Drilling and Testing the DOI-04-1A Coalbed Methane Well, Fort Yukon, Alaska

By Arthur Clark, Charles E. Barker, and Edwin P. Weeks

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By Arthur Clark[1], Charles E. Barker[2], and Edwin P. Weeks[3]

Introduction

The need for affordable energy sources is acute in rural communities of Alaska where costly diesel fuel must be delivered by barge or plane for power generation. Additionally, the transport, transfer, and storage of fuel pose great difficulty in these regions. Although small-scale energy development in remote Arctic locations presents unique challenges, identifying and developing economic, local sources of energy remains a high priority for state and local government.

Many areas in rural Alaska contain widespread coal resources that may contain significant amounts of coalbed methane (CBM) that, when extracted, could be used for power generation. However, in many of these areas, little is known concerning the properties that control CBM occurrence and production, including coal bed geometry, coalbed gas content and saturation, reservoir permeability and pressure, and water chemistry. Therefore, drilling and testing to collect these data are required to accurately assess the viability of CBM as a potential energy source in most locations.

In 2004, the U.S. Geological Survey (USGS) and Bureau of Land Management (BLM), in

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cooperation with the U.S. Department of Energy (DOE), the Alaska Department of Geological and Geophysical Surveys (DGGS), the University of Alaska Fairbanks (UAF), the Doyon Native Corporation, and the village of Fort Yukon, organized and funded the drilling of a well at Fort Yukon, Alaska to test coal beds for CBM developmental potential. Fort Yukon is a town of about 600 people and is composed mostly of Gwich'in Athabascan Native Americans. It is located near the center of the Yukon Flats Basin, approximately 145 mi northeast of Fairbanks (fig.1).

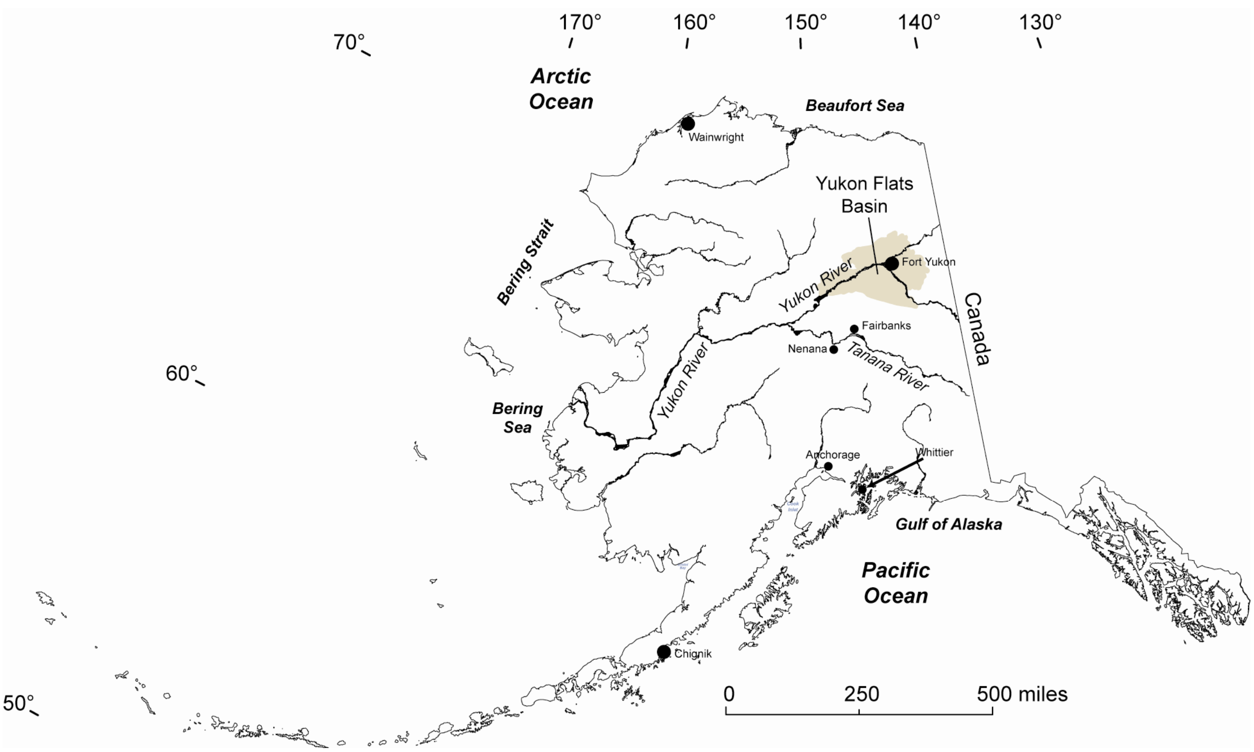

Figure 1. Map of Alaska showing location of Yukon Flats basin and Fort Yukon.

Background

The Yukon Flats basin in east-central Alaska is a 8,500 mi^2 basin containing up to 10,000 ft of Cenozoic fill including upper Miocene to upper Oligocene nonmarine coal-bearing lacustrine strata (Kirschner, 1994). CBM potential in the basin was primarily based on a 1994

USGS climate studies core hole that was drilled to a depth of 1,282 ft near the village of Fort Yukon at lat 66.55949°N, long 145.20616°W. After setting steel casing through the top 100 ft of Quaternary gravel deposits, the well was drilled through mid-Pliocene to early-Miocene lacustrine, fluvial, and paludal deposits (Ager, T.A., 2005, unpub. data) and penetrated a thick coal bed from a depth of 1,256 to 1,282 ft. When brought to land surface and extracted from the core tube, the coal cores were visibly and audibly degassing to the atmosphere. However, no gas desorption or sampling equipment was available at the site and no analysis of the gas content or chemistry was conducted. Due to concerns about the possibility of a gas blowout, drilling was terminated at 1,282 ft prior to penetrating the full thickness of the coal.

In 2000, the DOE funded the DGGS and USGS to conduct field investigations near the Alaskan communities of Wainwright, Fort Yukon, and Chignik to gather information in preparation for possible CBM exploratory drilling and testing programs. With this funding, the DGGS contracted the Kansas Geological Survey to conduct a high-resolution seismic reflection study at Fort Yukon to (1) characterize the geometry of the strata underlying the Fort Yukon area, (2) identify the lateral extent and continuity of the thick coal bed encountered in the 1994 core hole, and (3) identify deeper coal beds if present. The seven-line seismic survey, covering a 2 to 3 mi^2 area, was conducted in and around Fort Yukon in March, 2001 (Miller and others, 2002). The report concluded that (1) the coal bed penetrated in the 1994 Climate Studies well appeared to be relatively flat-lying and laterally continuous throughout the study area, (2) there appeared to be at least two more thick, laterally-continuous coal beds at greater depth, (3) no major structures existed underneath the study area, and (4) the coal intervals were well fractured and exhibited seismic attributes that in other settings indicated the presence of gas.

Using the information from these studies, the DGGS, BLM, USGS, and UAF decided to transport portable drilling equipment to Fort Yukon, reenter the surface casing set for the 1994 core hole, and drill and test a 2,500-ft-deep well to assess the potential for local-use CBM production. Funding for the project was provided by DOE, BLM, and USGS.

Project Objectives

Due to the remote nature of many of Alaska's rural communities, with few exceptions, there are little geologic, hydrologic, or chemical data available when evaluating an area's potential for local-use CBM production. Communities located in coal-bearing basins are often a dozen or more miles away from the closest coal outcrop making it conjectural as to the depth to, and thickness of, possible coal deposits. In addition, essential reservoir properties such as hydraulic conductivity and water chemistry, which can only be determined through drilling and testing programs, are generally not known. Given this dearth of information, the primary objectives of the 2004 Fort Yukon drilling effort were to (1) determine if lightweight, portable drilling equipment could be used to effectively and economically collect the data needed to evaluate an area's potential for local-use CBM production, (2) collect site-specific data that would allow an assessment of the CBM potential at Fort Yukon to be made, and (3) gain knowledge and experience that could be applied to future CBM drilling and testing programs conducted throughout rural Alaska and in other remote locations.

This report presents the findings of the 2004 drilling program. Section 1 provides a general overview of project activities including the equipment and procedures used, a project timeline, and difficulties and problems encountered. Section 2 discusses sampling techniques and presents canister desorption, reservoir saturation, coal chemistry, and desorbed gas data. Section 3 provides results of hydraulic testing. Although substantial difficulties were encountered during aquifer testing procedures, the results of each test are analyzed and summarized to as great an extent as possible. In addition, this section provides a brief discussion concerning the chemistry of water samples collected during project operations. The Summary of Results section uses the collected data to draw preliminary conclusions as to the potential of local-use CBM production at Fort Yukon.

Acknowledgments

Drilling, coring, geophysical logging, hydrologic testing, coal desorption, and other operations at Fort Yukon were conducted by a consortium consisting of the USGS Central Energy Resources Team (CERT), the USGS Central Region Research Drilling Project (CRRDP), the USGS Water Resources Division National Research Program (NRP), the BLM, the DGGS, and the UAF. The research team consisted of Arthur Clark, Charles Barker and Steve Roberts of the CERT, Edwin Weeks and Barbara Corland of the NRP, Bob Fisk and Beth Maclean of the BLM, Jim Clough and Karen Clautice of the DGGS, and David Ogbe and Amy Rodman of the UAF. Thanks to Fred Grub and Peter Galanis of the USGS in Menlo Park, Calif. for running the borehole temperature logs in May 2005. Special thanks go to the USGS drill crew personnel consisting of Jeff Eman, Rob Hunley, Steve Grant, Mike Williams, Mike Schulz, Thane Bird, and Andrew Ratliff for their hard work and effort, without which the project could not have been accomplished.

Many thanks are owed to the community of Fort Yukon for the help and cooperation provided during the project with particular appreciation extended to Fannie Carrol (Fort Yukon City Manager), Vickie Thomas (Fort Yukon Mayor), James Kelley (Gwitchya Zhee Corporation), Davey James (Gwitchya Gwich'in Tribal Government) and Bonnie Thomas (Council of Athabascan Tribal Governments). Special thanks is extended to David Lee Thomas (Gwitchya Zhee Utility Company) for the expert and enthusiastic assistance provided throughout the project. Thanks also to Jim Merry and Norm Phillips of the Doyon Corporation for their assistance and support. The U.S. Air Force 611 CER/CERR at Elmendorf AFB in Anchorage helped facilitate permitting and logistical requirements and the members of the U.S. Air Force Fort Yukon Long Range Radar Site provided support throughout. Their help was invaluable and greatly appreciated.

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Miller, R.D., Davis, J.C., Olea, Ricardo, Tapie, Christian, Laflen, D.R., and Fiedler, Mitchell, 2002, Delineation of coalbed methane prospects using high-resolution seismic reflections at Fort Yukon, Alaska: Kansas Geological Survey, Lawrence, Kansas, Open-File Report 2002-16, 47 p.

Section 1: Drilling and Testing Overview of the DOI-04-1A Coalbed Methane Well, Fort Yukon, Alaska

By Arthur Clark[1]

Introduction

In the spring of 2004, the Alaska Department of Geological and Geophysical Sciences (DGGS), using funds from the U.S. Bureau of Land Management (BLM), and working with the U.S. Geological Survey (USGS), purchased an Atlas Copco-Christensen CS-1000 P6L™ drilling rig and accessories, 3,000 ft of Atlas Copco-Christensen lightweight HCT™ wireline core rods, and a hydraulically-powered 35 gallon per minute (gpm) triplex mud-pump to conduct coalbed methane (CBM) test drilling at selected rural Alaska villages as part of the cooperative Alaska Rural Energy Project. The equipment, along with other drilling equipment owned and operated by the USGS in Denver, Colo., was transported to Fort Yukon, Alaska, where a 2,287-ft CBM test well was drilled, and select strata cored, from August 21 through September 9, 2004. Two significant coal zones were penetrated and partially cored in this well. The upper zone extended from 1,256 to 1,345 ft and contained individual coal beds from 1,256 to 1,315 ft and 1,340 to 1,345 ft. The lower zone extended from 1,878 to 1,926 ft and contained an individual coal bed from 1,900 to 1,920 ft. A partial set of geophysical logs were run on the full borehole thickness and a small-diameter monitor well was set in the upper coal bed for the collection of hydraulic properties.

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Equipment

In addition to the drilling rig, the wireline core rods, and the coring mud-pump, several transport and supply trailers were purchased specifically for this project. Other USGS-owned equipment including a large-capacity water truck, a 150 gpm duplex mud-pump, and a 1,000 gallon capacity mud-handling system, was used for drilling operations. Primary equipment included:

- CS-1000 P6L drilling-core rig
- HCT wireline core system including core rods, barrels, bits, and accessories
- 3,200-gallon Autocar water truck
- Bean 35 gpm triplex core pump
- Gardner-Denver 5 in. x 6 in. 150 gpm duplex mud-pump
- 1,000-gallon capacity mud recirculation and cleaning system
- Pickup truck with welder, torches, fuel tank, and tool boxes
- 25-ft flatbed supply trailer for transport of core rods, barrels, and accessories
- 25-ft flatbed trailer for transport of the drill rig
- 16-ft cargo trailer for transport and storage of tools, equipment, and supplies
- Light tower and 6 kW generator-trailer
- Washington Rotating Control Heads Inc. non-rotating diverter system
- Century Geophysical portable logging system and tools

Equipment Transport

On April 22, 2004, all equipment, with the exception of the drilling rig, was loaded onto Union Pacific railcars in Denver, Colo. for transport to Seattle, Wash. The drilling rig was delivered to the USGS on April 20 but needed to be assembled and tested prior to shipment. After initial testing, the rig was loaded onto a 25-ft flatbed trailer and driven from Denver to the

Alaska Railroad Barge Terminal in Seattle, Wash., arriving on May 3, where it was stored with the rest of the equipment awaiting barge transport to Alaska. All of the equipment was then transferred to the Alaska Railroad Corporation and loaded on an ocean-going barge for transport to Whittier, Alaska. At Whittier, the railcars were removed from the barge and transported by rail to Nenana, Alaska where they were unloaded at the Yutana Barge Lines facility. Yutana Barge Lines then loaded the equipment onto a river barge and transported it down the Tanana River to its confluence with the Yukon River, then up the Yukon River to Fort Yukon where it arrived on June 14. The equipment was unloaded from the barge and moved approximately two miles to the U.S. Air Force Fort Yukon Long Range Radar Site where it was stored until the drill crews arrived to commence drilling operations on August 19.

Drilling Operations

Drill-site planning, supervision, and operations were conducted by the USGS Central Region Research Drilling Project (CRRDP) based in Denver, Colo. Two 3-person drill crews, and one drill-site supervisor conducted 24-hour per day operations between August 19 and September 13, 2004. The crews flew from Denver to Fort Yukon on August 19, equipment was unpacked and prepared on August 20, drilling commenced on August 21, and a total depth of 2,287 ft was reached on September 3. Geophysical logging was conducted on September 4 and 5 and monitor well installation and hydraulic testing were conducted from September 5 through September 9. September 10 through 12 were spent cleaning, packing, loading, and storing equipment, and the crews returned to Denver on September 13.

The drill rig was set up over an abandoned USGS test hole that had been cored for a USGS Climate Studies project in 1994 to a depth of 1,282 ft (fig.1-1).

Figure 1-1. Drill rig at Fort Yukon CBM drill site DOI-04-1A, August, 2004.

The hole had an 8 $^5/_8$ –in. outer-diameter steel conductor casing cemented from ground surface to a depth of approximately 100 ft through unconsolidated Quaternary gravel deposits. By reentering the same casing, the 2004 project avoided having to drill, case, and cement these same deposits. Upon completion, the 1994 hole had been backfilled from the bottom of the well to ground surface with bentonite-abandonment grout and cement and these materials needed to be drilled and flushed from the hole before drilling could proceed to greater depths. After the initial setup of equipment, the cement was drilled from the inside of the conductor casing and the abandonment grout was flushed from the well by reaming to a depth of 1,282 ft using a 6 ¾-in. full-hole polycrystalline diamond composite (PDC) bit. Due to the unconsolidated and fluidized nature of the strata, it was anticipated that shortly after drilling through the conductor casing, the drill bit would wander from the 1994 well bore and a new hole would be drilled roughly parallel to the abandoned 1994 bore-hole. If this happened, coal core could be retrieved from the top of the upper coal bed through its full thickness for gas desorption and analysis. Although some abandonment grout was flushed from the well during the reaming process, fresh silt and clay drill cuttings made it appear as though the drill bit had deflected from the 1994 hole as anticipated and that a new hole was being drilled. Therefore, at a depth of 1,205 ft, the rotary bit was pulled and the wireline coring system installed so that, in addition to the coal bed, approximately 50 ft of overlying strata could be cored. However, while tripping the core system into the hole, a hoist bail came unthreaded from the core rods, allowing them to fall to the bottom of the mud-filled hole. During subsequent retrieval efforts, it was discovered that rather than coming to rest at a depth of 1,205 ft as expected, the bottom of the core system had come to rest at a depth of 1,282 ft. This meant that rather than drilling a fresh parallel hole as thought, the drill string had reentered the original 1994 well bore which was full of abandonment grout but still open to its total depth. Because of this, the upper coal bed interval from 1,256 to 1,282 ft could not be cored and desorbed as desired. After pulling the retrieved core rods from the well and cleaning and flushing the well to a depth of 1,283 ft with the 6 ¾-in. rotary bit, wireline coring operations began using the HCT wireline core system (2.4-in. diameter core) with an oversized 4 ¼-in. outside-diameter PDC core bit. Continuous core was taken from 1,283 to 1,835 ft with 91 percent core recovery in coal, silt, and clay intervals and 38 percent recovery in unconsolidated sand intervals. Little attempt was made to maximize core recovery in the sand as there was little project-priority information to be gathered in these sections. Rather, an emphasis was placed on maximizing borehole depth at the expense of core recovery in non-coal bearing zones. At a depth of 1,835 ft, the wireline retrieval cable became stuck in the core rods, requiring the rods to be pulled from the well. Rather than proceeding with continuous coring operations, it was decided to ream the previously cored section of the hole to a 6 ¾-in. diameter and to open-hole rotary drill until another significant coal bed was encountered. A second significant coal bed was penetrated at a depth of 1,900 ft, and, after drilling to 1,910 ft to confirm the presence of the coal and to collect coal cuttings for desorption analysis, the rotary bit was removed and the wireline system reinstalled. Continuous core was taken from 1,910 to 1,965 ft through coal (1,910 to 1,920 ft) and interbedded clay, silt, and carbonaceous shale. In an attempt to reach as great a depth as possible, a decision was made to resume rotary drilling with the 6 ¾-in. bit at 1,965 ft and to resume coring only if another significant coal bed was encountered. The rotary bit was reinserted, the previously cored portion of the hole was reamed, and open-hole rotary drilling was resumed. At a depth of 2,165 ft a thick, indurated, coarse-grained to conglomeratic sandstone was encountered causing a significant decrease in drill-penetration rates. Drilling continued through interbedded sandstone, siltstone, and claystone layers, but with no further significant coal beds encountered, and with penetration rates greatly reduced, a decision was made to discontinue drilling at a depth of 2,287 ft. The drill rods were pulled back to a depth of 1,600 ft and the hole reamed back to bottom. The well was then flushed with thin, clean drill mud and prepared for geophysical logging operations. Finally, the drill rods were removed from the well so that logging operations could begin.

A generalized lithologic log of the penetrated strata, based on geophysical log interpretation and unpublished core descriptions by the USGS (Ager, T.A., and Fouch, T.D., 1995, unpub. data) and Alaska DGGS (White, J.G., and Clough, J.G., 2005, unpub. data) is shown in figure 1-2.

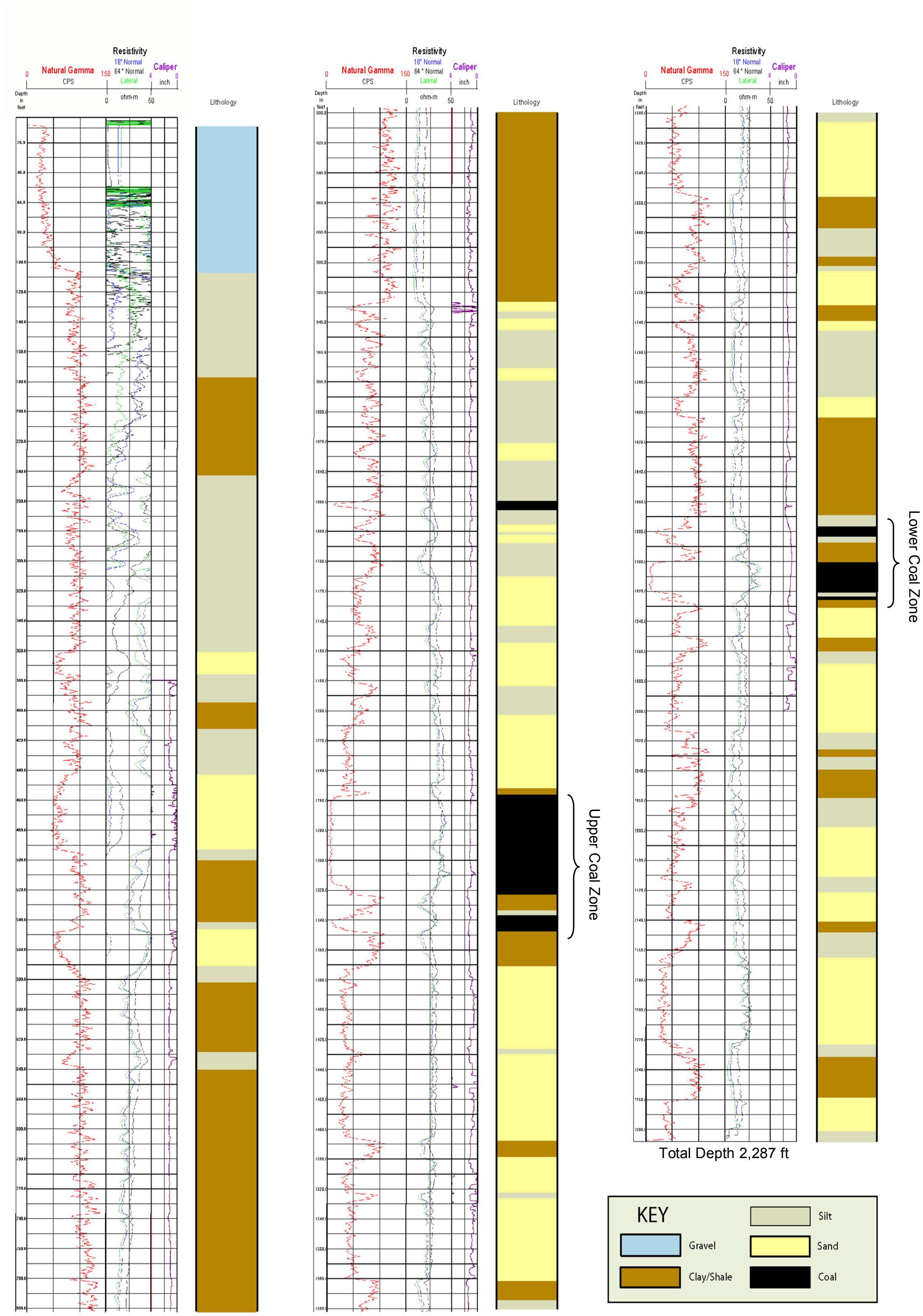

Figure 1-2. Generalized lithology of borehole DOI-04-1A, Fort Yukon, Alaska based on geophysical log interpretation and unpublished core descriptions.

Geophysical Logging

The well was logged using a portable Century Geophysical Corporation logging system. A logging winch with 5,000 ft of logging cable was purchased specifically for the project and the rest of the operating system was provided by the CRRDP (fig.1-3).

Figure 1-3. Geophysical logging winch and operating system.

Century logging tools consisted of a 9074 caliper-natural gamma tool, and a 9044 multi-function tool (16-in. normal, 64-in. normal, fluid, lateral, and single-point resistivity, spontaneous potential, temperature, and natural gamma). Additionally, Mt. Sopris Instrument Company density and sonic tools were borrowed from the USGS Borehole Geophysics Research Project in Denver. A MGX II box was utilized to provide the electronic conversion between the Century operating system and the Mount Sopris tools.

Logging operations started at 15:00 hours on September 4. The 9074 caliper-gamma tool was the first tool run and, due to tight sticky spots in the drill hole, could only be lowered to a depth of 2,000 ft. While logging, the tool experienced operational difficulties at a depth of 380 ft and was not run above that point. The 8044 multi-function tool was run next and, with great effort, was lowered to the bottom hole depth of 2,287 ft. Logs of the full borehole were obtained using this tool (fig.1-4). However, numerous problems were encountered when attempting to operate the Mt. Sopris tools with the Century system. Both the tool calibrations and the recorded borehole footages were off by a considerable amount and, even with repeated attempts to rectify the problem, could not be reconciled. Both tools were run from a depth of approximately 2,200 ft but, due to the various calibration and compatibility problems, the data gathered were of marginal quality. Logging operations were completed at 03:00 hours on September 5.

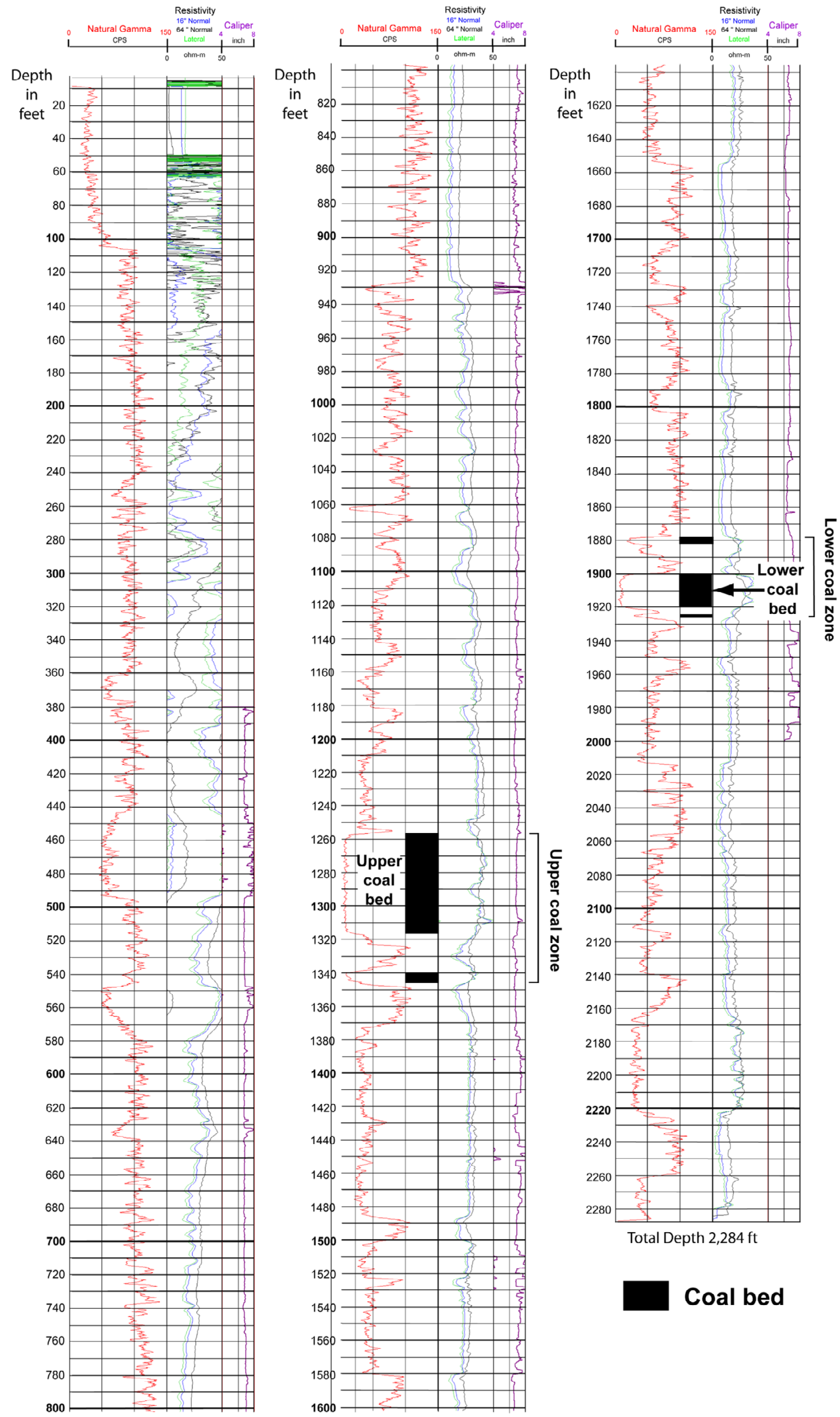

Figure 1-4. Geophysical logs of drill hole DOI-04-1A, Fort Yukon, Alaska

Monitor Well Installation

After reviewing core, desorption, and geophysical data, a decision was made to set a monitor well and collect hydraulic information from the upper coal bed. To seal the well below 1,315 ft, drill rods were lowered to a depth of 2,275 ft and abandonment grout was mixed and pumped from the bottom up to a depth of 1,330 ft. Bentonite pellets and chip were then poured through the rods, using tremie-suction methods, to a top depth of 1,313 ft. Several 5-gallon buckets of cleaned and sorted river gravel were poured on top of the bentonite to a top depth of 1,307 ft. A 2 ½-in., schedule 80, threaded flush-joint, polyvinyl chloride (PVC) monitor well with a 5-ft section of stainless steel pipe attached to the bottom was installed in the well with the open bottom of the pipe set at a depth of 1,272 ft and a set of rubber formation packers set at 1,265 ft. At ground surface, a coupler was attached to the top of the PVC pipe using glue and screws and a carbide-impregnated sandwich clamp was secured to the PVC pipe immediately below the coupler. The clamp was then set on the 8 ⅝-in. steel surface casing so that the full weight of the PVC pipe was suspended from the clamp. A 1 ½-in. stainless steel tremie pipe was inserted into the annular area between the borehole wall and the PVC pipe and ten 5-gallon buckets of ¼-in. bentonite pellets poured through the pipe and placed on top of the rubber packers. Abandonment grout was then mixed and pumped through the pipe from the top of the bentonite pellets to within 20 ft of ground surface. Portland cement was mixed and poured in the top 20 ft. This left the well with 42 ft of isolated open-hole monitor zone in the coal from 1,265 to 1,307 ft., with gravel extending to a depth of 1,313 ft (fig. 1-5*A*). The 1 ½ -in. tremie pipe was removed from the annular area, cleaned, and lowered into the monitor well to a depth of 1,300 ft. Fresh water was then slowly circulated through the well to remove drill mud and other material from the coal and the well.

Well Development and Testing

After circulating the drill mud from the monitor well, a portable air compressor (350 psi, 185 cfm) borrowed from the Air Force facility was used to develop the well using air lift methods. The tremie pipe was pulled to within 200 ft of land surface and compressed air was circulated through the pipe from progressively greater depths. On September 7, well development was conducted from depths of 200, 300, 400, and 500 ft with minimum water being produced from the well. After monitoring water-level recovery at 500 ft with a hand-held water-level meter, development was continued at a depth of 600 ft. However, as fluid inside the casing was removed from progressively greater depths, the pressure differential between the outside and the inside of the casing increased correspondingly. As a result, during air development at 600 ft, the downward pressure exerted on the rubber formation packers exceeded the holding capacity of the coupler secured to the top of the PVC pipe. As a result, the coupler sheared and the casing slipped through the carbide sandwich clamp, falling approximately 35 ft into the well before coming to rest on the gravel at 1,307 ft (fig. 1-5*B*). Due to the cold ground temperatures, the Portland cement that had been pumped into the upper 20 ft of the annular area had not properly cured and thus did not prevent the pipe from falling down the hole. Rather than latching onto the casing and attempting to pull it back to land surface, which would likely have resulted in the fracture of the casing and the total loss of the well, two 20-ft sections of 2 ½-in. PVC pipe, with a coupler attached face down, were lowered down the well and slipped over the top of the existing casing at 35 ft. This effectively extended the top of the well back to ground surface but theoretically decreased the monitored area in the well to the open zone between 1,300 and 1,307 ft and the gravel-filled zone between 1,307 and 1,313 ft (fig. 1-5*C*). The air development pipe was then pulled back to 300 ft and, using the air compressor, the well was cleared of fluid in 100 ft intervals to a depth of 800 ft. With only a minimal amount of water being produced, development was discontinued and a 1,000 psi pressure transducer placed in the well to a depth of 780 ft to collect overnight water recovery data.

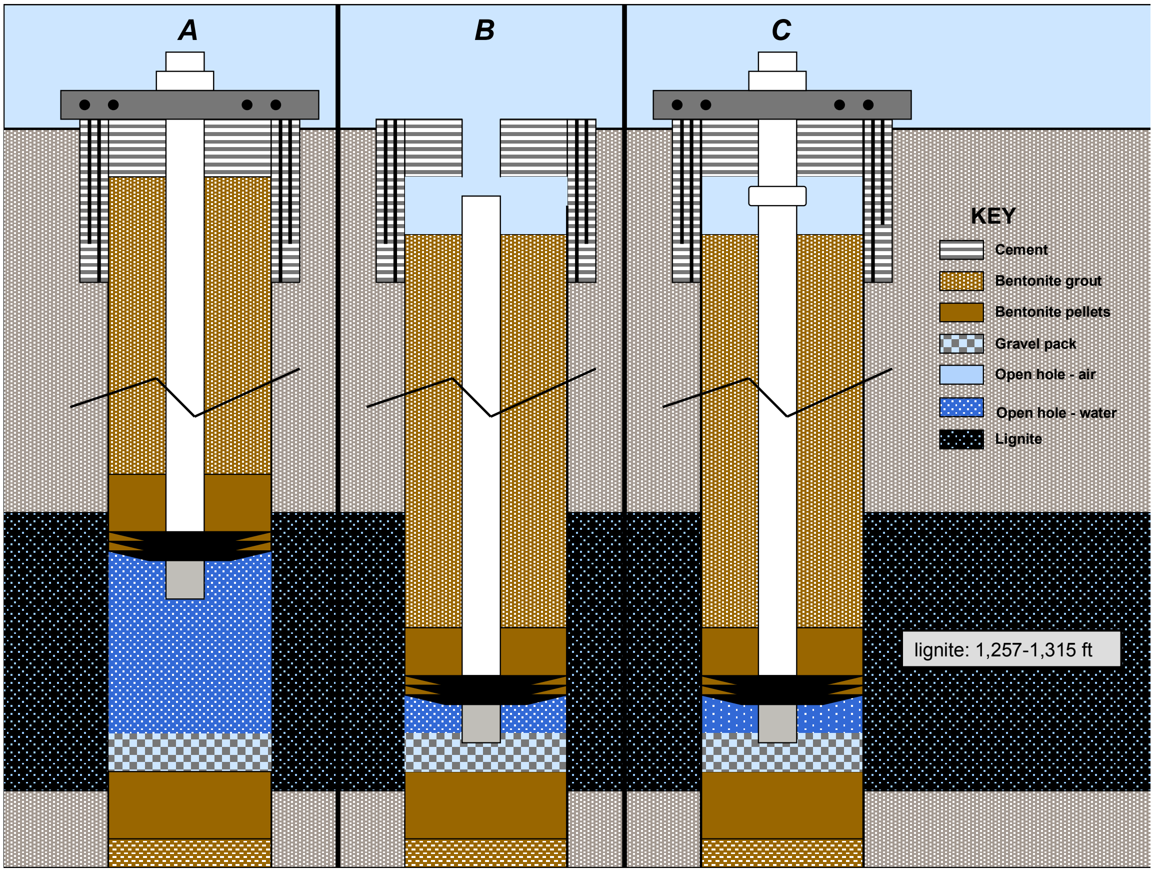

Figure 1-5. *A*. Initial configuration of monitor well DOI-04-1A; *B*. Configuration of monitor well after casing had slipped; *C*. Configuration of monitor well after casing was extended back to land surface.

On the morning of September 8, after reviewing the water recovery data, air development resumed at depths of 800, 900, and 1,000 ft with small water samples being collected for water-quality analysis. After installing the pressure transducer to 1,020 ft and collecting water-recovery data for two hours, a decision was made to again flush the well with fresh water in an attempt to clean the gravel and improve water production. The development pipe was ultimately lowered to a depth of 1,280 ft and fresh water circulated through the well before pulling the pipe back and continuing air development from 200 and 300 ft. With the well still producing minimal water, the development pipe was removed from the well and the transducer installed to a depth of 400 ft to collect overnight recovery data.

On September 9, after reviewing the overnight data, it was apparent that the amount of water being produced from the well was so small that further efforts at well development were futile. A pressure transducer was placed in the well to a depth of 600 ft to collect over-winter pressure data. Additionally, two lengths of heat trace were placed in the well to depths of 275 ft and 350 ft so that the permafrost portion of the well (approximately 300 ft) could be thawed and the transducer recovered in the spring of 2005. A 5-ft section of vented 14-in. diameter pipe was placed and cemented over the well to serve as a protective cover during the winter months (fig.1-6). The equipment was then cleaned, winterized, packed, and parked at the Air Force facility.

Figure 1-6. Fort Yukon drill site at conclusion of 2004 drilling operations with protective cover placed over well.

Spring 2005 Activities

A two-man crew flew to Fort Yukon on May 7, 2005 to thaw the well, remove the transducer, decommission the well, and prepare the equipment to be barged back to Nenana. After installing batteries and getting the equipment running, the heat traces were plugged in and, within several hours, the well was thawed. The transducer was removed and a temperature log of the well was taken by a USGS Geothermal Project crew from Menlo Park, Calif. (fig.1-7). After running the temperature log, water was bailed from the well to a depth of approximately 850 ft and water samples were collected from the bottom of the well using a stainless steel discrete-zone sampler. The well was then decommissioned by pumping a Portland cement slurry into the well from the surface. Steel and plastic well casings were cut 3 ft below land surface and a metal plate and cement cap placed over the well. All well abandonment operations were observed and approved by a representative of the Alaska Oil and Gas Conservation Commission (AOGCC). The area was cleaned and raked and all equipment loaded and prepared for barge transport to Nenana.

The equipment was loaded onto the Yutana Barge Lines barge on June 10 and arrived in Nenana, Alaska on June 17, 2005.

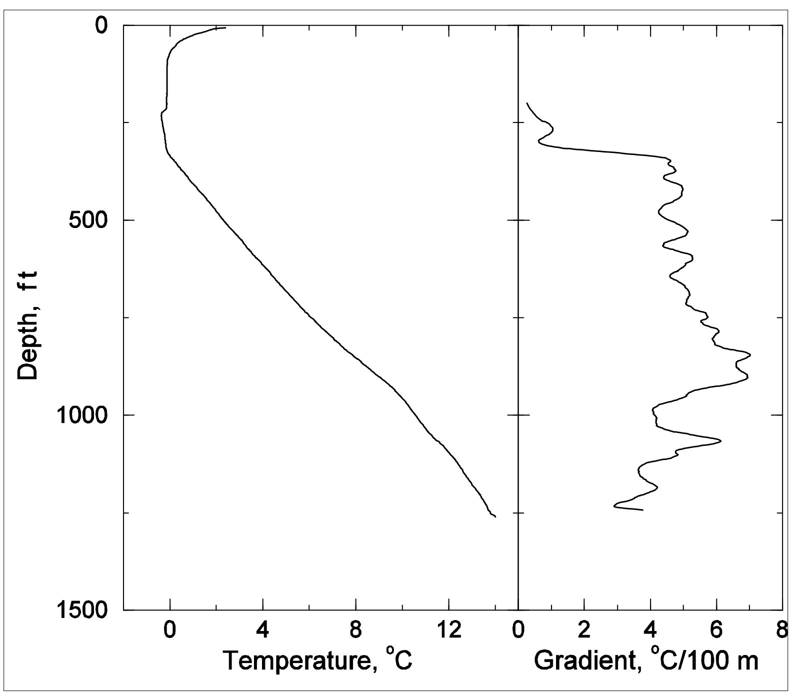

Figure 1-7. Temperature log for Well DOI-04-1A made in May 2005.

Results

The drilling of the 2004 Fort Yukon CBM test well confirmed that portable drilling equipment can effectively be used to conduct initial CBM assessment drilling in remote areas where little-to-no subsurface information exists. Although numerous difficulties were encountered during the project, the data required to make a preliminary determination concerning the viability of local-use CBM production were collected in a timely and economic fashion. However, as with any such project, there were lessons learned that can be applied to similar future operations.

Given more time, it would have been preferable to collect continuous core through the entire well bore rather than selectively coring in coal-bearing zones only. This is especially important in areas such as Fort Yukon where virtually no subsurface data exists. Even with the collection of drill cuttings, it is often difficult to quickly identify borehole lithology when conducting rotary drilling operations. This allows for the possibility of drilling through relatively thin coal beds or other strata before identifying them as zones of interest. Even though the coal bed encountered at 1,900 ft during rotary drilling in DOI-04-1A was quickly identified so that adequate core samples could be obtained, the upper ten ft of the bed were not cored and therefore not available for desorption or analyses. In areas that contain relatively thin coal beds, rather than the substantial coal beds encountered at Fort Yukon, this could prove problematic. Although the selective core approach may continue to be necessary for future projects due to time or budgetary constraints, the increased data gathered during continuous coring operations is probably worth the increased effort and cost.

Due to the portable nature of the equipment used during the drilling operations, the drill/core rods purchased and used for this project were thin-walled and light-weight in nature. This does not pose a problem for continuous core drilling operations and allows for a maximum well-bore depth to be obtained. However, when using these rods for open-hole rotary drilling, the increased torque and stress transferred to the rods significantly increases the possibility of rod and (or) rod thread fatigue and failure. Although no rods were fractured during the 2004 project, several hundred feet of rods suffered non-repairable thread damage due to excessive torque and “snap” exerted on them during rotary drilling and could no longer safely be used. Although the time and money involved in rotary drilling is significantly less than core drilling, if fracture of the light-weight core rods does occur, the possibility exists of losing the entire borehole. If this does happen, it will become necessary to utilize the core rods for coring purposes only.

Due to time and budget constraints, a decision was made to drill the Fort Yukon borehole, desorb the coal cores, and obtain geophysical logs, before choosing one coal bed from which to collect hydraulic data. Based primarily on its greater thickness, it was decided to collect hydraulic data from the upper coal bed at 1,256 ft rather than the lower bed at 1,900 ft. Therefore, no hydraulic data was collected from the lower coal bed even though it ultimately contained more methane on a standard cubic feet per ton (scf/ton) basis than did the upper bed (see section 2, p. 31). In hindsight, the collection of hydraulic data is of such importance when analyzing reservoir properties and production potential that priority efforts should be made to collect such data from all significant gas-bearing coal beds. This can be accomplished in one of two ways: (1) upon coring through the base of a significant gas-bearing coal bed, discontinue the drilling process, isolate the zone using a single inflatable pneumatic packer system, and collect discreet-zone hydraulic data; or (2) at the completion of all drilling, coring, and geophysical logging operations, use an inflatable straddle-packer system to isolate individual coal beds and collect the required data. Although leaving packers inflated in a fluid-filled borehole during the data collection process increases the risk of sticking the rods and losing the well, the importance of the data is such that, with proper precautionary measures, the benefits probably outweigh the risks involved in the collection process.

All core and cuttings samples collected from borehole DOI-04-1A have been transferred to the Alaska Geologic Materials Center in Eagle River, Alaska (contact Dr. John Reeder, 907-696-0079) and released to the public.

Section 2: Canister Desorption Results from the DOI-04-1A Well, Fort Yukon, Alaska

By Charles Barker[1], Arthur Clark[2], Beth Maclean[3], Karen Clautice[4], and Amy Rodman[5]

Introduction

The Fort Yukon coalbed methane (CBM) assessment study was conducted by reentering a 1994 USGS core hole to sample coal found in Tertiary strata in the Yukon Flats Basin (Ager, T.A., 2005, unpub. data). The 1994 well encountered a coal bed at 1,256 ft and cored 26 ft of coal before drilling was stopped at 1,282 ft, still in coal. In 1994, it was noted that gas was bubbling from the coal core but desorption testing of the coal was not possible at that time. Consequently, the reentry of the 1994 well, now officially named DOI-04-1A, was designed to test the methane content of the coal.

DOI-04-1A well (API no. 50-091-20001) is located at lat 66.55949°N. and long 145.20616°W. The total depth of the well was 2,287 ft. The strata encountered consisted of about 100 ft of gravel, followed primarily by sandstone, shale, siltstone, and coal associated with Pliocene to Miocene lake beds deposited some 1.5 to 15 million years ago (Ager, T.A., 2005, unpub. data). Permafrost was encountered in the well from just below the surface to a depth of about 300 ft. The well penetrated two primary coal zones: the shallower coal zone extended from 1,256 to1,345 ft and contained one major coal bed from 1,256 to 1,315 ft and a second

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coal bed from 1,340 to 1,345 ft. The deeper coal zone extended from 1,878 to 1,926 ft with a major coal bed from 1,900 to 1,920 ft. The net coal thickness for the primary coal beds in the two coal zones was 84 ft. Thin or high-ash coals, as picked from geophysical logs (fig. 2-1) at 1,061 to 1,063 ft, 1,878 to 1,882 ft, and queried coal at 2,024 ft, 2,030 ft, 2,038 ft, and 2,056 ft were not sampled for desorption.

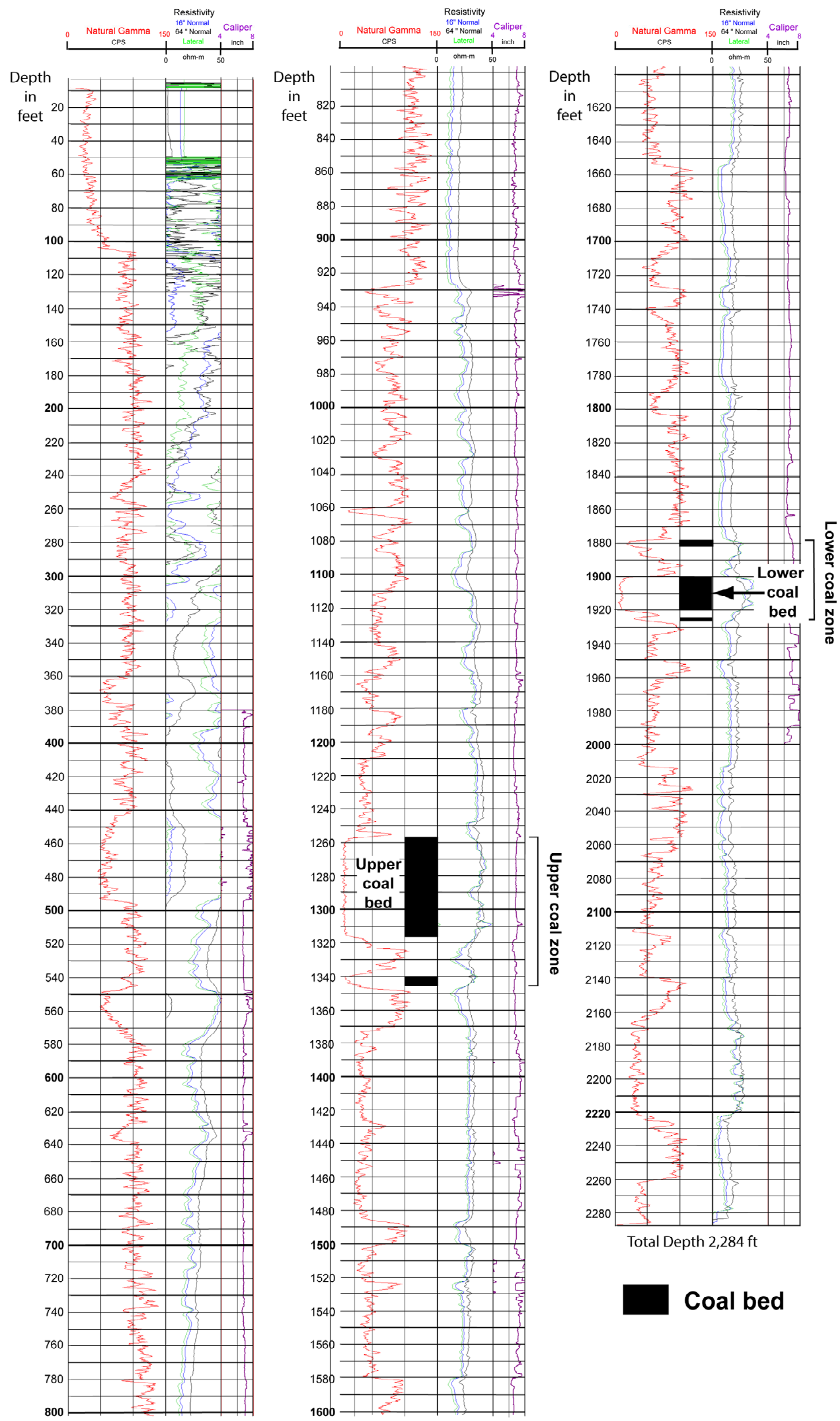

Figure 2-1. Geophysical logs of drill hole DOI-04-1A, Fort Yukon, Alaska

DesorptionTechnique

Coal desorption followed a modified U.S. Bureau of Mines (USBM) canister desorption method as described by Diamond and Levine (1981), Close and Erwin (1989), Ryan and Dawson (1993), McLennan and others (1994), Mavor and Nelson (1997), and Diamond and Schatzel (1998) as adapted and modified by Barker and others (1991, 2002) for the use of PVC canisters. Another major modification of the USBM technique in this study was the use of zero-headspace canisters (Barker and Dallegge, 2005) in which the headspace is filled with distilled water rather than with helium gas as described in Barker and others (2002). For this study, the distilled water was chilled to the approximate drilling mud temperature of 45 to 50 °F prior to adding it to the canister to minimize the time required to equilibrate the can and coal core to the lost-gas temperature. Because it is not necessary to measure internal can temperature for a headspace correction when using zero headspace canisters (Barker and Dallegge, 2005), a desorption log form modified from Barker and others (2002) was used to allow for this difference. All canisters were pressure tested for leaks at 6 PSI over a period of at least 24 hours prior to use.

Lost-Gas Estimate

Lost gas is the unmeasured gas desorbed from coal core from the time it is lifted from the bottom of the well until it is sealed within the canister. Lost gas is controlled by the coal diffusivity, cleat spacing, and the length of time required to retrieve a given sample and is estimated by measuring the apparent early rate (first two to four hours) of gas desorption from the sample sealed within the canister. Lost gas is estimated by plotting cumulative desorbed gas volume versus the square root of time since the core was lifted off bottom (zero time), and extrapolating the early data, which should form a straight line, back to zero time. The absolute value of the cumulative volume at the zero-time intercept of this straight line indicates the volume of lost gas.

In coalbed methane drilling conducted in the Maverick basin in Texas, the Nenana and Cook Inlet basins in Alaska, and again at DOI-04-1A, the temperature measured at the center of a freshly opened core face closely tracks the drill mud temperature used to cut the core (unpub. USGS data), implying that as the core is being cut in the drill hole, it quickly equilibrates to the drill mud temperature. As a result, once the core retrieval process starts and sample desorption begins (assumed to be at time zero in the USBM method), the mud temperature to which the core has equilibrated is the relevant temperature for estimating gas diffusion from the coal matrix during the lost-gas period rather than the in-situ reservoir temperature. Therefore, during the period used to determine lost gas, the canisters were desorbed at ambient mud temperature as discussed in Barker and others (2002). Digital infrared thermometers were used to monitor drilling mud, core-face, and tank temperature throughout the project. Towards the conclusion of the project, tank temperatures were allowed to rise to room temperature (65 to 70 °F) in preparation for canister transport from the drill site to the laboratory in Denver, Colo.

Sampling Desorbed Gas

After the lost gas period had ended, selected core canisters were not measured for several hours allowing them to accumulate enough gas to collect for analysis. Gas samples were collected in evacuated 75 ml stainless steel cylinders equipped with needle valves to control gas flow and seal the cylinder after sampling, by attaching the cylinders directly to the desorption canister via quick-connect fittings, opening the needle valve for a few seconds, and then closing the valve and disconnecting the cylinder. This method of gas sampling provided a sealed sample in a sturdy, transportable container and minimized atmospheric contamination.

Analysis of Desorption Data

Correction of the data to standard temperature and pressure (STP) and preparation of a lost-gas estimate uses a spreadsheet described in Barker and others (2002).

Coring Operations

The 2004 reentry well, DOI-04-1A, was spudded on August 22, 2004 by reentering the existing 100 ft steel casing set for the 1994 USGS well. After reaming to the bottom of the 1994 borehole (see Section 1, p.11) and collecting reamed cutting samples for desorption from the 27 ft of coal cored at the bottom of the 1994 borehole (1,256 to 1,283 ft; canister sample cuttings 1, 2, 3 in table 2-1*A*), core drilling began on August 26 at a depth of 1,283 ft.

Because the first 27 ft of the upper coal bed was not cored, and the full thickness of the bed was not known, all coal recovered from the first two core runs were placed in canisters for desorption to ensure that adequate data from this bed were collected. After eight canisters had been filled, a decision was made to only desorb every other foot of coal. Although core recovery in the coal zone was very good (91 percent), some coal core was lost during the coring and core retrieval process. In some cases the lost coal cores were recovered on the next core run and placed in canisters since they should have retained their gas by staying at the hydrostatic pressure extant at the bottom of the well. Continuous core was drilled to a depth 1,835 ft with coal encountered from 1,283 to 1,315 ft and 1,340 to 1,345 ft. Thus, the upper major Fort Yukon coal zone lies at depths from 1,256 to 1,345 ft (fig. 2-1) and contains 64 ft of net coal. In an attempt to maximize the final depth of the well, and because no coal had been encountered for almost 500 ft, a decision was made to discontinue coring activities at 1,835 ft and to resume open-hole drilling until another significant coal bed was reached.

A second significant coal bed was encountered at 1,900 ft and was penetrated for 5 ft before drilling was stopped. All drill cuttings were circulated from the well and another 5 ft drilled to confirm the presence of a significant coal bed. The resulting cuttings from 1,905 to 1,910 ft confirmed the presence of a significant coal bed and were collected and placed into canisters 104-31 and 104-32 for desorption. Coring commenced at 1,910 ft and continued to 1,965 ft with a total of 10 ft of additional coal core being taken from 1,910 to 1,920 ft. This core was placed in canisters 104-33 to 104-42 (table 2-1*B*) for desorption. With the subsequent gamma log indicating the presence of a thin high-ash coal or carbonaceous shale at a depth of 1,878 to 1,882 ft, and a thin carbonaceous shale at 1,925 ft, the lower coal zone extends from approximately 1,878 to 1,926 ft (fig. 2-1) and contains 20 ft of net coal and 5 ft of high-ash coal or carbonaceous shale.

Rotary drilling was resumed at 1,965 ft and the borehole reached a final depth of 2,287 ft on September 3 with no further coal beds encountered or core samples collected.

Results

Desorption

The raw gas content of the upper coal bed core samples average 13.1 standard cubic feet (scf)/ton with a standard deviation of 3.5 scf/ton for 21 samples (table 2-1*A*). The raw gas content of the lower coal bed core samples average 19.1 scf/ton with a standard deviation of 4.0 scf/ton for 10 samples (table 2-1*B*).

Coal Quality

The upper coal bed, as determined from 21 coal core samples, has a moisture content averaging 41.25 wt.-percent, consistent with its lignite rank (table 2-2*A*). This coal bed also averages 4.10 wt.-percent ash and has an average specific gravity of 1.34, a typical value for low-ash coal.

The lower coal bed, as determined from 10 coal core samples, has a lower moisture content averaging 31.98 wt.-percent, an ash yield averaging 15.73 wt.-percent and a specific gravity of 1.48 (table 2-2*B*).

Desorbed Gas Analyses

Four gas samples taken from canisters 104-1, 104-18, 104-37 and 104-40 were sent to Isotech Laboratories, Champaign, Ill. for their NG-1 level compositional and isotopic analyses plus CO_2 carbon isotope analyses. All of the gas samples have a significant content of O_2, N_2, and CO_2 that might represent either release of these gases from in situ sorption sites, from atmospheric contamination of the coal cores while exposed to air during sampling, or a combination of the two sources. However, the proportion of in-situ O_2, N_2 and CO_2 versus these gases absorbed from exposure to air during sampling is difficult to separate. Consequently, the CH_4 and CO_2 contents, which are key gases in determining the quality of the gas for sales, were arbitrarily corrected to an O_2- and N_2-free basis to provide a qualitative assessment of gas quality. This method presumes that all O_2 and N_2 are contaminants and that all CH_4 and CO_2 are natural coalbed gas components.

After correction to an O_2- and N_2-free basis, the CH_4 content of the four gas samples ranges from 90 to 96 mol-percent and averages 94 mol-percent. The CO_2 content ranges from 3.7 to 9.5 mol-percent and averages 5.4 mol-percent. The CH_4-rich character of the gas is reflected in the calculated calorific content of the gas that ranges from 910 to 970 BTU/Mscf and averages 950 BTU/Mscf on an O_2- and N_2-free basis. Pure methane has a calorific content of 1,015 BTU/Mscf.

The $\delta^{13}C_{CH4}$ of the four samples ranges from -72 to -76 $^{o}/_{oo}$ and averages -73 $^{o}/_{oo}$. The $\delta^{2}H_{CH4}$ for these samples ranges from -318 to -331 $^{o}/_{oo}$ and averages -324 $^{o}/_{oo}$. Methane with this isotopic signature suggests a biogenic source for the gas (Whiticar, 1999), with no apparent thermogenic component.

Coalbed Saturation from Isotherms

Methane adsorption isotherms are measured by reintroducing methane to a coal sample and measuring the equilibrium gas content at a given pressure and at a constant temperature, generally the reservoir temperature. Sorption isotherms were developed for one sample each from the upper and lower coal beds, both at a temperature of 15 ºC, since a temperature log for the well after it had thermally re-equilibrated with the formation was not available at the time isotherm analyses were conducted. The resulting curves (figs. 2-2, 2-3) can be used with the measured gas content from canister desorption (tables 2-1*A*, 2-1*B*) to estimate degree of saturation and the reduction in reservoir pressure needed to saturate the coal with methane, important factors when evaluating coal bed production potential. The sorption isotherm for the upper coal bed should be reliable as the May 2005 temperature log indicates a formation temperature at a depth of 1,260 ft of about 14 ºC (fig. 2-4), nearly the same as the isotherm temperature. The degree of saturation for the upper coal bed, as calculated in figure 2-2, is 31 percent and the reduction in reservoir pressure required to saturate the coal bed with methane is 435 psi. The sorption isotherm for the lower coal bed (fig. 2-3) may overstate its in-situ sorption capacity, as the May 2005 temperature log indicates a geothermal gradient for the interval between the bottom of the permafrost zone and the depth of 1,260 ft of about 5 ºC/100 m or 2.7 ºF/100 ft. Assuming that gradient persists to the depth of the lower coal bed, its temperature would be about 24 ºC. Sorption capacity decreases with increasing temperature, and the degree of saturation for the lower coal bed of 37 percent, as calculated in figure 2-3, may be somewhat low. The curve also indicates that the reduction in reservoir pressure required to saturate the coal bed with methane is about 580 psi, a value that may be somewhat high, due to the temperature effect on the isotherm. Regardless, these values indicate that the coal beds are undersaturated and imply that reservoir pressure would have to be reduced by several hundred PSI before methane would be desorbed from the coals.

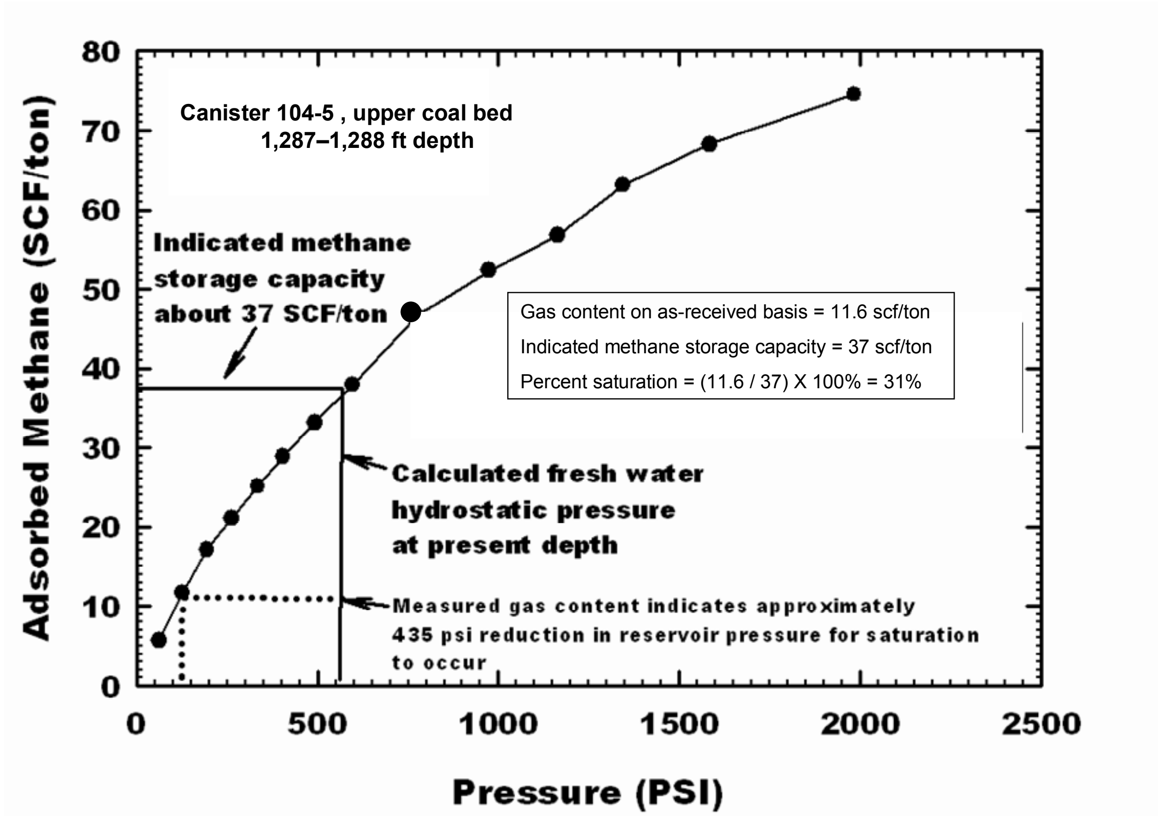

Figure 2-2. Methane adsorption isotherm for canister 104-5 at 1,287–1,288 ft depth in the upper coal bed, DOI-04-1A well, Fort Yukon, Alaska. Isotherm conditions were: 15 ^{o}C, coal at equilibrium moisture. Absorbed methane values reported on an as-received basis. Coal bed pressures calculated using a fresh water hydrostatic gradient of .433 psi per ft projected to the sample depth.

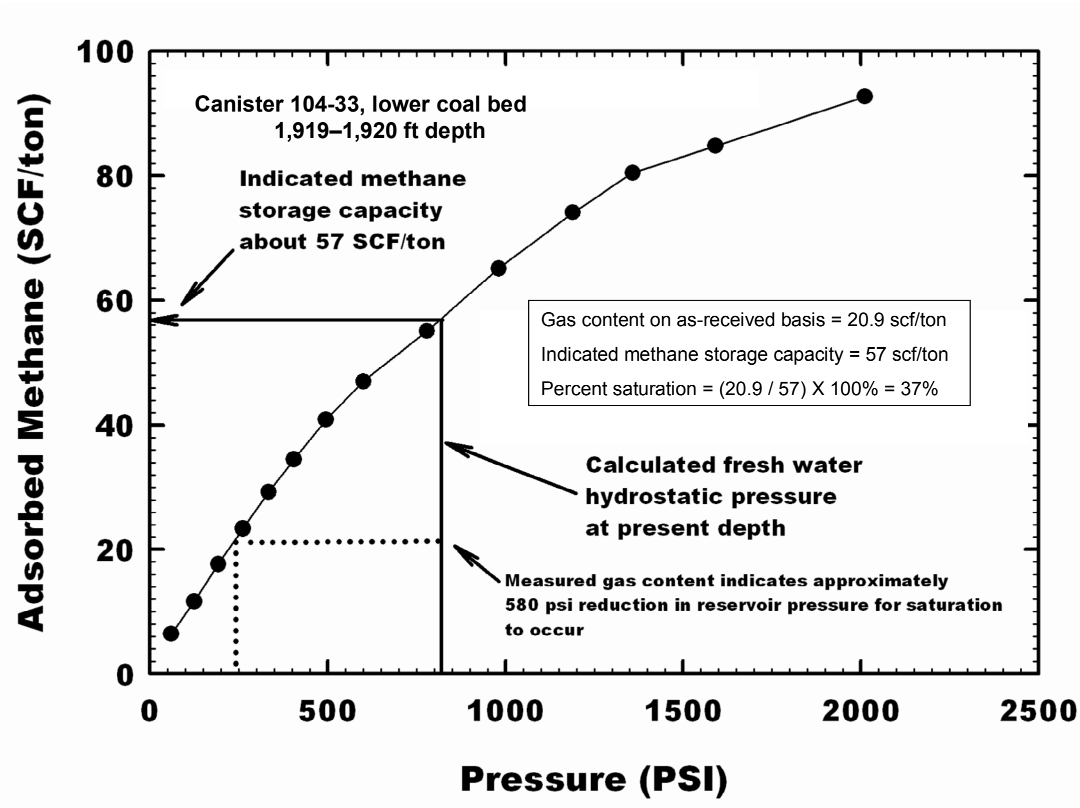

Figure 2-3. Methane adsorption isotherm for canister 104-33 at 1,910–1,911 ft depth in the lower coal bed, DOI-04-1A well, Fort Yukon, Alaska. Isotherm conditions were: 15 ^{o}C, coal at equilibrium moisture. Absorbed methane values reported on an as-received basis. Coal bed pressures calculated using a fresh water hydrostatic gradient of .433 psi per ft projected to the sample depth.

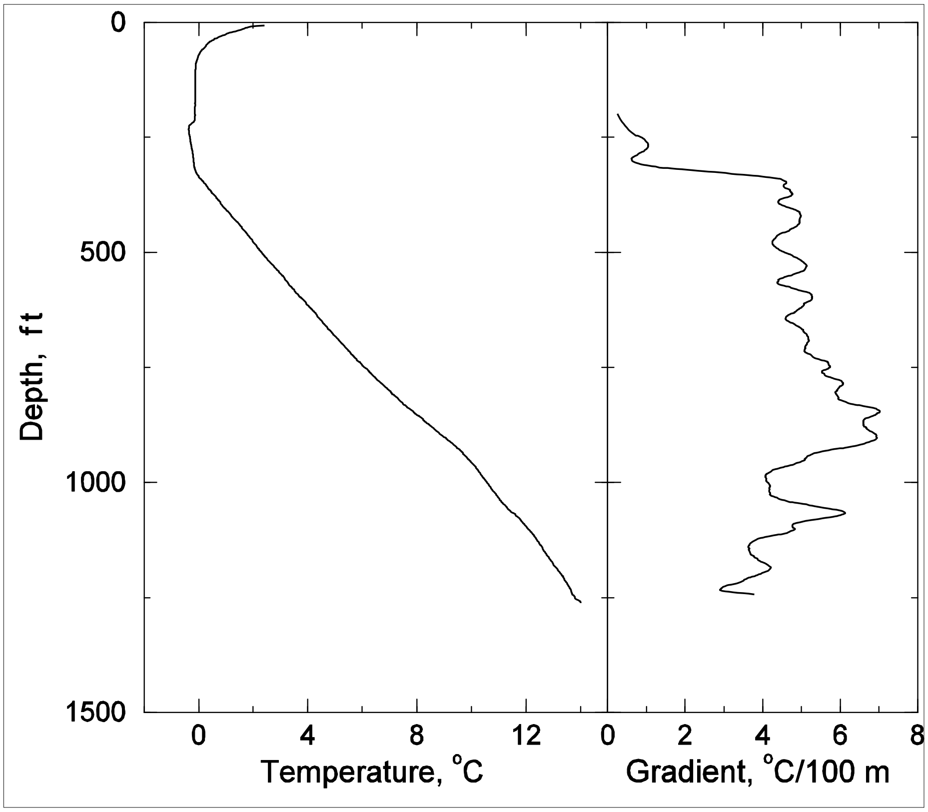

Figure 2-4. Temperature log for well DOI-04-1A made in May 2005.

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Table 2-1*A*. Summary of canister desorption results, upper coal zone.

Canister number	Depth interval		Canister sample lithology	Raw coal mass	Lost gas estimate	Total raw gas content
Upper coal zone	Top	Bottom				(as-received basis)
	(feet)	(feet)	% coal	(g)	(cc)	(scf/ton)
CORE						
104-1	1,283	1,284	100	1,056	60	14.1
104-2	1,284	1,284.5	50	490	40	13.5
104-3	1,285	1,286	100	907	85	10.8
104-4	1,286	1,287	100	905	80	9.8
104-5	1,287	1,288	100	951	80	11.6
104-6	1,288	1,289	100	1,009	115	21.1
104-7	1,289	1,290	100	1,149	85	7.0
104-8	1,290	1,290.7	70	471	85	14.5
104-9	1,295	1,296	100	961	85	13.4
104-10	1,304.5	1,305.5	100	1,087	110	13.8
104-11	1,306.5	1,307.5	100	1,193	95	12.1
104-12	1,308.5	1,309.5	100	1,115	130	13.6
104-13	1,310.5	1,311.5	100	1,132	130	13.9
104-14	1,312.5	1,313.5	100	842	80	11.0
104-15	1,315	1,316	100	1,038	80	12.9
104-16	1,319	1,320	100	1,171	85	8.6
104-17	1,324	1,325	100	1,518	100	9.0
104-18	1,339.7	1,340.7	100	1,082	100	18.7
104-19	1,342	1,343	100	749	100	19.5
104-20	1,343	1,344	100	1,028	110	15.2
104-21	1,344	1,345	100	1,098	100	10.9
Statistics:				Sample mean		13.1
				Standard deviation		3.5
CUTTINGS						
Cuttings-1*	1,265	1,270	80	575	45	7.7
Cuttings-2*	1,270	1,275	80	609	20	4.6
Cuttings-3*	1,275	1,280	80	886	20	2.0
Statistics:				Sample mean		4.8
				Standard deviation		2.9

* Depth interval estimated from lag time. These cuttings were not screened and the coal fines lose their gas quickly, thought to lead to the spuriously low raw gas content.

Abbreviations: g, grams; cc, cubic centimeters; scf, standard cubic feet

Table 2-1*B*. Summary of canister desorption results, lower coal zone.

Canister number	Depth interval		Canister sample lithology**	Raw coal mass	Lost gas estimate	Total raw gas content
Lower coal zone	Top	Bottom				(as-received basis)
	(feet)	(feet)	% coal	(g)	(cc)	(scf/ton)
CORE						
104-33	1,910	1,911	n.r. 100?	1,006	120	20.9
104-34	1,911	1,912	n.r. 100?	1,037	100	22.5
104-35	1,912	1,913	n.r. 100?	1,105	100	19.4
104-36	1,913	1,914	n.r. 100?	994	120	20.4
104-37	1,914	1,915	n.r. 100?	996	120	20.9
104-38	1,915	1,916	n.r. 100?	1,239	120	12.8
104-39	1,916	1,917	n.r. 100?	1,118	120	17.8
104-40	1,917	1,918	n.r. 100?	1,115	125	21.7
104-41	1,918	1,919	n.r. 100?	993	85	23.1
104-42	1,919	1,920	n.r. 100?	1,233	85	11.2
				Sample mean		19.1
				Standard deviation		4.0
Cuttings						
104-31*	1,900	1,905	100	1,104	100	8.1
104-32*	1,905	1,910	100	1,080	110	8.3
				Sample mean		8.2
				Standard deviation		0.1

* Depth interval estimated from lag time. These cuttings were not screened and the coal fines lose their gas quickly, thought to lead to the spuriously low raw gas content.

**Lithology about 100 percent coal from gamma log interpretation

Abbreviations: g, grams; cc, cubic centimeters; scf, standard cubic feet; n.r., not reported

Table 2-2*A*. Summary of proximate and specific gravity analysis with dry, ash free (DAF) basis canister desorption results, upper coal zone.

Canister Number	Depth interval		Specific gravity	Total moisture	Ash yield	DAF gas content
Upper coal zone	Top	Bottom		As received basis	As received basis	
	(feet)	(feet)		Wt.-%	Wt.-%	(scf/ton)
CORE						
104-1	1,283	1,284	1.31	42.30	2.62	25.6
104-2	1,284	1,284.5	1.29	39.29	3.45	23.5
104-3	1,285	1,286	n/a	42.83	2.91	19.9
104-4	1,286	1,287	1.20	46.36	2.37	19.2
104-5	1,287	1,288	n/a	40.85	2.85	20.6
104-6	1,288	1,289	1.33	40.78	2.81	21.5
104-7	1,289	1,290	1.30	45.08	2.75	13.5
104-8	1,290	1,290.7	1.49	39.08	3.33	25.1
104-9	1,295	1,296	1.30	41.10	2.85	24.0
104-10	1,304.5	1,305.5	1.26	41.38	3.17	24.9
104-11	1,306.5	1,307.5	1.20	41.66	5.05	22.8
104-12	1,308.5	1,309.5	1.28	39.93	2.33	23.5
104-13	1,310.5	1,311.5	1.27	41.29	1.76	24.4
104-14	1,312.5	1,313.5	n/a	41.59	2.05	19.6
104-15	1,315	1,316	1.27	41.88	2.34	23.2
104-16	1,319	1,320	1.37	52.04	5.58	20.3
104-17	1,324	1,325	1.81	42.65	15.45	21.6
104-18	1,339.7	1,340.7	n/a	31.54	3.9	29.0
104-19	1,342	1,343	1.25	36.33	2.61	31.9
104-20	1,343	1,344	1.48	38.29	5.05	26.8
104-21	1,344	1,345	1.40	39.95	10.92	22.2
Statistics:	Sample mean		1.34	41.25	4.10	23.0
	Standard deviation		0.15	3.89	3.26	3.8
CUTTINGS						
Cuttings-1*	1,265	1,270	1.35	63.20	2.52	22.6
Cuttings-2*	1,270	1,275	1.22	61.71	3.16	13.0
Cuttings-3*	1,275	1,280	1.20	59.42	5.54	5.6
Statistics:	Sample mean		1.26	61.44	3.74	13.7
	Standard deviation		0.08	1.90	1.59	8.5

* Depth interval estimated from lag time. These cuttings were not screened and the coal fines lose their gas quickly thought to lead to the spuriously low raw gas content.
Abbreviation: n/a = not analyzed; scf, standard cubic feet

Table 2-2*B*. Summary of proximate and specific gravity analysis with dry, ash free (DAF) basis canister desorption results, lower coal zone.

Canister number	Depth interval		Specific gravity	Total moisture	Ash yield	DAF gas content
Lower coal zone	Top	Bottom		As received basis	As received basis	
	(feet)	(feet)		Wt.-%	Wt.-%	scf/ton
CORE						
104-33	1,910	1,911	n/a	35.08	7.74	36.5
104-34	1,911	1,912	1.14	34.11	3.78	36.2
104-35	1,912	1,913	1.23	35.73	3.62	32.1
104-36	1,913	1,914	1.39	34.73	5.50	34.1
104-37	1,914	1,915	1.24	34.66	7.75	36.3
104-38	1,915	1,916	1.85	30.17	30.48	32.5
104-39	1,916	1,917	1.81	28.87	27.55	40.9
104-40	1,917	1,918	1.74	27.88	22.64	43.9
104-41	1,918	1,919	1.41	31.16	7.72	37.8
104-42	1,919	1,920	n/a	27.37	40.57	35.0
	Sample mean		1.48	31.98	15.73	36.5
	Standard deviation		0.28	3.24	13.37	3.6
CUTTINGS						
104-31*	1,900	1,905	1.25	55.69	2.8	12.8
104-32*	1,905	1,910	n/a	51.75	3.0	13.1
	Sample mean			53.72	2.9	13.0
	Standard deviation			2.79	0.1	0.2

* Depth interval estimated from lag time. These cuttings were not screened and the coal fines lose their gas quickly thought to lead to the spuriously low raw gas content.

Abbreviations: n/a, not analyzed; scf, standard cubic feet

Section 3: Aquifer Test and Water-Quality Analyses, DOI-04-1A Well, Fort Yukon, Alaska

By Edwin P. Weeks[1], Arthur Clark[2], and Cindy A. Rice[2]

Introduction

Methane production from coal requires that the hydraulic pressure maintaining sorption of the methane on the coal be reduced by co-producing water by pumping. Prediction of the hydraulic pressure response to pumping within the coal bed and assessment of the potential for methane production requires knowledge of the coal bed hydraulic properties, to be determined using aquifer tests. Based on the drilling schedule, only one coal bed was tested. The thick coal bed in the upper coal zone at a depth of 1,256 to 1,315 ft is substantially thicker than the thickest coal bed in the lower coal zone, and was initially estimated to have a slightly higher methane content (refuted after desorption experiments were completed; see tables 3-1*A*, 3-1*B*). Hence, an attempt was made to finish the borehole as a production well in that coal bed, followed by performance of a single-well aquifer test. Events described below precluded a true aquifer test, but several sets of recovery data were collected during the development phase, four of which were analyzed to provide estimates of the coal hydraulic properties.

Production of coalbed methane (CBM) is also contingent on management of coal bed water co-produced with the methane, requiring knowledge of the quality as well as the quantity of coalbed water. Consequently, water samples were collected for chemical analysis from the upper coal bed during well-testing and upon retrieval of the pressure transducer in May 2005. These samples are less than ideal, as water samples should be taken only after extensive well

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development to ensure that no drilling fluids or suspended solids alter the formation water characteristics. However, waiting was not possible during this test, due to the problems outlined below. Nonetheless, the resulting chemical analyses, augmented by analyses of a squeeze sample from a siltstone underlying the coal bed, and of water used in the drilling mud and in flushing the well, appear to be reasonably representative of coal bed waters determined in other areas, and presumably, then, reliable indicators of the upper coal bed water chemistry.

Table 3-1*A*. Summary of canister desorption results, upper coal zone.

Canister number	Depth interval		Canister sample lithology	Raw coal mass	Lost gas estimate	Total raw gas content
Upper coal zone	Top	Bottom				(as-received basis)
	(feet)	(feet)	% coal	(g)	(cc)	(scf/ton)
CORE						
104-1	1,283	1,284	100	1,056	60	14.1
104-2	1,284	1,284.5	50	490	40	13.5
104-3	1,285	1,286	100	907	85	10.8
104-4	1,286	1,287	100	905	80	9.8
104-5	1,287	1,288	100	951	80	11.6
104-6	1,288	1,289	100	1,009	115	21.1
104-7	1,289	1,290	100	1,149	85	7.0
104-8	1,290	1,290.7	70	471	85	14.5
104-9	1,295	1,296	100	961	85	13.4
104-10	1,304.5	1,305.5	100	1,087	110	13.8
104-11	1,306.5	1,307.5	100	1,193	95	12.1
104-12	1,308.5	1,309.5	100	1,115	130	13.6
104-13	1,310.5	1,311.5	100	1,132	130	13.9
104-14	1,312.5	1,313.5	100	842	80	11.0
104-15	1,315	1,316	100	1,038	80	12.9
104-16	1,319	1,320	100	1,171	85	8.6
104-17	1,324	1,325	100	1,518	100	9.0
104-18	1,339.7	1,340.7	100	1,082	100	18.7
104-19	1,342	1,343	100	749	100	19.5
104-20	1,343	1,344	100	1,028	110	15.2
104-21	1,344	1,345	100	1,098	100	10.9
Statistics:				Sample mean		13.1
				Standard deviation		3.5
CUTTINGS						
Cuttings-1*	1,265	1,270	80	575	45	7.7
Cuttings-2*	1,270	1,275	80	609	20	4.6
Cuttings-3*	1,275	1,280	80	886	20	2.0
Statistics:				Sample mean		4.8
				Standard deviation		2.9

* Depth interval estimated from lag time. These cuttings were not screened and the coal fines lose their gas quickly, thought to lead to the spuriously low raw gas content. Abbreviations: g, grams; cc, cubic centimeters; scf, standard cubic feet

Table 3-1*B*. Summary of canister desorption results, lower coal zone.

Canister number	Depth interval		Canister sample lithology**	Raw coal mass	Lost gas estimate	Total raw gas content
Lower coal zone	Top	Bottom				(as-received basis)
	(feet)	(feet)	% coal	(g)	(cc)	(scf/ton)
CORE						
104-33	1,910	1,911	n.r. 100?	1,006	120	20.9
104-34	1,911	1,912	n.r. 100?	1,037	100	22.5
104-35	1,912	1,913	n.r. 100?	1,105	100	19.4
104-36	1,913	1,914	n.r. 100?	994	120	20.4
104-37	1,914	1,915	n.r. 100?	996	120	20.9
104-38	1,915	1,916	n.r. 100?	1,239	120	12.8
104-39	1,916	1,917	n.r. 100?	1,118	120	17.8
104-40	1,917	1,918	n.r. 100?	1,115	125	21.7
104-41	1,918	1,919	n.r. 100?	993	85	23.1
104-42	1,919	1,920	n.r. 100?	1,233	85	11.2
				Sample mean		19.1
				Standard deviation		4.0
Cuttings						
104-31*	1,900	1,905	100	1,104	100	8.1
104-32*	1,905	1,910	100	1,080	110	8.3
				Sample mean		8.2
				Standard deviation		0.1

* Depth interval estimated from lag time. These cuttings were not screened and the coal fines lose their gas quickly, thought to lead to the spuriously low raw gas content.

**Lithology about 100 percent coal from gamma log interpretation.

Abbreviations: g, grams; cc, cubic centimeters; scf, standard cubic feet; n.r., not reported

Hydrogeologic Setting

The well penetrates about 100 ft of coarse surficial gravel deposited by the Yukon River, and deeper deposits tapped by the well consist of lacustrine deposits of interbedded clay, silty clay, silt, silty sand, and sand, with occasional coal beds. Permanent permafrost extends from about 25 to 300 ft, providing a hydrologic confining layer for the underlying materials. The main interest of this hydrologic investigation is of the tested upper coal bed and the beds immediately above and below it, as shown in figure 3-1. The coal bed is immediately overlain by a thin clay bed, separating it from a sand bed. A thicker clay bed separates the upper coal bed from an underlying thinner coal that is, in turn, underlain by another thick clay bed. These overlying and underlying clay beds should provide hydrologic confinement for the upper coal, allowing well test theory developed for confined aquifers to be applied.

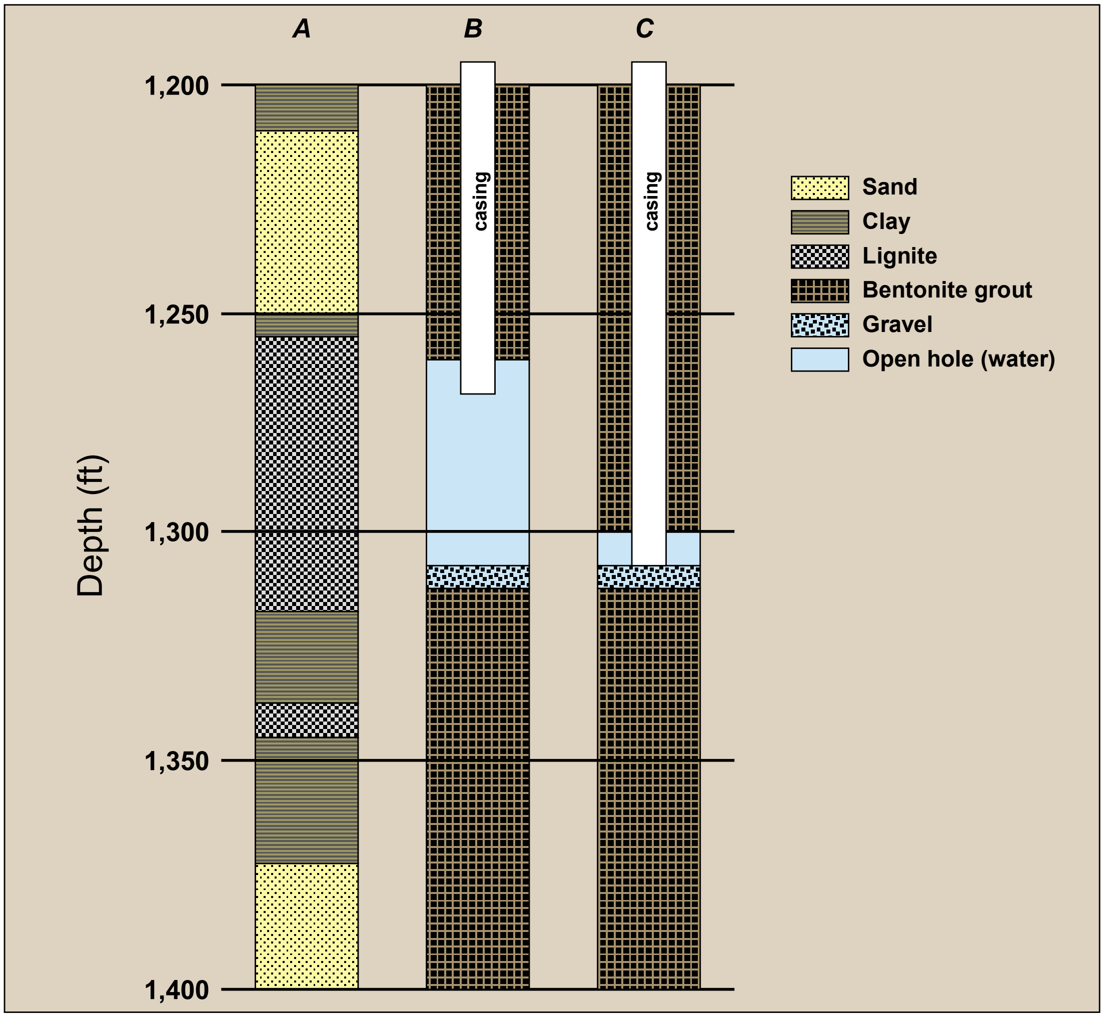

Figure 3-1. *A*. Geologic profile for 1,200–1,400 ft depth interval in DOI-04-1A CBM well, Fort Yukon, Alaska; *B*. Original well construction; *C*. Well configuration after the casing had slipped downhole by 35 ft. Scale approximate.

Well Completion and Initial Development

Well completion is described in detail in Section 1, but details relevant to interpretation of the hydraulic tests are briefly summarized here. To complete the well for testing, the borehole below the base of the upper coal was backfilled with Volclay™ abandonment grout mixed with thick bentonite, bentonite pellets, and bentonite chips to a depth of 1,313 ft, about 2 ft above the bottom of the coal bed, providing the bottom depth that would yield water to the well. Gravel was added to a depth of 1,307 ft to prevent bentonite from being pumped up into the planned open-hole interval. The lead section of well casing (2.5-in. schedule 80 PVC pipe) was equipped with five 6-in. shale baskets attached 7 ft above the bottom of a stainless steel tail section. The casing was hung from a clamp at land surface so that the shale baskets (packer) bottomed at 1,265 ft, about 9 ft below the top of the coal. Including the open hole surrounding the tail pipe and the 6-ft gravel-filled section, the well section open to the coal should have been 48 ft. Ten buckets of bentonite pellets were placed by tremie pipe immediately above the shale baskets, and the remainder of the annulus around the well casing was filled with abandonment grout. Details of well completion through the 1,200–1,400 ft zone are illustrated in figure 3-1.

Following completion of the well, drilling mud remaining in the open portion of the hole (1,265–1,307 ft) was flushed with fresh water using a tremie pipe installed to a depth of 1,302 ft. The driller reported that 400 gallons of fresh water were pumped down the casing before mud began to flow at land surface. The loss of this fluid may have resulted in additional formation damage and the apparent large skin effect described below.

Well Tests and Slug Test Theory

Following completion of the well, air-lift pumping was initiated to remove fines from the invaded zone surrounding the well bore in anticipation of the performance of an aquifer test. Several brief sets of recovery data were collected at various stages of development to provide data for test planning, but various problems that occurred during development precluded conducting the aquifer test. However, data for three of the recovery data sets, as well as head recovery following the end of development were analyzed using slug test theory to obtain estimates of the hydraulic properties of the upper coal bed.

The slug test theory used was that of Cooper and others (1967), as modified by Butler (1997, p. 173) to account for the effects of well-bore clogging or the development of a well skin. The analysis procedure was also modified to that of Earlougher (1977, p. 99) to better analyze data that represent water level recovery of only a few percent of its initial drawdown.The analysis relies on matching test data to a selected member of a family of theoretical log-log type curves of $1-H/H_0$ vs. KDt/r_c^2 for various values of $\alpha*$, defined as (Butler, 1997, p. 173):

$$\alpha* = \frac{r_w^2 S}{r_c^2}\exp(-2s) ,$$

where H is the remaining water level displacement, (length); H_0 is the initial (instantaneous) water level displacement, (length); K is aquifer hydraulic conductivity, (length/time); D is screen or open hole length; t is elapsed time since the instantaneous displacement; r_c is casing radius, (length); r_w is the open hole radius, (length); S is the aquifer storage coefficient; and s is dimensionless skin. Dimensionless skin is defined (Matthews and Russell, 1967, p. 19–21) as:

$$s = \left(\frac{K}{K_s} - 1\right)\ln\left(\frac{r_{skin}}{r_w}\right)$$

where K_s is hydraulic conductivity of the clogged annular layer surrounding the borehole, (length/time); and r_{skin} the outside radius of the clogged layer, (length). In theory, transmissivity, T, equal to Kb, where b is aquifer thickness, should be the parameter determined by slug test analysis. However, practice indicates that the T determined from slug tests represents the KD product, indicating that, at the scale of the slug test, flow to the well bore is governed by the screen or open-hole length, rather than by the full aquifer thickness (Butler, 1997, p. 52–53).

For analysis, a data plot of $1\text{-}H/H_0$ vs. t, as determined from measurements, is prepared to the same scale as the type-curve plot. To match the curves, values of $1\text{-}H/H_0$ for the data plot must coincide with those for the type-curve family, but the logarithmic data time axis is shifted, by use of a multiplier M, to provide a match of the data to a selected member of the type-curve family. M is equal to $\left(\frac{KDt}{r_c^2}\right)/t$, where $\left(\frac{KDt}{r_c^2}\right)$ is the type-curve match line value as read from the x axis, and t is the time at which the match data point was read. M has the unit of $time^{-1}$. KD is then found as $KD = Mr_c^2$. Selection of the type-curve to be matched can be quite subjective, as the type-curves are of nearly constant shape over a significant range of values.

Hydraulic conductivity, K, is widely used by hydrogeologists as the hydraulic property governing the movement of water through porous media. However, because of the need to consider the flow of various fluids through porous media, petroleum engineers generally use permeability, k, in units of Darcies, as the parameter-governing porous-media fluid flow. As this practice has been followed in most of the literature on coal-bed methane development, k values will also be presented. A permeability of one ft/d is equivalent to 0.43 Darcy at the temperature of 14 ºC prevailing at the depth of the upper coal bed, as determined from the temperature log (fig. 1-2) obtained in 2005.

Recovery data were either collected by use of an electric tape, by which depth to water (DTW) was measured directly, or by use of two absolute pressure transducers, one (an In-Situ Minitroll™ transducer) emplaced at some depth below the water surface in the well and the other (an In-Situ Barotroll™ transducer) at land surface to record barometric pressure. For the transducer data, DTW was computed as (DT-[TR-BP]) where DT is depth of emplacement of transducer below land surface, TR is the transducer pressure reading in ft of water, and BP is barometric pressure in ft of water as read from the Barotroll transducer. For all tests, the static water level (SWL) was assumed to be 6 ft below land surface, based on the approximate depth to water after the well was thawed in May 2005. Starting times for each test were assumed to coincide with the time at which air-lift pumping was stopped to allow for the test. This represents an approximation, as slug test theory assumes instantaneous displacement of the initial water level, whereas air-lift pumping for development was occurring for several hours prior to each water-level measurement period. However, in each case, the period of air-lift pumping was small relative to the time required for full water level recovery, and the assumption of instantaneous displacement was assumed to be adequately met. The initial head displacement was assumed to be the DTW when pumping was stopped minus the SWL. However, heads were not monitored during air lift, so the initial DTW was estimated by linearly extrapolating the average rate of head increase during the test back to the start time. For each of the short recovery tests, the rate of head recovery was quite uniform with time, so this extrapolation should create little error.

Test 1

This data set is the first reliable one available and was collected after the casing had been evacuated of water by air-lift pumping to a depth of 500 ft. Evacuation was accomplished in stages, beginning with a 200-ft evacuation starting at 08:18 hours on September 7. Measurements of recovery of the water level for this evacuation were made with an electric tape, but the readings were later recognized to have been affected by water draining down the inside wall of the casing, and hence were not reliable. The casing was evacuated in two additional stages to a depth of 500 ft, and recovery was again measured, after pumping halted at 11:30 hours. This time, the problem of false readings was noted after a false start, and a series of six good measurements was obtained, beginning at 11:43:15 hours, and lasting about

6 minutes. These data constitute test 1, which is the only test available for the full open hole interval of 48 ft. The water level at 11:30 hours was computed to be 496 ft (rounded) by assuming that the average recovery rate of 0.86 ft/min. extended over the preceding 13.25 minute interval. Subtraction of an assumed SWL below land surface of 6 ft provides an H_0 value of 490 ft. The length of drained column at each time t was computed as DTW-SWL.

Table 3-2. Water-level recovery following evacuation to 500-ft depth 09/07/04.

Time	DTW (Depth to Water, in ft)	Elapsed time, sec.	H/H_0
11:43:15	485	795	0.9776
11:44:25	484	865	0.9755
11:45:36	483	936	0.9735
11:46:45	482	1005	0.9714
11:47:53	481	1073	0.9694
11:49:01	480	1141	0.9674

Data for test 1 are listed in table 3-2 and shown as the open triangles in figs. 3-2*A* and 3-2*B*. Also shown in fig. 3-2 are type curves and test 1 matches for $\log_{10}\alpha* = -4, -9, -15$, and -30. For the test interval, both the data and the type curves form straight lines, with slope of the type curves increasing with decreasing α*. Data for test 1 match the type curve for $\alpha*=10^{-9}$ reasonably well. This match was achieved by multiplying the data curve t values, which are in days, by 11.3, so $\frac{11.3}{day} = \frac{KD}{r_c^2}$. Simplifying, $KD=11.3\ r_c^2$ /day, and, for the 1.125-in. (0.09375 ft) r_c, $KD=0.1\ ft^2/d$. For the 48-ft thick open-hole section, $K=2X10^{-3}$ ft/d. This value translates to a permeability of about 0.9 mD (milliDarcy) (table 3-3).

Table 3-3. Results of slug-test type curve analyses for tests performed on the Fort Yukon well.

Test	KD, $ft^2/dX10^{-2}$	K, $ft/dX10^{-3}$	k, millidarcies	b, ft
Type Curve $\alpha*=10^{-4}$				
1	3.1	0.6	0.3	48
Type Curve $\alpha*=10^{-9}$				
1	9.9	2	0.9	48
2	1.8	1.4	0.6	13
Type Curve $\alpha*=10^{-30}$				
1	30	6	3	48
3,4	0.9	1.5	0.6	6?

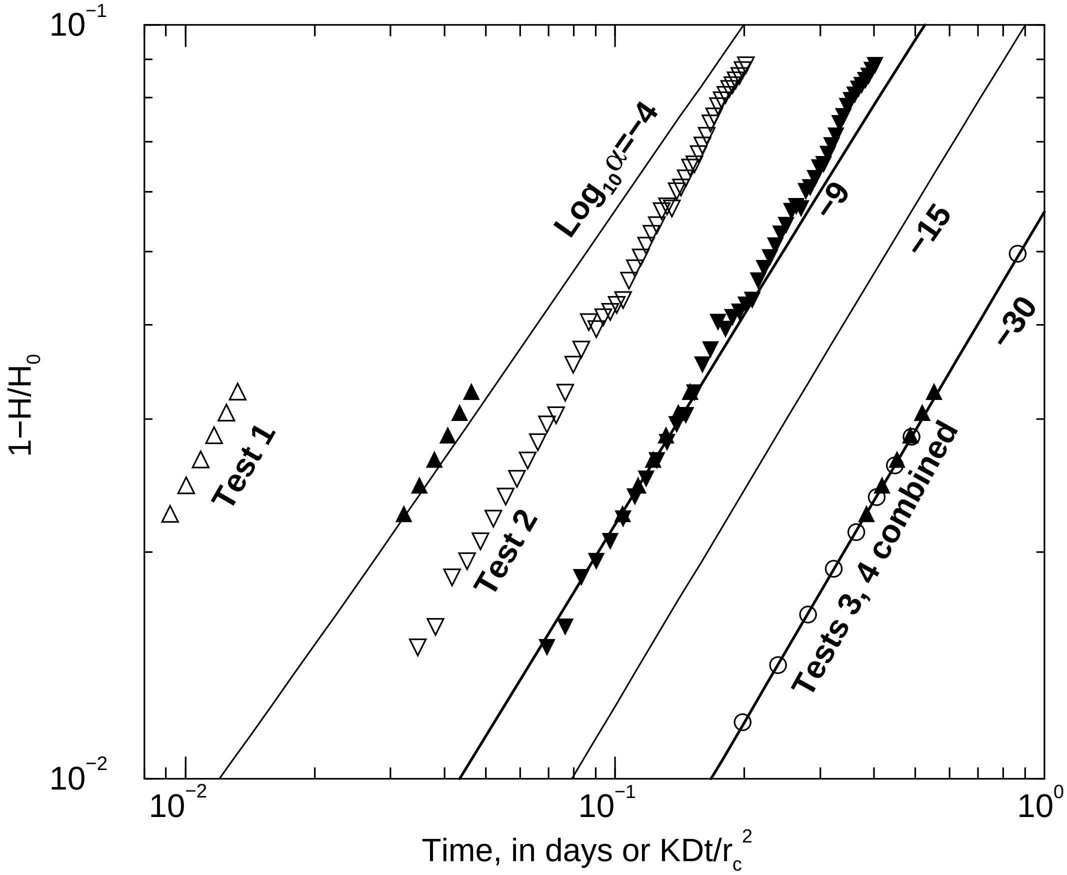

Figure 3-2*A*. Data plots (labeled, open symbols) at an expanded scale for real time in days and as matched (filled symbols) to selected type curves.

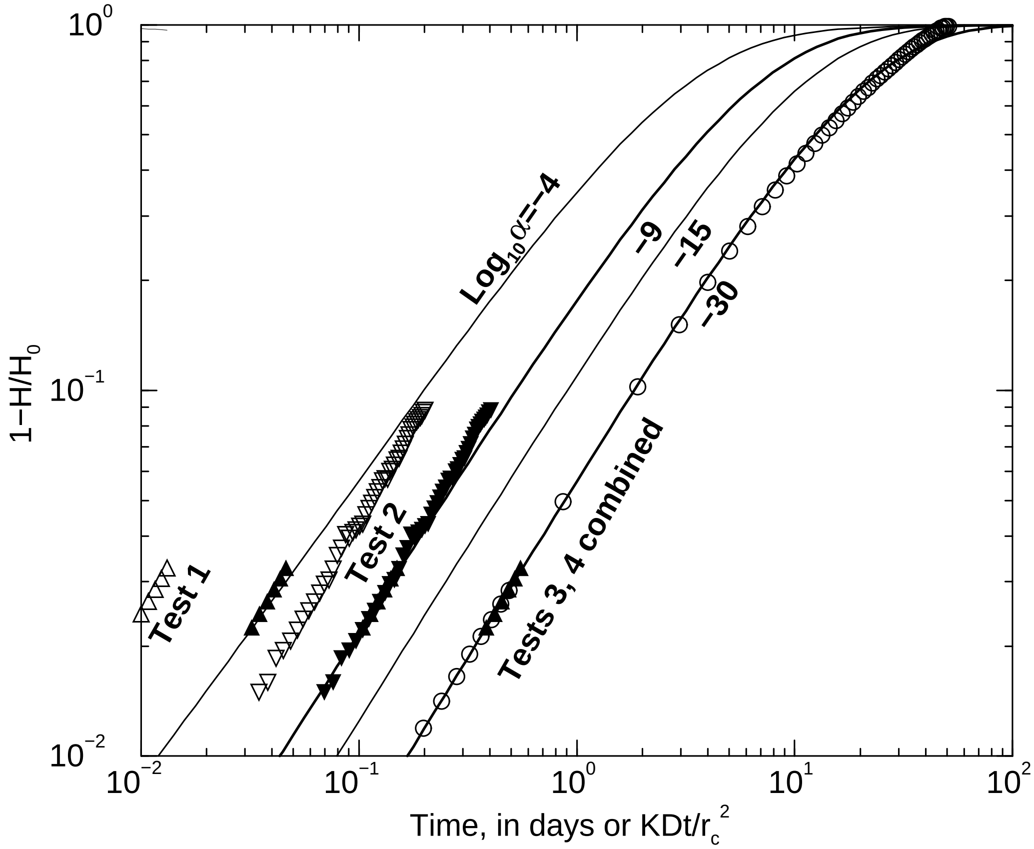

Figure 3-2*B*. Same as figure 3-2*A*, but showing the type curves to include complete recovery. Type curves generated using Fortran program of Greene and Shapiro (1995).

The α* value of 10^{-9} was chosen as the maximum value that matched the steepness of the data curve. The α* value that should be matched in the absence of well-bore clogging (s=0), $\alpha = \frac{r_w^2 S}{r_c^2}$, may be determined from well construction data and an estimate of S. Three well-controlled aquifer tests conducted on sub-bituminous coal beds in the Powder River Basin provide a specific storage (S_s) for coals of about $6X10^{-6}$/ft (Weeks, 2005, p. 254). Although the 48-ft thick (b) coal bed at this site is of lower rank, we assume, due to a lack of other data, a similar S_s, so we compute $S=S_s b=3X10^{-4}$. For this well, r_w= 3.5 in., and r_c=1.125 in. Thus, $\alpha=3X10^{-3}$, and a match to the $\alpha^*=10^{-9}$ type curve indicates substantial clogging. As a plausibility check, the exp(-2s) value needed to reduce α* to 10^{-9} from $3X10^{-3}$ is $3.3X10^{-7}$, results in s = 7.5.

Assuming a 1-in. thick clogged zone, ln (r_{skin}/r_w) is 0.25, so, based on the equation $s = \left(\frac{K}{K_s} - 1\right)\ln\left(\frac{r_{skin}}{r_w}\right)$, K_s is about 0.03 times that of the formation.

The fact that the log-log plot of head recovery for test 1 is steeper than the type curve plots for larger α^* values could be due to ongoing well development as water entering the well removes fine materials from the well bore wall. In that case, use of the $\alpha^*=10^{-9}$ type curve to analyze the test may over-estimate clogging, and the computed KD value may thus be too large. To obtain a probable minimum estimate for KD and K, the earliest data were also matched to the $\alpha = 10^{-4}$ curve, as that may be about the maximum α^* that would still allow well development to occur. For this match, KD=3.5r_c^2, or about 0.03 ft^2/d, providing a minimum K value of 0.6X10^{-3} ft/d or about 0.3 mD. A maximum estimate of KD and K for this test is more difficult to estimate. A match of the data to the $\alpha^*=10^{-30}$ curve provides a K of 6X10^{-3} ft/d or 3 mD. A 1-in. clogged layer would have to be about 100 times less permeable than the formation, within the realm of possibility, but perhaps unlikely at this stage of well completion and development.

Events Leading to Test 2

Following the end of electric tape recovery measurements at 11:50 hours, tremie pipe was added and the well was air-lift pumped from a depth of 600 ft until about 13:00 hours, when the casing slipped through the clamp and fell about 35 ft down the hole, the bentonite grout presumably slipping with it. Based on the various initial depths of packer, tail section bottom, and gravel top, the bottom of the well casing was now resting on the gravel surface, with 7 ft of open hole above the casing bottom. The resulting well configuration is shown in figure 3-1*C*. Two new sections of casing were installed over the tremie pipe to salvage the well. Following the well collapse, a water level depth of about 48 ft was measured in the casing.

Air-lift pumping in the salvaged well was resumed at 15:30 hours, and water levels were lowered to 500 ft by 16:30 hours. Water level recovery was monitored for several minutes beginning at 16:45 hours, but recovery was quite slow (about 0.2 ft/min.), with somewhat erratic behavior, possibly due to water running down the casing. Consequently, no attempt was made to analyze these data. Pumping resumed about 17:00 hours, and the well was evacuated to a depth of 780 ft by 18:30. Pumping from that depth continued until 20:10 hours. At that time, 3 sections of tremie pipe were added, and the pressure transducer was emplaced at the 780-ft depth to record recovery overnight, beginning at 21:00 hours.

Test 2

The record of overnight water level recovery constitutes test 2. Water levels were recorded every five minutes, and were found to be rising, based on a regression analysis, at a fairly uniform rate of about 0.23 ft/min. until 01:05 hours on September 8. After that time, the pressure head demonstrated major oscillations, presumably due to a well cave-in. After these oscillations, the rate of water level rise dampened, and by 03:00 hours, had stopped completely, with an indicated DTW of about 667 ft.

Data for the period 21:00 to 01:00 hours were chosen for slug test analysis. The initial water level, at 20:10 hours, was computed to be 758.4 ft, rounded to 758 ft. For the assumed static water level of 6 ft, H_0 becomes 752 ft. Transducer data were converted to DTW as described above, and SWL subtracted to provide H/H_0 at 5-minute intervals. Times were converted to days elapsed since 20:10 hours.

Data for test 2 are shown as the open inverted triangles in figure 3-2. The early data (solid inverted triangles) match the type curve for $\alpha^*=10^{-9}$ reasonably well, resulting in KD=2.0 r_c^2/d, or $1.8X10^{-2}$ ft^2/d. Assuming that the aquifer thickness had been diminished by an amount equal to the 35-ft drop of casing in the well, the aquifer thickness is now 13 ft (7 ft open hole plus 6 ft gravel zone), resulting in $K=1.4X10^{-3}$ ft/d or 0.6 mD. This value is, considering uncertainties in the analysis, basically the same as that of $2X10^{-3}$ ft/d determined from the short recovery test of the full open-hole section. This result indicates that the main factor affecting the results of test 2 relative to test 1 was a diminution in the section of hole providing water to the well. Later data for this plot show a somewhat steeper slope than any of the type curves. This may occur because of minor spalling that resulted in some well development prior to the hypothesized major spalling and cave-in occurring at about 01:05 hours on September 8.

Events Leading to Test 3

Prior to the resumption of air-lift pumping on September 8, it was noted that the well casing had risen about 1 ft overnight, probably at the time of the hypothesized well cave-in. Presumably, fine materials surged into the 7-ft open hole section surrounding the steel tail pipe at that time, creating substantial pressure on the bottom of the packer that lifted the well. The caved materials likely later settled on the gravel, effectively sealing the previous open-hole section from the bottom of the tail pipe, thus reducing the well section supplying water from the coal to no more than the gravel-filled section of 6 ft.

Air-lift pumping was conducted from 09:30 to 11:00 hours, lowering the water level from 667 ft to about 1,000 ft. The transducer was installed at the 1,020-ft depth from 11:16 until 13:00 hours to measure recovery. The water level recovered about 1.5 ft during this interval, indicating that severe clogging, probably associated with the well cave-in, had occurred. No attempt was made to analyze these data, but it was decided to circulate fresh water in an attempt to reduce clogging. While lowering tremie pipe through the casing to circulate, a plug was encountered at a depth of about 1,077 ft, or about 190 ft above the bottom of the casing. The plug was washed out, with particles of coal and of fine gravel being suspended in the return flow. Flushing was continued until the tremie pipe had reached the gravel installed during well completion. Circulation was continued at that depth for about an hour to clean out the remaining open hole. However, fine materials may have sifted into the gravel, clogging the surficial gravel now surrounding the bottom of the casing.

Test 3

Following flushing of the well, air-lift development, taking the water level down to 300 ft in two stages, starting about 19:00 hours on September 8. Air lift was halted at 20:15 hours, and the pressure transducer installed to monitor water levels overnight. The transducer was programed to read pressure head at 5-minute intervals starting at 21:00 hours, and was retrieved at 08:00 hours on September 9. These overnight readings were used to develop test 3. DTW, as measured with the electric tape, was 302.75 ft at 20:19:45 hours. Assuming a DTW at 20:15 hours of 303 ft, and subtracting the 6-ft assumed SWL, H_0 = 297 ft. The initial transducer reading at 21:00 hours translated to a depth to water of 302.2 ft, for a column length of 295.2 ft. Times were converted to days elapsed since 20:15 hours, and H/H_0 computed for hourly readings extracted from the record.

Results for test 3 are shown as the open circles in figure 3-2A, which fall on the $\alpha{*}=10^{-30}$ type curve, providing KD ($=r_c^2/d$) of $9X10^{-3}$ ft^2/d. For this match, the thickness to provide a K of 0.0015 ft/d d or 0.6 mD is 6 ft. This is equal to the thickness of the gravel layer, which would be consistent with the isolation of the well in the gravel by creation of a low-permeability layer at the gravel surface. Plausibility of the indicated well skin is difficult to assess, as the geometry of the bottom of the well casing resting in possibly clogged gravel does not fit the model of a radial annular clogged layer assumed in the development of slug test theory. Nonetheless, it seems reasonable that the effect of the low-permeability layer extending into the top of the gravel might mimic that of a clogged annular layer. Although the results of test 3 and 4 are not inconsistent with those for tests 1 and 2, the agreement may be fortuitous, and should be considered inconclusive.

Winter Data

Following removal of the transducer to obtain data for test 3, preparations were made to collect pressure head data from the well during the winter months of 2004–2005. The remaining annular space around the well casing, voided when the casing sank down the borehole, was back-filled with bentonite grout and with drill cuttings. Two 10-W/m heat tapes, one 270 ft and the other 350 ft in length, were installed to allow ice that would freeze in the well above the permafrost depth to be melted. Recovery data were recorded hourly over the winter, starting with installation of the transducer at 17:00 hours on September 9, 2004 and ending with its retrieval at 16:55 hours on May 7, 2005. The transducer was installed at a depth of 610 ft, and had been recording a barometric pressure of about 33.4 ft before it was installed.

Pressure head above land surface was determined from the transducer readings by subtracting 643 ft, the depth (rounded) of the transducer plus the barometric pressure, from the initial pressure transducer reading (in ft). The resulting hydrograph (fig. 3-3) shows very strange behavior. For about the first 50 days, pressure head follows the trend that would be expected for its recovery from the air-lift pumping that occurred on September 8. Beginning at 01:00 hours on October 30, the pressure head spiked up, rising more than 22 ft in seven hours, followed by a decline of about 17 ft in 3 hours. Pressure head rose slowly, with one minor excursion, until November 1, when another sharp rise occurred, raising the pressure head from about at land surface to a height of about 65 ft above land surface by November 11. Pressure head remained quite stable at that magnitude until 01:00 hours on February 28, when it began to rise rapidly, reaching a peak of about 360 ft above land surface on March 18. After that time pressure head fluctuated and declined slowly until April 27, when it began to decline rapidly. Pressure head had declined to a reading putting it about 35 ft above land surface on May 7, the date the transducer was retrieved. Retrieval involved powering the heat tapes, the longer one at 10:30 hours, and the shorter one at 11:45 hours. The pressure head declined rapidly once the ice column in the well partially thawed between 13:00 and 14:00 hours. The transducer was pulled up after 14:00 hours, but became stuck at a level at which the pressure read about 250 ft for two hours, after which time it was retrieved. Upon retrieval, the transducer was reading a barometric pressure of about 23 ft of water, rather than the 33+ ft that it had read on installation. The transducer had been significantly over-ranged during the period of high pressure head, and may be significantly out of calibration. An electric tape reading following retrieval of the transducer at 17:00 hours indicated a depth to water of 6 ft below land surface.

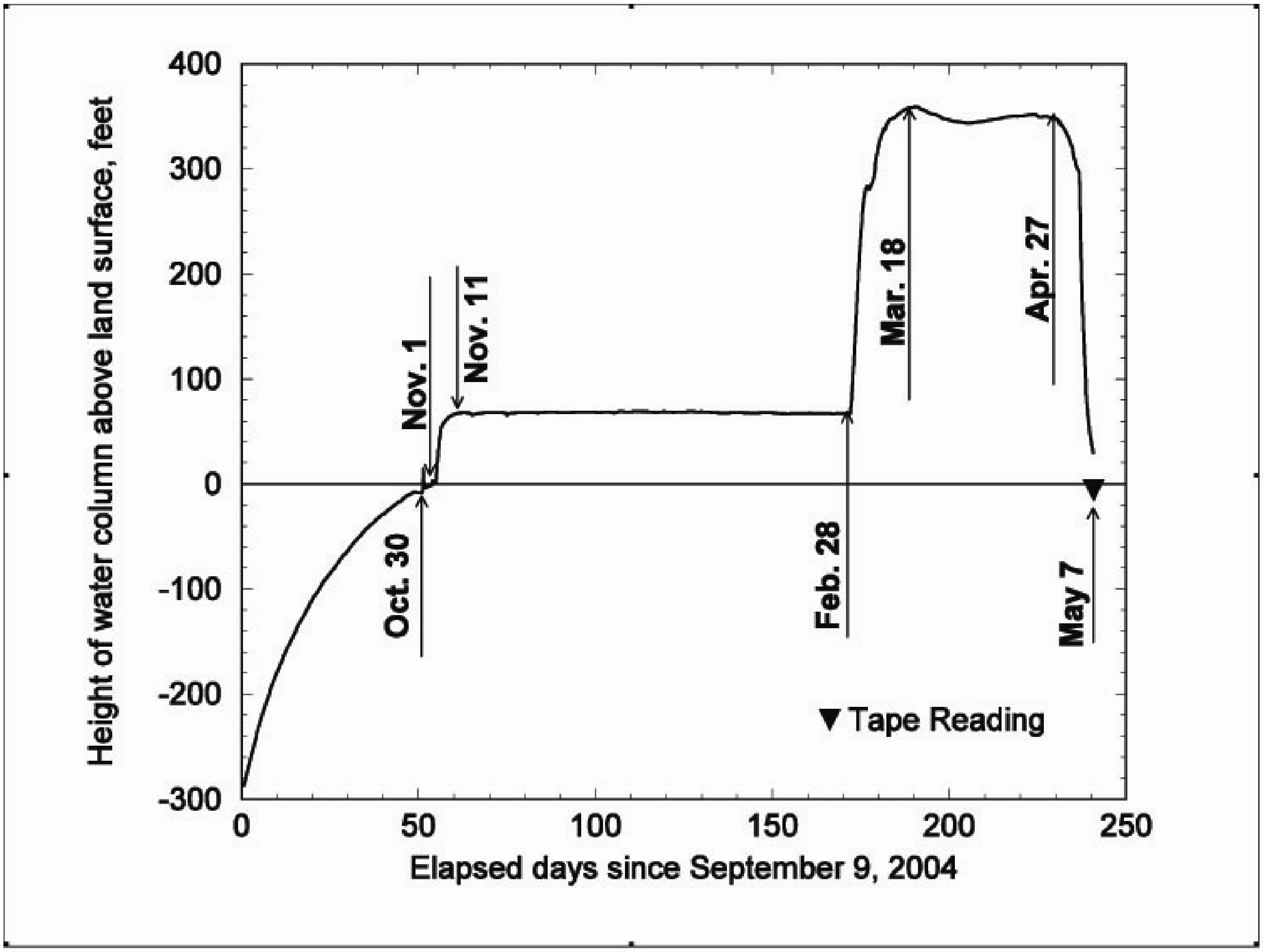

Figure 3-3. Graph of pressure head (in ft) vs. time for the Fort Yukon well, September 2004 to May 2005.

The pressure heads read by the transducer must represent a well phenomenon, indicating (possibly) that the bottom of the casing, sitting in the clogged gravel layer, became completely isolated from the coal aquifer at about the time that the water level fully recovered. The first pressure spike, on October 30, may have occurred as water froze over at some point in the well, sealing it from the surface. As the freezing front advanced downward, the expansion due to freezing may have pressurized the well, but this first ice seal may have fractured or slipped later that day. The well may have frozen over for good on November 1, with the freezing front again migrating downward to stabilize after about 10 days. The rise beginning February 28 is more problematic. Possibly bacterial action began to generate gas that overpressured the ice-capped water column, with the well beginning to make some re-connection with the aquifer in early May. The pressure clearly was released completely when the ice in the well was thawed. The above are merely conjectures, and the true cause of the strange well behavior may never be known. Nonetheless, it is extremely unlikely that the recorded pressure heads represent those in the formation.

Test 4

Despite these problems, the early data, extending to October 30, appear to represent recovery from the air-lift pumping on September 8, and will be analyzed as such. Pressure head was computed as 638 ft (depth of 610 ft+ barometric pressure of 34 ft-6 ft SWL), minus the transducer reading. H_0 of 297 ft, the same as for test 3, is assumed. The resulting plot of $1\text{-}H/H_0$ versus time is a continuation of the data plot for test 3, as it should be. The match points and determined KD and K values are the same for the two tests. After about 30 days and 80 percent recovery, the pressure head recovery is more rapid than predicted by slug test theory. The cause of this is unknown, but has been observed by the authors for a few other slug tests on coal beds in the Powder River Basin of Montana and in central Alaska.

Summary of Aquifer Test Analyses

In summary, the testing regime for this well was fraught with difficulties and uncertainties. Development of the well was in progress when the casing slipped 35 ft, precluding an extensive test on the fully developed well open to 48 ft of coal. Depressuring for the second test led to a cave-in of the well, further reducing its production capacity and effective KD. Despite these problems, the resultant slug tests provide a range of values that may bracket the true hydraulic conductivity or permeability of the coal. The results of matching the data for test 1 to a maximum probable α value indicate a minimum K (k) of $6X10^{-4}$ ft/d (0.3 mD). The maximum hydraulic conductivity is less easily obtained. A 1-in. thick clogged layer that is 100 times less permeable than the coal would result in a computed K (k) of about $6X10^{-3}$ ft/d (3 mD). Such a permeability reduction is within the realm of possibility, but may overstate conditions for test 1. A good estimate of the permeability of the coal at this site, based on reasonable agreement of k values for tests 1 and 2, may be about 0.6 mD. This permeability is lower than that determined from aquifer tests and slug tests conducted on several coal beds by the authors in the Powder River Basin in Montana, but is not anomalously low compared to k values for coal beds in the

San Juan and Black Warrior Basins (McKee and others, 1988). Coal bed methane development in those basins is accomplished by extensive hydraulic fracturing of the coal beds (Zuber, 1996, p. 3.18–3.19), a practice that almost certainly will be required for the development of coal bed methane at Fort Yukon.

The relatively low methane content and low permeabiliity of the coal indicate that the potential for methane development at Fort Yukon is limited, and plans for a multiple well aquifer test were abandoned. The well was plugged and abandoned following retrieval of the transducers, temperature logging, and water sampling in May 2005.

Water Chemistry Analyses

The water-chemistry analyses related to the upper coal bed are based on 3 water samples, two from the well and one from a core sample. Sample Well_1 was captured during air-lift development of the coal from a depth of about 1,300 ft and sample Well_2 was bailed from this same depth after the well was thawed in May 2005. The siltstone sample was obtained by squeezing a core sample collected from a depth of 1,400 ft, 55 ft below the bottom of the upper coal zone. For comparison, two samples of surface water used in the drilling operation (Truck A and Truck B) were also analyzed to ensure that the water samples from the well were not affected by the drilling fluids.

Unfiltered samples were refrigerated after collection prior to returning them to the USGS laboratory in Lakewood, Colo. At the laboratory, the samples were filtered through a 0.45 mm filter and the sample for cations was acidified to a pH of less than 2. Cations were analyzed by standard inductively-coupled plasma emission spectroscopy (ICP_AES) and anions were determined by standard ion chromatography. Tables 3-4*A* and 3-4*B* give the composition of major ions and selected trace elements respectively. The data on water quality presented here should be viewed as qualitative only because of the lack of stringent sampling and collection protocols.

The 3 samples from the coal and siltstone are Na-HCO3 type waters with total dissolved solids (TDS) ranging from 880 to 1,480 mg/L, and display the dominant characteristics of typical CBM waters: sodium and bicarbonate as dominant cation and anion, low sulfate values, implied low redox potential, and high sodium adsorption ratio[1] (SAR) (Table 3-4*A*). This similarity is demonstrated in fig. 3-4, which compares the analyses with those for a large suite of water samples collected from methane-bearing coal beds in the Powder River Basin, Wyoming and Montana (Rice and others, 2002). Surprisingly, the siltstone sample most closely resembles CBM water typified from the Powder River Basin (fig. 3-4). The sulfate value is very low (<10 mg/L), and, because of the low sulfate value, the Ba^{++} value is high (4.7 mg/L). The high Fe concentration suggests that the water was reducing, also consistent with typical CBM produced waters. The biogeochemical processes that produce water typical of CBM developments are discussed by Rice and others (2002) and by Van Voast (2003).

The samples collected from the coal and siltstone are distinctly different in both composition and TDS compared to the truck samples, which are representative of water used to drill the well (fig. 3-4, table 3-4*A*). The truck samples represent a low TDS (<400 mg/L) Ca-Mg-SO_4-HCO_3 type water with low concentrations of Na (<20 mg/L), small SAR values (<1), and major anions comprising both sulfate and bicarbonate. Lack of a discernible mixing trend between the well samples and the truck samples (fig. 3-4) indicates that contamination of the formation water samples by drilling fluid is minimal.

The water chemistry data suggest that problems associated with the disposal of water co-produced with methane from the upper coal bed would be minimal. Total dissolved solids for the formation waters are somewhat, but not drastically higher, than the primary drinking water standard of 500 mg/L, and the SAR is high enough that the water might not be suitable for irrigation applications, an unlikely use of the water. Trace elements for the well samples are below drinking water standard criteria, but those squeezed from the siltstone for Fe, Ba, and Al are above them. A final determination of needed disposal practices, assuming methane development was implemented, would require additional water quality sampling and analysis.

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1 $SAR = Na^{+} \Big/ \sqrt{[Ca^{++} + Mg^{++}]/2}$, where concentrations are in milliequivalents.

Table 3-4*A*. Concentrations of major ions in water samples from drill hole DOI-04-1A, Fort Yukon, Alaska. The concentration of HCO_3 is estimated from charge balance and represents total alkalinity.

Sample	TDS	Na	Ca	Mg	SAR	K	Cl	SO_4	HCO_3	NO_3	PO_4
	mg/L	mg/L	mg/L	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Well_1	978	310	37	27	9.45	20.0	12	130	900	bdl	bdl
Well_2	881	280	24	11	11.87	17.0	14	210	660	4	1.9
Siltstone	1478	430	55	75	8.85	45.0	25	8	1710	bdl	bdl
Truck_A	390	15	45	55	0.35	4.1	14	120	280	bdl	bdl
Truck_B	323	12	23	52	0.32	4.3	13	120	200	bdl	bdl

Abbreviations: mg/L, milligrams per liter; bdl, below detection limit

Table 3-4*B*. Concentrations of selected trace elements in water samples from drill hole DOI-04-1A, Fort Yukon, Alaska.

Sample	Si	Al	Fe	Mn	Ba	Sr	Zn
	mg/L	μg/L	μg/L	μg/L	μg/L	μg/L	μg/L
Well_1	4.4	110	58	110	430	290	120
Well_2	na	na	90	na	110	390	Na
Siltstone	25	7100	1580	<60	4700	820	480
Truck _A	9.4	1150	<250	87	100	210	290
Truck_ B	3.4	<625	<250	<60	92	190	270

Abbreviations: mg/L, milligrams per liter; μg/L, micrograms per liter

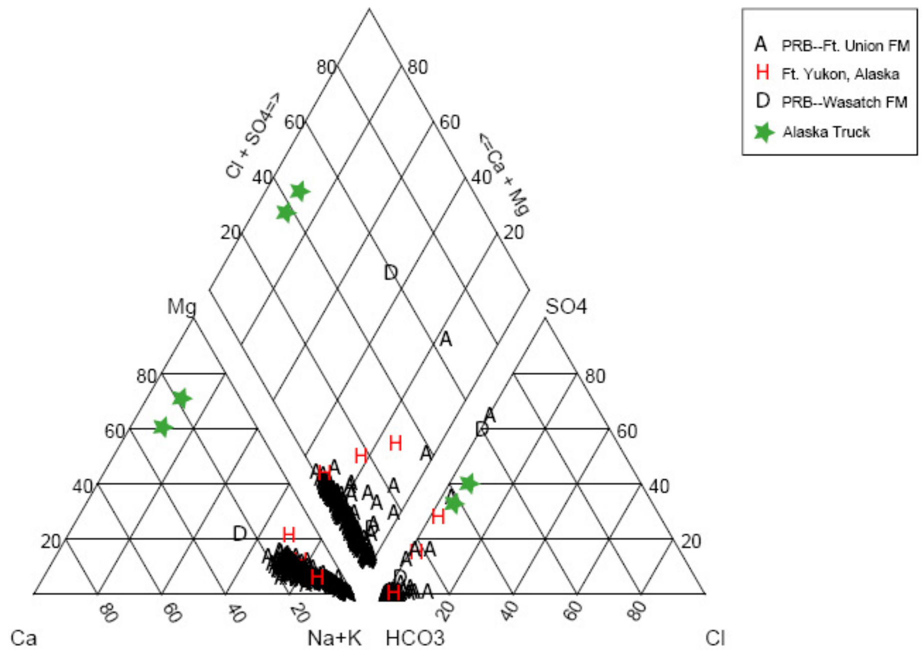

Figure 3-4. Piper Diagram comparing water samples from drill hole DOI-04-1A, Fort Yukon, Alaska to water samples from CBM wells in the Powder River Basin (PRB), Wyoming and Montana.

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Summary of Results:
Coalbed Methane Production Potential in Fort Yukon, Alaska as Derived from the DOI-04-1A Well

By Edwin P. Weeks[1], Arthur Clark[2], and Charles E. Barker[3]

Fort Yukon Production Potential

The permeability estimates provided for the upper coal bed in table 3-3, assumed to also apply to the lower coal, may be used in conjunction with the methane desorption data (tables 2-1*A*, 2-1*B*) and adsorption isotherms (figs. 2-1, 2-2), to roughly evaluate the potential for methane production at Fort Yukon. In particular, the results can be used to estimate the number of wells and well spacing required to produce 225,000 standard cubic feet of pure methane per day (scf/d), the estimated requirement for power generation and home heating at Fort Yukon (Ferguson and Ogbe, 2003, p. 14).

An absolute control on coalbed methane availability is imposed by the volume of gas initially in place per unit area. Volumetric gas in place can be determined from the equation: $IGIP = 1.359 C \rho_c h \chi$, where *IGIP* is initial gas in place, Mscf/acre; 1.359 is a conversion factor, [(Mscf)(ton)(cm^3)]/[(ac-ft)(scf)(gm)]; *C* is average as-received gas content of the coal, scf/ton; ρ_c is mean raw coal density, g/cm^3; *h* is coal bed thickness, ft; and χ is the mole fraction of methane in the desorbed gas. For the upper coal, *C*=13.1 scf/ton (table 2-1*A*), ρ_c=1.34 g/cm^3 (table 2-2*A*), *h*= 59 feet, and χ=0.94, resulting in *IGIP*=1.3 MMscf methane/acre. For the lower coal, the average gas content of 19.1 scf/ton (table 2-1*B*), coal density of 1.48 g/cm^3 (table 2-2*B*), combined with a coal

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thickness of 20 ft, results in *IGIP* of about 700 Mscf/acre.

For a pure methane fuel requirement for the village of 225 Mscf/d or 80 MMscf/yr, the village would require 1.6 billion scf over a 20-year period. Assuming a 100 percent recovery efficiency, all of the gas, if derived from the upper coal, would have to be removed from an area of about 1,200 acres, or, if dual completion of wells tapping the two zones is feasibile, could be obtained from a 800-acre area. However, complete gas recovery is not possible, and a rigorous evaluation of the 20-year recovery efficiency would require reservoir simulation, which is beyond the scope of this study. Nonetheless, a rough estimate of the number of wells needed to supply the village energy requirements may be obtained by analogy with results of simulations performed to evaluate recovery efficencies based on San Juan Basin coal properties. Zuber (1996, p. 3.18–3.19) provides illustrations for well spacings of 80, 160, and 320 acres, showing simulated 20-year recovery efficiencies vs. permeability and hydraulic fracture length for San Juan Basin coals. Zuber's curves indicate that computed recovery efficiency is nearly zero without hydrofracing for permeabilities less than 1 millidarcy, but increases sharply with diminishing well spacing and with stimulated fracture length.

Simulated efficiencies undoubtedly would be smaller for the low level of methane saturation for the Fort Yukon coals than those derived for methane-rich San Juan Basin coals. Nonetheless, estimates of the minimum number of hydrofraced vertical wells needed to meet the requirements can be made from recovery efficiencies illustrated in these figures, test-based permeability estimates, and the *IGIP* estimates. For the preferred estimate of coal permeability of 0.6 mD (table 3-3), the simulated curves for a spacing of 80 acres and an arbitrarily chosen stimulated fracture length of 200 ft (Zuber,1996, p. 3.18) indicate a 20-year recovery efficiency of about 30 percent. Based on this efficiency, about 50 wells tapping the upper coal, covering an area of 4,000 acres, would be required to meet village needs. For dual completion in the upper and lower coals, but the same recovery efficiency, about 30 wells in an area of 2,700 acres would be required. Zuber's curves also indicate that, for a given fracture length, recovery efficiency increases, at low K values, by about 12 percent for each halving of well spacing. Thus, 20-year recovery efficiency might be about 42 percent for a 40-acre spacing, indicating that about 50 dual-completion wells covering about 2,000 acres might be able to meet the village requirements.

Recent developments involving the use of horizontal wells indicates that the number of wells required might be decreased by a factor of three to five or more, reducing the number of wells required to as few as 5 to 10. However, the actual feasibility of developing the Fort Yukon coals using dual-completion hydrofraced horizontal wells would require thorough evaluation using a reservoir model. The above analyses only provide a basis for indicating whether such a study might be useful.

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