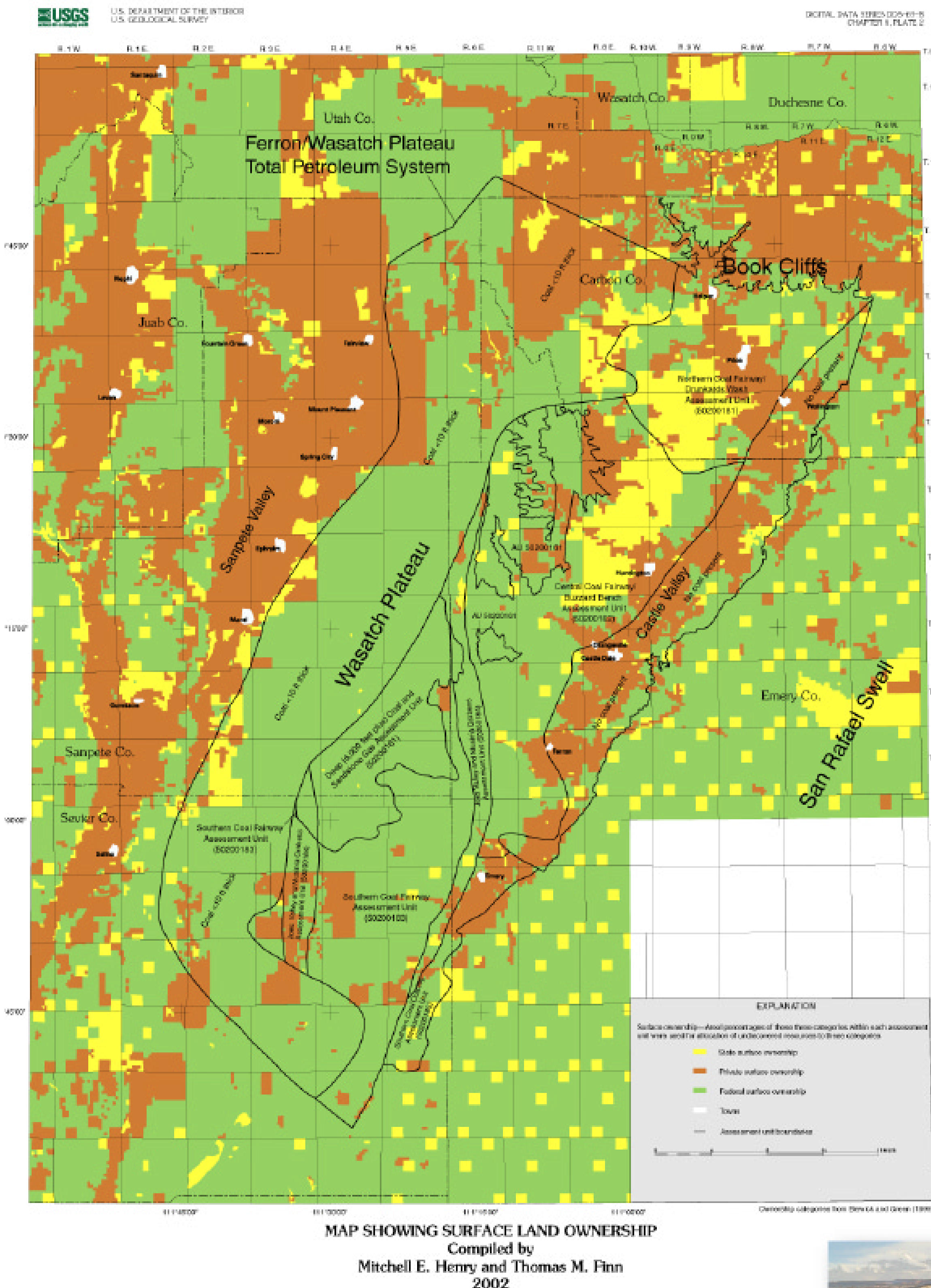
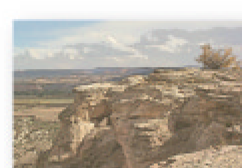


Plate 2. Map showing surface land ownership.



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