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The Significance of the Pinedale Field

Thomas Meyer
Santos Ltd., Adelaide, South Australia, Australia (e-mail: thomas.meyer@santos.com)

Mark Longman
QEP Resources, Inc., Denver, Colorado, U.S.A.
(e-mail: mark.longman@qepres.com)

INTRODUCTION

Pinedale field is located in the northern part of the Green River Basin in western Wyoming about 90 mi (145 km) southeast of Jackson, Wyoming, near the town of Pinedale (Figure 1). It is one of the largest natural gas fields in the United States with ultimate recoverable reserves estimated to be about 39 trillion cubic feet (tcf) of methane-rich natural gas. Despite the huge gas reserves, the field's productive areal extent is relatively small as it is only about 30 mi (48 km) long and less than 5 mi (8 km) wide. The field covers an area of about 84 mi^2 (220 km^2). In this sense, it is a very concentrated gas resource.

Production at Pinedale comes from the Lance Pool, which is nearly 6000 ft (1800 m) thick and consists of multiple stacked discontinuous Upper Cretaceous Lance and upper Mesaverde sandstones and siltstones that were predominantly deposited by fluvial processes and are encased in shales and mudstones. The reservoir rocks in Pinedale field occur at depths of about 8500 to 14,500 ft (2600–4400 m) and are tight with fairly low porosity (mostly $<10\%$) and very low (micro-Darcy) permeability. The tight nature of these reservoir rocks makes it difficult for gas to move laterally and vertically for significant distances. As a result, it is necessary to conduct multistage hydraulic fracturing in all of the field's wells to create pathways for the gas to enter the wellbores at commercial rates.

The tight nature of the reservoir rocks at Pinedale begs the question: "What makes Pinedale such a prolific natural gas field?" The field has some unique geologic characteristics. Production is reliant on a complex interplay of geologic factors, including structure, reservoir sandstone and siltstone thickness, porosity development, permeability, and reservoir pressure, which are in turn related to sedimentary facies, diagenesis, water saturation and its control on relative permeability to gas, and possibly fracture size, density, and distribution. Added to these geologic parameters is the overprint of hydraulic fracture stimulation, which is done in every well. The Pinedale reservoir interval has about 1 billion cubic feet (bcf) of gas in place per acre. This high concentration of gas is in part due to the tremendous thickness (~6000 ft, 1800 m) of the gas-saturated Lance and upper Mesaverde sections that comprise the Lance Pool. The gas volume is also enhanced by the overpressured character of the reservoir with pressures grading from about 0.57 psi per foot near the top of the Lance Pool up to 0.85 psi per foot near its base in parts of the field. In addition to the field's geologic characteristics, technological advances, particularly in drilling and hydraulic fracturing, have helped to release the gas trapped in the Lance Pool. Finally, high-density drilling, as dense as one well for five acres, has allowed for significantly improved recovery of natural gas from these tight reservoir rocks.

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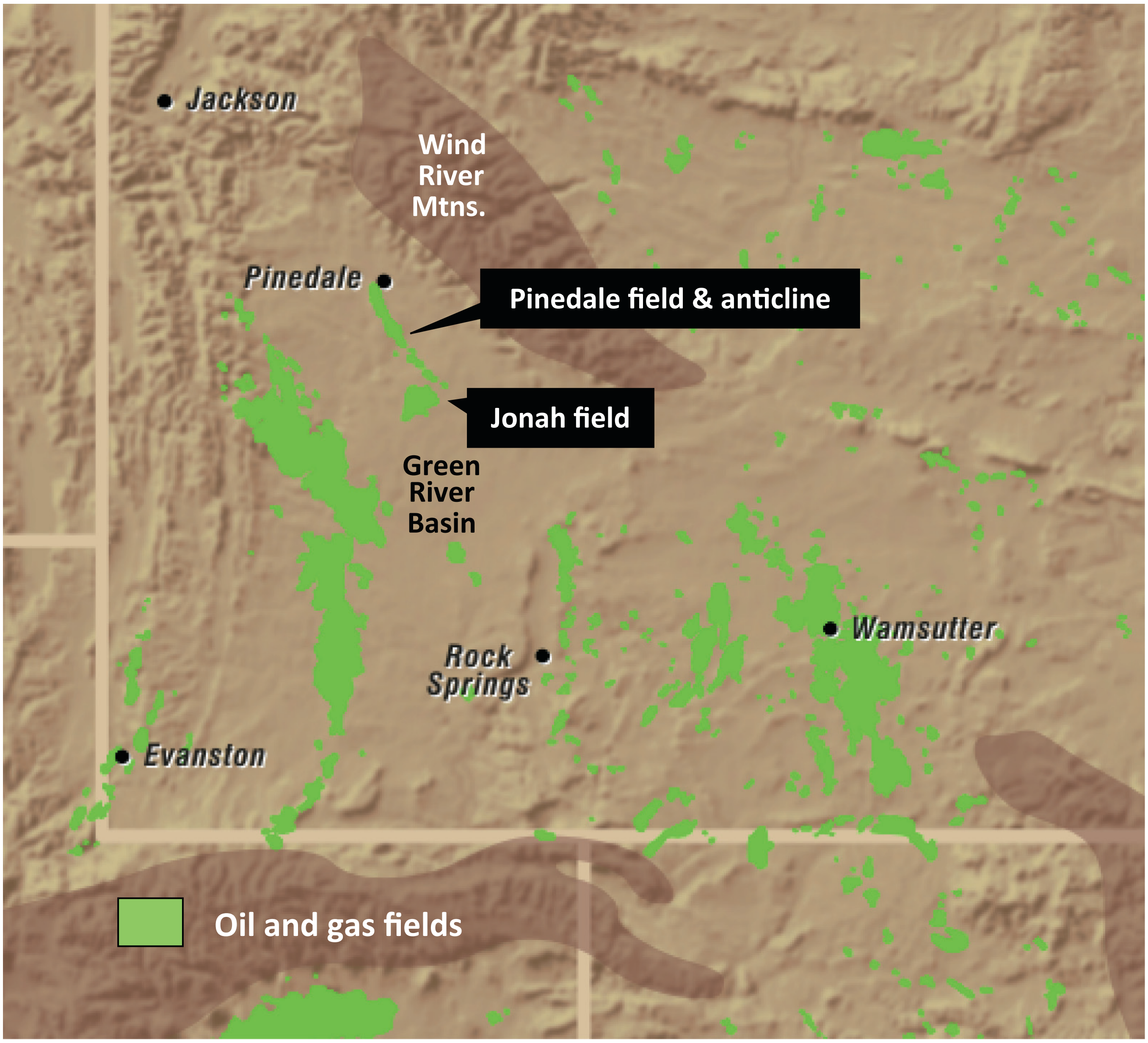

Figure 1. Location of the Pinedale field in the northern part of the Green River Basin just south of Pinedale, Wyoming. The field has a relatively small areal extent for its reserves, which are estimated at about 39 tcf of recoverable gas.

Pinedale field has had a long development history, which is described in detail in the following chapter by Kneller, Matheny, Albertus, and Riggs. The Pinedale anticline was first recognized from surface mapping in the early 1920s. The first well drilled on the anticline for hydrocarbons was the California Company's Government #1 drilled in 1939 and 1940. This well had gas shows in what is now recognized as the Lance Formation, but it tested at noncommercial rates and was eventually plugged and abandoned. Over the following 55 years, a number of other companies also attempted unsuccessfully to "crack the code" to produce economic quantities of natural gas from the micro-Darcy reservoir rocks within the anticline. However, it was not until the late 1990s when multistage hydraulic fracturing techniques that had been successfully employed in the nearby Jonah field, which lies just south of Pinedale field (Figure 1), were brought onto the anticline that commercial production was established. These techniques finally allowed Pinedale operators to stimulate sufficient volumes of this extremely tight rock to allow gas to flow at commercial rates. Simply stated, it was technological advancements and innovative thinking that led to the commercialization of the Pinedale field.

Today Pinedale is resource-wise and economically a very significant natural gas field. Through 2012, the field had produced 3.9 tcf of gas and 29.5 million barrels of condensate from 2200 wells. In 2012 alone, Pinedale produced 533 bcf (1.5 bcf per day), which is enough to heat 5.3 million homes, along with over 3.8 million barrels of condensate. This makes Pinedale not only the largest gas field in the state of Wyoming but also the second largest oil field. Today Pinedale has become a major part of America's energy supply, producing over 2% of the United States' demand for natural gas.

SIGNIFICANCE OF THE PINEDALE FIELD

Pinedale is special not only because of its geological characteristics and its size but also because of the efficiency in operations that the field's operators have achieved. As a result, it has become the model for tight gas sandstone development in fields around the world. In addition, Pinedale has been groundbreaking on environmental and regulatory issues, particularly in the creative ways that industry has worked with government and environmental regulators to shape policy and regulations that benefit both industry and the environment. Pinedale became the first major greenfield development in the United States in an environmentally sensitive area with thousands of wells planned on hundreds of pads. Furthermore, the field was only 10% developed when the Supplemental Environmental Impact Statement (SEIS) process was started in 2005.

The SEIS was one of the first Bureau of Land Management (BLM) documents built around the concept of adaptive management, meaning that the rules could be adjusted to reflect actual on-the-ground outcomes. Pinedale was also one of the first examples where companies voluntarily acted in a coordinated way for the benefit of both the environment and industry. This was truly unusual given that, other than Ultra Petroleum, no single operator had an interest in the other operators' wells.

A very innovative regulatory plan granting "limited year-round access" was cooperatively developed by the BLM and Pinedale operators and incorporated in the 2008 Record of Decision to the SEIS in exchange for environmental mitigations that cost the three major operators in the field (Ultra Petroleum, Questar/QEP Resources, and Shell Western E & P) over $1 billion. These mitigations included focusing year-round operations on pads within concentrated development areas, reducing air emissions, and installation of liquids gathering systems (LGSs) to reduce truck traffic to and from the anticline. Limited year-round access allowed Pinedale operators to operate within focused development areas throughout the year. Within these concentrated development areas, seasonal stipulations for big game animals and sage grouse are waived. Development progresses in a stipulated development pattern and reclamation is done after pads are fully developed. In each of the defined development areas, set development patterns exist. This ensures that at any one time, 92% of the anticline has no development activity. It also benefits wildlife in that it reduces habitat fragmentation by focusing operations, maintaining corridors for wildlife migration, and shortening the time for full field development. In addition, it leaves large areas of contiguous habitat available for migration corridors and places for animals to forage, rest, and reproduce.

The ability to operate year round within a concentrated development area benefits industry, the environment, the people of Wyoming, and wildlife. It provides continuity to operations that leads to efficient application of technology, which allows operators to drill more wells per rig with less emissions per well, and to fully develop the resource. It also makes it feasible to use the latest technologies to reduce emissions such as installing LGSs, applying selective catalytic reduction (SCR) devices to rig engines to reduce emissions of nitrogen oxides to near zero, and consolidating production facilities. Continuity of operations also promotes a stable workforce with steady employment and a consistent tax revenue stream for the state of Wyoming.

The continuity provided by year-round access led to significant performance improvements in drilling and completion efficiencies. Average drilling times have dropped from more than 60 days per well in the early 2000s to less than 12 days per well in 2013. In recent years, some wells have even been drilled to depths of over 14,000 ft (4300 m) in less than nine days (Figure 2).

The decline in drill times can be attributed to a number of factors including fit-for-purpose rigs, improved drill-bit technology, drilling wells with oil-based mud instead of water-based mud, consistently trained and experienced crews, use of down-hole mud-motors and steerable assemblies, new slim-hole well designs, multiwell pad drilling, and removing steps from the critical path of the drilling rig. Similar performance gains have been seen on the completions side where wells once took more than a month to complete. Now a pair of wells can be completely fracked with over 20 frack stages per well within four or five days. These efficiencies have given

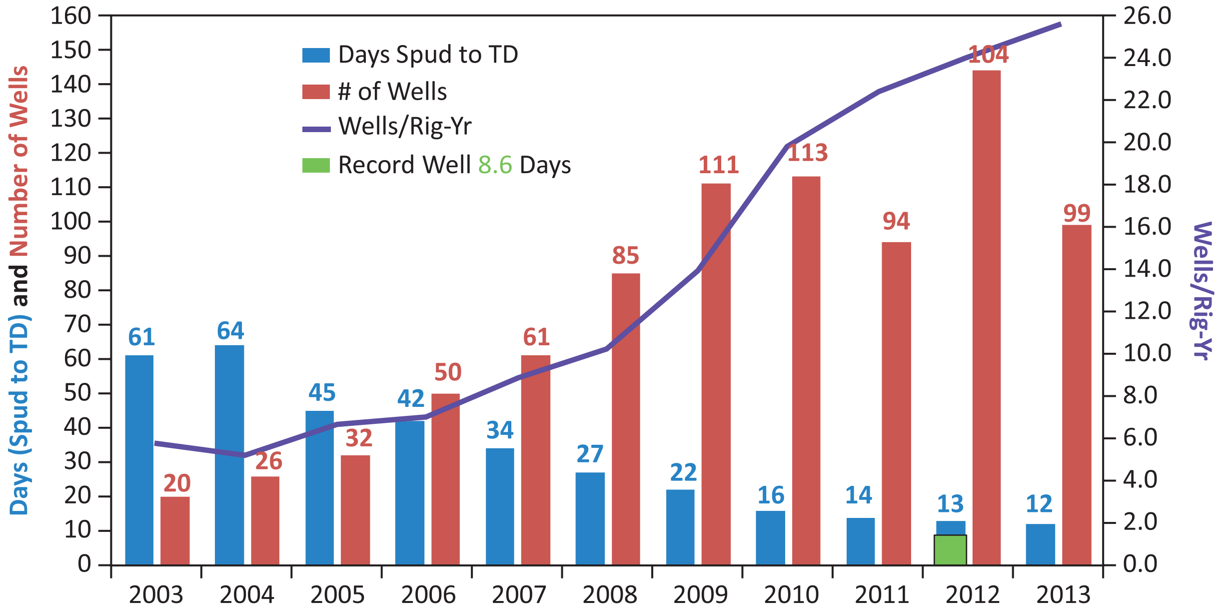

Figure 2. Average drill times from spud to attaining total depth (blue bars) for wells drilled by QEP in Pinedale field. With improved drill bits, mud systems, and crew efficiency, drill times decreased by more than 80% between 2003 and 2013. Also shown are the number of wells drilled each year (brown bars) and the wells per rig per year (purple line). The green box shows the record well drilled in just 8.6 days in 2012. Data in part from QEP Resources investor relations presentation (http://media.corporate-ir.net/media_files/IROL/23/237732/QEP1Q13OpsSlides.pdf accessed July 3, 2013).

Pinedale operators a cost advantage that has expanded the economic limits of the field and allowed for full field development through high density drilling.

Simultaneous operations (SIMOPS) are also now being done by all the major operators in Pinedale field with drilling, hydraulic fracturing, and facilities installations occurring at the same time (Figure 3). In order to fully develop the resource, wells are being drilled on dense spacing of as little as five acres per well. This makes Pinedale field one of the first places with such high-density pad drilling. Well bores are gently S-shaped and are drilled on pads to reduce the surface disturbance, which allows the development of a relatively large subsurface volume from a relatively small surface area (Figure 4).

PAD DRILLING IN PINEDALE FIELD

High-density development is conducive to *pad drilling*. In Pinedale field, the operators drill gently S-shaped directional wells from central surface pads. This is a technology that was originally developed for drilling offshore wells from a central platform, but that is now being applied onshore. Wells are arranged in pods of two to eight wells on a pad. Up to 50 wells can be drilled on an individual pad so that the physical footprint of operations and wildlife habitat fragmentation are minimized.

Pad drilling along with timely reclamation has allowed all Pinedale field operators to reduce disturbance of the land. As field development has progressed and the number of wells per pad increased, the disturbance per well has continued to decline. Surface disturbance per well is now less than one acre on some multiwell pads (Figure 5).

ENVIRONMENTAL CONCERNS

Pinedale operators have addressed a number of environmental concerns through new technologies and best management practices. Pinedale operators take air quality issues, particularly ozone, very seriously. Industry deals with ozone by reducing the volumes of volatile organic carbons (VOCs) and nitrous oxide (NOx) emissions, both of which are precursors to ozone formation. Pinedale operators had installed SCR devices on all of their rig engines by year-end 2011 to reduce NOx emissions, and, as previously mentioned, they also reduced VOCs by installing LGSs, which eliminated truck traffic, dust pollution, and associated emissions. These systems also eliminate the need for

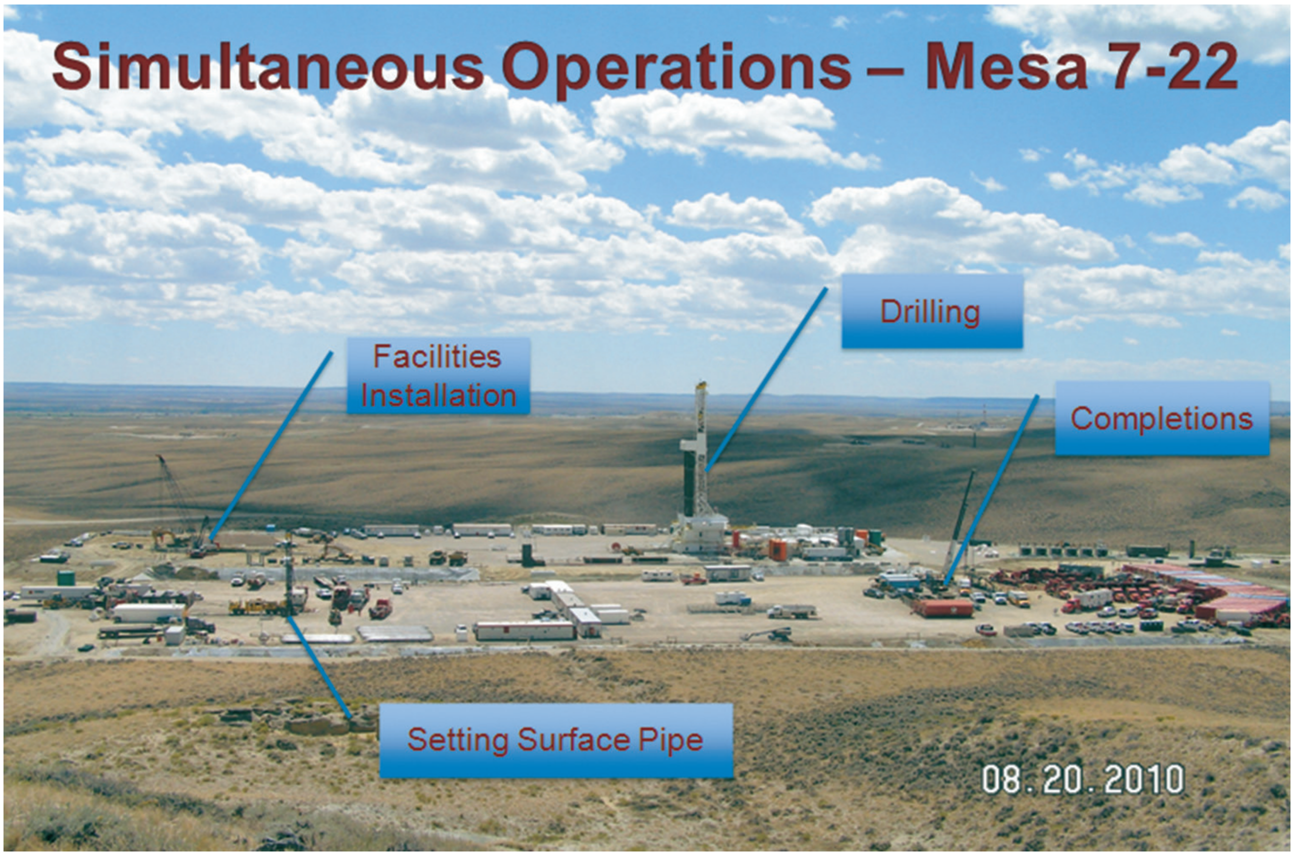

Figure 3. Simultaneous operations being conducted in Pinedale field with drilling, fracking, setting of surface pipe, and facilities installation all occurring concurrently.

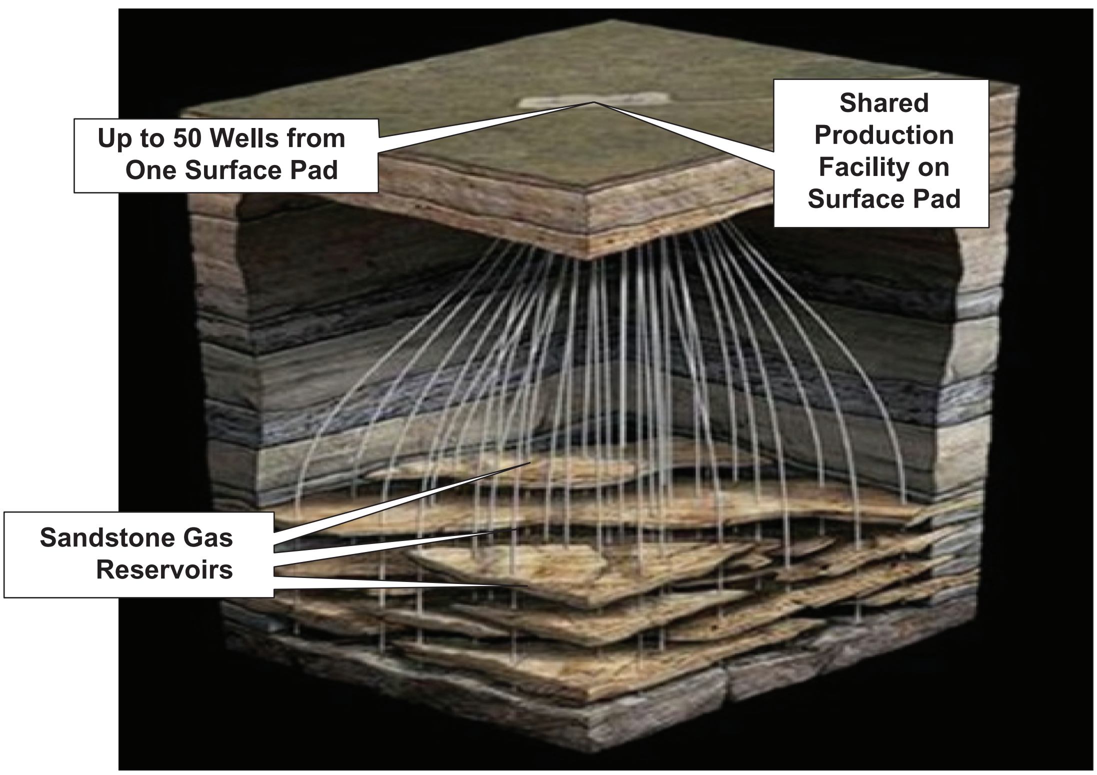

Figure 4. High-density pad drilling allows development of a large subsurface volume of the gas resource with minimal impact to the surface environment.

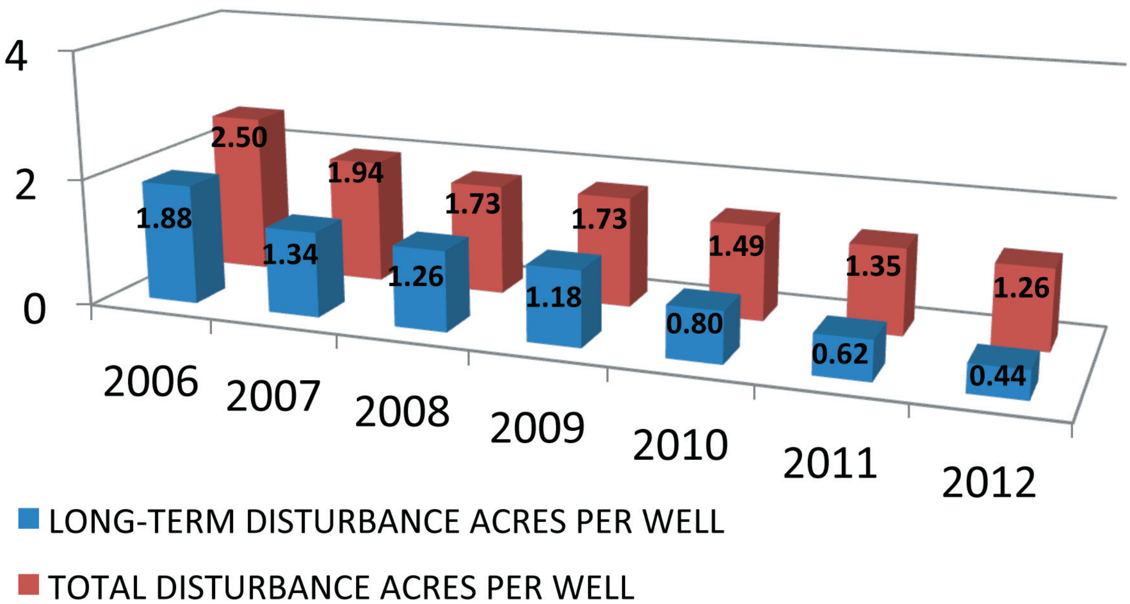

Figure 5. Total disturbance per well and long-term disturbance per well continue to decline with improved drilling techniques such as the pad drilling now being used to develop Pinedale field.

storage tanks and their associated VOCs. As well, the LGS has allowed operators to recycle their produced water and reuse it in fracking operations. This reduces the amount of water taken from local freshwater aquifers. Furthermore, in Pinedale operators do flareless completions. Rather than flaring gas during completions, they route the gas to sales during flowback, thereby eliminating emissions. And on days where Wyoming's Department of Environmental Quality determines that atmospheric conditions are ripe for ozone formation, Pinedale operators cancel all nonessential operations. The concentrated nature of production operations in the field along with the ability to conduct limited year-round activity make it feasible to consolidate facilities and employ these advanced emission-cutting technologies.

Pinedale field is a giant natural gas resource with unique geologic characteristics. Because of the advanced application of technology and innovative thinking, Pinedale has become the model for modern tight gas development in the United States and throughout the world. It is an efficient "gas factory" where the attention is on fully developing the natural gas resource economically and effectively, without waste, in a safe manner, with focus on the environment, wildlife, and the socioeconomic benefits for the people of the area. Many of the innovative practices developed in Pinedale have been and are being applied elsewhere around the world.

ABOUT THIS BOOK

We had two major purposes for compiling this volume on the Pinedale field. The first is to document how the development of a giant onshore field, be it oil or gas, requires the integration of knowledge and skills from many teams of people, including geologists, engineers, drillers, land, environmental, and so on to be successful. The second was to provide a venue for sharing previously unpublished and/or proprietary data on Pinedale field with other interested parties.

In Chapter 2, Stephen Kneller, Paul Matheny, Jerry Albertus, and Elliott Riggs discuss the discovery and exploration history that led to the development of Pinedale field. They describe how the efforts of many people and companies over a period of more than 60 years led to the commercialization of the field through a better understanding of its geology and the application of modern drilling and completion practices.

In Chapter 3, titled "The Pinedale Gas Field: A Sweet Spot in a Regionally Pervasive Basin-Centered Gas Accumulation, Green River and Hoback Basins, Wyoming," Ben Law and Charles Spencer propose that the Paleocene's "unnamed unit" overlying the Lance Formation that they described back in the 1980s be officially recognized as the Wagon Wheel Formation. The Wagon Wheel Formation does not crop out anywhere around the northern Green River Basin, so its characteristics and bounding surfaces can only be determined from well and seismic data. Law and Spencer infer that it is separated from the underlying Upper Cretaceous Lance Formation by an unconformity based on sparse palynological data, but the exact position of this unconformity, if there is one at all, is poorly constrained. They also describe how the Pinedale field is a *sweet spot* in a very large basin-centered gas accumulation (BCGA) in the northern Green River Basin with characteristics common to conventional accumulations but different in that the reservoir is contiguous with the underlying more regional BCGA. They determined that the likelihood of finding sweet spots such as Pinedale is highly dependent on the recognition of faults and/or fractures that served as avenues for upward migration of hydrocarbons that originated in regional BCGAs.

In Chapter 4, Tom Meyer, Bob McDermott, Stephen Kneller, and Mark Longman describe the general geology of the Pinedale field. The Lance Pool is defined in this chapter, and the field size and its reserve potential are described. This chapter then discusses the complex interplay of the various geologic characteristics, including the stratigraphy, depositional setting, sedimentary characteristics, structural geology, hydrocarbon sourcing, and diagenetic factors that make Pinedale one of the largest, most prolific gas fields in North America. In addition, the innovative developments that led to the commercialization of the field are addressed.

In Chapter 5, Sally Zinke describes the geophysical interpretation of Pinedale field based on her years of work collecting and interpreting data while she worked at Ultra Petroleum. Beginning with regional gravity and magnetic maps, and two-dimensional (2D) seismic lines, the goal of improving understanding of the field evolved to include three-dimensional (3D) seismic surveys that eventually covered the whole 30-mi-long (48 km) productive portion of the anticline plus an additional 2 or 3 mi (up to 5 km) beyond the productive limits, vertical seismic profiling in selected wells, cross-well seismic imaging, and microseismic data to detect the extent of induced hydraulic fractures. Mapping of sandstone reservoir quality based on root-mean-square amplitude analysis of the 3D data greatly aided in selecting well locations, in establishing vertical extension of the productive section down into the upper Mesaverde interval, in lateral expansion of the field through a delineation drilling program, and in wellbore hazards planning, well down-spacing, and reserve calculations.

A group of geologists and petrophysicists from Shell Western Exploration and Production Company including Mark Chapin, Andrew Govert, Nicholas Brandon, and Gustavo Ugueto prepared Chapter 6. They examined over 4000 ft (1200 m) of core and describe the sedimentology and reservoir characteristics of the Upper Cretaceous Lance Formation and upper Mesaverde producing interval above the Ericson Sandstone in Pinedale field. Their analysis found a good relationship between facies and petrophysical properties in the tight gas sandstone reservoirs. They then incorporated this relationship into detailed numerical models to reveal various field development options.

Chapter 7 by Mark Chapin and Andrew Govert describes the sedimentology and reservoir characteristics of the 1300-ft-thick (400 m) lower Paleocene Wagon Wheel Formation in Pinedale field. They found that the upper and lower intervals within the Wagon Wheel Formation have different lithologies and are separated by an unconformity that can be identified on seismic lines. This puts the unconformity stratigraphically a couple hundred feet higher than that inferred by Spencer and Law (Chapter 3) to occur between the Lance and Wagon Wheel Formations. Above the unconformity, sandstones of the upper Wagon Wheel are significantly more arkosic, and lack quartz-lithic sediments. The well-known *gamma-ray marker* is caused by an increased gamma-ray response above the unconformity related both to an increase in potassium feldspar grains and to increased thorium related to chlorite. The Wagon Wheel Formation beneath the unconformity is transitional with the underlying Lance Formation but differs from it in that it has conglomerates and significant feldspathic components.

Chapter 8 by Mark Longman, Denis Foley, and Joel Scoville discusses results of the three deep wells that have been drilled on the Pinedale anticline. These are the Wagon Wheel #1 drilled to a depth of 19,000 ft (~5800 m) in 1969 and 1970 by El Paso Natural Gas, the Stewart Point 15-29 drilled to a depth of 19,520 ft (5950 m) by Questar Exploration (now QEP) in 2004 and 2005, and the Mesa 10D-33 drilled to 19,500 ft (5940 m) and completed by Ultra Petroleum from 2006 to 2008. This chapter provides a thorough examination of the pre–Lance Pool rocks from the Ericson Sandstone down into the upper few hundred feet (~100 m) of the Hilliard Shale in these deep wells. To date, no rocks older than Upper Cretaceous have been penetrated on the Pinedale anticline. The aim of this chapter is to describe the reservoir and source potential of these pre–Lance Pool rocks along with their thermal maturity, the source of the gas in the field, and the timing of gas migration into the Lance Pool along the Pinedale anticline.

In Chapter 9, Paul Martin, Robert Lee, and John Dacy with Core Laboratories discuss the core analysis methodology for tight gas sandstone reservoirs that was developed for analysis of the tight reservoir rocks in Pinedale field. This protocol has become the standard methodology for analysis of tight gas sandstone reservoirs around the world. Topics covered include fresh-state versus restored-state core analyses, a review of clay-bound water chemistry, pluses and pitfalls of routine core analysis, and fresh-state special core analysis protocol, including the determination of formation water salinities, electrical properties, relative permeabilities, and capillary pressure curves. These special core analysis techniques proved critical to assessing the original gas-in-place reserves and the amount of recoverable gas present along the Pinedale anticline.

The petrophysics of the Lance and Upper Mesaverde reservoirs at Pinedale field are discussed in detail by Suzanne Cluff, Robert Cluff, Daniel Hallau, and Ryan Sharma in Chapter 10. This team examined wireline logs from 127 wells drilled throughout the field and determined net sandstone thickness, porosity, water saturation, and net pay thickness within the Lance and upper Mesaverde intervals. They also compared the petrophysical properties of the Pinedale reservoir rocks with those in Jonah field and show that the average porosity and gas saturations at Pinedale are lower than at Jonah but that Pinedale field has a greater net pay thickness that more than compensates for the difference in reservoir quality. This thickness of the pay interval partly accounts for the very high productivity of many of the wells in Pinedale, 10 of which have already produced more than 7 bcf each.

Keith Jagiello also examined the petrophysics of the Lance and upper Mesaverde in Pinedale in Chapter 11, but he focused his analysis to the northern third of the field. He used data from 10 cores in his study area, including three with special core analysis to calibrate his log data. Jagiello quantifies the porosity, permeability, water saturation, and mineralogy that he saw in these cores as well as the pressure gradient present in the northern Pinedale field. He also describes the porosity and permeability reductions that occur at *in situ* reservoir conditions as well as the permeability reductions that happen as a result of inherent higher water saturations. Finally, Jagiello determined from capillary pressure data that gas column heights in the northern part of Pinedale field represent a series of stacked gas columns rather than a single continuous column.

Because of the large size of the Pinedale anticline, it is commonly inferred that the reservoir rocks in the Lance Pool are highly fractured. In Chapter 12, Mark Longman, Erika Davis, and Randy Koepsell attempt to quantify the abundance and orientation of natural fractures in the field based on a study of 14 continuous cores totaling about 1300 ft (400 m) in length cut in eight wells and combining this dataset with formation imager (FMI) logs run in four wells in the northern part of the field. They conclude from these data that the Lance Pool on the north end of the Pinedale anticline is significantly *less* fractured than comparable Upper Cretaceous rocks in stable foreland basins elsewhere in the Rocky Mountain region (e.g., in the Piceance Basin), in part because of the very gentle dip of the flanks of the anticline (mostly <2°). They also observed that nearly all of the gas entry observed on the image logs came from matrix porosity in the sandstones rather than from naturally fractured intervals. They describe the dominant set of natural fractures in the northern part of the field as trending N60°W whereas the strike of the north end of the Pinedale anticline is about N15°W and present-day Sigma 1 is about N28°W. Because the natural fractures are oriented roughly 45° off the trend of the north end of the anticline, it appears that the Laramide orogenic event that formed the anticline was not the dominant process that formed the observed natural fracture sets, most of which are healed and tightly cemented with some combination of calcite, kaolinite, and quartz.

Because of their geographic proximity, Pinedale and Jonah fields may be thought of as fraternal twins, having many similar characteristics, including their productive lithologies and the source(s) of their natural gas, but they are completely different in terms of their structural trapping mechanisms. In Chapter 13, Dean DuBois (Encana Corporation), who has had the good fortune to work in some detail on both fields, compares and contrasts Pinedale and Jonah fields. DuBois recognizes the lack of a distinct top seal in each field and also notes their somewhat unusual pressure gradients, which suggest that the mudstones intercalated with the reservoir sandstones are partly sealing. He also concludes that "leak-off" has been complete near the top of Lance Pool and is progressively less so deeper below the top of the Lance Pool. This fact indicates that there are sealing beds distributed vertically throughout the reservoir complex, which is consistent with the finding of Keith Jagiello (Chapter 11, this volume) that the reservoir at Pinedale field consists of multiple stacked pay sands rather than forming one continuous gas column.

In Chapter 14, a team of Shell geologists and engineers headed by Mark Chapin summarizes their work creating both static and dynamic reservoir simulation models for the Pinedale field and the geological interpretations underlying those models. These models are based on the good correspondence of core and log petrophysical properties tied to depositional facies so a neural net was used to assign facies and populate the reservoir models. A multistep approach was used to populate small (approximately 1 sq mi [2.6 sq km]) "sector" models for different parts of the field. Gross channel ribbons and bar objects were placed first, guided by interpolated V-shale, which is a proxy for sand correlation. Detailed facies bodies were then distributed within those elements. Because net/gross, sandstone thickness, correlation of the sandstones, and overbank character change throughout the section, different zones were modeled using different body dimensions based on analogs. All model areas converge to around a 62% recovery factor for 5-acre well spacing after 50 years of simulated production.

The final chapter in this book, written by Philip Nelson with the U.S. Geological Survey, provides another comparison of Pinedale and Jonah fields. Nelson summarizes and compares the gas, oil, and water production characteristics in early wells in these two fields to shed more light on the nature of their respective reservoirs. He notes that initial gas production rates were higher in Jonah field than in Pinedale field whereas rates of water production were generally significantly higher in Pinedale. Furthermore, the water-gas ratios in Pinedale field tended to remain fairly constant through time, but that these ratios were roughly an order of magnitude greater than in Jonah. Nelson also found that water production rates declined in all wells in Pinedale field over the initial five-year interval he studied, whereas in Jonah field half the wells showed increases and half showed decreases in water production during their first five years. It is clear from these statistics that the fields differ significantly in some ways despite producing from very similar lithologies in the Upper Cretaceous Lance Pool.

CONCLUSIONS

Technology and innovative thinking, mainly during the past 15 years, have driven Pinedale field's development and unlocked a giant domestic energy resource in the United States. These techniques have benefitted all of the following: (1) the oil and gas industry, which through enhanced geologic understanding, better hydraulic fracturing techniques, reduced drilling times and improved operational efficiency has been able to convert what until the 1990s had been a subeconomic play unsuccessfully chased by dozens of companies into one of the most commercially successful fields; (2) wildlife, due to the well thought out regulations and field development plans that have led to geographically focused human and drilling activities and reduced habitat fragmentation; (3) the environment through water recycling, reduced noxious air emissions, and a network of pipelines for fluid transport; (4) safety by lowering the total recordable incidence rate through pad drilling, continuous operations, and long-term employment on the drill rigs; and (5) ultimately, the people of Wyoming through the millions of dollars spent for field development, the hundreds of jobs created both directly and indirectly by all the work done in the Pinedale field area, and the steady (and large!) stream of tax revenue that the field's production has provided to the state.

As editors of this book, we wish to extend our most sincere thanks to the notable list of companies and contributors who have given so much of their time and talents to provide this book with an excellent series of papers that should serve as a reference not only for Pinedale field but for understanding and developing other tight gas sandstone accumulations around the world for years to come.