CHAPTER 11

Petrology and Petrophysics of the Lance Formation (Upper Cretaceous), American Hunter, Old Road Unit 1, Sublette County, Wyoming

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ABSTRACT

The American Hunter Old Road unit 1 was drilled to test multiple, stacked sandstones in lower Tertiary and Upper Cretaceous sandstones but was completed in 1981 as a water well producing from a shallow aquifer. Poor fluid recoveries from a drillstem test in the middle Lance Formation indicated a low-permeability reservoir with probable formation damage. Two cores, totaling 106 ft (32 m), were cut in the middle and lower Lance Formation. The cored intervals consist of thin- to medium-bedded, fine- to medium-grained sandstone and chert pebble conglomerate interbedded with silty mudstone and shale. Conglomeratic beds are cross-bedded and massive to normally and inverse graded. Sandstones are trough cross-bedded, massive and ripple laminated, and locally root mottled. Mudstones are rooted and burrowed. Conglomerate and sandstone were deposited in fining-upward genetic units by small meandering rivers. Mudstones were deposited in flood plain, swamp, lacustrine, and brackish to normal marine environments.

Sandstones consist of sublithic to lithic arenite and are cemented by moderate amounts of mixed-layer illite-smectite and quartz, sparse siderite, pyrite, ferroan calcite, and kaolinite. Feldspars are very sparse. Rock fragments are dominated by chert, with sparse limestone, dolomite, shaly and silty mudstone, reworked glauconite, and phosphate grains. Porosity consists of moderate to sparse, modified primary intergranular, clay-lined and clay-filled intergranular, secondary intergranular and grain-moldic pores, and natural fractures. Most natural fractures are filled by kaolinite but retain some permeability. Core-measured in-situ porosities range from 4 to 13%. In-situ Klinkenberg permeabilities range from 0.001 to 2.66 md. “Irreducible” water saturations, representing water saturations at gas column heights of approximately 750 ft (230 m), range from 21 to 72%, in close agreement with log-derived data, indicating that most of the potential reservoir sandstones are at or near irreducible water saturation. Relative gas permeability at irreducible water saturation ranges from 46 to 99% of the absolute permeability. Common clay-filled microporosity is responsible for low measured permeability, relatively high values of irreducible water saturation, and moderate susceptibility to formation damage.

INTRODUCTION

The American Hunter Old Road unit 1 spud in January and was drilled to a total depth of 12,422 ft (3790 m) in March 1981. It is located approximately 10 mi (16 km) south of the southern bounding fault of Jonah field (Figure 1). Drilled before the discovery well was drilled at Jonah field, the nearest production at the time from Tertiary or Upper Cretaceous rocks was at Pinedale field, more than 20 mi (30 km) to the north, and at Big Piney field, approximately 25 mi (40 km) to the west. The Old Road well was drilled as a basin-centered gas prospect as part of an exploration program in the northern Green River basin conducted by American Hunter Exploration, Ltd., Calgary, Canada, and was slated to test the Fort Union Formation (Paleocene), Lance and Mesaverde sandstones (Upper Cretaceous), and the Upper Cretaceous Hilliard (Baxter) Shale.

A drillstem test (DST) in the middle Lance (8344–8406 ft; 2540–2560 m) recovered water-cut mud and a trace of gas and was interpreted to indicate a low-permeability formation with probable formation damage (Johnson Schlumberger Computerized Data Analysis, 1981). Core analysis and logs in the DST interval indicated fair to good porosity (4–14%) but low average permeability (0.001–4.2 md, geometric average 0.076 md). Traces of oil were reported in the fluid-saturation data (Core Laboratories, Inc., 1981). Results of a second DST in the underlying Blair sandstone were less encouraging, and the well was eventually completed as a water supply well in October 1981. Mud weight at total depth was reported at 9.1 lb/gal (1090 kg/m³). No other mud compositional data were reported. No mud logs are on file with the Wyoming Oil and Gas Conservation Commission. None of the potential reservoir zones in the well were fracture treated prior to abandonment.

A total of five cores were cut from what was originally identified as Lance, upper Mesaverde, and Blair formations. Our subsequent stratigraphic work indicates that...
the uppermost cored interval (Lance) falls within the Unnamed Tertiary unit, below the base of the lower Fort Union, whereas the middle cored interval (originally reported as upper Mesaverde) is correlated as middle and lower Lance (Figure 2; Table 1). Petrographic data indicate that sandstones of the Unnamed unit are feldspathic and may be genetically related to the lower Fort Union. Further stratigraphic work is needed to reconcile this issue.

Cores 2 and 3 (8346–8452 ft [2544–2576 m], Figure 3) in the middle Lance have sedimentologic, petrographic, and petrophysical characteristics of a prospective low-permeability gas reservoir that has been conventionally cored, logged with modern logs, and drillstem tested (Figure 3). All of the core material from this well is stored at the U.S. Geological Survey Core Research Center (USGS CRC), Denver, Colorado, and is available to the public (USGS CRC E-894). Routine core analysis data were provided by the operator and are archived at the USGS CRC (Core Laboratories, Inc., 1981). Special core analysis (SCAL) data, comprising analysis of in-situ Klinkenberg gas permeability ($k_g$), irreducible water saturation ($S_w$), and effective and relative gas permeability at $S_w$, were also obtained from samples of the Old Road unit 1. Copies of the SCAL data were provided to the USGS CRC as part of the sampling agreement (Byrnes, 1994). Petrographic data are based on analysis of 10 thin sections prepared from core samples of the middle and lower Lance (Table 2). Thin sections are archived at the USGS CRC. Three samples from the middle Lance were selected for x-ray diffraction (XRD) analysis (Table 2); four samples were selected from the middle Lance for scanning electron microscopy (SEM) analysis (Table 2). Additional supporting data are included in Appendix F on the CD-ROM accompanying this book.

**LITHOFAECIES**

Eight lithofacies are present in the cored intervals and are described below.

**Chert Pebble Conglomerate**

Chert pebble conglomerates are light gray to medium olive gray, moderately to poorly sorted, clast supported, having cross-bedded to massive, inverse, and normally graded beds (Figure 4A). Moderately to poorly sorted sandy matrix is common. The conglomerate occurs in 1.5 ft (0.5 m) thick beds above sharp basal contacts in fining-upward sequences. Net thickness in the cored interval is approximately 3.5 ft (1 m). Conglomerates are sharply overlain by massive to cross-bedded, medium-grained sandstone and pebbly sandstone (Figure 3).

**Medium-grained Sandstone and Pebby and Granulitic Sandstone**

Medium-grained sandstone and pebbly and granulitic sandstone are light gray, moderately to well sorted, massive to cross-bedded, with beds 1.5–2 ft (0.5–0.6 m) thick, and with angular shale lithoclasts locally present (Figure 4B). Net thickness in cored interval is 6 ft (2 m). Medium-grained sandstones are sharply overlain by fine sandstone and occur in the lower portions of fining-upward sequences (Figure 3).

**Fine-grained Sandstone**

Fine-grained sandstones are light gray, well sorted, planar tabular, trough, massive, and ripple cross-laminated with beds ranging from 1.5 to 4 ft (0.5 to 1.2 m) thick (Figure 4C). Net thickness in cored interval is 21 ft (6.3 m). This lithofacies is present in the middle to upper portions of fining-upward sequences and as discrete beds. Fine-grained sandstone is sharply overlain by conglomerate and medium sandstone or grades upward into bioturbated, fine-grained shaly sandstone (Figure 3).

**Fine-grained Shaly Sandstone**

Fine-grained shaly sandstones are moderate to dark olive gray, poorly sorted, massively bedded to strongly rooted, locally rippled, with beds ranging from 2 to 5 ft (0.6 to 1.5 m) thick (Figure 4D). Net thickness in the cored interval is 18 ft (5.5 m). Rooted, fine-grained, shaly sandstone grades into underlying sandstone or mudstone. Elsewhere, fine-grained shaly sandstone sharply overlies and is interbedded with ripple-laminated, bioturbated, very fine sandstone and mudstone. This lithofacies is present in the upper part of fining-upward sequences and is locally interbedded with shale and sandy and silty mudstone (Figure 3).

**Very Fine Sandstone**

Very fine sandstones are light gray to light olive gray, moderately to well sorted, locally shaly, low-angle planar cross-bedded, ripple laminated, having wavy and locally contorted bedding, and in 1–3 ft (0.3–1 m) thick beds (Figure 4E). Net thickness in cored interval is 5 ft (1.5 m).
Figure 2. North–south structural cross section of the Lance Formation (Upper Cretaceous), the overlying unnamed interval, and lower Fort Union (Paleocene), northern Green River basin, Sublette County, Wyoming. Wells included in the cross section are listed in Table 1. Note the thinning of the Lance Formation from north to south and the truncation of the upper Lance by unconformities.
This lithofacies is present in the upper part of fining-upward sequences and is locally interbedded with bioturbated shale and sandy and silty mudstone (Figure 3).

**Very Fine Shaly Sandstone**

Very fine shaly sandstones are medium to light olive gray, moderately to poorly sorted, ripple and planar laminated, rooted, locally burrowed, contorted, and slumped, with beds 0.5–2 ft (0.2–0.6 m) thick (Figure 4F). Net thickness in cored interval is 10 ft (3 m). This lithofacies is present in the upper part of fining-upward sequences and is interbedded with shale, silty and sandy mudstone, and siltstone (Figure 3).

**Shale, Silty and Sandy Mudstone, and Siltstone**

Mudstone and siltstone are dark gray to medium olive gray, moderately to poorly sorted, rooted, and locally carbonaceous, having common plant impressions, massive bedding, and irregular, blocky to conchoidal fracture (Figure 4G). Shale and silty and sandy mudstone beds range from 0.5 to more than 10 ft (0.2 to more than 3 m) thick, with a net thickness of 31.5 ft (9.5 m). Shale and silty and sandy mudstone beds occur in the upper parts of fining-upward sequences and overlie very fine sandstone and shaly sandstone with sharp to gradational contact. Siltstones are planar and ripple laminated and rooted, with local contorted bedding. Siltstone beds range from 0.5 to 2 ft (0.2 to 0.6 m), having a net thickness of 10 ft (3 m). Siltstone overlies shale and silty and sandy mudstone with sharp to gradational contacts. Siltstone is interbedded with shale and silty and sandy mudstone and occurs in the upper part of fining-upward sequences (Figure 3).

**Bioturbated Shale, Silty and Sandy Mudstone and Siltstone, and Shaly Sandstone**

These are black, dark gray to medium olive gray, moderately to poorly sorted, planar laminated to bioturbated, and locally carbonaceous, with sparse plant impressions and moderate sand-filled burrows, and blocky to planar fracture (Figure 4H). Bioturbated shale and silty and sandy mudstone beds range from less than 0.25 to 1 ft (0.07 to 0.3 m) thick, with a net thickness of 3.5 ft (1.1 m). Bioturbated shale and mudstone overlie very fine sandstone and shaly sandstone with sharp contact. Bioturbated shale and silty and sandy mudstone beds occur in the upper parts of fining-upward sequences and are interbedded with rooted and bioturbated siltstone (Figure 3). Siltstones and shaly sandstones are bioturbated, and planar and ripple beds

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laminated, with locally contorted bedding. Siltstone beds range from 0.5 to 2 ft (0.2 to 0.6 m), with a net thickness of 4 ft (1.2 m). Bioturbated siltstone and shaly sandstone is interbedded with shale, silty and sandy mudstone and rooted siltstone, and very fine shaly sandstone. Basal contacts are gradational, and upper contacts with rooted facies are gradational (Figure 3).

**LITHOFACIES DISTRIBUTION**

The cored interval can be subdivided into three lithologic units: (1) an upper sandstone consisting of lower fine to upper medium sandstone and conglomerate and sparse upper very fine sandstone (8344–8372 ft; 2543–2552 m); (2) a lower sandstone consisting of upper very to lower fine sandstone and sparse lower medium sandstone (7385–8406 ft; 2251–2562 m); and (3) mudstone, dominated by shale, silty mudstone, and siltstone, with sparse very fine sandstone (8307–8452 ft; 2532–2576 m). The upper and lower sandstones are separated by 3 ft (1 m) of mudstone and 14 ft (4.6 m) of lost core (Figure 3) and comprise the basal portion of the middle Lance Formation. Regional stratigraphic work suggests that the lower sandstone overlies an unconformity. The mudstone in the lowermost interval represents the top of the lower Lance.

**ENVIRONMENT OF DEPOSITION**

Sharp basal contacts, strongly fining-upward character, interbedded mudstone and carbonaceous mudstones, rooted intervals, and poorly developed paleosols indicate that the sandstones of the middle Lance were deposited in meandering fluvial channels and sparse crevasse splays (Figure 3). These features are similar to those reported for cores in the Lance Formation at Jonah field (Shanley, 2001). Sandstone bodies consist of stacked deposits of amalgamated point bars and channel levees. Conglomerates and medium-grained sandstones were deposited in the lower to middle portions of point bars. Fine- to very fine-grained sandstones were deposited in upper point bars, channel levees, and crevasse splays. Soft sediment deformation, including contorted and slumped beds, was observed in very fine- to fine-grained sandstone. These features are characteristic of collapsed point-bar and levee Figure 3. Core description for the middle and lower Lance Formation, American Hunter Old Road unit 1, Sublette County, Wyoming.
deposits caused by falling water level and channel migration. Overbank splays are encased in mudstone, are finer grained, and are thinner bedded than the point-bar sandstones. Subaerial exposure resulted in the development of rooted zones, incipient paleosols, the introduction of detrital clay by mechanical infiltration in conglomerate and medium sandstone, and bioturbation (primarily because of plant roots) in sandstones. This is especially prominent in the levee and splay sandstones. Thin, poorly developed paleosols and rooted zones indicate intermittent subaerial exposure of sediments deposited in overbank and floodplain environments. Massively bedded silty mudstone with conchoidal fracture and sparse carbonized plant impressions was deposited in abandoned channel (clay plug) and lacustrine environments.

Mudstones and shaly sandstones in several intervals are burrowed (Figure 5). Burrows have been tentatively identified as 

**Teichichnus sp.** (Pourrat, 1895), **Planolites sp.**, **Palaeophycus sp.** (Porat, 1983), and **Helminthopsis sp.** (R. Martinson, 2003, personal communication). In addition, probable **Thalasinoides sp.** and **Skolithos sp.** are present (Figure 5). These trace fossils occur in open-marine, upper offshore to brackish environments (Pemberton et al., 2001). **Helminthopsis sp.** are characteristic of deeper water, including lower to upper offshore environments, but has been reported from low-energy, fine-grained marine bay environments (Pemberton et al., 2001). Rooting overprints some of these occurrences. The overlying thin, sharp-based, fining-upward sequences associated with burrowed mudstone suggest that transition from brackish or marginal marine environments to nonmarine environments may have occurred under low-energy conditions, such as in marsh, lagoonal, or marine embayment settings. Associated ripple-laminated, rooted very fine sandstone, shaly sandstone, and siltstone may represent low-energy tidal channel and lagoonal shorelines.

**PETROGRAPHY AND MINERALOGY**

Conglomerates and conglomeratic sandstones are composed of well-rounded chert pebbles and sparse sandstone pebbles (maximum pebble diameter <1 cm), with sparse sandy matrix (in clast-supported conglomerate) to moderate amounts of fine- to medium-grained sand in pebbly sandstone (Figure 6). The conglomerates exhibit a bimodal sorting, with both the pebbles and interstitial sand grains being moderately to poorly sorted. Chert pebbles exhibit a wide variety of textures, including ghost textures from lime grainstone, skeletal packstone, spiculitic and probable bedded chert, dolomitic limestone, and phosphatic chert (Figure 6B). The chert pebbles were derived from older Paleozoic sediments, most likely the Phosphoria Formation and Madison Limestone. Extremely sparse volcanic rock fragments (altered to bentonite) are also present in the conglomerate. Based on textural and point count analysis, the conglomerates are classified as sandy sedlithrudites. Both samples of conglomerate plot very near to the lithic pole of the Q:F:L ternary diagram in Figure 7. Sedimentary rock fragments (primarily chert) are the most abundant lithic grains in the conglomerates (Table 2). In a ternary plot of volcanic + plutonic:metamorphic:sedimentary (V + P:M:S) composition of the lithic fraction, the conglomerates plot closest to the sedimentary rock fragment pole (Figure 8).

Moderate to common amounts of authigenic clay, quartz overgrowths, and sparse siderite, pyrite, and ferroan calcite cement the conglomerates (Table 2). Clay cement lines and partly fills intergranular areas (Figure 6C, D) and is composed of mixed-layer illite-smectite (ML-IS), kaolinite (Figure 9A, B), and local chlorite (Figure 9E). Illite was detected during XRD analysis of the clay fraction but was not observed as a discrete phase in either thin-section petrography or SEM analysis. A possible exception might be the fibrous projections on ML-IS crystals that were observed during SEM analysis of sandstone samples.

Porosity in the conglomerates and conglomeratic sandstone consists almost entirely of clay-filled intergranular microporosity (Figure 6D, E). The flaky to filamentosous crystal morphology and high specific surface area of the clay cement (in particular ML-IS clay) create microporosity by subdividing intergranular pores. Only traces of intergranular mesoporosity (Figure 6C) and fractures in chert grains are present (Figure 6F). Estimated mesoporosity (open intergranular and moldic pores) from point-count data ranges from trace to 1% of the entire rock volume in the conglomerates. Estimated microporosity (clay-filled intergranular and intragranular pores) ranges from 6 to 8% (Table 2).

Sandstones range from very fine to medium grained and are moderately to well sorted, with subangular to subrounded grains (Figures 10, 11). Fine-grained sandstone and fine-grained shaly sandstone comprise the bulk of the sandy lithofacies in the core. Angular to rounded shale lithoclasts (as much as 1.2 in. [3 cm]) are locally common (Figure 3). Plagioclase and potassium feldspar are conspicuously absent, with the exception of a sample from a crevasse-splay sandstone (8445 ft; 2574 m) in the lower, mudstone-dominated portion of the core (Table 2). Samples from the upper sandstone (8344–8372 ft; 2543–2552 m) are more coarse grained and contain more rock fragments than samples from the lower sandstone (Table 2, Figure 3). Samples from the upper sandstone are classified
Table 2
Petrographic Data for Middle and Lower Lance Sandstones, Old Road Unit 1, Sublette County, Wyoming.*

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<th>Air Permeability (md)</th>
<th>Grain Density** (g/cm³)</th>
<th>Water Saturation**</th>
<th>Member or Formation</th>
<th>XRD Sample</th>
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Cements Porosity Types

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Table 2
Petrographic Data for Middle and Lower Lance Sandstones, Old Road Unit 1, Sublette County, Wyoming (cont.).

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* All data are in percent unless otherwise specified.
** Core analysis data from Core Laboratories, Inc., file RP-2-6443, all data are conventional core analysis, measured at ambient conditions.
Figure 4. Representative close-up core photographs from the American Hunter Old Road unit 1 for the lithofacies described in text: 
(A) poorly sorted, clast-supported chert pebble conglomerate with medium-grained sandy matrix, 8360.8 ft (2548.4 m); 
(B) medium-grained, well-sorted, trough cross-bedded sandstone with angular mudstone rip-up lag, 8351.4 ft (2545.5 m); 
(C) fine-grained, ripple-laminated sandstone, 8392 ft (2558 m); (D) fine-grained shaly sandstone, 8355 ft (2547 m); (E) very 
 fine-grained, well-sorted, ripple-laminated sandstone, 8354 ft (2546 m); (F) very fine-grained, moderately sorted, rooted shaly 
 sandstone, 8380 ft (2554.2 m); (G) silty mudstone with carbonaceous plant fragments, 8384.7 ft (2555.7 m); (H) bioturbated 
mudstone and laminated silty mudstone, 8353 ft (2546 m).
as litharenite, whereas those from the lower sandstone are classified as sublitharenite (Figure 7).

Detrital grains consist of common monocrystalline quartz with moderate to sparse amounts of chert, carbonate and phosphatic rock fragments, altered volcanic rock fragments, polycrystalline quartz, and quartzose and micaceous rock fragments of probable metamorphic origin (Table 2). In a ternary plot of V + P:M:S composition of the lithic fraction in sandstones, the samples in the upper sandstone plot closest to the sedimentary rock fragment pole (Figure 8), primarily because of an abundance of chert grains. The samples from the lower sandstone contain more altered volcanic and metamorphic grains (Table 2). The detrital composition and porosity distribution of the upper sandstone are more typical of sandstones in the Lance Formation. Petrographic data for samples from a core of the Lance from Jonah field, the McMurry Jonah Federal 2-5, shown on cross section AA’ (Figure 2), were published by Yin et al. (2001). When plotted on a Q:F:L ternary diagram, the data fall in the middle to upper portion (quartzose) of the litharenite field (Figure 12). Petrographic data from a Lance sandstone in the cored interval (Figure 13A, B). They are lined by quartz cement at the top of the core slab, 8445 ft (2574 m), has replaced detrital potassium feldspar grains.

Porosity consists of a mixture of sparse to moderate modified primary mesopores, sparse to moderate amounts of microporous clay-filled intergranular pores, sparse moldic pores, and very sparse natural fractures (Figure 13A, B). Primary intergranular pores are lined by quartz overgrowths, ML-IS, kaolinite, and local chlorite clay cement (Figures 9C, D; 10D, E; 11C, D). The clay cements also completely fill intergranular pores and moldic pores (Figure 10G).

Partial to complete dissolution of detrital grains and intergranular cement has resulted in the creation of secondary porosity (Figures 9, 10). Recognition criteria include inhomogeneous packing, detrital grain-sized voids, relics of former detrital grains in moldic pores, and relics of intergranular cement in intergranular voids (Schmidt and McDonald, 1979). Based on dissolution relics and preserved lithic and feldspar grains, the grains that were dissolved to form moldic pores included carbonate rock fragments, plagioclase, and potassium feldspar. The presence of grain-sized moldic pores and clots of kaolinite indicates that small amounts of chemically unstable grains have been removed by dissolution, resulting in a slightly more mature (more quartzose) Q:F:L ratio than in the original sediment. However, reconstruction of the detrital modes does not alter the original ternary Q:F:L classification.

Natural fractures are present in the sandstones within the cored interval (Figure 13A, B). They are lined by quartz overgrowths (Figure 13B, C) but are more typically filled by kaolinite cement (Figure 13A, D). Kaolinite-filled fractures have retained porosity. In thin section,
blue-dyed epoxy has penetrated the kaolinite cement, indicating that microporosity is present in the kaolinite fracture filling (Figure 13D). Linear features that are locally present in some samples represent healed fractures (Figure 13E).

**COMPACATION**

Compaction is moderate, with long grain contacts being predominant. Curved contacts are common in the conglomeratic intervals, where the clast-supported fabric has
responded to overburden pressure. Sutured to stylolitic contacts and fractured chert grains are locally present in clast-supported conglomerates. Intergranular volume (porosity plus volume of intergranular cement from point count) for conglomerates ranges from 12 to 14%. The low intergranular volume is primarily caused by the poor sorting of the conglomerates instead of excessive compaction. Intergranular volume for sandstone samples ranges from 23 to 46%. This indicates that as much as 15% of the original volume of some sandstone samples has been lost because of compaction of the unconsolidated sand (Beard and Weyl, 1973). Intergranular volumes for samples of the upper sandstone (23–29%) are lower than those of the lower sandstone (38–46%). This indicates an extremely small loss of porosity because of compaction in the lower sandstone (2–8%), and in fact, for one sample (8394.8 ft; 2558.7 m), it suggests an increase in intergranular volume beyond the typical intergranular volume for uncompact ed sediments (Beard and Weyl, 1973). Ductile

Figure 6. Photomicrographs illustrating characteristics of sandy conglomerate lithofacies, American Hunter Old Road unit 1, 8360.8 ft (2548.4 m). (A) Clast-supported chert pebble conglomerate with well-sorted, medium-grained sandy matrix. Long dimension of view is 12.23 mm (0.48 in.). Plane light, 10×. (B) Clast-supported chert pebble conglomerate with well-sorted, medium-grained sandy matrix. The sandy matrix has significantly reduced the porosity of this lithofacies. Intergranular mesoporosity is sparse. Compaction has resulted in open and partly cemented fractures in the chert pebbles. Long dimension of view is 6.1 mm (0.24 in.). Plane light, 20×. (C) Clast-supported chert pebble conglomerate with sparse intergranular mesopores. The neighboring intergranular areas are filled by clay cement, resulting in poor connectivity and low permeability. Long dimension of view is 1.2 mm (0.047 in.). Plane light, 100×. (D) Intergranular areas are lined by mixed-layer illite-smectite and are filled by kaolinite cement. The abundant clay cement causes low permeability and high irreducible water saturation. Long dimension of view is 0.6 mm (0.024 in.). Plane light, 200×. (E) Microporosity is present in the clay cement. Mixed-layer illite-smectite precipitated prior to pore-filling kaolinite cement. Long dimension of view is 0.6 mm (0.024 in.). Plane light, 200×. (F) Fractures in crushed chert pebbles (lower portion of the view) can enhance permeability and connectivity of the pore system in the clast-supported chert pebble conglomerate. Long dimension of view is 12.23 mm (0.48 in.). Plane light, 10×.
grains are sparse in the conglomerates and sandstones. Therefore, deformation of ductile grains is responsible for only a minor proportion of porosity loss.

**POROSITY DISTRIBUTION**

Based on helium porosimetry, total porosity in these rocks ranges from 5 to 14%. Detailed petrography, SEM, and XRD analysis reveal that mesoporosity (intergranular, secondary intergranular, and moldic pores) comprises from 0 to 56% of the total porosity (Table 2). Microporosity (clay pore linings and fillings and intragranular porosity) is a large proportion of the total porosity of the middle Lance sandstone, ranging from 39 to 100% of the total porosity (Table 2). A ternary plot of the relative proportions of porosity types (intergranular mesoporosity:moldic: microporosity) illustrates the predominance of microporosity for samples from both the Lance sandstone and conglomerate (Figure 14).

**THERMAL MATURITY: VITRINITE REFLECTANCE**

Vitrinite reflectance (%R<sub>o</sub>) analyses for two samples from the cored interval were performed by G. J. Jansen of the Rocky Mountain Coal Petrography, Golden, Colorado, and are reported in the well data files at the U.S. Geological Survey Core Research Center (Jansen, 1994). The sample at 8384 ft (2555 m) exhibited a reflectance of 0.52% R<sub>o</sub>, and the sample from 8407 ft (2562 m) exhibited a reflectance of 0.64% R<sub>o</sub>. These data indicate that the cored interval reached the upper portion of the oil generation window, but did not reach the threshold value of 0.8% R<sub>o</sub> that has been linked to peak generation of natural gas and development of overpressure in the greater Green River basin (Pawlewicz, et al., 1986). Other types of kerogen were not identified, suggesting that the organic matter preserved in the samples from the Old Road core is gas-prone. Analyses of Mesaverde rocks in the greater Green River basin document the widespread occurrence of gas-prone humic, type III kerogen (Law, 1984).
Figure 10. Photomicrographs illustrating petrographic characteristics of moderately well-sorted, medium- and fine-grained litharenite lithofacies, upper sandstone in cored interval of middle Lance sandstone, American Hunter Old Road unit 1. (A) Moderately well-sorted, upper medium-grained litharenite lithofacies, upper sandstone in cored interval of middle Lance sandstone. Lithic grains are dominated by chert with sparse altered volcanic rock fragments. Long dimension of view is 6.1 mm (0.24 in.). Plane light 20×, 8349.7 ft (2545.0 m). (B) Moderately well-sorted, upper medium-grained litharenite lithofacies, moderately well compacted, with common linear and curved intergranular contacts, and quartz overgrowth cement. Long dimension of view is 3.05 mm (0.12 in.). Plane light, 40×, 8349.7 ft (2545.0 m). (C) Intergranular pores are lined and filled by quartz overgrowths and small amounts of mixed-layer illite-smectite and local chlorite clay cement. Intergranular mesopores are poorly connected, resulting in low permeability. Long dimension of view is 1.2 mm (0.047 in.). Plane light, 100×, 8349.7 ft (2545.0 m). (D) Intragranular microporosity is present in partly dissolved chert grains (upper left and lower right). Note well-developed quartz overgrowths that line and completely fill intergranular areas. Oversized intergranular pores at the center and top center may have been formed by dissolution of prior cement. Long dimension of view is 1.2 mm (0.047 in.). Plane light, 100×, 8354.5 ft (2546.5 m).
(E) Framework grain-sized patches of kaolinite cement (right center and lower left) are the result of replacement of unstable grains (such as feldspar) by kaolinite. Microporosity is present in the kaolinite cement. Long dimension of view is 1.2 mm (0.047 in.). Plane light, 100×, 8349.7 ft (2545.0 m). 
(F) Intragranular microporosity is present in partly dissolved chert and altered volcanic rock fragments. Note crushed chert grain at right center. Long dimension of view is 0.6 mm (0.024 in.). Plane light, 200×, 8349.7 ft (2545.0 m). 
(G) Oversized intergranular pores were created by dissolution of prior cement. Secondary pores are moderately well connected in this portion of the sample, resulting in locally improved permeability. Long dimension of view is 0.6 mm (0.024 in.). Plane light, 200×, 8349.7 ft (2545.0 m). 
(H) Intergranular pores are lined and locally filled by mixed-layer illite-smectite and kaolinite cement. The clay cement reduces permeability and causes elevated irreducible water saturation. Long dimension of view is 0.3 mm (0.012 in.). Plane light, 400×, 8354.5 ft (2546.5 m).
RESERVOIR QUALITY

Total in-situ porosities range from 4 to 13% as measured from core. Correcting for water saturation, corresponding effective gas porosities range from 1.4 to 10.3%. Wire-line, log-calculated effective porosities indicate that the middle Lance interval exhibits a total porosity-height of 29.82 ft. Extensive quartz overgrowth occlusion of pore space and pore throats, the presence of pore-bridging and pore-filling mixed-layer clays, and the abundance of microporosity in many samples result in lower permeability and high irreducible water saturation. Correcting routine air permeabilities to in-situ effective gas permeability values, the estimated permeability-height for the middle Lance interval is 508.3 md ft.

Average porosity and permeability measurements for fine-grained sandstones are 9.6% and 0.339 md. Average porosity and permeability data for medium-grained sandstones (9.7% and 0.265 md, respectively) is comparable to that of the fine-grained sandstones and is lower than might be expected, given the initially larger intergranular pores in the medium sandstone. Porosity in the medium-grained sandstones has been severely occluded by quartz and clay cement, leaving very little intergranular mesoporosity (2%) (Table 2). Similarly, the average porosity and permeability in the conglomerate samples (8% and 0.763 md, respectively) are lower than might be expected, given the very large intergranular pores of the conglomerates. Poor sorting and abundant clay cement are responsible for the relatively poor values of porosity and permeability in the conglomerate samples. Moldic pores are extremely sparse in both the medium sandstone and the conglomerate, but they comprise as much as 1% of the rock volume in the fine sandstones. This amount may seem insignificant, but where moldic pores are present, they are as much as 7% of the entire porosity and 13–17% of the total mesoporosity.

Total porosity, intergranular, moldic, and clay-filled intergranular porosity are all more abundant in samples from the lower sandstone than in samples from the upper sandstone (Table 2). Most importantly, the relative proportion of microporosity in the samples of the lower sandstone ranges from 39 to 62%, compared to 69–100% for the upper sandstone and conglomerate. This relationship is largely responsible for the higher values of permeability in samples from the lower sandstone.

Microporosity in clay cement causes increased irreducible water saturation because of the high specific surface area of clay and capillary attraction of water to the clay cement (Byrnes, 1997). This is reflected in water saturation measurements in the routine core data, which can be an indicator of the relative magnitude of irreducible
Figure 11. Photomicrographs illustrating characteristics of sublitharenite sandstones, American Hunter Old Road unit 1, 8390.7 ft (2557.5 m) core depth. (A) Well-sorted, upper fine-grained sublitharenite lithofacies, lower sandstone in cored interval of middle Lance sandstone. Lithic grains are sparse and consist of chert and altered volcanic rock fragments and traces of quartzose metamorphic rock fragments. Long dimension of view is 6.1 mm (0.24 in.). Plane light, 20×. (B) Well-sorted, upper medium-grained litharenite lithofacies, moderately compacted, with common point and linear intergranular contacts, and only trace of quartz overgrowth cement. Long dimension of view is 3.05 mm (0.12 in.). Plane light, 40×. (C) Intergranular pores are lined by mechanically infiltrated clay that has inhibited the development of quartz overgrowth cement. Inhomogeneous packing and oversized intergranular pores are indicative of secondary porosity. Intergranular mesopores are moderately connected, resulting in improved permeability over that observed in the overlying litharenite sandstone. Long dimension of view is 1.2 mm (0.047 in.). Plane light, 100×. (D) Cross-polarized light reveals the mechanically infiltrated clay that coats many intergranular areas. Note local spalling of the coating because of compaction. Long dimension of view is 1.2 mm (0.047 in.). Cross-polarized light, 100×.
Figure 11. (cont.). (E) Oversized intergranular pores are commonly notched because of peripheral replacement of the surrounding grains by a prior cement, most likely calcite or ferroan calcite. Dissolution of unstable grains may have created moldic pores, such as the oversized void at left center. Long dimension of view is 0.6 mm (0.024 in.). Plane light, 200 x. (F) Inhomogenous packing of framework grains is another criteria for recognition of secondary porosity. Partly dissolved rock fragments in this view contain intragranular microporosity. Long dimension of view is 1.2 mm (0.047 in.). Plane light, 100 x. (G) Grain-sized patches of kaolinite cement are the result of replacement of an unstable grain by kaolinite. The kaolinite contains microporosity. Oversized intergranular pores were created by dissolution of prior cement. Long dimension is 0.6 mm (0.024 in.). Plane light, 200 x. (H) Secondary intergranular pores are well connected and provide permeability pathways around more tightly cemented areas in this sandstone. Long dimension of view is 1.2 mm (0.047 in.). Plane light, 100 x.
water that would be quantified by more accurate methods (Table 2). A crossplot of the percentage of clay-filled microporosity observed in thin section versus water saturation from core analysis reveals the strong influence of clay cement on water saturation in the Lance sandstones (Figure 15).

Based on an examination of photomicrographs and data published for samples from the Lance sandstone at Jonah field (Yin et al., 2001), the porosity distribution in samples from the upper sandstone in the Old Road core is more typical of the Lance at Jonah field.

FORMATION DAMAGE

Changes in water saturation or chemical composition of pore fluids that occur during drilling, completion, and production can result in a significant reduction in the relative permeability of gas (Byrnes, 1997). The reduction in relative permeability to gas caused by increased water saturation in the near-wellbore or fracture face is known as “water block.”

Two factors influencing the susceptibility of a formation to water block are small pore-throat diameter and low permeability. Both of these factors are increased by the presence of clay cement. Because clay cement-filled porosity is a large proportion of the total porosity in the middle Lance sandstones, they are extremely susceptible to water block.

The sandstones of the middle Lance also contain swelling clay (in ML-IS) that may expand when contacted by fresh water in mud filtrate and massive hydraulic fracture fluids. Expansion of swelling clay minerals reduces pore-throat diameters and increases water saturation, resulting in reduced permeability to both gas and water. Traces of iron-bearing, acid-soluble ferroan calcite cement and chlorite are locally present, but we consider that this formation damage hazard is minimal. The formation damage reported by Schlumberger in the computer-analyzed DST report and poor fluid recovery is consistent with the reservoir characteristics of the middle Lance (Johnson Schlumberger, 1981).

LOG ANALYSIS

The open-hole logs available for this well include a dual induction log, a compensated formation
density-compensated neutron log, and a borehole-compensated sonic log. The caliper shows a rugose borehole in many intervals, and consequently, the density tool reads unreasonably high porosities in those intervals. Therefore, the shale-corrected sonic-neutron cross-plot porosity was used for effective porosity. In the cored interval, the effective porosities of the sandstones are mostly in the 8–13% range, with some shaly sandstone in the 2–6% range. The calculated log porosity and measured core porosity compare very closely (Figure 16).

The general procedures used for log analysis of the Lance sandstones are the same as those applied to Jonah field wells as described in Cluff and Cluff (2004). Water saturations were calculated using the dual water model, with 0.18 ohm m for the free-water resistivity and 0.2 ohm m for the bound-water resistivity. Calculated water saturations in the lower sandstone from 8397 to 8420 ft (2559 to 2566 m) ranged from 39 to 80%, whereas saturations in the upper sand from 8334 to 8380 ft (2540 to 2554 m) ranged from 25 to 65%. These saturations compare favorably with routine core water saturations, both in magnitude and trend, as shown in Figure 16.

Permeabilities were estimated using a modified Timur equation. Timur-calculated permeabilities ranged from less than 0.001 to 1 md, based on calibration to routine air permeabilities from core analyses (Figure 16).

**CORE ANALYSIS**

Both routine and advanced core analysis data are available for the Fort Union, the middle Lance interval 8346–8447 ft (2544–2575 m) (missing shaly intervals, 8372–8389 and 8418–8440 ft [2552–2575 and 2566–2573 m]), and the underlying Mesaverde Blair Formation. For the two sandstone intervals (8346–8362 and 8400–8417 ft; 2544–2549 and 2560–2566 m) cored in the middle Lance, routine core porosities ($\phi$) range from 7.4 to 13.8%, averaging 10.4%. Porosities in the shaly interval (8363–8399 ft; 2549–2560 m) average 3.8 ± 2%. Routine full-diameter horizontal air permeabilities range from 0.07 to 13.0 md, with an arithmetic mean of 0.81 md and a geometric mean of 0.34 md (Figure 17). Only four samples exhibited permeability greater than 1 md and give indication of having been influenced by fracturing. Vertical permeabilities average 88 ± 70% of horizontal permeabilities. Grain densities average 2.65 ± 0.02 g/cm$^3$. Minor calcite cementing in the upper sandstone interval results in slightly higher grain densities (2.66–2.67 g/cm$^3$), whereas the lower interval exhibits lower grain densities (2.64–2.65 g/cm$^3$). Water saturations in the upper sandstones average 50 ± 14%, and in the lower sandstone, water saturations average 43 ± 16%, with saturations in the shaly interval averaging 76 ± 20%.

Comparison of petrophysical trends and properties of the middle Lance in the Old Road well with other western United States Upper Cretaceous low-permeability sandstones, including the Mesaverde and Frontier, illustrates that, as with most low-permeability sandstones, Old Road in-situ Klinkenberg permeabilities ($k_{ik}$) are significantly less than routine air permeabilities ($k_a$) and exhibit increasing difference with decreasing permeability (Figure 18). This difference is attributed to the influence of both confining stress on pore-throat size and Klinkenberg gas slippage effect. The Old Road Upper Cretaceous rocks, including the Lance, generally exhibit greater decrease in permeability under confining stress than the average Mesaverde rocks and can be characterized by the following relationship derived from the Old Road core plug data:

$$k_{ik} = 0.298k_a^{1.773}$$

In-situ porosity ($\phi_{in situ}$) data are not available for the Old Road, but in-situ values can be approximately predicted.
from routine porosity ($\phi_{\text{routine}}$) values using the general relationship for Mesaverde and Frontier rocks (Byrnes, 1997):

$$\phi_{\text{in situ}} = \phi_{\text{routine}} - 0.8$$

Using these equations to predict $\phi_{\text{in situ}}$ porosity and $k_{ik}$ from the routine full-diameter $\phi_{\text{routine}}$ and $k_a$, respectively, and using measured $k_{ik}$ values on selected middle Lance core plugs, Figure 19 shows that the Old Road middle Lance interval exhibits properties similar to Mesaverde and Frontier rocks. Measured core plug $k_{ik}$ values from the middle Lance sandstones generally exhibit permeability that is as much as an order of magnitude greater for a given porosity than the average Mesaverde and Frontier rocks and represents the high end of permeability for Upper Cretaceous low-permeability sandstones. The difference between the full-diameter, predicted $k_{ik}$ values and the measured core plug $k_{ik}$ values may be caused by the inaccuracy of the routine to in-situ equation or may be related to lower permeabilities exhibited.
by full-diameter cores because of bedding and lithofacies heterogeneities that exist in full-diameter core but not in smaller, more homogeneous, core plugs.

Comparison of both middle Lance water saturations measured in core and irreducible water saturations ($S_w$) measured on core plugs (measured at 600 psi air-brine capillary pressure, equivalent to approximately 750 ± 100 ft [230 ± 30 m] above free-water level, depending on exact pressure and water density) with general Mesaverde and Frontier $S_w$ (Figure 20) reveals that the core averages
approximately 15% higher saturations than the average Mesaverde and Frontier but are within the range of $S_{iw}$ observed in Mesaverde and Frontier rocks. Measured $S_{iw}$ values on middle Lance plug samples exhibit saturations similar to the full-diameter core saturations. The slightly higher water saturations in the full-diameter core would indicate the possible conditions that saturations were increased slightly during coring, or that saturations in the core are slightly greater than the $S_{iw}$, because the reservoir is not at the gas column height corresponding to that which was defined for the Mesaverde and Frontier population as $S_{iw}$. Given the good correlation between core and wire-line log saturations, it can be interpreted that water saturations in core were not significantly disturbed from those in the reservoir.

Relative gas permeability at $S_{iw}(k_{rg,S_{iw}})$ for the middle Lance is consistent with relative gas permeability properties exhibited by Mesaverde and Frontier low-permeability sandstones regionally (Figure 21). Samples with higher permeability and corresponding low $S_{iw}$ that is less than 30% exhibit $k_{rg,S_{iw}}$ greater than 95%. With decreasing permeability, $S_{iw}$ increases, and gas-relative permeability decreases.

**CONCLUSIONS**

Poor fluid recovery, low flow rates, low calculated permeability, and interpreted formation damage in the middle Lance are typical of low-permeability tight-gas
reservoirs that have been successfully exploited in the Rocky Mountains since the early 1980s.

Petrographic characterization of the distribution and mineralogy of clay cements and porosity in the middle Lance suggests that the middle Lance should be capable of economic rates of natural gas production, provided formation damage is minimized, adequate reservoir thickness is encountered, and sufficient hydrocarbon saturation and reservoir pressure are present. Massive hydraulic fracturing treatments would probably be necessary to establish economic flow rates.

The most serious potential formation damage hazard is water block, a result of reservoir pressures being insufficient to displace mud or fracture filtrate from clay-filled matrix porosity. Possible low-resistivity pay, caused by pore-lining clay cement, may have been overlooked in Figure 16.

Figure 16. Gamma-ray, caliper, and resistivity log profiles are displayed in the left-hand column. Porosity log files and measured core porosity data are plotted in the second track from the left. Calculated $V_{shale}$ and bulk volume water values are plotted in the two tracks right of center. Calculated $S_w$ and core $S_w$ data and calculated and core permeability data are plotted in the right-hand tracks. Pay flags are displayed in the far right track. Log-calculated porosities, water saturation, and permeability compare closely with measured core data for the cored interval in the middle and lower Lance Formation, American Hunter Old Road unit 1, Sublette County, Wyoming.
At the time the Old Road well was drilled, the full potential of low-permeability natural gas reservoirs was only beginning to be recognized by the petroleum industry. If this well had been drilled 10 yr later, it is likely that modern fracture-stimulation treatments may have been able to establish hydrocarbon production from the cored interval in this well.

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samples and analytical data. Triple O. Slabbing, Denver, Colorado, slabbed cores from the middle and lower Lance. Basin Exploration and Stone Petroleum funded core slabbing. Snyder Oil Company supported special core analysis. Core analysis and DST data were provided by the operator and are on file with the Wyoming Oil and Gas Conservation Commission, Casper, Wyoming, and at the U.S. Geological Survey Core Research Center, Denver, Colorado. Drafting of the core description was completed by Ken Graff.

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