COALBED METHANE STREAM DEPLETION STUDY

SAND WASH BASIN, COLORADO

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EXECUTIVE SUMMARY

CBM potential exists in the Upper Cretaceous Mesaverde Group as well as the Paleocene Fort Union Formation on the east side of the Sand Wash Basin. To date, approximately 1.7 Bcf of CBM gas and 4,000 acre-feet of water have been produced from the Mesaverde Group and essentially no CBM has been produced from the Fort Union Formation. Currently, only Slater Dome Field in the northeast part of the Basin is producing CBM; all other fields are either shut in or abandoned. Historically, annual gas production gradually rose from less than 0.1 Bcf in 2002 to just over 0.45 Bcf in 2008. Production then declined to just over 0.25 in 2009 after Pioneer Resources shut-in wells and sold their Encore Field. Water production similarly peaked in 2008 at a rate of approximately 1,000 ac-ft/yr and then declined sharply to approximately 200 ac-ft/yr after pumping at Encore ceased. The sharp decline in water production following cessation of production at the Encore Field reflects the high volume of water production associated with CBM development at that field. High rates of water production and water management challenges have been cited as impediments to CBM development in the Basin. Given high rates of water production, future CBM production may be limited to existing fields until economic or technological conditions change to make it more viable.

CBM is produced primarily from coal seams in the lower Williams Fork Formation and Iles Formation of the Late Cretaceous Mesaverde Group. Coal seams are interbedded with laterally discontinuous fine-grained sandstone and shale layers and the sequences are collectively known as the Middle and Lower Coal group, respectively. Layers of marine shale lie above and below each formation on the east side of the Basin forming distinct hydrostratigraphic units. The hydrostratigraphic units outcrop along a broad arcuate belt across the southeast end of the Basin and are traversed by the Yampa River and Williams Fork River along with many lesser tributaries. Recharge enters the system in elevated areas that receive abundant precipitation and groundwater discharges to streams at lower elevations.

Groundwater flows through coal cleats, fractures, and sandstone layers in the hydrostratigraphic units. In addition, fracturing and faulting traverse the area along a prevailing northwesterly structural grain. Faults may act as barriers to groundwater flow from areas of recharge in the highlands east of the CBM production areas, while faults and fracture systems may enhance flow to the northwest. The Cedar Mountain fault zone is a major structural feature of the Basin and groundwater data appear to confirm these hydrogeologic hypotheses. Fracturing may also hydraulically connect the coal-bearing intervals with underlying regional sandstone aquifers. Hydraulic connection with deeper aquifers probably adds water to the Mesaverde Group coal zones, increasing the water production necessary to sufficiently reduce pressures for methane desorption from the coals.

Considering geologic and hydrogeologic complexities of the eastern part of the Sand Wash Basin, the Glover analysis is not well suited to evaluate basin-wide stream depletion effects from CBM production. Numerical modeling that could better account for geologic complexity would require a more robust data set for the Basin than is currently available.

Impact to surface water resources from historic CBM production is probable, although the magnitude is probably small because of the low volumes extracted to date. Direct hydraulic connection likely exists to surface water at the outcrop areas. Faulting and fracturing may play a strong role in modifying hydraulic connection to the surface. Faults may reduce or enhance depletions depending on age, permeability, and orientation. Fractures may enhance depletions.

An analytical drawdown analysis was performed to estimate water level impacts at wells tapping the same hydrostratigraphic units as CBM wells. Model runs used generalized aquifer parameters and averaged CBM water production rates for the Encore Field. Drawdown estimates within the field reach 360 feet while drawdown estimates one-mile away from the field approach 260 feet after long-term pumping (30 years) in a steady-state model run. Drawdown at the nearest well completed in the same hydrostratigraphic unit approximately nine miles away approached 45 feet. Fault barriers may impact effects by enhancing drawdown within the same block as the pumping field while reducing drawdown across faults.

Water extraction for CBM production is now considered a beneficial use and permits from DWR are required for all CBM wells. Where water extraction by CBM wells impacts over-appropriated streams, depletions must be offset through augmentation plans or temporary substitute water supply plans. Water produced by CBM extraction in the Sand Wash Basin is generally of fair quality and could be used for a number of purposes. However, high sodium content in some areas renders it unsuitable for irrigation because it can severely damage soil structure.

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1.0 INTRODUCTION

1.1 Background

Abundant coal resources occur in Late Cretaceous and Paleocene sedimentary formations of the Sand Wash Basin (Basin) of northwestern Colorado (Figure 1.1). Methane is present in the coal beds and the basin has long been recognized as a potential target for coalbed methane (CBM) development. Potential gas resources in the coal-bearing formations at shallow drilling depths, less than 6,000 feet, are estimated to be between 14 and 24 trillion cubic feet (Tcf) (Boreck and others, 1981; Kaiser and others, 1995). However, despite the presence of the potential for CBM development in the basin, large-scale and sustainable production has not materialized with production hampered by the low gas content and high-volume water production.

Production of CBM at shallow depths typically requires dewatering to reduce the hydrostatic pressure within the coal beds, thus allowing methane to desorb from the coal. Normally the “produced water” is disposed of in injection wells and evaporation pits, used in other drilling operations, or released to surface water under discharge permits when of good quality. In other similar basins of Colorado, CBM is produced on a large-scale basis and concern exists over the potential impacts to critical water resources from the dewatering process and diversion of the produced water. As with all other oil and gas production in the state, CBM production and disposal of associated exploration and production waste, including produced water, has been regulated by the Colorado Oil and Gas Conservation Commission (COGCC). However, the Colorado Division of Water Resources (DWR) has jurisdiction over the production of groundwater that is either tributary to surface water or nontributary water that is put to beneficial use.

Historically, produced water was considered exempt from DWR regulation under COGCC Rule 907 as long as the water was used for specific applications related to oil and gas production. This has changed with the recent Vance court case (Vance v. Wolfe, Colorado State Supreme Court, April 20, 2009) which determined that pumping water to produce methane is indeed a beneficial use in its own application. HB-1303 was passed in 2009 that exempted oil and gas wells from the regulation described in Vance v. Wolfe and gave the State Engineer rulemaking authority for the purpose of making determinations of nontributary groundwater for formations that are subject of oil and gas production. These new rules apply to any future CBM production in the Sand Wash Basin.

In 2004, concerns with potential impacts to surface water resources led to quantitative CBM depletion assessments in the Piceance, Raton, and San Juan Basins (Figure 1.2) ― basins with active CBM production and recognized surface water limitations (SSPA, 2006; 2008a; 2008b). These studies were collaborative efforts by COGCC, DWR and the Colorado Geological Survey (CGS) aimed at developing a reliable assessment of the levels of surface water depletion due to CBM production. They also provided preliminary nontributary delineations for the CBM producing geologic formations. Subsequent nontributary rule-making revised the nontributary delineations. In addition, the studies also sought to provide general basin hydrogeologic characterizations that could eventually be used in future administration of CBM water production in the three basins or other basins where CBM development may arise. The Sand Wash Basin was not included with these original studies because of limited CBM development and the status of available water in the not over-appropriated Yampa River basin watershed.

Water production varies considerably from basin to basin as do the impacts from that water production. The interaction of geologic and hydraulic conditions causes each basin to have unique characteristics. In the Raton Basin, where gas production approaches about 80 billion cubic feet (Bcf) per year, water production ranges between 10,000 and 16,000 acre-feet per year (ac-ft/yr). The CBM depletion assessment estimated that annual depletions from surface water were approximately 2,500 ac-ft/yr as of 2006 (SSPA, 2008a). At the other end of the spectrum, CBM production in the Piceance Basin has been very limited because of low permeability of the coal beds combined with water disposal limitations. Total CBM production in this basin is more than 22 Bcf of methane and 1,200 acre-feet (ac-ft) of water. Depletions to surface water were estimated to be minimal as of 2008 (SSPA 2008b). The San Juan Basin is the most productive CBM basin in North America. In the Colorado portion of the basin, over 450 Bcf of methane are produced per year and 3,000 to 4,000 ac-ft of water are pumped each year. The CBM assessment study estimated that depletions to surface water were up to 160 ac-ft/yr as of 2006 (SSPA, 2006). These depletion rates were preliminary basin-wide estimates intended to provide perspective of potential impacts to water-resources resulting from CBM water extraction. Subsequent numerical modeling in the Raton and San Juan Basins has generated newer estimates based on finer input detail.

Moffat County, through its Land Use Board, recognized the potential for CBM development in the Sand Wash Basin and that large-scale CBM development might profoundly impact both surface- and groundwater resources within the region. Although the Sand Wash Basin was not included with the original CBM depletion studies, the County believed it was in its citizens' best interests to assess the CBM development potential and possible impacts to the basin's water resources. Moffat County approached the CGS about conducting a study similar to those conducted in the other basins. Through the Yampa/White Basin Roundtable, Moffat County obtained Water Supply Reserve Account grant funding. Routt County, which adjoins Moffat County on the east and includes part of the Sand Wash Basin, joined with Moffat County in providing part of the funding for this project. The scope of this study mimics the previous studies with modifications to address concerns that the County had about potential impacts to water wells in the basin.

1.2 Objectives

As originally envisioned, the primary objectives of this CBM study were to

- Provide an overview of the geology, hydrology, water quality, and regulatory setting in the Sand Wash Basin as it relates to the production of CBM and CBM produced water;
- Evaluate the suitability of the Glover analysis (Glover and Balmer, 1954) for determining stream depletions and its suitability to administer CBM water production in the Sand Wash Basin;
- Develop a quantitative assessment of the levels of stream depletion or reduction in formation outflows that may be occurring as a result of the removal of water by CBM wells and;
- Evaluate potential impacts of CBM dewatering on existing, permitted water-well users within the basin.

1.3 Original Scope of Work

Given these objectives, a scope of work was implemented to analyze CBM production and its potential impacts within the Sand Wash Basin of Colorado. CBM exploration, and limited production in the Sand Wash Basin, is primarily from coals in the Late Cretaceous Mesaverde Group as well as the Paleocene Fort Union Formation. Analyses carried out under this scope of work focused on the Sand Wash Basin as defined by the base of the Mesaverde Formation, extending across northern Moffat County and into western Routt County. This study examined existing information relating to the geographic setting, geology, hydrogeology, CBM gas and water production, and water chemistry of these coal-bearing and adjacent formations. Specific tasks included in this study are outlined below:

- Assess CBM gas production and associated water production
- Characterize basin stratigraphy and structure
- Characterize regional groundwater flow systems
- Relate CBM producing formations to local groundwater resources;
- Relate target CBM intervals to surface water systems
- Characterize water quality of CBM intervals, local aquifers, and surface water
- Identify data insufficiencies and devise plan to fill critical data gaps
- Collect pertinent field data
- Perform depletion modeling/define nontributary produced water areas
- Conduct public meetings
- Prepare a summary report

The goal of this study was to provide background information and data regarding CBM production and to evaluate stream depletions associated with CBM production. As such, there are many related topics or analyses that fall beyond the scope of this study. Topics not evaluated as part of this study include:

- Reservoir optimization, i.e., production or well spacing issues;

- Dual-phase flow dynamics;
- Historical conditions and climatic influences on streams and springs;
- Impacts of other basin extraction activities on streams or water levels; and
- Evaluation of localized groundwater elevation changes at specific sites.

That certain topics are not evaluated in this study does not imply less importance; rather, it is a reflection of this study's specific focus on evaluation of potential CBM-production-induced stream depletion.

1.4 April 2010 Change in Scope

By April 2010 the CGS had completed many of the characterization tasks in the original scope. Findings indicated that CBM and water production had been very limited so far and that the potential for future development was limited under current economic and technological conditions. Furthermore, geologic complexity of the basin indicated that regional quantitative assessments as originally proposed would not be suitable in this basin. Finally, the DWR oil and gas, produced-water rulemaking process in early 2010 reduced the need for delineating basin-wide nontributary areas. Consequently, the scope was changed to eliminate the depletion modeling and definition of nontributary produced water areas. An analysis of impacts to existing permitted water wells remained in the scope. The change in scope was agreed to by the Yampa/White Basin Roundtable in its April 21, 2010 meeting.

2.0 AVAILABLE DATA AND RESOURCES

This study draws on existing data and studies to provide an overview of conditions in the basin. Water and CBM well information along with their respective production data are provided. The key datasets reviewed are described below.

2.1 Previous Work

CBM potential in the Sand Wash Basin has been recognized for some time. In 1981 the CGS published an open-file report providing an overview of coal resources and CBM potential in the Sand Wash Basin (Boreck and others, 1981). It described CBM potential in the Mesaverde Group, Lance Formation, and Fort Union Formation estimating that nearly 14 Tcf could be present in the Mesaverde Group. Insufficient data were available to estimate CBM volumes in the shallower Lance and Fort Union Formations. In the early 1990s the Texas Bureau of Economic Geology, in cooperation with the CGS, conducted an in-depth evaluation of CBM potential in the Sand Wash Basin of Colorado and Wyoming for the Gas Research Institute (GRI) with emphasis on the Mesaverde Group and Fort Union Formation. Results were published in a series of reports with the compilation by Kaiser and others (1994) providing a comprehensive description of stratigraphy, structure, and hydrodynamic conditions within the basin. This assessment estimated that up to 24 Tcf of CBM resources were present at depths shallower than 6,000 feet deep in the Basin. It also concluded that production at that time had been limited by overall low gas content and high water production. In 2005, the USGS completed a total petroleum assessment for the entire Southwest Wyoming Province that includes the Sand Wash Basin (USGS, 2005). This assessment by the USGS also concluded that, although CBM was indeed present in the Sand Wash Basin, production attempts to date had met limited success due to high water production (Finn and others, 2005). The USGS estimated that approximately 1.2 Tcf of total undiscovered CBM existed in the Fort Union Formation and Mesaverde Group within the entire Southwestern Wyoming Province. This estimate did not break out Sand Wash Basin but using a ratio based on relative surface area results in approximately 0.3 Tcf. The USGS estimate is lower than that of Kaiser and others (1994).

In 2003 CGS published a study assessing coal resources in the Williams Fork Formation of the Yampa Coal Field (Carroll, 2003). This assessment compiled existing data to quantify coal resources in an area spanning the southeastern perimeter of the Sand Wash Basin coincident with areas of CBM potential. Spatial data for coal distribution from this earlier effort supported the assessment as explained in this report.

The Little Snake Field Office of the Colorado State office of the U.S. Bureau of Land Management (BLM) contracted Norwest/Questa Engineering (Norwest) to assess CBM potential in the Sand Wash Basin to support preparation of an Environmental Impact Statement for its Resource Management Plan. CGS provided geological support for this effort by contributing structural maps, coal isopach maps, and stratigraphic cross-sections of the Mesaverde Group and Fort Union Formation. The results were not published, however, CGS retains these datasets and Norwest supplied data and preliminary draft reports to the BLM. CGS obtained these materials from BLM. Norwest also concluded that high water production rates limited the potential for CBM production in the basin and that future activities would likely be limited to existing fields with established infrastructure (Norwest, 2006).

2.2 Ongoing Investigations by CGS

CGS is currently mapping areas along the southern perimeter of the Sand Wash Basin through its STATEMAP cooperative mapping program. This program produces geologic maps at a 1:24,000 scale derived from the USGS 7.5 minute topographic quadrangle with greater detail than previous regional mapping efforts. Field mapping is complete in the Milner and Hayden Gulch quadrangles and is planned for the Breeze Mountain and Hayden quadrangles for 2011. Concurrently, CGS has been mapping geologic structures and compiling geologic data as part of a three-year carbon sequestration pilot study centered near the Craig power plant. Although results of these ongoing investigations have not been published, observations and data supporting the CBM assessment are described herein.

2.3 Sources of Spatial and Digital Data

Digital and spatial data for geographic descriptions, CBM production records, water well information, water quality information, and surface water conditions were obtained from a variety of sources. Appendix A provides details of sources for these supporting data.

3.0 SAND WASH BASIN PHYSIOGRAPHIC AND GEOLOGIC SETTING

3.1 Regional Physiography

As defined by the outcrop of the Late Cretaceous Mesaverde Group, the Sand Wash Basin covers an area of approximately 3,300 square miles in northwestern Colorado within the Wyoming Basin physiographic province. It is bound on the east by the Park Range and on the south by the White River Plateau, Danforth Hills, and the east end of the Uinta Mountains (Figure 1.1). Rolling plains, badlands, plateaus, mesas, sub-alpine highlands, as well as canyons and broad alluvial valleys characterize a diverse area spanning the northeastern half of Moffat County and the western half of Routt County. Elevations at the east end of the basin reach heights of over 10,500 feet above mean sea level (MSL) at West Elk Peak in the Elkhead Mountains. The lowest point is at an elevation of approximately 5,800 feet MSL near Sunbeam where the Little Snake River leaves the Sand Wash Basin.

Precipitation patterns across the Basin reflect the diverse topography as shown in Figure 3.1. Average annual precipitation can exceed 50 inches in the interior highlands of the Elkhead Mountains with much of that coming in the form of winter snowfall. Elsewhere, in the lower elevations of the Basin interior, annual precipitation drops to between 10 and 16 inches per year. Where the coal-bearing Mesaverde Group is exposed, annual precipitation ranges between 18 and 34 inches per year, providing potential recharge to the exposed strata.

Three main stream systems cross the Sand Wash Basin in a westerly to southwesterly direction (Figure 3.1) eventually flowing into the Green River. The Yampa River originates outside of the basin along the west side of the Park and Gore Ranges east of Steamboat Springs to flow west across the southeastern part of the basin. A portion of the Little Snake River watershed extends up into the northern side of the Elkhead Mountains. The river then flows west along the Colorado-Wyoming border for nearly 45 miles before swinging southwest across the Sand Wash Basin to join the Yampa River west of Maybell. Vermillion Creek originates in Wyoming and flows southwest across the west end of the basin before flowing directly into the Green River in Browns Park near the Colorado-Utah border.

A number of tributaries to these major rivers are sourced from the highlands within the interior of the Sand Wash Basin. Included in the Yampa River watershed are Elkhead and

Fortification Creeks which are sourced entirely from highlands within the basin. The Williams Fork River is sourced from highlands south of the Basin and follows much of the southwestern boundary of the basin. Many other tributaries within the basin are either ephemeral or support very low base flow (on the order of 1 cubic foot per second or less).

3.2 Geologic Evolution of the Basin

Although the region has a long and complex geologic history, geologic events most relevant to the development of the Sand Wash Basin CBM resource commenced during the Late Cretaceous Epoch. At that time compressional tectonism far to the west in the Cordilleran thrust belt forced a chain of high mountain ranges to rise during the Sevier Mountain Building Event (Figure 3.2). Concurrently, the area that is now the Rocky Mountain region sagged as a broad crustal downwarp roughly parallel to the thrust belt. Seawater flooded this downwarp to form the Western Interior Seaway for a period of approximately 20 million years (Hamilton, 1994; Hettinger and Kirschbaum, 2002).

As a downwarp, the Basin preserves a thick sequence of sedimentary rocks dating back to the Paleozoic Era (Boreck and others, 1981). Figure 3.3 shows the stratigraphic column preserved in the Basin that records a progression from a predominantly marine environment, during Cambrian through Pennsylvanian time, upward to a non-marine environment starting in the Permian Period. Non-marine rocks dominate the stratigraphy through the Early Cretaceous Period. These older sediments predate and form the base of the broad foreland basin downwarp that accommodated the Western Interior Seaway.

A thick sequence of marine and coastal sediments accumulated within the foreland basin as the Western Interior Seaway evolved. Sandstone and shale of the Lower Cretaceous Dakota Group mark the initial transgression of the seaway across the region. Shallow marine sedimentation followed, depositing the Mowry Shale, Frontier Sandstone, Niobrara Limestone, and Mancos Shale. River systems approached the seaway along the western shoreline depositing a distinct package of fluvial, shoreline, and deltaic sediments that comprise the Mesaverde Group. This coal-bearing package of sediments is further described in Section 3.3. The ancient shoreline shifted in position back and forth from west to east in response to tectonic movements and changes in sea-level. Its final advance to the west before the seaway finally withdrew is represented by the Lewis Shale.

At the close of the Late Cretaceous Epoch, approximately 70 million years ago, deformation spread eastward into the Rocky Mountain region. As this wave of deformation advanced eastward, the Western Interior Seaway withdrew. The Fox Hills Sandstone and overlying non-marine Lance Formation mark the seaway's final retreat eastward. This deformation, known as the Laramide Mountain Building Event, continued for at least 25 million years into the Eocene Epoch.

As the foreland basin was fragmented by the Laramide Mountain Building Event into a series of fault-bounded uplifts. Rivers carried non-marine clastic sediments down from the rising uplifts and filled the subsiding basins. The Sand Wash Basin is one of these Laramide intermontaine basins. Sediments accumulating within it include the Paleocene Fort Union Formation overlain by the Eocene Wasatch Formation. Section 3.3 further describes the coal-bearing Fort Union Formation. Later in the Eocene Epoch a lake developed in the deepening basin depositing shale, oil-shale, limestone, evaporite, and sandstone of the Green River Formation (MacLachlan, 1987). Renewed inflow of coarse-grained clastic sediments into the basin deposited the Bridger Formation (also called Uinta Formation depending on location) above the Green River Formation.

Deformation of the region continued after the Laramide Mountain Building Event under changing stress conditions and in a different style. The stress regime shifted sometime after 40 million years ago so that it was one dominated by extension approximately 25 million years ago (Chapin and Cather, 1994). Sediments derived from erosion of the highlands surrounding the basin were deposited during this period of extensional deformation include the basal Bishop Conglomerate and overlying Browns Park Formation (Honey and Izet, 1988). These sediments consist of conglomerate, fluvial sandstone, and siltstone, volcanic ash, as well as thick accumulations of eolian sand. They still blanket much of the region and conceal many of the basin's earlier structural features. Honey and Izett (1988) interpret that the Browns Park Formation represents an ancestral alignment of the Yampa River based on clast composition and aerial distribution patterns.

Widespread igneous activity within and adjacent to the Basin accompanied this transition and continued well into the Pliocene. Voluminous volcanic outpourings covered much of the region, and while subsequent erosion removed much of the volcanic cover, numerous igneous stocks, volcanic plugs, and dikes attest to its much larger former extent. Numerous dikes and sills of intermediate to basaltic composition cut through the sedimentary basin fill in the eastern part of the basin. Remnants of intermediate volcanic flows cap mesas and hills along the Little Snake River in the northeastern part of the basin and in the Elkhead Mountains. Younger basaltic flows cap the alpine and sub-alpine highlands south of the basin as well as Cedar Mountain just northwest of Craig within the basin.

The Rio Grande Rift system, a mid-continental extensional feature active since the mid Miocene, extends northward from New Mexico across central Colorado (Chapin and Cather, 1994). Many northwest trending faults within the Sand Wash Basin area display evidence of Late Cenozoic movement indicating that this feature continues this far north. Compositional changes of igneous rocks found in the eastern Sand Wash Basin may record a transition from compressional to extensional tectonism as the rift developed in this area (Leat and others, 1988; 1989). Historical seismic activity within the basin further indicates that ongoing deformation associated with the Rift system extends into this area. On August 18, 2009 an earthquake with a magnitude of 3.7 was felt in the area with an epicenter estimated approximately 12 miles north-northwest of Craig (Figure 3.3).

Regional uplift accompanied the development of the Rio Grande Rift system (McMillan et al, 2006; Moucha, et al, 2008). Stream courses carved deeply into the rising landscape as the modern-day river system integrated. Alluvial deposits of unconsolidated sand, gravel, and silt fill the deep alluvial valleys along the modern stream drainages, while higher terrace deposits above the modern stream levels mark gradual incision starting in the Miocene epoch and continuing today. Today's landscape reflects the gradual incision of the drainage system into a complex fabric of structural blocks and diverse rock types wherein rocks resistant to erosion form elevated terrain while more easily eroded rocks form the lowlands. Figure 3.4 is a generalized geologic map illustrating the patterns of rocks exposed at the surface in the region of the Sand Wash Basin.

3.3 Geology of the Coal-Bearing Intervals of the Sand Wash Basin

3.3.1 Stratigraphy and Coal Bed Occurrence

CBM potential occurs primarily in the non-marine coastal plain sediments of the Late Cretaceous Mesaverde Group and the fluvial sediments of the Paleocene Fort Union Formation (Tyler and others, 1994). Coal beds in the Late Cretaceous Lance Formation, however, tend to be thin and discontinuous thus having low CBM potential (Boreck and others, 1981). Figure 3.5 illustrates the stratigraphic relationships of these formations and the following section describes the characteristics of the primary CBM intervals.

Mesaverde Group Coal Stratigraphy For almost 20 million years the Western Interior Seaway inundated the North American mid-continent before final withdrawal near the end of the Cretaceous period (Hamilton, 1994; Hettinger and Kirschbaum, 2002). During this time, primary geographic elements consisted of a wave-dominated deltaic shoreline backed by a vast coastal plain extending westward to the mountain chain in the distance (Cole et al., 2005). Streams originating in the western highlands crossed the coastal plain and back-bar swamps and flowed into the seaway via distributary channels in the wave-dominated deltas. Stratigraphic relationships within the sediments deposited during this time indicate that the ancient shoreline trended in a north to northeasterly direction across the area where the Sand Wash structural basin later developed as shown in Figure 3.2 (Hamilton, 1994; Blakely, 2008). Because of the manner in which the seaway retreated, the stratigraphic sequence consists of non-marine Mesaverde Group deposits overlying marine Mancos Shale.

Over time, the western shoreline gradually retreated; however, this retreat was not constant. Instead, the shoreline position underwent repeated cycles of eastward advance, or progradation, followed by westward retreat, or inundation, by the shallow seaway. This cyclic pattern was believed to have been driven by pulses of tectonism along the Sevier Orogenic belt active to the west as well as changes in sea level.

In an actively subsiding basin, shoreline progradation best preserves each of the sedimentary facies found along the shoreline. Each time the shoreline advanced eastward, shoreface, beach, and delta sands buried the offshore marine shale. Peat deposits derived from coal-forming plant debris accumulating in the back-bar swamps followed, burying the shoreline sands. Non-marine sediments consisting of fluvial sands combined with over-bank silts and clays eventually buried the back-bar peat deposits and coalification began. Basal coals deposited in the extensive back-bar environment can be laterally continuous over many tens of miles. Peat also accumulated in smaller swamps along the river systems further to the west; however, these resulting coal deposits tend to be thinner and have much less lateral continuity.

In this region three major cycles of shoreline progradation followed by retreat are represented in the stratigraphic record of the Mesaverde Group as shown in Figure 3.5. As a result of the cyclic episodes of marine inundation, the non-marine deposits are interrupted by intervals of marine shale similar to the Mancos Shale. Indeed, these tongues of marine shale thicken to the east while the non-marine deposits of the Mesaverde Group pinch out so that further east the entire stratigraphic column is dominated by marine shale. Conversely, the marine shale tongues pinch out to the west, closer to the active sediment source where the entire section becomes dominated by non-marine sediments.

Nomenclature for the many depositional sequences preserved during episodes of shoreline advance and retreat vary across the region. This report uses nomenclature summarized by Brownfield and Johnson (2008) for the southern Sand Wash Basin shown in Figure 3.5. According to COGCC records, industry throughout the Sand Wash Basin prefers the formation names shown in Figure 3.5.

This relationship of coal-bearing non-marine sediments separated by layers of marine shale creates important geometry relevant to both the coal resources and the hydrogeology of the Mesaverde Group within the basin. On the east side of the basin, layers of marine shale effectively segregate the sedimentary package into three distinct units. Each unit consists of a basal shoreline sandstone unit overlain by coal-bearing non-marine coastal plain sediments. This differentiation becomes less distinct to the west.

Figure 3.6 is a resistivity log from a well in Section 3, Township 7 North, Range 92 West near Craig illustrating the Mesaverde Group units and rock types. The Iles Formation represents the first and lowermost sequence of non-marine sediments shed into the foreland basin. It consists of the shoreline Tow Creek Sandstone member overlain by non-marine sediments that form the Lower Coal Group of the Mesaverde. A tongue of marine shale separates the non-marine coal-bearing sediments of the Iles Formation from the next package of prograding shoreline and coastal plain sediments above. This next sedimentary package includes the Trout Creek Sandstone member (also called the Rollins Sandstone member further south) overlain by the Williams Fork Formation. Non-marine sediments above the Trout Creek Sandstone contain the Middle Coal Group of the Mesaverde. Another tongue of marine shale divides the Williams Fork Formation into two members with the Twenty Mile Sandstone member forming the base of the next prograding package. Non-marine sediments above the Twenty Mile Sandstone contain the Upper Coal Group of the Mesaverde.

In the Sand Wash Basin the greatest accumulation of widespread and continuous coal deposits are found in the Middle Coal Group. This coal group consists of an interval of varying thickness that contains many individual coal seams ranging in thickness from 2 to 25 feet, as discernable in the geophysical logs. Figure 3.7 illustrates net thickness patterns of coal within the Lower Williams Fork Formation, or Middle Coal Group. The greatest accumulations of coal in this group underlie the area surrounding Craig where net coal thickness exceeds 100 feet. Lateral continuity of individual coal seams is variable, yet the entire coal-bearing interval as a whole remains consistent in sedimentary characteristics such as facies patterns.

Fort Union Formation Coal Stratigraphy The Laramide Mountain Building Event fragmented the region into a series of fault-bound ranges and basins. Rising mountains sourced rivers that flowed into the subsiding basins depositing a mix of fluvial, paludal, and lacustrine sediments (Tyler and McMurry, 1994). Figure 3.8 is a resistivity log from a well in Township 10 North, Range 93 West near Craig showing the stratigraphic relationships of primary members of the Fort Union Formation. A laterally extensive sandstone unit of Upper Cretaceous and Paleocene age known as the Massive K/T Sandstone marks the base of the package of sediments deposited in the actively subsiding Laramide Sand Wash Basin. This unit represents a time when a large braided stream system flowed across the basin from south to north depositing a series of multi-storied sand bodies that amalgamated into a continuous body of sandstone.

Eventually, this high energy fluvial environment gave way to a lower energy environment where finer grained fluvial sediments accumulated in floodplains and abandoned channels along the trunk streams. Fluvial sandstone, shale, and coals deposited in this subsequent stage of basin development form the lower coal-bearing unit of the Fort Union

Formation. Tyler and McMurry (1994) suggest that a trunk stream system sourced from the Laramide Sawatch uplift to the south flowed generally to the north and was fed by tributary streams flowing in from uplifts to the east and southwest. In time, volumes of coarse grained fluvial sediment decreased, while fine grained floodplain and/or lacustrine deposits increased forming the Gray-Green Mudstone unit of the Fort Union Formation. This unit interfingers with the central Basin Sandy Unit deposited by the trunk stream system. The Upper Shaley unit overlies much of the Basin Sandy unit in the basin center and the Gray-Green Mudstone along the margins. This unit represents even lower-energy, fluvial and lacustrine conditions and possible tectonic quiescence.

The most favorable conditions for coal deposition occurred during deposition of the lower part of the Fort Union Formation. Stream morphology, sediment load, and groundwater conditions created ideal conditions for the preservation of peat in marshy areas adjacent to the trunk stream systems where frequent changes in stream course created abandoned channels where peat could accumulate and later be buried during subsequent stream avulsions. Individual coal seams can be as thick as 50 feet and can have lateral continuity for up to 18 miles (Tyler and McMurry, 1994). Figure 3.9 is a net coal thickness map for the Lower Fort Union coal-bearing unit that shows the thickest accumulation of coal covering an irregular north trending band northwest of Craig. This alignment follows the ancestral course from south to north of the ancestral trunk river system when the Basin was forming in the Paleocene.

3.3.2 Structural Geology of the Coal-Bearing Intervals

Trending roughly northwest to southeast, the Sand Wash Basin is the southeast extension into Colorado of the Greater Green River Basin (Figure 3.10). This larger basin is a Laramide structural downwarp extending across much of the southwest corner of Wyoming that formed soon after retreat of the Western Interior Seaway. A complex network of faults, arches and sub-basins divides this regional basin into several sub-basins including the Sand Wash Basin.

Figure 3.11 is a structural map of the Sand Wash Basin with elevation contours drawn on the top of the Trout Creek Sandstone, or base of the Lower Williams Fork Formation. This map includes structural features relevant to the geohydrology of CBM production and potential impacts to water resources. As shown, the overall structural fabric of the Sand Wash Basin trends northwest and the basin deepens to the west. A number of structural elements both define the perimeter of the basin and deform its interior. These structural elements may affect CBM potential as well as groundwater flow pathways. The structures are categorized below according to basin spatial relationships and type of deformation.

Basin Perimeter This study uses the base of the Mesaverde Group, or more specifically the Iles Formation, to delineate the Basin perimeter, as shown by the red outline in Figure 3.11. The perimeter follows outcrops of the Iles Formation where exposed; however, younger sediments deposited after the Laramide Mountain Building Event conceal much of its extent. Where exposed, deformed strata indicate that the structural features bounding the basin vary considerably, depending on location. These varying structural features follow a triangular outline with a northwest trending southwestern boundary, a north-south eastern boundary and an east-west northern boundary.

At the west end near the deepest part of the basin, the Uinta Fault system forms the basin’s southwestern edge and continues further to the west into Utah. This complex basin-bounding structural feature dips to the southwest placing older basement rocks and strata of the Uinta Uplift over younger strata (Hansen, 1986). In northwest Colorado, the fault system is exposed at the surface over a distance of approximately 25 miles trending to the southeast before disappearing beneath the Miocene Browns Park Formation at Vermillion Bluffs. Where the Laramide feature is concealed, a series of normal faults displace the nearly flat lying younger sediments with offsets of up to 150 feet (Tweto, 1976). The direct relationship of these younger faults to the underlying Laramide structural feature is not clear, but they may have resulted from reactivation of the older feature during the post-Laramide Cenozoic extensional tectonic regime.

Pre-Laramide strata and the Laramide structural boundary of the basin remain concealed beneath younger strata for over 30 miles along the Axial Basin Arch (Figure 3.11). Spring Creek and Sand Creek expose northwest dipping Late Cretaceous and Paleocene strata in the vicinity of Maybell where McKay and Bergin (1974) interpret the structural flank of the Axial Basin Arch to be a monocline. Faulting has not been identified in the Late Cretaceous sediments exposed here as mapped; however, a basin-bounding fault system may be present at depth. Although the basic style of Laramide deformation remains one of compression, it may have been limited to folding at the stratigraphic depth of the Late Cretaceous sediments in this portion of the basin margin.

The boundary of the basin is again concealed for another six to eight miles toward the area south of Lay, where the exposed basin margin emerges as a broad belt of deformation that continues to the southeast for approximately 50 miles. This segment, which includes the Williams Fork Mountains south of Craig, separates the basin from the White River Uplift to the south. Here, Laramide deformation is expressed as a series of predominantly northwest trending anticlines and synclines which may have developed over fault-bound basement blocks within the complex Cedar Mountain fault system described later in this section. Post-Laramide faults with similar trends to the folds offset young sediments and volcanic rocks and may represent reactivation of the underlying basement fault system during Cenozoic extension.

Near Oak Creek, south of Steamboat Springs, the perimeter swings northward to parallel the Sierra Madre-Park-Gore Range Uplift (Figure 3.11). Segerstrom and others (1972) mapped this uplift as a low angle thrust fault placing Precambrian crystalline rocks on the east over younger basin strata on the west. Basinward of this fault, folds in the strata also trend in a north to northeast direction in contrast to the predominant northwest structural grain to the west. Over much of its extent in this area, the perimeter of the basin is concealed by younger sediments and is cross-cut by numerous Oligocene igneous intrusions. Further to the north, near the Colorado-Wyoming Stateline, the perimeter swings sharply to the west to follow the Cherokee Arch fault system. This complex structural feature marks the north boundary of the Basin and extends from the Sierra Madre-Park-Gore Range Uplift into the Greater Green River Basin.

Fault Patterns and Characteristics Faulting accompanied basin development both along its perimeter and within its interior. Subsequent fault development occurred following the main phase of Laramide basin development deforming or possibly reactivating the earlier structural features. The style of faulting changed according to changes in stress regimes, with different styles of faulting having dramatically different ramifications on fluid flow patterns within the basin. Depending on type and extent of deformation and orientation, faults can act either as barriers to fluid flow or conduits to flow. Faults often cross and deform the basin boundary and are of particular relevance to characterizing potential groundwater pathways from CBM production areas to surface water or nearby water wells. Not only do faults cross through the basin in close proximity to CBM production areas, but where they cross the basin boundary they appear to provide potential groundwater flow pathways to areas outside of the basin. The manner in which fault characteristics affect groundwater flow is described in more detail in Section 5.2.

Using geophysical and borehole data, Tyler and Tremain (1994) identified two areas of deformation as primary fault systems dominating the basin. These fault systems, shown in Figure 3.11, include the Cedar Mountain fault system on the south side of the basin and the Cherokee Arch fault system on the northern edge of the basin. Trending in a northwesterly direction into the Basin, the features enclose a broad, less-deformed shelf that ramps down to the northwest. While these form basin boundary features, they trend obliquely to the primary Laramide uplifts and extend into the basin interior. Surface expression may appear simple; however, subsurface evidence points to great structural complexity. Both systems also deform post-Laramide Miocene sediments and may have Oligocene and Miocene igneous intrusions associated with them. These fault systems may act as long-lasting zones of crustal weakness that accommodate strain during changing stress regimes. During the Late Cretaceous to Eocene Laramide Mountain Building Event the systems underwent compressive deformation dominated by reverse faulting with a possible component of strike-slip movement. More recently, the systems are in an extensional stress regime and appear to be undergoing deformation dominated by normal faulting.

The Cedar Mountain fault system consists of a broad belt of deformation at least 10 miles wide that extends approximately 30-miles northwest into the basin from the Williams Fork Mountains northwest of Craig. Tyler and Tremain (1994) identified at least 6 faults that, combined, displace strata down to the northeast over 5,000 feet into the basin. Miocene sediments along this zone also show deformation by normal faults with up to 150 ft of offset as mapped at a 1:250,000 scale (Tweto, 1976).

Recent seismicity near the alignment of the Cedar Mountain fault system suggests continuing movement along this zone in today's extensional stress regime. On August 18, 2009 an earthquake with a magnitude of 3.7 was felt in the area with an epicenter estimated approximately 12 miles north-northwest of Craig (Figure 3.11). This location does not coincide directly with any mapped faults and lies just northeast of the broad band of deformation comprising the fault system, as currently mapped. The event also had a component of strike-slip movement. However; not every fault within the system has been mapped and precise epicenter locations are not possible due to a limited seismograph array. Furthermore, the location is on trend with other faults mapped further to the southeast between Hayden and Oak Creek.

The Cherokee Arch fault system consists of a broad, uplifted band of complex deformation trending west to northwest from the Park Range Uplift into the Greater Green River Basin. A complex system of folds and faults with normal and reverse displacement characterize the system (Tyler and Tremain, 1994). Overall displacement is down to the north into the Washakie Basin with as much as 2,500 feet of vertical offset and there may be a component of left-lateral strike-slip movement. It shares characteristics with the Cedar Mountain fault system in that it acts as a zone of structural weakness subject to recurring movement over time through different stress regimes.

Other faults have been mapped along the perimeter of the Basin outside of the Cedar Mountain and Cherokee Ridge fault systems (Figure 3.11). In particular, a set of northwest trending faults offset Cretaceous sediments at the southeast end of the Basin between Hayden and Steamboat Springs. This set of faults follows the predominant structural grain of the Basin, but cuts across the north-south eastern edge of the basin. Parallel and sub-parallel Oligocene and Miocene igneous dikes and alignment of volcanic necks southeast of the Basin (Tweto, 1976) hint that many more faults may exist that have not been mapped because of poor outcrop exposure.

Fold Patterns and Characteristics Folding within the Sand Wash Basin occurs primarily along its southeastern perimeter (Figure 3.11) where anticlines form the complex southern and eastern boundaries of the Basin. Along the perimeter south of Craig a series of northwest plunging anticlines and synclines trace the Cedar Mountain fault zone and may have formed above deeper fault blocks during the Laramide Mountain Building Event. Based on the limited borehole data these folds appear to attenuate to the northwest deeper in the basin. At the east end of the basin the prevailing northwest orientation of fold axes shifts rather abruptly to north-northeast roughly parallel to the Sierra Madre-Park-Gore Range Uplift. Deformation by the Tow

Creek Anticline and Twentymile Syncline effectively create a salient sub-basin between Hayden and Oak Creek.

Anticlines form structural traps for oil and gas. In addition, fracturing that developed in brittle rocks along the axes of folds can enhance permeability and hydraulic conductivity. Favorable oil and gas production may arise from a combination of structural trapping mechanisms with enhanced fracture permeability.

Igneous Activity Late Cretaceous through Miocene dikes and sills intrude the sedimentary rocks throughout the northeastern part of the Sand Wash Basin (Figure 3.11). Orientations of many of the dikes coincide with the predominant northwest regional structural grain that includes the Cedar Mountain and Cherokee Arch fault systems. Relationships between the igneous bodies and the coal-bearing sediments in Sand Wash Basin have not been reported in the literature. However, pervasive igneous activity throughout this part of the basin may impact the CBM resources, as well as regional geohydrology, in several ways. Cooper (2005) reports that intrusive igneous bodies can stimulate methane generation from coal under favorable conditions. Heat from the igneous activity could increase coal rank and the generation of methane in the coals. Fracturing may also increase secondary permeability. On the other hand, cross-cutting relationships of the igneous bodies with the stratigraphic architecture of the basin combined with probable associated fracturing may compromise trapping mechanisms within potential reservoirs. Linearly extensive dikes may act as barriers to horizontal fluid flow within the coal-bearing intervals and they may create vertical pathways between the coal-bearing intervals and overlying aquifers.

Fracture Patterns and Characteristics Fracturing of the sedimentary rocks greatly impacts both regional groundwater flow dynamics and gas production (Cumella and Ostby, 2003; Lorenz, 2003). Natural fracture occurrence in the Basin falls into three primary groups: 1) coal seam cleat system, 2) regional fracture systems, and 3) local fracture sets associated with specific folds and faults (Tyler, 1991; Tremain and Tyler, 1995). Artificial fractures created by oil and gas producers in rocks surrounding well bores fall in a separate category and are very local to production areas.

Cleats are natural systematic fractures in coal seams (Tremain and others, 1991) believed to have formed soon after coalification. Typically oriented normal to the bedding, cleats break up the coal seams along sub-parallel open-mode planar sets. The first sets to form tend to be longer and are called "*face*" cleats. Subsequent cleat sets, or "*butt*" cleats, terminate against, and are typically perpendicular to, the face cleats. Primary cleats extend across multiple coal-type layers and secondary or tertiary cleats are vertically discontinuous between layers. Spacing between cleats is believed to be a function of coal rank and type, coal seam thickness, structural setting, and stratigraphic position.

Cleat orientations are most commonly obtained from the basin margin at surface exposures or underground mine workings. Basin interior cleat orientations require oriented cores or borehole imaging and these data typically are proprietary. The only published cleat orientations found for the Sand Wash Basin were reported by Tyler and Tremain (1994). CGS also collected additional cleat orientation data in the spring of 2010. Figure 3.11 includes the cleat point measurements and Figure 3.12 shows the distribution of face cleat orientations using both sets of data. Face cleats in coals of the Sand Wash Basin, both Mesaverde and Fort Union, generally have a northwest orientation, although local variations exist and data are sparse in the northern part of the basin. This orientation generally parallels the regional structural grain of the Basin. Spacing values vary widely from 0.5 inch to more than 12 inches.

Fracturing also develops in brittle indurated sandstone, siltstone, and calcareous shale either in response to regional stress patterns or local folding and faulting. Published fracture data specific to Sand Wash Basin were not found in the literature. However, CGS did collect fracture measurements from outcrops of Mesaverde Group strata at 53 locations in 2010 and Figure 3.11 includes these new data. Figure 3.12 also shows the distribution of fracture orientations using these data. As with the coal face cleats, fractures in brittle sandstone layers trend to the northwest along the regional structural grain of the Basin. Although a systematic study has not been performed, many of the best developed sets of fractures appear to correspond to axes of folds along the Cedar Mountain fault system. Figure 3.13 is a photograph of a set of northwest fractures in sandstone beds of the Iles Formation exposed in the Williams Fork River valley east of Hamilton.

Lorenz (2003) recognized that most fractures occur mainly in the well-indurated sandstone layers and rarely, if ever, do they connect through bounding layers of shale and mudstone. Hence, fractures observed at the surface do not necessarily indicate vertical hydraulic connection throughout the stratigraphic column. This relationship bears directly on gas migration and trapping mechanisms as well as potential groundwater flow pathways. However, site specific data pertaining to fracture patterns and distribution have not been reported in the literature for the Sand Wash Basin. Nevertheless, observations of fracture patterns in the basin suggest that fracturing may indeed enhance horizontal hydraulic conductivity through the strata.

Fracture patterns throughout the basin are complex and show great variation due to gradual changes in stress regimes across the region over geologic time. Compressional stress accompanied deposition and burial of the coal-bearing Mesaverde group in the Late Cretaceous period and continued as the Laramide Mountain Building Event evolved into the Tertiary (Tyler, 1995). Stress patterns changed dramatically following the Laramide Mountain Building Event to an overall east-west extensional environment that continues today (Chapin and Cather, 1994). As a result current extensional stress oblique to the older structural grain may enhance permeability through the regional fracture systems.

4.0 COALBED METHANE PRODUCTION

This assessment specifically addresses gas produced from coal-bearing sediments by pumping water to reduce the hydraulic head on the coals to desorb the methane gas directly from the coal matrix. CBM production to date totals less than 2 Bcf. All of the production is derived from the Mesaverde Group on the east side of the Basin. According to COGCC records there has been no economic CBM production from the Fort Union Formation to date. Gas produced from the Fort Union Formation in active fields may be sourced from coal, but it is produced from conventional sandstone or tight sand reservoirs.

In 2005, the USGS prepared a petroleum systems and geologic assessment of oil and gas for the southwest Wyoming province that included the Sand Wash Basin (USGS, 2005). That assessment broke out units of petroleum potential by formations and resource type. Coal gas was treated as a separate type of unit in the assessment. The USGS assessment defines both a Mesaverde Coalbed Gas Assessment and a Fort Union Unit (Finn et al., 2005). Figure 4.1 shows the Mesaverde Coalbed Gas Assessment Unit along with Mesaverde wells classified as "coalgas" wells in the COGCC database. Delineation of the unit is based on a practical depth criterion of 6,000 feet for CBM production. This delineation has been used in our assessment to isolate Mesaverde CBM development from other Mesaverde gas production in the Basin. Figure 4.2 shows the Fort Union Coalbed Gas Assessment Unit along with Fort Union wells classified as coalgas wells in the COGCC database. Because there has been no CBM production from the Fort Union Formation to date the remainder of this assessment will focus on the CBM production from the Mesaverde Group. Although both the Mesaverde and Fort Union CBM units are present on the west side of the basin, COGCC records and conversations with operators indicate that there has been no CBM production in that area to date.

4.1 Sand Wash Basin CBM Production History

The Sand Wash Basin region is well known for its economic energy resources that include conventional oil and gas, oil shale, and coal. CBM potential in the basin has long been recognized (Boreck and others, 1983; Kaiser and others, 1994); however, economic CBM development to date has been limited. Conventional gas and oil resources have been developed from sandstones within the Cretaceous Dakota Sandstone, Niobrara Formation, Mancos Shale and Mesaverde Group as well as the Tertiary Wasatch Formation (USGS, 2005). Conventional oil has been developed from the Permian Weber Sandstone and, to a lesser extent, the Jurassic Entrada Sandstone and Morrison Formation. Sources for oil and conventional gas are believed to be the older marine Pennsylvanian Belden Shale and Minturn Formation, Permian Phosphoria Formation, and Cretaceous Mancos Shale. One of the primary sources for gas in the Upper Cretaceous and Lower Tertiary sandstone reservoirs is believed to be coal in the Fort Union Formation and the Mesaverde Group.

Coal resources present in the Mesaverde Group, in what is known as the Green River Coal Region, have played an important role in the economic development of the region, particularly along the southwestern edge of the basin in Moffat County. The region has produced more than 350 million tons of coal from 300 mines. This equates to over 34% of Colorado's total coal production, making this the state's largest coal producing region (Carroll, 2004). As of 2004, there were four active coal mines producing from the Mesaverde Group coal beds around the perimeter of the Sand Wash Basin (Carroll, 2005).

Methane has long been known to be present in the coals of the basin (Boreck et al., 1981) and, at times, has been a major hazard associated with historic underground coal mining. Development of gas derived from the coal-bearing Mesaverde Group in the region has early beginnings. Production from the White River Dome at the north end of the Piceance Basin goes back to 1890 (Olson, 2003). Actual CBM production, where coal beds are specifically targeted for production, started much later in the region, with a reported first completion in the Piceance Basin in 1978 (Johnson and Roberts, 2003). In 1993 Bayless Energy drilled several wells in the Big Gulch Field west of Craig targeting the Mesaverde; however, it is not clear from the records whether coal gas was a primary objective. The first commercial large-scale production of CBM gas did not occur until 1999 when gas was tapped from the Lower Coal Group, or Iles Formation, by New Frontier Energy (now Entek Energy) at the Slater Dome Field, located near the northeastern edge of the Basin (Figure 4.1).

In the early 2000s, interest in CBM blossomed in the Sand Wash Basin when a number of operators initiated several pilot projects (Norwest, 2006). Properties and operating companies tend to change but the primary operators in developing CBM in the Basin included Tipperary (now Pioneer Resources), Burlington Resources (now Meridian), New Frontier (now Entek) and Patina (now CDX). Other operators included Cockrell and Cyprus. Pilot projects undertaken at several fields west of Craig included Yampa Field, Big Gulch Field, Encore Field, and an un-named area west of Encore, shown as "Wildcat" in Figure 4.1. Other attempts at coal gas production have been made at the Craig Field, Pelt Field (Breeze Basin), Bull Mountain Field; as well as scattered wildcat locations around the eastern part of the basin.

To date, the only sustained CBM production has been from the Slater Dome and Encore fields (Figure 4.1). In 2009 the Encore Field was sold by Pioneer Resources to Foundation Energy and the wells were shut-in or temporarily abandoned. COGCC records as of October 2010 indicate that Encore currently remains shut-in. Currently, only Slater Dome is in operation.

To date, a total of approximately 1.7 Bcf of gas has been produced and approximately 4,000 acre-feet of water has been extracted in association with CBM gas production for the entire Sand Wash Basin. CBM production in the Sand Wash Basin has not met expectations and the total below 2 Bcf is low compared to other CBM plays in Colorado. This volume represents approximately 0.5 percent of the annual CBM produced in the Colorado portion of the San Juan Basin, and 4 percent of the annual CBM produced in the Colorado portion of the Raton Basin. Gas production in the Northern San Juan Basin has been approximately 400 Bcf **per year** with water production ranging between 3,000 and 4,000 acre-feet **per year** since 1991. Closer to the Sand Wash Basin, the Piceance Basin was estimated to have produced just over 22.5 Bcf of CBM gas by 2006 (SSPA, 2008).

4.2 CBM Gas and Water Production

Figures 4.3 and 4.4 show the geographic distribution of CBM gas and produced water totals, respectively, throughout the Sand Wash Basin with most of the production originating from the Encore and Slater Dome Fields. Elsewhere, limited production has come from isolated pilot projects that have been abandoned or shut in. Slater Dome Field produces CBM from 11 wells in the Lower Williams Formation and Iles Formation located in about a square mile area at the northeast edge of the Basin. Close spacing in this area reflects strong structural control of favorable production. At Slater Dome cumulative gas totals per well reach a high of 0.25 Bcf, the highest for Sand Wash Basin, while cumulative water totals for wells reach a high of 267 acre-feet. Encore Field, west of Craig, produced CBM from 24 wells completed in the Lower Williams Fork Formation within an approximate, three-square-mile area trending northwest along the northwest extension of the Williams Fork-Bell Rock Anticline. At this field cumulative gas totals reach a high of 0.05 Bcf per well, while cumulative water production totals reach a high of 307 acre-feet per well, the highest water production for the Sand Wash Basin.

Water yields vary considerably, as illustrated in Figure 4.5. These yields were estimated as average gallons per minute (gpm) from monthly totals reported in the COGCC database. The highest rate of 113 gpm is from a well at Encore Field possibly explaining why the field is currently shut-in. High rates of water production at the various pilot study sites explain the limited CBM success rate.

Figure 4.6 shows annual production for gas and water from Mesaverde CBM wells in the Basin from 1993 through 2009. An upturn beginning in about 2003 and peaking in 2008 represents development at both the Slater Dome and Encore Fields. The down-turn after 2008 is a result of the suspension of operations at the Encore Field as Pioneer prepared to sell the property. Gas production rates reached a high of just under 0.5 Bcf per year in 2008 whereas water production reached a high of about 1,000 acre-feet per year in the same year just before Encore was shut in.

In a typical CBM well, such as found in the San Juan Basin, water production peaks soon after the well is brought on line and then it falls off as methane production rises. Ideally CBM production increases and a well may have a long productive period with relatively high gas production and little to no water production. This pattern occurs because CBM is adsorbed on the surfaces of the coal itself and is held in place by the hydrostatic pressure of the water that fills the fractures, or cleats, of the coal. As water is pumped out of the coal-bearing formation and the pressure in the formation drops, gas desorbing from the coal replaces water in the cleats and water production declines. This contrasts to traditional oil and gas wells, where water production tends to increase during the later portion of a well's life as the hydrocarbon production falls off.

Figure 4.7 compares gas and water plots for two Mesaverde Group CBM wells from the Sand Wash Basin with plots from a typical well in the San Juan Basin. Data from the Sand Wash Basin wells scatter and do not follow discernable trends. However, water production does not fall off as it does in the typical San Juan Basin well. Pioneer Resources indicated that high water yields and water management issues were primary reasons for selling off their CBM assets in the Sand Wash Basin. Indeed, when Pioneer Resources shut in their wells at Encore, water production decreased more than gas production as shown in Figure 4.6.

4.3 CBM Production Projections

The annual gas production history for the Basin is not encouraging for future growth in production. Future production of CBM gas in the Sand Wash Basin depends not only on the previous production history, but also on the technical and logistical hurdles that must be overcome simply to produce the gas. Future CBM production also depends on produced water management strategies and the complex intermixing of socio-economic factors that affect the development of all energy resources. In 2006 Norwest (2006) concluded that future CBM development in the Sand Wash Basin under current conditions would be limited to fields with established infrastructure. The rapid fall of natural gas prices since 2008 and the onset of gas production from the Marcellus Shale in the eastern U.S. may be contributing factors to suspended CBM production in the Sand Wash Basin.

Estimates of producible CBM gas-in-place in the Sand Wash Basin are on the order of 14 Tcf (Boreck et al., 1981) to 24 Tcf (Kaiser et al., 1994) – a resource reserve not to be overlooked. High gas prices in the recent past and technological advances in hydraulic fracturing of tight formations spurred economic development of this type of resource elsewhere. However forecasting technological and economic changes that might enable widespread CBM development in the Basin would be mere speculation. Therefore, this assessment limits itself to historic and current production.

5.0 HYDROGEOLOGIC CONDITIONS

5.1 Sand Wash Basin Groundwater Resources

Several potential aquifers underlie the Sand Wash Basin, including the Quaternary alluvium along the main stem of the Yampa River and the Little Snake River, as well as their tributaries (Topper et al., 2003). Bedrock aquifers include coarse-grained strata within the Oligocene to Miocene Browns Park Formation/Bishop Conglomerate, Eocene Wasatch Formation and Tipton Tongue of the Green River Formation, and the Paleocene Fort Union Formation. These regional bedrock aquifer systems supply predominantly domestic and livestock uses scattered widely across much of the interior of the Basin. They overlie the Mesaverde Group and are separated from it by the predominantly fine-grained strata of the Lance Formation and Lewis Shale, which form a regional confining unit. The Cretaceous Mesaverde Group also forms a regional aquifer around the perimeter of the basin where the younger bedrock aquifers have been removed by erosion. As a very heterogeneous sequence of sediments, the Mesaverde Group contains many layers of sandstone and coal that can form local aquifers. Of these, the Trout Creek and Twentymile Sandstones are considered regional aquifers in their own standing (Robson and Stewart, 1990).

This section addresses groundwater and water well distribution in the coal-bearing Mesaverde Group and Fort Union Formation. Discussion and analysis focuses on the Mesaverde Group aquifer system because current and foreseeable future CBM development is limited to the Mesaverde coal group.

5.2 Outcrop Areas of the Coal-bearing Intervals

Outcrop patterns of the coal-bearing intervals provide insight to their hydrogeologic setting. Areas where the intervals come to the surface can either be areas of recharge or areas of discharge depending on pressure relationships within the formations. Outcrop patterns of the Mesaverde Group and Fort Union Formation reflect the general structural shape of the basin overprinted by the distribution of younger sediments covering much of the basin perimeter. The Basin's structural trend results in an overall triangular shape extending west-northwest into Wyoming. Widely distributed deposits of younger sediments on the west side of the basin conceal the coal-bearing formations, so that their exposures are generally limited to crescent shaped bands at the southeastern end of the Basin. However, on the west side of the basin downcutting of streams and rivers through the younger sediments reveals localized exposures of the coal-bearing formations. Outcrop patterns are reflected in the distribution of water wells tapping groundwater and the location of groundwater recharge and discharge regions in the coal-bearing formations (Figure 5.1).

5.2.1 Mesaverde Group Outcrop Patterns

Outcrop patterns reflect a combination of structural dip, total thickness of the sedimentary units, and topographic expression along the perimeter. Accordingly, outcrop width of the Mesaverde Group varies considerably depending on location along the Basin perimeter as shown in Figure 5.1. The following section describes primary characteristics of the Mesaverde Group starting at the west end of the Basin and continuing to the northeast corner.

At the west end near Vermillion Creek, erosion of the younger Eocene and Miocene sediments exposes a limited outcrop of the Mesaverde Group. Here, steep northeast dips along the Uinta-Sparks fault system result in a narrow outcrop belt. Spatial relationships show that this exposure lies in the hanging wall of the fault system (Tweto, 1976). As such, bedding exposed at the surface is not necessarily physically connected with the bedding within the basin.

The Mesaverde Group outcrops again further to the east in the valley of Spring Creek near Maybell (Figure 5.1). Here, erosion exposes a narrow band of the Williams Fork Formation with a steep northeast dip of approximately 50° along the north edge of the Axial Basin Uplift. The surface elevation of approximately 6,000 feet above MSL at Spring Creek makes this the lowest exposure of the Mesaverde Group around the basin perimeter. Although a detailed description of the outcrop is not available, it is likely that most of the coal-bearing intervals in the Williams Fork Formation and the top of the Iles Formation are exposed at this location. McKay and Bergin (1974) interpret the structure here as a monocline, implying that the strata exposed here are connected with strata within the Basin. This interpretation may be valid, however, normal faults in the Eocene Wasatch Formation just to the north, as well as in the Miocene Browns Park Formation to the west, could affect this connection. The relationship of these younger faults to hydraulic connection between the Basin perimeter and its interior requires better definition before undertaking robust analysis of groundwater flow patterns in this area.

When next exposed, the Mesaverde Group outcrop forms a broad arcuate belt up to six miles wide that extends over 60 miles to the east before turning north near Oak Creek (Figure

5.1). From there the belt continues over 35 miles further to the north before it is again concealed beneath younger sediments. This outcrop belt spans the Williams Fork Mountains south of Craig and the Elkhead Mountains northeast of Hayden. These are both areas of potential groundwater recharge. The outcrop belt also includes the main stem of the Yampa River and the lower Williams Fork River including its many tributaries above Hamilton, which are potential areas of groundwater discharge. This belt exposes the entire Mesaverde Group along with the three coal groups which have been targeted for extraction since the late 1800's.

To the north the outcrop belt passes beneath a cap of younger sediments and volcanic rocks in the Elkhead Mountains (Figure 5.1). High elevation and precipitation in this area provides potential for recharge to the Mesaverde Group if there is hydraulic connection through the younger cover. This area includes a number of Oligocene through Pliocene igneous dikes, sills, and plugs that intrude the Basin sediments. Faulting and fracturing associated with the igneous activity could enhance hydraulic connection to the underlying Mesaverde Group. Further to the north outcrops of Mesaverde Group remain limited to a few exposures created by erosion through the younger sedimentary cover in the watershed of the Little Snake River. Outcrops of Mesaverde Group also extend across the Cherokee Arch fault system (Figure 3.11). Tweto (1976) mapped exposures along the Little Snake River as undifferentiated Mesaverde Group, however stratigraphic relationships with the Lewis shale suggest that Williams Fork Formation is likely at the surface in this part of the belt.

5.2.2 Fort Union Formation Outcrop Patterns

With a higher stratigraphic position than the Mesaverde Group, outcrops of the Fort Union Formation extend further into the basin (Figure 5.2). Younger sedimentary cover on the west side of the basin conceals the Fort Union Formation and its exposure is limited to a broad belt east of Maybell. Erosion through the Browns Park Formation in the vicinity of Spring Creek exposes Fort Union Formation along the monocline mapped by McKay and Bergin (1974). Steep dips to the north create narrow outcrop patterns in these limited exposures. The outcrop belt broadens to almost two miles to the east as dips decrease, yet portions remain partially covered by the Miocene Browns Park Formation. In this area the outcrop belt crosses the Cedar Mountain fault zone where near-vertical faults juxtapose Fort Union Formation with Browns Park Formation creating a fragmented pattern (Figure 5.2).

East of Craig the outcrop belt swings north at the axis of the basin where it widens to more than six miles between Fortification Creek and Elkhead Creek. In this area elevations rise from about 6,300 feet above MSL from Fortification Creek, a possible groundwater discharge area, to over 7,500 ft MSL at the south side of the Elkhead Mountains, a possible recharge zone. Nearly all of the Fort Union Formation is exposed in this belt including the lower coal-bearing unit. Further to the north, nearly flat-lying upper Eocene Wasatch Formation and Miocene Browns Park Formation are capped with younger volcanic flows and extend into the Basin. These younger rocks form the Elkhead Mountains and conceal the Fort Union Formation outcrop belt. Elevations rise above 10,500 ft where annual precipitation totals over 50 inches per year, making this area a potential recharge zone for the Fort Union Formation. Faulting and fracturing associated with the igneous activity could enhance hydraulic connection through the younger rocks covering the underlying Fort Union Formation.

North of the Elkhead Mountains, the Fort Union Formation reappears in an irregularly shaped outcrop area bounded on the south by the overlying Eocene Wasatch Formation and on the northeast by the Cherokee Arch Fault zone (Figure 3.11). Outcrop relationships appear complex near this fault zone. In this area elevations range between 6,500 ft above MSL near the Wyoming border and 7,800 ft above MSL just north of the Elkhead Mountains.

5.3 Water Well Distribution

This study included an evaluation of impacts to permitted water wells by CBM production in the Basin. The evaluation required identification of water wells completed in the coal-bearing intervals. This was accomplished by comparing well completion depths with depths of both the Fort Union Formation and Mesaverde Group using GIS spatial analysis. Water well depths were obtained from DWR permit records while formation depths were obtained from structural contour maps of stratigraphic intervals above and below the coal-bearing intervals. Figures 5.1 and 5.2 show the distribution of permitted water wells in the Mesaverde Group and Fort Union Formation, respectively, based on this analysis.

In the absence of water rights administration constraints, water wells typically need be drilled only deep enough to penetrate an aquifer that yields water of sufficient quantity and quality to meet anticipated needs. In most cases this is the first good water-bearing stratigraphic interval or fractured interval penetrated. Drillers often know this ahead of time and reference nearby well completion data, or they simply drill until they hit “good” water. Hence, local bedrock aquifers usually reflect nearby bedrock outcrop patterns. In areas where fine-grained and impermeable bedrock, such as marine shale, is at the surface, wells penetrate deeper to find the first water-bearing permeable horizon. Exceptions to this arise when the anticipated water demand exceeds the capacity of the shallow aquifer, or the water in the shallow aquifer is already adjudicated by someone else. The latter case is not common in Western Colorado.

Water well distribution in both the Mesaverde Group and Fort Union Formation fit this generalization well as illustrated in Figures 5.1 and 5.2. For both aquifers well density increases in areas where rural development patterns involve smaller parcels in areas not served by municipal water systems. The Mesaverde Group wells are further differentiated by the Upper and Lower Williams Fork Formations and Iles Formation. Well distribution by member of the Mesaverde Group also generally reflects outcrop patterns of the units.

Several Lower Williams Fork wells fall further into the basin away from the outcrop belt west of Craig. These deep wells were originally drilled as unsuccessful wildcat oil and gas wells that hit water of sufficiently good quality to be converted to water wells. Several are known to flow under artesian conditions.

Within the Basin away from the outcrop belts of the Fort Union Formation and Mesaverde, permitted water wells typically tap shallower aquifers. These shallower aquifers include the Wasatch Formation and Browns Park Formation. Many of the rural developments west of Craig rely on the Browns Park Formation for their water supply.

CBM well locations extend further into the basin interior away from the outcrop belt than the water wells tapping the Mesaverde Group. This provides horizontal spatial separation between CBM wells and water wells completed in the same stratigraphic interval of nine miles or more in the southeastern part of the Basin (Figure 5.1).

5.4 Mesaverde Group Hydrostratigraphy

This section addresses groundwater conditions within the Mesaverde Group where historic CBM production has taken place. Stratigraphically, the Mesaverde Group is isolated between the deeper Mancos Shale and the overlying Lewis Shale. This geometry creates an aquifer system that is essentially confined in the basin interior and transitions to unconfined at the outcrop. Faulting and fracturing disrupt the formations where they crop out in the eastern part of the basin. However, Lorenz (2003) argues that fractures in shale tend to self-heal within a basin. If this is the case in the Sand Wash Basin, then the Mesaverde Group aquifer system would remain hydraulically isolated in the basin interior. Exceptions may arise, however, where Neogene extensional faulting and igneous intrusions disrupt the basin sedimentary layering. This possibility should be evaluated as part of any detailed site-specific analyses, which requires data not available for the broad-based analyses described herein. For the purposes of this basin-wide analysis the assumption is made that the Mesaverde Group is hydraulically isolated where the Lewis Shale has not been removed by erosion. Vertical connection should, however, be addressed with more local detailed assessments in the future.

5.4.1 Hydrostratigraphic Unit Geometry

Internally, the Mesaverde Group is quite complex containing at least three sequences of marine flooding followed by shoreline regression. Marine shale is common within the Mesaverde Group on the eastern side of the Basin. Shale layers that can form confining units separate the Mesaverde Group into the Upper Williams Fork, Lower Williams Fork, and Iles formations (Figure 3.5). Each of these, in turn, can be treated as a hydrostratigraphic unit with more favorable aquifer parameters near the base, where the laterally extensive coals and shoreface sandstone layers predominate. In contrast, on the west side of the Basin coarse-grained sediments predominate, allowing greater vertical hydraulic connection through the Mesaverde Group. Thus, the segregation into three hydrostratigraphic units fades to the west.

Cleat systems in the coal seams create the primary permeability within the bulk of the Mesaverde Group sediments. Coal seams near the base of coal groups also tend to be laterally continuous and are likely to have greater permeability than surrounding strata. Thus these coal seams provide the most probable pathways for lateral groundwater flow. In this conceptual model, each coal group behaves as a single hydrologic unit consisting of the entire package of coal seams and interbedded sandstone and shale layers. In addition, laterally continuous shoreface sandstone deposits extend across much of the region beneath each of the coal groups. Specifically, the Trout Creek Sandstone underlies the Middle Coal Group and the Twentymile Sandstone underlies the Upper Coal Group. Robson and Stewart (1990) consider these two sandstone members of the Mesaverde Group as regional aquifers. CBM wells typically just hit the top of these sandstone units and are often plugged back when they do intercept the sandstone. Because of this typical drilling practice, the coal-bearing sequence above the sandstone will be considered the hydrologic unit in this discussion. This is done with the understanding that the Trout Creek and Twentymile sandstones may very well be primary aquifers that could contribute water into the system. DWR would consider these units to be in hydraulic connection with the coal-bearing interval in evaluating tributary status.

Basin geometry brings the hydrostratigraphic units to the surface along the outcrop belt. Exposure at the outcrop allows recharge or discharge depending on head (water pressure) relationships between water in the aquifer and surface water or atmospheric pressure.

5.4.2 Recharge

Recharge to the hydrostratigraphic units occurs through three primary pathways: 1) direct recharge of precipitation on the outcrop, 2) recharge by infiltration from intersecting stream-beds, and 3) vertical inflow from overlying younger geologic formations. Upward flow from pressurized formations below may also occur through faults and fracture systems. It could be inferred that recharge to the Mesaverde coal groups may be limited overall due to the geologic and topographic characteristics of the basin. However, elevated water production at the CBM pilot projects is evidence to higher recharge rates than might be expected. This recharge may be enhanced by the prevailing structural fabric characterized by northwest-trending faults and fracture patterns.

Throughout the outcrop belt, the Mesaverde Group is exposed over a broad range of elevations ranging from approximately 6,100 ft above MSL at the Yampa River west of Craig to over 9,200 ft above MSL in the Elkhead Mountains northeast of Hayden. Direct precipitation can vary greatly over this range in elevations as can the opportunity for direct recharge. Characteristics favoring recharge at the outcrop include weathering of the strata and the release of overburden pressure as overlying strata have been eroded away. Over much of the outcrop belt, particularly at lower elevations, annual precipitation is probably lower than annual evapotranspiration rates so that direct precipitation is often lost before infiltration can recharge deeper groundwater (Topper et al., 2003). It is only at the higher elevations, such as in the Elkhead Mountains and Williams Fork Range, where direct recharge from precipitation is likely.

Direct recharge from intersecting streams is possible under favorable potentiometric head conditions. Potentiometric head must be lower in the hydrostratigraphic unit than the intersecting stream for water to flow from the stream into the underlying formations. Given the topographic relationships of the major streams crossing the Mesaverde outcrop belt, it is more likely that these major drainages receive discharge from the Mesaverde coal groups rather than provide recharge. Recharge from streams may occur in higher elevations of the Elkhead Mountains and Williams Fork Range. Site-specific data regarding stream recharge-discharge relationships were not obtained for this study.

Younger Oligocene and Miocene sediments also cover the Mesaverde coal groups potentially impeding recharge. Recharge by downward infiltration through the younger sediments may be possible, however. Although the vertical hydraulic conductivity of the overlying formations may be low, water will flow downward through them if the head differential exists to drive the flow. Flow rate is a product of hydraulic conductivity, gradient, and surface area so that high gradients across large areas can result in significant flow rates even if hydraulic conductivity is low. Downward flow could potentially contribute the largest component of recharge over much of the basin, particularly for areas where the overlying topography and precipitation are high such as in the Elkhead Mountains. The potential for downward recharge may be facilitated where fracture systems cross-cut the Mesaverde Group and overlying younger formations along structural features. Vertical igneous dikes and stocks can also enhance vertical hydraulic connection through internal brittle fracturing or deformation of surrounding host-rock. In the center of the basin over-pressurized conditions exist and would preclude downward infiltration of water into the Mesaverde Group coal-bearing intervals (Scott and Kaiser, 1994).

5.4.3 Discharge

The hydrostratigraphic units discharge water through direct outflow to surface water through seeps and springs and by evapotranspiration from outcropping areas. Upward flow into shallower formations may also occur within the Basin through faults and fracture systems. Total discharge must balance total recharge and both may be quite limited over the entire basin.

Direct discharge to surface water most likely occurs where streams cross the outcrop belt at its lowest elevations. Ferricrete deposits along the banks of the Yampa River, where the river crosses the Mesaverde Group outcrop belt near Duffy, may be evidence of regional groundwater discharge. Groundwater under reducing conditions containing dissolved iron may discharge from the Mesaverde Group to precipitate iron as it mixes with oxygen rich meteoric water. These deposits, observed by CGS in June 2010, warrant further investigation. Evapotranspiration is possible anywhere along the outcrop belt.

5.4.4 Groundwater Flow Pathways

Groundwater flow follows basic physical principles where flow patterns are driven by pressure differential, or head gradient, through open pathways. Water flows from areas of higher head to areas of lower head, taking the most direct route through materials with the greatest hydraulic connection. Laterally continuous, basal coal seams and the underlying shoreface sandstone members probably constitute the most hydraulically connected pathways within the heterogeneous Mesaverde Group hydrostratigraphic units.

Individual coal seams eventually pinch out laterally. However, over the extent of the basin, many seams overlap each other separated by layers of shale, siltstone, and sandstone. This shingled architecture may seemingly compartmentalize groundwater flow through the system. AHA (2000) evaluated this geometry in the Fruitland Formation of the San Juan Basin using a two-dimensional numerical model. The model indicated that the large surface area of the layers separating the coals counteracts their relative low hydraulic conductivity. As a result, the shingled architecture would not diminish flow through the entire package.

Face cleat orientation may impose a preferred orientation for groundwater flow through the coal seams. However, previous stream depletion studies argue that close spacing of both face cleats and butt cleats creates a relatively isotropic hydrologic media (SSPA, 2006; 2008b). Fractures in siltstone and sandstone layers adjacent to the coal seams may provide additional pathways for groundwater flow through the hydrostratigraphic units. Fractures along the southern outcrop belt of the Mesaverde Group display a dominant northwesterly trend as shown in Figure 3.12 parallel to the prevailing structural grain of the basin. This trend may result in increased hydraulic connection in a northwesterly direction creating an anisotropic aquifer system. Furthermore, greater fracture density near anticlines and synclines may localize this effect. Without site-specific data, potential lateral anisotropy within the hydrostratigraphic units cannot be evaluated beyond inferring probable effects. Any site specific analyses should consider fracture induced anisotropy as an important factor in local groundwater flow.

In addition to creating lateral anisotropy within coal-bearing intervals, fracturing may provide vertical hydraulic connection between the coal-bearing intervals and other aquifers above and below. In particular, fracturing could connect target CBM intervals with the regional Trout Creek and Twentymile Sandstone aquifers beneath them (Figure 3.5). Enhanced vertical fracturing may contribute to undesirable elevated water yields from some CBM wells (Johnson and Roberts, 2003).

Scott and Kaiser (1994) suggest a flow model for the Sand Wash Basin wherein groundwater flows basinward from areas of recharge following regional topographic slope and structural dip. Groundwater then discharges directly to the Yampa River valley or upward through the center of the basin. The latter implies some vertical hydraulic connectivity that could be enhanced by faulting and fracturing. They further suggest that within the deepest part of the basin, low permeability combined with hydrocarbon generation creates over-pressurized conditions. This effectively creates a hydraulic barrier between the shallower east part of the basin, where CBM potential exists, and the deeper west part of the basin. Structural elements such as the Cedar Mountain and Cherokee Arch fault zones may also impede groundwater flow within specific areas of the basin. In contrast, these features may enhance groundwater flow parallel to the prevailing structural grain. The relative position of the fault zones with respect to areas of recharge and discharge, strongly influence groundwater flow pathways through the Basin.

Figure 5.3 shows a potentiometric map for the Upper Williams Fork Formation from Scott and Kaiser (1994) incorporating water-level data from water wells completed in the Mesaverde Group. The map also shows inferred generalized groundwater flow pathways based on this potentiometric surface. Groundwater pathways within the other two hydrostratigraphic units of the Mesaverde Group probably mimic those shown in Figure 5.3 because they generally share outcrop patterns and structural features. Several aspects of these inferred flow pathways are summarized below:

- **Outcrop flow patterns.** The greatest component of groundwater flow likely occurs very near the outcrop where the relatively impermeable geologic materials have been weathered and overburden pressures have been released. This has been suggested for the outcrop along the south flank of Grand Mesa (Wright Water Engineers, 2000), and was identified as a key characteristic defining the hydrologic characteristics of the Fruitland-Pictured Cliffs aquifer in the northern San Juan Basin (SSPA, 2006).
- **Fault Systems and Prevailing Fracture Trends.** The Cedar Mountain Fault Zone probably acts as a barrier to westward flow from areas of recharge to the east. Conversely, prevailing fracture sets parallel to this fault zone could enhance northwestward flow. Both factors may cause the northwest-trending ridge shown in the potentiometric surface.
- **Basin Discharge.** Head distribution drawn by Kaiser and Scott (1994) direct flow pathways to a potentiometric low in the basin center north of Craig. This would imply discharge from the system possibly in an upward direction through overlying sedimentary layers. Mechanisms for this discharge need to be better defined through future head measurements and geologic characterization.

5.5 Water Chemistry

Water quality data has been compiled from several sources to assess surface- and groundwater geochemistry as it pertains to CBM development in the Sand Wash Basin. Sources include U.S.G.S. records, COGCC records, BLM records of the CBM study by Norwest, and a set of surface samples collected by the CGS in November 2009. Data encompass samples of surface water and alluvial, Fort Union Formation, and Mesaverde Group groundwater. This allows a broad comparison of water types to help understand hydrologic relationships of the surface water and groundwater system. Sampling by CGS, covers locations above and below outcrops of both the Fort Union Formation and the Mesaverde Group during baseflow conditions to identify contributions from the coal-bearing intervals.

The dataset encompasses a wide variety of water quality parameters. However, this discussion focuses on Total Dissolved Solids (TDS) and Sodium Adsorption Ratio (SAR) since they have greatest relevance for a broad-based assessment. TDS is a general measure of water quality encompassing all dissolved ions present in the water. The secondary drinking water standard for TDS is 500 milligrams per liter (mg/L). Water with TDS concentrations between

1,000 and 10,000 mg/L is considered brackish and over 10,000 mg/L is considered saline (Freeze and Cherry, 1979). Brackish water is considered potentially useable for domestic and agricultural purposes by the Colorado Water Quality Control Commission groundwater classification system. However, TDS concentrations above 2,000 to 3,000 mg/L are considered too salty to drink. Furthermore, elevated TDS concentration increases the possibility that constituents with primary drinking water standards will exceed maximum concentration limits.

Crop tolerances to salinity vary considerably and the usability of water for irrigation depends on the type of crop and general soil conditions. SAR is a ratio of dissolved sodium to dissolved calcium and magnesium and is used to assess water usability for irrigation. When SAR is high, sodium tends to replace the other ions in clays within the soil, rendering the soil sticky and impermeable. Values of SAR below 10 indicate little risk of sodium replacement in soils while values above 18 indicate that damage to the soils is likely. SAR is included in this discussion because one of the possible uses for CBM produced water is crop irrigation.

5.5.1 Mesaverde Water Quality

Figure 5.4 shows the distribution of TDS concentrations reported for groundwater samples from the Mesaverde Group as color shaded contour intervals. Because of the limited number of sample sites across the basin, the data have not been discriminated by sub-unit within the Mesaverde Group. Most of the sample locations occur in the southern part of the Basin near the outcrop belt which coincides with the area most likely to be impacted by CBM development. As shown, water quality near the areas where recharge enters the system and depths of the water-bearing intervals are shallow tends to be good with many concentrations falling below 1,000 mg/L. Water quality tends to deteriorate basinward with TDS concentrations approaching 5,000 mg/L due to greater depth and groundwater residence time. This overall pattern generally reflects the groundwater flow pathways illustrated in Figure 5.3.

High TDS concentrations reported for wells at the northeastern corner of the basin are contrary to what is seen in the southern part of the basin in that concentrations decrease basinward from the outcrop. The elevated concentrations at the basin edge are indeed anomalous and may reflect localized conditions related to structure, igneous activity, or other hydrologic conditions. Detailed analysis of specific areas is beyond the scope of this study; yet this remains an intriguing area.

Figure 5.4 includes point SAR values calculated from reported sodium, calcium, and magnesium concentrations. SAR values vary; however, they tend to be low near the outcrop and increase basinward, similar to the general decrease in water quality. This suggests that water produced from CBM operations in the basin interior would not be suitable for irrigation.

5.5.2 Surface Water Quality

Figure 5.5 shows TDS concentrations from surface-water samples collected from sites on the Yampa River and Little Snake River as well as tributaries within the Basin. Data were selected from the master dataset by season to characterize water quality during baseflow, which is the period when contributions from groundwater can best be assessed. The data also span a variety of sources over a period of time from 1974 to 2009.

Water quality on the main stems of the Yampa and Little Snake Rivers is quite good with TDS concentrations nearly all below 500 mg/L. Tributary water quality is not quite as good with many reported TDS concentrations falling between 500 and 3,000 mg/L. Several tributaries have reported concentrations between 3,000 and 10,000 mg/L making these streams brackish. Tributaries with elevated TDS concentrations drain areas largely underlain by the Lewis Shale and the shale-dominant Lance Formation (Figure 5.5). Relationships between water quality and outcrop patterns of the coal-bearing formations are not readily apparent with this limited set of data. SAR values fall below 10 for nearly all of the surface water samples (Figure 5.5) which is typical for fresh surface water.

5.5.3 Alluvial Groundwater Quality

Alluvial deposits are somewhat limited in extent within the Basin and do not constitute widely used aquifers. Consequently, water quality data for alluvial aquifers from the sources compiled for this analysis are sparse. Figure 5.6 shows the TDS concentrations from a few scattered locations along the Yampa River and a few of its tributaries. Water quality is generally poorer than the surface water for the same streams where corresponding data are available (Figure 5.5). Alluvial groundwater TDS concentrations are typically between 1,000 and 3,000 mg/L. This may reflect residence time of ground water in the alluvium as well as impacts from agricultural land-use typical of the alluvial lowlands along the river and stream valleys. SAR values are generally below 10.

5.6 Potential Impacts to Water Resources

Based on this assessment of hydrogeologic conditions in the Sand Wash Basin, both surface water and groundwater could potentially be impacted in certain areas by historic CBM production. Geologic and hydrologic complexity of the Basin precludes robust quantitative analysis given limited data. However, general conditions can be characterized.

5.6.1 Surface Water Resources.

Water extraction associated with CBM production from the Mesaverde Group could potentially impact surface water resources along the Mesaverde outcrop belt shown in Figure 5.7. Much of the topographically high areas likely provide recharge to groundwater as surface water infiltrates into the coal-bearing units. In topographically lower areas where the streams and rivers cross the outcrop, impacts could be greater. The most vulnerable reaches would be the lower three-mile reach of the Williams Fork along with the Yampa River from its confluence with the Williams Fork River downstream to Duffy where the river exits the outcrop belt.

Figure 5.7 shows potential areas of impact to water resources by water production from existing Mesaverde CBM production areas in the east side of the basin. Alignments illustrate the more direct pathways between the fields and areas where the production intervals intersect surface water features. Figures 5.8 and 5.9 are cross-sections along the pathways shown in Figure 5.7 illustrating the structural and stratigraphic relationships between the CBM fields and the potentially impacted surface water features. CBM production areas include Encore and Slater Dome Fields which have a record of sustained CBM production and the Breeze and Bull Mountain CBM pilot sites. The latter two areas provide a comparison of structural characteristics at other parts of the basin.

Encore field extracted water from the Middle Coal Group at a distance of approximately 8.8 miles north of the closest bend of the Yampa River where it directly crosses the outcrop belt. While this might appear as direct hydraulic connection between the field and outcrop, the pathway crosses several mapped surface faults. If the faults continue at depth as shown in Figure 5.8, and offset the coal-bearing intervals, they may form barriers to flow thereby minimizing potential impacts. The faults could also act as conduits to vertical flow that could connect with smaller streams such as Big Gulch and Lay Creek. On the other hand, the Yampa River also crosses the outcrop belt approximately 12 miles southeast of the field. The lower cross-section in Figure 5.8 shows the primary structural relationships along this alignment. This pathway parallels the prevailing structural grain and the predominant northwest fracture trend. These structural features may enhance hydraulic connection along this pathway.

CBM wells at Slater Dome extract water from the Lower Coal Group within 1000 feet of the Little Snake River. According to the 1:250,000-scale geologic map, the Little Snake River valley exposes undifferentiated Mesaverde Group in this area (Tweto, 1976). The cross-section in Figure 5.9 was constructed using structural maps prepared by CGS for the BLM and surface outcrop patterns from Tweto (1976). This cross-section shows that the Lower Williams Fork Formation outcrops in the valley floor potentially exposing the Middle Coal Group at the surface. The Lower Coal Group of the Iles Formation, which is the primary target for CBM production at the Slater Dome Field is approximately 1,500 feet beneath the Little Snake River. While this might provide some separation between the producing intervals at Slater Dome and the Little Snake River, fracturing along the Cherokee Arch fault system may allow vertical connection.

Two wells at the southwest and structurally deeper end of the Slater Dome Field produce from the Lower Williams Fork Formation, or Middle Coal Group (Figure 5.9). Connection from this producing interval with surface water resources is more direct through the coal-bearing interval.

Gas seeps beneath the Little Snake River just north of Slater Dome may indicate direct connection between a gas producing interval and the surface. Details of this gas seep, shown as the Robidoux Seep in Figure 5.7, have not been published and little may be documented about its source and history. COGCC has sampled this seep and there are reports that the seep's presence has been known since homesteaders settled the region in the nineteenth century. The cross-section in Figure 5.9 suggests that a likely source for the gas could be the Middle Coal Group, however, there could be multiple sources interconnected by fracturing. Further investigations may help resolve the source, or sources, of this seep.

Figure 5.9 also includes cross-sections between Breeze and Bull Mountain Fields and the surface. Although the alignments of the two cross-sections are the most direct to the surface, they do not directly intersect major surface water features. Instead, the alignments intersect highlands in watershed areas that probably source recharge to the coal-bearing intervals. The alignment from the Breeze Field intersects the north side of the Williams Fork Valley where several small tributaries to the Williams Fork River drain the Williams Fork Mountains. These tributaries include the intermittent courses of Jeffway, Deal and Peak Gulches. The alignment from Bull Mountain intersects the west side of the Elk Creek watershed. Perennial tributaries in this area include the upper reaches of Deep Creek.

The original scope for this assessment included a Glover-Balmer analysis of depletions to surface water as a result of historic and future CBM production. However, the hydrogeologic complexity of the basin combined with a change in the regulatory framework prompted the CGS to recommend that this approach be dropped from the assessment. Instead, a pumping well interference analysis was completed for two model scenarios: and Encore Field scenario and a rural domestic well scenario as described in Chapter 6.0.

5.6.2 Groundwater Resources.

Water extraction associated with CBM production from the Mesaverde Group could potentially impact current permitted groundwater wells in the rural areas developing around the outcrop belt south of Craig. The closest permitted water wells tapping the same Middle Coal Group strata as in the Encore Field are approximately nine to ten miles east, near Craig. These wells were originally drilled to test CBM potential in this area but were unsuccessful and they were converted to water wells.

Currently, there are only two permitted Mesaverde Group water wells in Colorado near Slater Dome. Comparing the completion intervals of the water wells with the completion intervals of the CBM wells in a robust manner requires structural details currently not available. However, neither well appears to be completed within the coal-bearing intervals tapped by CBM wells in the Slater Dome field. The closest well, Permit No. 213539A is just less than one mile from the nearest CBM well at Slater Dome. However, its 475-foot depth suggests that it taps the upper Williams Fork Formation, stratigraphically above the coal-bearing intervals. The other well, Permit No. 258947, is approximately three miles away and probably taps the upper part of the Iles Formation, well above the CBM producing interval near the formation base.

The following section addresses potential head drawdown impacts at water wells completed in the Mesaverde Group hydrostratigraphic units because of nearby CBM production.

By virtue of the overall hydrologic isolation of the Mesaverde Group hydrostratigraphic units within thick confining shale layers, impacts to water wells in shallower bedrock aquifers are unlikely.

6.0 WELL INTERFERENCE ANALYSIS

6.1 Purpose

Under the original scope for this assessment, a stream depletion analysis was to be conducted to evaluate the potential impacts of CBM water production on flow in streams traversing the Sand Wash Basin. The scope also called for delineating areas where groundwater could be classified as nontributary. Pursuant to C.R.S. 37-90-103(10.5) and 37-92-103(11), nontributary groundwater is defined as groundwater withdrawn by a well which will not, within 100 years, deplete the flow of a natural stream at an annual rate greater than one-tenth of one percent of the annual rate of withdrawal. As with the previous basin-focused CBM stream depletion studies, the analysis was to be performed using a Glover-Balmer analysis, because of its ease of application and utility in administrative processes. However, the scope also called for an evaluation of the suitability of the Glover analysis within the Basin, given its hydrodynamic conditions.

During the course of this study the CGS determined that application of the Glover analysis is not appropriate at this time. The data indicate the hydrogeologic and structural complexity of the basin make it difficult to use the Glover-Balmer analysis with confidence. In addition, changes in the regulatory framework within which CBM produced water is now administered contributed to this decision. This conclusion is based on the following factors:

1. CBM production to date has had very limited success in the basin due to overall high water production and lower than anticipated gas yields. Given this history of CBM production, depletions to water resources to date have probably been very small. Predicting future depletions would be difficult with the uncertainty in predicting future CBM production potential. While economic conditions and technologies may change to further CBM development in the basin, a prediction as intended in the original scope would be quite speculative.

2. The geology of the area where the greatest potential for CBM development exists is complex, more so than other basins in Colorado where the depletive effects from CBM production have been assessed. Of primary concern are geologically recent structural features which likely compartmentalize the coal-bearing intervals that are the primary CBM targets as well as local aquifer systems. Fault systems fragment these sedimentary formations and have the potential of being both barriers and conduits to groundwater flow, depending on orientation and amount of displacement. The analytical modeling considered in the original scope requires, as an assumption for its proper use, a relatively

homogenous and isotropic aquifer. Yet the local geology does not fit these assumptions well. Any future modeling must take into consideration this complexity and will require site-specific data that currently are not available.

3. Water extraction for CBM production is now considered a beneficial use. Should CBM development ever gain momentum in the east side of the basin, water produced by CBM wells will be assumed to be tributary in nature until proven otherwise and permitting of those wells will need to consider impacts to existing water rights. Where surface water is over-appropriated, wells will be required to pump according to approved augmentation plans to offset injurious depletions. Augmentation plans require detailed assessments of the depletions using adequate modeling. Any modeling will require site-specific data.

4. Recent rulemaking by the Division of Water Resources (DWR) for oil and gas production determined nontributary areas for productive formations on the west side of the Basin. The determinations were made at the request of producers. Requests were not made for the east side of the Basin where CBM potential exists suggesting that there currently is little interest in CBM development. Furthermore, the submittals for the west side of the basin used Glover analyses to support the nontributary determinations. These analyses provide rough delineations of tributary areas for the same formations addressed by our evaluation so our performing Glover analyses would be duplicative.

The Roundtable agreed to a change-in-scope that removed the Glover analysis from the assessment. The original scope of work also included evaluating potential drawdown impacts to existing water wells due to pumping groundwater to produce CBM. This second task remained a priority for the Yampa/White Basin Roundtable and remained in the scope. For this evaluation the CGS recommended an analytical model of groundwater pumping by CBM wells to forecast interference patterns with permitted water wells completed in the CBM production intervals. This analysis considered only historic groundwater extractions by CBM wells without future CBM forecasts. CBM production has had limited success and there is no basis for formulating trends in future production levels or geographic distribution patterns. The evaluation was performed only on the Mesaverde Group because it has had the only CBM production to date.

6.2 Analytical Drawdown Analysis

A two-dimensional analytical groundwater flow model was selected for evaluating potential drawdown impacts as a relatively simple and cost-effective approach to the problem. This approach provides general patterns of interference within the basin that might be expected from historic CBM water withdrawal practices. Because of the hydrogeologic complexity of the basin, this model exercise is limited to providing a qualitative assessment rather than a robust quantitative assessment.

6.2.1 Description of Method

The analysis utilized TWODAN® which is a commercially available two-dimensional computer model with advantages over numerical modeling in simple input, accuracy, speed and lack of a fixed grid. Computation is based on the analytical method described by Strack (1989). It has flexibility in scaling; multiple well input; and applying aquifer heterogeneities such as barriers that can mimic faults, and stratigraphic heterogeneities. Well discharge can be modeled under steady-state conditions that utilize boundary conditions, or it can be modeled under transient conditions wherein confined storage can be input and changes in patterns can be modeled over time.

6.2.2 Assumptions and Limitations

As with any groundwater flow model this analysis is premised on several simplifying assumptions regarding aquifer conditions and geometry. Few natural environments fully satisfy these model idealizations. However, through careful configuration and application of the model, the error associated with divergence from the ideal case can be minimized and useful information for planning and management can be obtained. Model idealizations inherent in this analysis and comments regarding the application of the method to the Sand Wash Basin are provided below:

- *The aquifer is homogeneous*. As described in Section 3, the aquifers in the Sand Wash Basin are heterogeneous with materials of various lithologic descriptions, and in some areas, these materials are disrupted by faults and fractures that may inhibit or enhance hydraulic conductivity. Heterogeneity can be modeled in a homogeneous media through identification of "effective average parameters" that, on the scale of the problem to be solved, will reasonably characterize the aggregate properties of aquifer (SSPA, 2006). Effective average parameters, ideally, are determined through examination of system-scale stress-response data, for example, wellfield production and fluid pressure data. Where such operational data are not available, best estimates must be developed from localized or site-specific test data. The latter method is applied in this study to derive best-estimate hydraulic parameters that will reasonably incorporate the heterogeneity known to exist in the basin.

- *The aquifer is isotropic*. Most solution methods assume radial or horizontal flow toward the pumping well which implies "idealized" isotropic aquifer conditions.

This assumption relates to the contrast in horizontal and vertical hydraulic conductivity within an aquifer. Analytical models assume that hydraulic conductivity is the same in three-dimensional space (isotropic). This assumption is critical to a problem where the lateral distances evaluated are close to the well bore and vertical flow dominates the solution. This assumption becomes less important as distances increase to be much greater than the thickness of the aquifer. At the scale of the Sand Wash Basin regional analysis, wells are typically located at distances many times the thickness of the aquifer and horizontal flow will dominate. Variations in hydraulic conductivity, or anisotropy, in a horizontal direction can be important at the scale of a regional analysis, however. Horizontal anisotropy may indeed occur in places in the Sand Wash Basin where the northwest trending fracture set prevail thus violating the assumption. Currently insufficient data preclude evaluating the impact of this variable. Any site specific analysis should address this important variable.

- *The aquifer is semi-infinite in extent.* Regional faulting may form hydraulic barriers. The effects of aquifer boundaries were tested for this project in areas where they are likely to be the greatest.
- *Flow within the aquifer is horizontal*. On a regional scale, wherein most wells are located at distances many times the thickness of the aquifer, the flow can be treated as horizontal without introducing significant error. The overall results of this study are not sensitive to this approximation.
- *Flow is dominated by one phase*. This method only considers one-phase flow. Where water extraction and pressure changes dominate the flow regime, this assumption is acceptable

The implementation of this analysis has been structured to conform to these idealizations to the extent possible, as described in the following sections.

6.2.3 Model Scenarios

Two scenarios herein assess interference patterns caused by CBM well groundwater extraction and by typical domestic wells completed in the Mesaverde Group. The first scenario models groundwater extraction at a CBM production field to estimate drawdown within the field along with areas surrounding the field where water wells might be completed. The second scenario models groundwater extraction by neighbor domestic wells in a rural setting to estimate interference. This scenario serves as a comparison to potential interference by distant CBM wells.

Encore CBM Field Scenario This CBM field, also known as the Lay Creek project, consists of 25 wells completed in the lower Williams Fork Formation, or Middle Coal Group of the Mesaverde Group approximately 12 miles west-northwest of Craig. Pioneer Resources operated the field from 2001 to 2009 and recently sold the field to Foundation Energy. Currently all wells are either shut-in or temporarily abandoned. Even though it is currently shut-in, the field has had a period of continuous CBM production. Water wells tap the same stratigraphic interval relatively close by. Average groundwater extraction rates range from 1 to 113 gpm based on average monthly rates from COGCC water production records.

This analysis evaluated drawdown effects under both transient flow and steady-state conditions. Transient flow calculations allow comparisons of impacts for different time periods. Steady-state flow calculations allow input of various boundary conditions such as fault barriers and surface water bodies.

Rural Water Well Scenario Section 20 of Township 6 North, Range 90 West is approximately four miles south of Craig and typifies rural development patterns in this region. DWR records indicate that nine permitted water wells tap the Upper Williams Fork Formation in this rural setting not supplied by centralized water. Although these wells do not tap the same stratigraphic interval as the Encore Field CBM wells, aquifer parameters in the tapped interval probably resemble those at the Encore Field.

Permitted water wells in Section 20 supply water to properties of five acres or more. Annual appropriations for domestic wells range from one to five acre-feet per year, depending on size of tract on which the well is located. Reported pump rates range between 0.2 and 15 gpm and distances between wells are over 250 feet. One of the wells in the section is an adjudicated well with an annual appropriation of 100 acre-feet. Water meters are not required for exempt wells including domestic water wells. No flow rate records are available. Model-runs under steady-state conditions used extraction rates based on reported yields for individual wells as well as rates calculated from annual appropriations. The former rate predicts exaggerated patterns under short-term peak well usage, while the latter predicts long-term patterns under constant use.

6.2.4 Aquifer Geometry

Two-dimensional analytical modeling requires simplification of complex stratigraphic and structural conditions and generalization of aquifer parameters. Aquifer geometries for both scenarios mimic actual conditions as close as possible using well records and known geologic conditions as follows:

Encore CBM Field Scenario Depths of CBM wells in the Encore Field range from 3,700 to 4,520 feet. Perforated intervals range in thickness from 25 to 797 feet and overlap almost the entire Middle Coal Group hydrostratigraphic unit. This unit includes a heterogeneous sequence of coal seams, fluvial sandstone layers, and layers of overbank siltstone and shale. Laterally continuous coal seams near the base of coal group are likely to have the greatest hydraulic conductivity within the sequence providing the most probable pathways for horizontal flow. Strata above this hydrostratigraphic unit contain fewer and less continuous coal seams and could be considered a semi-confining layer. The Trout Creek Sandstone underlies the coal group and could be a regional aquifer (Robson and Stewart, 1990), however, CBM-well perforated intervals normally do not extend into the sandstone. This analysis assumes that water enters the wells solely from the perforated intervals. As a simplification, the averaged perforated interval thickness of 390 feet was used as the aquifer thickness overlain by a 3,500 foot low permeability semi-confining layer.

This model simulation treats the base of the coal group as impermeable. As will be explained later, the assumption that water does not enter the system from below may not be valid. However, treating the base as impermeable allows this model to estimate greater impacts to surrounding water wells providing a conservative estimate. Contribution of water from the deeper Trout Creek Sandstone aquifer, which implies vertical hydraulic communication, would potentially dampen impacts to nearby water wells.

The analytical model only allows simulations of flat-lying aquifers, yet the Encore Field is located on a gentle northwest plunging anticline. Modeling as a flat-lying aquifer was considered acceptable for this model since it is assumed that flow through the aquifer is horizontal and is not impacted by gentle folding of the layers. As a simplification necessitated by this analytical model, the average elevation of the base of the perforated intervals was used as the base of the aquifer. Head, or water level, above the simulated aquifer was based on the water level elevation map in Figure 5.3. The CGS was unable to obtain data from Pioneer Resources to provide more site-specific conditions.

Boundary conditions included fault barriers and a constant head boundary to the south where the Williams Fork Formation outcrops along the Yampa River and in the Williams Fork Mountains. Fault barriers approximate subsurface faults in the Cedar Mountain fault system mapped by Tyler and Tremain (1994).

Vertical recharge to the aquifer was set at zero. Regional flow was estimated to produce a potentiometric surface similar to that reported by Scott and Kaiser (1994) with a gentle gradient of 0.04 ft per ft to the southwest.

Rural Water Well Scenario Water wells in section 20 have depths ranging between 275 and 777 feet and open intervals between 10 and 40 feet. This scenario used the same assumptions and methodology to simulate a flat-lying aquifer as applied to the Encore Field Scenario. However, the average open interval is only 26 feet and the thickness of the overlying layer of lower permeability was 340 feet.

6.2.5 Aquifer Parameters

In addition to the aquifer geometries described above, the two-dimensional analytical model input of aquifer parameters hydraulic conductivity and storativity. Limited published aquifer parameter data exist for the Sand Wash Basin. Parameters summarized below combine published data for the Sand Wash Basin with data from other basins with similar characteristics.

Hydraulic Conductivity Table 6.1 lists hydraulic conductivity data available in the literature for the Mesaverde Group and the Mesaverde coals. As shown, measured or estimated coalbed fresh water hydraulic conductivities range between 0.3 and 5.8 ft/day, which are higher than observed in other basins (SSPA, 2006 and 2008b). Model simulations were run with an average and with a lower-end value of this range to assess sensitivity.

Storage Coefficient Storage coefficient (S) is a measure of volume released from a confined aquifer per unit decline in head. It is used in the transient flow model simulations. Robson

(1990) reports an S value of $1x10^{-3}$ from a pump test near the outcrop (Table 6.1). Values between $1x10^{-2}$ and $1x10^{-4}$ are reported for the Laramie-Fox Hills aquifer of the Denver Basin (Robson, 1987) which shares stratigraphic and structural similarities with the Mesaverde coal groups. In the absence of other data, $1x10^{-3}$ was used as a low- to mid-range value for S.

6.3 Results of Analytical Drawdown Analysis

6.3.1 Encore Field CBM Well Scenario

The first model runs described below assess potential water-level impacts at different time intervals after initiation of pumping: one-year for a short-term impact, eight-years for the time that the field has been in production, and thirty-years for a long-term simulation. This analysis assumes that a decrease in head produces a corresponding drop in water level in a well completed at the specified location distant from the pumping well. Pump rates and time steps for each well are based on COGCC records.

Table 6.2 lists head drawdown estimates for the Encore pumping well with the maximum yield of 113 gpm for the three different time steps. Listed are estimates for the pumping well itself, a hypothetical well one mile away from the pumping well, and the closest existing well at approximately nine miles. Model runs used the lower hydraulic conductivity value of 0.5 ft/day to maximize the drawdown away from the field. As indicated, drawdown at the pumping well increases over time from approximately 100 feet to 127 feet. One mile away, drawdown increases over time from approximately 12 feet to 33 feet. At nearest existing well, drawdown is minimal until the 30-year time step where it approaches five feet.

Table 6.3 expands this analysis to include drawdown estimates with all wells pumping over the three time steps as well as under long term steady state conditions. Table 6.3 also gives the range of drawdown for low to average values of Mesaverde Group hydraulic conductivity. The steady-state run allowed boundary conditions of the outcrop belt and cross-cutting faults. Drawdown estimates are also included for the center of the well field and for a well separated from the Encore Field by fault barriers. Faults break the area into several blocks and the Encore Field sits in the middle block. This analysis compares impacts within the same block as the Encore Field with areas outside of the block.

As indicated, drawdown increases dramatically due to combined interference of all wells pumping simultaneously. Long-term drawdown at the 113 gpm well could exceed 510 feet while drawdown at the nearest existing well may reach 45 feet. In the middle of the field drawdown could reach 360 feet while drawdown one mile away from the field could reach 260 feet.

A secondary effect of regional drawdown of this magnitude is a potential for increase in natural methane seepage in existing water wells. Water wells in coal-bearing regions like the Sand Wash Basin can have natural methane in groundwater produced from wells, particularly when those wells are open to coal-bearing intervals. Regional pressure-drops in a coal-bearing aquifer, manifested as water-level declines in wells, can enhance this natural methane seepage. It does not matter what causes those regional water level declines, whether it is water extraction for CBM production, or groundwater extraction from close-spaced domestic wells.

Figures 6.1 and 6.2 illustrate the drawdown results from the model runs under long-term steady-state conditions with and without fault barriers. Comparing these two figures illustrates how faults can affect drawdown impacts away from the field. In Figure 6.1, the pattern around the pumping field without the presence of faults forms a nearly circular depression with a uniform surface. Figure 6.2 illustrates that the six fault barriers fragment the surface and deflect the contours in a stair-step pattern. The existing well is within the same fault-bound block as the Encore field and the drawdown estimate increases to approximately 44 feet (Table 6.3). For comparison, drawdown at a well the same distance from the field outside the fault block may only experience approximately two feet of drawdown.

6.3.2 Rural Water Well Scenario

Figure 6.3 illustrates the estimated drawdown pattern within Section 20 with all wells pumping at reported yields under steady-state conditions. As shown, well interference in the open area between the wells results in drawdown between 50 and 60 feet. Figure 6.4 illustrates the estimated drawdown pattern within Section 20 with all wells pumping at rates calculated from annual appropriations. Using these lower pumping rates, drawdown in the same area from well interference drops to approximately 10 to 20 feet. Reported well yields normally exceed the rate calculated from annual appropriations and often reflect the permitted maximum allowed

As indicated, drawdown increases dramatically due to combined interference of all wells pumping simultaneously. Long-term drawdown at the 113 gpm well could exceed 510 feet while drawdown at the nearest existing well may reach 45 feet. In the middle of the field drawdown could reach 360 feet while drawdown one mile away from the field could reach 260 feet.

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6.3.2 Rural Water Well Scenario

Figure 6.3 illustrates the estimated drawdown pattern within Section 20 with all wells pumping at reported yields under steady-state conditions. As shown, well interference in the open area between the wells results in drawdown between 50 and 60 feet. Figure 6.4 illustrates the estimated drawdown pattern within Section 20 with all wells pumping at rates calculated from annual appropriations. Using these lower pumping rates, drawdown in the same area from well interference drops to approximately 10 to 20 feet. Reported well yields normally exceed the rate calculated from annual appropriations and often reflect the permitted maximum allowed rate. For example a domestic well may be permitted for a maximum rate of 15 gpm, and has a reported yield of 13 gpm, yet an annual appropriation of 2.5 acre feet per year translates to a sustained rate of 1.5 gpm. The permitted maximum rate allows peak well operation while the annual appropriation limits sustained groundwater withdrawal. Drawdown estimates using reported well yields shown in Figure 6.3 predict exaggerated impacts with all wells operating at peak flows simultaneously. Drawdown patterns shown in Figure 6.4 may better predict impacts under sustained pumping.

6.4 Discussion of the Analytical Drawdown Analyses

These analytical analyses provide a qualitative perspective of potential impacts to regional water levels by groundwater extraction under two scenarios. Each scenario represents historic Mesaverde Group groundwater practices in the Sand Wash Basin. The first scenario simulates extraction by a CBM field where water production is high and well spacing is close. The second scenario simulates extraction by predominantly domestic water wells in a settled rural setting. Under both scenarios impacts will be felt by nearby wells and regional drawdown will occur in response to overlapping areas of influence. In the case of the CBM field where water production rates are high, the effects may extend over a large area. Although the values reported at first may seem high, they need to be kept in perspective. Several factors must be considered when viewing these results:

1) The modeling is based on highly generalized aquifer conditions using average hydraulic parameters from a very limited database. Because of this, the assessment should be considered qualitative.

2) Vertical recharge was not factored into the calculations since data are too limited to estimate reasonable recharge values. Recharge would reduce drawdown impacts.

3) Similarly, bounding strata above and below probably contribute water to the system, thereby reducing drawdown impacts. For example, the Trout Creek Sandstone is considered a regional aquifer and is probably hydraulically connected to the Middle Coal Group by faults and fracture systems. Contribution from the Trout Creek Sandstone is likely to be one of the reasons water production has been so high at the Encore Field. If this is actually the case, it would reduce the impacts seen away from the field.

4) Drawdown does not constitute injury in Colorado water law. Water law and the body of regulations built around it do not protect water levels in wells. Furthermore, deep wells such as those closest to CBM production in the Basin, are up to 3,000 feet deep with water levels near the surface. Water column heights in the wells approach 3,000 feet and a head decrease of 44 feet is just over 1% of the workable head in the well.

7.0 SAND WASH BASIN CBM WATER PRODUCTION AND REGULATORY IMPLICATIONS

Depletions to surface-water streams from CBM groundwater production have potential implications to water rights holders, the State of Colorado, and to downstream water users. For these reasons it is necessary to evaluate the current regulatory framework associated with the production of CBM water, the potential for beneficial uses of such water, and the interstate ramifications of the consumptive uses of such water.

7.1 Regulatory Framework and Potential Beneficial Uses of CBM Produced Water

7.1.1 Groundwater Extraction Regulations

As of this year, the regulatory framework under which groundwater is extracted by CBM wells changed. This change stems from the April 20, 2009 Colorado Supreme Court ruling in the Vance v. Wolfe case, which stated that the withdrawal of groundwater through the CBM extraction process is a beneficial use. Now, the State Engineer has the administrative responsibility of requiring well permits for **all CBM wells** regardless of whether that water is tributary or nontributary. Permits from DWR are only required for non-CBM wells when the produced water is applied to beneficial use. The changes are summarized in a March 24, 2010 Memorandum by Mr. Kevin Rein, Assistant State Engineer titled **"Revised Memorandum: Submittals to the Division of Water Resources for approval of substitute water supply plans and well permits for oil and gas wells that produce ground water while producing oil and gas."**

Classification of groundwater as tributary or nontributary, as defined by **Section 37-90-103(10.5),** at a specific location determines the necessity of replacing depletions to surface water though an augmentation plan or substitute water supply plan. Replacement of depletions through a court-approved augmentation plan or a temporary substitute water supply plan is required of any well withdrawing tributary groundwater (for beneficial use) affecting an over-appropriated stream.

In Colorado, all groundwater is presumed to be tributary unless demonstrated to be nontributary. DWR has promulgated Rules and Regulations titled **"Produced Nontributary**

Ground Water Rules" 2 CCR 402-17, for the determination of the nontributary nature of groundwater produced though wells in conjunction with mining of minerals including oil and gas. These rules define the process for obtaining a nontributary determination of groundwater for a specific site. They also specify requirements for documentation to accompany the petition for a nontributary determination in the form of a professional report. The rules define engineering and scientific methodologies and standards for submittals. Methodologies used to demonstrate a nontributary nature of a specific area include development of a conceptual model of the geologic and hydrogeologic characteristics, along with mathematical modeling of depletion volumes and timing in accordance with **Section 37-90-103(10.5)**. There is also a provision for using alternate methodologies through robust characterization utilizing site-specific geological, hydrogeochemical, petrophysical, and geotechnical data, as well as other professional reports.

Most significantly, the State Engineer adopted determinations of nontributary ground water for several oil and gas-producing formations in the state in **Rule 17.7D**. The determinations in this rule apply to groundwater in specific formations beneath specific portions of the Piceance, Northern San Juan, Paradox, Denver-Julesburg, and Sand Wash Basins as well as the Rangely, Wilson Creek, Hiawatha, and West Hiawatha fields. With this determination, replacement of depletions to surface water through court decreed augmentation plans or temporary substitute water supply plans will not be required.

Rule 17.7D (5a and b) and (6a and b), as adopted by the State Engineer, includes a portion of the western Sand Wash Basin shown in Figure 7.1. Although the nontributary determination includes the Fort Union Formation and Mesaverde Group, the area does not extend into the area where CBM production has been attempted on the east side of the basin. As such, all groundwater in areas where CBM production has been attempted or is currently active is presumed to be tributary. However, much of the Yampa River Basin is currently not over-appropriated.

The Division of Water Resources' administration, largely shaped by the Vance v. Wolfe decision and the newly adopted rules, affects CBM operators in several ways:

1. All CBM wells require permits from DWR for withdrawing groundwater.

2. In areas of the Basin where reaches of streams are not over-appropriated, the permit process for CBM wells is straight forward, since replacing depletions through an augmentation plan or substitute water supply plan is not required. Essentially, there is no need to make a nontributary determination in these areas.

3. CBM wells that impact over-appropriated streams (or reaches of streams) in the Basin will require replacing depletions through an augmentation plan or substitute water supply plan. In these areas a nontributary determination may be advantageous to avoid the replacement requirement.

4. Developing augmentation plans and obtaining a nontributary determination for CBM wells impacting over-appropriated streams involves detailed geologic and hydrogeologic characterization and probable robust mathematical modeling.

5. Operators of non-CBM wells in areas of the basin outside of that area outlined in Rule 17.7D will also be required to obtain permits from DWR only if the produced water is put to beneficial use as defined by DWR. Replacement of depletions is required where over-appropriated streams (or reaches of streams) are impacted, unless a nontributary determination is obtained.

6.

7.1.2 Produced Water Disposal

CBM well water production in the Sand Wash Basin has been relatively high as compared to other basins, with the exception of the Raton Basin. Water quality tends to be fair to marginal and classified as fresh to brackish with reported TDS values falling between 5,000 mg/L and 1,000 mg/L. These concentrations exceed the secondary water quality standard of 500 mg/L but are potentially usable for domestic and agricultural purposes. High SAR values, however, make much of this water unsuitable for irrigation. Because better quality water is available throughout most of the watershed, there is no demand for the CBM produced water that would make treatment or transportation economically attractive.

Historically, most CBM produced water has been disposed in evaporation pits, into Class II Underground Injection Control (UIC) wells, or hauled away by commercial disposal companies. Regulation of this disposal has historically fallen under the jurisdiction of COGCC. With treatment this water could be discharged to surface water, however, this has not happened in the Basin yet. When CBM produced water is discharged to the waters of the state, a permit must be obtained from the Colorado Department of Public Health and Environment, Water Quality Control Division (CDPHE-WQCD).

7.2 Interstate Stream Compact Ramifications

Interstate stream compacts that relate to surface waters from the Sand Wash Basin in Colorado (where the border of the basin is defined by the Mesaverde Formation outcrop) include the Colorado River Compact (C.R.S. 37-61-101) and the Upper Colorado River Compact (C.R.S. 37-62-101).

Article III(a) of the Colorado River Compact apportions 7.5 million ac-ft/yr of water both to the states of the "Upper Basin," of which Colorado is one, and to the states of the "Lower Basin." In accordance with the compact, surface waters that flow from the Sand Wash Basin in streams tributary to the Colorado River constitute a portion of the 7.5 million ac-ft/yr of water that must be delivered to the lower basin at Lee Ferry in northern Arizona. The Upper Colorado River Compact further apportions the waters of the upper basin of the Colorado River among the states of Colorado, New Mexico, Utah, and Wyoming. In accordance with Article III(a)(2) of the compact, Colorado is apportioned 51.75 percent of the water that is available for consumptive use from the Colorado River and its tributaries in the upper basin. Whether Colorado over-appropriates water under this compact depends on total consumptive use from all the streams in the upper basin in Colorado, not on consumptive use from any single stream. The Colorado Department of Natural Resources must evaluate whether current regulation of the depletions resulting from CBM produced water is appropriate in the context of the Upper Colorado River Compact.

8.0 SUMMARY OF CONCLUSIONS

For this study, information was reviewed to provide background on the hydrogeologic setting related to CBM production in the Sand Wash Basin. Literature and existing data were reviewed to evaluate potential impacts to surface and groundwater resources.

Primary study findings include:

- *Gas and water production*: CBM potential exists in the Upper Cretaceous Mesaverde Group as well as the Paleocene Fort Union Formation on the east side of the Basin. Approximately 1.7 Bcf of CBM gas and 4,000 acre-feet of water have been produced from the Mesaverde Group and no CBM has been produced from the Fort Union Formation. Currently, only Slater Dome Field in the northeast part of the Basin is producing CBM; all other fields are either shut in or abandoned. Historically, annual gas production gradually rose from less than 0.1 Bcf in 2002 to just over 0.45 Bcf in 2008. Production then declined to just over 0.25 in 2009 after Pioneer Resources shut-in wells and sold their Encore Field. Water production similarly peaked in 2008 at just over 1,000 ac-ft/yr and then declined sharply to just over 200 ac-ft/yr after pumping at Encore ceased. The sharp decline in water production following cessation of production at the Encore Field reflects the high volume of water production associated with CBM development at that field. High rates of water production and water management challenges have been cited as impediments to CBM development in the Basin. Given high rates of water production, future CBM production may be limited to existing fields until economic or technological conditions change to make it more viable.

- *Hydrogeologic setting*: CBM is produced primarily from coal seams in the lower Williams Fork Formation and Iles Formation of the late Cretaceous Mesaverde Group. Coal seams are interbedded with laterally discontinuous fine-grained sandstone and shale layers and the sequences are collectively known as the Middle and Lower Coal group, respectively. Layers of marine shale lie above and below each formation on the east side of the Basin forming distinct hydrostratigraphic units. The hydrostratigraphic units outcrop along a broad arcuate belt across the southeast end of the Basin and are traversed by the Yampa River and Williams Fork River along with many lesser tributaries. Recharge enters the system in elevated areas that receive abundant precipitation and groundwater discharges to streams at lower elevations.

  Groundwater flows through coal cleats, fractures, and sandstone layers in the hydrostratigraphic units. In addition, fracturing and faulting traverse the area along a prevailing northwesterly structural grain. Faults may act as barriers to groundwater flow from areas of recharge in the highlands east of the CBM production areas, while fracture systems may enhance flow to the northwest. The Cedar Mountain fault zone is a major structural feature of the Basin and groundwater data appear to confirm these hydrogeologic hypotheses. Fracturing may also hydraulically connect the coal-bearing intervals with underlying regional sandstone aquifers. Hydraulic connection with deeper aquifers probably adds water to the Mesaverde Group coal zones, increasing the water production necessary to sufficiently reduce pressures for methane desorption from the coals.

- *Suitability of the Glover method:* Considering geologic and hydrogeologic complexities of the eastern part of the Sand Wash Basin, the Glover analysis is not an ideal tool for evaluating stream depletion effects from CBM production. Numerical modeling would be preferable, but would require a more robust data set for the Basin than is currently available.

- *Potential impact to water resources:* Impact to surface water resources from historic CBM production is probable, although the magnitude is probably small because of to low volumes extracted to date. Direct hydraulic connection of the coal-bearing intervals likely exists to surface water at the outcrop areas. Faulting and fracturing may play a strong role in modifying hydraulic connection to the surface. Faults may reduce or enhance depletions depending on age, permeability, and orientation. Fractures may enhance depletions.

- *Analytical drawdown analysis*: An analytical drawdown analysis was performed to estimate water level impacts at wells tapping the same hydrostratigraphic units as CBM wells. Model runs used generalized aquifer parameters and averaged CBM water production rates for the Encore Field. This model also uses basic assumptions about aquifer characteristics and is a less than ideal tool in this geologic setting. However, it is presented to provide some measure of potential impacts to water wells from CBM development. Drawdown estimates within the field reach 360 feet while drawdown estimates one mile away from the field approach 260 feet after long-term pumping (30 years) in a steady state model run. Drawdown at the nearest well completed in the same hydrostratigraphic unit approximately nine miles away approached 45 feet. Fault barriers may impact effects by enhancing drawdown within the same block as the pumping field while reducing drawdown across faults.

- *Regulatory framework and possibilities for beneficial use of CBM produced water:* Water extraction for CBM production is now considered a beneficial use and permits from DWR are required for all CBM wells. Where water extraction by CBM wells impacts over-appropriated streams, depletions must be offset through augmentation plans or temporary substitute water supply plans. Water produced by CBM extraction in the Sand Wash Basin is generally of fair quality and could be used for a number of purposes. However, high sodium content in some areas renders it unsuitable for irrigation because it can severely damage soil structure.

8.0 SUMMARY OF CONCLUSIONS

For this study, information was reviewed to provide background on the hydrogeologic setting related to CBM production in the Sand Wash Basin. Literature and existing data were reviewed to evaluate potential impacts to surface and groundwater resources.

Primary study findings include:

- ***Gas and water production***: CBM potential exists in the Upper Cretaceous Mesaverde Group as well as the Paleocene Fort Union Formation on the east side of the Basin. Approximately 1.7 Bcf of CBM gas and 4,000 acre-feet of water have been produced from the Mesaverde Group and no CBM has been produced from the Fort Union Formation. Currently, only Slater Dome Field in the northeast part of the Basin is producing CBM; all other fields are either shut in or abandoned. Historically, annual gas production gradually rose from less than 0.1 Bcf in 2002 to just over 0.45 Bcf in 2008. Production then declined to just over 0.25 in 2009 after Pioneer Resources shut-in wells and sold their Encore Field. Water production similarly peaked in 2008 at just over 1,000 ac-ft/yr and then declined sharply to just over 200 ac-ft/yr after pumping at Encore ceased. The sharp decline in water production following cessation of production at the Encore Field reflects the high volume of water production associated with CBM development at that field. High rates of water production and water management challenges have been cited as impediments to CBM development in the Basin. Given high rates of water production, future CBM production may be limited to existing fields until economic or technological conditions change to make it more viable.

- ***Hydrogeologic setting***: CBM is produced primarily from coal seams in the lower Williams Fork Formation and Iles Formation of the late Cretaceous Mesaverde Group. Coal seams are interbedded with laterally discontinuous fine-grained sandstone and shale layers and the sequences are collectively known as the Middle and Lower Coal group, respectively. Layers of marine shale lie above and below each formation on the east side of the Basin forming distinct hydrostratigraphic units. The hydrostratigraphic units outcrop along a broad arcuate belt across the southeast end of the Basin and are traversed by the Yampa River and Williams Fork River along with many lesser tributaries. Recharge enters the system in elevated areas that receive abundant precipitation and groundwater discharges to streams at lower elevations.

  Groundwater flows through coal cleats, fractures, and sandstone layers in the hydrostratigraphic units. In addition, fracturing and faulting traverse the area along a prevailing northwesterly structural grain. Faults may act as barriers to groundwater flow from areas of recharge in the highlands east of the CBM production areas, while fracture systems may enhance flow to the northwest. The Cedar Mountain fault zone is a major structural feature of the Basin and groundwater data appear to confirm these hydrogeologic hypotheses. Fracturing may also hydraulically connect the coal-bearing intervals with underlying regional sandstone aquifers. Hydraulic connection with deeper aquifers probably adds water to the Mesaverde Group coal zones, increasing the water production necessary to sufficiently reduce pressures for methane desorption from the coals.

- ***Suitability of the Glover method:*** Considering geologic and hydrogeologic complexities of the eastern part of the Sand Wash Basin, the Glover analysis is not an ideal tool for evaluating stream depletion effects from CBM production. Numerical modeling would be preferable, but would require a more robust data set for the Basin than is currently available.

- ***Potential impact to water resources:*** Impact to surface water resources from historic CBM production is probable, although the magnitude is probably small because of to low volumes extracted to date. Direct hydraulic connection of the coal-bearing intervals likely exists to surface water at the outcrop areas. Faulting and fracturing may play a strong role in modifying hydraulic connection to the surface. Faults may reduce or enhance depletions depending on age, permeability, and orientation. Fractures may enhance depletions.

- ***Analytical drawdown analysis***: An analytical drawdown analysis was performed to estimate water level impacts at wells tapping the same hydrostratigraphic units as CBM wells. Model runs used generalized aquifer parameters and averaged CBM water production rates for the Encore Field. This model also uses basic assumptions about aquifer characteristics and is a less than ideal tool in this geologic setting. However, it is presented to provide some measure of potential impacts to water wells from CBM development. Drawdown estimates within the field reach 360 feet while drawdown estimates one mile away from the field approach 260 feet after long-term pumping (30 years) in a steady state model run. Drawdown at the nearest well completed in the same hydrostratigraphic unit approximately nine miles away approached 45 feet. Fault barriers may impact effects by enhancing drawdown within the same block as the pumping field while reducing drawdown across faults.

- ***Regulatory framework and possibilities for beneficial use of CBM produced water:*** Water extraction for CBM production is now considered a beneficial use and permits from DWR are required for all CBM wells. Where water extraction by CBM wells impacts over-appropriated streams, depletions must be offset through augmentation plans or temporary substitute water supply plans. Water produced by CBM extraction in the Sand Wash Basin is generally of fair quality and could be used for a number of purposes. However, high sodium content in some areas renders it unsuitable for irrigation because it can severely damage soil structure.

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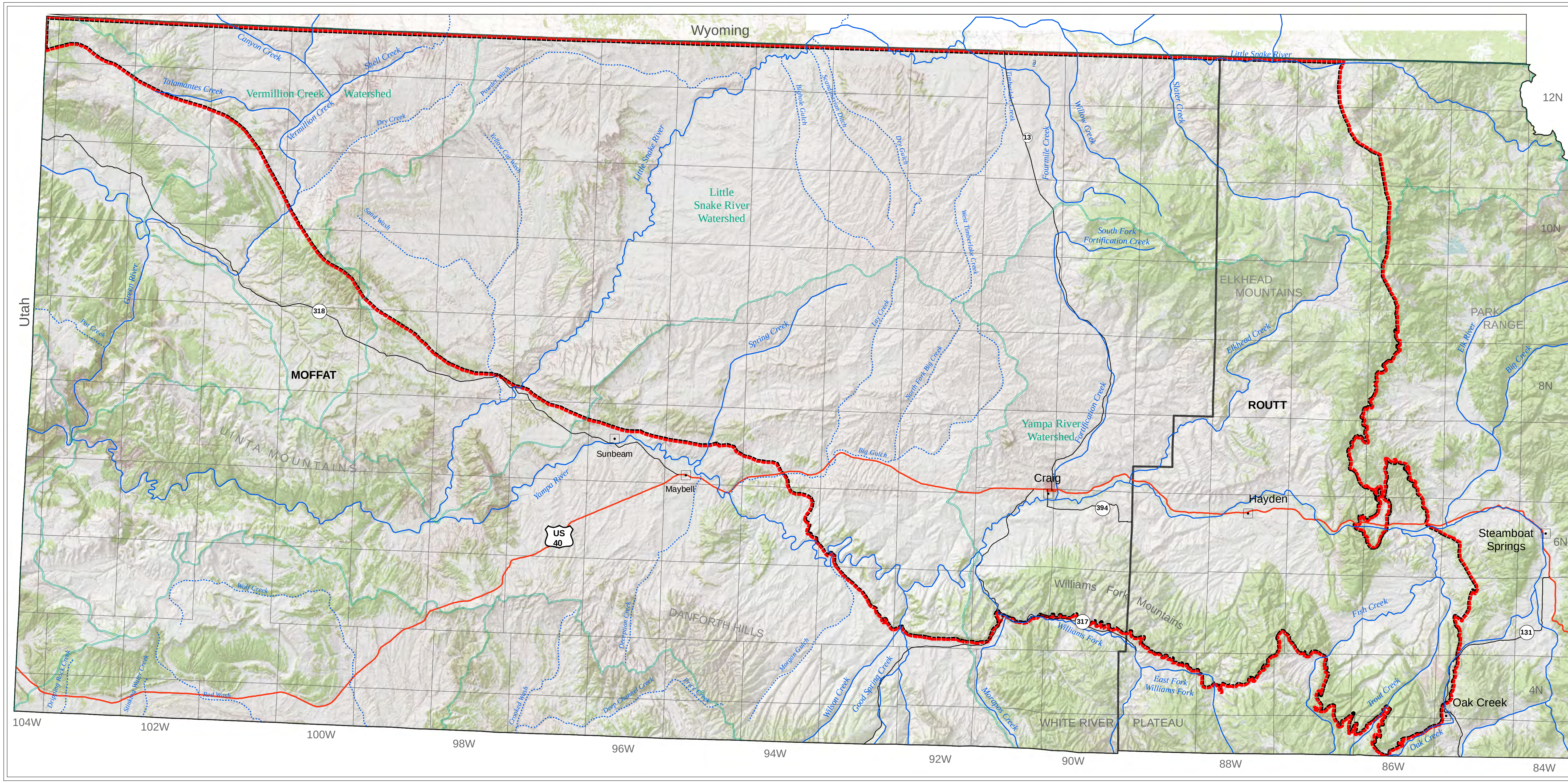


Legend

River Class

Perenial

Intermitant

Watershed boundary

Sand Wash Basin outline, base of Mesaverde Group

0 2.5 5 7.5 10 Miles

Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 1.1 Physiographic Map of the Sand Wash Basin Showing its Major Drainage Systems

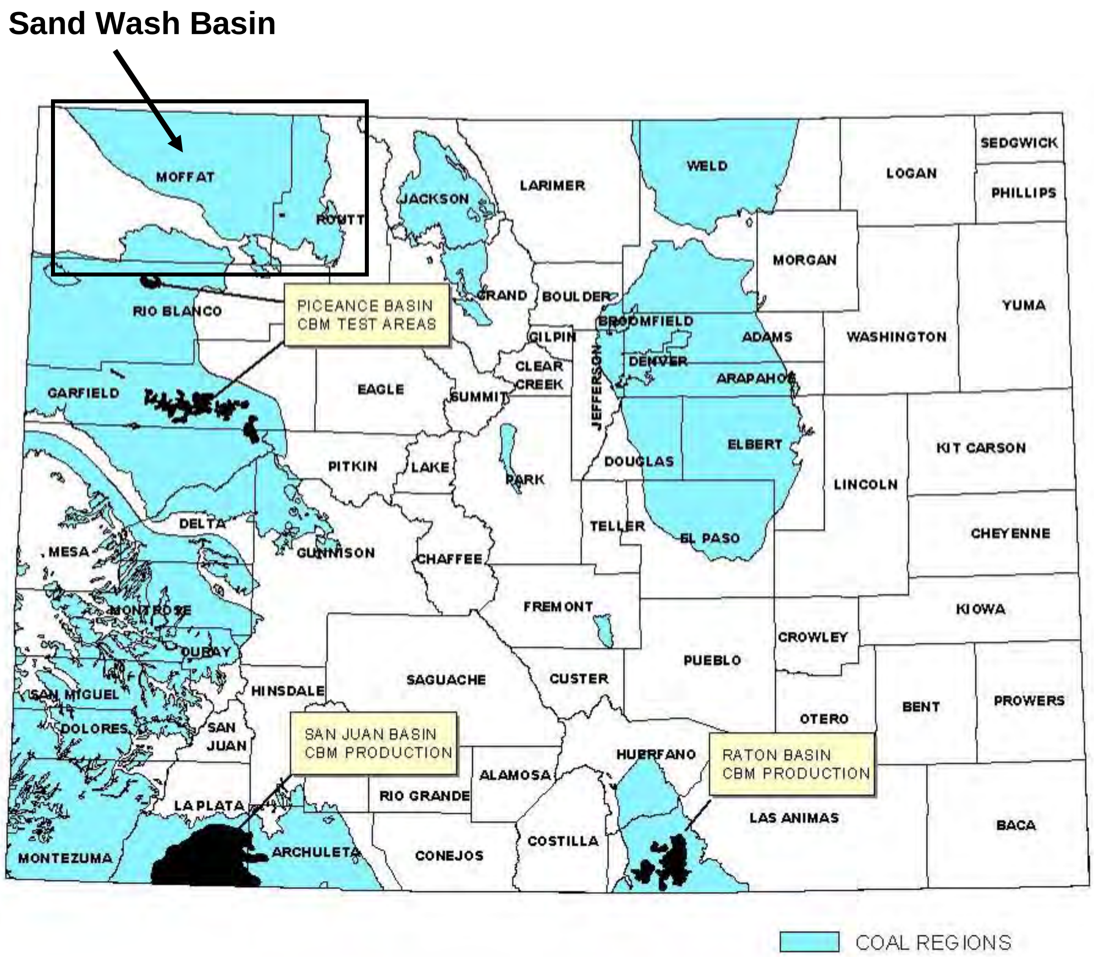


Figure 1.2 CBM Regions of Colorado. Sand Wash Basin, in the northwest corner of the state, is one of several coal regions in the State. Primary CBM production in the state is from the San Juan and Raton Basins along the southern border.

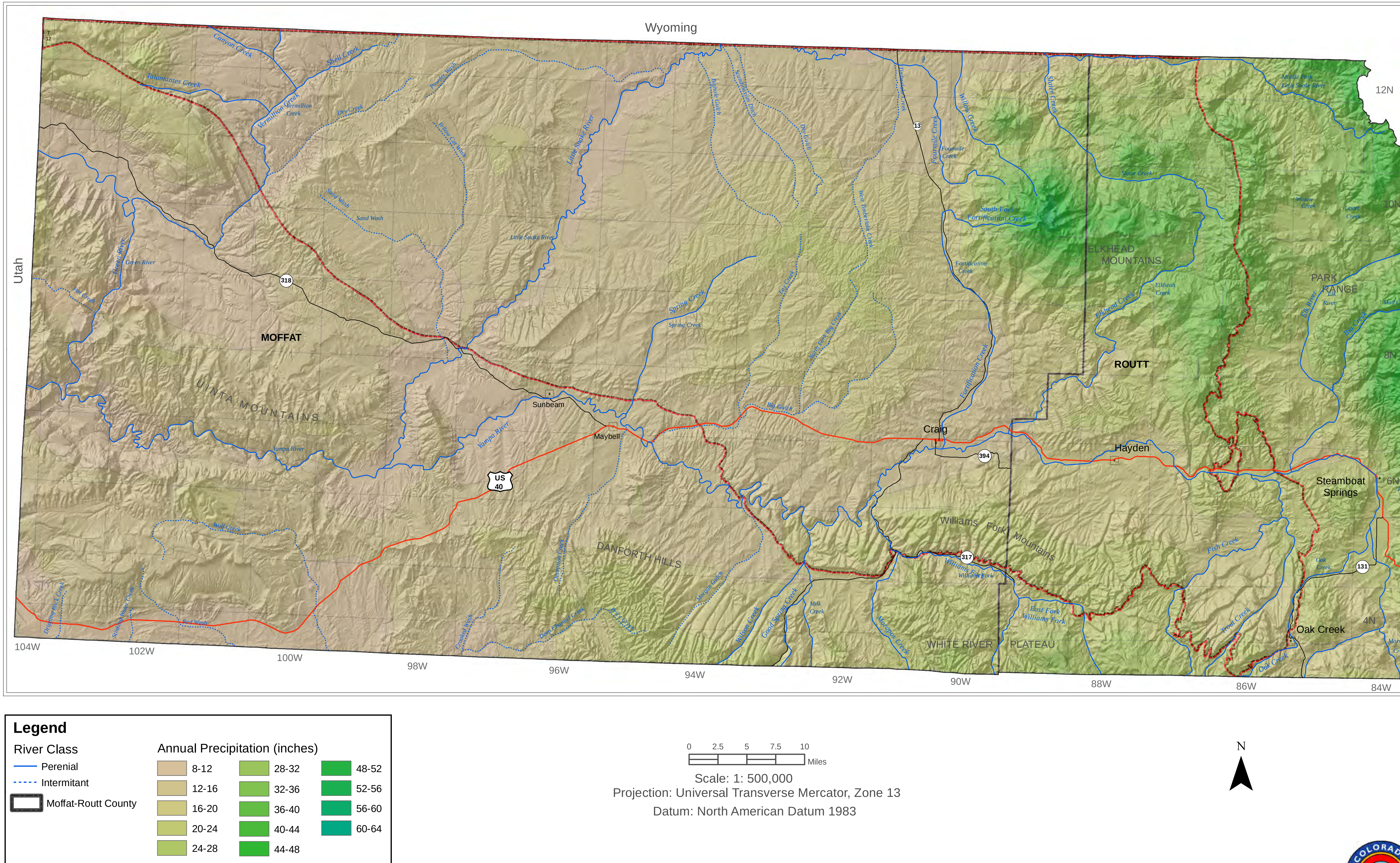
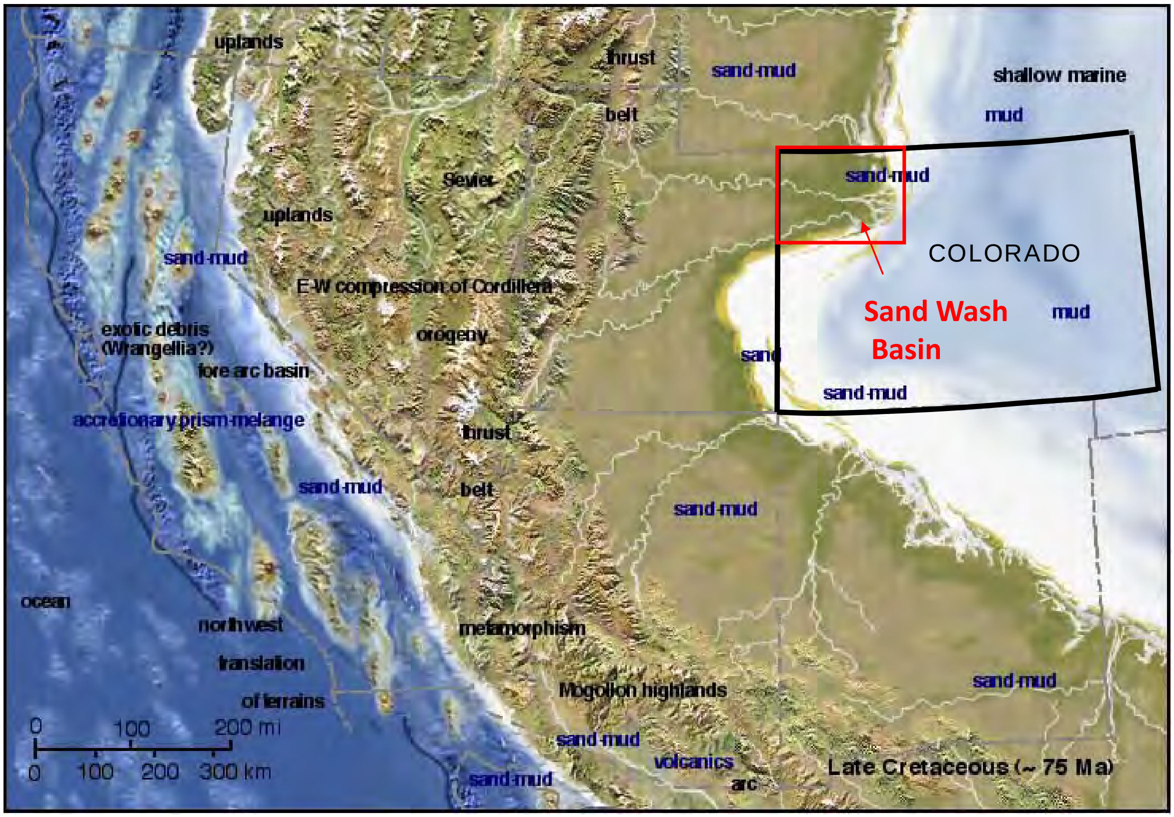


Figure 3.1 Average Annual Precipitation In the Sand Wash Basin Region



Ron Blakey, Northern Arizona University (http://jan.ucc.nau.edu/~rcb7/)

Figure 3.2 Paleogeography of the Late Cretaceous Western Interior Seaway. During the Late Cretaceous the Western Interior Seaway extended across the interior of the North American Continent. The coal-bearing Mesaverde Group was deposited along a broad coastal plain between the seaway and the tectonically active highlands further to the west. Tectonism later moved eastward to form a series of uplifts and basins, including Sand Wash Basin, where the seaway once was.

PERIOD	FORMATION			THICKNESS (feet)	LITHOLOGY	ENERGY RES.
Neogene	Browns Park Fm.			0-2,000	Sandstone and siltstone	
	Bishop Conglomerate			0-300	Pebbles and boulders of quartzite and schist	
Paleogene	Bridger Fm.			800 +	Claystone and mudstone	
	Green River Fm.			1,200 ±	Claystone, shale, oil shale, sandstone, and marlstone	Oil shale
	Wasatch Fm.			6,000 ±	Claystone, shale, sandstone, and minor coal	Oil Gas Coal
	Fort Union Fm.			0-2,500 ?	Grey sandstone, gray shale, and coal	Oil Gas Coal
Cretaceous	Lance Fm.			0-2,500	White sandstone, gray shale, and coal	Oil Gas Coal
	Fox Hills Sandstone			0-100	Gray sandstone and sandy shale	
	Lewis Shale			1,500-2,100	Gray marine shale, minor gray sandstone	Oil Gas
	Mesaverde Grp	Williams Fork Fm.		1,100-2,000	Sandstone, gray shale, and coal	Oil Gas Coal
		Iles Fm.		1,300-1,550	Sandstone, gray shale, and coal	Oil Gas Coal
	Mancos Shale			5,000 ±	Gray marine shale, minor gray sandstone	Oil Gas
	Niobrara Limestone			900 ±	Gray marine calcareous shale	Oil Gas
	Frontier Sandstone			600 ±	Sandstone (calcareous)	Oil Gas
	Mowry Shale			100-200	Gray to black marine shale	Oil
	Dakota Group			100-250	Sandstone, shale, and shaley sandstone	Oil
Jurassic	Morrison Fm.			300-800	Claystone, siltstone, sandstone, shale, and limestone	Oil Gas
	Curtis Fm.			0-100	Sandstone (glauconitic., oolitic), sh. (calc.), limestone (oolitic)	Oil
	Entrada Sandstone			75-175	Pink and gray sandstone (siliceous)	Gas
	Carmel Fm.			0-600	Siltstone, sandstone, shale (calcareous)	
Triassic	Navajo Fm.			0-800	Sandstone (fine grain)	
	Chinle Fm.			0-450	Red & orange siltstone, (calc), ss, sh., and red claystone	
	Shinarump Fm.			30 ±	Red shale, sandstone, and qtz. pebble conglomerate	Oil Gas
	Moenkopi Fm.			0-850	Red siltstone, green & gray shale, sandstone, and anhydrite	
Permian	Park City Fm. (Phosphoria Fm.- State Bridge Fm.)			0-300	Orange siltstone, orange & red shale, dolomite (oolitic) & anhydrite	
Pennsyl-vanian	Weber Sandstone			100-200 ±	Light gray to white sandstone (siliceous)	Oil Gas
	Maroon Fm.			0-2,000	Red sandstone, siltstone, rare limestone, and conglomerate	
	Morgan Fm.			500-1,400	Tan limestone (bioclastic), sandstone (calc. & silic.eous), shale (calcareous)	
	Minturn Fm.			0-1,000	Sandstone and cgl. (arkosic), shale, carbonate and anhydrite	Oil
	Belden Shale			0-100	Gray to black shale, limestone, and sandstone stringers	
	Molas Fm.			30 ±	Variegated shale, limestone and sandstone stringers	
Mississip-pian	Madison Fm (Leadville Ls.)			0-700	Light gray limestone (cherty, crystalline), dolomite	
Devonian	Chaffee Grp.	Dyer Fm.	Coffee Pot Mbr	>190	Dolomite (stromatolitic)	
			Broken Rib Mbr		Limestone (dolomitic)	
		Parting Sandstone		80 ±	Sandstone (siliceous. and dolomitic), shale and dolomite. streaks	
Cambrian	Ladore Sandstone			0-300	Sandstone (siliceous and glauconitic)	
Pre-cambrian	Uinta Mtn Grp			Undetermined	Quartzite and conglomeritic sandstone	
	Crystalline Rocks				Metamorphic and Igneous Rocks	

Figure 3.3. Stratigraphic Chart of the Sand Wash Basin Region. Light brown shading indicates predominantly non-marine environment, light blue indicates lacustrine, and blue indicates generally marine. After Boreck and others (1981).

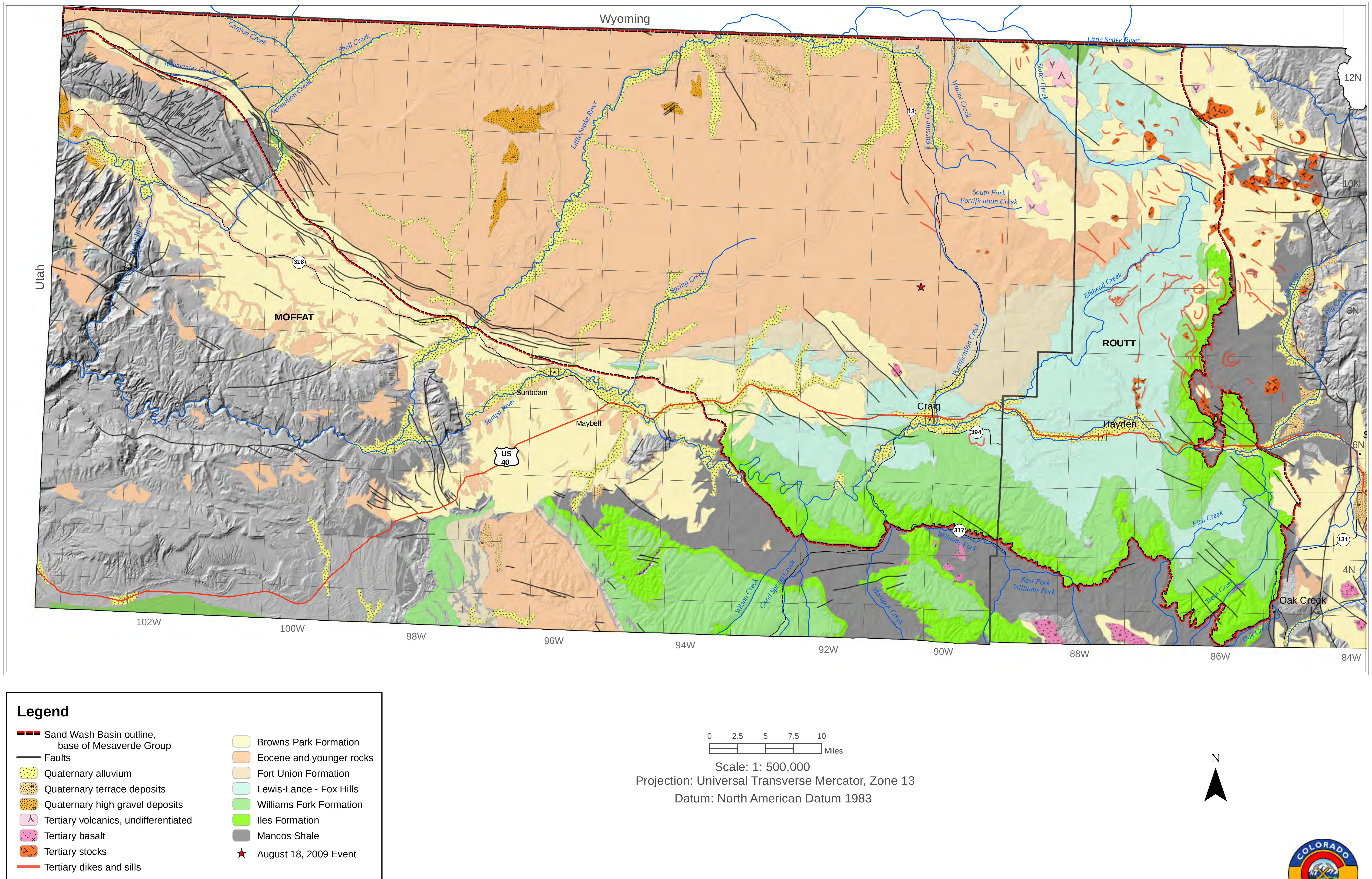


Figure 3.4 Generalized Surface Geologic Map of the Sand Wash Basin Region

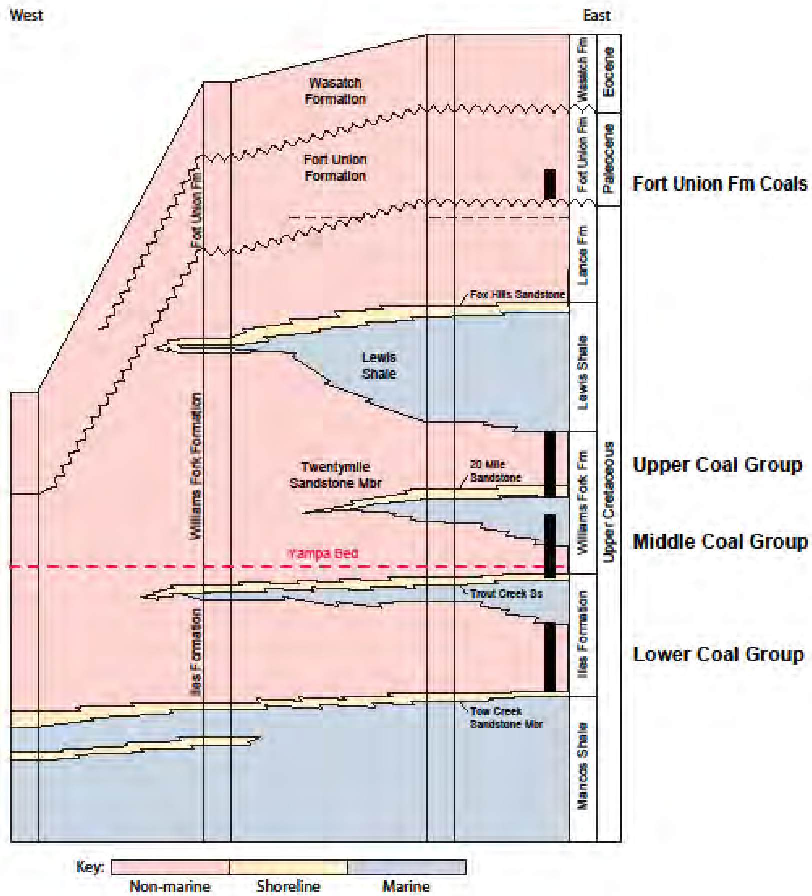


Figure 3.5 Stratigraphic Relationships of the Coal-Bearing Rocks, Southern Sand Wash Basin. Late Cretaceous and Paleogene sedimentary rocks record the retreat of the Western Interior Seaway and fragmentation of the Rocky Mountain region by the Laramide Mountain Building Event. The ancient shoreline moved back and forth several times, so that there are multiple intervals of marine shale interbedded with non-marine coastal plain sediments. Coal deposits that favor CBM resources are found in the coastal plain sediments in the Mesaverde Group and the basin fill sediments of the Fort Union Formation. Vertical black bars identify relative position of coal-bearing intervals. After Brownfield and Johnson (2008).

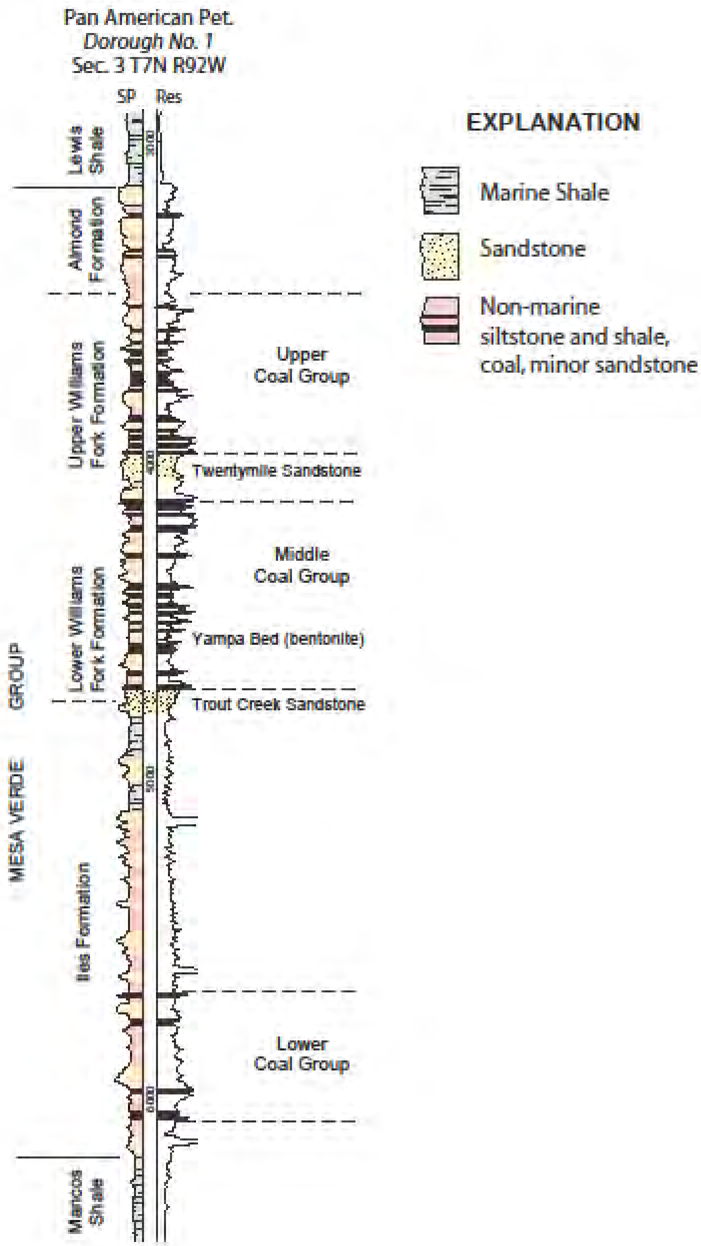


Figure 3.6 Geophysical Log for a Mesaverde Group Well. This spontaneous potential (SP) and resistivity (res) log shows the Stratigraphy of the Mesaverde Group with its major coal groups. Coal seams are indicated by black bands. After Hamilton, 1994.

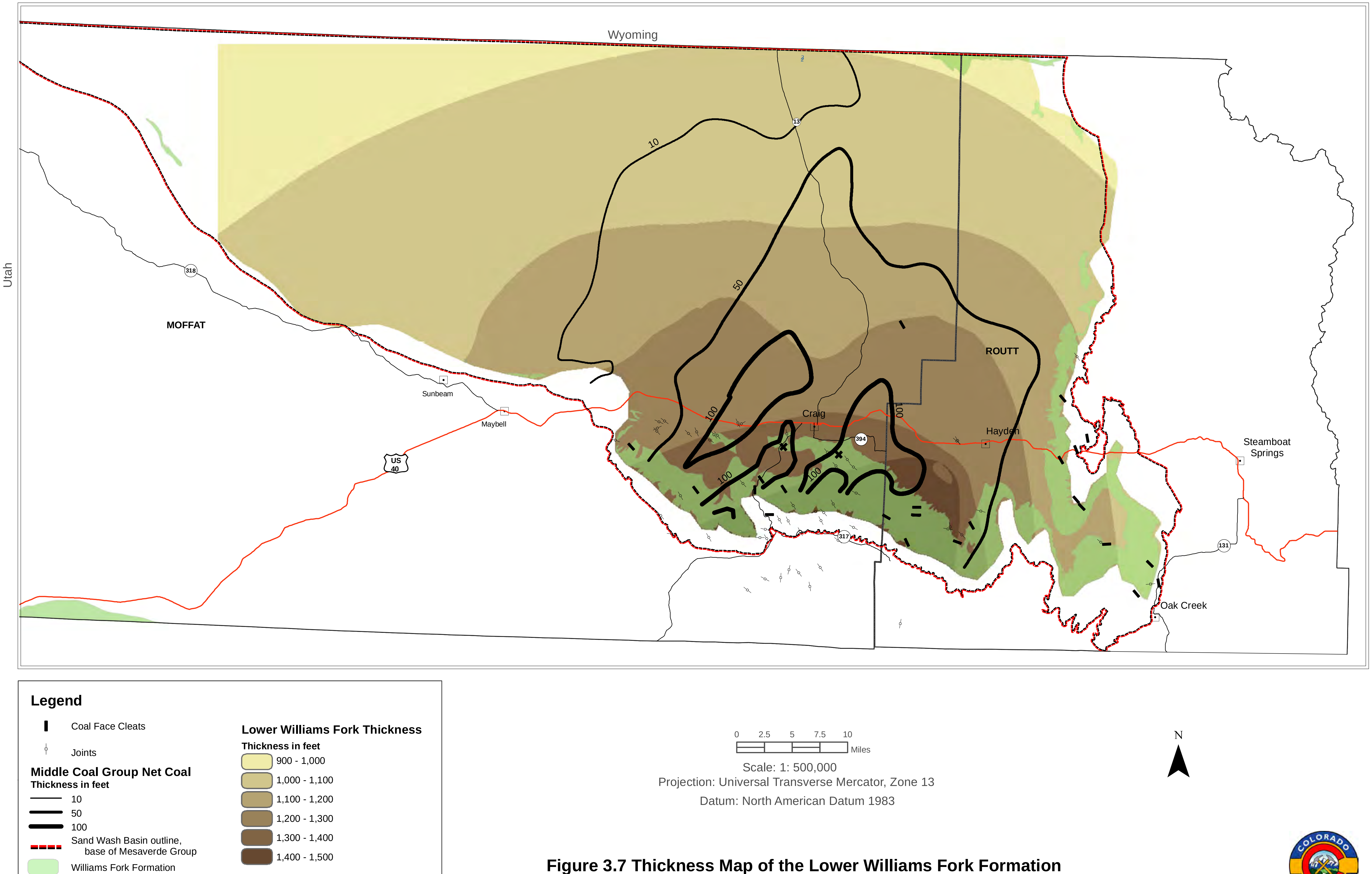


Figure 3.7 Thickness Map of the Lower Williams Fork Formation

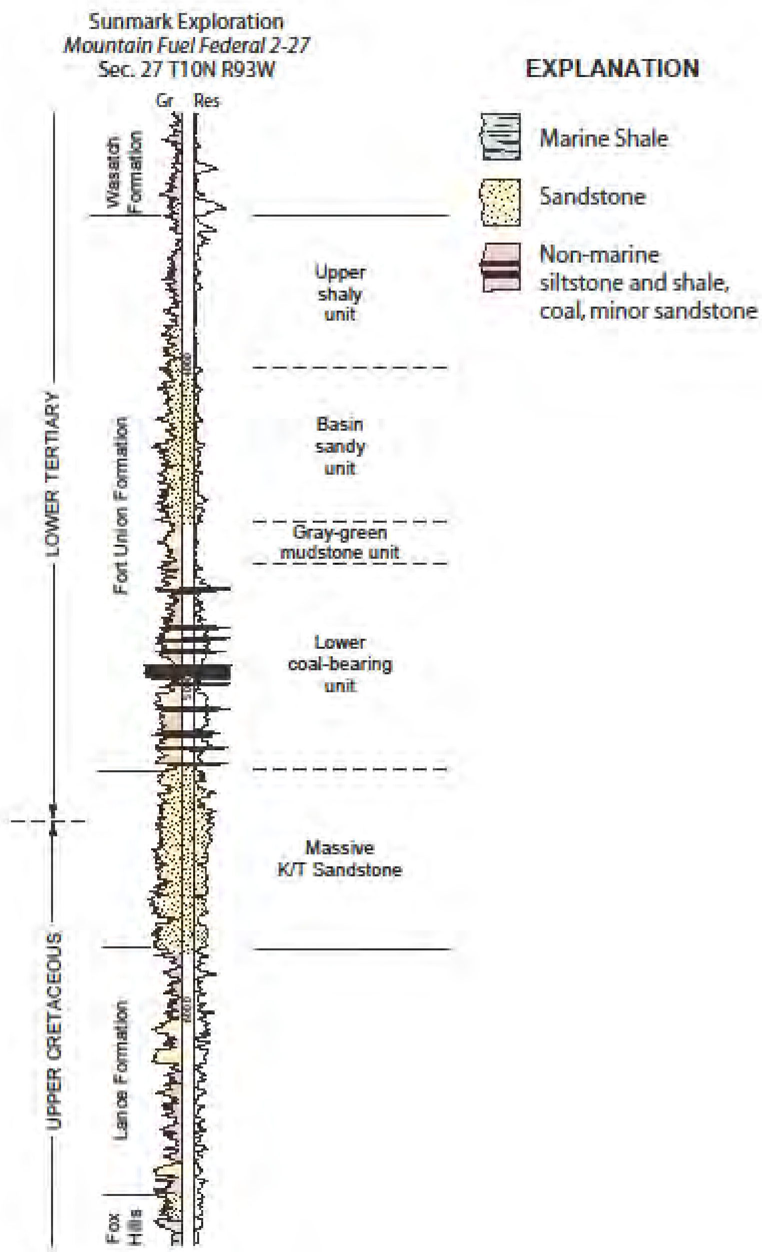
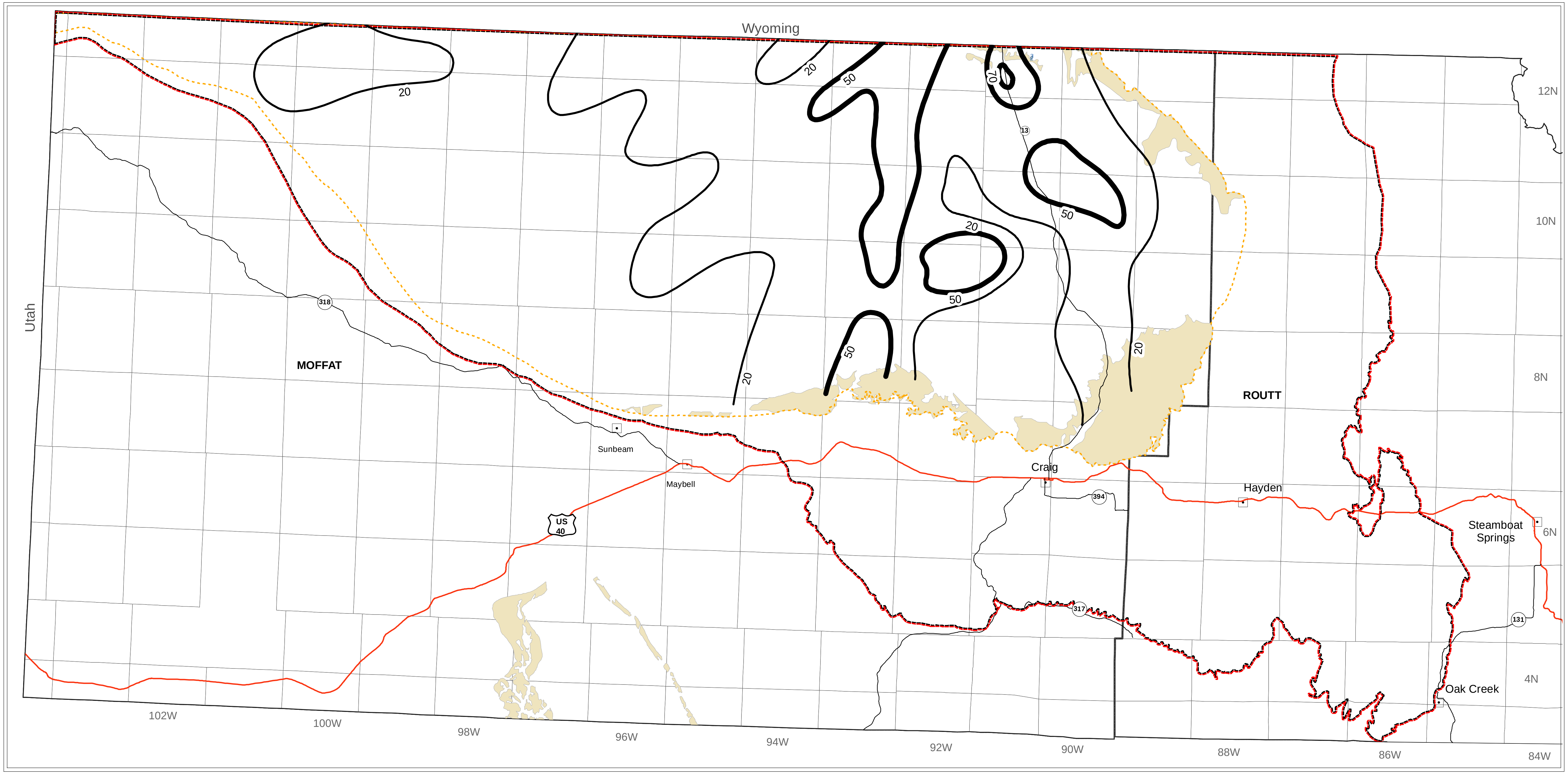


Figure 3.8 Geophysical Log for a Fort Union Formation Well. This gamma-ray (Gr) and resistivity (Res) log shows the stratigraphy of the Fort Union Formation with its coal group. Coal seams are indicated by black bands. After Tyler and McMurry, 1994.



Legend

Fort Union Net Coal

Thickness in feet

- 20
- 50
- 70
- Sand Wash Basin outline, base of Mesaverde Group
- Extent of Fort Union Formation
- Fort Union Formation

0 2.5 5 7.5 10 Miles

Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 3.9 Net Coal Thickness in the Fort Union Formation Lower Coal-Bearing Unit

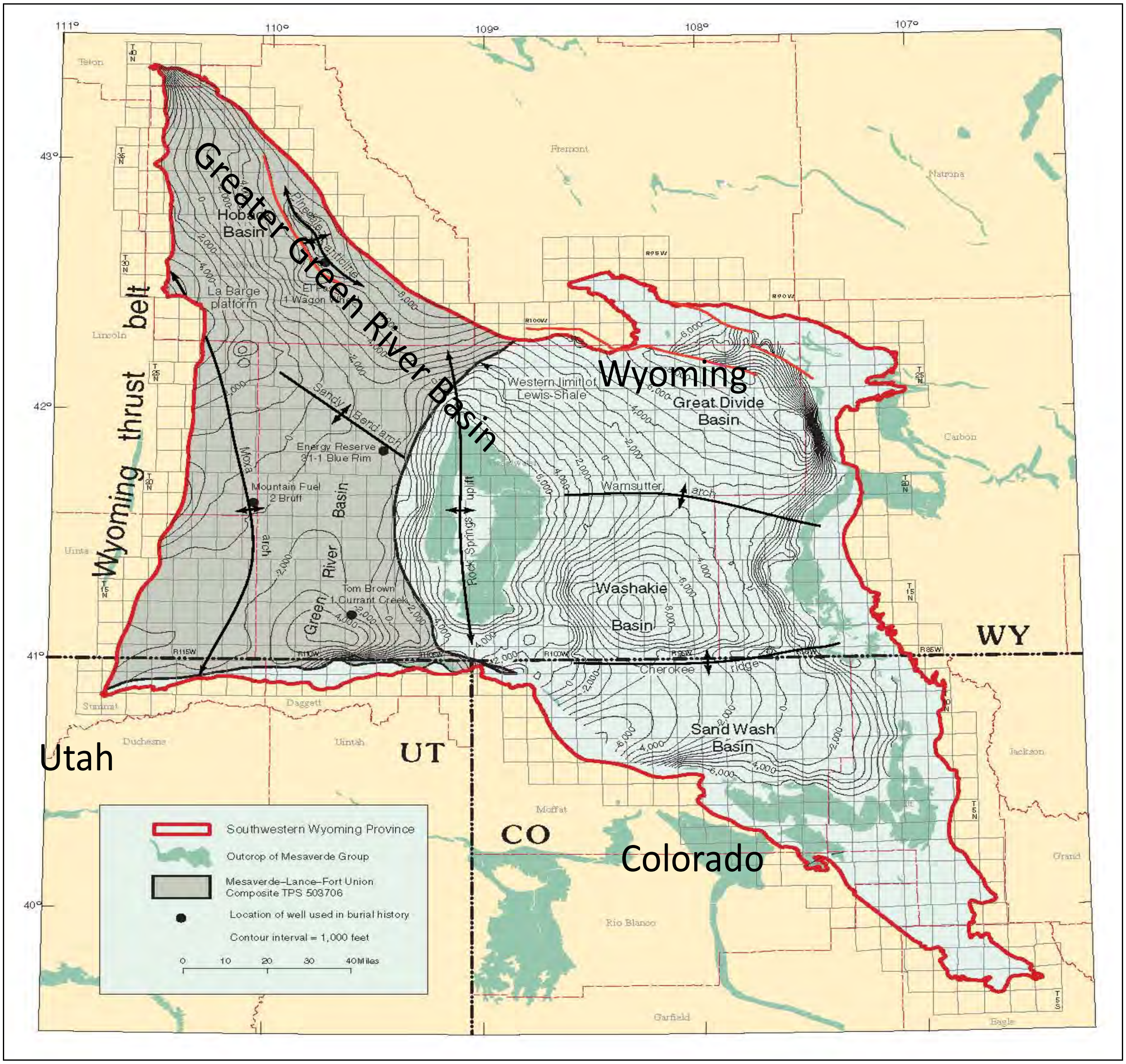
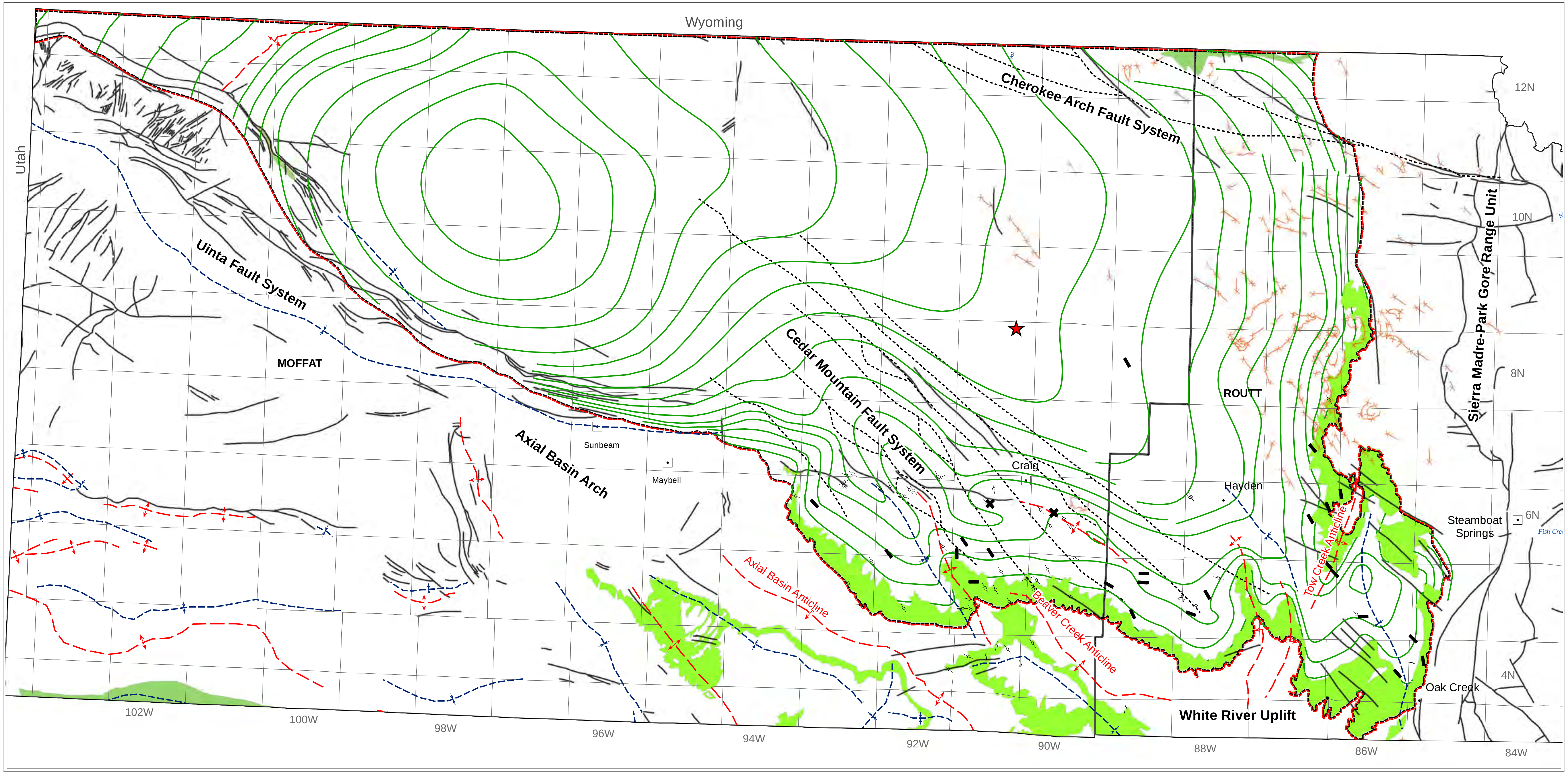


Figure 3.10 Regional Map of the Greater Green River Basin. Sand Wash Basin is the southeast extension of this larger complex feature that covers a large area of southwestern Wyoming. Source USGS (2005).



Legend

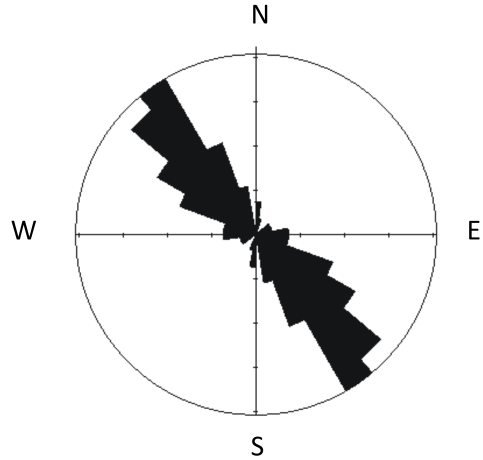
- Coal face cleats
- Joints
- August 18, 2009 event
- Sand Wash Basin outline, base of Mesaverde Group
- Surface faults
- Faults from Tyler and Tremain,1994
- Synclines
- Anticlines
- Iles top structural contour: CI= 1,000 ft
- Tertiary dikes and sills
- Iles outcrop

0 2.5 5 7.5 10 Miles

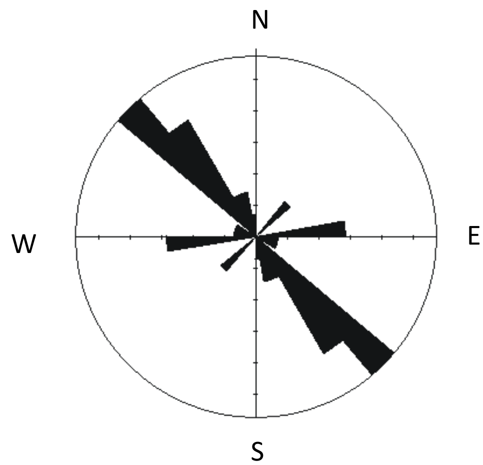
Scale: 1: 500,000
Projection: Universal Transverse Mercator, Zone 13
Datum: North American Datum 1983

N

Figure 3.11 Generalized Structure Map of the Sand Wash Basin



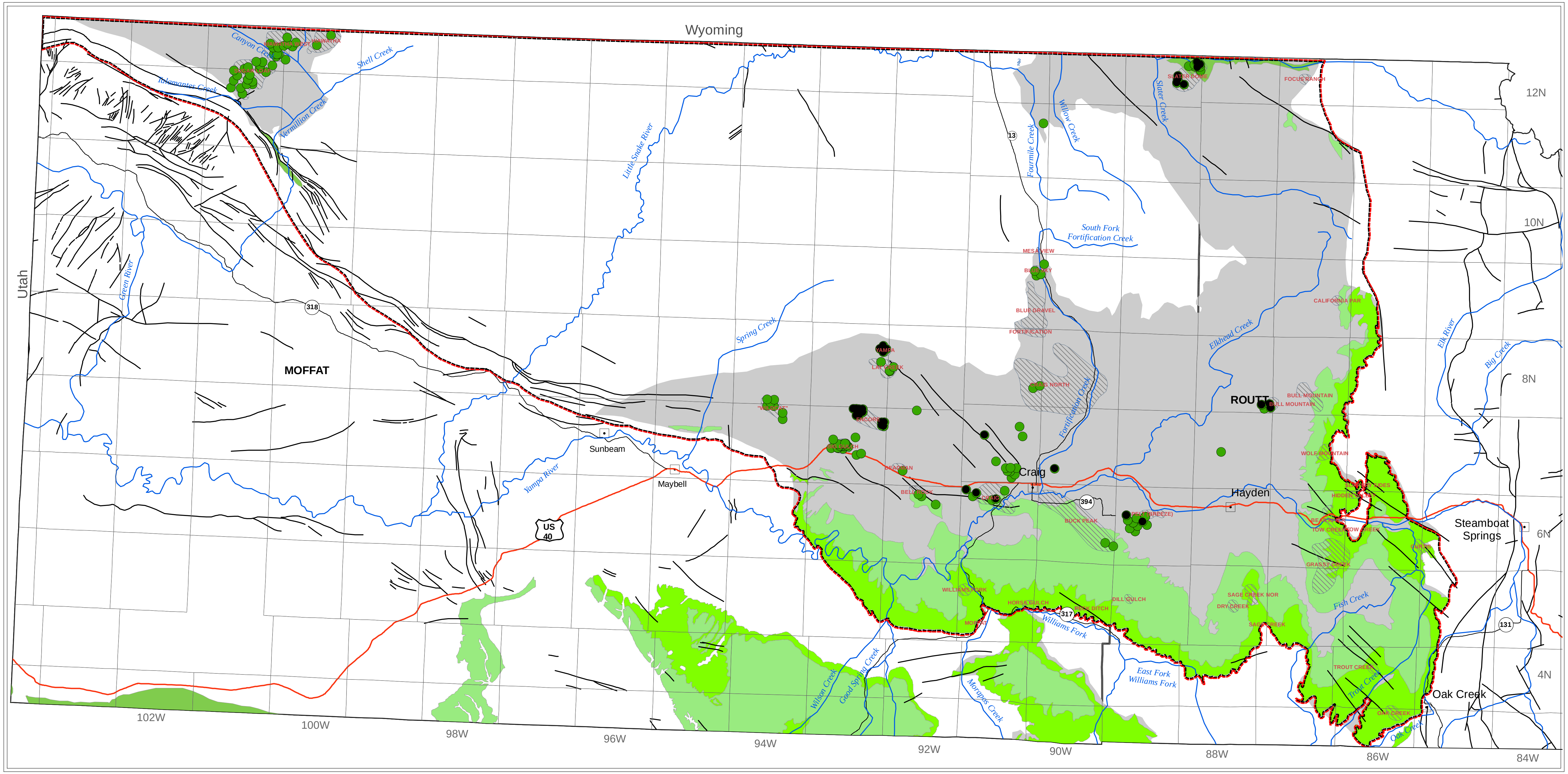
Fractures in brittle sandstone layers (54 measurements).



Coal seam face cleats (28 measurements).

Figure 3.12. Rose Diagrams of Fracture and Coal-cleat Directions in the Mesaverde Group Outcrop Belt. Diagrams plot fracture orientations from measurements collected at outcrops of Upper Cretaceous sedimentary rocks along the southeastern perimeter of the Sand Wash Basin. Plots illustrate a prevailing northwest trend with an azimuth direction between 300° and 340°. Top diagram shows prevailing northwest trend of 54 measurements collected from sandstone layers in Upper Cretaceous Mesaverde Group, Fox Hills Sandstone, and Lance Formation. Bottom diagram shows similar trend of 28 measurements from coal cleats in the Mesaverde Group. [Source of fracture data: CGS field data; source of coal cleat data: CGS field data and Tyler and Tremain (1994).]

Figure 3.13. Photograph of Northwest Trending Fractures in the Iles Formation. Fractures are best developed in sandstone beds exposed near the axis of the Beaver Creek anticline above Williams Fork River east of Hamilton.



Legend

- Mesaverde Group coalgas wells
- Mesaverde Group oil-gas wells in USGS CBM unit
- Sand Wash Basin outline, base of Mesaverde Group
- Faults
- Oil and gas fields in USGS CBM unit
- Williams Fork Formation outcrop
- Iles Formation outcrop
- Mesaverde USGS CBM Unit

0 2.5 5 7.5 10 Miles

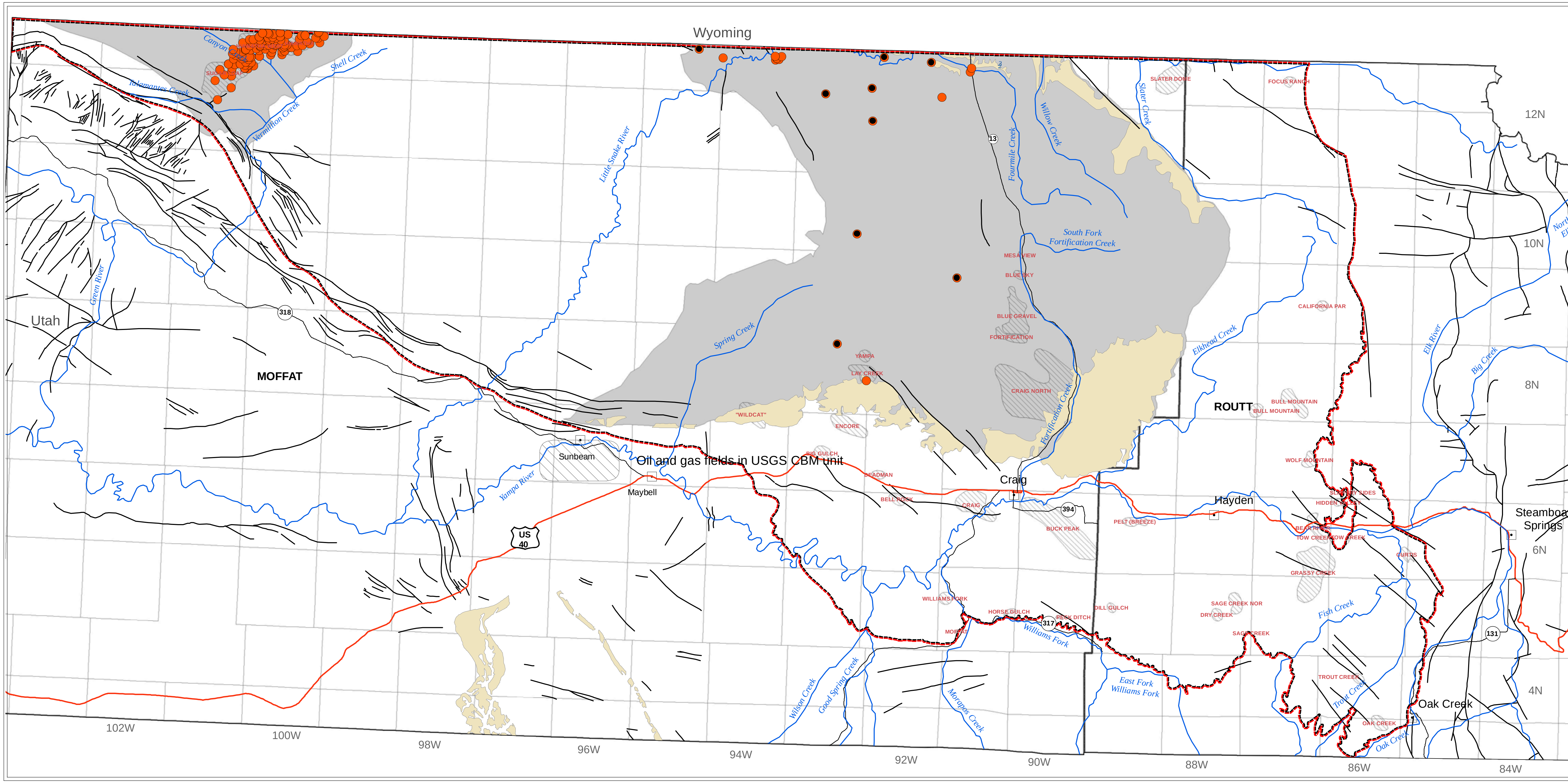
Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 4.1 Mesaverde Coalgas Wells in the Sand Wash Basin



Legend

- Fort Union Formation coalgas wells
- Fort Union Formation oil and gas wells
- Faults
- Sand Wash Basin outline, base of Mesaverde Group
- Oil and gas fields in USGS CBM unit
- Fort Union Formation outcrop
- USGS Fort Union Fm. CBM unit

0 2.5 5 7.5 10 Miles

Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 4.2 Fort Union Coalgas Wells in the Sand Wash Basin

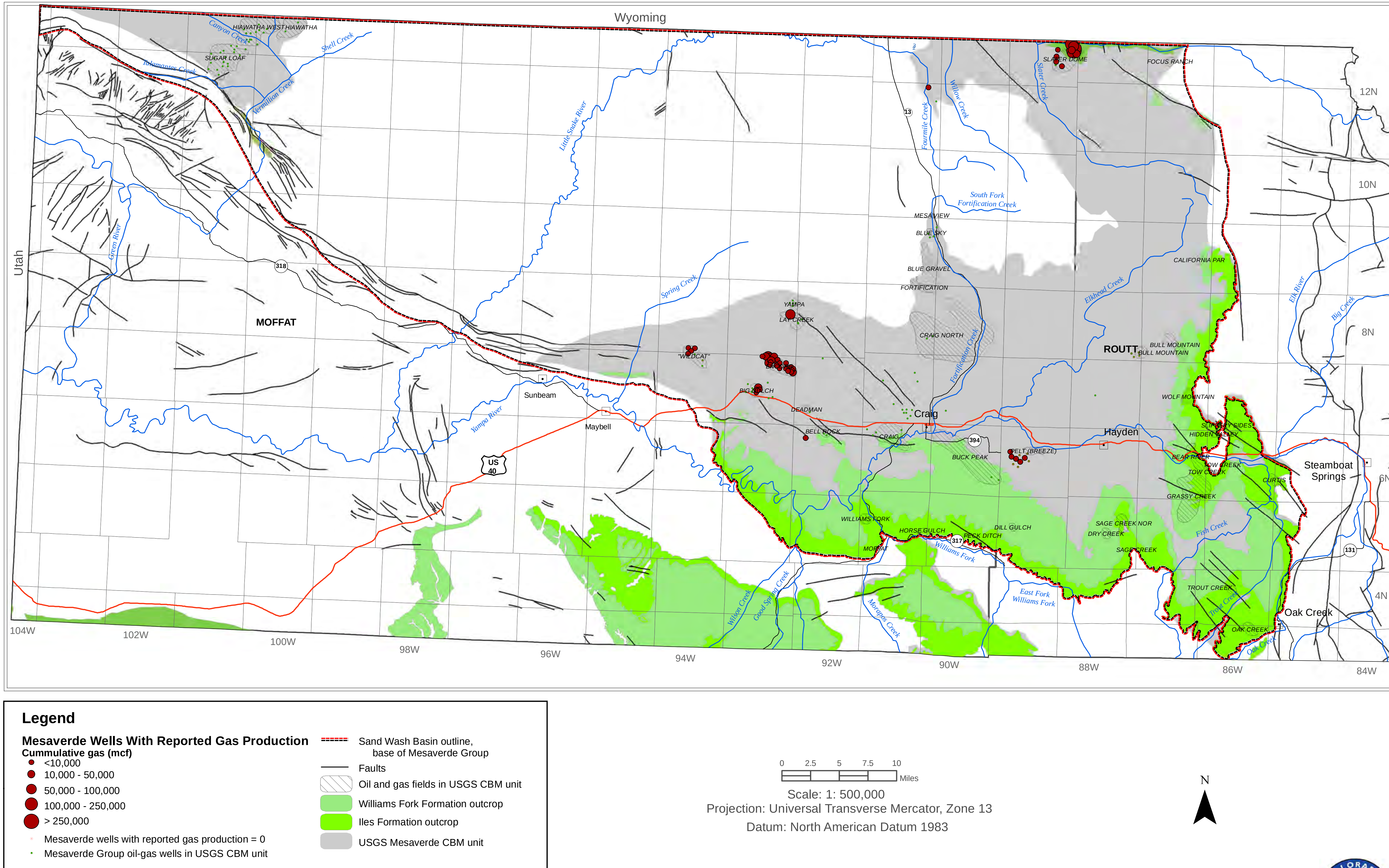


Figure 4.3 Mesaverde CBM Production in the Sand Wash Basin

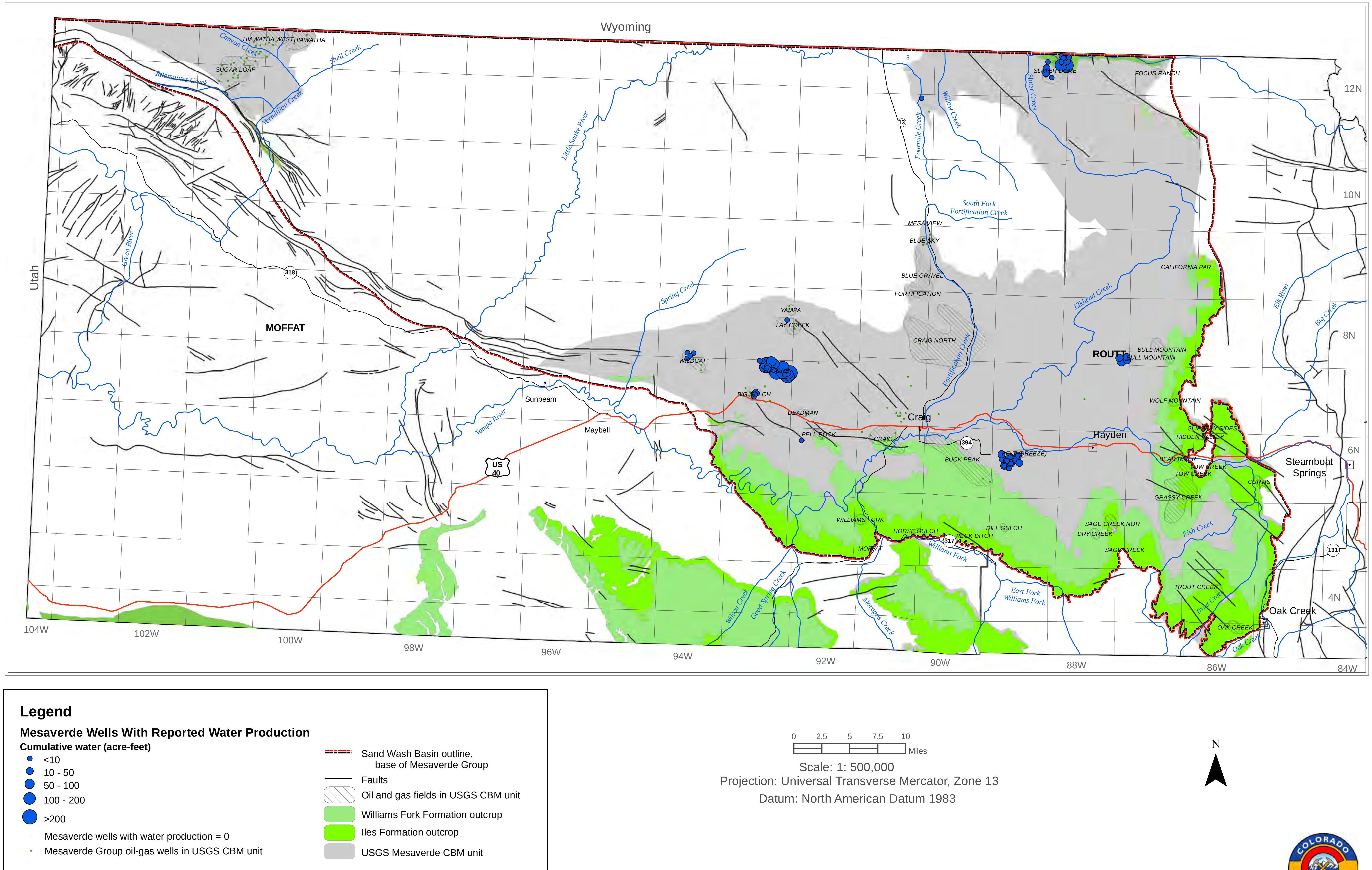
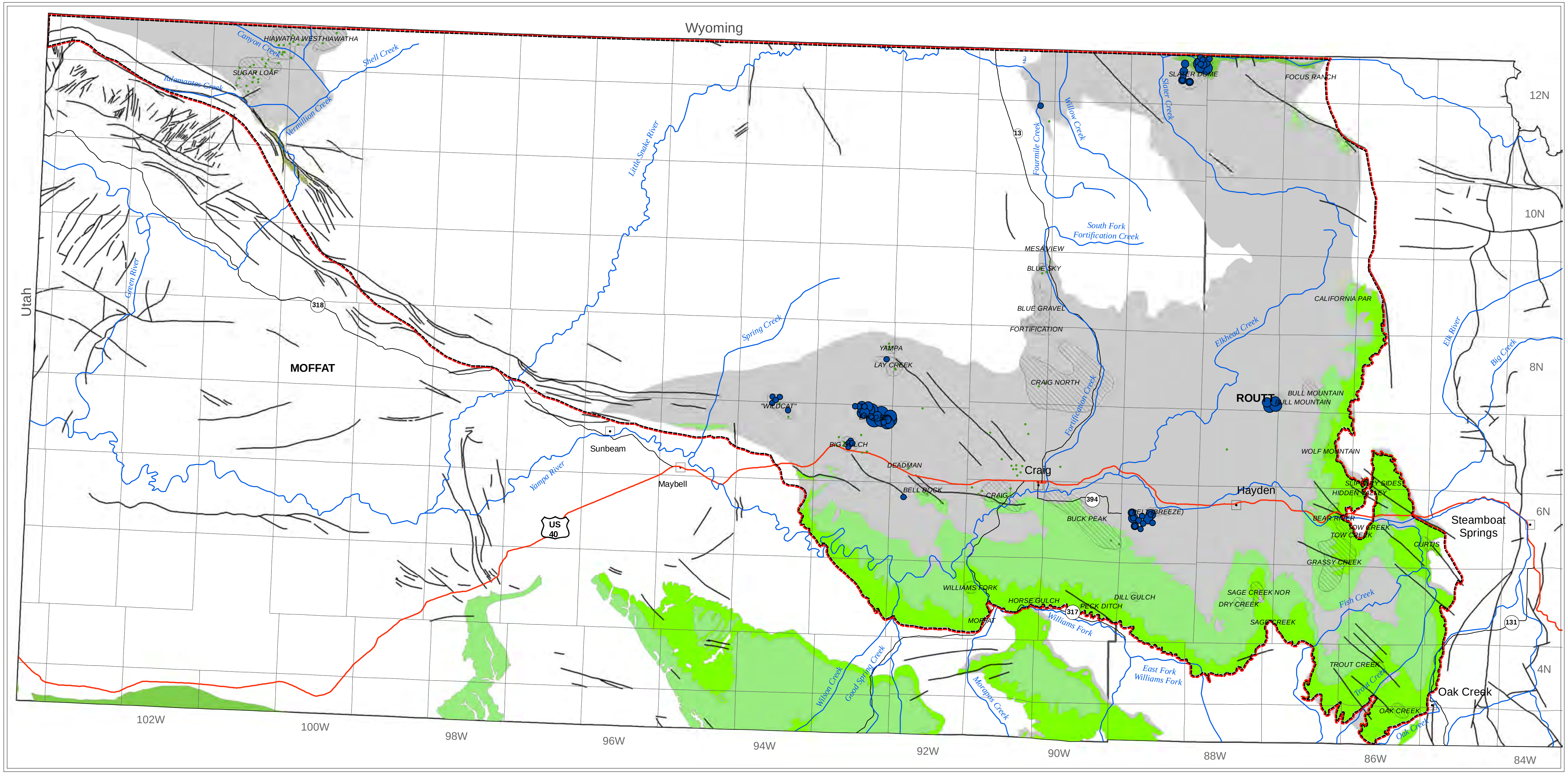


Figure 4.4 Mesaverde CBM Water Production in the Sand Wash Basin



Legend

Average Water Pumping Rates

Based on monthly totals in gpm

- < 5
- 5 - 10
- 10 - 25
- 25 - 50
- 50 - 100
- > 100

Mesaverde wells with water production = 0

Mesaverde Group oil-gas wells in USGS CBM unit

Sand Wash Basin outline, base of Mesaverde Group

Faults

Oil and gas fields in USGS CBM unit

Williams Fork Formation outcrop

Iles Formation outcrop

USGS Mesaverde CBM unit

0 2.5 5 7.5 10 Miles

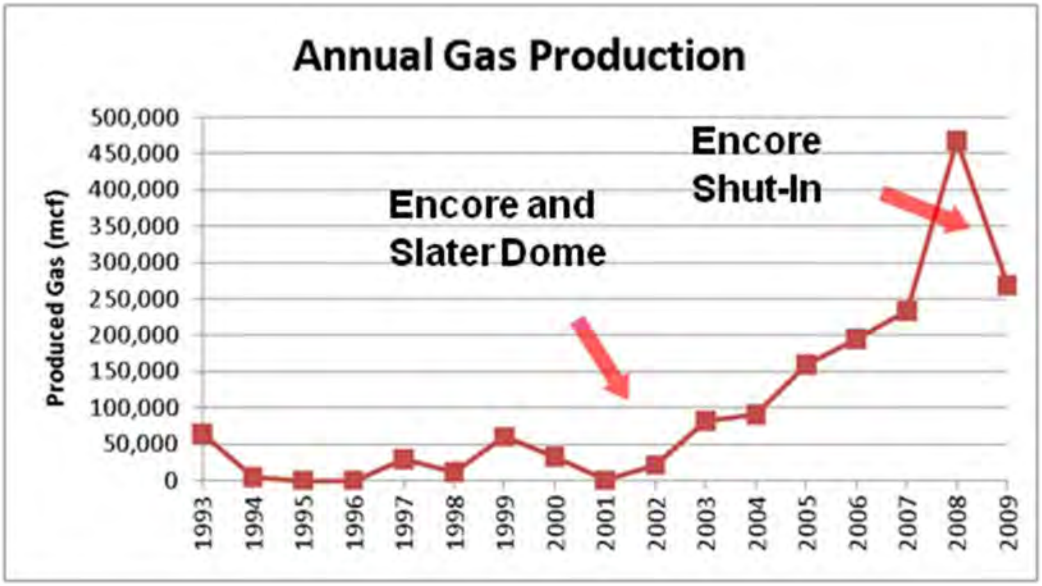
Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 4.5 Mesaverde CBM Well Water Yields in the Sand Wash Basin



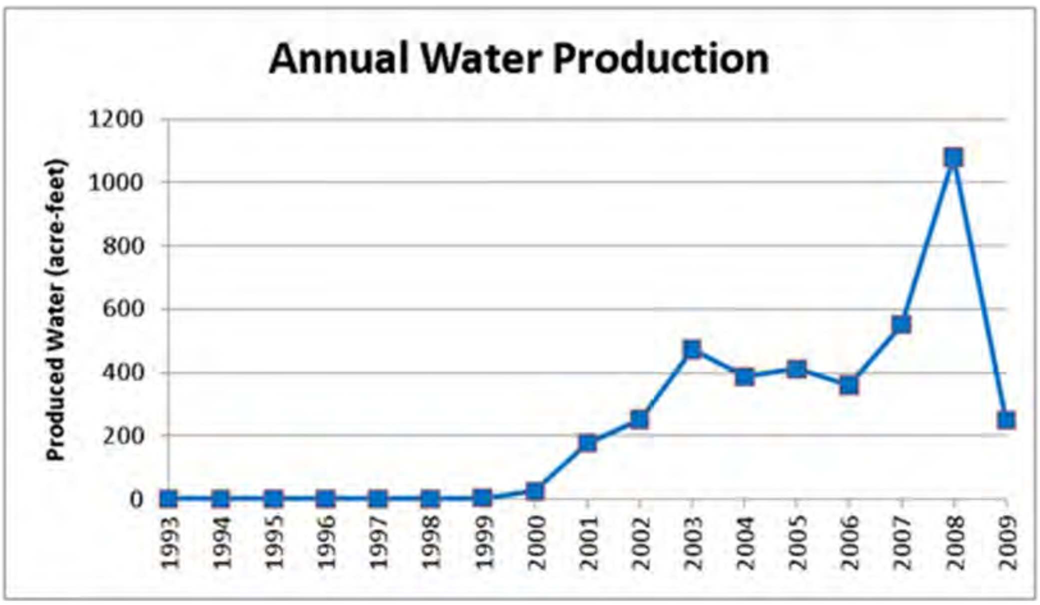
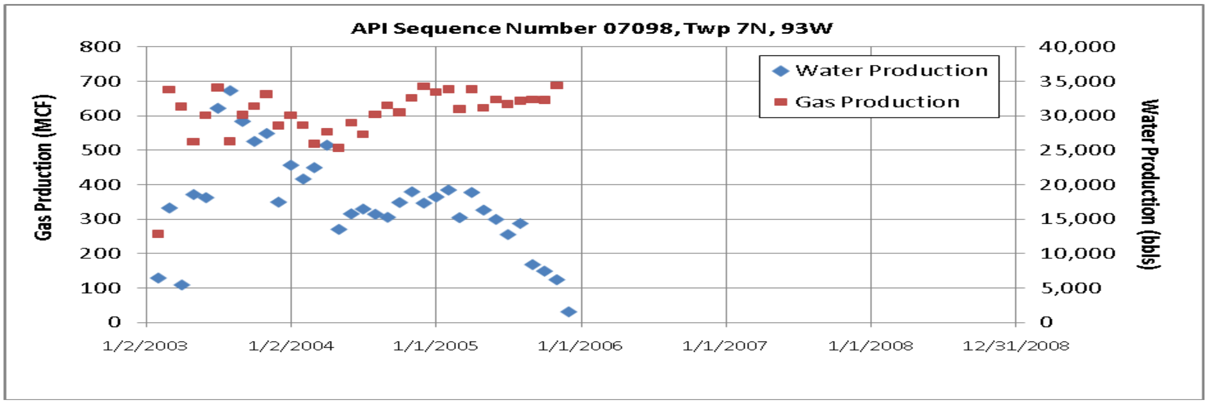
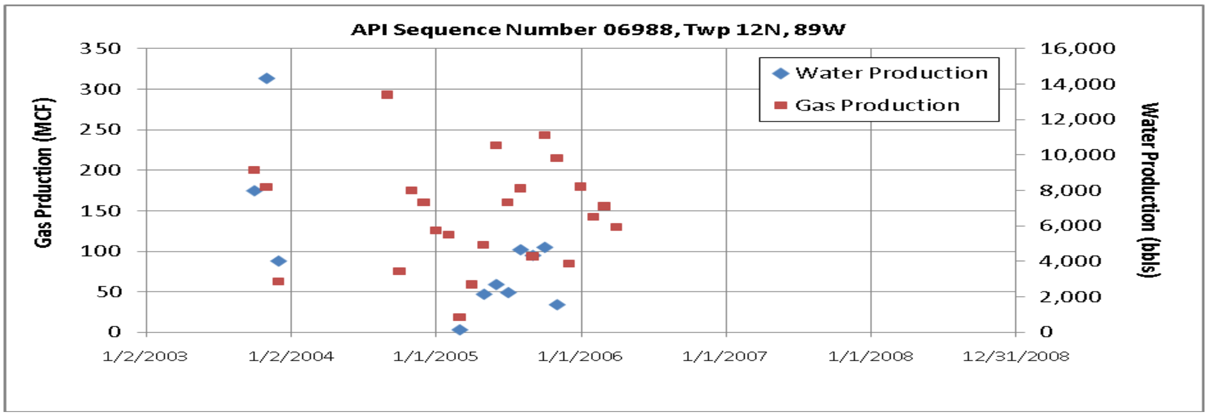


Figure 4.6 Annual Gas and Water Production from the Sand Wash Basin, 1993 to 2009. Graphs illustrate gradual rise in production beginning in 2002 (for gas) and peaking in 2008. Decline in 2009 reflects shut-in of Encore Field. Sharper decline in water production hints at high water production rates at Encore. Source of data, COGCC production records.



Encore Field Plot



Slater Dome Field Plot

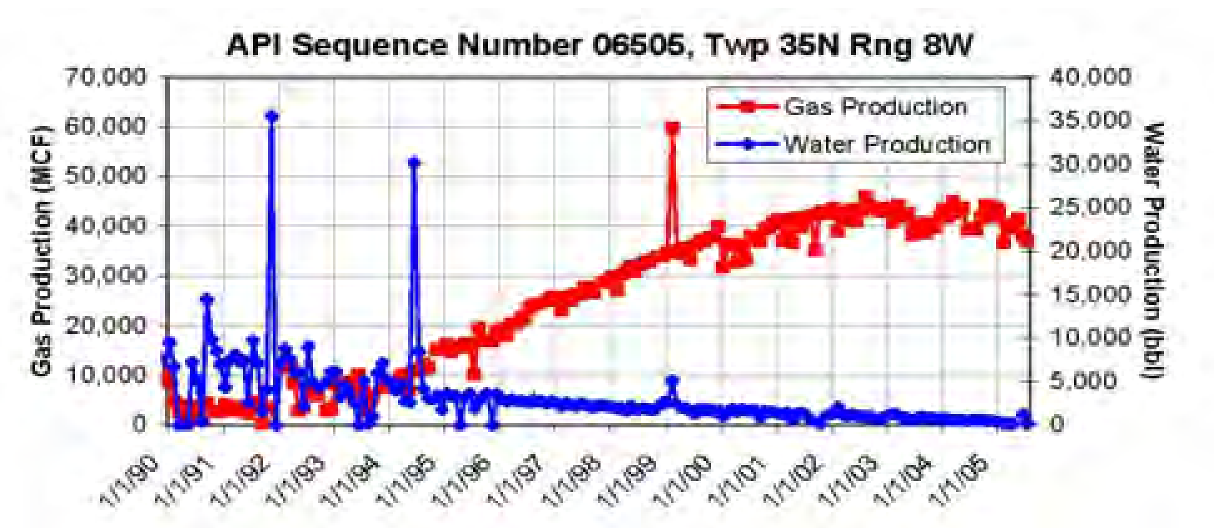
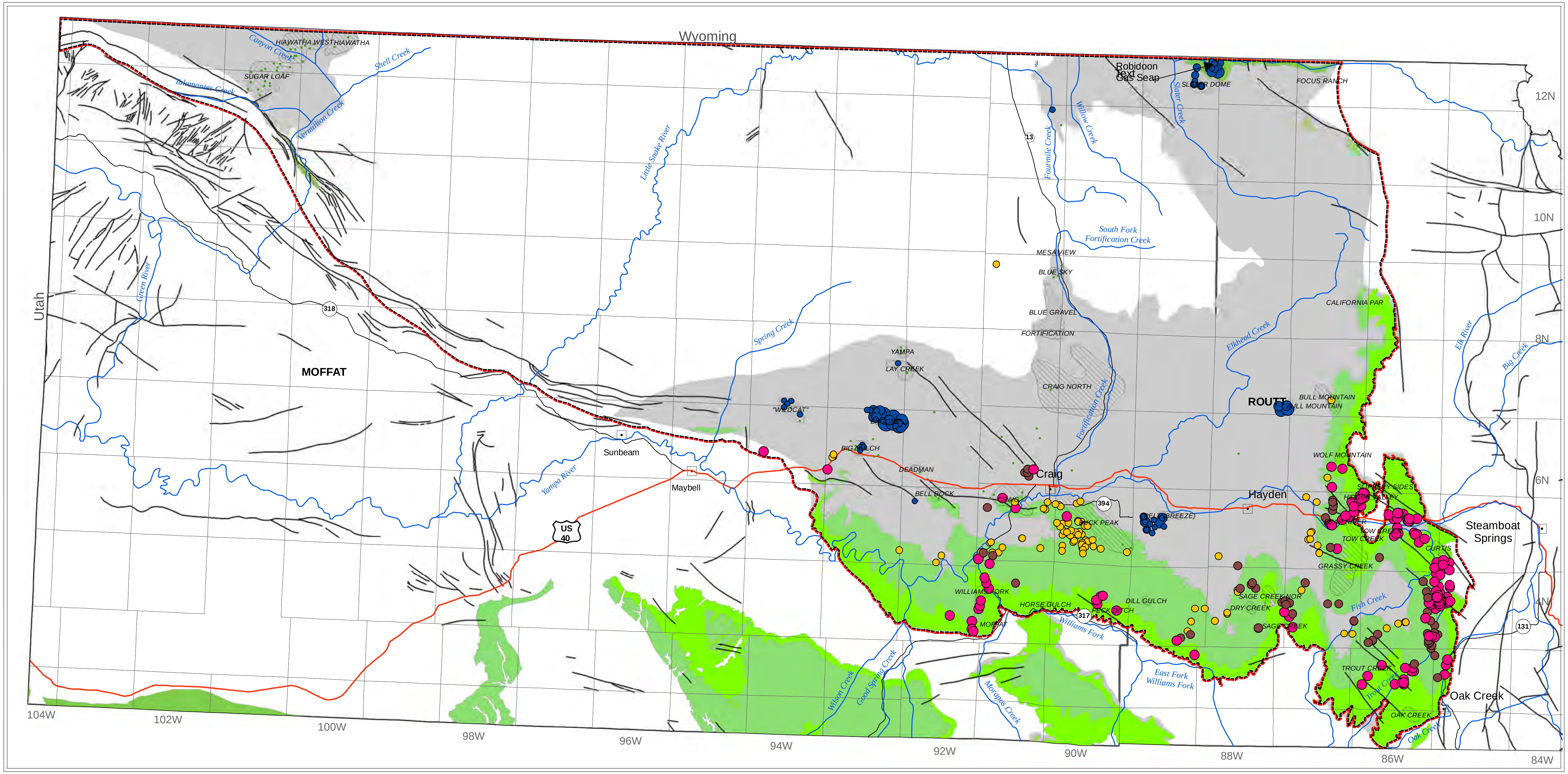


Figure 4.7 Gas-Water Production Plots for Two Sand Wash Basin CBM Wells. First graph shows declining gas production as water production holds steady or rises slightly at Encore Field. Second graph shows very scattered data with rising gas production and possible declining water production. Third graph shows a typical plot from the San Juan Basin. Source COGCC production data.



Legend

Average Water Pumping Rates

Based on Monthly Totals in gpm

- < 5
- 5 - 10
- 10 - 25
- 25 - 50
- 50 - 100
- > 100
- Mesaverde wells with water production = 0
- Mesaverde Group oil-gas wells in USGS CBM unit

- Sand Wash Basin outline, base of Mesaverde Group
- Faults
- Oil and gas fields in USGS CBM unit
- Williams Fork Formation outcrop
- Iles Formation outcrop
- USGS Mesaverde CBM unit

Mesaverde Water Wells

Formation Completion (Estimated)

- Upper Williams Fork (Lower Coal Group)
- Lower Williams Fork (Middle Coal Group)
- Iles Formation (Lower Coal Group)

0 2.5 5 7.5 10 Miles

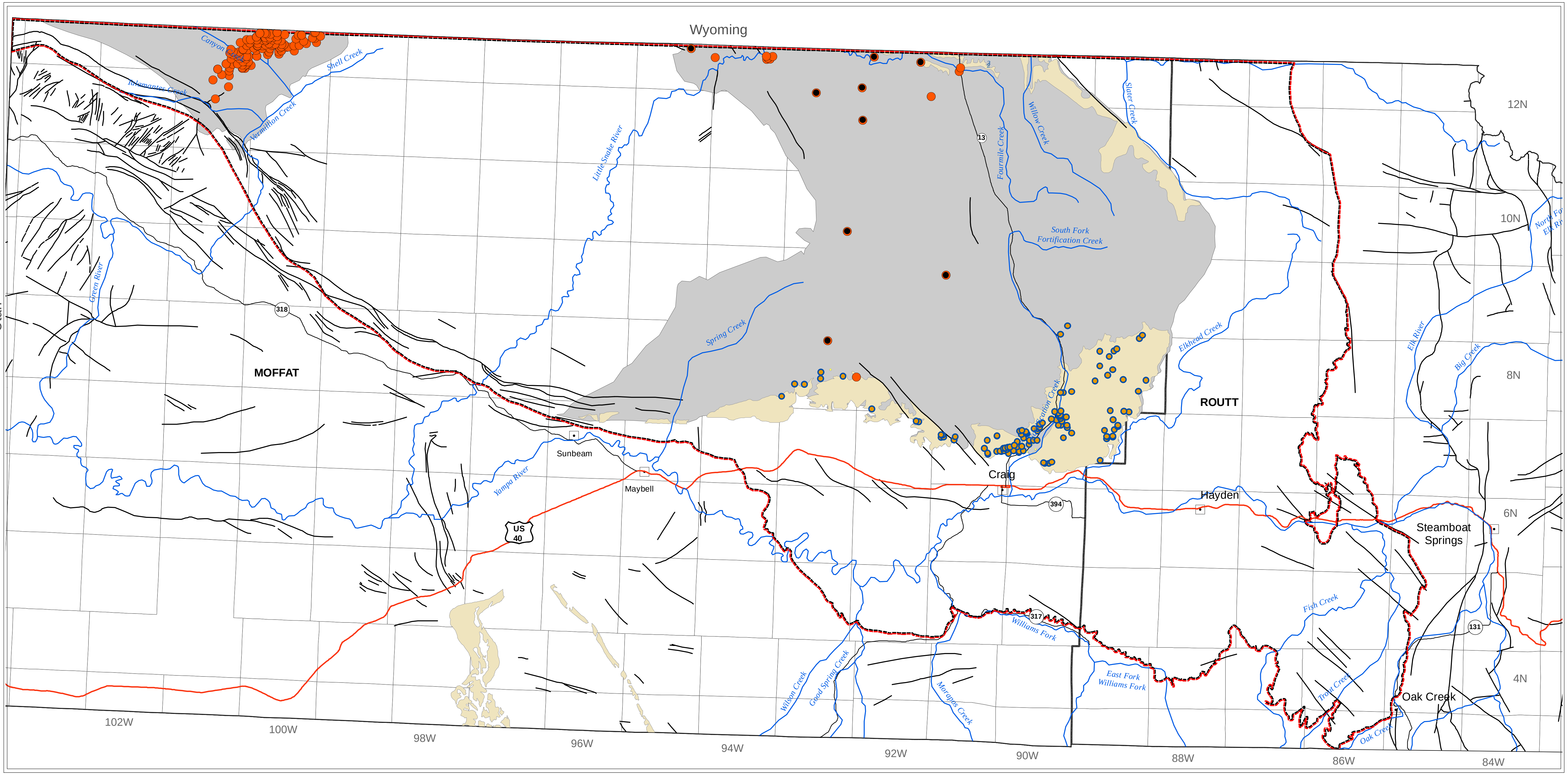
Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 5.1 Permitted Water Wells in the Mesaverde Group



Legend

- Probable alluvial wells (<130 ft deep)
- Probable Ft Union wells (>130 ft deep)
- Permitted water wells in Ft Union (probable)
- Fort Union Formation coalgas wells
- Fort Union Formation oil and gas wells
- Sand Wash Basin outline, base of Mesaverde Group
- Faults
- USGS Fort Union Fm. CBM unit
- Fort Union Formation outline

0 2.5 5 7.5 10 Miles

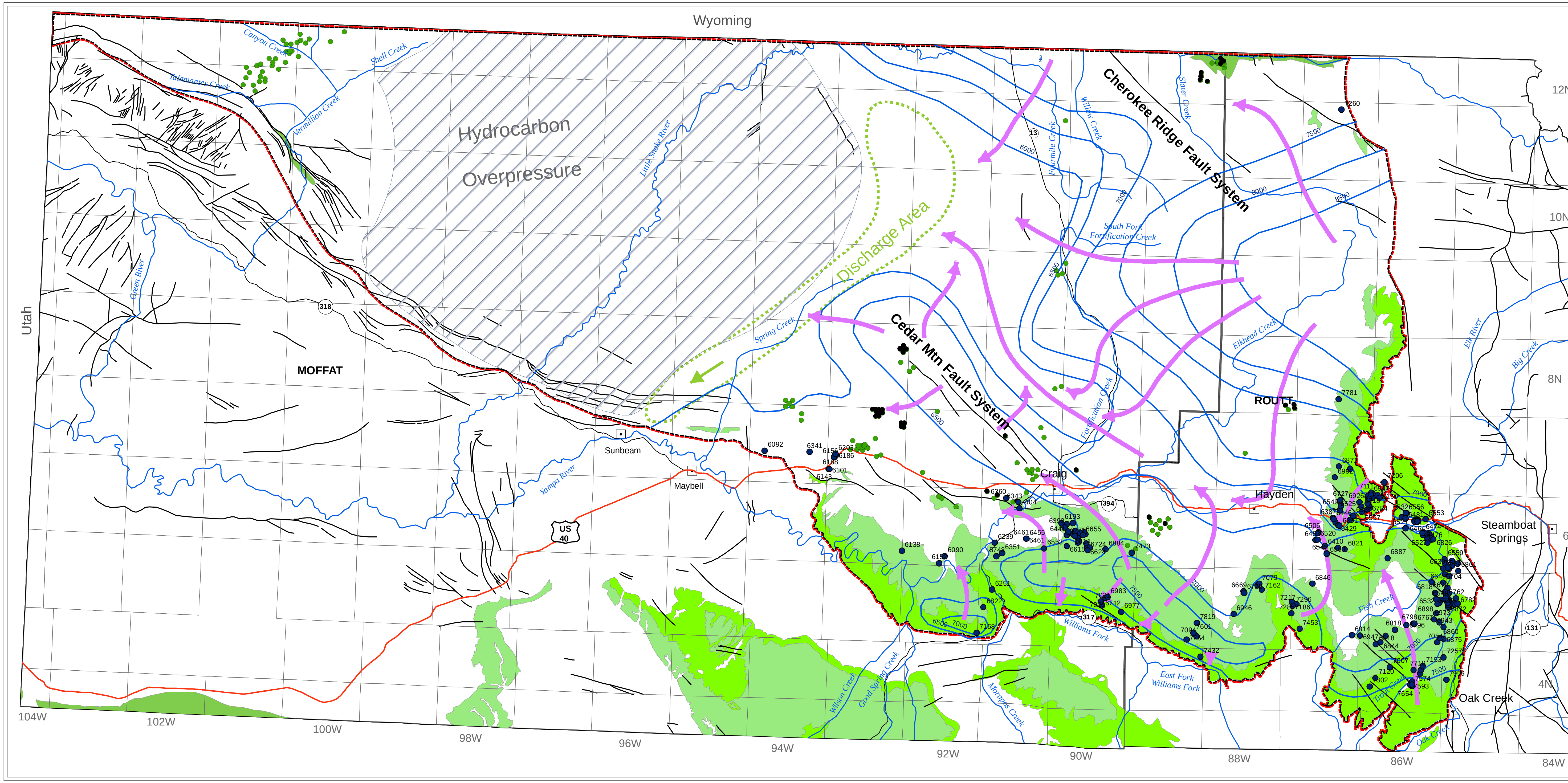
Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 5.2 Permitted Water Wells in the Fort Union Formation Coal-Bearing Interval



NOTES:

1. Potentiometric surface in basin interior is from Scott and Kaiser (1994).
2. Scott and Kaiser (1994) postulate an area in basin interior that is overpressured due to hydrocarbon generation and low permeability.
3. Combination of flow patterns and interior overpressured area implies discharge to southwest.

Legend

- Mesaverde water well with water level elevation
- Mesaverde Group coalgas wells
- Mesaverde Group oil-gas wells in USGS CBM unit
- Sand Wash Basin outline, base of Mesaverde Group
- Estimated groundwater flow direction in Upper Williams Fork Fm.
- Upper Williams Fork Fm. water level elevation countour (CI = 500")
- Faults
- Inferred discharge pattern
- Overpressure area
- Williams Fork Formation outcrop
- Iles Formation outcrop

0 2.5 5 7.5 10 Miles

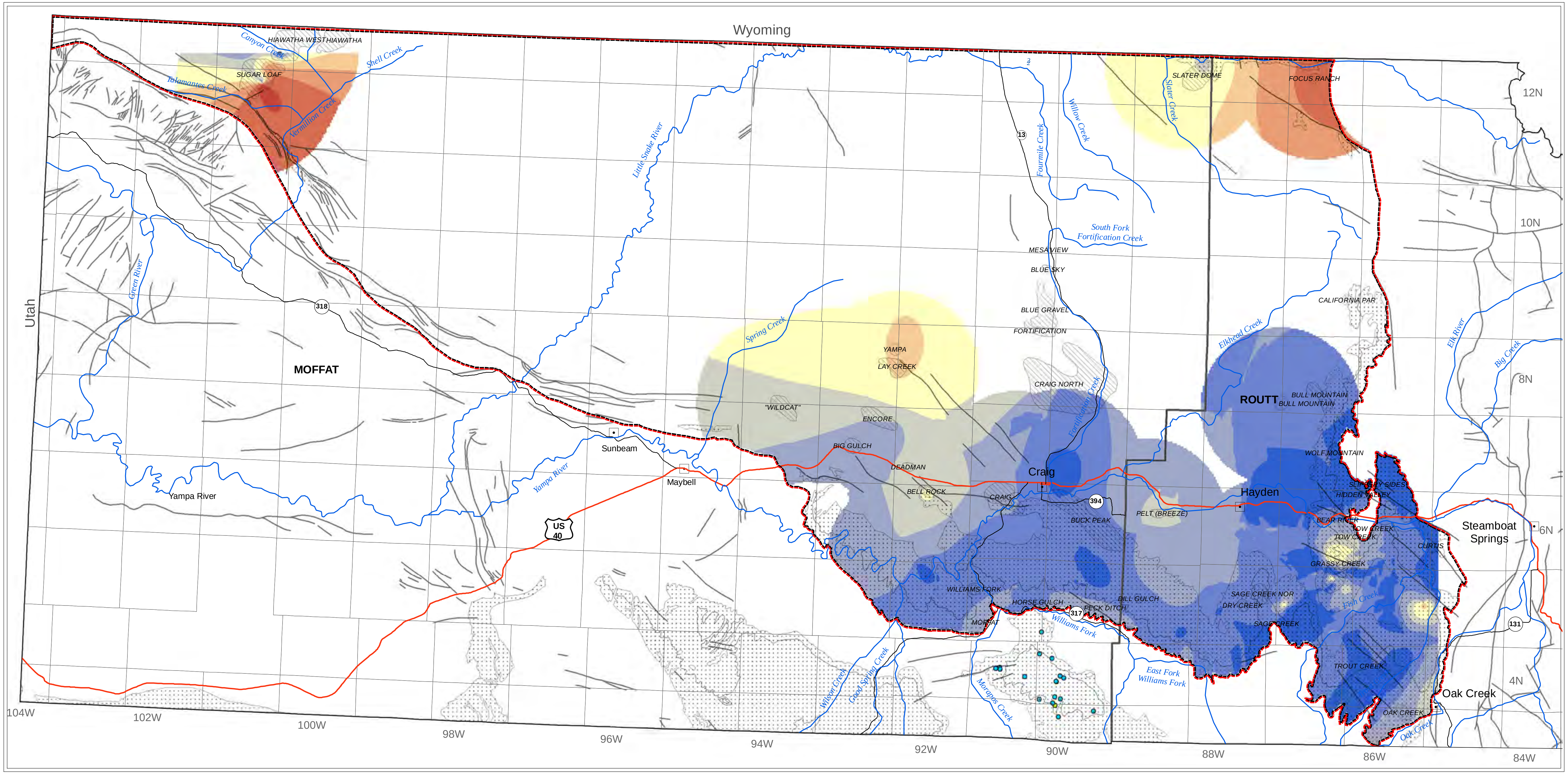
Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 5.3 Inferred Groundwater Flow Patterns in the Upper Williams Fork Formation



Legend

- Sand Wash Basin outline, base of Mesaverde Group
- Faults
- Mesaverde Group outcrop

Sodium Adsorption Ratio (SAR)

- < 10
- 10 - 18
- 18 - 50
- 50 - 100
- >100

Total Dissolved Solids (TDS)

Range (mg/L)

- <500
- 500 - 1,000
- 1,000 - 2,000
- 2,000 - 3,000
- 3,000 - 5,000
- 5,000 - 7,000
- 7,000 - 10,000
- 10,00 - 15,000
- 15,000 - 20,000

0 2.5 5 7.5 10 Miles

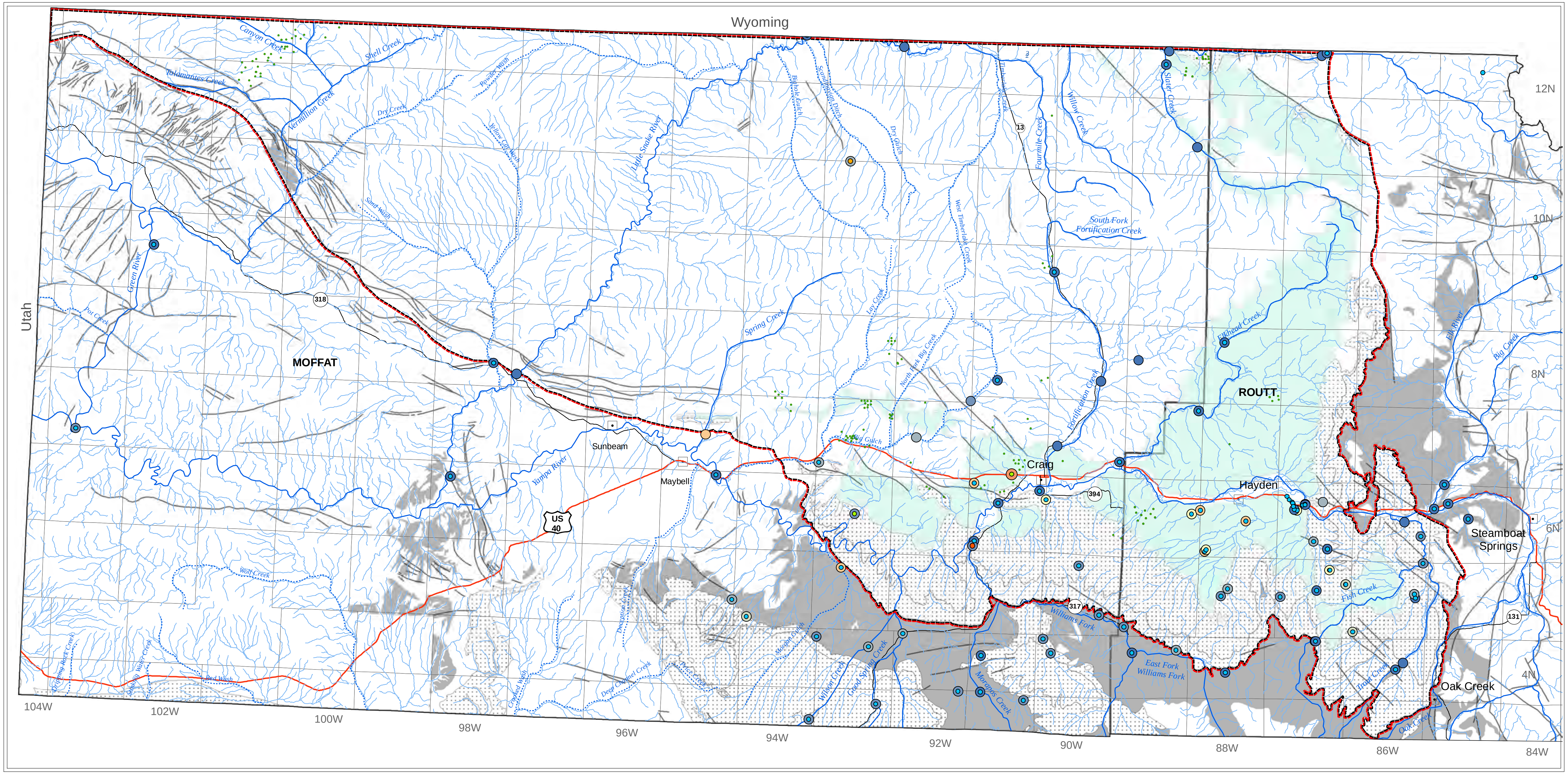
Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 5.4 Map of Total Dissolved Solids and Sodium Adsorption Ratios in Mesaverde Group Groundwater



Legend

- Mesaverde Group oil-gas wells in USGS CBM unit
- Sand Wash Basin outline, base of Mesaverde Group
- Streams
- Faults
- Lewis-Foxhills-Lance
- Mancos Shale
- Mesaverde Group Outcrop

Sodium Adsorption Ration (SAR)

- < 10
- 10 - 18
- 18 - 50
- 50 - 100
- >100

Total Dissolved Solids (TDS)

mg/L

- < 500
- 500 - 1000
- 1000 - 2000
- 2000 - 3000
- 3000 - 5000
- 5000 - 10000
- >10000

NOTE:
Selected from low-flow season surface water quality data.

0 2.5 5 7.5 10 Miles

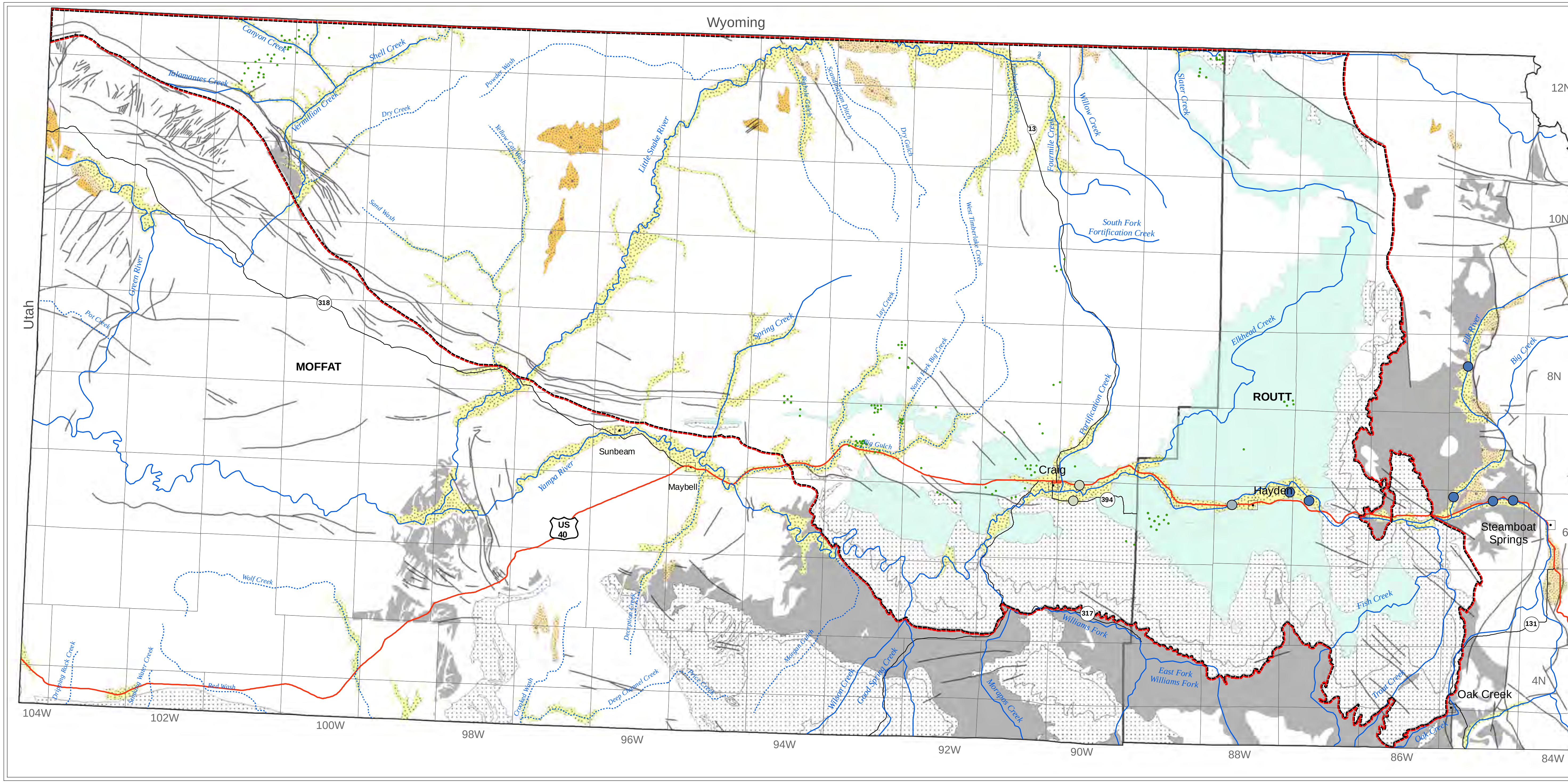
Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 5.5 Total Dissolved Solids and Sodium Adsorption Ratios in Yampa Basin Surface Water



Legend

- Mesaverde Group oil-gas wells in USGS CBM unit
- Sand Wash Basin outline, base of Mesaverde Group
- Faults
- Lewis-Foxhills-Lance
- Mancos Shale
- Mesaverde Group Outcrop

Sodium Adsorption Ration (SAR)

- < 10
- 10 - 18
- 18 - 50
- 50 - 100
- >100

Total Dissolved Solids (TDS)

mg/L

- < 500
- 500 - 1000
- 1000 - 2000
- 2000 - 3000
- 3000 - 5000
- 5000 - 10000
- >10000

0 2.5 5 7.5 10 Miles

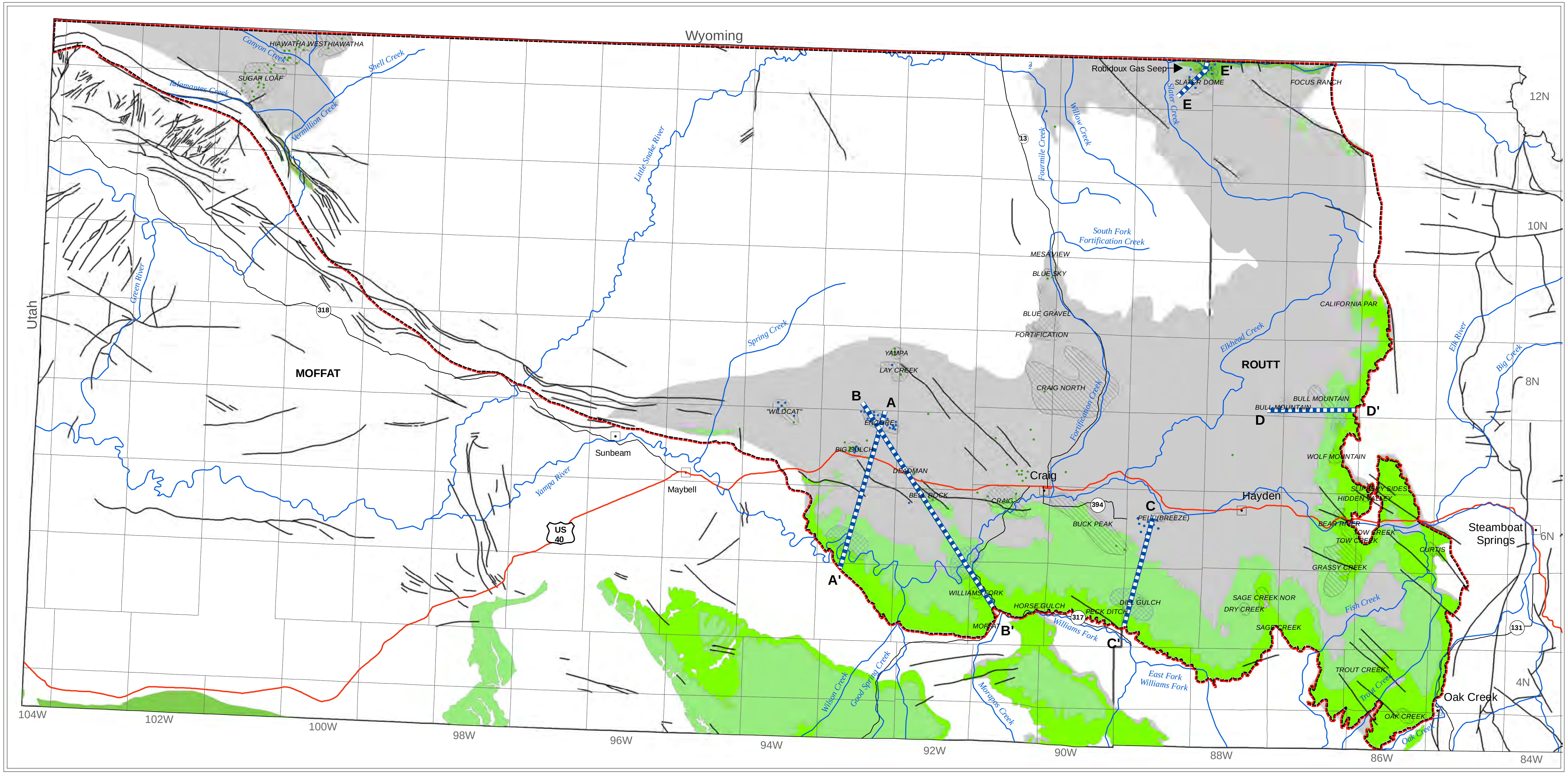
Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 5.6 Total Dissolved Solids and Sodium Adsorption Ratios in Alluvial Groundwater



Legend

- CBM well with a record of water production
- Mesaverde Group oil-gas wells in USGS CBM unit
- Sand Wash Basin outline, base of Mesaverde Group
- Faults
- A—A' Potential groundwater pathway alignment and line of cross section
- Oil and gas fields in USGS CBM unit
- Area where surface water could be impacted by CBM water extraction
- Williams Fork Formation outcrop
- Iles Formation outcrop
- USGS Mesaverde CBM unit

0 2.5 5 7.5 10 Miles

Scale: 1: 500,000

Projection: Universal Transverse Mercator, Zone 13

Datum: North American Datum 1983

N

Figure 5.7 Map of Potential Connections Between CBM Production Areas and Surface Water Resources

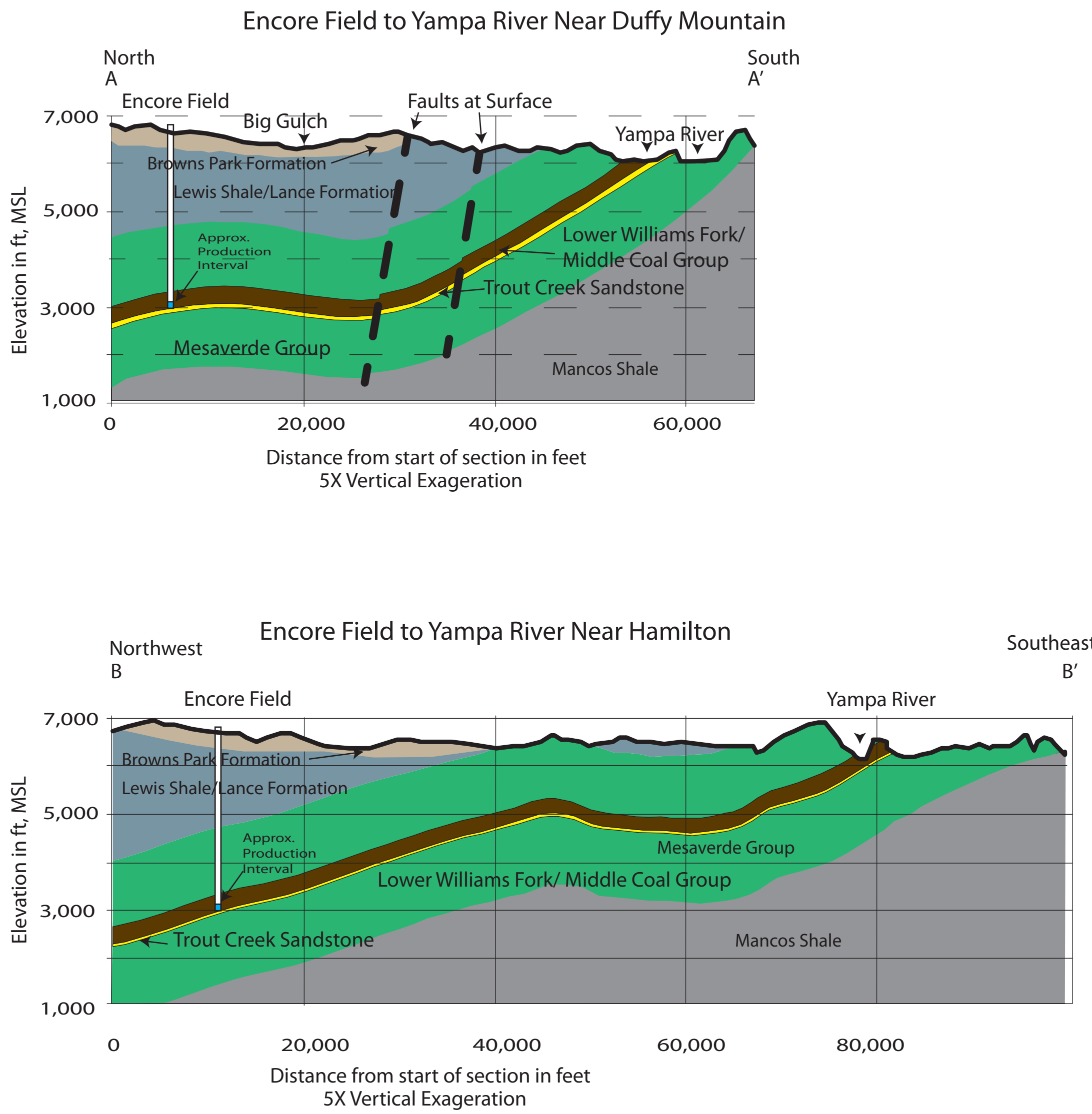


Figure 5.8 Cross-sections of Potential Connection from Encore Field to Surface Water Resources. Diagrammatic cross-sections show stratigraphic relationships and general structure between CBM production interval at Encore Field and surface water; specifically the Yampa River. See Figure 5.7 for cross-section alignments. Upper section shows that the shortest pathway crosses faults which can be barriers to flow. Lower section shows a longer pathway that parallels the structural grain and fracture trends observed in brittle sandstone layers. The Trout Creek Sandstone underlies the coal-bearing interval and is considered a regional aquifer. Depths and stratigraphic thicknesses are approximate. Sources: Tweto (1976), and CGS structural maps for BLM study.

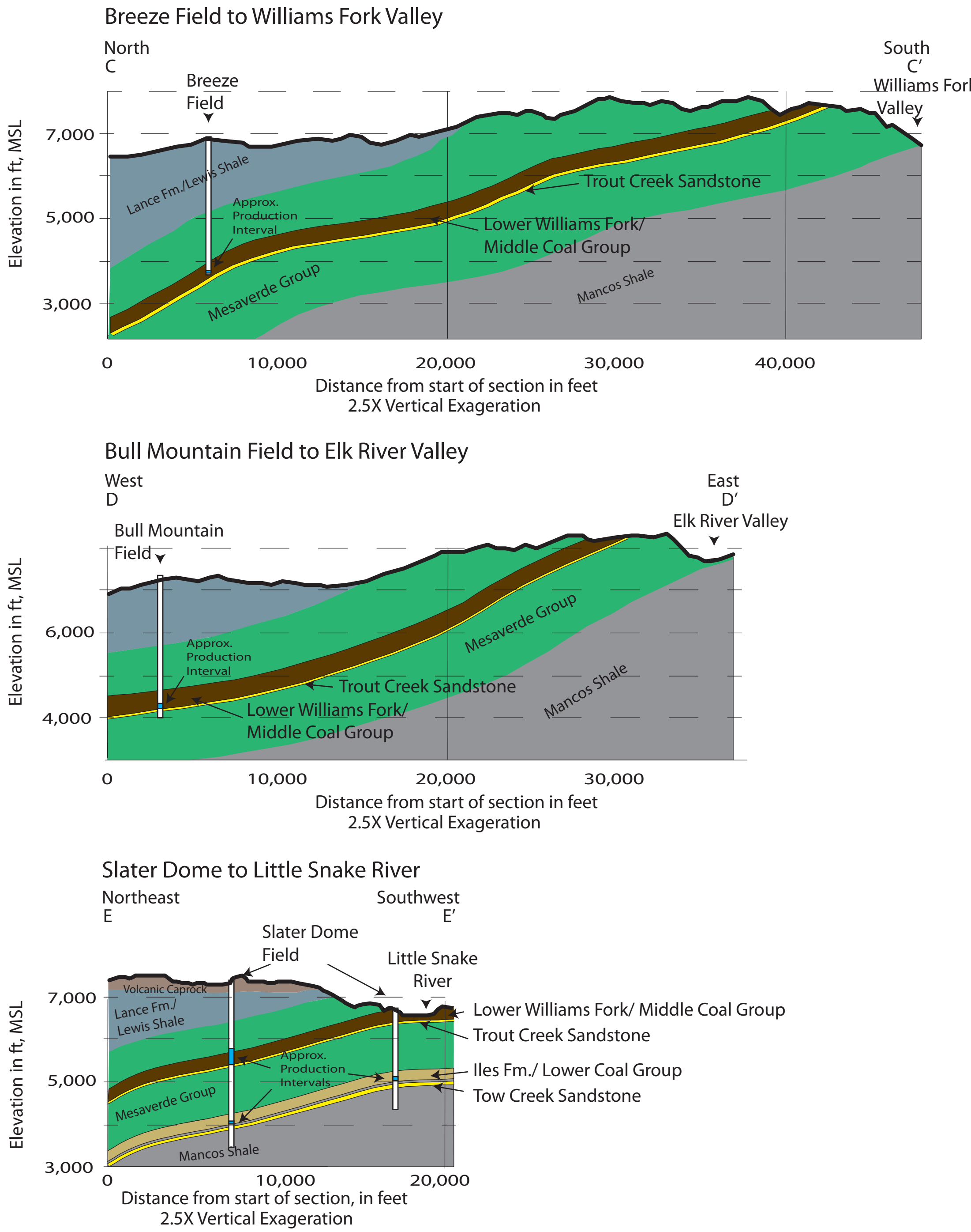


Figure 5.9 Cross-sections of Potential Connection from Slater Dome, Breeze, and Bull Mountain Fields to Surface Water Resources. Diagrammatic cross-sections show stratigraphic relationships and general structure between CBM production intervals at Breeze, Bull Mountain, and Slater Dome Fields and surface water resources. The Tow Creek and Trout Creek Sandstones underlie the coal-bearing intervals and are considered regional aquifers. Depths and stratigraphic thicknesses are approximate. See Figure 5.7 for cross-section alignments. Note that horizontal scale is larger than in Figure 5.8 for Encore Field. Sources: Tweto (1976), and CGS structural maps for BLM study.

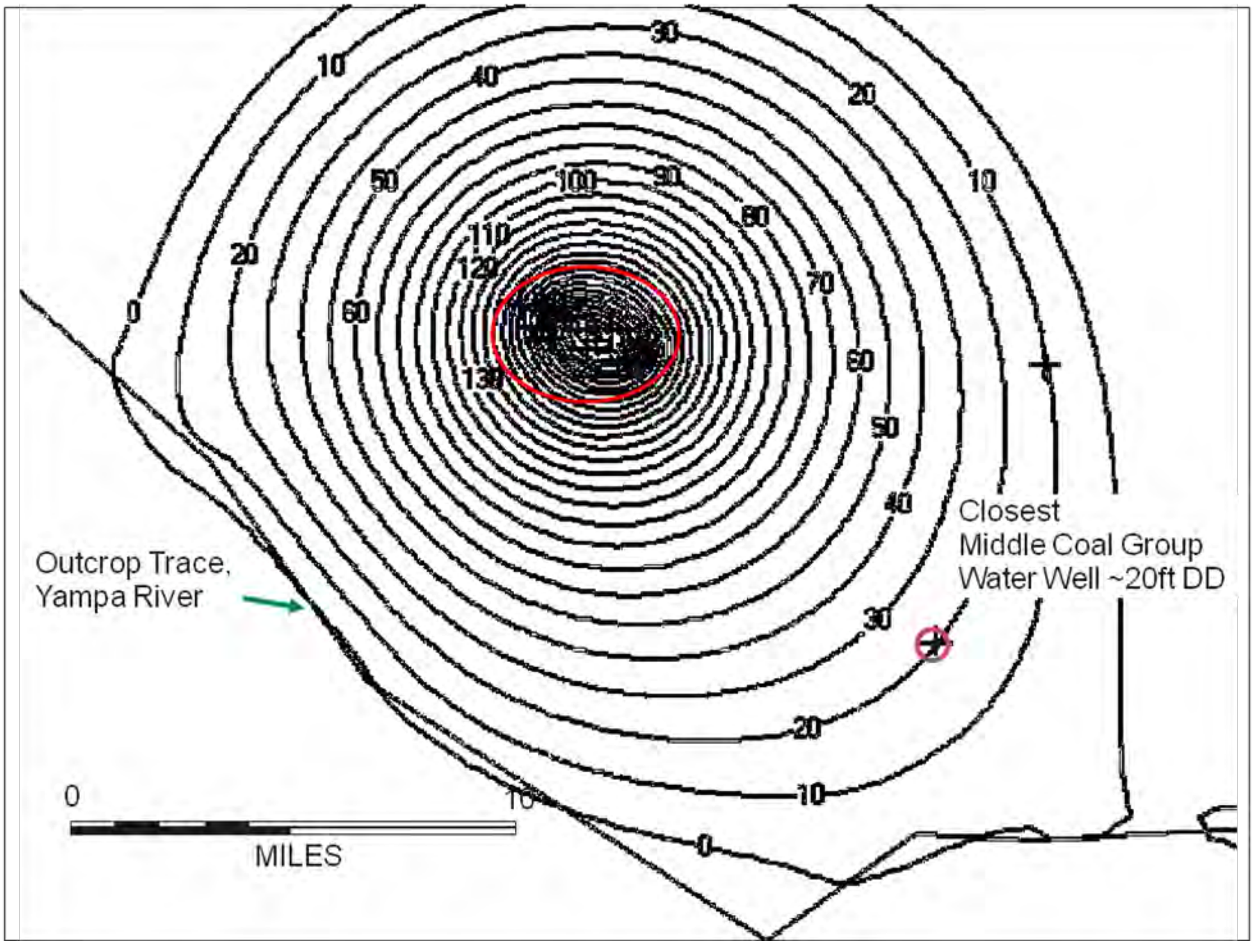


Figure 6.1. Steady-state Drawdown Plot for Encore Field without Fault Barriers. Drawdown contours drawn at a ten-foot interval center around the Encore wellfield with all wells pumping at rates calculated from monthly water production totals. Oval shape is driven by the outcrop trace constant head boundary. Drawdown at the closest water well completed in the same stratigraphic interval is about 20 feet. The TWODAN® model uses general aquifer parameters and assumes a uniform and isotropic aquifer. Results should be considered qualitative.

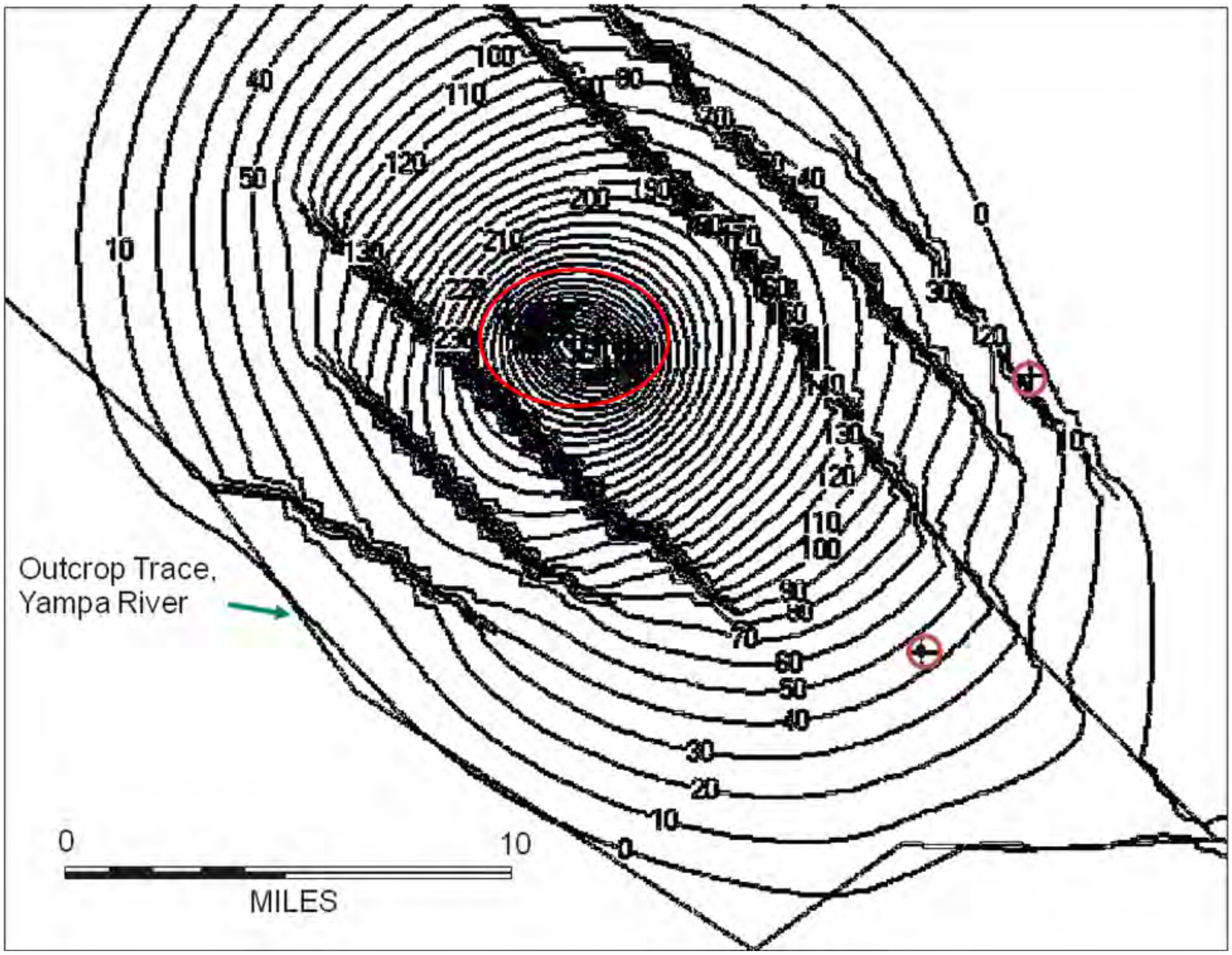


Figure 6.2. Steady-state Drawdown Plot for Encore Field With Mapped Fault Barriers. Drawdown contours drawn at a ten-foot interval center around the Encore wellfield with all wells pumping at rates calculated from monthly water production totals. Traces of mapped surface faults deflect contours and fragment the surface. Drawdown at the closest water well completed in the same stratigraphic interval is now about 45 feet. A well the same distance away, but across three fault barriers shows less than 5 feet of drawdown. Drawdown within the same block is enhanced while drawdown outside is reduced. The TWODAN® model uses general aquifer parameters and assumes a uniform and isotropic aquifer. Results should be considered qualitative.

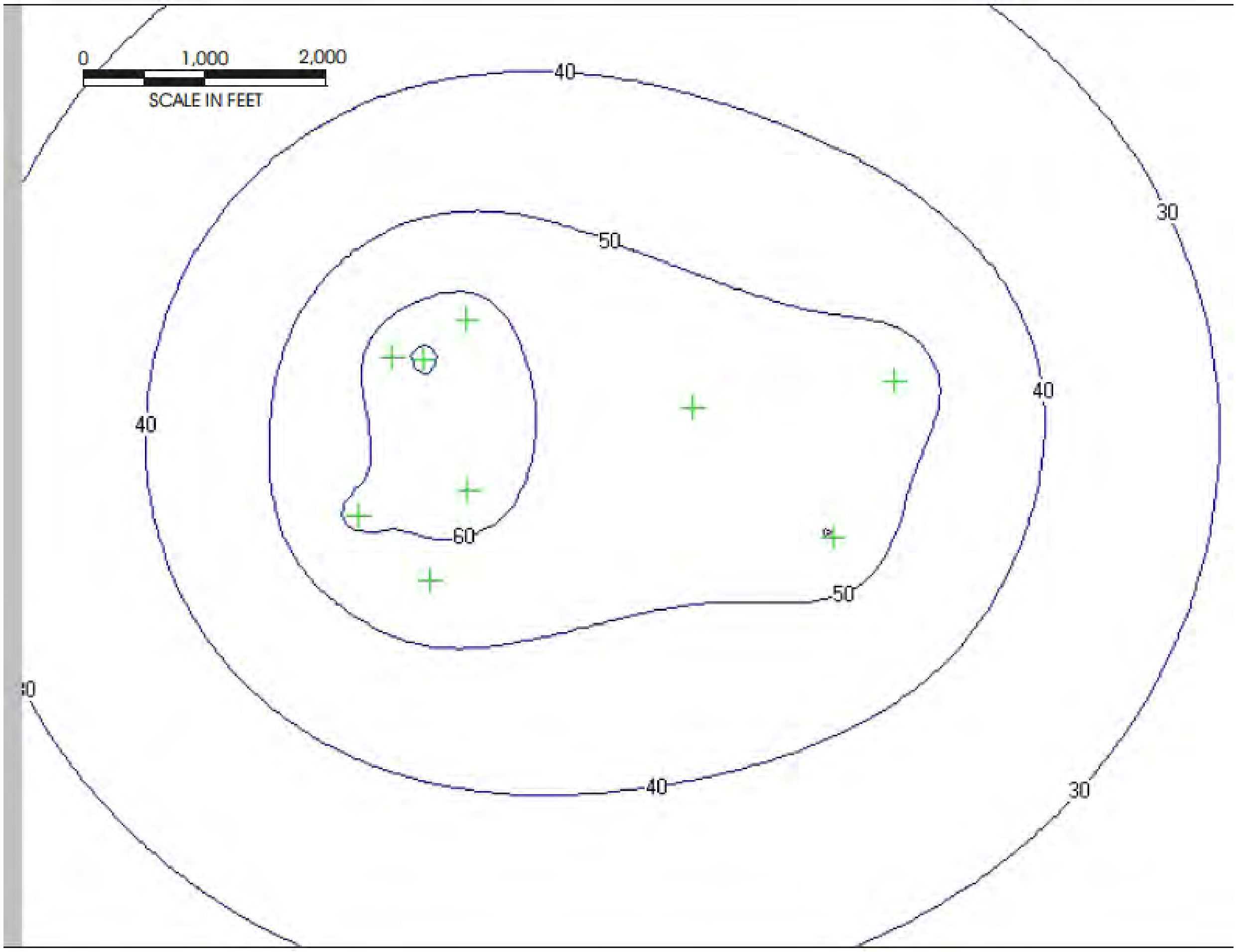


Figure 6.3. Steady-state Drawdown Plot for Section 20 with Wells Pumping at Reported Yields. Drawdown contours drawn at a ten-foot interval show combined interference around close-spaced domestic wells. Domestic well permits list yields based on short-term pump tests or simply listed permitted rate. Rates exceed rates based on annual appropriations and allow peak usage. Note the difference in scale compared with the Encore scenario in Figures 6.1 and 6.2. The TWODAN® model uses general aquifer parameters and assumes a uniform and isotropic aquifer. Results should be considered qualitative.

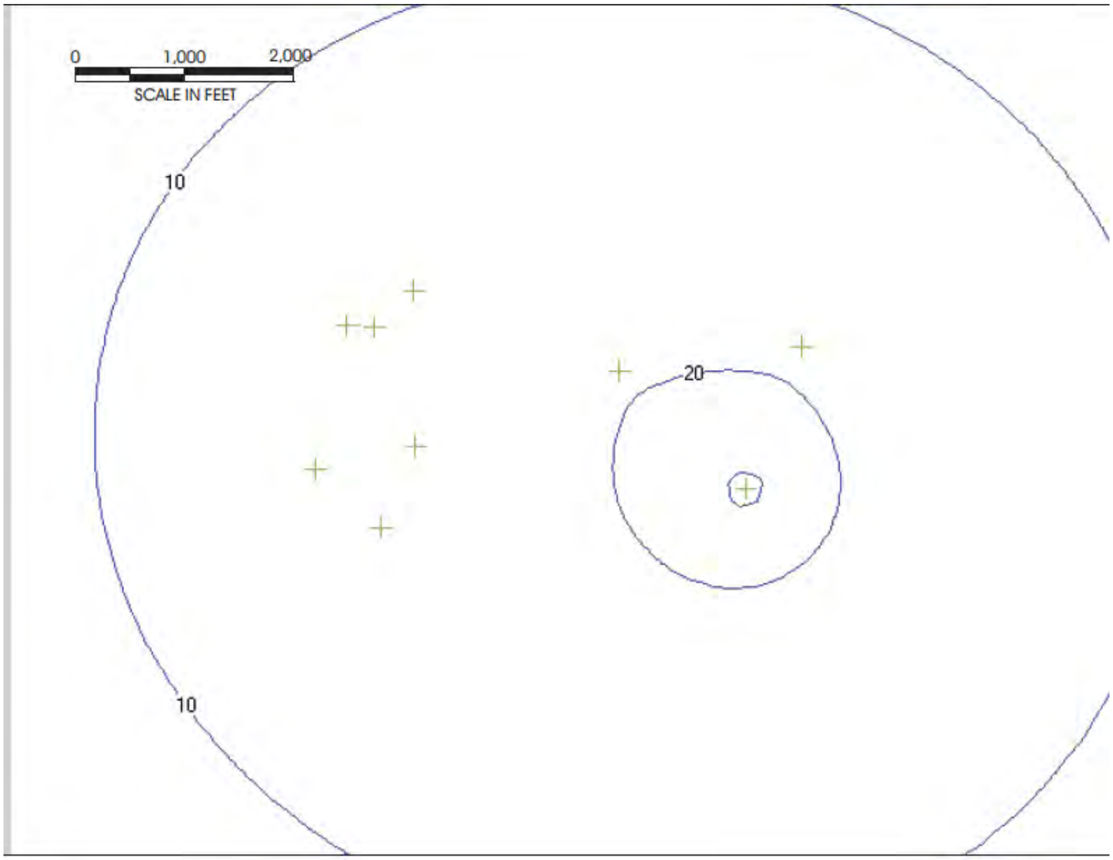


Figure 6.4. Steady-state Drawdown Plot for Section 20 with Wells Pumping at Appropriated Rates. Drawdown contours drawn at a ten-foot interval show combined interference around the close-spaced wells. Domestic well permits have a maximum allowed annual volume and rates calculated for those volumes are lower than reported yields. Contours now center around well with highest annual appropriation and drawdown in the area between wells is on the order of 10 to 25 feet. Note the difference in scale compared with the Encore scenario in Figures 6.1 and 6.2.The TWODAN® Model uses general aquifer parameters and assumes a uniform and isotropic aquifer. Results should be considered qualitative.

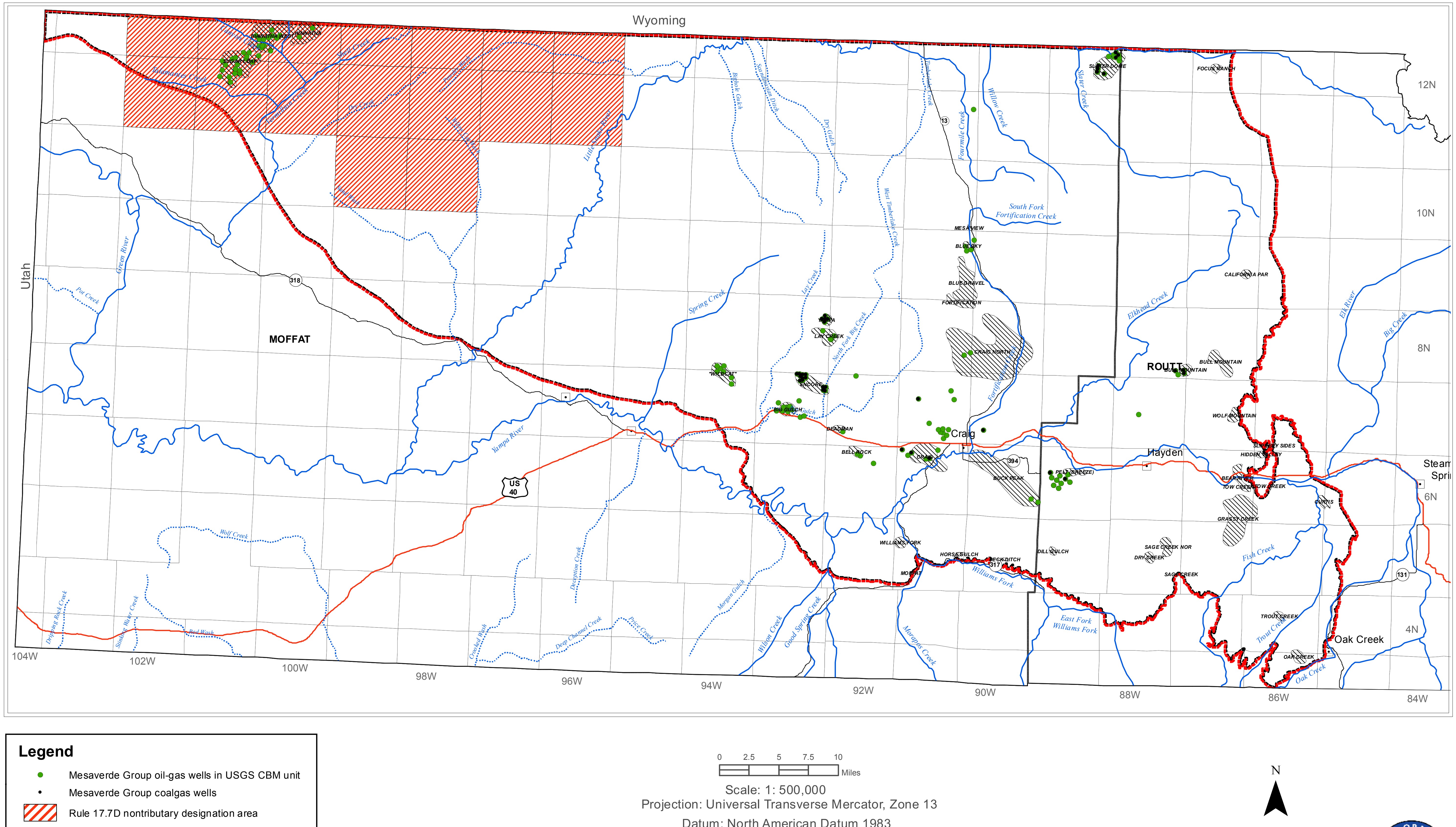


Figure 7.1 Nontributary Designated Area for Western Sand Wash Basin.

Table 6.1
Summary of Mesaverde Group Hydraulic Property Data

Stratigraphic Interval	Transmissivity (ft2/d)		Thickness (ft)		Hydraulic Conductivity (ft/d)		Storage Coefficient (unitless)		Basin Location/Source of data
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	
Lower Williams Fork Fm.	121-147	134		23	5.3-6.4	5.8			SE margin/ Well 164261 pump test by CGS 11/09
Lower Williams Fork Fm. Wadge seam and overburden/underburden	0.7-43	12.8	11-157	56	0.02-0.6	0.3		1x10^{-3}	SE margin, outcrop belt/ Robson and Stewart, 1990
Iles Fm. Trout Creek Sandstone	1-2,800	21.5	106-532	250	0.006-6	1.9			SE margin, outcrop belt/ Robson and Stewart, 1990
Upper Williams Fork Fm. Twentymile Sandstone	50-3,000	973	110-210	144	.4-10	2.3			SE margin, outcrop belt/ Robson and Stewart, 1990
Iles Formation Coal-bearing strata	NL	-	NL	-	0.27-3.2	1.2			Northeast corner/ Slater Dome New Frontier Energy
Laramie-Fox Hills Aquifer, Denver Basin							1x10^{-2} - 1x10^{-4}		Denver Basin/ Robson, 1987
Used in Analytical Model					**0.5 - 2.5**		**1x10^{-3}**		

Table 6.2
Head Drawdown Estimates For a Single Encore CBM Well Under Transient Flow Conditions

Time Step (years)	Estimated Drawdown[1)] (ft)		
	Pumping Well	1-Mile Distance	Nearest Kmv Well
1.	106	12	<1
8	119	23	<1
30	127	33	5

Notes:

1. Using the lower hydraulic conductivity of 0.5 ft/day to maximize drawdown effects.

Table 6.3
Head Drawdown Estimates For the Encore CBM Wellfield Under Transient Flow Conditions

Time Step (years)	Estimated Drawdown [1] (ft)					
	113 gpm well	Field Centroid	1-Mile Distance	Well at 9-miles	Well at 9-miles In Fault Block	Well at 9-miles Out of Fault Block
1	73-277	45-145	21-42	<1-1		
8	95-379	65-245	42-128	8-11		
30	108-445	85-312	55-192	23-41		
Steady State With Boundaries [2]	129-514	100-360	78-260		15-44	<1-2

Notes:
1) Using two values for hydraulic conductivity of 2.5 and 0.5 ft/day for a range of drawdown effects, higher hydraulic conductivity yields lower drawdown estimates.
2) Barriers for mapped surface faults, constant-head linesinks for outcrop belt.

APPENDIX A
SOURCES OF DATA

Geographic and Geologic Data

The Sand Wash Basin topographic, hydrographic and cultural details were obtained from public domain sources from the USGS, CGS, DWR and COGCC. Medium-resolution National Hydrography Datasets for the Yampa River basins, including tributaries present in the Sand Wash Basin, were obtained from the USGS. Coordinates of wells and other hydrologic measurement stations were obtained from the USGS National Water Information System (NWIS) online database (http://waterdata.usgs.gov/nwis/). CGS retains geologic data, in the form of GIS shape files and Petra® project files, generated during the CBM resource study conducted for the BLM in 2005. Additionally, relevant spatial layers were obtained from the USGS total petroleum assessment digital datasets (USGS, 2005). Coordinates were obtained for water supply and CBM production wells in the Sand Wash Basin from the DWR and COGCC, respectively.

Well Production Data

COGCC maintains oil, gas, and CBM well production data and their databases are available for browsing on the internet at http://oil-gas.state.co.us. COGCC provided CGS with monthly oil and gas production data assembled from pre-1999 lease production and post-1999 well production databases. Data covered wells perforated in, and producing from, the coal seams of the Mesaverde coal groups and Fort Union Formation.

Water Level Data

Water level data in the Sand Wash Basin for the Fort Union Formation and Mesaverde Group in general, and for the coal-bearing intervals in particular, are sparse with the exception of permitted water wells in the outcrop areas. Well completion reports filed with the DWR often list initial water level measurements for water wells. The permit database included over 3800 permitted water wells within the Basin. Of these, 86 were identified as being completed in the Fort Union Formation and 246 were found to be completed in the Mesaverde Group coal-bearing intervals. These water level measurements span a period from 1961 through 2007 and are the only comprehensive widely distributed set of water level measurements known to be available for these stratigraphic intervals.

A regional potentiometric surface map of the Upper Mesaverde formation was prepared by Scott and Kaiser (1994) for the basin interior using equivalent fresh-water heads for the Upper Williams Fork Formation. Scott and Kaiser (1994b) also provided equivalent fresh-water heads for the Fort Union Formation for the basin interior but did not contour due to a limited set of data and poor hydraulic connection within the strata.

Stream and Spring Data

Stream and spring flow data maintained by the USGS were obtained from the website http://waterdata.usgs.gov/nwis/. Twenty springs were identified in the USGS dataset as originating within the Mesaverde Group outcrop area; none were identified within the Fort Union Formation outcrop area. Locations of 97 surface water monitoring stations were identified in the area that extends beyond the outline of the Mesaverde Formation to capture streams entering and exiting the basin.

Water Quality Data

Water quality data were obtained primarily from COGCC databases, USGS sources, and field sampling performed as part of this study. COGCC produced water sample data were provided specifically for this study and USGS water quality data for streams, springs, and various types of wells from the USGS and can be access from the website http://waterdata.usgs.gov/nwis/. References to water quality data from near-outcrop areas are also available in other reports on file with the Division of Reclamation and Mine Safety (DRMS); most relating to coal mining permitting and operations, and were reviewed for this study (e.g., Eagle Mine, Foidel Creek Mine, Seneca Mine, and Trapper Mine).

BLM provided CGS with data files from the Norwest study in 2005 and water quality data were included in these files. This set of water quality data were integrated with USGS and COGCC data for this study.