

Methane Hydrate Production from Alaskan Permafrost

Technical Progress Report

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by

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Abstract

Natural-gas hydrates have been encountered beneath the permafrost and considered a nuisance by the oil and gas industry for years. Engineers working in Russia, Canada and the USA have documented numerous drilling problems, including kicks and uncontrolled gas releases, in arctic regions. Information has been generated in laboratory studies pertaining to the extent, volume, chemistry and phase behavior of gas hydrates. Scientists studying hydrate potential agree that the potential is great – on the North Slope of Alaska alone, it has been estimated at 590 TCF. However, little information has been obtained on physical samples taken from actual rock containing hydrates.

This gas-hydrate project is in the final stages of a cost shared partnership between Maurer Technology, Noble Corporation, Anadarko Petroleum, and the U.S. Department of Energy's Methane Hydrate R&D program. The purpose of the project is to build on previous and ongoing R&D in the area of onshore hydrate deposition to identify, quantify and predict production potential for hydrates located on the North Slope of Alaska.

The work scope drilled and cored a well The HOT ICE #1 on Anadarko leases beginning in FY 2003 and completed in 2004. An on-site core analysis laboratory was built and utilized for determining the physical characteristics of the hydrates and surrounding rock. The well was drilled from a new Anadarko Arctic Platform that has a minimal footprint and environmental impact. The final efforts of the project are to correlate geology, geophysics, logs, and drilling and production data and provide this information to scientists developing reservoir models. No gas hydrates were encountered in this well; however, a wealth of information was generated and is contained in this report.

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1. Introduction

The purpose of this project is to plan, design and implement a program that will safely and economically drill/core and produce natural gas from arctic hydrates. This project documents planning, operations and lessons learned to assist in future hydrate research and field operations to make an objective technical and economic assessment of this promising natural gas reservoir potential.

On February 7, 2004 the well reached its planned depth of 2300 ft, about 300 ft below the zone where temperature and pressure conditions would theoretically permit hydrates to exist. Although significant gas shows were encountered in highly porous sandstones, no methane hydrates were found. The continuous coring rig used in the project proved to be a safe and efficient drilling system, with 93% of the core recovered.

This project used a special purpose on-site laboratory to help analyze hydrate cores. Live data and images were transmitted from the rig over the internet, which reduced the number of engineers and scientists required to oversee the project. Additionally, the well was drilled from a special purpose-built arctic platform. A massive 3D VSP seismic survey was also conducted to investigate lateral variations of the potential hydrate reservoir.

2. Executive Summary

Objectives and Scope of Work

The objectives of this gas-hydrate project are to analyze existing geological and geophysical data and obtain new field data required to predict hydrate occurrences; to test the best methods and tools for drilling and recovering hydrates; and to plan, design, and implement a program to safely and economically drill and produce gas from hydrates in Alaska.

The overall Scope of Work is to:

1. Evaluate geological and geophysical data that aid in delineation of hydrate prospects
2. Evaluate existing best technology to drill, complete and produce gas hydrates
3. Develop a plan to drill, core, test and instrument gas-hydrate wells in Northern Alaska
4. Characterize the resource through geophysics, logging, engineering and geological core and fluids analysis
5. Test and then monitor gas production from hydrate wells for one year
6. Quantify models/simulators with data for estimating ultimate recovery potential
7. Learn how to identify favorable stratigraphic intervals that enhance methane production
8. Assess commercial viability of developing this resource and ultimately develop a long-term production plan
9. Provide real hydrate core samples for laboratory testing
10. Develop and test physical and chemical methods to stabilize hydrate wellbores and improve core recovery
11. Step outside the well-known Prudhoe Bay/Kuparuk River area to further delineate hydrate deposits in Alaska
12. Report results to the DOE and transfer technology to the Industry

Well planning, site selection and equipment construction and field operations have been completed.

Phase II Participants:

Maurer Technology Inc. – Performs project coordination, project management and DRC testing.

Anadarko Petroleum Corporation – Overall project management for the design, construction, and operation of the Arctic Drilling Platform, mobile core lab, and field coring operations.

Noble Engineering and Development – Provides personnel and real-time data collection and transmitted digital data and video to project participants located offsite and wellsite drilling personnel.

University of Alaska – Supports studies on geology, tundra, and produced water disposal.

Lawrence Berkley National Lab (LBNL) – Performs reservoir modeling used for well test planning and onsite portable X-ray scanner with wellsite operator.

Sandia National Lab – Provides downhole mud pressure and temperature recording tool.

Pacific National Lab (PNL) – Provides portable infrared scanner.

United States Geological Survey (USGS) – Provides synthetic core for drilling tests, phase behavior model for hydrates, pressure vessels for hydrate core storage and technical advice. Models hydrate preservation and dissociation. Provides personnel for coal core and analysis.

Schlumberger Oilfield Services – Provides CMR equipment used in mobile core lab and two onsite analysts; and well-logging services.

Paulsson Geophysical Services – Performs vertical seismic profiling.

Advisory Board – Craig Woolard, University of Alaska, Anchorage; Steve Bartz, Schlumberger; Steve Kirby, USGS; Tim Collette, USGS; Theresa Imm, Arctic Slope Regional Commission; C. Sondergeld, University of Oklahoma; Richard Miller, University of Kansas; and David Young, Baker Hughes Inteq.

Accomplishments

- Design and construction of Anadarko's Mobile Core Laboratory completed in August 2002. This lab permits cores to be maintained and analyzed at a reduced temperature and in close proximity to the drill site.

- Operational and logistics planning, geology and geophysics analysis, and site selection completed and environmental and operations permits obtained by the end of December 2002.
- Anadarko's Arctic Platform was installed on site in February 2003. Technology being tested here could help to achieve three goals independent of this project:
 - allow operators to work outside the present operations season
 - provide access to remote areas where water to build ice roads is scarce and steep grades make it difficult to set or supply a drilling rig
 - reduce the environmental impact of a well location on the tundra
 - met expectations through a summer season
 - was successfully removed with no adverse environmental impact
- Arctic Platform topside facilities were set during March 2003.
- Hot Ice #1 Well was spudded on March 31, 2003.
- Well cored, logged and cased to the base of the permafrost during April 2003.
- Drilling operations resumed on January 30, 2004.
- Well successfully cored to 2300 ft with 93% core recovery
- Well was logged and a massive VSP survey conducted
- Geological models have been calibrated
- Final report is in progress

The Hot Ice No. 1 well is located approximately 20 miles south of the Kuparuk River oil field center and about 40 miles southwest of Prudhoe Bay. Based on evidence from nearby offsets in the Cirque and Tarn gas hydrate accumulations, hydrates are expected to be found in sands near the base of the permafrost. The well was spudded on March 31, 2003, and was continuously cored from a depth of 107 feet to 1400 feet (RKB) with core recovery of 93%. The base of the permafrost was crossed at about 1250 ft. Open-hole logs were acquired and 7-inch casing set in a shale zone between the Ugnu and West Sak formations.

Status and Remaining Tasks

Operations on the Hot Ice well were suspended after the first drilling season on April 21, 2003 pending the return of cold weather (**Figure 1**). Drilling operations were resumed during the current quarter on January 30, 2004 at the opening of the conventional operations season. An ice road was constructed from an existing road to the west of the well location (see **Figure 2**).



Figure 1. Arctic Platform during Summer

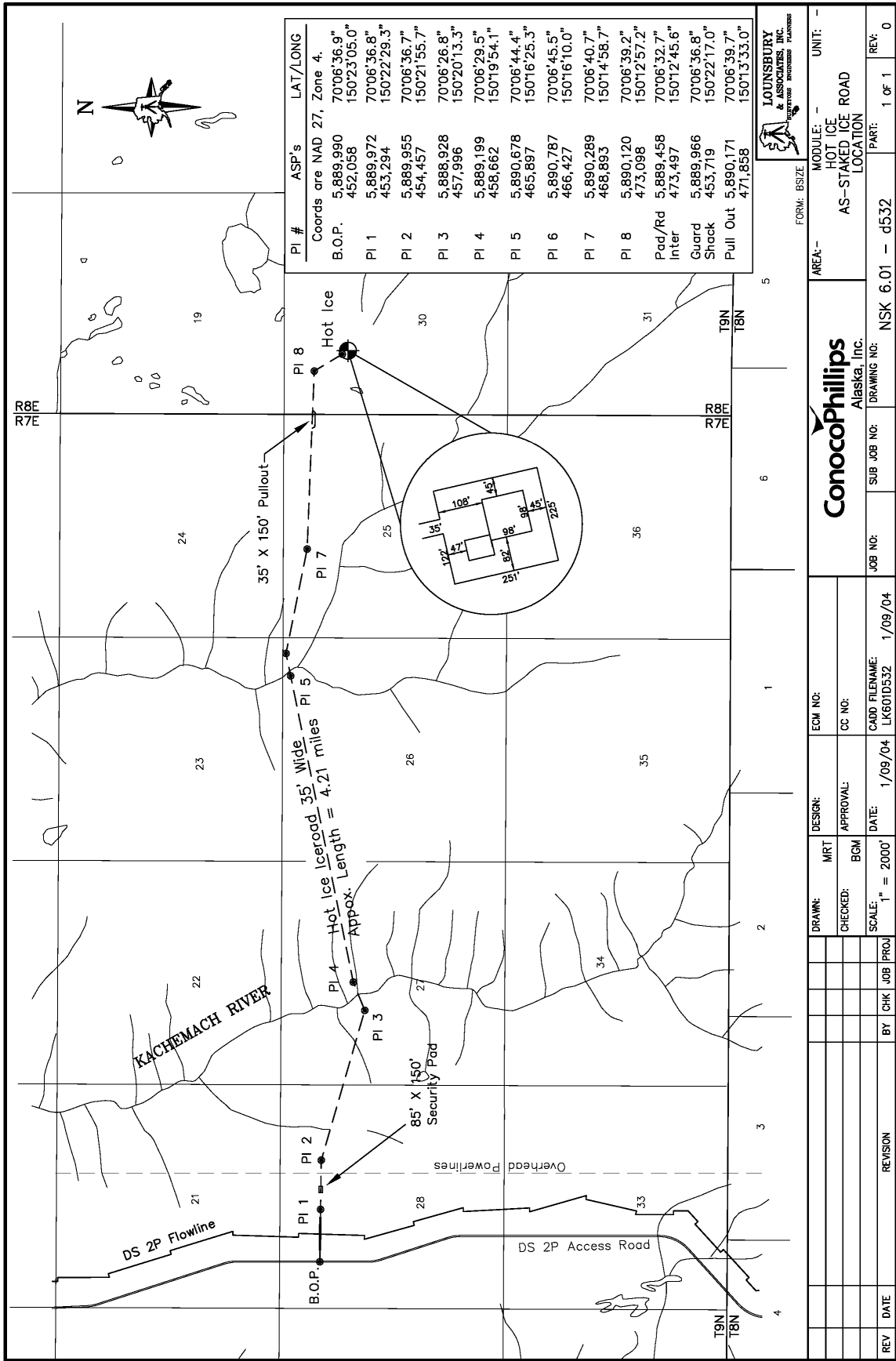


Figure 2. Map of Ice Road to Site

The Hot Ice No. 1 well was cored with a wireline retrievable coring system using drilling mud that had been chilled to 23°F (-5°C) to preserve the 3.3-inch (8.5-cm) core and to prevent any hydrate from dissociating during core recovery. The mobile core laboratory was employed to immediately perform measurements on both whole core and 1-inch plugs taken from the whole core, while maintaining that temperature. Whole core measurements included: core gamma log, infrared temperature, velocity measurement, geologic description and white light photographs, high resolution CT scan (equipment from LBNL), and a nuclear magnetic resonance measurement (with CMR tool from Schlumberger) on a portion of each section of core. Plug measurements included: bulk volume, grain density, helium porosity and permeability at confining stress, P and S wave velocity, resistivity, and thermal conductivity. For hydrate samples, the NMR system (Schlumberger CMR Tool) is used to determine the fluid volume in the sample at various steps in the dissociation process, while released gas volumes and composition are also recorded.

After the well was suspended on April 21, 2003 due to unseasonably warm conditions that prevented transport of heavy loads over the tundra, the mobile core lab and collected core were moved to Deadhorse, Alaska, to permit continuation of core analysis. The lab was shipped to Tulsa, Oklahoma where repairs and upgrades were made by the University of Oklahoma. The lab was shipped back to the location in January, 2004. Following the demobilization, the core was provided to the University of Alaska and the mobile lab was sent to the University of Oklahoma, where it is now available for other research projects.

As mentioned, drilling operations were resumed during January 2004, and the well was successfully cored to 2300 ft with 93% core recovery on February 7, 2004. The well was logged and a massive VSP survey conducted. Casing was set directly above the West Sak formation. Gas-bearing sands were encountered in highly porous sandstones that were situated within the hydrate stability zone. The sands were areally extensive and stratigraphically equivalent to sand units in offset wells. Total depth was reached at 2300 ft, which was approximately 300 ft below the gas-hydrate-stability zone. A localized temperature model was developed for predicting the base of the hydrate-stability zone. This model was verified by the well results and used to determine the TD of the well. The well was logged, VSP was run and, because no hydrates were encountered, the planned completion and testing program was not implemented.

A complete set of core, well log, production and downhole pressure and temperature data has been provided for use in evaluating the hydrate reservoir's quality and to determine potential for production from arctic hydrate intervals. The data are now available for incorporating into hydrate reservoir models to test possible scenarios for producing methane from hydrates in similar settings.

Several officials from the State of Alaska, U.S. Department of the Interior and Department of Energy visited the site. DOE NETL has also established a special web page for references to their support of gas-hydrate development. At their site (<http://www.netl.doe.gov/scng/hydrate/>) are posted updates describing the Hot Ice

project as well as "Fire in the Ice," the National Energy Technology Laboratory Methane Hydrate Newsletter.

Drilling operations at the Hot Ice No. 1 well marked the first test of Anadarko's Arctic Platform. The primary platform consists of 16 lightweight aluminum modules fitted together and mounted on steel legs 12 ft above ground. The platform is large enough to contain a coring rig, auxiliary equipment, mud tanks, and the mobile core analysis laboratory. Another five modules form an adjacent platform with living quarters for up to 40 people. An IADC/SPE paper (SPE 87140 "Onshore Mobile Platform: A modular Platform for Drilling and Production Operations in Remote and Environmentally Sensitive Areas,") was presented to the industry on March 2, 2004 by Ali Kadaster of Anadarko.

The Final Report for Phase II is currently being compiled. The report will include a number of topical reports on planning operations and characterization of the reservoir. Presentations on operations, geology, and geophysics are going to be presented at the AAPG Hedberg Research Conference, "Natural Gas Hydrates: Energy Resource Potential and Associated Geologic Hazards," on September 12-16, 2004, Vancouver, BC, Canada.

3. Experimental

3.1 BACKGROUND

Natural-gas hydrates (**Figure 3**) beneath the permafrost have been encountered by the oil and gas industry for years. Numerous drilling problems, including gas kicks and uncontrolled gas releases, have been well documented in the arctic regions by Russian, USA and Canadian engineers. There has been a significant volume of scientific information generated in laboratory studies over the past decade as to the extent, volume, chemistry and phase behavior of gas hydrates. However, virtually all of this information was obtained on hydrate samples created in the laboratory, not samples from the field.



Figure 3.
Methane Hydrate

Discovery of large accumulations around the world (**Figure 4**) has confirmed that gas hydrates may represent a significant energy source. Publications (Makogon and others) on the Messoyakhi gas-hydrate production in Siberia (which has produced since 1965), document that the potential for gas-hydrate production exists. Several studies have also addressed the potential for gas hydrates in the permafrost regions of North America. The results from the Mallik Hydrate, Mackenzie Delta Northwest Territories, Canada wells (hereafter, the "Mallik wells") drilled by JAPEx, JNOC and GSC, provide a significant amount of useful background information. The USGS made sizeable contributions to the Mallik project, as well as many other investigations on gas hydrates in the USA (especially Alaska), and has a tremendous amount of basic information on the presence and behavior of hydrates.

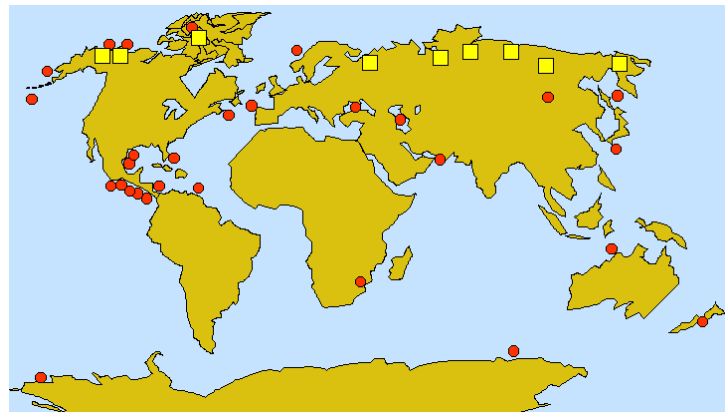


Figure 4. Methane Hydrate Deposits (USGS)

This knowledge is being applied around the world for environmentally sound development of this resource. This project work represents the first attempt to drill, core and monitor hydrate wells in the USA. The specific objective of this effort is to obtain the field data required to verify geological, geophysical and geochemical models of hydrates and to plan, design and implement a program to safely and economically drill and produce gas from arctic hydrates.

North America's emphasis on utilizing clean-burning natural gas for power generation has increased demand for gas and resulted in higher gas prices. A number of forecasts, including the NPC Study on Natural Gas (2000), indicate higher demand with prices in the range of \$4 to \$8/mcf. This is sufficiently high to allow investments in sources previously deemed uneconomic. The projected US demand for natural gas may grow to nearly 30 TCF by the end of the decade. This demand, particularly on the West Coast of the US, strongly suggests that a proposed Alaska Natural Gas Pipeline may now be economically feasible. This pending pipeline should provide a commercial market for natural gas, thereby allowing the necessary investments in new technology to develop and market the hydrate resource.

Anadarko is the one of the largest independent oil and gas exploration and production companies in the world, with proved reserves of 7.7 TCF of gas and 1.2 BBO of crude oil, condensate and NGL's (approximately 2.5 BBOE). Domestically, it has operations in Texas, Louisiana, the Mid-Continent and Rocky Mountains, Alaska and the Gulf of Mexico. Anadarko, one of the most active drillers in North America, is balancing its current exploration and production programs by investing in developing new gas resources in North America, including areas where the risks and potential rewards are high with the application of advanced technology. It is now one of the largest leaseholders in Alaska, with an ongoing program of exploratory drilling and seismic studies. Anadarko's Alaska holdings number about 2 million net acres; some of which may hold potential for commercial production from hydrates. Anadarko also has extensive holdings in the Mackenzie Delta region of the Northwest Territories of Canada, which also may have potential for hydrates. Thus, Anadarko is very interested in seeing this resource become commercially viable.

With the amount of information on hydrates now available and the potential of developing this huge resource, this project makes good economic sense at this time. The best resources and ideas from around the world will be used to implement the technology in the field. Thorough planning of the test wells should allow avoiding some of the problems encountered in previous gas-hydrate wells.

This project will provide valuable information to the DOE, industry, and research community to identify key barriers and problems related to gas-hydrate exploration and production. This information will be highly useful in developing innovative, cost-effective methods to overcome these barriers. An Advisory Board was used for the planning of the well operations that included Teresa Imm, Arctic Slope Regional Corp., Craig Woolard, University of Alaska Anchorage, Steve Kirby, USGS, Steve Bartz, Schlumberger, Timothy Colette, USGS, David Young, Baker Hughes Inteq, Rick Miller, Kansas Geological Survey, and Carl Sondergeld, University of Oklahoma.

3.2 OBJECTIVES

The objectives of this gas-hydrate project are to:

1. Analyze existing geological and geophysical data and obtain new field data required to predict hydrate occurrences
2. Test the best methods and tools for drilling and recovering hydrates
3. Plan, design, and implement a program to safely and economically drill and produce gas from hydrates.

3.3 SCOPE OF WORK

The overall scope of the work for this Alaskan Hydrates project is to:

1. Evaluate geological and geophysical data that aid in delineation of hydrate prospects
2. Evaluate existing best technology to drill, complete and produce gas hydrates
3. Develop a plan to drill, core, test and instrument a gas-hydrate well in Northern Alaska
4. Characterize the resource through geophysics, logging, engineering and geological core and fluids analysis
5. Test and then monitor gas production from the hydrate wells for an extended period of time.
6. Quantify models/simulators with data for estimating ultimate recovery potential
7. Learn how to identify favorable stratigraphic intervals that enhance methane production
8. Assess commercial viability of developing this resource and ultimately develop a long-term production plan
9. Provide real hydrate core samples for laboratory testing
10. Develop and test physical and chemical methods to stabilize hydrate wellbores and improve core recovery

11. Step outside the well-known Prudhoe Bay/Kuparuk River area to further delineate hydrate deposits in Alaska
12. Report results to the DOE and transfer technology to the Industry

4. Results and Discussion

4.1 DELIVERABLES

During **Phase I**, an effective plan was developed for drilling new hydrate wells in Alaska. This included geological and geophysical assessment, site selection, and developing well plans.

In separate reports the project team provided DOE with the following Phase I Deliverables:

- Digital map of well locations
- Well log correlation sections
- Seismic maps and sections showing stratigraphic and lithologic units within gas hydrate stability zone
- Reservoir modeling report
- Well data for control wells used for site selection
- Site selection plan
- Testing and analytical procedures (Topical Report)
- Well plan
- Permit application
- NEPA requirements

Additional Phase I achievements beyond the original contract obligations were also delivered. These include:

- Topical reports from University of Oklahoma and the Drilling Research Center on hydrate core apparatus and testing
- Support of other DOE hydrate projects including the Westport Core Handling Manual
- Three reports from the University of Alaska Anchorage:
 1. Geological Research of Well Records

2. Water Generated during Production of Gas Hydrates

3. Permafrost Foundations/Suitability of Tundra Platform Legs

- USGS report on dissociation of hydrates at elevated pressures
- LBNL report on hydrate preservation in cores
- Arctic platform video
- National Press Release and Conference in Washington, DC
- First-ever North Slope coal cores provided to the USGS for coalbed methane study
- New equipment for measuring hydrates

Phase II encompassed drilling/coring a new hydrate well.

- The well was cored to 2300 ft with 93% of core recovered successfully.
- A geologic model was developed and quantified to predict the potential hydrate-bearing strata.
- The continuous coring rig proved to be a safe and efficient drilling system.
- The ability to characterize whole core on site was demonstrated using a mobile core lab. Tools developed for making hydrate-specific measurements were tested on gas-bearing sands and permafrost.
- Petrophysical measurements were quickly performed on site.
- A state-of-the-art CT scanner from Lawrence Berkley was used to analyze whole cores on site.
- The USGS collected and analyzed coal cores in real time.
- A massive 3D VSP was designed and conducted. The data are being processed and will be included in the Final Report.
- Viability of the concept of extending the drilling season on the North Slope of Alaska by using a low impact platform was demonstrated.
- Live data feed from the North Slope to Houston and other areas was demonstrated during the project.

4.2 TEAM ORGANIZATION

Team organization is shown in **Figure 5**.

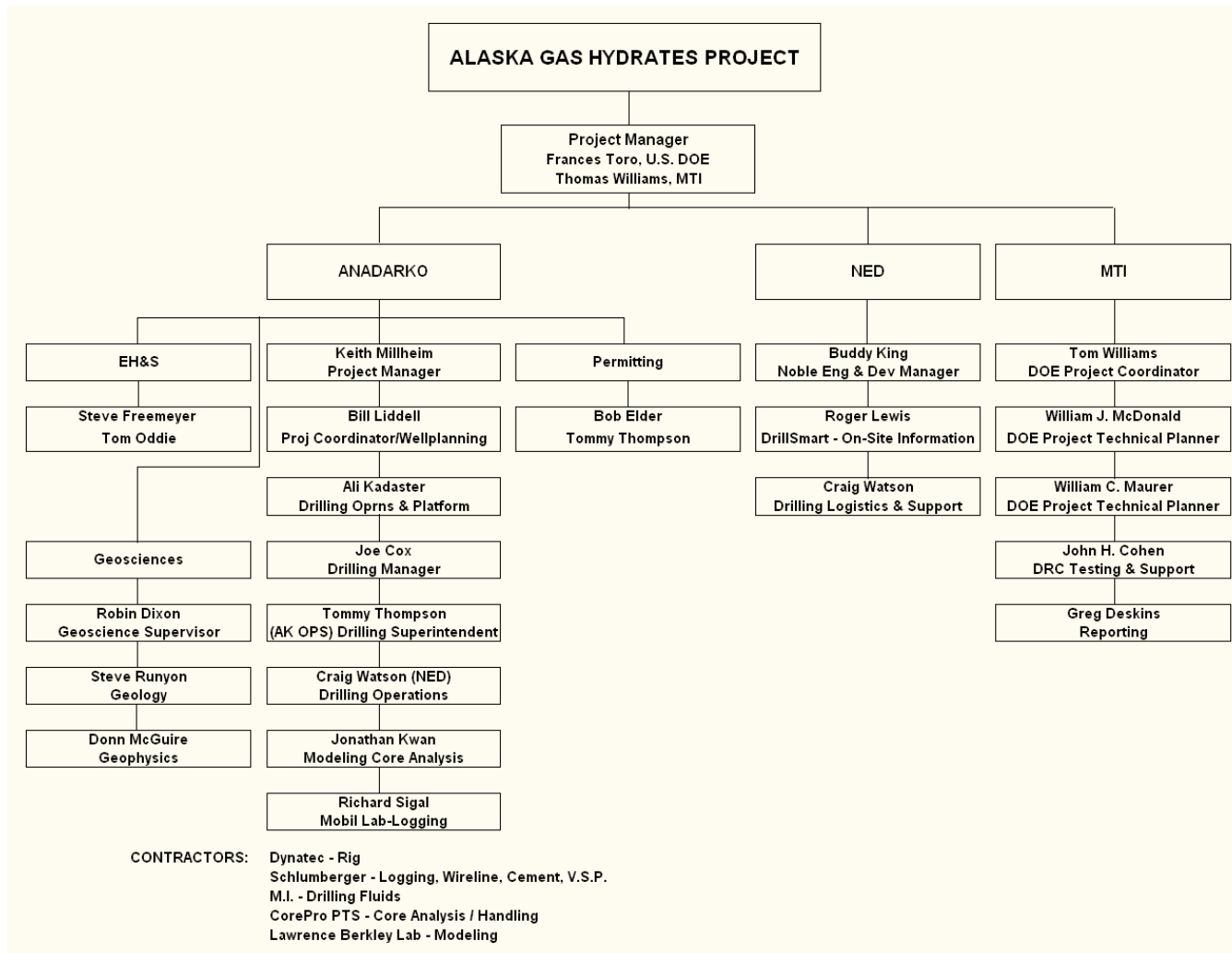


Figure 5. Project Team Structure

4.3 ACCOMPLISHMENTS

PHASE I

Phase I is now complete. Tasks 1-7 were completed.

Phase I Task Activities that Continued into Phase II

A “lessons learned” workshop was held at Anadarko’s office in the Woodlands on June 12-17, 2003. Each activity and task were reviewed and a budget revision was completed. Cost of the unanticipated demobilization and stand-by fees have significantly increased the cost of the project.

Subtask 4.2 – Permitting

Permitting was completed; however revisions for re-mobilization prior to the normal drilling season (due to freezing of the permafrost) are on-going. Permitting the VSP is currently an issue. The platform has not moved due to thawing this summer and it is anticipated Anadarko will be allowed on the well early. Three wells were initially permitted, named Hot Ice #1, #2 and #3 (HOT ICE = High Output Technology Innovatively Chasing Energy). Following the Anadarko Geological and Geophysical assessment and the Site Selection task, the best location was selected in November and final permitting activity has focused on this location for HOT ICE #1. With the addition of the Arctic Platform, new permitting activities and costs have been required. Meetings with and inspections by State and Federal regulators have continued. A number of positive reports complimentary of the operation have resulted.

The permit application was provided to the DOE.

A recent map showing the location of the site is presented in **Figure 6**.

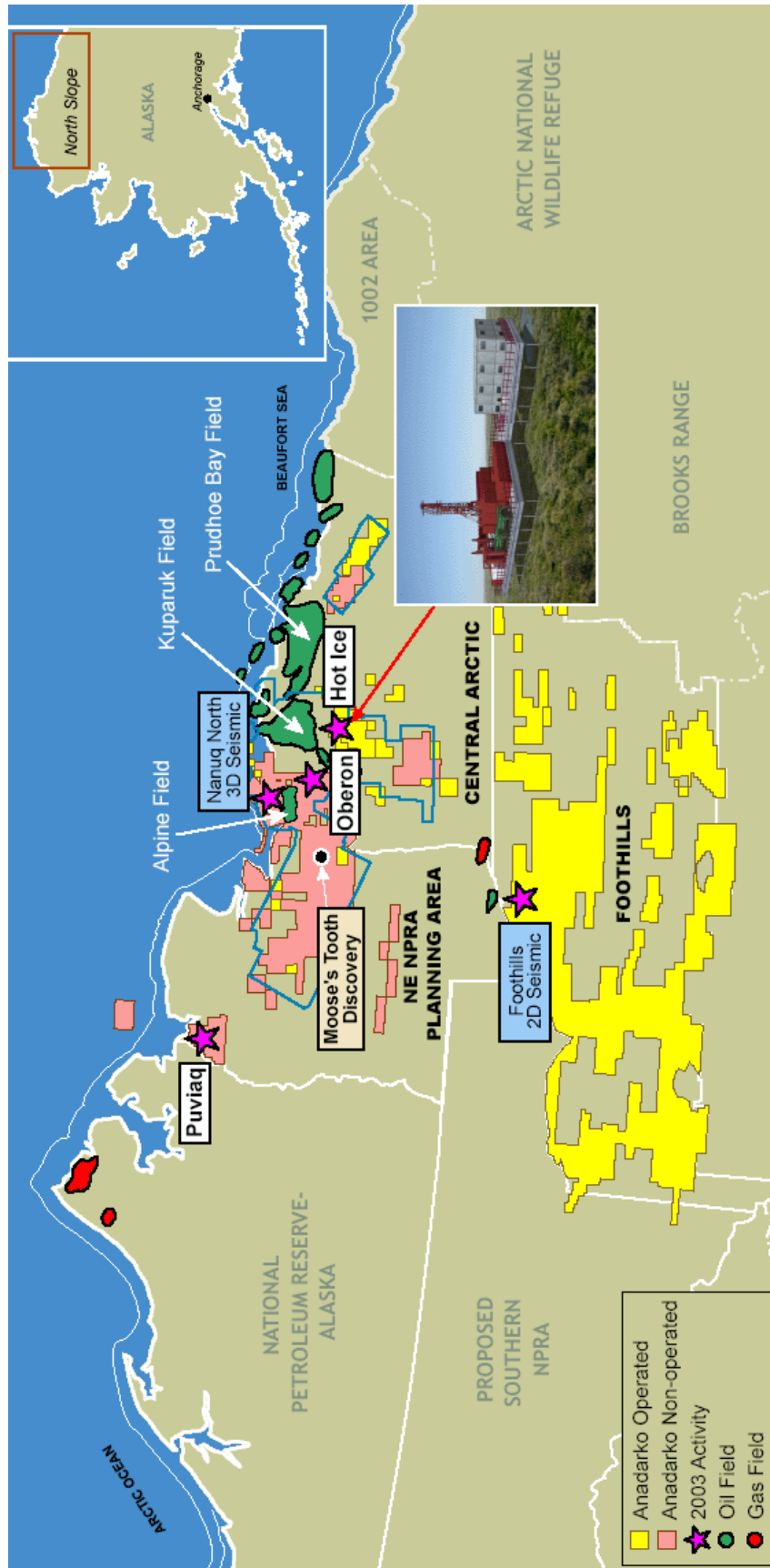


Figure 6. Map of North Slope Showing Location of Hot Ice #1

Task 7.0 – Posting Data on Existing Web Sites

Maurer constructed an Internet web site (<http://www.maurertechnology.com/index-hydrates.html>) for hydrate project updates. It is linked to the NETL hydrate web site and displays presentations, progress highlights and photos. This site will continue to be updated to make results available to the R&D community. Special information is available to the project team (including DOE) through a password-protected page. Information about our project is being exchanged with other hydrate research organizations and meetings. Press releases have been issued, and the energy press has contacted Maurer and Anadarko for progress updates and information about the project. A number of articles and papers have appeared in *Petroleum New Alaska*, *Hart's E&P*, *World Oil*, *IADC/SPE* and others. These articles and publications are shown in the attached project bibliography.

PHASE II

The overall objective of Phase II is to test exploitation techniques developed in Phase I by drilling/coring and completing the well, and then performing a battery of well tests and logs. Because no gas hydrates were encountered the completing and testing tasks of the well were not conducted. Tasks to accomplish these objectives are described below.

The schedule for Phase II is shown in **Figure 7 and Table 1**.

**Methane Hydrate Production from Alaskan Permafrost
PHASE II**

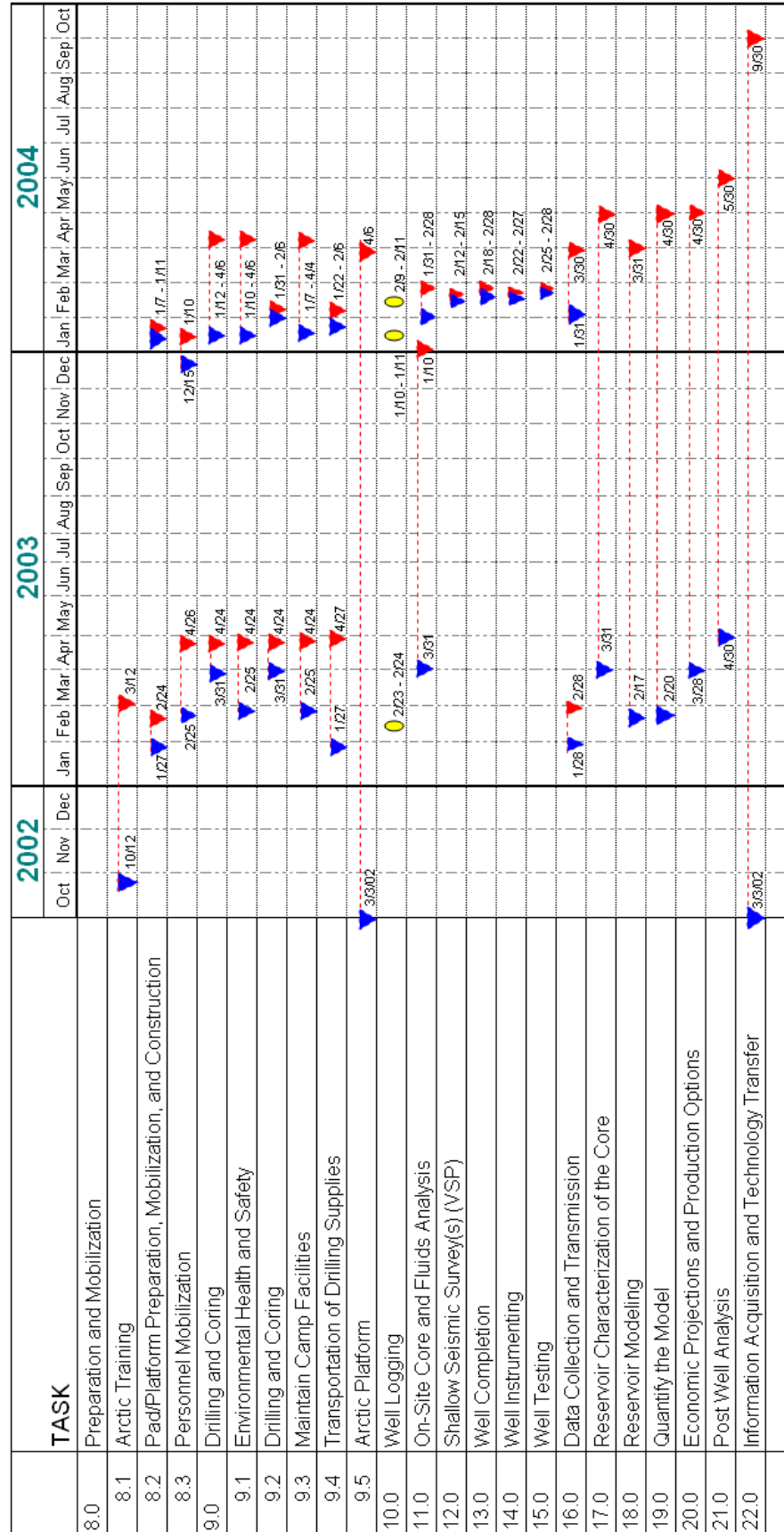


Figure 7. Phase II Project Schedule

Table 1. Hot Ice No. 1 – Time Line

ID	Task Name	Duration	Start	Finish	Predecessors
1	Tundra Opening (Actual)	0 days	1/9/2004	1/9/2004	
2	Open Deadhorse w/ key Personnel	4 days	1/7/2004	1/11/2004	
3	Hot Ice Project Resumption	67 days	1/12/2004	3/19/2004	
4	Mobilization	10 days	1/12/2004	1/22/2004	
5	Build 4-mile Ice Road From Meltwater	10 days	1/12/2004	1/22/2004	
6	Deadhorse Office Officially Open	0 days	1/12/2004	1/12/2004	
7	Prep Hot Ice Camp	4 days	1/18/2004	1/22/2004	
8	MOB Crews to Deadhorse	0 day	1/20/2004	1/20/2004	
9	Training & Pre-Spud Mtg in Deadhorse	3 days	1/18/2004	1/21/2004	
10	Rig Up & Preparation for Spud	12 days	1/18/2004	1/30/2004	
11	RU Electrical	6 days	1/18/2004	1/24/2004	
12	RU Plumbing	2 days	1/19/2004	1/21/2004	
13	RU Communications	1 day	1/22/2004	1/23/2004	
14	Haul Fuel and Fluids	5 days	1/21/2004	1/26/2004	
15	RU Rig and Support Equipment	5 days	1/21/2004	1/26/2004	
16	Set up & RU Lab	3 days	1/23/2004	1/26/2004	
17	RU Instrumentation	6 days	1/24/2004	1/30/2004	
18	Test BOP	1 day	1/28/2004	1/29/2004	
19	Drilling & Coring Operations	17 days	1/29/2004	2/15/2004	
20	RIH w/BHA, DO Ice Plugs & Displace Hole	1 day	1/29/2004	1/30/2004	
21	Test Casing, DO Shoe & 20', FIT/LOT	1 day	1/30/2004	1/31/2004	
22	Core 1425' to 2300'	7 days	1/31/2004	2/7/2004	
23	TOH, Test BOP, TIH, C&C	1 days	2/6/2004	2/7/2004	
24	C&C, TOH & RU Loggers	1 day	2/7/2004	2/8/2004	
25	OH Log	1 day	2/8/2004	2/9/2004	
26	Wiper Trip	1 day	2/9/2004	2/10/2004	
27	VSP	5 days	2/10/2004	2/15/2004	
28	Abandonment & Demobilization	25 days	2/15/2004	3/11/2004	
29	Test BOP	1 day	2/15/2004	2/16/2004	
30	P&A/ L/D CHD 134 & Set Packer & Plugs	1 day	2/16/2004	2/17/2004	
31	Rig Down & Demob. Rig Topside	10 days	2/17/2004	2/27/2004	
32	Rig Down & Demob. Rig Platform	2 days	2/27/2004	2/29/2004	
33	Remove Rig Platform Legs	3 days	2/29/2004	3/3/2004	
34	Rig Down Camp	2 days	3/3/2004	3/5/2004	
35	Remove Camp Platform & Legs	2 days	3/5/2004	3/7/2004	
36	Remediate Site	4 days	3/7/2004	3/11/2004	
37	Wrap up at Deadhorse	19 days	2/29/2004	3/19/2004	
38	Wash Bay Operations	12 days	2/29/2004	3/12/2004	
39	Long-term Storage	7 days	3/7/2004	3/14/2004	
40	Inventory	17 days	3/2/2004	3/19/2004	
41	Hot Ice Project Complete	0 days	3/19/2004	3/19/2004	

Task 8.0 – Preparation and Mobilization

Subtask 8.1 Arctic Training

The required training will be conducted for personnel who will be working on the North Slope overnight in support of this project. Training courses included: First Aid, Respiratory, FIT Test, H₂S Training, NSTC Training, Hazcom/Hazwoper, PPE, Alaska Safety Handbook, Arctic Survival, Bear Awareness, NPRA Training, and Fire Extinguisher Training. Refresher training and updated certifications were provided for the 2004 drilling season.

Subtask 8.2 Pad/Platform Preparation, Mobilization, and Construction

Permits were issued, and the arctic platform was installed at the well location in February 2003. The recipient mobilized the drill platform equipment to the well location, using an existing gravel road and a staging area at the end of the road. The permits allowed the platform to remain during the summer months. An ice road was permitted and utilized for access during operations in 2004.

Phase 2 of the drilling operation will incorporate an ice road (**Table 2 and Figure 2**) instead of making use of Rolligons.

Table 2. Hot Ice Location Winter Access Alignment

Point Name	Lat (WGS 84)	Long (WGS 84)	Comments
001	70.10992	150.38774	Road Alignment
002	70.11032	150.38779	Road Alignment
003	70.10943	150.38774	Road Alignment
HI Start	70.10991	150.38741	Beginning of Ice Road Alignment off road
PL-X-1	70.10997	150.38255	Pipeline crossing
004	70.10959	150.37146	
005	70.11026	150.37123	Power line alignment
HI PI-03-1	70.10712	150.34009	Point of Intercept
HI X-03-1	70.10763	150.33920	Stream Crossing 1
HI X-03-2	70.11195	150.27660	Stream Crossing 2
HI-1	70.10836	150.21756	Hot Ice #1 Platform location (West Side)

The three pipelines at the single pipeline crossing are protected by casings and 7 ft of coarse gravel. The gravel ramp on each side is shown in **Figure 8**.

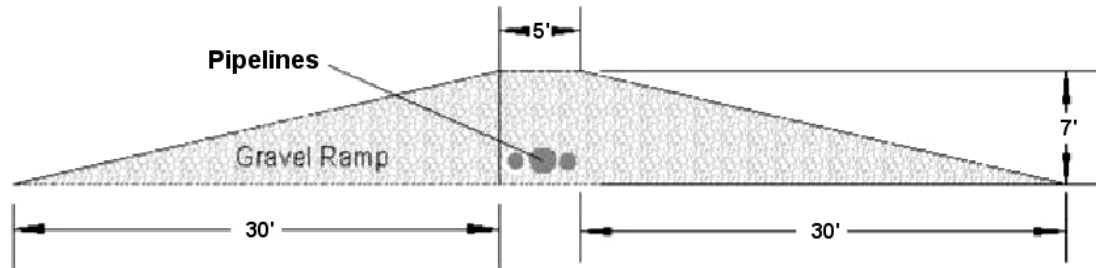


Figure 8. Gravel Ramp for Pipeline Crossing

The sites for Stream Crossings 1 and 2 are shown in **Figure 9**.

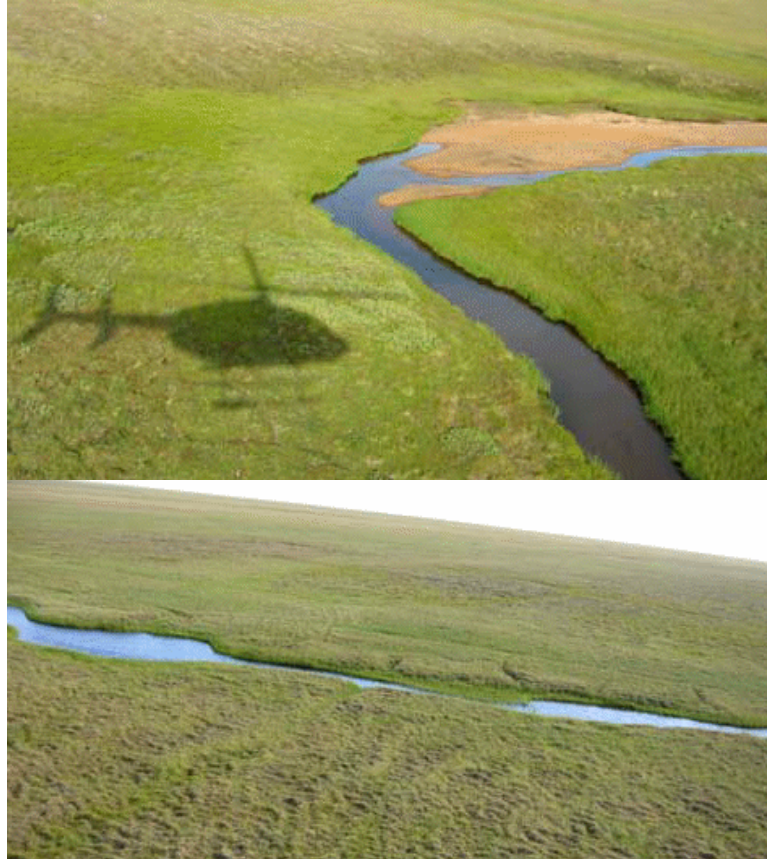


Figure 9. Stream Crossing 1 (upper) and 2 (lower) for Ice Road

Subtask 8.3 Personnel Mobilization

The recipient shall transport all project personnel to and from the well site. This task shall include transport of camp crew, catering staff, maintenance crew, rig crew, lab crew, logging crew, cementing crew, mud crew, and supervisory personnel.

Task 9.0 – Drilling and Coring

The recipient winterized the drill rig and mobilized it to Deadhorse and then to the well location. The recipient drilled and cored the HOT ICE #1 well from the arctic platform.

Subtask 9.1 Environmental Health and Safety

The recipient monitored and responded to environmental health and safety concerns, including monitoring and manifesting waste, in order to ensure compliance with regulations specified in permits.

Subtask 9.2 Drilling and Coring

The recipient drilled the HOT ICE #1 well from the arctic platform constructed in Subtask 8.2. The recipient used chilled drilling fluids and monitored the downhole temperature and inclination using a tool provided by Sandia National Lab. The recipient used the Noble Engineering and Development Drill Smart System to allow engineers to monitor and view drilling operations live from Houston. Owing to unseasonably warm weather, the recipient was unable to complete the drilling program as originally scheduled during the Spring of 2003. The recipient resumed and completed drilling operations during the Winter 2004 drilling season.

Subtask 9.3 Maintain Camp Facilities

The recipient provided camp facilities to house and feed the crews rotating on a 12/12 shift schedule.

Subtask 9.4 Transportation of Drilling Supplies

The recipient transported by trucks and Rolligons personnel, equipment, and supplies that were used in the drilling operations, including drilling fluids and drilling mud. The recipient constructed a new ice road during the Winter 2004 season, to facilitate the mobilization of equipment, supplies, and personnel to the Hot Ice #1 Site to complete the drilling and coring operations.

Subtask 9.5 Arctic Platform

The Anadarko Arctic Platform was constructed and tested in Houston, Texas. The structure is made of lightweight aluminum. It was mobilized to the base camp in January 2003, and inspected prior to mobilization to the well location in February (**Figure 10**). The legs were tested and put on location as soon as the freeze period began in January. A video of the transportation and construction was provided to the DOE. Legs were installed into the tundra permafrost and frozen into place. The platform can be mobilized by either helicopter and/or Rolligon from the base camp and assembled at the well location. Environmental monitoring equipment was also installed.



Figure 10. Arctic Platform at Hot Ice #1

The platform drilling area is 100 x 100 ft, and the base camp is 62.5 x 50 ft on an adjacent platform. The rig, equipment and base camp were installed on the platform by Rolligon and two cranes. After completion of drilling and completion operations, the equipment was demobilized and there was no adverse environmental impact at the drill site (**Figure 11**). The entire platform was demobilized to Dead Horse. The platform was thoroughly inspected by a third party and a post-analysis study was conducted with recommendations on future operations. A thorough report will be provided after completion of this subtask.



Figure 11. Final Stage of Platform Removal and Site Remediation

Task 10.0 – Well Logging

The recipient ran a suite of logs in the well(s) to characterize gas hydrate-bearing intervals, including the following: 1) electrical resistivity (dual induction), 2) spontaneous potential, 3) caliper, 4) acoustic transit-time, 5) neutron porosity, 6) density, and 7) nuclear magnetic resonance. Core data will be used to calibrate and quantify log information. A report on NMR log measurements of core taken during the 2003 drilling season is presented in **Appendix E**.

Task 11.0 – On-Site Core and Fluids Analysis

The recipient analyzed core and fluids using a specially constructed mobile core laboratory, staffed by trained laboratory technicians. Core was received in the cold module, where it was photographed and assessed for the presence of hydrate. One-inch plugs were removed from the core, and these plugs were measured for porosity, permeability, compressional and shear wave velocity, resistivity, thermal conductivity, and NMR with specialized equipment specifically designed for making these hydrate core measurements, including a Schlumberger CMR tool. All of these measurements were made under controlled pressure and temperature. Because no hydrates were encountered no hydrate dissociation testing was conducted, although the procedures and equipment will be included in the final report. Laboratory technicians assisted in preparing core for additional testing at other locations. Laboratory equipment is shown in **Figure 11**. Results of core and fluids handling procedures were provided for the DOE-funded Westport Hydrate Core Handling Manual. The results of the analysis will be incorporated in Tasks 17, 18, 19 and 20.

Subtask 11.1 Mobile Lab Repair and Upgrade

The recipient repaired and upgraded the mobile core lab in Tulsa during the summer and fall of 2003; specifically to: 1) redesign the pressure and cooling system for the NMR spectrometer, in order to achieve significantly lower temperature capability required for analysis of hydrate samples; 2) improve insulation for the velocity-thermal conductivity-resistivity measurement system; 3) configure the NMR and VCR systems with capability to allow positive pore pressures of methane for hydrate stability; and 4) develop a central database for managing and storing all data measured in the mobile core lab.

Regarding the use of the LBNL CT on site:

1. We partitioned one end of a 20-ft Conex with a separate door to the outside for the X-ray room
2. There is a heater located in the room or an electrical outlet to add a portable heater
3. The x-ray room is adjacent to the station where the core will be cut to 3-ft lengths

4. Core sections were taken outside and then into the x-ray room
5. The x-ray machine can be started in a temperature-controlled environment
6. During shipment, the machine will be subjected to ambient temperatures as low as -40°F, (unless special measures are taken)

The x-ray scanner is certified to be "cabinet safe." This means that any personnel can be near it for normal operation, and the user does not need to be fitted with a dosimeter. Only a certified "system maintainer" can use tools to perform maintenance and has the ability to modify or override interlock safety features. This authority is granted from our EH&S department, and Victor will be the system maintainer. He will bring his own badge.

Regarding operation – the machine will need to be "tuned" to the samples that are collected. This means that adjustments must be made to both x-ray voltage and current depending on the density and composition of the samples. There could also be adjustments to the camera behind the image intensifier. It is hard to predict how often and when this task will need to be performed. Since we will be performing dual-energy scanning, both our hard and soft x-ray energies will need to be periodically readjusted depending on the collected core density and composition.

LBNL modified the machine so that it will hold a 3-ft piece of core. Four-ft long core holders were constructed since the extra space at the top of the core holder will be empty, preventing concern about core length. The quick scan will be performed in about two to three minutes from the time the sample in the sample holder is placed in the x-ray unit, to when it can be removed from the x-ray unit. A more detailed full 3-D CT characterization will take about 12 minutes for the entire 3-ft length. A shorter interval (i.e., 4 inches) can be scanned in full 3-D mode in about 2 minutes. We will have three to five core holders so that one can be loaded, while another one is being cleaned or prepped and a third can be in the scanner.

Task 12.0 – Shallow Seismic Survey(s)

After the well was logged, a 3D vertical seismic profile (VSP) was conducted to calibrate the shallow geologic section with seismic data and to investigate techniques to better resolve lateral subsurface variations of hydrate-bearing strata. Paulsson Geophysical Services, Inc. deployed their 80 level 3C clamped borehole seismic receiver array in the wellbore to record samples every 25 ft. The surface vibrators successively occupied 800 different offset positions arranged around the wellbore. This technique generated a 3D image of the subsurface. Correlations of these seismic data with cores, logging, and other well data was generated. This task shall include additional fabrication of receiver cables, rental of field vibrators and recording equipment and associated personnel. This work will be summarized in a Topical Report.

Task 13.0 – Well Completion

Because no gas hydrates were encountered, the project team was not able to complete the well. Completion methods were developed based on the results of drilling, coring, and logging and will be included in the Final Report.

Task 14.0 – Well Instrumenting

Because no hydrates were encountered, the pressure and temperature gauge and a surface sensor to provide monitoring capabilities were not installed.

Task 15.0 – Well Testing

There was no well testing, although a comprehensive well testing plan was developed by the recipient. Water and gas samples were collected to determine their composition. The well was plugged and abandoned according to State regulations.

Task 16.0 – Data Collection and Transmission

The project team performed lab work on fluids captured during operations.

Task 17.0 – Reservoir Characterization of the Core

The recipient characterized the reservoir, based on analyses of fluids, geology, engineering, logs, geophysics, and rock physics. All these data have been included in a report and provided to Lawrence Berkeley Lab for incorporation into the well simulator.

Task 18.0 – Reservoir Modeling

The team will use information developed in reservoir characterization efforts to quantify Lawrence Berkeley National Laboratory's hydrate simulator. LBL's advanced simulator system is based on EOSHYDR2, a new module for the TOUGH2 general-purpose simulator for multi-component, multiphase fluid and heat flow and transport in the subsurface environment. Reservoir simulation during this phase of the project will focus on considering production schemes, both short and long term, for hydrate production on the North Slope based on all the reservoir characterization data obtained. Depressurization, injection and thermal methods are some of the production processes to be considered with the simulation.

Task 19.0 – Quantify the Model

This task is conducted in parallel with Tasks 17 and 18. The reservoir model used will need to be continuously refined as well test data are acquired. This effort is required for making projections. Models will be enhanced iteratively to incorporate dynamic production data during the well test period.

Task 20.0 – Economic Projections and Production Options

The recipient will provide in the report economic projections and production options. The recipient shall present the results of the program to the DOE. Information from other gas-hydrate projects shall be reviewed and included in our recommendations. Model-based estimates and production options will then be developed. If it is determined that a significant volume of gas production from hydrates is technically possible, an economic analysis will be conducted.

Task 21.0 – Post Well Analysis

This task will include a lessons-learned report based on past operations, and is designed for planning to conduct operations on other areas of the North Slope of Alaska. A report will include a budget for an additional well and an extended well test based on the information generated from the Phase II activities (including lessons learned). It will be determined if an additional well and/or extended production test is warranted, and recommendations will be presented to the DOE in sufficient time for FY 2005 budget planning. The production test plan will help determine the producibility of hydrate deposits. These plans will be valuable for future hydrate operations, even if this project is not extended into Phase III.

Task 22.0 – Information Acquisition and Technology Transfer

The recipient shall communicate and exchange information with experts in the field of hydrate well drilling, coring, and testing, including Advisory Board members, to stay abreast of the latest technology and preferred methodologies. The recipient shall also document results of the field tests and transfer this technology to the industry.

Subtask 22.1 Information Acquisition

The recipient shall identify and network with other experts in the field of hydrate well drilling, coring, testing, and analysis to gain insights into the latest methodologies and technologies. The recipient shall follow the latest developments related to hydrate wells by meeting with experts in the scientific and drilling communities.

Subtask 22.2 Technology Transfer

The recipient shall document project results and transfer the new information and technology to the industry, via web site postings, meetings, workshops, and at least one technical paper. Abstracts were accepted at the AAPG Hedberg Conference in September, 2004. The recipient used the NED Smart Drill system to allow well activities to be viewed by scientists, engineers, and DOE project managers who are not present at the well site.

DELIVERABLES

The periodic, topical, and final reports shall be submitted in accordance with the attached Reporting Requirements Checklist and the instructions accompanying the checklist. In addition, the Recipient shall submit the following:

Phase I

1. Digital Map of all well locations in and adjacent to project area (Task 2.1)
2. Well log correlation sections showing lithologic and stratigraphic units that fall within the gas hydrate stability zone in and adjacent to the project area (Task 2.1)
3. Seismic maps and sections showing extent of stratigraphic and lithologic units that fall within the gas hydrate stability zone in and adjacent to the project lease area (Task 2.2)
4. Reservoir modeling report for proposed site (Task 3.0)
5. Well Data for individual control wells used for site selection (Tasks 2.1 & 4.1)
6. Site Selection Plan (Task 4.1)
7. Testing and analytical procedures report (Task 5.0)
8. Well plan(s) (Task 6.0)

Phase II

1. Drilling and Coring Report (Task 9.2)
2. Well Logging Report (Task 10.0)
3. Core and Fluid Analysis Report (Task 11.0)
4. Bibliography of Publications by Project Personnel (see Section 6)
5. Seismic Survey Report (Task 12.0)
6. Well Completion Report (Task 13.0)
7. Well Testing Report (Task 15.0)
8. Hydrate Reservoir Characterization and Modeling Report (Tasks 17, 18, & 19)
9. Economic Projections (if production volumes dictate) and a Production Options Report (Task 20.0)

10. Plan for Future Hydrate Well on the North Slope (Task 21.0)
11. Technical Publications Summarizing Project Findings (All Tasks)
12. Final Report Summarizing Project Findings (All Tasks)

In addition to the required reports, the recipient shall submit informal status reports directly to the COR. These are preferred monthly with short descriptions of successes, problems, advances or other general project status information. The report should not exceed one page in length and shall be submitted via e-mail.

The Contractor will also provide the following to DOE: a copy of all non-proprietary data, models, protocols, maps and other information generated under the cooperative agreement, when requested by DOE, in a format mutually agreed upon by DOE and the participant. A number of maps, well logs and charts were provided to the DOE COR.

A four-day internal workshop was conducted prior to the project review meeting with the DOE, where a briefing of the program results was presented at the Anadarko facility in the Woodlands, Texas on May 13, 2004.

5. Conclusions

The conclusions to date are best summed up in the DOE *Techline* issued on March 1, 2004:

“Alaska Well Targets Gas Hydrates, Produces Wealth of Information”

Deadhorse, AK - Reflecting on his invention of the incandescent bulb, Thomas Edison claimed to have first discovered "a thousand ways not to make a light bulb," with each effort yielding valuable information that contributed to his eventual success. Scientists and engineers today are having a similar experience as they work to unravel the secrets and potential of methane hydrate. Their latest project, the "Hot Ice No. 1" well recently drilled in Alaska, did not encounter methane hydrate as expected, but it did produce information that should help to overcome the substantial technical obstacles to the eventual commercial production of this abundant energy resource.

Methane hydrate is a compound of water and methane (the major component of natural gas) that forms under pressure at cold temperatures. The amount of natural gas in methane hydrate is estimated to be far greater than all the world's conventional natural gas resources. It could potentially become a significant source of natural gas. Methane hydrate exists beneath large portions of the world's arctic permafrost, as well as within deep-sea sediments. On Alaska's North Slope, the volume of hydrate-based natural gas has been estimated at several times the volume believed to exist there in conventional gas-bearing formations.

The Hot Ice No. 1 well was drilled as part of a two-year cost-shared partnership between the U.S. Department of Energy's Office of Fossil Energy, Anadarko Petroleum Corp., Maurer Technology Inc., and Noble Engineering and Development. The project is part of the Energy Department's Methane Hydrates R&D Program, and supports the President's National Energy Policy, which calls for increasing domestic energy supplies, including more speculative "frontier" resources such as methane hydrate, to enhance national security.

"We're just beginning to understand the nature of methane hydrate distribution in the subsurface," said Brad Tomer, of the Energy Department's National Energy Technology Laboratory, which oversees the methane hydrate research program. "Each time we are able to successfully gather high-quality scientific data from the subsurface - as we did with the Hot Ice No. 1 well - we add significantly to our understanding of how hydrate forms, how it can be located, and what its resource potential might eventually be." The well also provided an opportunity to showcase several unique and previously untested Arctic drilling technologies that can be expected to play a role in future Alaskan drilling operations.

Hot Ice No. 1, located just south of the Kuparuk River field, 60 miles west of Deadhorse, Alaska, is the first dedicated hydrate well in Alaska. Spudded on March 31, 2003, drilling operations at the well were suspended because of warming weather and

resumed in January 2004. On February 7, the well reached its planned total depth of 2,300 feet, about 300 feet below the zone where temperature and pressure conditions would theoretically permit gas hydrates to exist. Although significant gas shows were encountered, no methane hydrate was found.

"The absence of hydrate at the site is in itself a significant scientific finding," said Tom Williams, Vice President with Maurer Technology Inc. and a member of the team drilling the well. "Based on detailed evaluation of log data from adjacent offset wells, the Hot Ice No. 1 well was expected to encounter a significant thickness of reservoir quality sands in the Upper West Sak unit. The sands were there just as expected but we found free gas and water rather than hydrate in the hydrate stability zone. Figuring out why will require a thorough post-mortem analysis of the core, log, and seismic data from the well."

Although disappointed by the missed opportunity to evaluate a hydrate-filled formation, the researchers believe that a tremendous amount of knowledge will be gained for future hydrate exploration through analysis of the unique suite of collected data. "Clearly, the model for distribution of methane hydrate on the North Slope may be more complex than we previously thought," added Williams.

The Hot Ice #1 well successfully demonstrated for the first time a number of innovative technologies, including the Arctic Drilling Platform, a mobile hydrate core analysis laboratory, and a new application of a continuous coring rig.

Anadarko's Arctic Platform consists of 16 lightweight aluminum modules fitted together and mounted on steel legs to create a platform large enough to contain a rig, auxiliary equipment, and a mobile laboratory. Another five modules form an adjacent platform with living quarters for 40 people. The Arctic Platform design permits light and air to reach the tundra grass at a drill site during the summer months, and the relatively small and shallow holes created by the legs can be filled when drilling is completed. The system eliminates the need to build drilling pads of ice or gravel that have more impact on the tundra landscape.

Leaving the modular platform in place during the summer appears to have had no adverse impact on the environment or wildlife, lending support to the idea that such a system could be used to safely extend the drilling season on the North Slope by several months.

The mobile core lab, developed by engineers and scientists at the University of Oklahoma, makes it possible to analyze cores at a reduced temperature and in close proximity to the drill site. This is critical to the accurate characterization of hydrate in cores because methane hydrate quickly separates into methane gas and water when warmed. At Hot Ice #1, the mobile lab was successfully employed to immediately perform measurements on both the whole core retrieved from the well and on one-inch plugs taken from the full-sized core.

The well also provided an Arctic test of a state-of-the-art CAT scan tool developed by Lawrence Berkeley Laboratory specifically for pinpointing methane hydrate concentrations within cores immediately upon retrieval.

The continuous coring rig used to drill the Hot Ice #1 well proved to be a safe and efficient system for drilling and coring relatively shallow wells through permafrost intervals. In this first attempt at continuously coring permafrost to detect methane hydrate, the well was cored from a depth of 82 feet to 2,300 feet, with 93 percent of the core successfully recovered.

The well also produced a high resolution, three-dimensional vertical seismic profile (VSP) survey that should help to delineate the stratigraphy and structure that control the occurrence of hydrate in the area. The VSP recorded shallow seismic data using a dense spacing of receivers and vibrators that allows geophysicists to interpret lateral variations in potential hydrate reservoirs.

"The entire drilling system-including all the well control safeguards, the Noble DrillSmart system, and the chilled drilling fluid system, which are not normally associated with this type of rig-performed exceptionally well," added Williams. "This has been well documented, so it can be replicated to save future drilling programs a lot of time, and provide a safe and very efficient way to explore for hydrate in the future."

"Although we did not find the hydrate we expected, we were able to advance a whole suite of technologies that could ultimately make exploration for and production of the Arctic methane hydrate resource economically feasible," added Tomer. "These new technologies can be taken to future hydrate research sites where they will ultimately aid in building a better characterization of this potentially important frontier resource." In addition, the geologic knowledge gained from an ongoing comprehensive analysis of the core, log, and seismic data from the well will improve models for the genesis and distribution of hydrate accumulations on the North Slope.

6. References

Project Bibliography

Magazines and Newspapers (longer articles only)

Antosh, Nelson, 2003: "New Drilling Rig in Tundra Faces Chilling Challenges," *Houston Chronicle*, February 21.

Bradbury, John, 2003: "Drilling in the Freezer," *Hart's E&P*, August.

Bradner, Tim, 2004: "Hydrate project nets data, lacks hydrates," *Alaska Oil & Gas Reporter*, May 4.

Bradner, Tim, 2003: "Anadarko Suspends Gas Hydrate Drilling Until Fall," *Alaska Oil & Gas Reporter*, May 6.

Bradner, Tim, 2003: "The Woodlands, Texas-Based Oil Firm Suspends Alaska Gas Hydrate Drilling," *Alaska Oil & Gas Reporter*, May 5.

Jones, Patricia, 2003: "Tapping Hot Ice," *Petroleum News*, Volume 8/15, April 13.

Moritis, Guntis, 2003, "Seeking Flammable Ice," *Oil and Gas Journal*, Volume 101/21; May 26.

Nelson, Kristen, 2003: "Arctic Platform in Place," *Petroleum News Alaska*, April 6.

Nelson, Kristen, 2002: "Hot Ice Project: Anadarko to Core Hydrate Well South of Kuparuk Unit," *Petroleum News Alaska*, November 10.

Perin, Monica, 2003: "Firms Warm up to the 'Ice that Burns'," *Houston Business Journal*, January 27.

Schempf, F. Jay, 2004: "Arctic Platform to Resume Drilling This Month," *The Rig Zone News*, article id=10337, January 9.

Snyder, Robert E., 2003: "Innovative Arctic Platform. (Drilling Advances)," *World Oil*, May.

Staff, 2003: "Anadarko Petroleum Corp. Debuts New Arctic Drilling Platform," *Anchorage Daily News*, Alaska, April 10.

Technical Articles and Presentations by Project Personnel

Aleshire, Lynn and Zubeck, Hannele, 2003: "Permafrost Foundations and Their Suitability as Tundra Platform Legs," University of Alaska Anchorage, School of Engineering, February 10.

Barker, Charles E., 2003: "Coalbed Methane Studies at Hot Ice #1 Gas Hydrate Well; First Report," US Geological Survey, Denver, April.

Barker, Charles E., Clough, James G. and Roberts, Stephen B., Clark, Arthur and Fisk, Bob, 2003: "Physical Limitations on Coalbed Gas Content of Low Rank Coals, North Slope, Alaska: An Apparent Widespread Depletion of Coalbed Gas in Permafrost," US Geological Survey, Alaska Division of Geological and Geophysical Surveys, and Bureau of Land Management, presented at 18th International Low-Rank Fuels Symposium, Billings, Montana, June 24-26.

Circone, S., Stern, L.A., and Kirby, S.H., 2003: "The Role of Water in Hydrate Dissociation," *J. Phys. Chem. B.*, (submitted).

Cohen, John and Williams, Thomas, 2002: "Hydrate Core Drilling Tests," Topical Report by Maurer Technology Inc., November.

Ebanks, W.J. and Zogg, W.D., 2003: "Coring for Methane-Hydrate in Shallow Sands of the Sagavanirktok Formation North Slope, Alaska – Phase I: Progress and Geologic Description," PTS Labs and Corpro, June.

Friefeld, B.M., Kneafsey, T.J., Tomutsa, L., Stern, L.A., and Kirby, S.H., 2002: "Use of Computed X-Ray Tomographic Data for Analyzing the Thermodynamics of a Dissociating Porous Sand/Hydrate Mixture," Proceedings of the 4th International Conference on Gas Hydrates, Yokohama Japan, 2002, pp. 750-755.

Kadaster, Ali G. and Keith K. Millheim, 2004: "Onshore Mobile Platform: A Modular Platform for Drilling and Production Operations in Remote and Environmentally Sensitive Areas," SPE 87140 presented at IADC/SPE Drilling Conference held in Dallas, Texas, 2-4 March.

Kirby, Stephen H., Circone, Susan and Stern, Laura A., 2003: "Dissociation Rates of Methane Hydrate at Elevated Pressures and of a Quartz Sand-Methane Hydrate Mixture at 0.1 MPa," US Geological Survey, Menlo Park, March 5.

Millheim, Keith, 2002: "Methane Hydrate Production from Alaska Permafrost," presented at AAPG Hydrate Meeting, Houston, Texas, March 12.

Millheim, Keith, Kwan, Jonathan and Maurer, Bill, 2002: "A Field Oriented Natural Gas Hydrate Research Project for the Alaska North Slope – Resource Evaluation and Possible Testing," presented at ACS National Meeting, Orlando, Florida, April 9.

Millheim, Keith, Kwan, Jonathan, Maurer, Bill, McDonald, Bill, and Williams, Tom, 2004: "The First Hydrate Experimental Well in Alaska – A Joint US DOE and Industry Effort," (invited paper to the book *Advances in the Studies of Gas Hydrates* to be published by Kluwer Academic/Plenum Publishers in 2004).

Moridis, George J., 2003: "FY2002 Studies–Hydrate Preservation in Cores (LBNL)," Lawrence Berkley National Laboratory, Earth Sciences Division.

Moridis, George J., 2003: "FY2003 Studies–Scoping Analyses Of Gas Production From Hydrates," Lawrence Berkley National Laboratory, Earth Sciences Division.

Newsham, Kent, 2003: "Recalculation of Base of Hydrate Stability Zone," Anadarko Petroleum Corporation, June.

Newsham, Kent, Sigal, Richard, Kleinberb, Robert, and Kwan, Jonathan, 2004: "Using Diffusivity Calculation and Regional Temperature Profile to Determine the Base of Permafrost in a Hydrate Field Experiment," (invited paper to the book *Advances in the Studies of Gas Hydrates* to be published by Kluwer Academic/Plenum Publishers in 2004).

Ross, Z., Crossen, K. and Munk, L., 2002: "Geologic Research of Well Records and Stratigraphy of the North Slope Region near Kuparuk, Alaska," University of Alaska Anchorage, November 25.

Sigal, Richard and Runyon, Steve, 2003: "Interim Report on Hot Ice #1 Coring, Core Analysis, and Logging Program," Anadarko Petroleum Corporation, May.

Stern, L.A., Circone, S., Kirby, S.H., and Durham, W.B., 2002: "New Insights into the Phenomenon of Anomalous or 'Self' Preservation of Gas Hydrates," Proceedings of the 4th International Conference on Gas Hydrates, Yokohama Japan, 2002, pp. 673-677.

Stern, L.A., Circone, S., Kirby, S.H., and Durham, W.B., 2003: "Temperature, Pressure, and Compositional Effects on Anomalous or 'Self' Preservation of Gas Hydrates," *Can. Journal of Physics*, 81 (1-2), pp. 271-283.

Tomutsa, L., Freifeld, B., Kneafsey, T., and Stern, L., 2002: "X-ray Computed Tomography Observation of Methane Hydrate Dissociation," Proceedings of the SPE Gas Technology Symposium, Calgary 2002, paper SPE 75533.

Williams, Thomas E., 2002: "Project Review – Methane Hydrate Production from Alaskan Permafrost," Methane Hydrate Conference, Washington DC, August 28.

Williams, Thomas E., 2002: "Project Review – Methane Hydrate Production from Alaskan Permafrost," Methane Interagency R&D Conf., Washington DC, March 21.

Williams, Thomas E., 2003: "Methane Hydrate Production – Application of Arctic Hydrate Research to Deep Water," presented at American Association of Drilling Engineers, Deep Water Quarterly Forum, Houston, Texas, February 11.

Woolard, C.R., Schnabel, W., Munk, L. and Hines, M., 2003: "Fundamental and Applied Research on Water Generated During the Production of Gas Hydrates (Phase 1)," University of Alaska Anchorage, February 17.

Woolard, Craig R., 2002: "Fire and Ice: Gas Hydrates in the Last Frontier," presented at University of Alaska Anchorage, October 8.

Appendix A: Hot Ice #1 Site/Rig Photos



Figure A-1. Hot Ice Well #2 Site

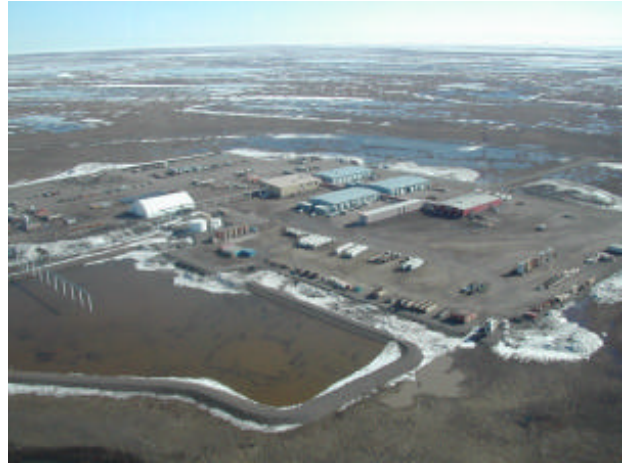


Figure A-2. Base Camp



Figure A-3. Setting the First Platform Module



Figure A-4. Assembling the Platform



Figure A-5. Complete Camp Ready for Drilling



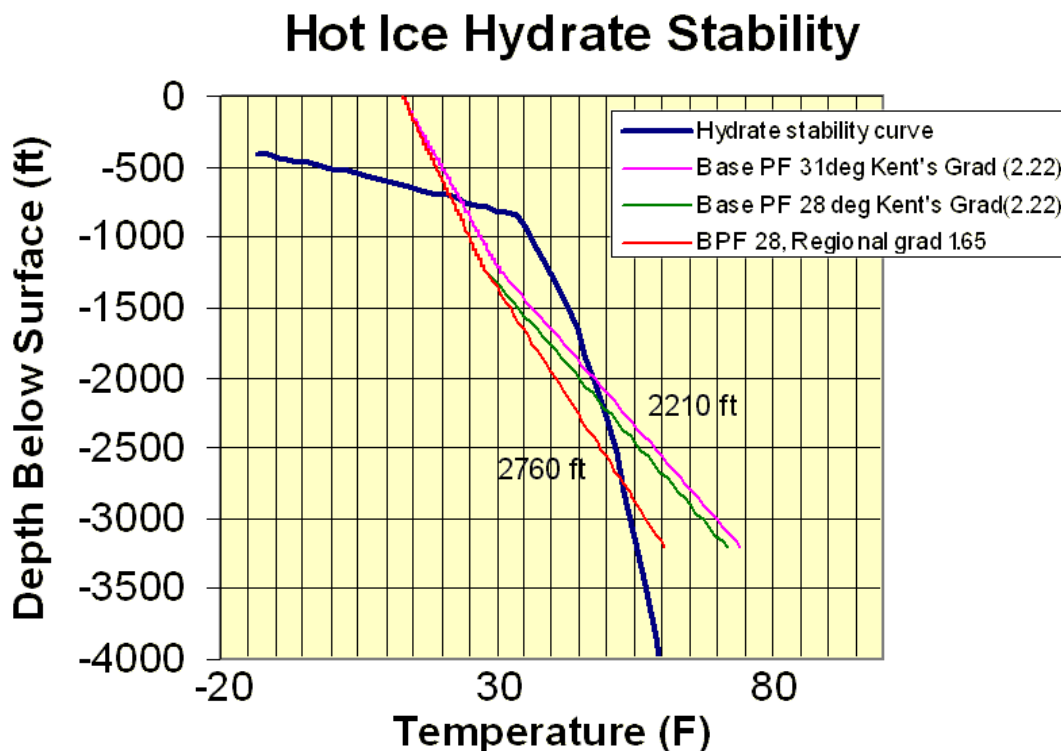
Figure A-6. Team Members on the Rig Floor

Appendix B. Recalculation of Base of Hydrate Stability Zone

Information from the Hot Ice well and an analysis of the local geothermal gradient provided a new estimate for the base of the hydrate stability zone (BHSZ). This re-analysis places the BHSZ at **2210 ft** below the surface at the Hot Ice location. This is 400 ft shallower than the estimate based on regional maps from Collett et al. (1988).

Both core and log data show the well entering into unfrozen material at 1240 ft below the surface at the Hot Ice location. The base of frozen material occurs in a thick sand interval. Because of this, 1240 ft is the base of permafrost. The BHSZ then depends on temperature at this depth, thermal gradient, and the methane hydrate stability curve. Collett et al. find the average temperature at base of permafrost to be 28°F. The BHSZ only weakly depends on the exact temperature chosen within the possible range of values. The most important variable is the thermal gradient.

Newsham (Internal Anadarko Report) examined logs from West Sak 20 Cirque 2 and Ruby State 1. Using the log-identified base of permafrost, corrected bottom hole temperatures, and a temperature at base of permafrost of 28°F, he finds a local thermal gradient of 2.22°F per 100 ft. The most critical part of this calculation is the correction to the log-recorded bottom hole temperature. Newsham corrected the bottom hole temperature data using the diffusion model documented by Lachenbruch et. al. (1982). This local gradient is somewhat larger than the regional gradient of 1.65°F per 100 ft given in Collett et al. (1988). The figure below shows the BHSZ determination using both gradients and two possible temperatures at the base of permafrost.



References (for Appendix B):

Collett, T. S., 1993, "Natural Gas Hydrates of the Prudhoe Bay and Kuparuk River Area, North Slope, Alaska," AAPG Bull., v. 77, no. 5, p.793-812.

Collett, T.S., Bird, K. J., Kvenvolden, K. A., and Magoon, L. B., 1988, "Geologic Interrelations Relative to Gas Hydrates Within the North Slope of Alaska," USGS Open-file Report 88-389, 150 p.

Lachenbruch, A. H., et al., 1982, "Temperature and Depth of Permafrost on the Arctic Slope of Alaska," USGS Professional Paper 1399, p. 645-657.

Appendix C. Notice of Opening of Tundra for 2003-2004 Winter Season

STATE OF ALASKA

FRANK H. MURKOWSKI, GOVERNOR

DEPARTMENT OF NATURAL RESOURCES

DIVISION OF MINING, LAND AND WATER

NORTHERN REGION

3700 AIRPORT WAY
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January 8, 2004

NORTH SLOPE WINTER OFF-ROAD (Tundra) TRAVEL

NOTICE OF OPENING Western Coastal Area

Department of Natural Resources staff has documented differential ranges of ground hardness and snow cover within the various tundra opening areas. The Western Coastal area has reached the same hardness as the East Coastal Area, which was opened on December 23, 2003. However, the Lower Foothills and Upper Foothills areas are still much softer than the coastal areas. Therefore, the Department of Natural Resources going to open the Western Coastal Area.

The tundra is open to all vehicles in the Western Coastal Area for the 2003-2004 winter season effective at 8:00 AM January 9, 2004.

This opening applies only to those operators who have *valid off-road vehicle travel permits* to operate on state-owned lands on the North Slope.

Note that the ground may be relatively soft in areas with heavily drifted snow. Special attention should be given to the Division of Mining, Land and Water's stipulation regarding winter off-road vehicle travel, which requires adequate frost and snow cover. Site inspections will be conducted periodically by state personnel to ensure compliance.

Note also that DNR staff will continue to travel to the North Slope to determine when the Lower Foothills and Upper Foothills areas can be opened. Until these areas are open, projects in these areas (especially those using low ground pressure vehicles) will be approved on a case-by-case basis.

If you have any questions concerning this opening, direct them to Leon Lynch at 659-2830 or Chris Milles at 451-2711. Please note that this and subsequent notifications will be distributed only by e-mail; faxes will no longer be sent out.

*Harry Bader
Regional Manager*

Develop, Conserve, and Enhance Natural Resources for Present and Future Alaskans

Appendix D. Geological Exhibits – HOT ICE #1

The following will be developed during and following the completion of the well:

Base Map with Structural Contours:

This exhibit will be the primary reference map for Anadarko Petroleum Corporation's geological investigation for gas hydrates on the North Slope of Alaska with the following information:

- Anadarko's acreage position with the prospective Hot Ice locations spotted.
- Well control displayed on the map are those with available shallow log data that could be utilized for this study.
- Color coding on well control depicts the presence of free gas as red, gas hydrates in green or the presence of neither as blue based on data presented in USGS open file reports or from our own investigations. The text indicates the presence of free gas, gas hydrates or both by Z-zonation and alphabetically designated units based on USGS cross-section presented in this report as cross-section A-A' and USGS open file reports.
- Cross-section lines A-A' (USGS cross-section), B-B', C-C' and D-D' and NW – SW lithologic section annotated.
- Revised structure map on Top of the West Sak sequence (basal Ugnu shale) at a contour interval of 200'. Structural strike is generally north and south with monoclinal east dip. Structural contours and faults are a digitized and slightly edited version of maps for the Milne Point and West Sak units that are exhibits of public record available from the AOGCC. The maps will probably include both seismic and subsurface controlled and generated by the operator Conoco/Phillips. The horizon mapped by the operator to match picks for the Top of the West Sak interval.

Gas Hydrate Potential Map:

A transparency designed to overlay the base map to illustrate the potential areal extent of gas hydrates and concomitant free gas accumulations that may exist as delineated by investigations conducted by the USGS and Anadarko Petroleum in this general area. The western and eastern boundaries of the potential gas hydrate accumulation in the Tarn/Cirque/Meltwater roughly defined as the entry and exit point of the West Sak and Ugnu interval in the HSZ. The southern boundary established by the absence of any indications of free gas or gas hydrates in wells of that area. To the north, the potential undefined. The USGS has documented the presence of gas hydrates in some of the wells situated to the north of the dashed line that indicates a loosely defined border in that direction.

A Post drill assessment will reduce the areal extent of the Probable Gas Hydrate realm.

Appendix E. NMR Measurements of Permafrost: Unfrozen Water Assay, Growth Habit of Ice, and Hydraulic Permeability of Sediments

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12 January 2004

Abstract

Nuclear magnetic resonance (NMR) measurements have been made on permafrost recovered from a well on the North Slope of Alaska. These measurements show that unfrozen water is correlated with the clay content of the sediments, and inversely correlated to ash content of the coals. NMR is sensitive to the pore-scale distribution of liquid water, so the growth habit of ice within the pore space of the sediment can be determined. Hydraulic permeability can be rapidly estimated, and has been found to depend strongly on the unfrozen water content. The ratio of the permeability of ice-affected sediment to the permeability of the same sediment saturated with liquid water appears to be surprisingly independent of lithology. Comparison between core measurements and wireline logs demonstrates that the unfrozen water content of permafrost can be predicted from borehole NMR measurements of thawed formations.

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1. Introduction

Anadarko Petroleum Corporation, Maurer Technology Inc., and Noble Drilling Corporation collaborated to drill the Hot Ice #1 well on the North Slope of Alaska. During the 2002-2003 drilling season an innovative drilling rig was constructed and a well drilled to the base of permafrost. A mobile arctic core laboratory was installed on the drilling rig to process core cut continuously from surface to total depth. Schlumberger-Doll Research provided personnel and a nuclear magnetic resonance (NMR) instrument to this laboratory *gratis*. After completion of drilling, Schlumberger Oilfield Services logged the well; magnetic resonance was included among the borehole measurements.

The objective of the project was to assess the potential gas hydrate reservoir and initiate production tests. No gas hydrate was detected in the permafrost zone, and time constraints prohibited drilling to hydrate deposits expected at greater depths. Therefore all scientific results from the first drilling season at Hot Ice #1 pertain to permafrost. The permafrost results are of interest in themselves. Moreover, although permafrost and gas hydrate deposits differ in many respects, similarities between ice and gas hydrate suggest that insight into one may be gained by study of the other.

Permafrost has been studied for many years, but fresh perspectives can be derived from the use of magnetic resonance well logging tools that have been developed over the last decade [Kleinberg, 1996]. One of these instruments [Kleinberg *et al.*, 1992] has the unusual capability of making measurements on compact samples external to the antenna and magnets of the apparatus. Because this instrument is designed to withstand the rigors of oilfield deployment, it can be used on an arctic drilling rig under conditions that would challenge the survivability of conventional laboratory equipment.

Nuclear magnetic resonance is commonly thought of as either a spectroscopic probe for organic chemistry or a medical imaging modality. The petrophysical applications of NMR are quite different from either of these [Kleinberg and Flaum, 1998; Kleinberg, 1999]. As used to characterize sedimentary rock, NMR quantitatively determines oil and water content, oil viscosity, and the pore size distribution of water-saturated rock. Knowledge of pore size distribution is used to estimate hydraulic permeability.

Recently these capabilities have been applied to the study of methane hydrate synthetically produced in rock and sediment under conditions thought to mimic earth processes [Kleinberg *et al.*, 2003a, 2003b], and to the well log evaluation of natural gas hydrate deposits [Kleinberg *et al.*, 2004]. These techniques are directly applicable to the study of permafrost, both in recovered core and *in situ* in the earth.

2. Location, Apparatus, and Methods

Measurements were made on the Anadarko Hot Ice 1 drilling rig, located approximately 35 km (22 miles) south of the Arctic coast of Alaska, 67 km (42 miles) east of Deadhorse AK, latitude N 70°06.535', longitude W 150°12.508' (NAD 83). Ground level elevation was 57 meters (188 feet) above mean sea level, and the kelly bushing of the drilling rig was 65 meters (214 feet) above mean seal level. Unless otherwise stated, all reported depths are relative to the kelly bushing. Continuous 7.6-cm (3.0-inch) diameter core was taken from surface to 428 meters (1403 feet) during March and April 2003. Lithologies in the drilled interval are unconsolidated fine sands ("sandstone"), clays ("mudstone"), ice lenses typically thinner than 1 cm, and coals.

Average temperature a few meters below the surface is -9°C [*Shiklomanov and Nelson*, 1999]. Observed base of permafrost is at a depth of 384 meters (1260 feet) (376 meters (1234 feet) below ground level). The base of permafrost does not, in general, correspond to the 0°C isotherm, which can be considerably deeper [*Lachenbruch et al.*, 1982; *Collett et al.*, 1993]. The cored interval overlaps several hundred meters of the gas hydrate stability zone [*Collett et al.*, 1993], but no evidence of free gas or gas hydrate was found.

Special core handling techniques were used to preserve the integrity of the permafrost core. After drilling a 3-m interval, a wireline-retrieved core barrel was recovered from the well, the core extracted, and then cut into 1-m lengths. The core was immediately delivered to a core analysis trailer adjacent to the rig floor for petrographic description and NMR measurement. The wellbore was maintained near -3°C, the rig floor and cutting shack were typically -14°C, and temperature of the core-analysis trailer was maintained between -5°C and -2°C. Generally speaking, approximately 60 minutes elapsed from the time core was recovered at the wellhead to the start of NMR measurements, which took approximately 5 minutes per sample.

The nuclear magnetic resonance instrument used in this investigation was the Schlumberger Combinable Magnetic Resonance Tool (CMR). The CMR is an oilfield wireline logging tool rated to survive and operate in arctic, tropical, desert, and marine environments. Deployment of this tool to drilling rigs on the North Slope of Alaska is routine. For the purpose of measuring whole core as it was retrieved from the well, the CMR was installed in the chilled core analysis trailer adjacent to the rig floor.

The CMR volume of investigation is approximately 15 cm long and 2x2 cm in cross-section, centered about 2.5 cm inside the sample. The primary calibration was a water-filled Plexiglas tube whose dimensions were identical to the recovered core. The calibration sample had the same concentration of potassium chloride as the drilling fluid, [KCl] = 1.4 moles/liter, and was doped with iron sulfate for

measurement convenience. The calibration sample was remeasured about once a day to detect instrument drift; none was detected.

Typically, each 1-m long piece of core was measured at one location; hence coverage was 15 cm per meter of core length. Some attempt was made to minimize selection bias. Grossly washed-out sections and conglomerates were both undersampled, on the basis that measurements of these intervals would be meaningless in any event. Visible ice lenses, which comprised a very small fraction of the recovered core, were generally excluded from the measured volumes, as the goal of the investigation was to understand how permafrost interacts with pore space of the sediment.

The CMR is sensitive to electromagnetic interference at 2.2 MHz, and to broadband noise sources in general. To minimize measurement noise in the core analysis trailer, a 38-cm diameter x 85-cm long open-ended wood-frame copper screen shield was installed around the tool antenna and core sample. It was found that when core protruded from the end of the shield it could conduct significant interference to the antenna. Thus, cores were broken when necessary so that the measured piece would fit entirely within the shield enclosure. Similarly, noise could be conducted to the antenna by salty debris on the conveyor belt used to position the cores at the CMR antenna. Occasional cleaning of the belt was required.

3. NMR Fundamentals

3.1 NMR Relaxation of Water in Sediments

Measurements of transverse nuclear magnetic relaxation times, T_2 , have proven to be useful in porous media studies. The Carr-Purcell-Meiboom-Gill (CPMG) [Carr and Purcell, 1954; Meiboom and Gill, 1958] pulse sequence is used. When irradiated with this sequence, a nuclear spin system will radiate back a series of equally spaced magnetic field pulses, called spin echoes. Echo spacing, T_E , is typically on the order of 10^{-4} s. Measuring the decay of echo amplitudes during the sequence monitors the transverse magnetization relaxation. Zero-time amplitude of the proton NMR signal is proportional to the hydrogen content of the sample.

For most liquids in bulk, including water, transverse magnetization decay is exponential, so the amplitude of the n^{th} spin echo, occurring at time $t = n \cdot T_E$, is

$$M(t) = M_0 \exp\left[-\frac{t}{T_{2B}}\right] \quad (1)$$

Amplitude M_0 is proportional to the number of hydrogen nuclei in fluids in the volume of investigation. Characteristic decay time of the echo amplitudes, T_{2B} , is called the bulk transverse relaxation time. Bulk relaxation times, which are independent of the concentration of salt at ocean salinities, are $T_{1B} = T_{2B} = 1.762$ s at 0°C [Simpson and Carr, 1958].

NMR relaxation rate of fluids in porous media is largely controlled by relaxation at the pore/grain interface [Bloch, 1951]. Molecules in a fluid diffuse, eventually reaching a grain surface where their nuclear spins can be relaxed. For water in sediments and sandstones, the rate limiting step is the relaxation process at the surface, not the transport of unrelaxed spins to the surface [Kleinberg *et al.*, 1994]. Magnetization decay, $M(t)$, in an individual pore is exponential:

$$M(t) = M_0 \exp\left[-\frac{t}{T_{2S}}\right]. \quad (2)$$

Decay rate does not depend on pore shape but only on the surface-to-volume ratio, S/V , of the pore:

$$\frac{1}{T_{2S}} = \rho_2 \left(\frac{S}{V}\right)_{\text{pore}}. \quad (3)$$

Thus, water in small pores relaxes rapidly, while water in large pores relaxes more slowly. The surface relaxivity coefficient ρ_2 is a characteristic of magnetic interactions at the fluid/solid interface [Kleinberg *et al.*, 1994; Foley *et al.*, 1996]. In sandstones and analogous materials it is dominated by paramagnetic ions residing at grain surfaces. It is independent of temperature [Latour *et al.*, 1992] and hydrostatic pressure [Chen *et al.*, 1994] over broad ranges. Its value is typically $\rho_2 = 5 \mu\text{m/s}$ for sandstones [Kleinberg, 1999], which is expected to hold, at least approximately, for sediments encountered here.

Bulk and surface relaxation processes operate in parallel, so the observed magnetization decay is written as

$$M(t) = M_0 \exp\left[-\frac{t}{T_2}\right] \quad (4)$$

where

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} \quad (5)$$

Rocks and sediments generally have very broad distributions of pore sizes, and therefore magnetization decays can be expressed as a sum of exponential decays [Gallegos and Smith, 1988]:

$$M(t) = \sum_i m_i \exp\left[-\frac{t}{T_{2i}}\right] \quad (6)$$

where m_i is proportional to the volume of fluid relaxing at the rate $1/T_{2i}$. The sum of the volumes is proportional to the fraction of the material occupied by liquid, the porosity ϕ_{NMR} :

$$M_0 = \sum_i m_i \sim \phi_{\text{NMR}} \quad (7)$$

Thus there is a direct mapping from the distribution of pore sizes, or more precisely the distribution of surface-to-volume ratios, to the distribution of relaxation times.

To analyze measurements reported here, monotonic but non-exponential magnetization decays were fit to Eqn (6), where $M(t)$ typically represented the amplitudes of 5000 spin echoes with $T_E = 200 \mu s$, and the T_{2i} were typically 50 preselected time constants, equally spaced on a logarithmic scale between 0.3 ms and 5000 ms. The number of terms in the summation is somewhat arbitrary since the exponentially decaying basis functions are not linearly independent. In fact, there are far less than 50 independent pieces of information in a typically noisy decay. Therefore, the set of 50 $m(T_{2i})$ was found using a regularized nonlinear least-squares technique that renders the results smooth and stable in the presence of random noise [Butler *et al.*, 1981]. The function $m(T_2)$, conventionally called a T_2 distribution, maps linearly to a volumetrically weighted distribution of pore sizes [Gallegos and Smith, 1988; Kleinberg, 1999].

3.2 The Effect of Ice

Ice contains abundant hydrogen, but this hydrogen is invisible because the CMR is not sensitive to nuclei in solids. Therefore the presence of ice, like methane hydrate, reduces apparent NMR porosity [Kleinberg *et al.*, 2003a]. It also diminishes the integrated amplitude and changes the shape of the apparent (i.e. water-filled) pore size distribution. These changes depend on where the ice resides within the pore space, and on the magnetic coupling between pore water and ice.

If ice coats grain surfaces, its relaxivity to liquid water, $\rho_2(\text{water-ice})$, replaces $\rho_2(\text{water-rock})$ in Eqn (3). In principle, pore size information will be retained, but the transformation between T_2 and pore diameter is changed. On the other hand, if ice grows in the interior of pores, its surfaces add to the silica grain surfaces, and Eqn (3) must be generalized to account for the simultaneous influence of two different surfaces.

Relaxivity of the ice/water surface is unknown, but the following end-member scenarios can be identified:

1. Ice coats grain surfaces and $\rho_2(\text{water-ice}) \ll \rho_2(\text{water-rock})$: In all but the smallest pores, the bulk relaxation process will dominate, and the relaxation time distribution $m(T_2)$ will tend to pile up at $T_{2B} \sim 1.7$ s.
2. Ice coats grain surfaces and $\rho_2(\text{water-ice}) \gg \rho_2(\text{water-rock})$: Shapes of the relaxation time distributions are approximately preserved, but are reduced in amplitude and displaced toward shorter relaxation times relative to the same sediment fully saturated with liquid water.
3. Ice fills the largest pore spaces and $\rho_2(\text{water-ice}) \ll \rho_2(\text{water-rock})$: Water relaxes at grain surfaces while being excluded from large pore bodies. Signal disappears first at the longest

values of T_2 . Paradoxically, there will be a concomitant increase of signal at short values of T_2 , which occurs due to rapid relaxation of remnant liquid water coating mineral grains in large pores mostly filled with ice.

4. Ice fills the largest pore spaces and $\rho_2(\text{water-ice}) \gg \rho_2(\text{water-rock})$: Water relaxes at both grain and ice surfaces, so the relaxation time distribution is concentrated at short values of T_2 .

In reality, the NMR response might be composed of a combination of these effects, for example if the grains are partially coated with ice. In general, as the pore space fills with ice, the amplitude will decrease, with likely distortion of the T_2 distribution.

4. Recovered Core Results

4.1 Unfrozen Water Assay

As expected, apparent permafrost NMR porosity (liquid-water-filled pore space as a fraction of total sediment volume) was generally less than 0.1, considerably lower than would be expected for shallow unfrozen liquid-water-saturated sediments. In contrast, coals were characterized by unfrozen water contents of about 0.20-0.25 of total volume. At the base of permafrost, which occurred within a reasonably massive sand body, NMR determined porosity increased rapidly over an interval of 4 m. A sudden systematic increase in NMR-determined unfrozen water content was an earlier indication of the base of permafrost than petrographic examination. These results are discussed further in connection with borehole log data in Section 5.

4.2 Growth Habit of Ice: Observations While Thawing

Two typical 30-cm lengths of core, one sand (from depth 211 m (692 feet)) and one mud (from depth 202 m (662 ft)), were removed from storage at -14°C and allowed to thaw in an 18°C room. NMR measurements were made on the cores approximately once an hour for nine hours. The unfrozen water porosities are plotted as a function of time in Figure 1. The sand started with significantly lower unfrozen water porosity than the mud. The mud completely thawed in 4.5 hours, and the sand in 6 hours. The data reflect conditions in a volume centered 2.5 cm from the surface of the 7.6-cm diameter cores, as described in Section 2.

In both cases, the unfrozen water at -14°C was significantly lower than the unfrozen water found when the core was first removed from the well, at a temperature of approximately -3°C . Wellhead values of apparent NMR porosity are denoted by horizontal lines in **Figure 1**.

Relaxation time distributions are shown in **Figure 2** for the mud and **Figure 3** for the sand. A pore space model is required to convert relaxation time to pore diameter. A convenient model is a network of interconnected cylindrical tubes; this is the model used (often implicitly) to analyze mercury porosimetry data for natural earth materials. In this model, surface-to-volume ratio of a pore is $S/V = 4/D$, where D is pore diameter. Then NMR-determined pore diameter is related to relaxation time T_2 by

$$D = 4\rho_2 T_2 = (20\mu\text{m/s}) \cdot T_2 \quad (8)$$

For both sand and mud, the frozen cores are characterized by low amplitude distributions centered on short relaxation times. As the cores thawed, amplitude increased, especially at the longest relaxation times. In both **Figures 2** and **3** the topmost curves represent thawed fully liquid-water-saturated pore size distributions.

In **Figure 3**, growth of the porosity component around 2 ms (0.04 μm pore diameter) is not monotonic. This effect is widely observed in NMR well logs of natural gas reservoirs, and is easily explained. When a nonwetting phase occupies large pores, water generally continues to coat pore walls. Surface-to-volume ratio (S/V) of this pore-lining water is much greater than S/V of water when it completely filled the same pore. Thus the remnant water relaxes at a faster rate, thereby appearing to add to the smaller-pore population [Kleinberg and Boyd, 1997].

Comparing these results to the four possibilities listed in Section 3.2, the mudstone results are consistent with (2), (3) or (4). Sandstone results are consistent only with (3).

4.3 Growth Habit of Ice: Transition Zone Sands

Fortuitously, the base of permafrost (at a depth of 384.0 m (1260 ft)) lay within a reasonably massive and homogeneous sand body. This sand body thus constituted a natural laboratory for exploring the development of frozen sediment. The transition from fully liquid water-saturated sediment to permafrost occurs over a depth interval of 4 m.

Relaxation time distributions through the transition zone are shown in **Figure 4**. Distributions at 384.7 m (1262 ft) and 386.8 m (1269 ft) appear to be trimodal while the others are bimodal. The trimodal curves are unlikely to represent three distinct populations in the liquid-water-filled pore size distribution, but instead represent a limitation of the nonlinear signal processing. A reasonable interpretation of the 384.7 m and 386.8 m curves is that they are essentially flat-topped.

Above the base of permafrost, the water signal is small and concentrated at short relaxation times. Following the same reasoning used in the discussion of the thawed samples, these observations indicate that unfrozen water is localized in small pore spaces, where it is in contact with grain surfaces that are not coated with ice. As depth increases, unfrozen water occupies more of the pore space. In the transition

zone, water occupies small, mid-sized and large pore spaces of this sand, as reflected by the low NMR signal amplitude. At a depth of 387.7 m (1272 feet), water is completely unfrozen and the relaxation time distribution reflects the pore size distribution of the sediment.

As for the samples discussed earlier, excess signal at short relaxation time in the frozen samples reflects the presence of water coating the grain surfaces of large pores, the interiors of which are filled with ice. Results are consistent only with possibility (3) listed in Section 3.2: ice preferentially fills the largest pore spaces, and it is not an effective relaxing surface for liquid water.

4.4 Hydraulic Permeability

Hydraulic permeability of a porous medium depends generally on the square of the cross-sectional dimension of the flow channels [Scheidegger, 1960]. Sensitivity of NMR measurements to pore size makes it a good permeability indicator for sandstones [Straley *et al.*, 1994]. The NMR estimate of permeability has been tested on thousands of sandstones over the years; order-of-magnitude agreement with laboratory measured values is expected. However, the technique has not been systematically tested in unconsolidated sediments, nor in sediments consolidated by ice. Therefore we must proceed with some caution.

The empirical correlation that connects hydraulic permeability k_0 to porosity and a one-parameter measure of relaxation time, T_{2LM} , is

$$k_0 = C \cdot \phi_{NMR}^4 \cdot T_{2LM}^2 \quad (9)$$

where T_{2LM} is the logarithmic mean value of the T_2 distribution.

$$T_{2LM} = 10^{\left[\frac{(1/\phi) \sum_i m(T_{2i}) \cdot \log_{10}(T_{2i})}{\sum_i m(T_{2i})} \right]} \quad (10)$$

C is a coefficient which depends on mineralogy and on the magnetic impurity content of the grain material. A large number of measurements on water-saturated clean and clay-rich sandstones showed that typically $C = 4000 \text{ D/s}^2$ [Straley *et al.*, 1994] ($1 \text{ Darcy} \approx 0.987 \times 10^{-12} \text{ m}^2$).

4.5 Relative Permeability

Relative permeability is the permeability of sediment to a single fluid when two or more constituents occupy the pore space. In a rock or sediment containing oil, water, and/or or gas, each of these fluids will have different relative permeability, which depends on the saturations. Here we use the term to describe hydraulic permeability when part of the pore space is partially filled with ice:

$$k_{rw} = \frac{k(S_w)}{k_0} \quad (11)$$

where k_0 is permeability of the fully liquid-water-saturated sediment, and $k(S_w)$ is permeability at water saturation S_w , with the remaining pore space filled with ice at saturation $S_i = 1 - S_w$.

Relative permeability may be found when permeability measurements of both fully water-saturated sediment and the same sediment partially saturated with ice are available. This is the case in the thawing studies, where NMR properties of a sample are followed over a range of water saturations. It is also the case at the base of permafrost, to the extent that sediment properties are uniform over the transition zone. Water saturation is found from

$$S_w = \frac{\phi_{NMR}(S_w)}{\phi_{NMR}(S_w = 1)} \quad (12)$$

where $\phi_{NMR}(S_w)$ and $\phi_{NMR}(S_w=1)$ are apparent NMR porosities in the partially and fully water saturated sediment, respectively. Using this and Eqn (9), NMR estimated relative permeability is

$$k_{rw} = \frac{k(S_w)}{k_0} = S_w^4 \cdot \left(\frac{T_{2LM}(S_w)}{T_{2LM}(1.0)} \right)^2 \quad (13)$$

The mineralogy-dependent coefficient C does not appear in this ratio.

As noted above, this approach has some important limitations: the permeability estimate is based on an empirical correlation, not a flow measurement, and it assumes that the correlation is as valid for ice-affected sediment as it is for water-filled rock. A subsidiary assumption is that NMR relaxation of liquid water at an ice surface is no stronger than at a mineral grain surface, i.e., $\rho_2(\text{water-ice}) \ll \rho_2(\text{water-rock})$, as concluded in Sections 4.2 and 4.3. It also assumes that differences of the microgeometrical distribution of water in unfrozen and partially frozen rock do not invalidate the correlation.

Relative permeability estimates for the thawed samples, and for sands at the base of permafrost are shown in **Figure 5**. All data follow a common trend as a function of liquid water saturation. This is surprising since k_0 differs widely among these three samples, as noted above. However, the proportionate impact of the presence of ice appears to be the same.

The data can be compared to simple models for relative permeability derived elsewhere [Kleinberg *et al.*, 2003b]. Results for various models are:

ice coating the walls of capillary tubes:

$$k_{rw} = S_w^2 \quad (14)$$

ice growing in the centers of capillary tubes:

$$k_{rw} = 1 - (1 - S_w)^2 + \frac{2S_w^2}{\log(1 - S_w)} \quad (15)$$

ice coating the surfaces of a grain pack:

$$k_{rw} = S_w^{n+1} \quad (16)$$

For this model, the saturation exponent n equals 1.5 for $0 < S_i < 0.8$ ($1 > S_w > 0.2$) [Spangenberg, 2001]. For $S_i > 0.8$ ($S_w < 0.2$), the saturation exponent diverges, but in this regime relative permeability to water is already small, and the increase of the saturation exponent has only a minor effect.

ice growing in the centers of a grain pack pore space:

$$k_{rw} = \frac{S_w^{n+2}}{(1 + (1 - S_w)^{0.5})^2} \quad (17)$$

Neglecting the effects of capillary pressure, the saturation exponent increases from $n = 0.4$ at $S_i = 0.1$ ($S_w = 0.9$) to unity at $S_i = 1$ ($S_w = 0$), [Spangenberg, 2001].

NMR estimates of relative permeability agree better with the models that assume ice fills the centers of pores than with those that assume ice coats pore walls. The same conclusion is independently drawn from the relaxation time distributions discussed above.

5. Core/Log Comparison

In addition to measurements made on recovered core, magnetic resonance well log measurements were made in the borehole after the completion of coring. The NMR instrument used for well logging was a nearly identical copy of the instrument used in the core lab to measure retrieved core samples. The pulse sequence was the same as that used for the core measurements. Pulse sequence parameters were somewhat different, but the differences are not expected to affect the results.

During the 15 days of coring operations the 428 m (1403 feet) deep wellbore was substantially thawed by the 1.4M KCl drilling fluid. Unconsolidated sediment sloughed into the wellbore with the result that it was

enlarged beyond the 216-mm (8½-inch) diameter of the drill bit (**Figure 6**). The wireline tool was pressed against the borehole wall with a bow spring, but in the irregular borehole the sensor can intermittently lose contact with the surface. The wireline magnetic resonance measurement, like the NMR measurement on core, is made in a volume centered 25 mm from the face of the apparatus. If there is borehole fluid in this volume, the NMR amplitude will be erroneously high.

As **Figure 7** reveals, well log porosities frequently exceeded the maximum porosity expected in shallow terrestrial sediments, about 0.4. Except for a few minor intervals at the top of the well, there is no agreement between core measurements of unfrozen water porosity and well log porosity measurements, even where the borehole was not enlarged beyond bit size. This suggests that not only was the wellbore enlarged but also thawed, at least to the radial depth of the NMR measurement volume, prior to well logging. Even if near-wellbore sediments were below the freezing point of fresh water, KCl migration from the borehole into the pore space lowered the freezing point of the pore fluid.

In conventional interpretation of petrophysical measurements, the NMR signal is partitioned into bound water (small pore) and free water (large pore) porosity [*Kleinberg, 1999*]. In sandstone formations, this partition is conventionally made at $T_{\text{cutoff}} = 33$ ms. Water in pore spaces relaxing faster than 33 ms, corresponding to a pore diameter of about 0.7 μm , is not movable at a pressure difference of less than 0.7 MPa (100 psi). Taking into account the details of how water is trapped in porous media by capillary forces, a tapered function is applied to the fully-water-saturated pore size distribution to determine the amount of porosity included in the small-pore fraction [*Kleinberg and Boyd, 1997*]. For T_2 components below $T_{2\text{cutoff}}/4$ all measured porosity is included in the small-pore estimate. For $T_2 > T_{2\text{cutoff}}/4$

$$m(T_2)_{\text{taper}} = m(T_2) \left[\frac{T_{\text{cutoff}}}{2T_2} - \left(\frac{T_{\text{cutoff}}}{4T_2} \right)^2 \right] \quad (18)$$

The small pore analysis is illustrated at 365.8 m (1200 ft) in **Figure 8**. The topmost curve is the well log relaxation time distribution of the thawed formation; the corresponding porosity is 0.317. Within it is plotted the small pore relaxation curve computed using Eqn (18), with a porosity of 0.047. The lowest curve (inverted for clarity) is the relaxation time distribution measured on the core taken from the same depth, with a porosity of 0.039. The small-pore-porosity from the well log and the unfrozen-water-porosity from the core agree to within the ± 0.01 error bars of the measurement.

This analysis was repeated for the entire borehole, a representative section of which is shown in **Figure 9**. Below the base of permafrost (horizontal line at 384 m (1260 feet)), core unfrozen water includes both small-pore-porosity and large-pore-porosity, and therefore the core points fall above the log-derived small-pore-porosity. Above the base of permafrost the data are in excellent agreement.

Agreement persists even where the borehole is grossly washed out and NMR values spike to values well above 0.4, indicating that substantial amounts of borehole fluid must be included in the well log measurement, see e.g. 250–300 m. Log small-pore-porosity agrees with core unfrozen-water-porosity in washed out intervals because the borehole water contributes only to the free fluid (large pore) signal with $T_2 > 33$ ms. Although conventional oilfield drilling muds usually have T_{2B} around 20 ms, the drilling fluid used here had a relaxation time of 50 ms.

Since permafrost unfrozen water correlates with small-pore-porosity, it should be in greatest abundance in fine-grained sediments. During data taking it was noted that higher values of unfrozen water porosity were found in mudstone than in sandstone (see e.g. **Figure 1**). **Figure 10** shows a cross plot between log small-pore-porosity and log gamma ray amplitude. The latter is predominantly a clay indicator [*Hearst et al.*, 2000]. A correlation between high clay content and high small-pore-porosity is common in sandstones and sediments. The anomalous jet extending to the upper left is isolated in **Figure 11**. All the points in the jet originate in coals, identified petrographically in the recovered core. Natural gamma radioactivity correlates with ash content [*Reeves*, 1971]. **Figure 11** suggests that small pore porosity in coal is inversely correlated with ash content, and that therefore it is primarily associated with the organic component.

6. Conclusions

Nuclear magnetic resonance methods used in evaluation of oil- and gas-bearing formations are also useful in understanding pore-scale interactions between sediments and ice in permafrost. The quantitative assay of unfrozen water content is model independent and does not depend on any adjustable parameters.

NMR-derived pore size distribution is subject to interpretation. However, the preponderance of experimental results shows that the silt and clay sediments investigated here remain liquid-water-wet in the presence of ice, which tends to accumulate in the largest pore spaces.

Permafrost retrieved from the wellbore was well-consolidated and robust. The cohesiveness came from ice which, when melted, left loose silt and clay. Data presented in this work suggest that ice does not preferentially cement grain contacts, but perhaps it stiffens the sediment by bridging large pores. This hypothesis is supported by the NMR and sonic well logs of the Mallik 5L-38 gas hydrate test well. There the dependence of sound speed on NMR-derived hydrate saturation was found to be consistent with hydrate partially supporting the granular matrix without coating the grains or cementing the grain contacts [*Kleinberg et al.*, 2004].

Although permeabilities of the various sediments, as estimated by NMR, vary widely, their relative permeabilities to water as a function of ice saturation are remarkably uniform. However, use of NMR to

estimate permeability in permafrost is unproven. It would be very desirable to make laboratory permeability measurements of samples that are also characterized by NMR.

Although the borehole was thawed and washed out during the drilling process, and therefore no permafrost remained in the NMR volume of investigation during well logging, there is a strong correlation between well log NMR small-pore-porosity and core measurements of unfrozen water in intact permafrost.

Coals in permafrost formations have large unfrozen water contents that correlate inversely with ash content.

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Appendix: Notation

C:	coefficient of NMR permeability correlation
k_{rw} :	relative permeability to water of ice-affected sediment
k_0 :	permeability to water of water-saturated sediment
m_i :	i^{th} coefficient of relaxation time distribution
$m(T_2)$:	relaxation time distribution
$m(T_{2i})$:	i^{th} coefficient of relaxation time distribution
M_0 :	initial amplitude of magnetization decay
$M(t)$:	magnetization decay as function of time
S_i :	fraction of pore volume filled with ice
S_w :	fraction of pore volume filled with water
S/V :	surface to volume ratio of pore space
T_{cutoff} :	T_2 value separating small-pore and large-pore water
T_E :	spin echo spacing in CPMG sequence
T_{1B} :	longitudinal relaxation time of bulk liquid

T_2 :	NMR transverse relaxation time
T_{2B} :	transverse relaxation time of bulk liquid
T_{2i} :	transverse relaxation time of i^{th} component
T_{2LM} :	logarithmic mean of the relaxation time distribution
T_{2S} :	relaxation time due to surface relaxivity
ϕ_{NMR} :	apparent porosity measured by NMR
ρ_2 :	relaxivity of a solid surface to water protons

References (for Appendix E)

- Bloch, F., 1951. Nuclear relaxation in gases by surface catalysis. *Phys. Rev.*, 83: 1062-1063.
- Butler, J.P., Reeds, J.A. and Dawson, S.V., 1981. Estimating solutions of first kind integral equations with nonnegative constraints and optimal smoothing. *SIAM J. Numer. Anal.*, 18: 381-397.
- Carr, H.Y. and Purcell, E.M., 1954. Effects of diffusion on free precession in nuclear magnetic resonance experiments. *Phys. Rev.*, 94: 630-638.
- Chen, R., Stallworth, P.E., Greenbaum, S.G. and Kleinberg, R.L., 1994. Effects of hydrostatic pressure on proton and deuteron magnetic resonance of water in natural rock and artificial porous media. *J. Magn. Reson.*, A110: 77-81.
- Collett, T.S., Bird, K.J. and Magoon, L.B., 1993. Subsurface temperatures and geothermal gradients on the North Slope of Alaska. *Cold Regions Sci. Tech.*, 21: 275-293.
- Foley, I., Farooqui, S.A. and Kleinberg, R.L., 1996. Effect of paramagnetic ions on NMR relaxation of fluids at solid surfaces. *J. Magn. Reson.*, A123: 95-104.
- Gallegos, D.P. and Smith, D.M., 1988. A NMR technique for the analysis of pore structure: Determination of continuous pore size distributions. *J. Colloid Interface Sci.*, 122: 143-153.
- Hearst, J.R., Nelson, P.H. and Paillet, F.L., 2000. *Well Logging for Physical Properties*. Wiley, Chichester.
- Kleinberg, R.L., 1996. Well logging. In: D.M. Grant and R.K. Harris (Editors), *Encyclopedia of Nuclear Magnetic Resonance*, Vol. 8. Wiley, Chichester, pp. 4960-4969.
- Kleinberg, R.L., 1999. Nuclear magnetic resonance. In: P.-Z. Wong (Editor), *Experimental Methods in the Physical Sciences*, Vol. 35: Methods in the Physics of Porous Media. Academic, San Diego, Calif., Chap. 9.
- Kleinberg, R.L. and Boyd, A., 1997. Tapered cutoffs for magnetic resonance bound water volume, Society of Petroleum Engineers Paper 38737.
- Kleinberg, R.L. and Flaum, C., 1998. Review: NMR detection and characterization of hydrocarbons in subsurface earth formations. In: B. Blumich, P. Blumler, R. Botto, E. Fukushima (Editors), *Spatially Resolved Magnetic Resonance*. Wiley-VCH, Weinheim, Chap. 54.

Kleinberg, R.L., Sezginer, A., Griffin, D.D. and Fukuhara, M., 1992. Novel NMR apparatus for investigating an external sample. *J. Magn. Reson.*, 97: 466-485.

Kleinberg, R.L., Kenyon, W.E. and Mitra, P.P., 1994. Mechanism of NMR relaxation of fluids in rock. *J. Magn. Reson.*, A108: 206-214.

Kleinberg, R.L., Flaum, C., Straley, C., Brewer, P.G., Malby, G.E., Peltzer, E.T., Friederich, G. and Yesinowski, J.P., 2003a. Seafloor nuclear magnetic resonance assay of methane hydrate in sediment and rock, *J. Geophys. Res.* 108(B3): 2137. doi:10.1029/2001JB000919

Kleinberg, R.L., Flaum, C., Griffin, D.D., Brewer, P.G., Malby, G.E., Peltzer, E.T. and Yesinowski, J.P., 2003b. Deep sea NMR: Methane hydrate growth habit in porous media and its relationship to hydraulic permeability, deposit accumulation, and submarine slope stability, *J. Geophys. Res.* 108(B10): 2508. doi:10.1029/2003JB002389

Kleinberg, R.L., Flaum, C. and Collett, T.S., 2004. Magnetic resonance log of Mallik 5L-38: Hydrate saturation, growth habit, relative permeability and control of accumulation. In: S.R. Dallimore and T.S. Collett (Editors), Scientific Results from the Mallik 2002 Gas Hydrate Production Research Well, Mackenzie Delta, Northwest Territories, Canada, Bulletin 585. Geological Survey of Canada, Ottawa.

Lachenbruch, A.H., Sass, J.H., Marshall, B.V. and Moses Jr., T.H., 1982. Permafrost, heat flow, and the geothermal regime at Prudhoe Bay, Alaska. *J. Geophys. Res.* B87: 9301-9316.

Latour, L.L., Kleinberg, R.L. and Sezginer, A., 1992. Nuclear magnetic resonance properties of rocks at elevated temperatures. *J. Colloid Interface Sci.*, 150: 535-548.

Meiboom, S. and Gill, D., 1958. Modified spin echo method for measuring nuclear relaxation times. *Rev. Sci. Instrum.*, 29: 688-691.

Reeves, D.R., 1986. In situ analysis of coal by borehole logging techniques. In: D.J. Buchanan and L.J. Jackson (Editors), Geophysics Reprint Series, No. 6: Coal Geophysics. Society of Exploration Geophysicists, Tulsa.

Scheidegger, A.E., 1960. *The Physics of Flow Through Porous Media*. Macmillan, New York.

Shiklomanov, N.I. and Nelson, F.E., 1999. Analytic representation of the active layer thickness field, Kuparuk River Basin, Alaska. *Ecological Modeling* 123: 105-125.

Simpson, J.H. and Carr, H.Y., 1958. Diffusion and nuclear spin relaxation in water. *Phys. Rev.*, 111: 1201-1202.

Spangenberg, E., 2001. Modeling of the influence of gas hydrate content on the electrical properties of porous sediments, *J. Geophys. Res.* B106: 6535-6548.

Straley, C., Rossini, D., Vinegar, H., Tutunjian, P. and Morriss, C., 1994. Core analysis by low field NMR. Society of Core Analysts Paper SCA-9404. Proceedings of the 1994 International Symposium of the Society of Core Analysts, Stavanger, Norway.

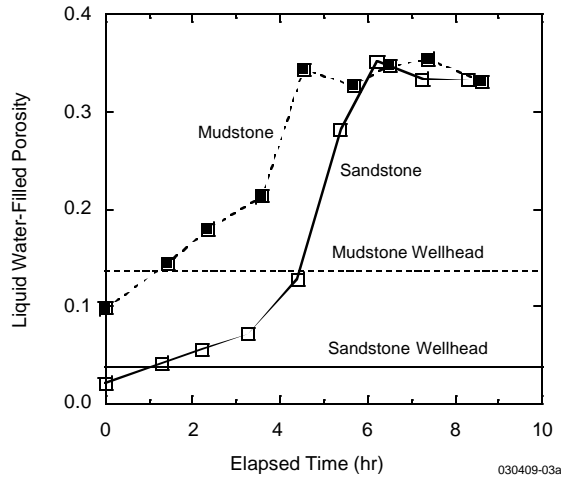


Figure 1. Thawing of mudstone and sandstone cores monitored by NMR porosity measurements. Cores were precooled to -14°C , then warmed in an 18°C room. The horizontal lines indicate porosity measurements immediately after retrieval of the core from the borehole, which was approximately -3°C .

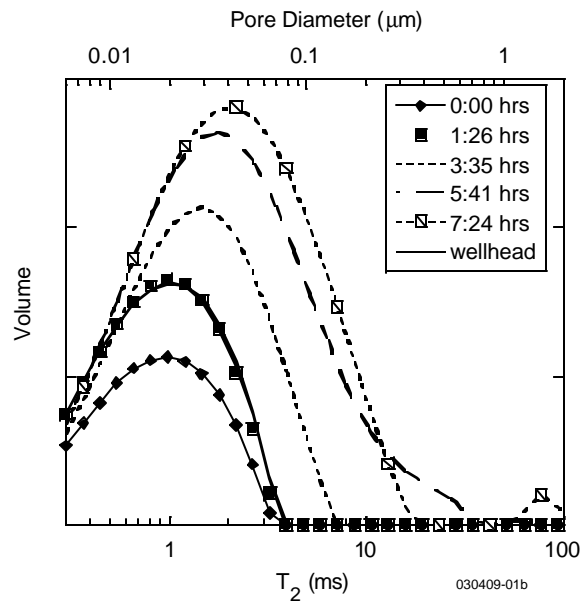


Figure 2. Relaxation time distributions of mudstone during thawing from -14°C to 18°C . Frozen samples are characterized by low NMR amplitudes and short relaxation times. After 1.5 hours of warming, the core returned to the state in which it was removed from the wellbore (solid squares, heavy solid line). During the melting process the amount of NMR-visible (liquid) water increased, and successively larger pore spaces thawed. By 7.5 hours (outermost line) the permafrost had completely melted, revealing the pore size distribution of the water-saturated sediment.

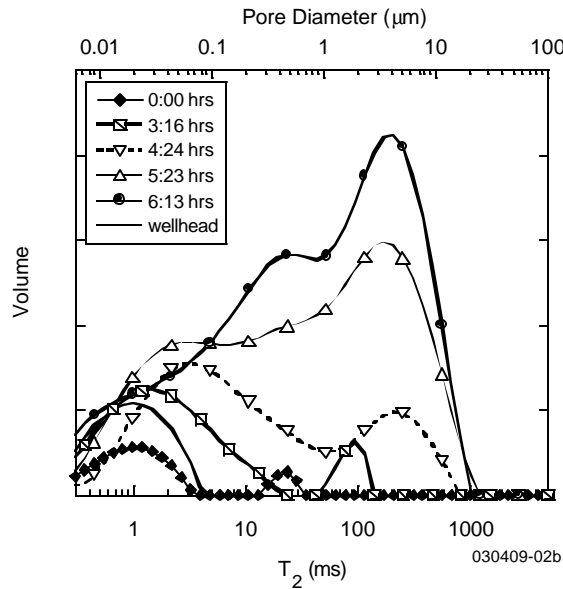


Figure 3. Relaxation time distributions of sandstone during thawing from -14°C to 18°C . Frozen samples are characterized by low NMR amplitudes and short relaxation times. During the melting process the amount of NMR-visible (liquid) water increased, and successively larger pore spaces thawed. By 6.25 hours (outermost line) the permafrost had completely melted, revealing the pore size distribution of the water-saturated sediment.

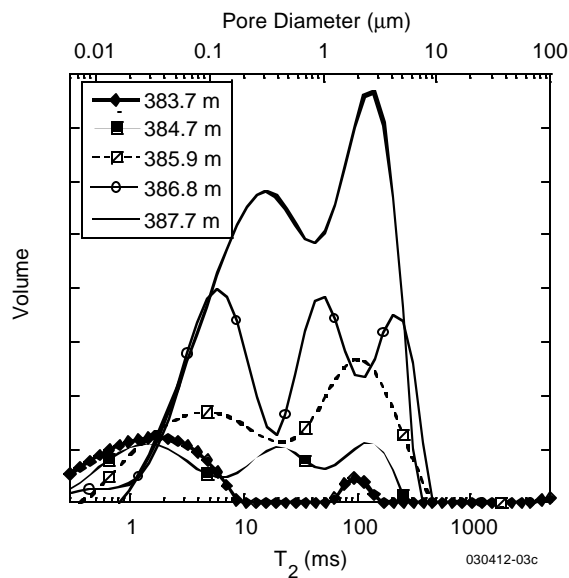
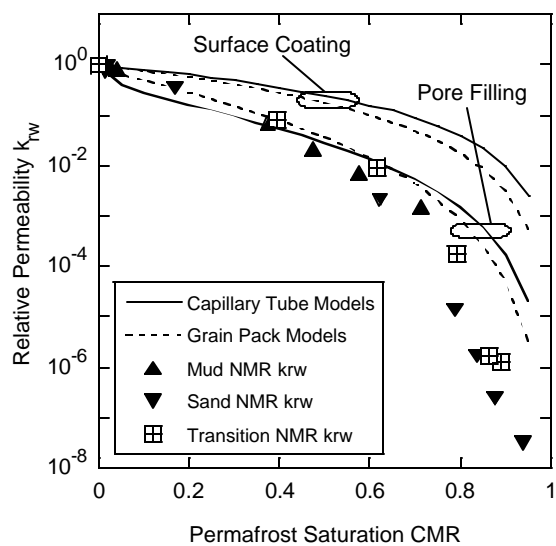


Figure 4. NMR relaxation time distributions near the base of permafrost (384 m, 1260 ft). Above the base of permafrost, cores are characterized by low NMR amplitudes and short relaxation times (solid diamond curve). As depth increased, successively more of the pore space was occupied by liquid water. The rock was fully liquid-water saturated 4 m below the base of permafrost, revealing the pore size distribution of the liquid-water-saturated sediment (topmost curve). The apparently trimodal curves are discussed in the text.



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Figure 5. Relative permeability to water computed using Eqn (13) for three groups of samples: thawing mudstone (▲), thawing sandstone (▼), and cores from the base of permafrost (crossed squares). Curves are predictions of grain coating and pore filling models, as described in the text.

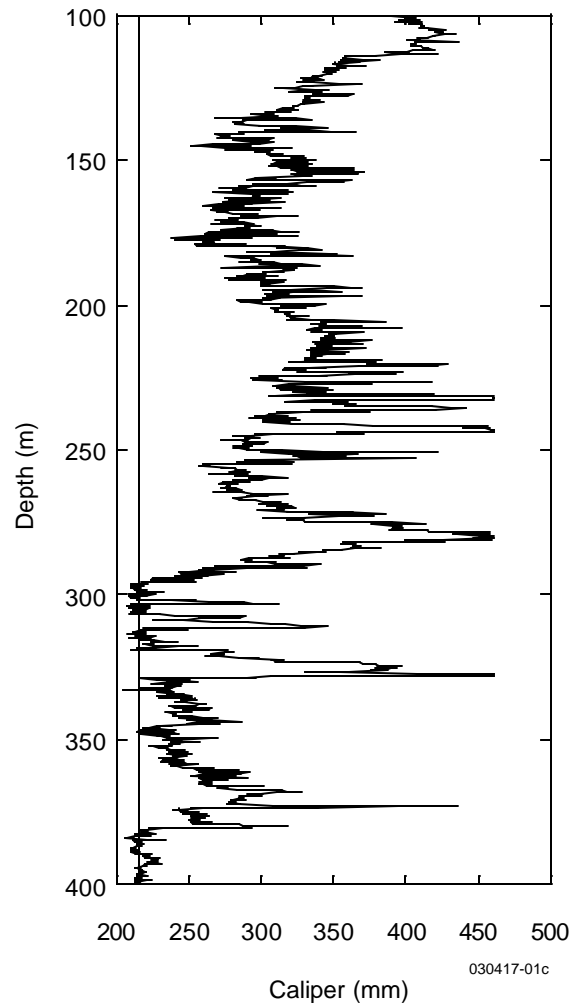


Figure 6. Wireline caliper log of borehole diameter. Vertical line is the 216-mm (8½-inch) bit size. The borehole was significantly washed out during coring operations.

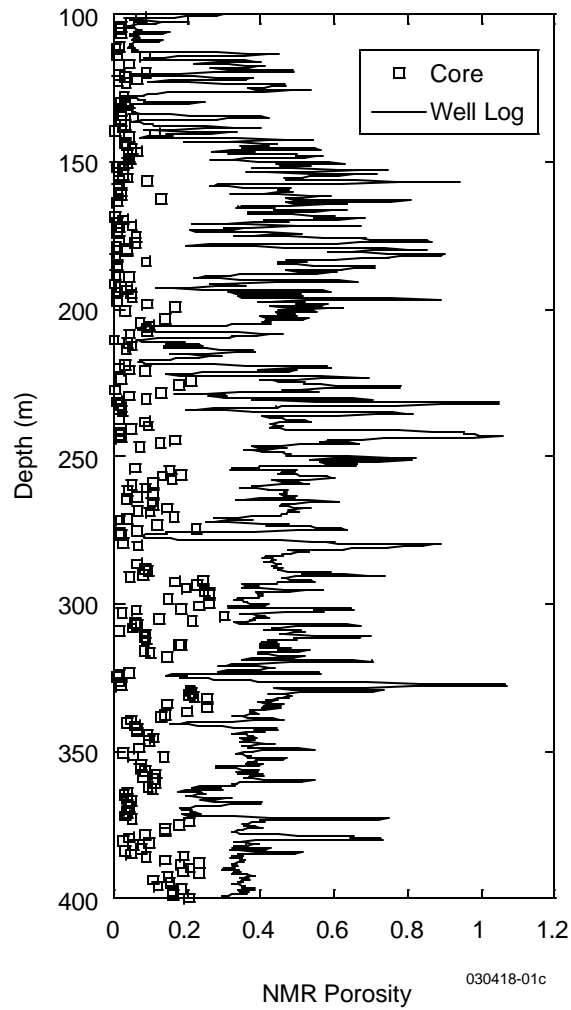


Figure 7. Wireline NMR log total porosity (solid curve) and laboratory NMR core unfrozen water porosity (squares). Anomalously high values of log porosity (>0.4) occurred at edges of washouts (see previous figure), where the sensitive volume of the logging tool included borehole water.

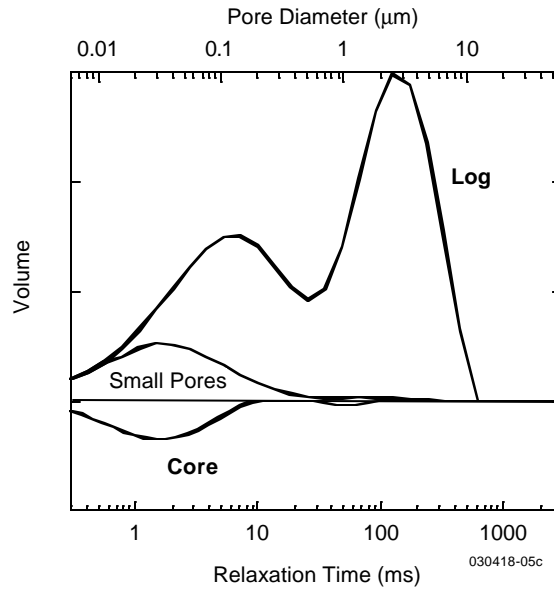


Figure 8. *Above horizontal line:* Relaxation time distribution from log at 365.8 m (1200 ft) (upper curve) and its small pore porosity computed from Eqn. (18) (lower curve). *Below horizontal line:* Relaxation time distribution of unfrozen water from permafrost core sample at the same depth (inverted for display purposes). Note similarities in the T_2 distributions of log small pore water and core unfrozen water.

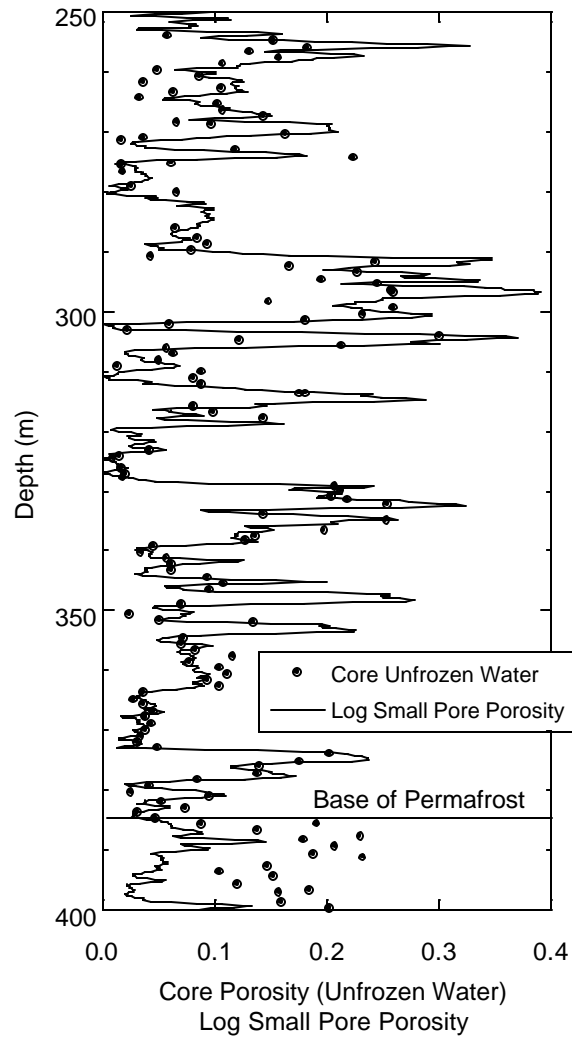


Figure 9. Log small-pore-porosity (solid curve) and core porosity (unfrozen water content) (symbols). Above the base of permafrost (horizontal line at 384 m, 1260 ft) the data are in excellent agreement. Below the base of permafrost, core unfrozen water includes both small pore porosity and large pore porosity, and therefore the core points fall above the log small-pore-porosity.

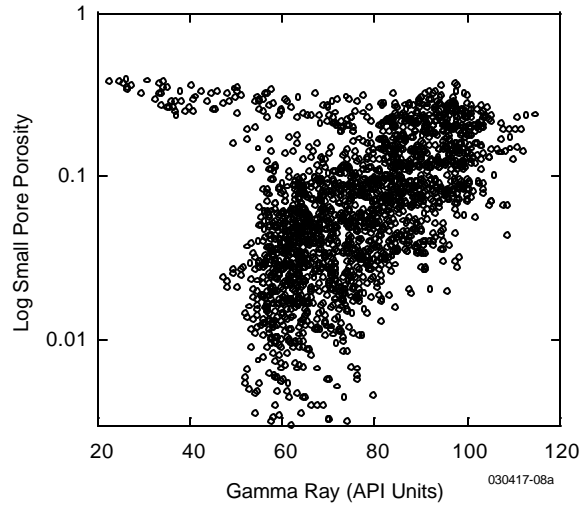


Figure 10. Cross plot of log small-pore-porosity and natural gamma-ray log. The latter is predominantly a clay indicator. A correlation between high clay content and high small-pore-porosity is common in sandstones and sand sediments. The anomalous jet extending to the upper left is explained in the text and the next figure.

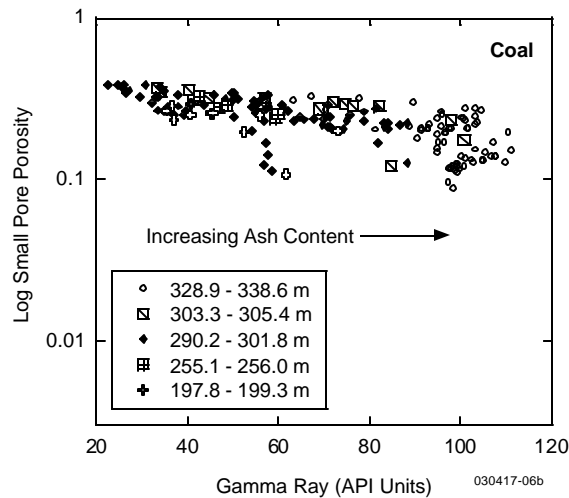


Figure 11. Points comprising the anomalous jet of Figure 10 are all from coals. The depth intervals indicated in the plot legend were identified as coal-bearing by visual examination of the cores. In coal, natural gamma radioactivity is associated with ash [Reeves, 1971]. Therefore, small-pore-porosity is proportional to organic matter content.