Resource Characterization and Quantification of Natural Gas-Hydrate and Associated Free-Gas Accumulations in the Prudhoe Bay – Kuparuk River Area on the North Slope of Alaska

December 2004 Quarterly Technical Report
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ABSTRACT

This cooperative project between BP Exploration (Alaska), Inc. (BPXA) and the U.S. Department of Energy (DOE) facilitates collaboration between industry, government, and university researchers. Project results will help identify technical and commercial factors that must be better understood for government and industry to make informed decisions regarding the energy resource potential of gas hydrate accumulations on the Alaska North Slope (ANS).

Gas hydrates are present in many arctic regions and offshore areas around the world. In the U.S., notable deposits of gas hydrate occur in the offshore Atlantic, Gulf of Mexico (GOM), offshore Pacific, offshore Alaska, and also onshore Alaska regions beneath and within permafrost. Collett (1998) estimates that up to 590 TCF of in-place ANS gas resources may be trapped in clathrate hydrates. Of that total, an estimated 44 to 100 TCF of in-place gas hydrate resources may occur beneath existing ANS production infrastructure within the Eileen and Tarn trends, respectively (Collett, 1993). Much like conventional oil and gas resources, potential gas hydrate resource accumulations require a unique combination of factors, including all required petroleum system components (source, migration, trap, seal, charge, and reservoir), adequate industry infrastructure, industry access to acreage, and feasible production technology. In addition, industry would need to estimate ultimate recovery potential, production rates, operating costs, and commercial feasibility within reasonable risk limits. Currently, the most likely areas for a favorable combination of these factors are the ANS and the GOM.

ANS gas hydrate and associated free gas-bearing reservoirs are being studied to determine reservoir extent, stratigraphy, structure, continuity, quality, variability, and geophysical and petrophysical property distribution. The objective of Phase 1 (October 2002 – December 2004) is the characterization of reservoirs and fluids, leading to estimates of recoverable reserve and commercial feasibility, and the study of procedures for gas hydrate drilling, data acquisition, completion, and production. If justified by prior phase results, an integrated future program would be planned to include recommendations to acquire specific well, core, log, and production test data at candidate site(s). Ultimately, the program could determine whether or not gas hydrates might become a part of the overall ANS gas resource portfolio.

Previous USGS estimates indicate large volumes of in-place gas (44-100 TCF) exist as hydrates beneath ANS development infrastructure. Potential gas hydrate and associated free-gas resources within the shallow reservoirs of the Prudhoe Bay – Kuparuk River – Milne Point Eileen trend area are interpreted to correlate with gas hydrates that were cored and tested in the 1972 Northwest Eileen State #2 well and are penetrated by other wells targeting deeper reservoirs within the ANS development area. Correlation of geophysical attributes to gas hydrate occurrence are also under investigation. Seismic modeling of shallow (<950 ms) velocity fields suggests that both amplitude and waveform variations may help locate gas hydrate-bearing reservoirs. Permafrost can also complicate seismic identification of gas hydrates due to its similar acoustic properties. Identification of gas hydrate prospects within the Milne 3D seismic volume are based on seismic interpretation and modeling, gas hydrate-similar waveform classes, and fault-seal geometries integrated with well log-derived properties. Seismic and well data interpretation within the Milne Point Unit have revealed gas hydrate prospects within the shallow sands of the fluvial-deltaic Sagavanirktok Formation. However, these prospects remain largely unproven and require confirmation, delineation, and further data acquisition to mitigate uncertainties.

The shallow gas hydrate-bearing reservoirs of the Tertiary Sagavanirktok formation are part of a complex fluvial-deltaic system further complicated by structural compartmentalization within the Eileen trend. Stacked sequences of fluvial, deltaic, and nearshore marine sands are interbedded with both terrestrial and marine shales. Facies changes, intraformational unconformities, and high-angle normal faults disrupt reservoir continuity. Phase 1 work related to volumetric assessment includes detailed well-log analyses and description of reservoir facies and fluids as integrated with the 3D seismic data. In conjunction with structural analyses, the identification and mapping of net pay in discrete sand bodies improves understanding of resource quality, quantity, distribution, and continuity. This work helps refine volume estimates, reservoir models, recovery factors, and production forecasts. Gas may have migrated into conventional hydrocarbon traps before regional geothermal gradient depression, creation of gas hydrate stability conditions, and conversion of gas and water into gas hydrate. The structural and stratigraphic compartmentalization reduces lateral continuity of prospects and complicates the shallow velocity field. Velocity pull-ups associated with high-velocity gas hydrate prospects and velocity push-downs associated with low-velocity free gas prospects can also affect seismic interpretation of deeper, oil-bearing targets.

Reservoir production models of ANS gas hydrate prospects help investigate whether or not this gas might be technically recoverable. Production feasibility may be aided in areas where local uses for gas exist. Potential production methods involve in-situ dissociation of solid, pore-filling gas hydrate into gas and water components through reservoir depressurization, thermal stimulation, and/or chemical stimulation. Preliminary production models indicate that depressurization of in-situ gas hydrate from producing adjacent free gas might more than double the expected ultimate recovery available from the associated free gas alone. Gas hydrate prospects without an adjacent free gas might also be depressurized by producing in-situ connate waters if sufficient mobile waters co-exist with gas hydrate. Thermal and/or chemical stimulation techniques are also under investigation as methods to enhance gas recovery from gas hydrate-bearing reservoirs.

Studies completed in the July – December 2004 period include documentation of many Phase 1 research results. Many of these results were presented in September 2004 at the AAPG Hedberg Research Conference on Gas Hydrates. Phase 1 of the project was scheduled for completion by end-December 2004. Research has continued into 2005, beginning with refining the scope-of-work to quantify the regional resource potential and to recommend specific potential future data acquisition operations within suitable candidate site(s). Following feasibility discussions, subcontracts to initiate this work were completed by end-March 2005.

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2.0 INTRODUCTION

This project is helping to address the technical and economic issues to enable government and industry to make informed decisions regarding potential future commercial feasibility of unconventional gas-hydrate resources. The project is characterizing and quantifying in-place and estimating recoverable ANS gas-hydrate and associated free-gas resources, initially using Eileen trend area well and seismic data in the Milne Point Unit (MPU) and well data in the Prudhoe Bay Unit (PBU) and Kuparuk River Unit (KRU) areas. The project is also investigating gas hydrate phase equilibrium and relative permeability within porous media. Additional laboratory and desktop investigations include recommendation of procedures for drilling, completion, and production operations within and near gas hydrate-bearing reservoirs.

Determination of the resource potential of gas hydrate and associated free gas resources could increase current developable ANS gas. Proving technical production and commercial feasibility of this unconventional gas resource could lead to greater energy independence for the U.S., providing for additional future gas needs through an abundant, safe, secure, and stable domestic resource.

2.1 Project Open Items

Contracts updated in September 2004 fully obligated Phase 1 project funding, allowed Phase 1 time extension for the full 2-year Phase 1 research program through end-October 2004, and pre-funded $195,000 of potential Phase 2 activities. A no-cost extension followed to extend the Phase 1 research through end-December 2004. Phase 1 results, reservoir-fluid characterization, reservoir modeling, and economic modeling were anticipated to contribute to a Phase 2 progression decision during fourth quarter 2004. DOE and BPXA executed contract amendments 8 and 9 to assess the regional resource productivity potential and to develop plans recommending specific potential field operations. However, progression into field operations has not yet been determined pending review of regional resource potential and operations recommendations.

2.2 Project Status Assessment and Forecast

Project technical accomplishments from July 2004 through end-December 2004 are presented by associated project task. The attached milestone forms (Appendix A) present project Phase 1 tasks 1 through 13 with task duration and completion timelines.

2.3 Project Research Collaborations

Project objectives significantly benefit from DOE awareness, support, and/or funding of the following associated collaborations, projects, and proposals. Section 5.4 provides additional detail on collaborative research accomplishments during the reporting period.

1. **Reservoir Model studies (Ryder Scott Co., UAF, LBNL)**: LBNL delivered the TOUGHfX reservoir model in early July 2004 following training at the NETL facility in June 2004. This research includes reservoir model code calibration to data collected during the 2002 Mallik gas hydrate test program. Regional reservoir modeling and local modeling of characterized MPU gas hydrate prospects are in-progress by Ryder Scott Company (RS) in collaboration with BPXA, UAF, and USGS. RS provides industry-standard reservoir modeling using CMG STARS for evaluation of gas hydrate prospects, input into the well operations project progression decision, and optimization of potential future development and delineation plans.
2. **DE-FC26-01NT41248:** UAF/PNNL/BPXA studies to determine effectiveness of CO_2 as an enhanced recovery mechanism for gas dissociation from methane hydrate. DOE currently supports this associated project research through 2005. A project update was provided during the AAPG Hedberg research conference in September 2004. PNNL has adapted the reservoir modeling package STORM to model gas hydrate dissociation behavior.
3. **UAF/Argonne National Lab project:** This associated project was approved for funding by the Arctic Energy and Technology Development Lab (AETDL), forwarded to NETL for review, and was funded in mid-2004. The project is designed to determine the efficacy of Ceramicrete cold temperature cement to future gas hydrate drilling and completion operations. Evaluating the stability and use of a cold temperature cement may enhance the ability to maintain the low temperatures of the gas hydrate stability field during drilling and completion operations, helping to ensure safer and more cost-effective operations.
4. **Precision Combustion, Inc. (PCI) – DOE collaborative research project:** Potential synergies from this DOE-supported research project with the BPXA – DOE gas hydrate research program were recognized in December 2003 by Edie Allison (DOE). Communications with Precision Combustion researchers indicate some significant potential synergies, particularly regarding potential in-situ reservoir heating. Successful modeling and lab work could potentially proceed into field application of gas hydrate thermal recovery enhancement testing if this project progresses into field operations. BPXA provided a letter in April 2004 in support of progression of PCI's project into their phase 2: prototype tool design and possible surface testing and communications continue into 2005. Testing of this technology is also being considered for application to enhanced recovery of viscous oil.
5. **UAF shallow resource (gas hydrate and viscous oil) research initiatives:** UAF is proposing that AETDL fund shallow resource research initiatives in Alaska. This associated research would benefit this project.
6. **Japan gas hydrate research:** Progress toward completing the objectives of this project remain aligned with gas hydrate research by Japan Oil, Gas, and Metals National Corporation (JOGMEC), formerly Japan National Oil Corporation (JNOC). JOGMEC remains interested in research collaboration, particularly if the project proceeds into production testing operations.
7. **India gas hydrate research:** India's Institute of Oil and Gas Production Technology (IOGPT) indicated an interest in participating with the BPXA – DOE research program in correspondence with DOE during September 2003. BPXA has not initiated contact with IOGPT.

8. **Korea gas hydrate research:** Korea is developing a gas hydrate research program. They have discussed potential participation in future Alaska gas hydrate research with USGS. BPXA has not initiated contact with Korea.
9. **U.S. Department of Interior, USGS, BLM, State of Alaska DGGS:** An additional collaborative research project under the Department of Interior (DOI) provides significant benefits to this project. The BLM, USGS, and the State of Alaska recognize that gas hydrates are potentially a large untapped onshore energy resource on the North Slope of Alaska. To develop a more complete regional understanding of this potential energy resource, the BLM, USGS and State of Alaska Division of Geological and Geophysical Surveys (DGGS) have entered into an Assistance Agreement to assess regional gas hydrate energy resource potential in northern Alaska. This agreement combines the resource assessment responsibilities of the USGS and the DGGS with the surface management and permitting responsibilities of the BLM. Information generated from this agreement will help guide these agencies to promote responsible development if this potential arctic energy resource is proven. The DOI project is working with the BPXA – DOE project to assess the regional recoverable resource potential of onshore natural gas hydrate and associated free-gas accumulations in northern Alaska, initially within current industry infrastructure.

2.4 Project Performance Variance

Release of shallow portions of PBU and/or KRU seismic data under confidentiality constraints to the project is not currently feasible. BPXA has consistently recognized that contribution (under confidentiality constraints) of PBU and/or KRU seismic data to the project is dependent upon industry partner approval. Future plans include presentation of project results to potential stakeholders to help facilitate understanding of research objectives and results.

The BPXA and DOE decision whether or not to acquire additional data through well operations was delayed pending results of regional resource quantification, potential regional development planning, specific potential operations planning, and options evaluation. Phase 2 project objectives were modified to accomplish these additional desktop studies.

3.0 EXECUTIVE SUMMARY

This Quarterly report encompasses project work from July 1, 2004 through December 31, 2004. Sections 4 and 5 provide a detailed project activities report.

- Updated project contracts and modified scope-of-work and budget as needed
    - Drafted scope-of-work to assess operations plans and regional resource
- Coordinated, compiled, and wrote project status, technical, and financial reports
- Planned and coordinated reservoir modeling work and regional resource assessment
    - Studied reservoir productivity sensitivities to varied reservoir parameters of heat flux, aquifer influx, permeabilities, and gas, gas hydrate, and water saturations
    - Evaluated possible coalbed-methane analog to connate water depressurization
- Planned MPI-16 shallow data/logging program with USGS, BPXA, and Schlumberger
    - Determined low Staines Tongue saturations within hydrate-gas-bearing reservoirs
- Maintained communications with Precision Combustion, Inc. gas hydrate research
    - Recommended possible MPU/KRU application to enhance recovery of viscous oil

- Coordinated oral and poster presentations for 9 submitted abstracts regarding Phase 1 interim results to AAPG Gas Hydrate Hedberg Research Conference
  - 1 project overview abstract, 3 UAF Abstracts, and 5 UA abstracts
- Completed collaborative study with USGS of MPU gas-hydrate reservoir character and properties using MPU 3-D seismic and well data
- Evaluated, compared, and ranked 14 MPU gas hydrate prospects with 620 BCF in-place
  - Recommended candidate areas and prospects for potential data acquisition
  - Recommended potential data to acquire within candidate prospect areas
- Evaluated partial hydrate saturation issues and potential for mobile connate waters
  - Determined potential for relative permeability in pore-filling gas hydrate reservoir
  - Mobile Connate waters could enable in-situ depressurization drive (CBM analog)
- Studied variation in shallow fault throws and inferred fault seal potential across the MPU
- Studied timing and influence of fault reactivation on deposition of shallow reservoir sands
- Studied sedimentary facies-related gas emplacement in gas hydrate-bearing reservoirs
- Interpreted a diffuse and segmented northwest-trending structural hingeline controlled deformation of shallow sequence of gas hydrate-bearing rocks by north-northeast trending syn- and post-depositional faults
- Linked northwest-trending hingeline to deeper fault zones that segment deeper oil-bearing reservoirs and define important oil/water contacts
- Interpreted significant fault complexity including differential offset near fault terminus, en echelon faults, relay zones, and possible rotation
- Developed theory for transtensional basin architecture within MPU structural setting
  - Interpreted small, northeast-trending pull-apart basin that may have influenced sediment deposition and the later emplacement of gas hydrates
  - Interpreted local structural controls on sediment deposition and gas migration
  - Observed higher net/gross sand ratio within basin, suggesting syndepositional faults may have influenced facies distributions and depositional environments
  - Observed anomalous stratigraphic thickening and thinning correlative to graben distribution within Marker 34 (USGS Zone C equivalent)
  - Interpreted probable gas hydrate-bearing reservoirs to be nearer faults within basin
- Interpreted sigmoidal fault geometries and related to transtensional deformation in weak sedimentary cover above a deeper left-stepping sinistral strike-slip fault system
  - Considered linkage of this sinistral shear zone to gas migration conduits or barriers
- Confirmed six distinct, laterally continuous gas hydrate-bearing reservoir units with lithostratigraphic correlations
  - Applied sequence stratigraphic framework to show more reservoir heterogeneity
  - Identified numerous intraformational unconformities defining many sequences
- Calculated 620 BCF in-place preliminary volumetrics for gas hydrate-bearing intervals within a 2-mile radius of MPU S-pad area using sequence stratigraphic-based assessment
  - Approach differs significantly from high-graded, seismic driven assessment
- Integrating seismic interpretation with regional log-based chronostratigraphic correlations
- Studying possible gas hydrate occurrence connections including active deeper-seated thermogenic fault-related migration conduits and possible coalbed methane relation
- Connecting geomorphologic evidence to gas hydrate occurrence and structural control

- Considering sealing-faults, gas-conduit/migration faults, reservoir depositional geometry, and structural framework as controlling factors of gas hydrate-bearing sands
- Applying artificial neural network analysis (ANN) to help characterize and predict lithologies (sand, coal, shale) and fluids (gas hydrate, gas, water) in normalized well data
  - Created two basic types of training sets using various combinations of log data
  - Determined good match of ANN to well log expert system of Glass (2003)
  - Determined good correlation of ANN classification and expert system results to cored hydrate intervals in NWEileen-02
- Performed unsupervised (untrained) classification using three seismic attributes
  - Extracted instantaneous frequency, amplitude acceleration, and dominant frequency from 3D seismic data.
  - Matched classification of interpreted gas hydrate-bearing zones in several areas with gas hydrate-bearing zones identified in well logs.
  - Determined zones identified as possible gas hydrate-bearing layers were predominantly characterized by relatively high dominant frequency

4.0 EXPERIMENTAL

During the reporting time period from July through December 2004, primary experimental activities consisted of experiment apparatus design, setup, and execution at UAF as well as reservoir and fluid characterization studies using 3D seismic and well data at UA and at USGS. Reservoir modeling tasks significantly progressed during the reporting period.

4.1 TASK 5.0, Logging and Seismic Technology Advances – USGS, BPXA

The U.S. Geological Survey (USGS) completed analysis of seismic attributes within the Milne 3D dataset and determined a relation between seismic amplitude attribute and gas hydrate-bearing zone thickness and saturation. With sufficient delineation from future data acquisition, this investigation may prove that direct seismic detection of pore fluids within gas hydrate-bearing reservoirs is feasible. Modeling and interpretation confirm that seismic velocity, amplitudes, and wavelet character may respond to fluid and reservoir changes within the gas hydrate-bearing reservoir system. Multiple gas hydrate-bearing prospects have been interpreted within fairways of the Eileen gas hydrate trend within the MPU.

4.2 TASK 6.0, Reservoir and Fluids Characterization

The University of Arizona (UA) continued resource characterization studies revealing shallow sand reservoir stratigraphic heterogeneity and structural compartmentalization. Progress continues on geologic/geophysical project tasks. Full integration of well and seismic data interpretations remains incomplete. Section 5.6 provides additional details, results, recommendations, and Hedberg Research Conference materials.

4.3 TASK 7.0: Laboratory Studies for Drilling, Completion, and Production Support

The University of Alaska Fairbanks (UAF) compiled and presented the results of several experiments for gas hydrate phase behavior and relative permeability studies. Section 4.7 provides additional details, results, and recommendations.

4.4 TASK 8.0: Evaluate Drilling Fluids and Assess Formation Damage – UAF

UAF completed experimental apparatus setup and continued to refined standard testing procedures. Section 4.8 provides additional details, results, and recommendations.

4.5 TASKS 11.0 and 13.0: Reservoir Modeling and Project Commerciality and Progression Assessment – UAF, BP, Ryder Scott Co.

Significantly progressed reservoir simulation studies using CGM STARS to analyze MPU-area gas hydrate-bearing reservoirs and potential productivity. Section 4.11 provides additional details, results, and recommendations.

5.0 RESULTS AND DISCUSSION

Project technical accomplishments from July 2004 through December 2004 are presented in chronological order by associated project task.

5.1 TASK 1.0: Research Management Plan – BPXA and Project Team

Task schedules are presented in the attached milestones forms (Appendix A). Project expenditures are reported separately on financial forms 269A and 272.

- Updated project contracts and modified scope-of-work and budget as needed
    - Executed contract amendments 5, 6, and 7
    - Summarized contract amendments and reviewed consistency with contract
    - Evaluated Continuation Application and other contract options
    - Drafted scope-of-work and budget to assess operations plans and regional resource
    - Prepared project budget estimates and tracked subcontracts spend/invoices
    - Updated BP Authority for Expenditure per DOE-BPXA contract amendments
- Participated in project teleconference discussions with DOE project manager
- Coordinated, compiled, and wrote project status, technical, and financial reports
- Prepared project briefs and coordinated Phase 1 results documentation
- Monitored scope-of-work task accomplishments and coordinated modifications
- Maintained current contacts and specifications for U.S. Treasury ASAP system
- Prepared and presented Phase 1 resource characterization study results
    - Determined need to develop specific operations plans and quantify regional resource potential
    - Operations plans would require BPXA and DOE approval before implementation
- Prepared and presented Phase 1 study technical results to MPU technical staff
    - Discussed gas hydrate-bearing reservoir effects on shallow velocity field
    - Discussed project status and future resource potential

5.2 TASK 2.0: Provide Technical Data and Expertise – BPXA, USGS

- Planned and coordinated reservoir modeling work, meetings, teleconferences
- Prepared and executed project electronic file backups and maintained hardcopy files
- Evaluated 1974 Amoco gas hydrate research for insight to current study
- Provided location maps for reservoir modeling efforts
- Coordinated transfer of USGS gas hydrate resource polygon maps into Landmark format
- Reviewed university theses and provided recommendations for modifications
    - Reviewed Namit J. thesis – UAF

    - Reviewed S. Howe thesis – UAF, incorporated economics information
- Reviewed Barrow, Alaska area energy and gas hydrate resource assessment reports
    - Evaluated resource potential of thinner gas hydrate-bearing reservoir and compared to Eileen trend area resource and reservoir potential

5.3 TASK 3.0: Wells of Opportunity, Data Acquisition – BPXA

- Initiated discussions for shallow log data acquisition in MPI-16 new well
    - Determine Staines Tongue saturations within probable hydrate-bearing reservoir
- Planned MPI-16 shallow data/logging program with USGS, BPXA, and Schlumberger
- Investigated potential Well-of-Opportunity at PBU Z-pad
- Monitored drilling schedules and communicated with operations groups

5.4 TASK 4.0: Research Collaboration Link – BP, USGS, Project team

- Reviewed, edited, and provided ANS location map for NRC report
- Responded to NRC report with project accomplishments, publications, and conferences
- Maintained communications linkage with Precision Combustion, Inc. research
    - Recommended possible application to enhance recovery of viscous oil
    - Setup BP and ConocoPhillips contacts to discuss possible viscous oil application
    - Provided some ANS reservoir specifications and other information
- Distributed Huifang Hong University of Calgary thesis on reservoir modeling of gas hydrates using CMG STARS to internal project team and DOE
- Visited USGS/BLM Christiansen CS1000 P6L rig when drilling Ft Yukon CBM project
    - Evaluated rig for potential future shallow gas hydrate research application
    - Coordinated participation of and preliminary evaluation by ASRC Energy Services engineers
    - Provided input to potential future Alaska shallow energy resource drilling plans
- Coordinated oral and poster presentations for 9 submitted abstracts regarding Phase 1 interim results to AAPG Gas Hydrate Hedberg Research Conference
    - 1 project overview abstract, 3 UAF Abstracts, and 5 UA abstracts
- Prepared project summary presentation with summary of project presentations at Hedberg for Gas Hydrate Advisory Committee Meeting and participated in meeting discussions
- Prepared and submitted project update abstract for June 2005 AAPG Calgary meeting
    - Plan to develop project poster presentation
- Participated with USGS in project summary presentation to Alaska Geological Society and Geophysical Society of Alaska (Hedberg research conference summary materials)
- Participated in research update presentations by USGS at AOGCC

5.5 TASK 5.0: Logging and Seismic Technology Advances – USGS, BP

<u>**United States Geological Survey**</u>
USGS Principle Investigator: Timothy Collett
USGS Participating Scientists: David Taylor, Warren Agena, Myung Lee, Tanya Inks (IS)

This project funded a portion of this research during the reporting period. The major portion of the research was funded internally by the U.S. Department of Interior.

5.5.1 December 2004 Task 5.0 Summary

In September 2003, a collaborative study was initiated, using 3-D seismic in the Milne Point area of northern Alaska, to help answer questions about gas-hydrate reservoir characteristics and properties as input to possible production methods and commercial viability. Historical log correlation work and analysis of gas hydrates in the Milne Point area (Collett, et al., 1993, 2001) was used as a starting point for a seismic driven analysis of the Milne Point 3-D survey area. Interpretation of modern seismic data helped to gain a better understanding of the geologic controls related to gas hydrate petroleum systems in the Milne Point area. The Landmark software suite was used to integrate and analyze detailed log correlations, specially processed log data, gas-hydrate composition information and specialized 3-D seismic volumes. Structural and stratigraphic interpretations encompassed the interval from the Base of Ice Bearing Permafrost (IBPF), into the Gas Hydrate Stability Zone (GHSZ), and into potential gas-bearing reservoirs immediately below the Base of the Gas Hydrate Stability Zone (BGHSZ).

The seismic data was also used to analyze reservoir fluid properties in comparison to theoretical modeling results by Lee (2005). The modeling showed that a relatively strong impedance contrast will occur when moderate to highly saturated gas hydrates exist within the GHSZ. Modeling shows that shallow gas hydrates and associated trapped sub-hydrate free gas may cause velocity anomalies that would effect the depth conversion of deeper, conventional hydrocarbon targets in the North Slope region. The primary result of the study has been the interpretation of “intra-hydrate” stability zone prospects and “sub-hydrate” free gas prospects. These prospects have been analyzed relative to the petrophysical parameters in analog wells, for comparable reservoir intervals. Monte Carlo style volumetrics were performed using Crystal Ball™ software to calculate the potential range of in-place resources from the interpreted range of potential reservoir properties. Fourteen gas hydrate-bearing prospects were identified and calculated to contain a total of 620 BCF gas in hydrate in-place.

The study focused on the Milne Point 3-D seismic survey within the MPU (Figure 1), provided to the USGS by BP Exploration Alaska, Inc. (BPXA) as co-sponsor of this research. A small portion of the NW Eileen 3D survey just to the south of the Milne Point survey within the MPU was also provided. However, poor shallow (<950 ms) data resolution within the NW Eileen 3D survey prevented extension of the interpretation methods into this area. Regional 2-D seismic data, licensed by the USGS, supplemented the 3-D seismic data and was used along with well data to constrain and improve the quality of critical maps, such as time structure maps, fault maps and base hydrate stability zone maps within the MPU.

The initial interpretation of the structural framework in the Milne Point 3-D seismic survey within the MPU shows that faulting may play a significant role in the migration and trapping of the gas associated with the gas hydrate-bearing reservoirs. North Slope gas hydrates are known to be composed of mostly methane gas sourced from more deeply buried hydrocarbon-bearing formations, which likely accumulated as free gas in conventional traps prior to formation of the gas hydrate stability zone beneath permafrost with onset of arctic conditions. Therefore, a detailed fault interpretation is critical to understanding the relationship between faults, as the gas conduits, and shallow gas hydrate accumulations. The age relationship between various fault sets may play a significant role in determining migration pathways and the compartmentalization of these gas hydrate reservoirs. Fault analyses on a 3-D seismic volume enhanced by ESP (coherency) processing show that the fault orientation, above and below the Canning Formation, is distinctly different, and as such, the secondary and tertiary migration from deeper hydrocarbon reservoirs may be complex. Some faults may not be connected through the Canning Formation to deeper hydrocarbon-bearing reservoirs.

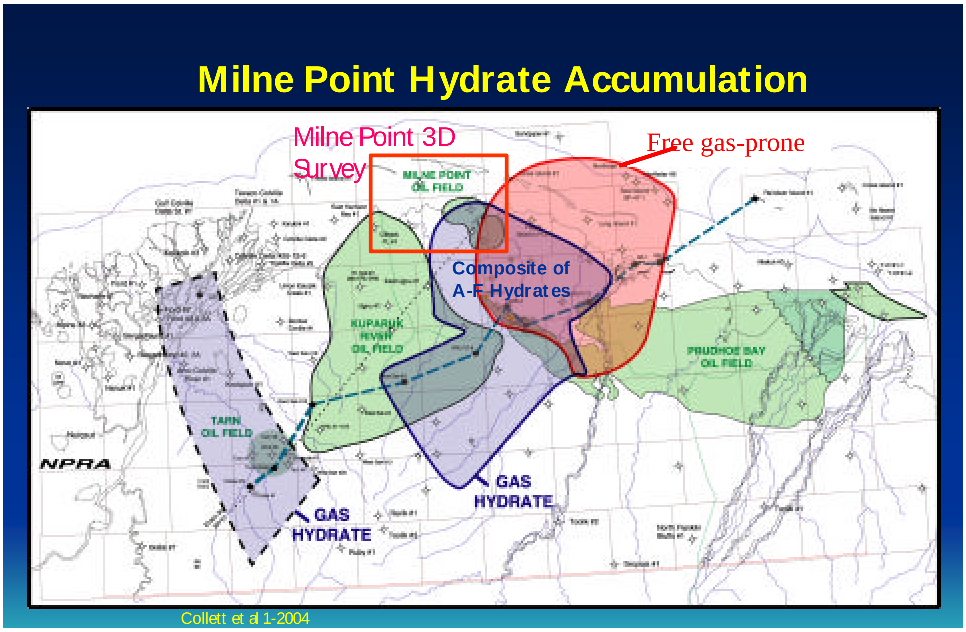


Figure 1: Map of the Milne Point 3D study area and regionally interpreted Tarn and Eileen trend gas hydrate accumulations. Gas hydrate and possible free gas-prone areas are shown within these trends.

The interpretation of faulting on the ESP (coherency) volume greatly improved the overall understanding of fault compartmentalization at each mapped horizon. An example time structure map for the Top of the Staines Tongue horizon is shown in Figure 2. Figure 3 shows the same map in perspective view. Notice that some faults trend more North-South, similar to the predominant younger fault trend. Some of the larger-offset faults within the Staines Tongue interval trend more NNE to SSW, similar to the older sub-Canning fault trend. These faults may be better connected to deeper hydrocarbon systems and may serve as gas migration conduits.

Theoretical seismic modeling of boundaries between ice-bearing permafrost to gas hydrate-bearing reservoirs, shale to gas hydrate-bearing reservoirs, and shale to free gas-bearing reservoirs as well as transitional gas hydrate to free gas reservoirs at the base of the gas hydrate stability zone has been used to understand the acoustic properties of these complex systems in the pre and post stack domain. The similarity in acoustic properties between ice and gas-hydrate makes it difficult to differentiate between ice- and gas hydrate-bearing sediments. That makes gas hydrates adjacent to permafrost, while prospective, both difficult to quantify and to produce. In the Milne Point 3-D area, some assumptions can be made to constrain modeled results describing the relationship of these boundaries in the stack and offset domains. First, if thermogenically-derived gas originally migrated into what are now fully saturated gas hydrate-bearing reservoirs, then a gas hydrate concentration within the pore system of a sandstone reservoir might also range between 80 - 85%, similar to saturations within conventional gas

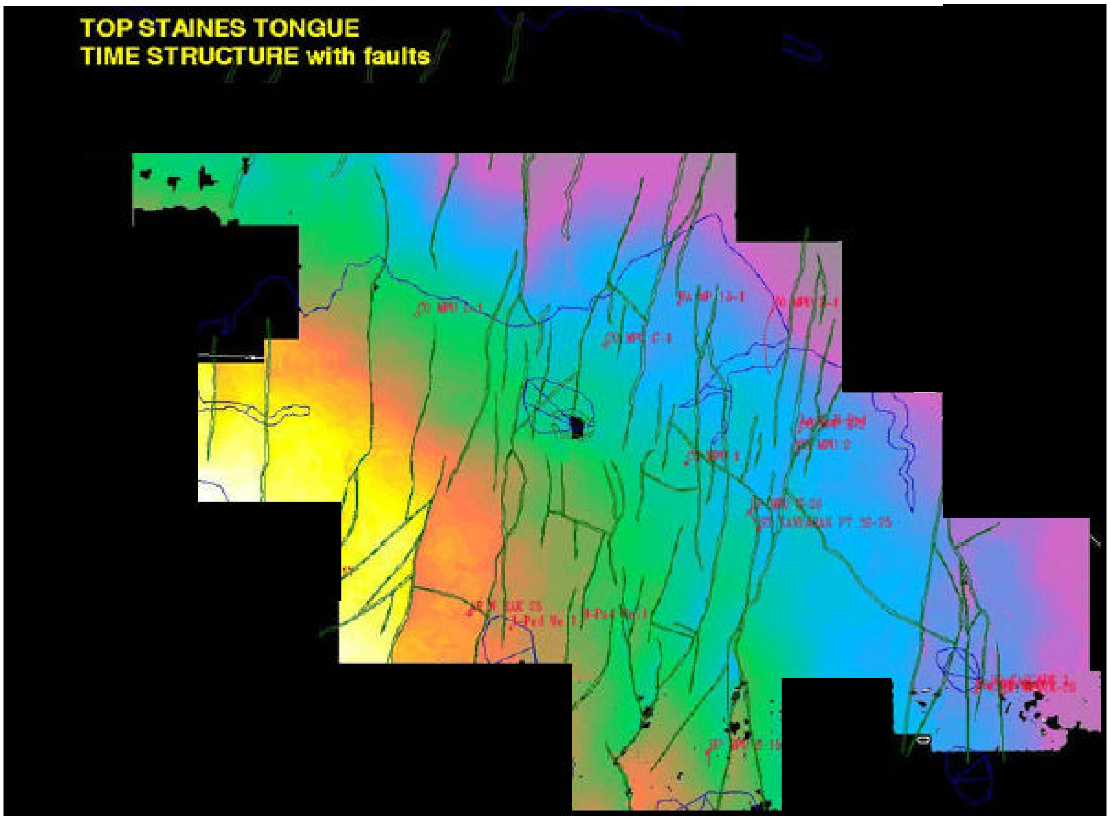


Figure 2: Top Staines Tongue time structure map with interpreted shallow faults

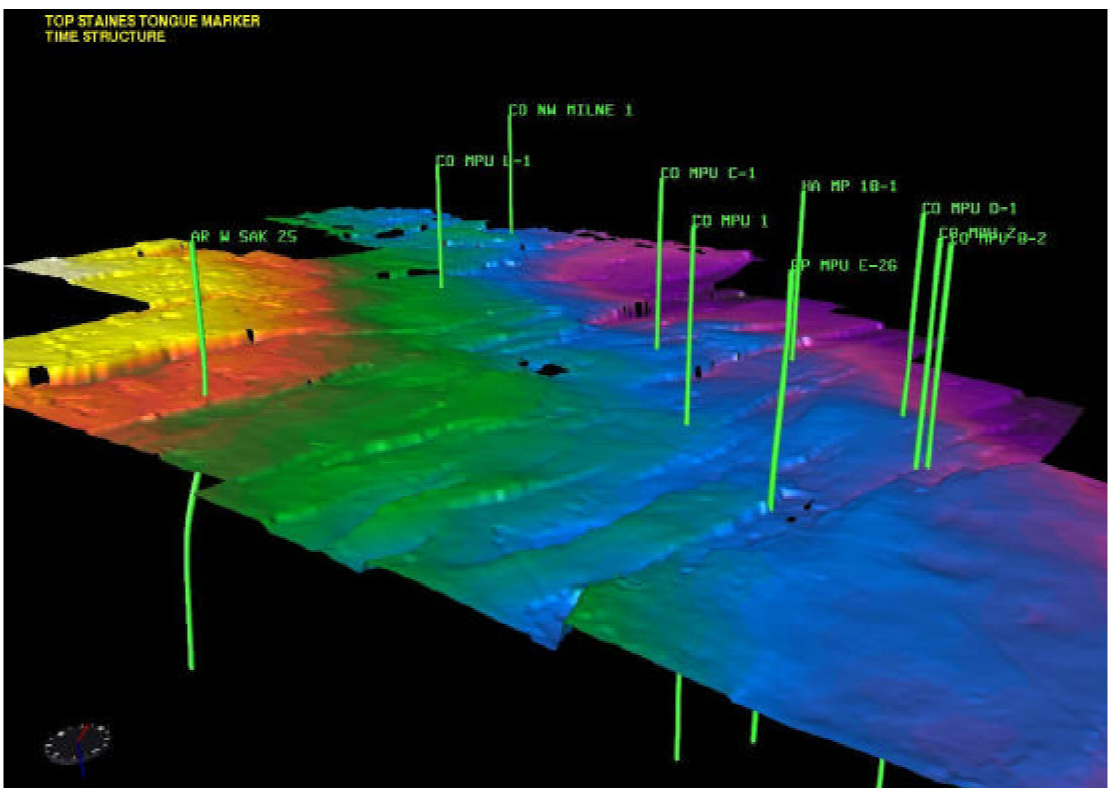


Figure 3: Top Staines Tongue time horizon in north-perspective view.

reservoirs. Thin bed seismic modeling shows that hydrate saturation is variable and that these gas hydrate-bearing reservoirs may be under-saturated with respect to gas hydrate, and may, therefore, possibly contain movable connate waters in some areas. Undersaturation could occur possibly due to the gas volume reduction occurring when a free gas-bearing reservoir is transformed into gas hydrate in the presence of water within the GHSZ. Unconsolidated sandstone reservoirs within the Sagavanirktok Formation that contain the majority of gas hydrates within the MPU area typically have 30-40% porosity. Reservoir thickness is the main variable used in modeling acoustic attributes and in calculating volumetrics. However, thickness can be calculated using "thin-bed" modeling where these reservoirs are isolated and in a single pore-filling phase.

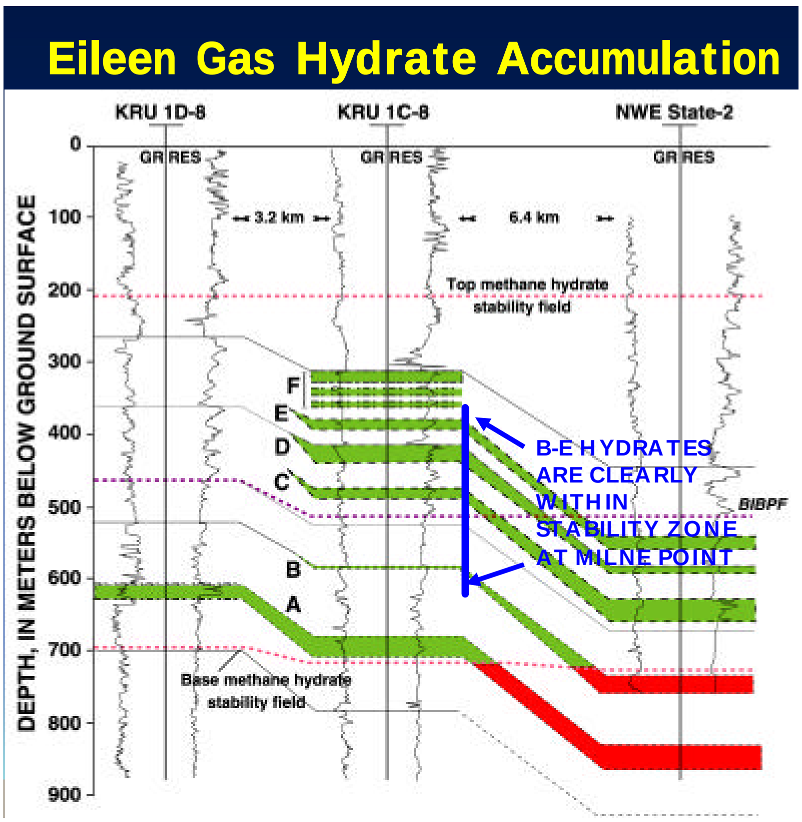


Figure 4: Eileen gas hydrate accumulation log correlations. In the Milne Point area, the base of the hydrate stability field is generally near the Top of the Staines Tongue, or approximately the A-zone hydrate of Collett, 1993.

The base of the gas hydrate stability zone was computed using well log-interpreted ice-bearing permafrost (IBPF) depths and high resolution borehole temperature surveys. Figure 4 shows an Eileen trend gas hydrate accumulation log correlation for interpreted regional gas hydrates. This study confirms the stratigraphic consistencies of this correlation into the Milne Point study area. Gas hydrate-bearing reservoir stratigraphy interpreted within wells within the MPU area have been correlated using both seismic and well log data. A pair of horizons representing the upper and lower limits of the base gas hydrate stability zone were mapped and displayed on the seismic data. The error range of the base gas hydrate stability zone was considered to be plus or minus

75 feet, or plus or minus 15 milliseconds. Gas hydrate reservoirs below the IBPF and within the hydrate stability zone ("intra"-gas hydrate prospects) have acoustic properties allowing them to be interpreted by several simple seismic attributes. Several candidates for intra-hydrate prospects were found during reconnaissance mapping of this interval as shown in Figure 5.

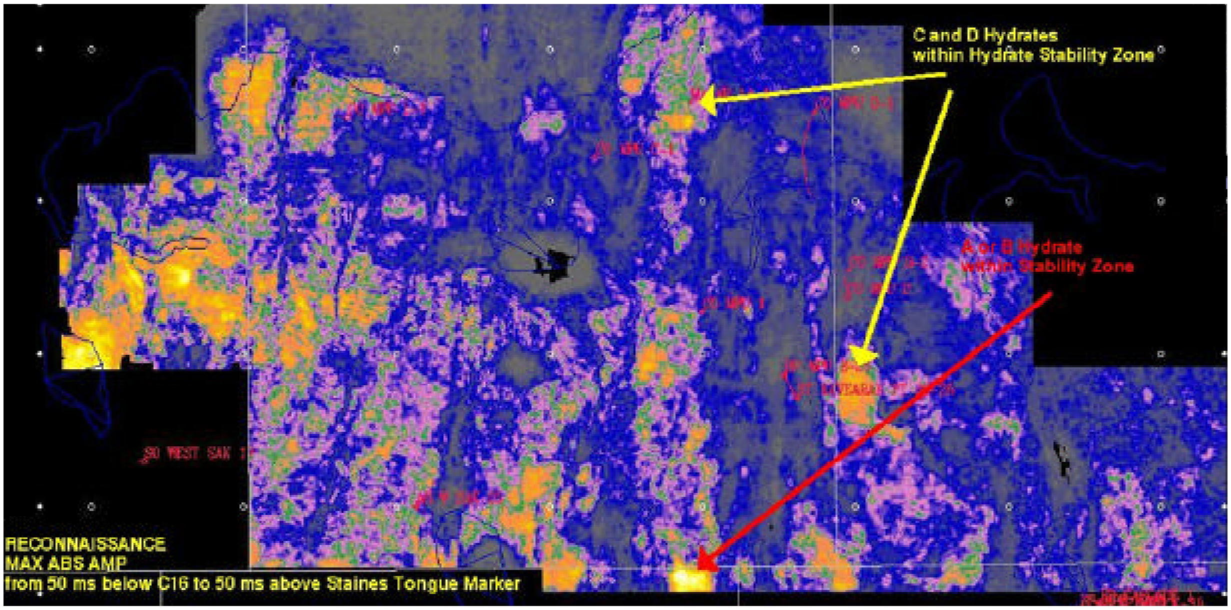


Figure 5: Reconnaissance mapping of 100 millisecond interval around Staines Tongue marker.

Free gas trapped below gas hydrates and/or below the gas hydrate stability zone can be identified by seismic attributes in this geologic setting. However, low saturation free gas can give nearly the same acoustic signature as higher saturation free gas reservoirs. The seismic amplitude anomalies are commonly associated with free gas near the base of the interpreted gas hydrate stability field and may be connected to up-dip gas hydrate-bearing reservoirs in some cases (Figure 6). In other cases, no distinct amplitude anomalies attributed to gas hydrates above the free-gas to gas-hydrate boundary have been identified, even though convention would indicate that gas hydrates must be present to form a hydrate-seal trap. One hypothesis would be that there were changes in migration pathways and the rate of migration during the formation of the gas hydrate stability zone, or that the hydrates never reach the minimum values for thickness and/or saturation that would allow them to be imaged by the seismic data. The recent movement along younger faults in the post-Canning interval likely influenced migration pathways and may effect the location of sub-hydrate free gas accumulations. Another hypothesis would be that the charge is limited and/or the seal leaky for some of these systems.

From the analysis of the seismic data, several intra-gas-hydrate stability zone prospects have been identified in the Milne Point 3-D survey area. Interpreted intra-gas-hydrate prospects are typically conventional fault bounded traps and are identified primarily by their acoustic properties. As a rule, areas that are currently structurally high within prospective fault blocks can be shown to have acoustic properties that are interpreted to correspond to higher concentrations of gas-hydrate. This structural relationship is similar to conventional gas prospects, pointing back to the likely free-gas origin of these gas hydrates. Some of these fault blocks are interpreted as not "fully charged", as there are down-dip limits to the mapped acoustic anomalies. Several of these intra-hydrate prospects might be candidates for gas-hydrate data acquisition and/or production testing, due to their proximity to existing roads and infrastructure.

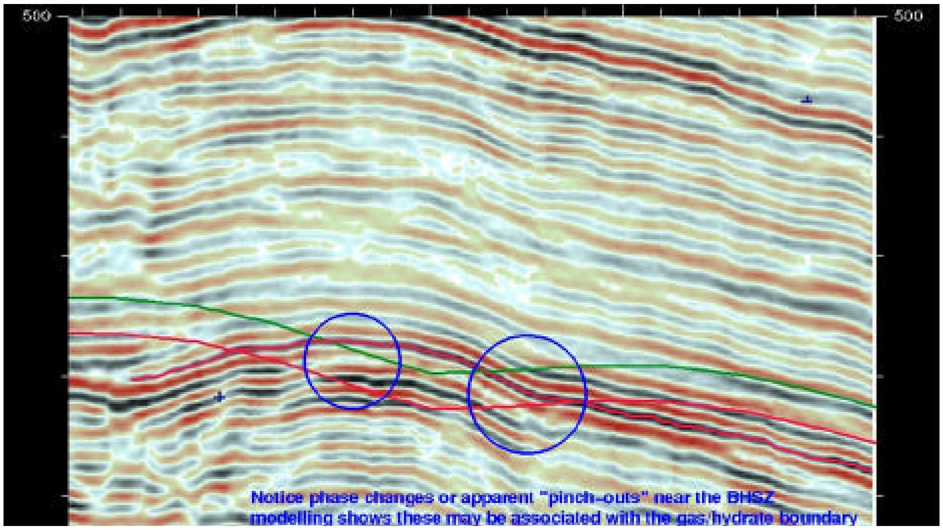


Figure 6: The minimum (green line) and maximum (red line) BHSZ relative to truncated high amplitude seismic reflections that are interpreted to be sub-gas hydrate accumulations of free gas. However, as shown in well-of-opportunity log data collected in this study from MPS-15i and MPI-16, saturations in the interpreted free gas may be lower than 10% in some cases.

The Milne Point area study has identified both intra-gas hydrate and possible sub-gas hydrate free gas prospects that may become candidate areas for future data acquisition. The historical log analysis work conducted by the USGS in this area combined with interpretation of 3-D seismic attributes has promoted a better understanding of the geologic setting for the gas hydrate-bearing reservoirs. Delineation of prospects through future well-log data acquisition in this area would help verify assumptions used in the modeling used to evaluate the candidate prospects.

5.5.2 Partial Summary of Work Accomplished

5.5.2.1 July 2004

- Interpreted zones C and D zone through Milne 3D survey area and zone B in south
- Analyzed Staines Tongue zone, including coal sequences & amplitude modeling
- Completed full Archie Sw analyses for 13 wells from permafrost through Staines Tongue
- Studied attributes for interpreted gas hydrate, free gas, coal, and water-bearing reservoirs
- Provided time-depth and GHSZ information to UA

5.5.2.2 August 2004

- Coordinated approach to volumetrics calculations, MPU area prospects
- Evaluated S-15i petrophysics montage, Staines Tongue saturations, and water salinities
- Considered conversion of original free gas to gas hydrate and changing saturations effect
    - Saturations appear significantly less than possible original free gas saturations
    - If migration shutoff, limited source, or leaky seal, then result could be undersaturated gas hydrate- and gas-bearing reservoirs within Staines Tongue
- Checked time-depth conversion interpretation; primarily pseudo-resistivity

  - Early versions had some discrepancies
  - Determined if/how sonic logs incorporated – Acoustic tools provide better formation data, but can be much more susceptible to common borehole washouts
- Evaluated partial hydrate saturation issues; may see similar indications in NWEileen-02
  - Might be enough relative permeability within gas hydrate-bearing reservoirs
  - NWEileen-02 zones D & E gas saturations apparently relatively low, 50-60%
  - GR api is 30-40, some shale, but not enough to account for 40-50% Swirr
  - Expect possible Sw = 20% unbound connate waters
  - Mallik studies showed 5-8% unbound connate waters in clean sand reservoirs
  - Concluded may have relative permeability in presence of pore-filling gas hydrate
- Evaluated USGS purchase of 2D line from MPU through NWEileen-02 and into PBU
  - Seismic data broker has CP 2D line through K-pad to NWEileen through PBU L and V pad – asking $1,800/mile for 16 mile line ($28,800)
  - Consider purchase at least the northern portion of the line, EP 80-10X, since USGS already has the EP 80-10.
  - According to calculations, that would be from shot 516 to 902 or 397 shots.
  - Using shotpoint interval of 440 feet, as described in the side label, that totals 397 times 440 equals 174,680 feet equals 33 miles for total cost of $43,009.

5.5.2.3 September 2004

- Finalized Hedberg Gas Hydrate Research Conference plans and presentation materials

5.5.2.4 October 2004

- Determined evaluation criteria for MPU prospect ranking and volumetrics

5.5.2.5 November 2004

- Studied amplitude response and character range of intra-gas hydrate accumulations
  - Prospects consistent except all of Staines Tongue sequence
  - Questioned validity of method or perhaps a significant saturation difference
  - Determined need well data to understand the gas hydrate and free gas potential of the Staines Tongue
  - Evaluated well-of-opportunity, mid-September 2004 shallow logs of MPI-16
  - Assessed Staines Tongue, especially fault-trapped potential free gas with updip gas hydrate component; included evaluation of coal-bearing sequences
- Reviewed PBU L-106 gas hydrate-bearing reservoir intervals
  - Reviewed 3 zones totaling 178 feet gas hydrate with up to 80-90% saturation

5.5.2.6 December 2004

- Evaluated, compared, and ranked gas hydrate and free gas-bearing prospects within MPU
- Recommended candidate areas and prospects for potential data acquisition
- Recommended potential data to acquire within candidate prospect areas
- Prepared T-chart for comparison and ranking of MPU gas hydrate prospects (Table 1)
- Output reservoir characterization of top-ranked Mt. Elbert prospect for reservoir model

Table 1: MPU Gas Hydrate Prospect Ranking

Mt Elbert C and D --> E-Pad, B-Pad	
Estimated Rank - #1	
POSITIVE QUALITY (PQ)	**NEGATIVE QUALITY (NQ)**
135 BCF Gas Hydrate In-Place	Requires Delineation
Stacked Prospects (C and D horizons)	No Staines Tongue gas hydrate or free gas
Conventional, Fault-bounded structural trap	
Well organized and consistent amplitude anomaly	No well penetration, fault-separated from correlative wells
MPB-02 and MPE-26 confirm gas hydrates in C and D	
Both MPB-02 and MPE-26 have excellent synthetic ties	
Gas hydrate in C/D causes velocity pull-up in Staines T.	
Interpreted 45 feet C-hydrate thickness	Requires Delineation
Interpreted 45 feet D-hydrate thickness	Requires Delineation
Interpreted high-saturation in gas hydrate at crest	Requires Delineation
Potential movable connate waters downdip position	Requires Delineation
Facilities	
E-pad gas compression and injection available	
Good distance from E-pad for horizontal well	Need delineation well and data before production testing
3000 feet from E-pad, 3500 feet from B-pad	Possible limitations for wireline & core acquisition?
Reservoir Model	
Import Structure, thickness, saturation grids	
Test water saturation and connate water mobility	
Horizontal well test	
Depressurization test (connate water mobility)	
Test hot gas injection/circulation	
Test hot water injection/circulation	
Blanca --> A-Pad	
Estimated Rank - #2	
PQ	**NQ**
23 BCF Gas Hydrate In-Place (C-horizon only)	
Stacked Prospects (C and D horizons)	
Penetrated/delineated by MPA-01	
35+ feet D; 30+ feet C	
Thicknesses nearer seismic resolution limits	Less well-organized amplitudes
Possible destructive interference affecting amplitudes	Less well-organized amplitudes
Possibly more stratigraphically controlled	Flat structure, less 4-way-type closure
Possibly more lateral extent upside	
Possibly more thickness upside	
Facilities	
On A-pad; readily accessible from A-pad	No facility infrastructure other than gravel
Crestone C and Sneffels D -- C-pad	
Estimated Rank - #3	
PQ	**NQ**
186 BCF Gas Hydrate In-Place (Crestone C-horizon)	Gas Chimney in updip position to SW may be leaky seal

46 BCF Gas Hydrate In-Place (Sneffels D-horizon to SE)	
4.8+ upside free gas in Shavano Mid-Staines with Crestone	
MPC-01 has good gas shows in Mid-Staines	
Fault-bounded and 4-way closure traps	Structurally compartmentalized into 6 fault blocks
MP18-01 delineated good C and D gas shows in NE	
Best amplitudes in North and Northeast Crestone	Not as well-organized amplitudes in South and Southwest
Interpret ~40 feet Crestone C hydrate reservoir thickness	
Interpret ~45 feet Sneffels D hydrate reservoir thickness	
Interpret 60-70% Saturation gas hydrate in C and D	

Facilities

SW corner directly beneath C-pad (Crestone C)

Actions

Potential for C-pad WOO - Review drilling schedule

Princeton D -- K-pad
Estimated Rank - #4

PQ	NQ
38 BCF Gas Hydrate In-Place in D-horizon	Very structurally complex and likely compartmentalized
Good K-pad delineation in MPK-38 and MPK-25	
K-pad area very active gas-prone area	Very structurally complex and likely compartmentalized
200 feet free gas in C and D zones delineated in wells	
Stacked prospect potential in Staines Tongue	
Staines Tongue Yale prospect with 3.6-10 BCF	Probable low-saturation Staines tongue

Facilities

K-pad area not very active; Minimal disruption/distraction

Antero C -- H-pad
Estimated Rank - #5

PQ	NQ
68 BCF Gas Hydrate In-Place in C-horizon	No confirmation wells; seismic-only anomaly
Interpreted 45 feet C-horizon reservoir thickness	Structurally compartmentalized, may require delineation
	Patchy saturation interpretation
Stacked with Staines Tongue Prospect	Staines Tongue likely low-saturation as tested at MPI-16
May provide potential fresh water source	Possible coal-associated gas versus free gas?
Gas Hydrate in upper Staines	Closely associated with updip-edge gas chimney
Free gas potential in middle Staines	Gas Chimney may indicate leaky seal
	Free gas requires delineation

Facilities

Prospect very near road access - 100 feet from road	
Prospect near H-pad - 1,600 feet from pad	
Possible option to inject produced gas into Staines Tongue	Question whether hi-pressure gas injection option available

Actions

Check for new well data over shallow intervals

Pikes Peak B -- S-pad
Estimated Rank - #6

PQ	NQ
13-26 BCF Gas Hydrate In-Place in B-horizon	Low-Saturation B-horizon directly below S-pad
Upside as off 3D survey edge on NW Eileen Structure	
B-zone is clean marine sandstone	
Additional upsides in C, D, E, F horizons	
Stacked with Mt Holy Cross Staines Tongue Prospect	
Upper Staines Tongue Free Gas - 3.5 BCF w/ upside	Low Saturations calculated in Staines Tongue (25%)
Downdip Staines in Longs Peak gas hydrate prospect	MPI-16 was low-saturation in Staines Tongue
(23 BCF w/ upside potential if greater saturations)	
Mid-Staines Tongue free gas potential 9+ BCF	Likely low saturation in Staines Tongue
Facilities	
	Long Stepout, 6,840 feet from S-pad may be prohibitive

Beirstadt E -- B-Pad and D-Pad
Estimated Rank - #7

PQ	NQ
42 BCF Gas Hydrate In-Place in E-horizon	Very cold & near Permafrost
Opportunity for E-horizon evaluation	Possible Ice formation on production testing
Interpreted to 50 feet E-horizon reservoir thickness	
Excellent geophysically-constrained prospect	
Very organized amplitude anomaly	Not an obvious velocity pull-up in Staines Tongue below
Fault closure with downdip amplitude dimming	
Saturation may have significant upside	Surface statics (inlet) may decrease amplitude anomaly
Stacked with Little Bear Staines Tongue Prospect	Amplitude anomaly is limited in Staines Tongue
Well-constrained prospect	Low Saturations are likely (10-40%)
Gas hydrate/free gas/water contacts follow contours	MPD-01 well is only 20 ohm*m resistivity
	Small volumes in Staines Tongue
Facilities	
B-pad on location	Horizontal well option may be limited from B-pad
Consider horizontal well design turn up into gas hydrate	E-horizon penetration may not allow Staines penetration
This design could help mitigate water production	(may be possible to mitigate with well design)
D-pad near location & may provide better horizontal well	

5.6 TASK 6.0: Reservoir and Fluids Characterization – UA

University of Arizona
UA Principle Investigator: Robert Casavant
UA Co-Principle Investigator: Roy Johnson, Mary Poulton
UA Participating Scientists: Karl Glass, Ken Mallon
UA Graduate Students: Casey Hagbo, Bo Zhao, Andrew Hennes, Justin Manuel, Scott Geauner
UA Undergraduate Student Assistant: Greg Gandler

This section discusses gas hydrate research activities that were completed or are in progress as of December 30, 2004 at the University of Arizona (UA). Task activities during the reporting period included preparation of Phase 1 research results for presentation to the AAPG Hedberg Gas Hydrate Research Conference in Vancouver in September 2004. Progress in the UA geological and geophysical reservoir characterization of the gas hydrate and associated free gas resources in the MPU area and southward into the northern KRU and western Eileen block of PBU has involved the continued investigation and characterization of:

- Variation in fault throws and inferred fault seal potential across the MPU
- Lateral and vertical variations in the timing and influence of fault reactivation on deposition of the reservoir units within the Sagavanirktok and Gubik Formations
- Variations in seismic amplitude responses associated with gas hydrate-prone intervals via supervised waveform classifications and the role of faulting on compartmentalization and migration of hydrocarbons within the MPU area
- Facies-related contributions to gas emplacement
- Alternative interpretations to facies controls on gas hydrate-bearing reservoirs (paleosols, coal, etc.)
- The base of the ice-bearing permafrost and gas hydrate stability fields based on available empirical, wireline log and temperature log data
- Linkages between fault morphology, sediment deposition, and interpreted gas hydrate- and free gas-bearing reservoirs

The research program at the University of Arizona (UA) is focused on a detailed and comprehensive characterization of heterogeneous gas hydrate- and associated free gas-bearing reservoirs on the central North Slope of Alaska. In addition to geological and geophysical characterizations, research objectives also include the assessment of resource volumes, fluid distribution, and other geological and reservoir engineering inputs that will help determine the commercial viability of this potential unconventional energy resource. The current area of interest (AOI) includes a large portion of the Kuparuk River Unit (KRU), all of the Milne Point Unit (MPU), and the western quarter of the Prudhoe Bay Unit (PBU) on the North Slope of Alaska (Figure 7). The analysis includes shallow well log data from 67 wells across the AOI and the shallow portions of a 3D seismic volume within the MPU (Figure 7).

5.6.1 Subtask 6.1: Reservoir and Fluid Characterization and Visualization – UA

5.6.1.1 Modified 2004 Hedberg Research Conference Abstract

Structural analysis of a proposed pull-apart basin: Implications for gas hydrate and associated free-gas emplacement, Milne Point Unit, Arctic Alaska, R. R. Casavant [1], A. M. Hennes[2], R. A. Johnson[2], and Tim S. Collett[3]
[1]Department of Mining and Geological Engineering, University of Arizona, Tucson, AZ 85721
[2]Department of Geosciences, University of Arizona, Tucson, AZ 85721
[3]U.S. Geological Survey, Denver Federal Center, Denver, CO 80225

A robust petroleum system is in place for the generation and emplacement of shallow gas hydrate and associated free-gas resources on the central North Slope of Alaska. Current interpretations place these resources within the eastern portion of the Kuparuk River Unit (KRU), the southeastern portion of the Milne Point (MPU), and the west-northwest edge of the Prudhoe Bay Unit (PBU) [1] (Figure 7). The majority of reservoirs are contained within a thick sequence of Late Cretaceous to Late Tertiary fluvial-deltaic and nearshore marine gravels, sands, and shales (Figure 8).

Near the MPU, the depths of gas hydrate-bearing reservoirs range from 220 to 1,400 meters below sea level. Where pressure-temperature conditions form stable clathrate, gas has combined with water to form hydrates within the porous, thin-bedded, multistory sand-rich intervals[1]. Individual gas hydrate-bearing sands can range in thickness from a few meters to over 30 meters thick. Across the MPU, the net thickness of free-gas intervals ranges from less than a meter to tens of meters. Thin free gas-bearing zones occur sporadically within the study area downdip and below the gas hydrate stability zone (GHSZ). Porosity and resistivity logs indicate more than 10 meters of free gas-bearing sands can occur downdip of gas hydrate-prone intervals. Interbedded free gas- and gas hydrate-bearing intervals may locally occur due to variations in structural and stratigraphic constraints, varying pressure-temperature conditions, and/or changes in pore-fluid salinity.

Regional structural mapping within the MPU and KRU indicates that gas hydrates and free gas occur along the highly faulted, northeast-dipping flank of a large anticlinal structure[2, 3]. This southeast-plunging antiform lies along a regional east-west trending basement antiform, known as the Barrow Arch, which coincides with the northern rifted margin of the Arctic Alaska terrane (AAT) that rifted and docked into its present position during the mid-late Mesozoic[4] (Figure 9). Fault reactivation and structural inversion along weakened and long-lived basement fault blocks beneath MPU and KRU have been linked to basinal fluid migration and variations in permafrost thickness. Periodic crustal shortening along the southern margin of the terrane continues to reactivate basement deformation across the major structural provinces[2].

Interpretations of 3-D seismic data in the MPU reveal that the shallow sequence of gas hydrate-bearing rocks in the area is extensively deformed by north- and north-northeast trending syn- and post-depositional faults[3]. The presence of a diffuse and segmented northwest-trending structural hingeline can be identified on seismic maps as well as by (1) the alignment of termini of north- and north-northeast-trending faults, (2) alignment of inflections, jogs or offset of those fault sets, (3) the offset/termination of some graben structures, and (4) first-order changes in the structural attitude of downdip stratigraphic units, although no northwest-trending offset is resolvable in the vertical seismic sections. These hingelines have been linked to deeper fault zones that segment oil reservoirs and define important oil/water contacts in deeper Cretaceous-age reservoirs[6] (Figure 10). Shallow fault displacements, vertical morphologies, and plan-view distribution suggest that MPU is dominated by down-to-the-east northeast-trending and down-to-the-north northwest-trending systems of normal faulting (figures 11-13). A similar conjugate set has been illustrated in numerous studies and by Fry (center-to-center) structural analysis of discrete fault blocks at shallow structural levels (figures 14-15). Studies reveal significant fault complexity including differential offset near fault terminus, en echelon faults, relay zones, and possible rotation.

Fault patterns and displacements across the central portion of the MPU suggest the presence of a small, northeast-trending pull-apart basin that may have influenced sediment deposition and the later emplacement of gas hydrates in the area (figures 12-13). Analog modeling (figures 16-17) suggests that the sigmoidal fault geometries in this part of the MPU relate to transtensional deformation in weak sedimentary cover above a left-stepping sinistral strike-slip fault system at depth (Figure 18). En echelon fault patterns support the proposal that the basin formed from the linkage of basement faults across a 30-60° releasing sidestep[7]. Dimensions of the better-defined portion of the basin, herein referred to as the "Milne Point Basin" (MPB), are approximately 5.6 km-wide by 13.7 km-long. The current length/width aspect ratio of the MPB (~2.5:1) suggests that the basin may be close to fully developed[7]. The northern extent of this transtensional basin is estimated to be near the convergence of 3-4 fault zones just onshore and west of a pronounced orthogonal bend in the coastline referred to as Milne Point. Southward extrapolation of fault trends into the KRU suggests probable convergence of basin-bounding faults above an offset northeast-trending principal shear.

Intrabasinal structures include an arrangement of cross-basin faults and en echelon fault segments (figures 12-13). The MPB is dominated by relatively undeformed half-grabens and an interesting alignment of grabens along the western and eastern margins of the basin (Figure 12). Experimental models and field examples such as the MPU show that pull-apart basins are bounded by complex sidewall faults that exhibit the largest displacements and steep oblique-extensional slip[7]. The sidewall faults of the MPB are characterized by a "lazy-Z" geometry that may be related to the formation of structural terraces, and in some locations, small grabens, and fault kinks[5]. These sidewall fault zones are dominated by right-stepping en echelon and overlapping fault segments. The overlaps may mark the locations of transfer fault zones or relay ramps that probably controlled local sediment input and erosion along the basin margins. These patterns may imply linkage to a deeper through-going sinistral shear zone beneath the basin that may serve as either conduits or barriers to gas migration. Recent seismic interpretations at U. S. Geological Survey (Task 5.0) support the interpretation of fault linkage at depth.

Seismic cross-sections such as that shown in figure 13 and fault mapping (Figure 12) support the pull-apart model interpretation. Dominant half-graben structures are mostly north trending and bordered by en echelon normal fault segments of variable length. Fault displacement along the axis of the basin is dominated by two elongated, 3.5-km long lozenge-shaped inline rhombs. The sidewall faults are broadly antithetic to each other and characterize the pull-apart as a broad graben. Analog models demonstrate that although inline antithetic fault zones (grabens) do occur in pull-apart basins, half-grabens should be the dominant structures. In this sense, the

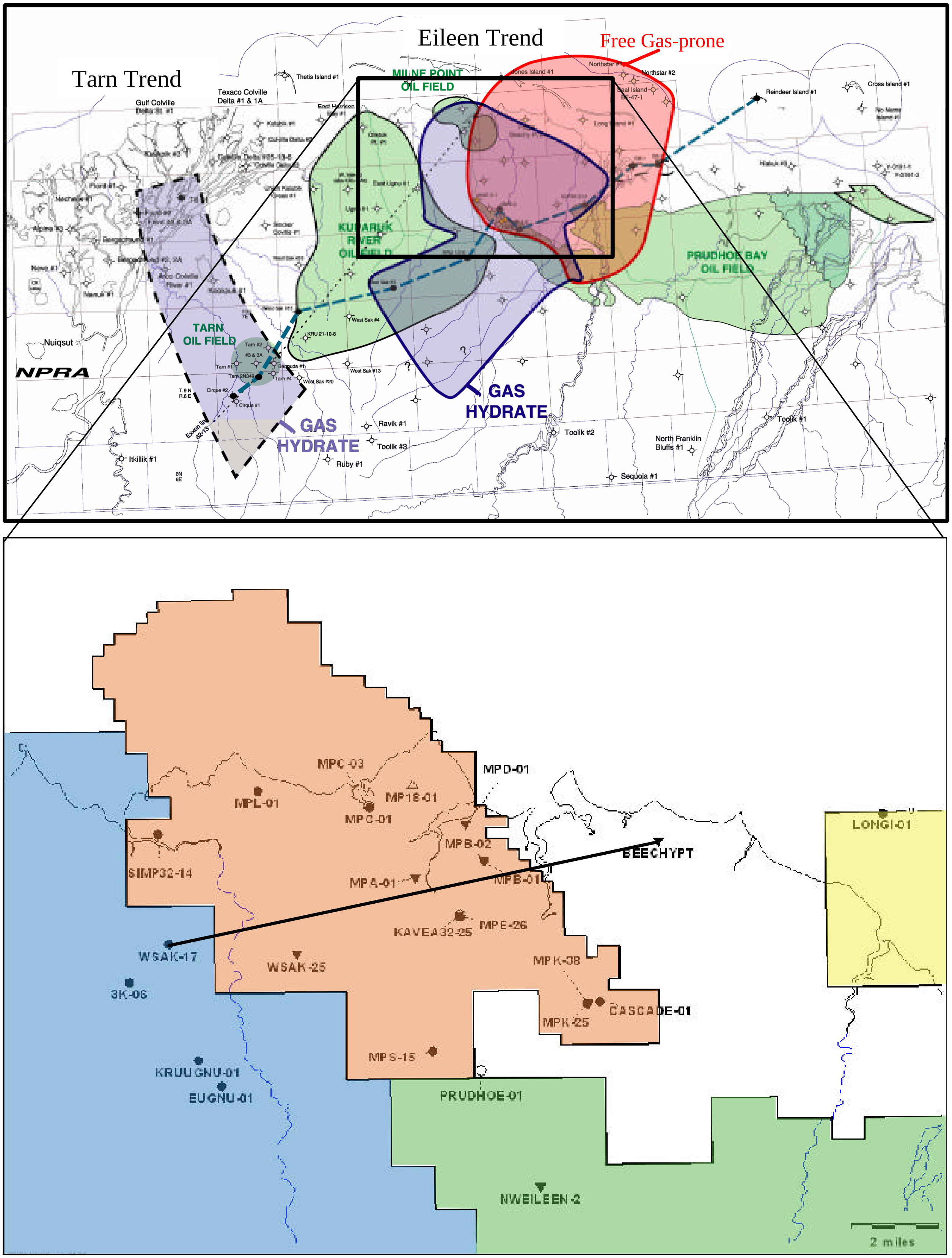


Figure 7: Eileen and Tarn Gas Hydrate Trends, Alaska North Slope (USGS); cutout displays select wells within AOI. Cross-section line is along interpreted basin shown in figures 19 and 20.

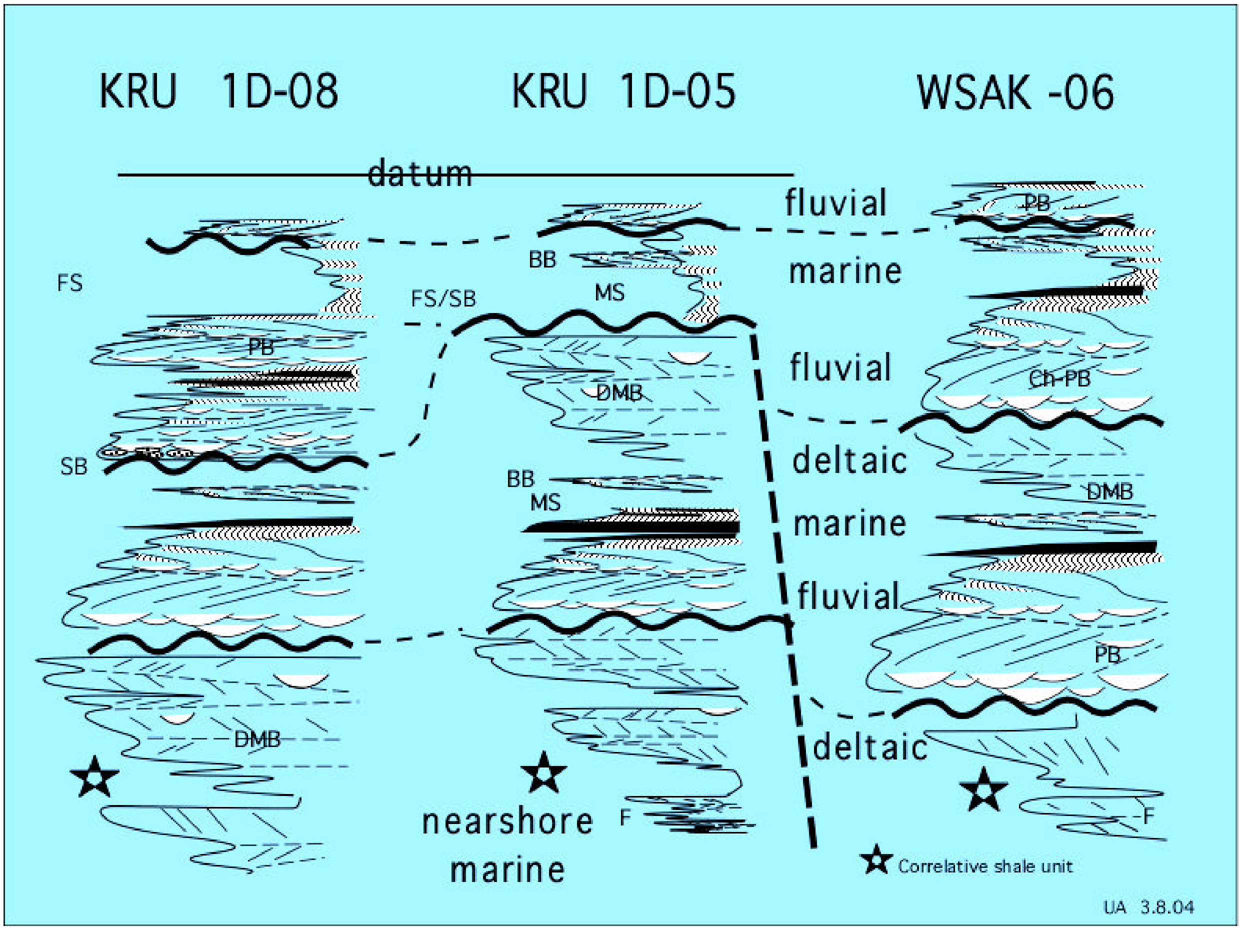


Figure 8: Shallow Stratigraphy of Gas Hydrate-bearing Sequences, Alaska North Slope

MPB appears to be somewhat unique since segments of its western margin and almost all of its eastern flank are bordered by well-developed en echelon grabens.

These basin-margin grabens were probably reactivated and downdropped during renewed transtension across the region that resulted from loading in the Eastern Brooks Range and regional tilting of the Barrow Arch. Preliminary USGS (Task 5.0) interpretation of industry 3D seismic data in the MPU shows some larger-displacement basin-bounding sidewall faults extending from basement to the surface. Overlying these faults, shallow reflectors within the permafrost, gas hydrate, and underlying intervals appear to be more disrupted and displaced relative to intrabasinal areas, attesting to the fault activity. Wells located within basin-margin grabens generally exhibit a higher net/gross sand ratio, suggesting that the deep-seated sidewall fault zones were in-part syndepositional and may have influenced facies distributions and depositional environments (figures 19-24). Based on the diagrammatic representation of the basin shown in figures 19 and 20, wells on the eastern and western edges of the basin (WSAK17, WSAK25, and BeechyPt) are interpreted to have penetrated thicker coal-bearing sequences and wells in the center of the basin should be dominated by sand. The net-to-gross mapping shown in figures 21-23 verify this interpretation. Methane hydrate occurrence should be near faults, in sand dominated units, moving toward the center of this interpreted basin (Gandler et al., 2004). Fault seal probabilites[9] and juxtaposing of reservoir sands along these faults is the topic of ongoing research. The axis of the interpreted basin coincides with the location and orientation of a north and northeast-trending depositional hingeline as seen on gross and net sand maps of the upper gas-hydrate-bearing sequences in the MPU (figures 21-23). This proposed MPB structure might play a significant role in sediment deposition, gas (gas hydrate) emplacement, and GHSZ contact.

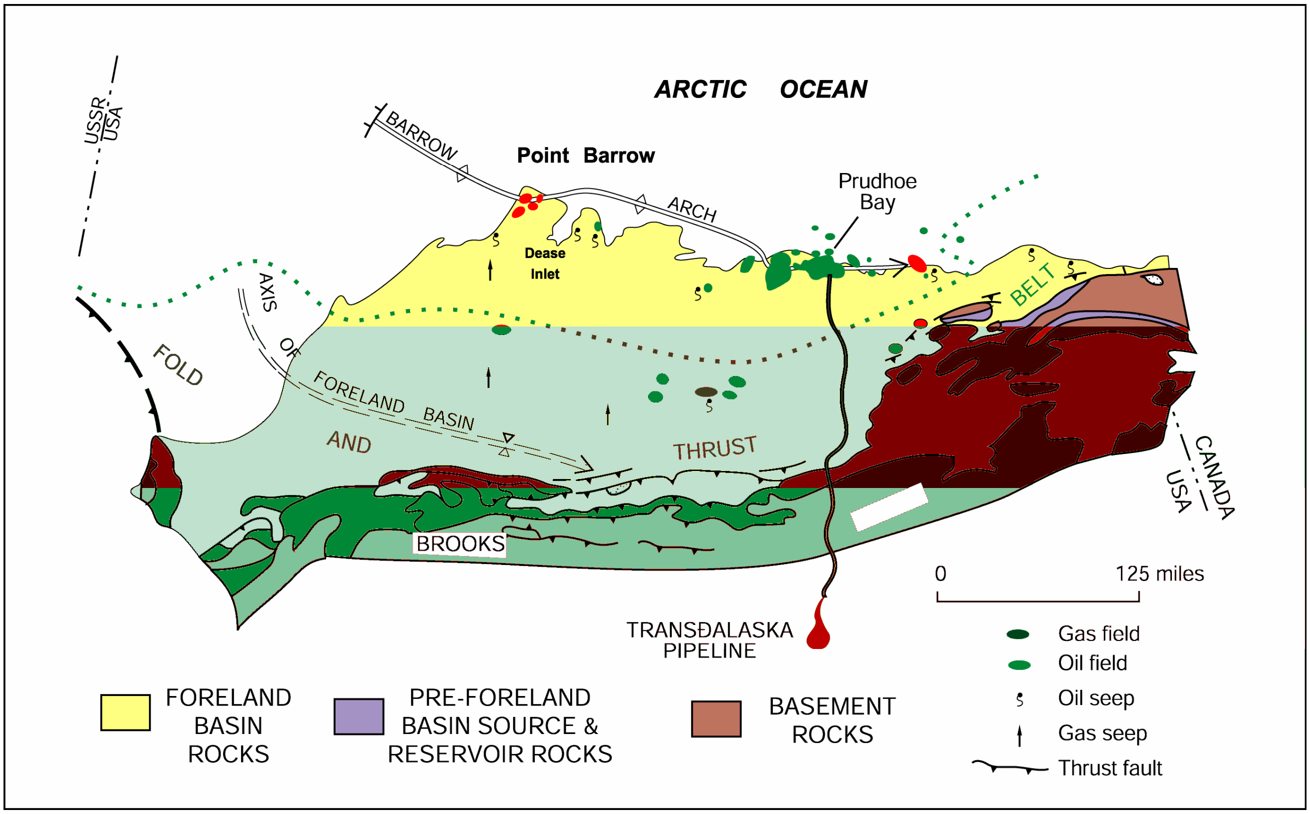
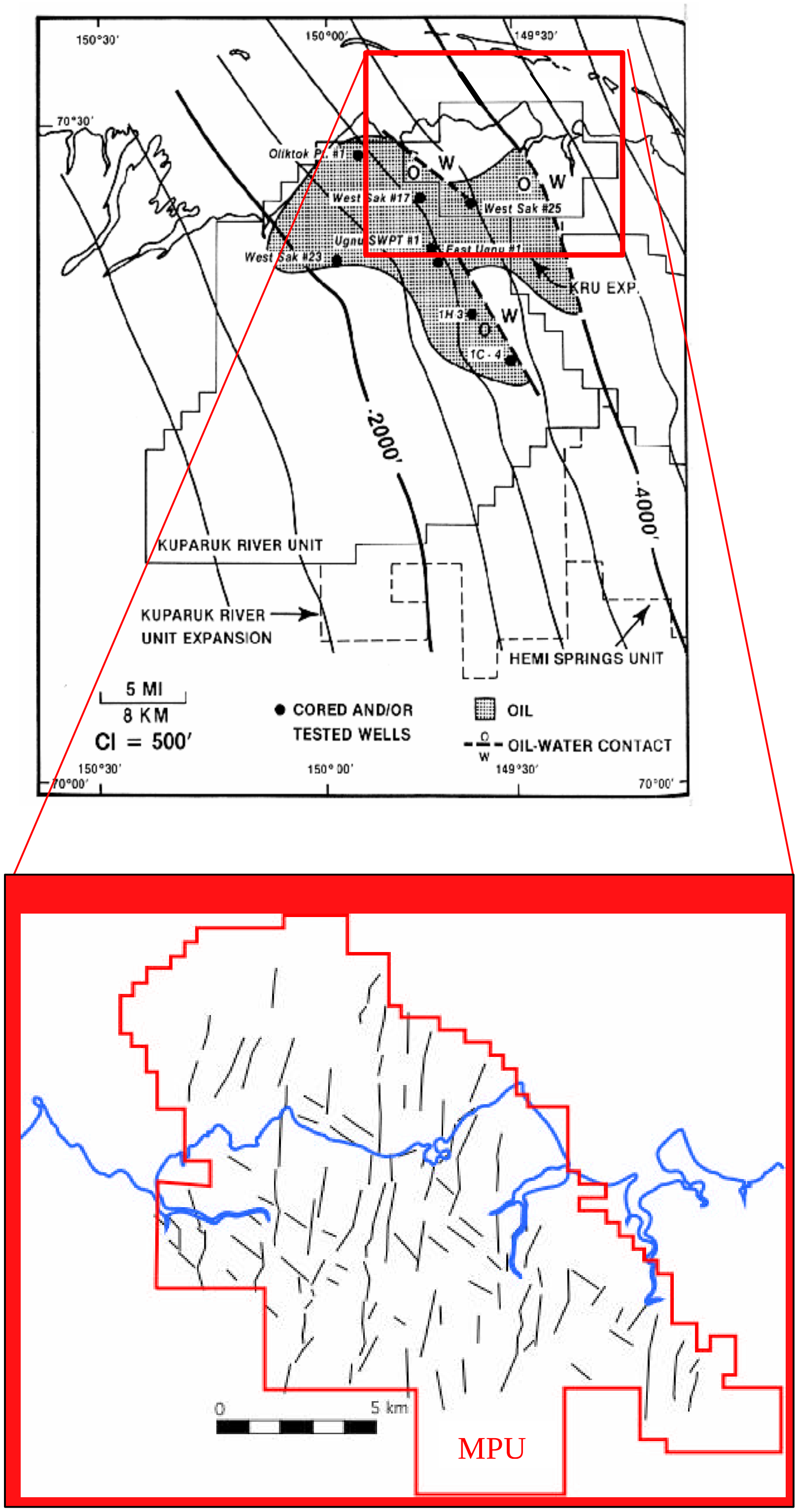


Figure 9: Regional structural setting, Alaska North Slope (USGS)

Regional stratigraphic and geophysical studies show that periodic reactivation along basement block boundaries resulted in localized sagging and structural inversion along zones of weakened crust that were constrained to the margins of basement blocks. Morphotectonic analyses of numerous locales across the Arctic Alaska terrane suggests that basement faulting has long influenced the surface geomorphology, location of modern to ancient fluvial-deltaic to nearshore marine systems, and upward migration of fluids and heatflow[2, 8, 9]. Seismic interpretation and mapping of shallow sequences within MPU reveals potential spatial correlation between subsurface structure and geomorphic features at the surface. These spatial associations suggest the influence of shallow basement control on the morphology of coastal and fluvial elements across the Arctic coastal plains[2].



- NW lineament swarm overlies NW-trending O/W contact in Ugnu, WSak
- NW hingeline may constrain facies & fluid distributions as it does for deeper Cretaceous-Tertiary reservoirs in KRU, MPU (Werner, 1987).
- Significant variation in displacement north of the northwest hingeline
- Basement fault control on shoreline, rivers, continental shelf, paleodeposition and basin morphology (Casavant, 2001)

Figure 10: Structure map and Oil-Water contacts, Lower Ugnu Sandstone. (Werner, 1987). Inset shows MPU area shallow fault lineaments in relation to Ugnu fluid contact interpretation.

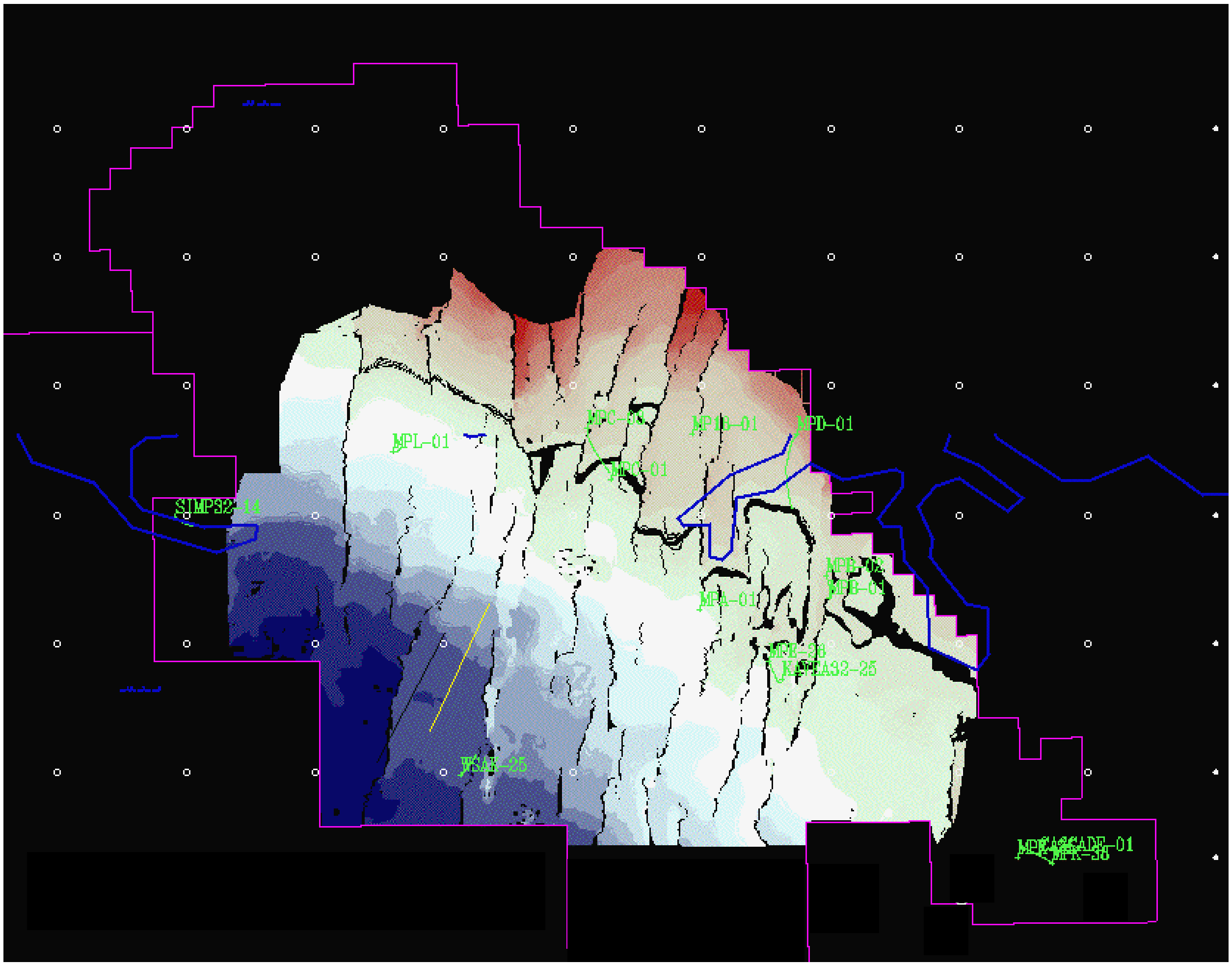


Figure 11: Structure Map of Marker 34 (USGS Zone C equivalent) within MPU study area.

Seismic attribute analyses and geologic mapping confirm that, in addition to fault compartmentalization, reservoir continuity is also related to changes in facies type and geometry. Both regional lithostratigraphic and chronostratigraphic correlation frameworks address the stratigraphic and reservoir rock continuity. Lithostratigraphic correlation across the study area confirmed the presence of at least six distinct and laterally continuous gas hydrate-bearing reservoir units[1] (figures 19-20). Application of a more recent sequence stratigraphic framework implies a higher degree of reservoir heterogeneity. The distribution and quality of reservoir sands relates not only to rapid changes in depositional environments and facies, but also to the preservation and scouring of reservoir units along numerous intraformational unconformities that define many sequences. A study of facies, sand body dimensions, and related seismic facies mapping are planned to help develop a more accurate model of reservoir description needed for estimating volumetrics and recovery factors. Another factor which may influence local gas sourcing and reservoir continuity is the coal-bearing sequences (figures 24-26). Coal formation is also controlled by basin geomorphology and syndepositional faulting. The sequence stratigraphic analysis and paleodepositional reconstruction is the subject of current research[10]. However, most of the interpreted coals are within the Staines Tongue stratigraphic interval; task

5.0, documented in sections 5.5.2.2 and 5.5.2.5 indicates that gas- and gas hydrate-bearing reservoirs within the Staines Tongue are significantly under-saturated.

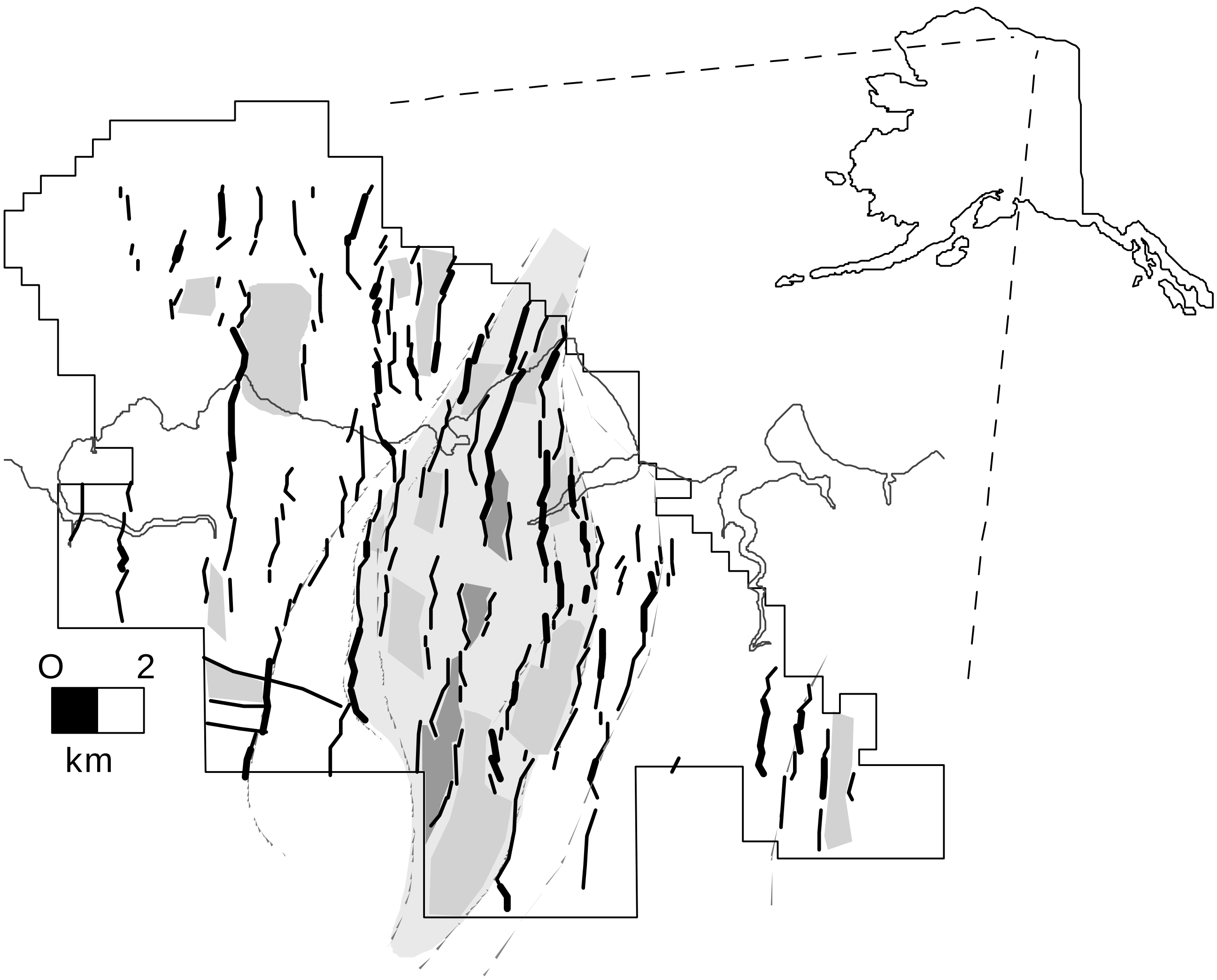
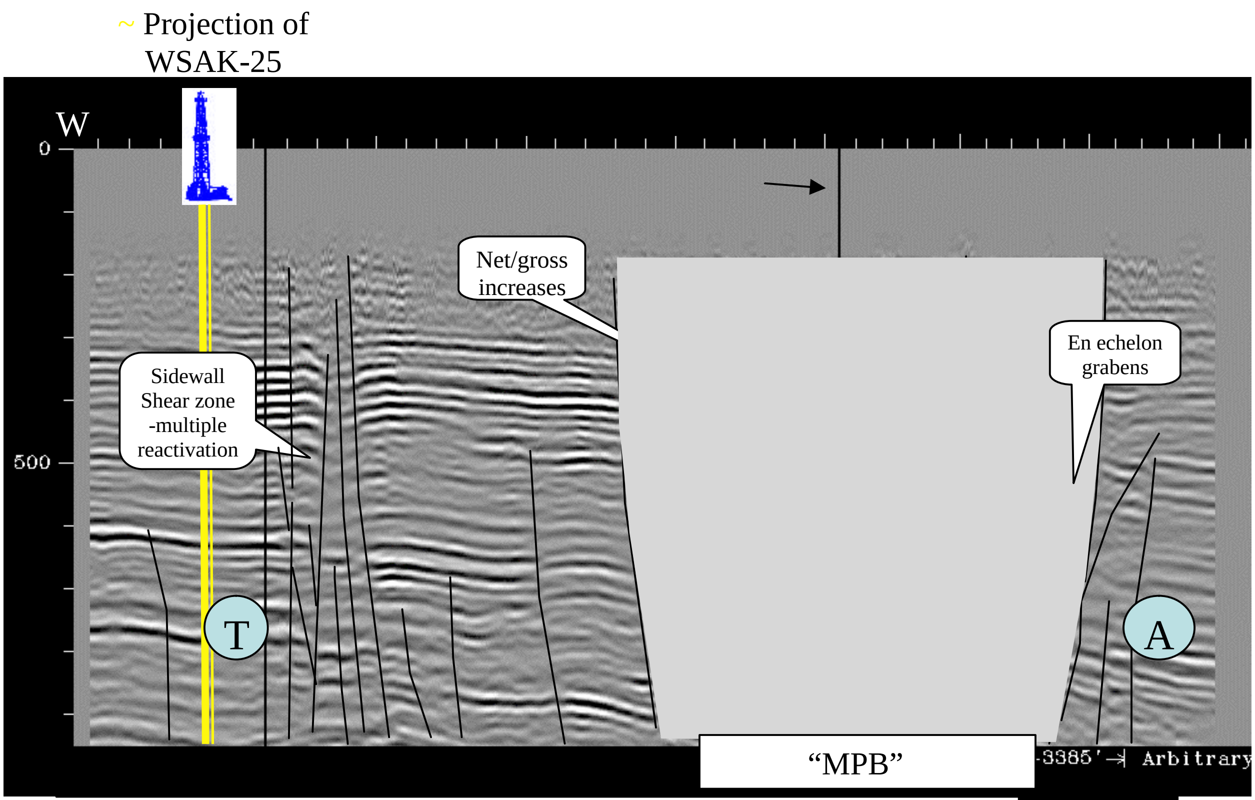
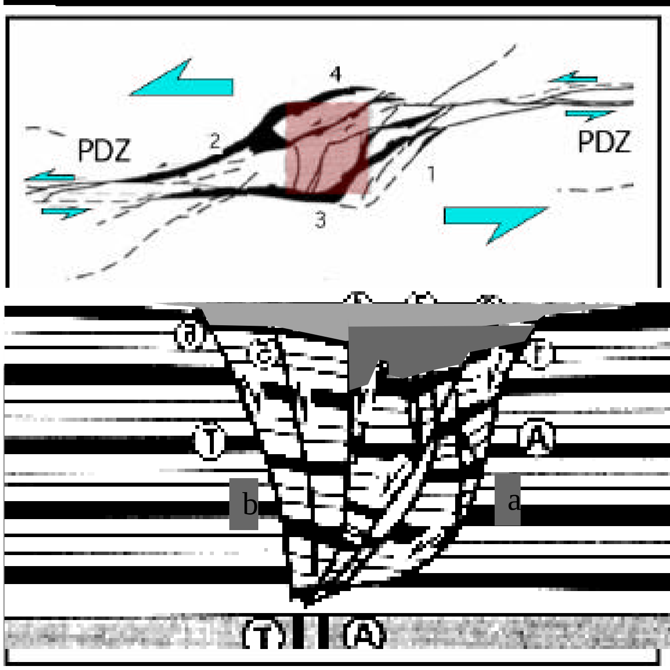


Figure 12: Shallow fault map within the MPU at Marker 34 (USGS C-zone) horizon and proposed pull-apart basin (light gray stipple). Regional structural dip is to the east. Fault segments with dip slip greater than 100 feet are shown as bolder lines. Axial inline rhomb-shaped half-grabens shown in dark gray. Grabens marked with stripe pattern. Unit boundary and coastline shown for reference.





- a-d = timing of major sidewall faults
- Rhomboidal shape of analog basin above 90 degree overlap = MPU East Basin (EB) architecture
- EB PDZ aligns w/ regional transcurrent FZ (Casavant, 2001)
- Analog x-section Milne Point Basin faulting at shallow depth (950ms)- model suggests deeper linkage to basement block boundary
- Active sidewall faults (a,b) of analog relate to MPU faults that exhibit greatest throw, shearing, & reactivation

Figure 13: West to East shallow seismic cross-section in southern portion of Milne 3D survey and analog modeling (Dooley & McClay, 1997; McClay & Dooley, 1985).

Fry Analysis (1979)
"center-to-center"

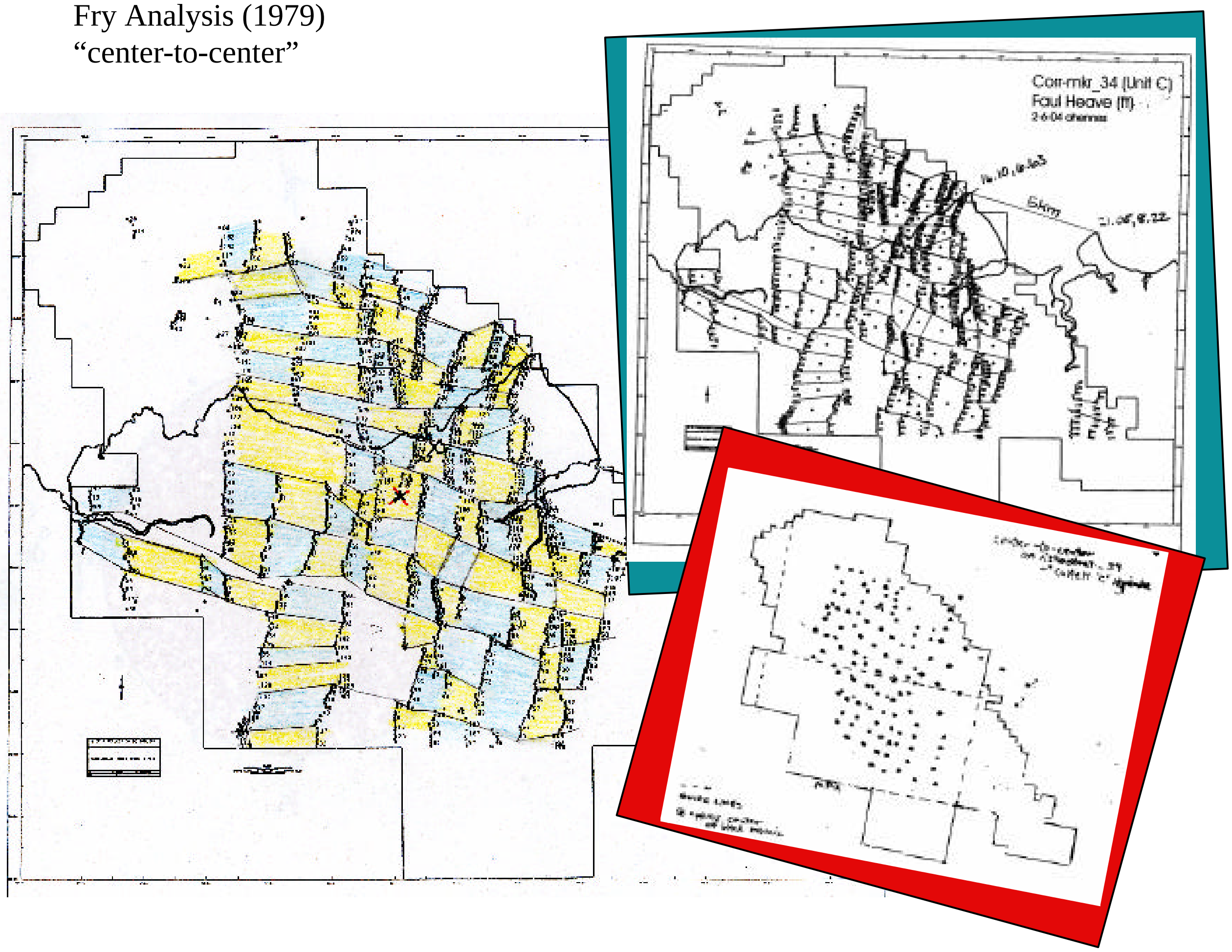


Figure 14: Fault heave and stress field analyses, MPU area

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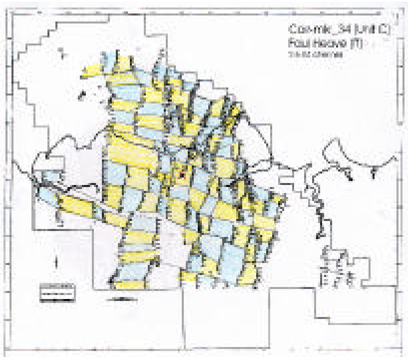
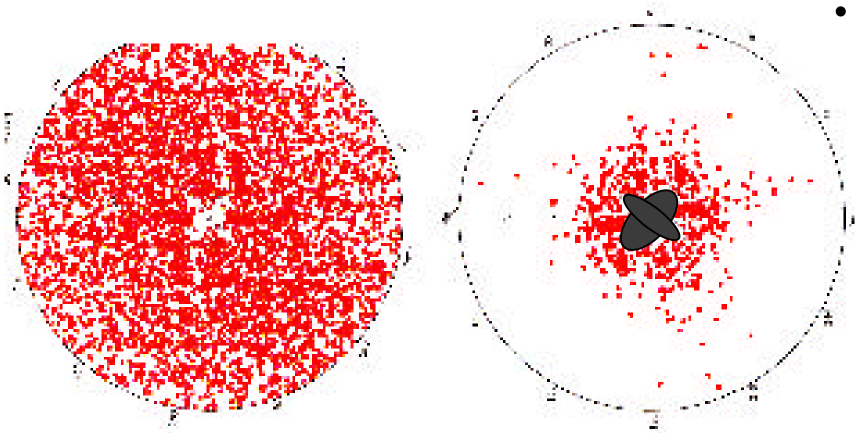


Assumption: Initial random, “anticlustered” distributed points or polygons, Deformation of object centers

Closer together = shortening direction

Further apart = parallel to maximum horizontal stress S_1

- Finite strain ellipse results
- Fry plot + en echelon, relays + normal faulting = oblique normal deformation



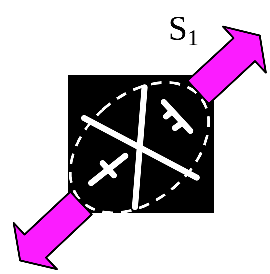


Figure 15: Analyses of maximum horizontal stress field and shallow fault polygon interpretations, MPU area

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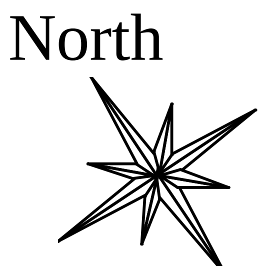


Idealized pull-apart basin attributes from analog modeling

- Inactive borderland structures
- Oblique-reverse fault
- Terraced sidewall fault zone
- Cross-basin fault zone
- Negative flower structure
- Relay ramp
- PDZ in-line graben/push-ups

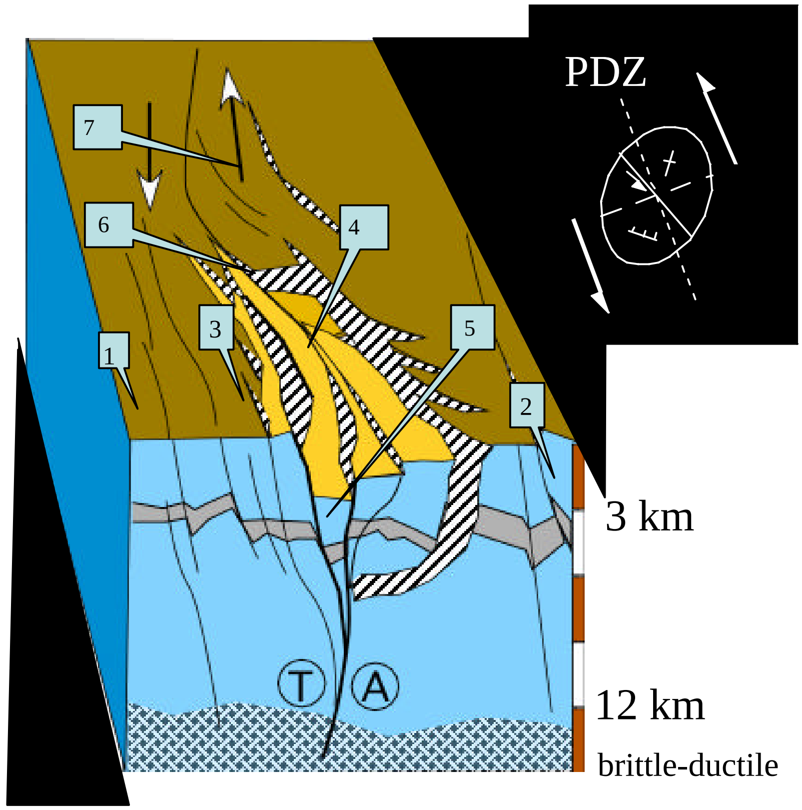
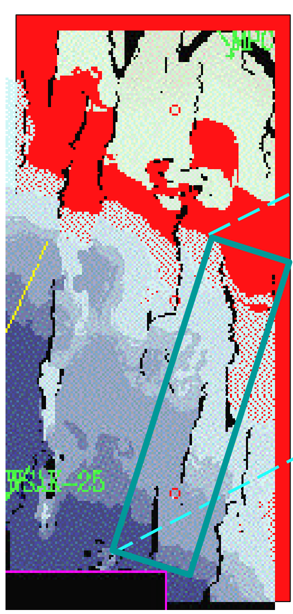
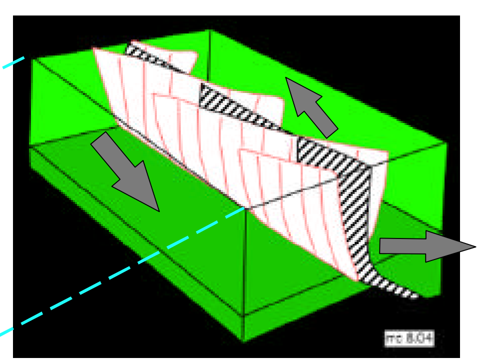


Figure 16: Diagrammatic interpretation of “Milne Point Basin”



En echelon Riedel shears



1. releasing right-stepping overlaps
2. Riedel shears link to PDZ at depth
3. transtensional; oblique normal offset
4. prone to inversion & fault reactivation

Figure 17: Transtensional features and Riedel shears in relation to fault interpretations

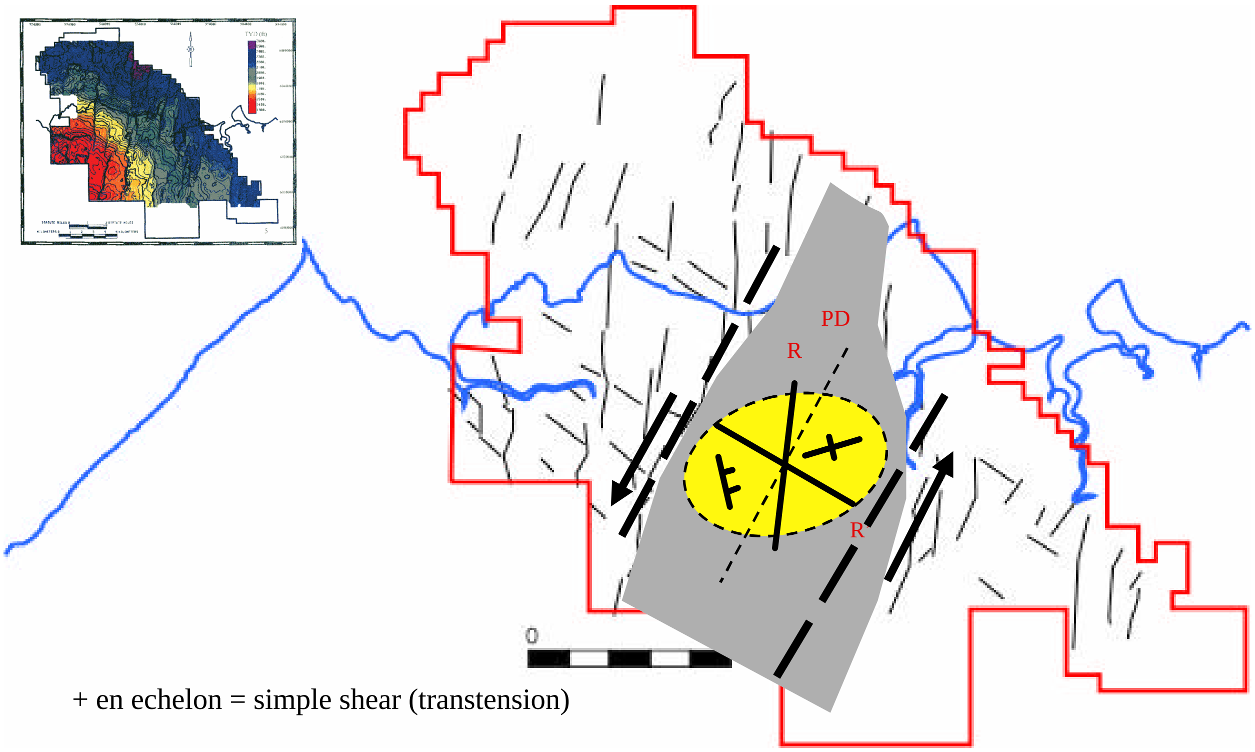


Figure 18: Lineament study and en echelon faults relative to interpreted pull-apart basin.

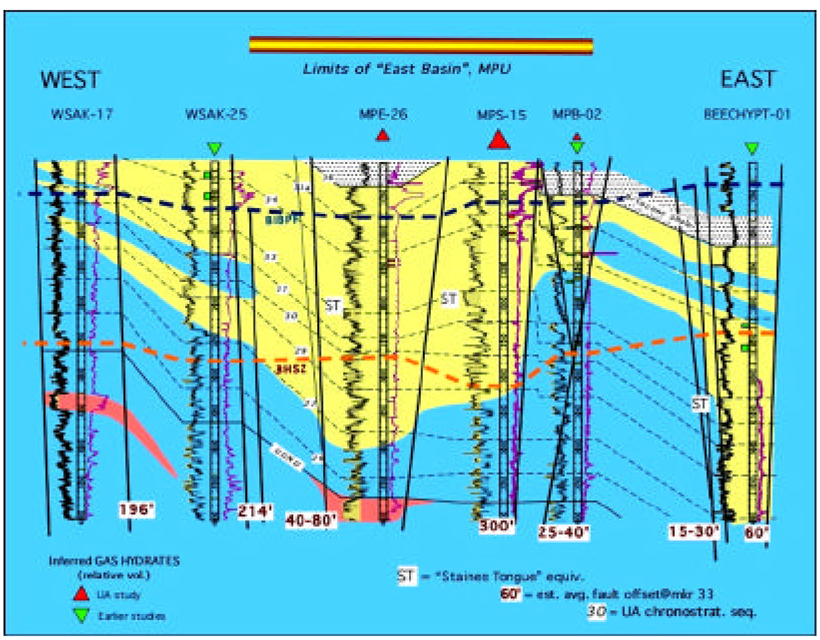


Figure 19: Log-based shallow stratigraphic interpretations in MPB with wells projected from the south of cross section line in Figure 7.

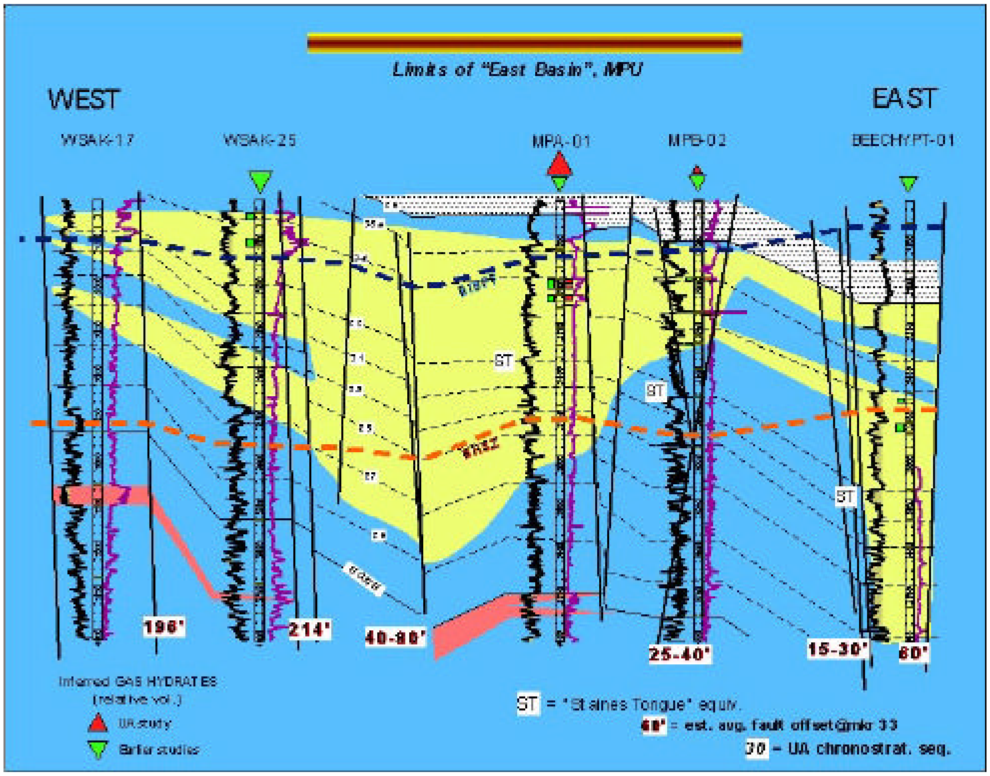


Figure 20: Log-based shallow stratigraphic interpretations in MPB with wells projected from the north of cross section line in Figure 7.

5.6.1.3 Summary of Milne Point Transtensional Basin Interpretation

- Developed theory for transtensional basin architecture within MPU structural setting
  - Localized structural controls on sediment deposition and petroleum migration
  - Interaction with regional basement tectonics and potential reactivation of deeper-seated structures for basin inversion
  - Linkage of basin and fault morphology to gas hydrate occurrence in petroleum system
  - Interaction of potential thermogenic, biogenic, and coal sources for gas
  - Study of reservoir continuity, distribution, heterogeneity, thickness, net-gross, porosity, and permeability variations
  - Observation of anomalous stratigraphic thickening and thinning correlative to graben distribution within Marker 34 (USGS Zone C equivalent).
  - Interpretation of transtensional features and Riedel, or additive, shears in relation to regional stress field, maximum compressive stress, and fault interpretations.
  - Analyzed fault heave and mapped spatial relations of stress fields.
  - Interpretation of en echelon fault trends, lineaments, and left-lateral pull-apart basin.
  - Interpretation of potential stratigraphic depocenters in relation to fault system.
  - Influence of deep-seated NW-trending lineament on shallow fault system.
  - Relation of depocenters, geomorphology, and fluid contacts to structural hinge lines.
  - Establishment of chronostratigraphic framework from well log correlations.
  - Explanation of discontinuous gas hydrate-bearing reservoir systems complicated by intraformational unconformities and structural discontinuities.

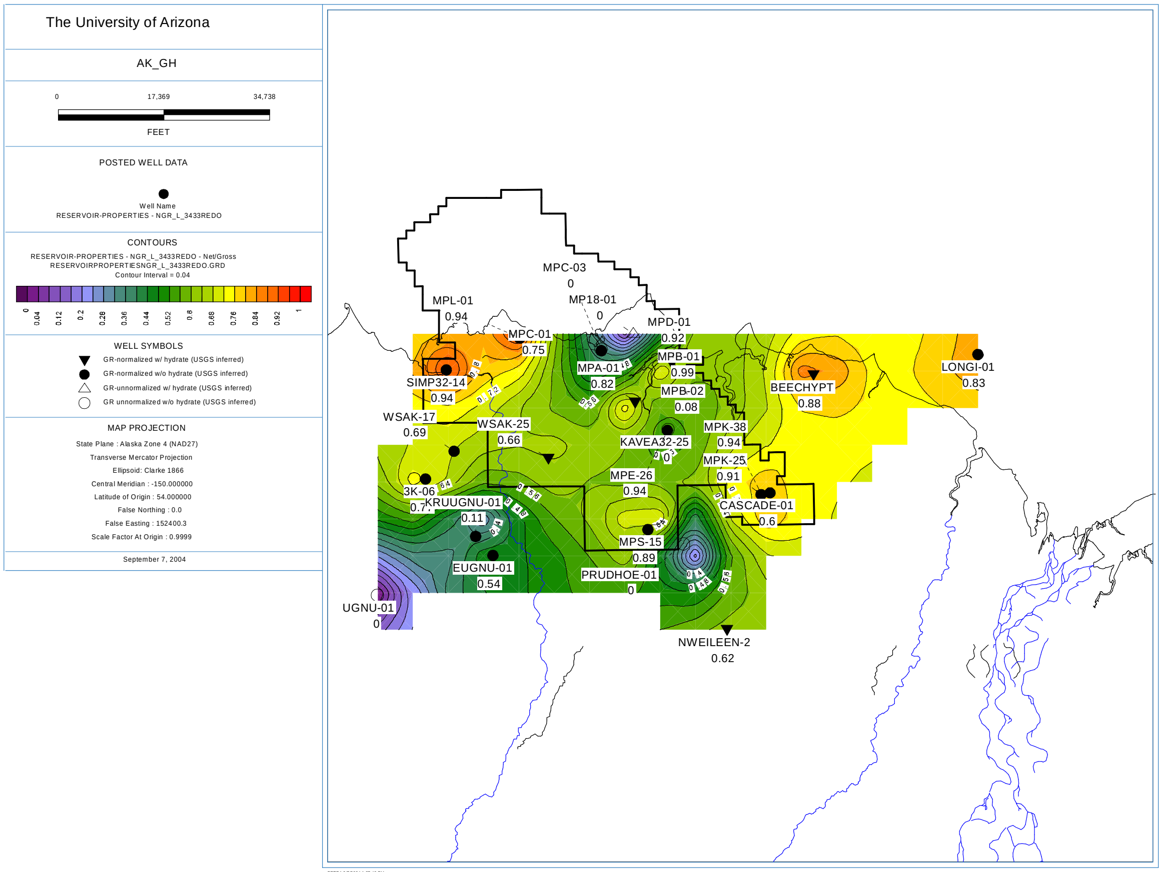


Figure 21: Net to gross (sand/shale) isopachs from normalized gamma ray logs for Lithostratigraphic interval L_34-33, corresponding to the USGS Hydrate C horizon.

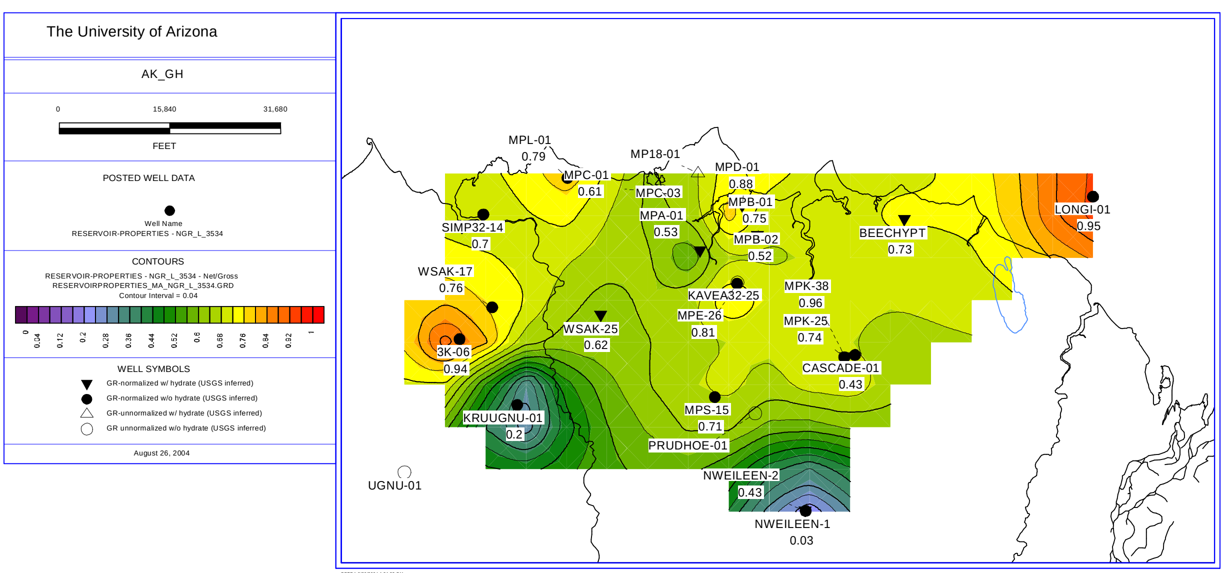


Figure 22: Net to gross (sand/shale) isopachs from normalized gamma ray logs for Lithostratigraphic interval L_35-34 corresponding to the USGS Hydrate D horizon.

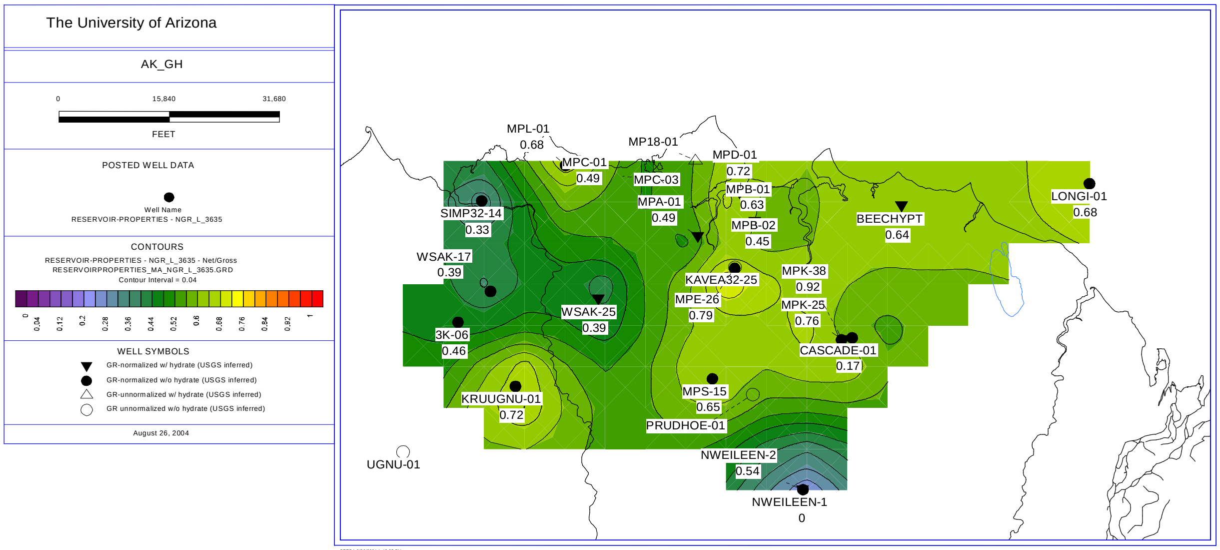


Figure 23: Net to gross (sand/shale) isopachs from normalized gamma ray logs for Lithostratigraphic interval L_36-35 corresponding to the USGS Hydrate E horizon.

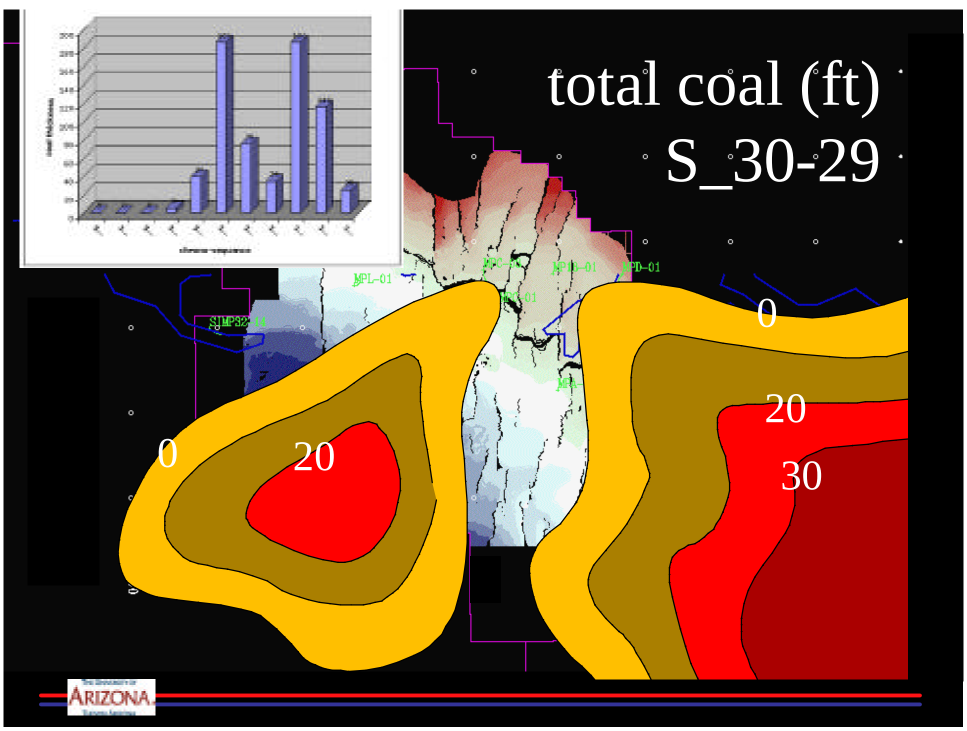


Figure 24: Analysis of coal-bearing stratigraphic interval 30-29 studied in relation to potential gas hydrate-bearing reservoir units. Isopach of coal thickness adjacent to interpreted MPB. Coal thicknesses are reflected in lithostratigraphic interval L_30-29 in the graph inset. The base map is a seismic structure map from Hagbo (2003) at the top of the USGS Hydrate C horizon or lithostratigraphic interval L-34. Blue represents shallow and red represents deeper depths.

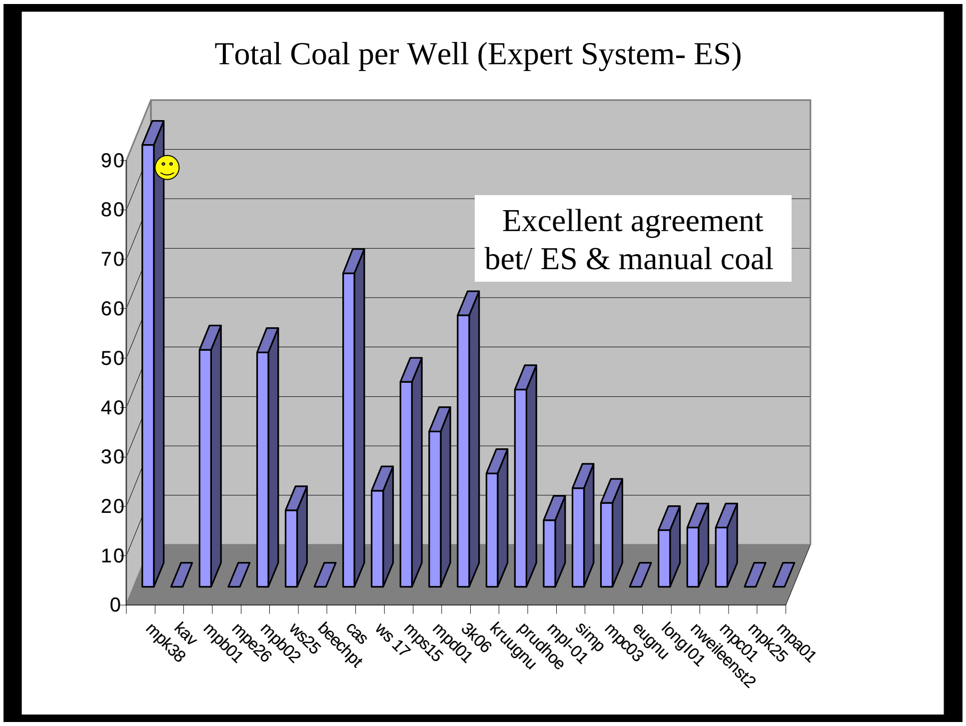


Figure 25: Well data interpretation of coal-bearing sequences

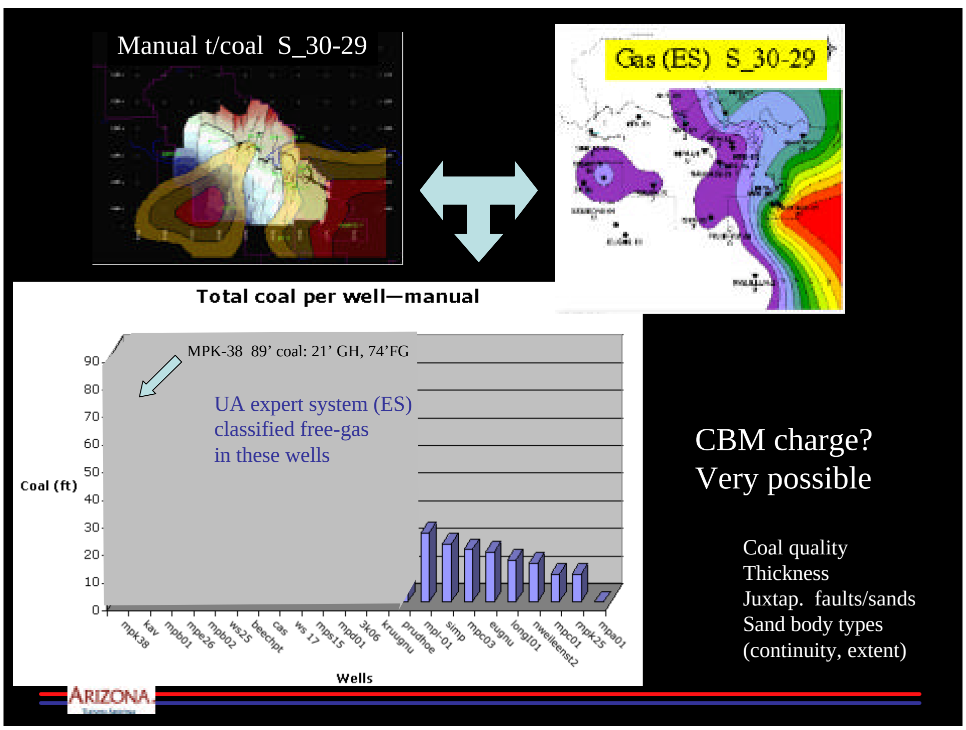


Figure 26: Study of possible coal-bed methane charge for potential gas hydrate bearing reservoirs

5.6.1.4 Alternative Volumetrics Interim Findings

Calculated preliminary volumetrics for gas hydrate- and associated free gas-bearing intervals within a 2-mile radius of the MPU S-pad area using sequence-stratigraphic approach (Table 2). This volumetric assessment differs significantly from the high-graded, seismic-driven prospect (Task 5.0) approach discussed in Section 5.5.

Table 2: MPU S-pad area preliminary, log correlation-based volumetrics calculations for gas hydrate and associated gas, UA gas hydrate- and free gas-bearing stratigraphic sequences

Sequence	Area (ft^2)	Thickness (ft)	Porosity	Saturation	1/Bg	Pore-filling Fluid Type	Volume (BCF)
35-34	188958626	19	43%	80%	164	Gas Hydrate	199
34-33	188958626	36	40%	80%	164	Gas Hydrate	355
33-31	58222494	19	37%	80%	164	Gas Hydrate	55
30-29	123231091	2	40%	80%	83	Gas	6
29-28	58222494	13	38%	80%	87	Gas	20
Total	**617593333**	**88**					**635**
Average			**40%**	**80%**			

5.6.1.5 Work In-Progress

- Fine-tuning geological and geophysical interpretations
- Evaluating and selecting prospective areas
- Helping guide regional and local reservoir model descriptions
- Planning slice mapping of established chronostratigraphic units
    - Determine relation to sand body geometry and depositional environment
    - Recalculate gas and gas hydrate-bearing reservoir petrophysics and volumetrics
- Integrating seismic interpretation with regional log-based chronostratigraphic correlations
- Studying possible gas hydrate occurrence connections including active deeper-seated thermogenic fault-related migration conduits and possible coalbed methane relation
- Connecting geomorphologic evidence to gas hydrate occurrence and structural control
- Evaluating regional structural-stratigraphic controls
- Linking reservoir unit heterogeneity to structure, fluid occurrence, paleodepositional reconstructions, and reservoir connectivity

5.6.1.6 Continuing Needs and Future Work

- Development of a new seismic-based_sequence stratigraphic framework in the MPU that will be guided/trained by the current log-based sequence stratigraphic framework.
- Use this seismic framework to guide development of a new seismic facies classification scheme and assessment of lateral and vertical continuity of sand bodies in the Sagavanirktok formation that may provide input into a seismic expert system or neural network.
- Development of spatial analysis of fault morphology relative to porosity, reservoir and non-reservoir facies development for prospect development.
- Development of a comprehensive set of geologic maps for all sequences across the AOI
    - Help prioritize locations for potential future data acquisition
    - Help quantify potential regional resource and structural/stratigraphic compartmentalization

5.6.2 Subtask 6.2: Seismic Attribute Characterization and Fault Analysis – UA

5.6.2.1 Modified from 2004 AAPG Gas Hydrate Hedberg Research Conference Poster

Seismic Characterization of a Shallow Gas-Hydrate-Bearing Reservoir on the North Slope of Alaska, Andrew M. Hennes, Roy A. Johnson, and Robert R. Casavant, University of Arizona, Department of Geosciences, Tucson, AZ, 85719

Naturally occurring gas hydrates on the North Slope of Alaska represent a potentially large resource of methane gas. In the Milne Point Unit (MPU), gas hydrates occupy thin, highly faulted, syndepositional sand intervals in the Tertiary Sagavanirktok Formation within and below ice-bearing permafrost within the gas hydrate stability zone. Detailed structural analysis, including mapping of fault throw and growth using a modern 3-D seismic volume constrain the recent faulting history. Time- and space-variant fault activity during gas migration through and into shallow reservoir sands imply models for 1) initial migration of deeper thermogenic gas into the current gas hydrate stability zone (GHSZ) and 2) deposition of reservoir and gas hydrate-prone facies. Field-wide fault-seal calculations, based on modified shale gouge ratio (SGR) and clay smear potential (CSP) algorithms show lateral variability in fault seal potential along gas hydrate-bearing horizons and suggest a mechanism for trapping initial free gas which later combined with water to form gas hydrates. Seismic waveform classification along with well-log-interpreted gas-hydrate-bearing horizons helps define distributions of gas hydrate-similar waveforms, representing potential gas hydrate, whose lateral variations are consistent with fault location, fault activity and fault-seal calculations. Potential gas-hydrate distributions bounded by faults with greater sealing potential yield potential future production targets.

Detailed analyses of fault trends, throw, growth, and seal with respect to interpreted gas hydrate accumulations within 3 major stratigraphic intervals were presented in the June 2004 Quarterly Report (pages 15-28, figures 1-12, and table 2) and at the AAPG Hedberg Research Conference in September 2004. Interpreted gas-hydrate distributions are strongly controlled by north-northeast-trending faults, especially in the eastern MPU, which is consistent with trends observed in fault activity and fault-seal potential. These results support a model in which thermogenic free-gas migrated up active faults into the most permeable sand intervals and was subsequently trapped by sealing faults (Figure 27). This trapped free-gas most recently formed gas hydrates with regional depression of the geothermal gradient (Collett, 1993). Distribution of gas-hydrates within the MPU is likely controlled by sealing/barrier/baffle-faults, location of original gas-conduit/migration faults, and depositional and structural geometry of gas hydrate-prone sands.

5.6.2.2 Work in Progress

- Rationalizing differing time-depth interpretations for UA versus USGS study
- Studying effects of permafrost on waveform classification.
- Incorporating revised MGE picks for stratigraphy, BIBPF, and gas hydrate stability base
- Continuing revision of supervised waveform classification based on gas hydrate and no gas hydrate waveforms as other interpretations are revised.
- Reviewing Task 5.0 gas hydrate prospects within MPU
    - Interpreting free gas near K-pad and Cascade.
    - Tracking high-amplitude responses.
- Creating amplitude scan on BGHSZ surface for free-gas interpretation.

    - Dependent upon receipt of improved surface from USGS or UA.
- Incorporating edits from BP and others into Hennes prepublication manuscript.
- Cataloging work done to date and relevant Landmark files for smooth transition between Reflection Seismology students.

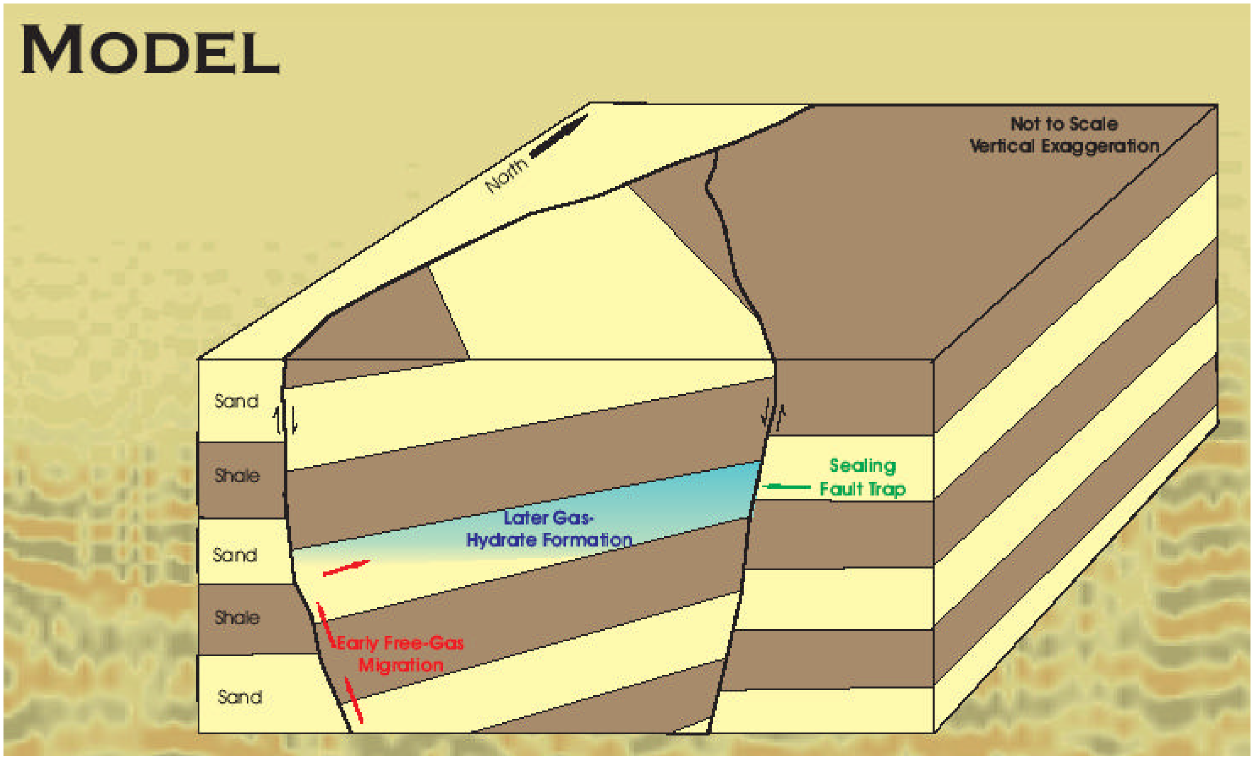


Figure 27: Diagrammatic model showing migration of thermogenic free-gas up active faults into reservoir sands with trap by sealing faults. Trapped free-gas later formed gas hydrates in combination with connate waters with regional depression of the geothermal gradient.

5.6.2.3 Future Work

- Identify target areas for gas hydrate-bearing reservoirs
    - Include highly detailed seismic interpretation, fault models, migration models.
- Submit Hennes Prepublication to AAPG Bulletin following BP/project review.
- Complete processing on NW Eileen 3D survey to further increase Signal/Noise ratio.
- Interpret seismic horizons at top and bottom of hydrate-bearing intervals (if increased resolution allows) to yield better volumetric estimates.
- Continue search for associated free gas.
    - Rectify free-gas interpretations in Cascade well with NW Eileen 3D survey
    - Track and tie this interpretation to Milne Point 3D survey.
- Obtain GIS information from North Slope, if possible, to correlate surface features to anomalous events in the 3D seismic data. Possible questions:
    1. Do lakes occur over gas chimneys?
    2. Do lakes thin permafrost, thus affecting shallow statics and time/depth conversion?
    3. Do lakes/rivers/surface features trend with faults?

4. Did lakes/rivers affect acquisition and statics that may explain areas of anomalous seismic data?

- Obtain raw shot gathers (from BPXA) for additional processing, if available.
- Obtain cubes (from BPXA) for AVO analysis, if available.
- Obtain deeper data to complete more comprehensive fault analysis, if available.

5.6.3 Subtask 6.3: Petrophysical and Neural Network Attribute Analysis – UA

5.6.3.1 Introduction

One component of the UA research is applying artificial neural network analysis (ANN) to help characterize and predict gas hydrate and free-gas resources. In this subtask, trained neural networks classify lithologies (sand, coal, shale) and fluids (gas hydrate, gas, water) in 0.5 foot increments from normalized gamma ray, resistivity, sonic, density, and neutron porosity well log curves.

A neural network is also able to analyze seismic waveform characteristics that represent a horizon and form robust templates that can be used to match waveforms through a seismic volume (Poulton, 2001, 2002). A very preliminary study uses neural networks to identify and map interpreted gas hydrate-bearing facies within the MPU seismic volume by analyzing the morphology of wavelets within a specified horizon. A preliminary analysis resulted in an initial model for methane hydrate formation in the MPU using a self-organizing map (SOM) (Zhao, 2003). An unsupervised (untrained) classification was performed using three seismic attributes: instantaneous frequency, amplitude acceleration, and dominant frequency extracted from 3D seismic data. The classification results of the seismic attributes showed that the SOM classification of interpreted gas hydrate-bearing zones correlated in several areas with gas hydrate-bearing zones identified in well logs. The dominant frequency attribute produced the most consistent results for tracking layers of suspected methane hydrate. In general, zones identified as possible gas hydrate-bearing layers were characterized by relatively high dominant frequency. Early SOM classifications were completed before satisfactory time-depth corrections for the seismic data, full stratigraphic analyses, chronostratigraphic sequencing, and fault pattern analyses were completed. Future plans include tying lithology and fluid classifications for each well to the seismic data and conducting a detailed investigation of the wavelet morphology for each class. Refined volumetric estimates of gas hydrate and gas within the MPU are planned based on the identification of waveform signatures for gas hydrate- and associated gas-bearing reservoirs.

As previously reported, an expert system has been developed to interpret the type of fluids present within reservoir intervals from the well logs (Glass, 2003). Results of this expert system for the NWEileen-02 well show good correlation with the ANN results.

5.6.3.2 Radial Basis Function Neural Networks

All neural networks have at least three components in common: the neuron, node, or processing element (PE), the connection weight, and discrete layers that contain the PEs and are connected by the weights (Figure 28). The PE is the basic computational unit in a network and is classified according to its role in the network. A PE that receives information only from an external source, an input file for example, is called an input PE. Input PEs may scale the incoming values before passing them on but otherwise, they perform no computation. A PE that passes its computed values to an external source, an output file for example, is called an output PE. The output PEs also compute the error values for networks performing supervised learning (learning in which a desired output value is provided by the operator). Any PE that is not in an input or output layer is referred to as a hidden PE. The term hidden is used because these PEs have no direct connection to the external world. In a biological model, input PEs would be analogous to sensory neurons in our eyes, ears, nose, or skin; output PEs would be motor neurons that cause muscles to move; hidden PEs would be all the remaining neurons in the brain and nervous system that process the sensory input.

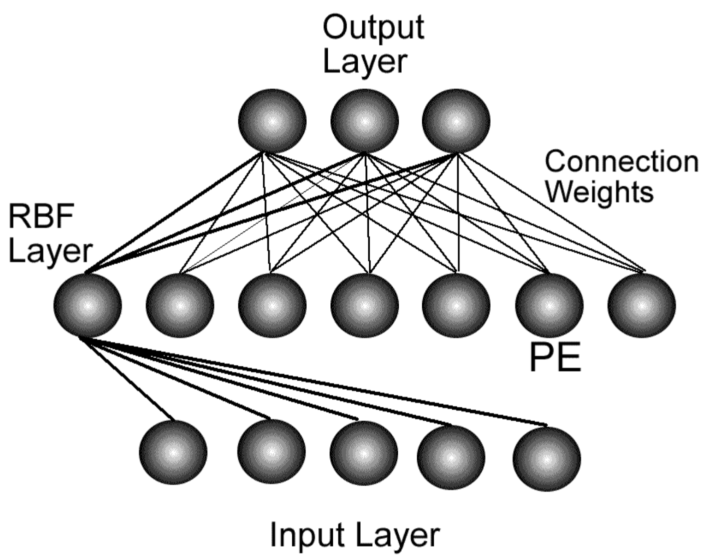


Figure 28: Example architecture of a radial basis function (RBF) neural network. Samples of well log data such as gamma-ray, resistivity, or sonic velocity are passed through the input layer. The RBF layer finds appropriate centers and widths of Gaussian kernel functions to separate the log values into user-defined classes such as gas hydrate, gas, or water and sand, coal, or shale defined by the output layer.

There are many types of neural networks. A radial basis function was used for the well log classification. The basic premise of Radial Basis Function (RBF) neural networks is that if input patterns are mapped to a higher dimensional space, there is a greater chance that the problem will become linearly separable based on Cover's Theorem (Cover, 1965; Haykin, 1999). The input pattern is non-linearly mapped to this higher dimensional space through the use of radially symmetric functions (usually Gaussian). Input patterns that are similar will be transformed through the same RBF node. The training process starts with an unsupervised phase during which the center and width of each RBF node must be trained. The centers start with random values and for each input pattern; the center with the minimum distance to the input pattern is updated to move closet to that input pattern. Once the center vectors are fixed, the widths of the RBFs are established based on the root-mean-squared distance to a number of nearest neighbor RBFs. When the unsupervised phase is over, the connection weights between the RBF layer and the output layer are trained. The basic equations for an RBF network are shown in Section 5.6.3.4.

5.6.3.3 Estimating Pore Fluid Concentrations Using an Expert System

The foundation for using an expert system to estimate pore fluid concentrations is the Bulk Elastic Moduli (BEM) model. The BEM model treats the porous media of the Alaska North Slope as uncemented, two-phase mixtures of quartz and pore fluids. Bulk elastic moduli of such a porous media can be estimated by knowing:

1. The volume fractions of the constituents,
2. The elastic moduli of the constituents, and
3. The geometric details of the arrangements of the constituents.

Since the geometric details of the packing and cementation are unknown and cannot be inferred from down-hole logging tools available to us, estimates of only upper and lower bounds for the elastic moduli can be made (Mavco et al., 1998). Geometrically, the BEM model consists of spheres of material one surrounded by a shell of material two. The upper bound on moduli is realized when the higher modulus material forms the shell. The lower bound on moduli is realized when the lower modulus material forms the shell.

The Vsaturated term in Equation 4 (Section 5.6.3.5) is plotted in Figure 29 along with measured sonic velocity in well WSAK-17. Regions where the behavior of the two curves differs in shape in Figure 29 (blue arrows are examples) cannot be explained solely by pore saturation with water, hence we assume pore fluid constituents other than or in addition to water exist. In all cases identified by the blue arrows in Figure 29, the measured sonic velocity is lower than the expected water saturated velocity, so an interpretation of free methane gas is made. Where the behavior of the two curves is similar (red arrows are examples), variations in velocity are assumed to be due to porosity changes in water saturated sediment. Deviations of the measured sonic velocity above Vsaturated indicate hydrate, ice, petroleum, or cementation. The decision among the first three possibilities is based on the position of the measurement relative to the ice and hydrate stability fields. Cementation is not considered.

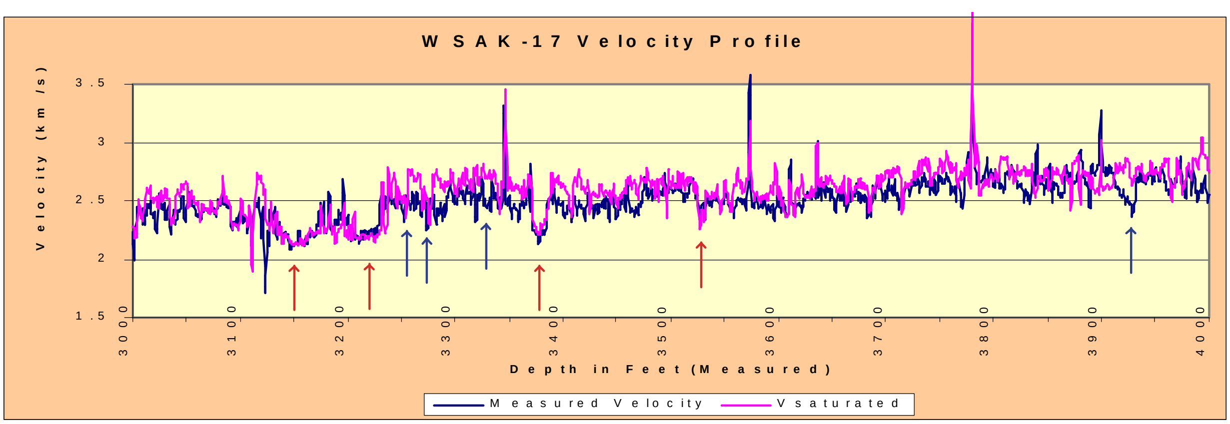


Figure 29: Velocity profile for well WSAK-17 showing a comparison of measured velocity and estimated water saturated sediment velocity (Vsaturated).

The expert system approach uses logical inference to accomplish decision making. The tree structure comprising the knowledge base can be represented as shown in Figure 30, where Vsat and Rsat are the compressional wave velocity and electrical resistivity for water saturated sediments, r200 and Nf200 are the bulk density and Neutron Porosity profiles smoothed using a 200 foot low pass filter, g is the gamma ray signature in API units, p(wi) is the a priori probability that a given pore fluid exists and HSF is the depth to the base of the hydrate stability field (estimated using temperature and pressure). Vsat is estimated using the BEM algorithm and Rsat is estimated using the Archie equation.

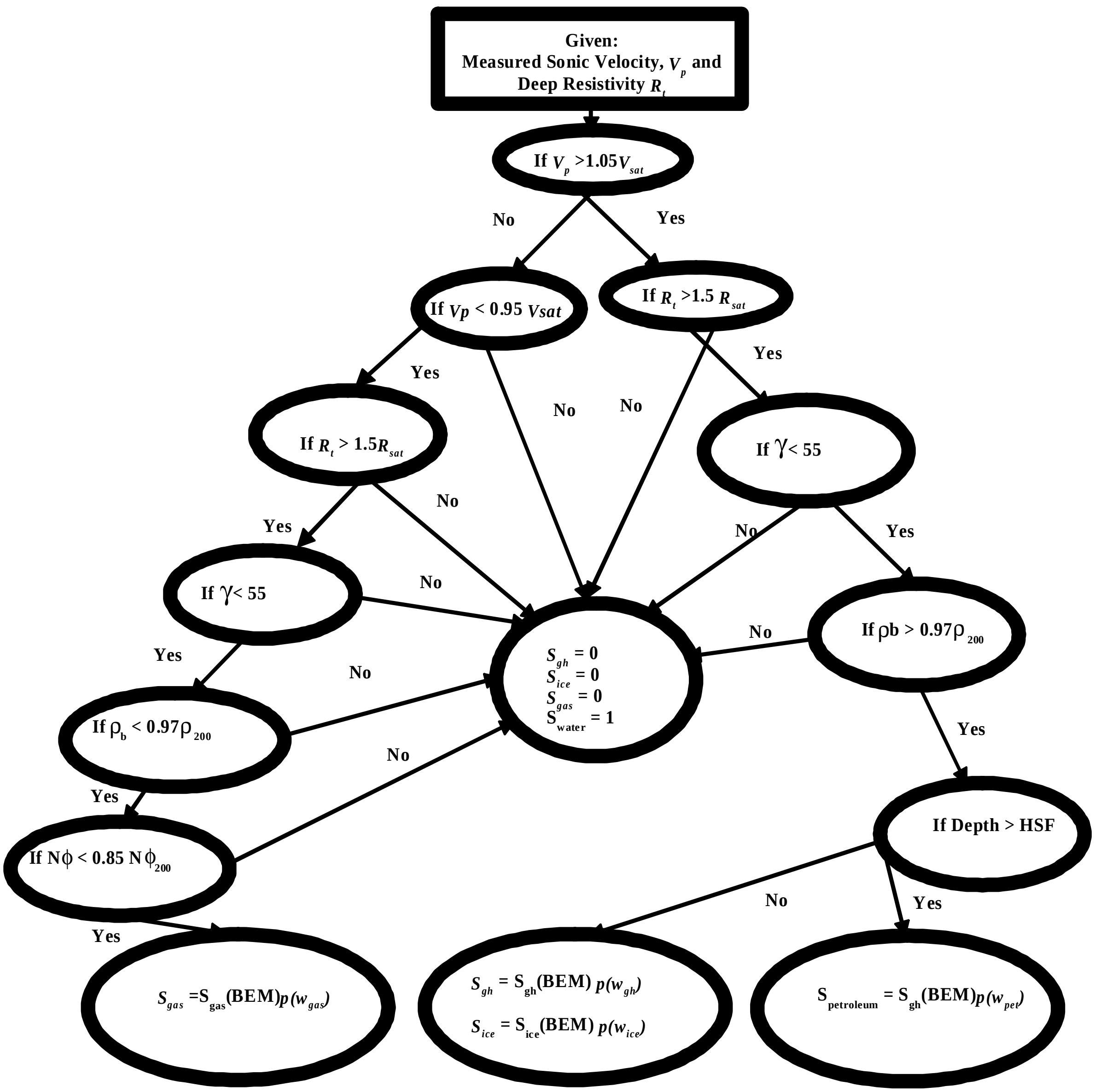


Figure 30: Tree Structure for the Expert System

5.6.3.4 Basic Equations for an RBF network

Radial basis function (RBF) neural networks are a class of feed forward neural network implementations that are not only used for classification problems, but also for function approximation, noisy interpolation and regularization. RBF methods have their origins in work by Powell (1987), in which he shows that RBFs are a highly promising approach to multivariable interpolation given irregularly positioned data points. This problem can be formulated as finding a mapping function f that operates from a n-dimensional input or data space R^n to a one-dimensional output or target space R, which is constrained by the interpolation condition,

$$f(\vec{x}_i) = y_i \quad \forall i = 1, 2, \ldots, P, \tag{1}$$

where each of the P known data points consist of an input vector $\vec{x}_i$ and a corresponding real value y_i. The system of functions used for this interpolation is chosen to be from the set of RBFs b_i, which depend on the selection of the known data points $\vec{x}_i$. The RBFs $b_i(\|\vec{x} - \vec{x}_i\|) \quad \forall i = 1, 2, \ldots, P$ are continuous non-linear functions, where the i-th RBF b_i depends on the distance between any data point $\vec{x}$ and the i-th known data point $\vec{x}_i$, typically the Euclidean norm of $\Re^n$. Therefore, the mapping function can be approximated as a linear combination of the RBFs b_i with the unknown coefficients w_i,

$$f(\vec{x}) = \sum_{i=1}^{P} w_i \cdot b_i(\|\vec{x} - \vec{x}_i\|). \tag{2}$$

Inserting the interpolation condition (1) in the mapping function (2) results in a system of linear equations for the w_i

$$\sum_{i=1}^{P} w_i \cdot b_i(\|\vec{x}_j - \vec{x}_i\|) = y_j \quad \forall j = 1, 2, \ldots, P, \tag{3}$$

which can be rewritten in matrix notation as,

$$B\vec{w} = \vec{y} \quad with\ \vec{y} = \begin{bmatrix} y_1 \\ \vdots \\ y_P \end{bmatrix}, \vec{w} = \begin{bmatrix} w_1 \\ \vdots \\ w_P \end{bmatrix} and\ B = \begin{bmatrix} b_1(\|\vec{x}_1 - \vec{x}_1\|) & \cdots & b_P(\|\vec{x}_1 - \vec{x}_P\|) \\ \vdots & \ddots & \vdots \\ b_1(\|\vec{x}_P - \vec{x}_1\|) & \cdots & b_P(\|\vec{x}_P - \vec{x}_P\|) \end{bmatrix}. \tag{4}$$

Equation (4) can be solved by inverting the matrix B, assuming its inverse matrix B^{-1} exists

$$\vec{w} = B^{-1}\vec{y}. \tag{5}$$

Assuming that a Gaussian G_j is used in a generalized radial basis function (GRBF) neural network (Broomhead and Lowe, 1988; Moody and Darken, 1989; Poggio and Girosi, 1989; Girosi and Poggio, 1990; Musavi et al., 1992, Haykin, 1994; Zell, 1994; Bishop, 1995), then not only the centers $\vec{\mu}_j$ are calculated during the network training, but also the widths σ_j of each G_j. Both are calculated during the initial unsupervised training phase.

5.6.3.5 Equations for Bulk Elastic Modulus used in the Expert System

The bulk moduli are estimated using the equations in Appendix B (Hashin and Shtrikman 1963).

$$K^U_{bulk} = \left[\sum_i \frac{f_i}{K_i + \frac{4}{3} G_{shell}} \right]^{-1} - \frac{4}{3} G_{shell} \qquad \textbf{Equation 1}$$

$$G^U_{bulk} = \left[\sum_i \frac{f_i}{G_i + \Omega_{shell}} \right]^{-1} - \Omega_{shell} \qquad \textbf{Equation 2}$$

$$\Omega_{shell} = \frac{G_{shell}}{6} \left[\frac{(9K_{shell} + 8G_{shell})}{(K_{shell} + 2G_{shell})} \right] \qquad \textbf{Equation 3}$$

In the above equations the lower bounds are found by substituting "*sphere*" for "*shell*," f_i, K_i and G_i are the volume fraction, bulk modulus and shear modulus for material i. Parameters used in the model are provided in Table 1.

Table 3: **Parameters Used in BEM Model.**

Parameter	Value
$K_{Hydrate}$	7.9 GPa
$G_{Hydrate}$	3.3 GPa
$\rho_{Hydrate}$	0.9 g/cm^3
K_{Ice}	8.3 GPa
G_{Ice}	4.0 GPa
ρ_{Ice}	0.917 g/cm^3
K_{Water}	2.25 GPa
G_{Water}	0
ρ_{Water}	1.0 g/cm^3
K_{Quartz}	36.6 GPa
G_{Quartz}	45 GPa
ρ_{Quartz}	2.65 g/cm^3
$K_{Methane}$	0.4 to13 MPa*
$G_{Methane}$	0
$\rho_{Methane}$	2.6x10^{-3} to 72x10^{-3} g/cm^3*

**Value is a function of depth*

The seismic velocity (compressional wave and shear wave) of water-saturated porous media ($V_{saturated}$) is estimated using the bulk modulus values from Equations 1 through 3 together with measured or estimated bulk density. The degree of saturation of gas hydrate is then estimated as

$$S_{Hydrate} = \frac{V_{measured} - V_{saturated}}{V^U_{Hydrate} - V_{saturated}}. \qquad \textbf{Equation 4}$$

Similar equations are used for ice and free gas.

5.6.3.6 Training Set Description

Two basic types of training sets were created for this stage of the project. The first training set uses data from 3 log curves, gamma, resistivity, and sonic, for classifying log curves into fluid and lithologic classes (i.e. gas hydrate, coal, or sand). This network is denoted as ANN3 and uses representative signatures for each class from the wells in Figure 31. The wells in figure 31 show the log curves (normalized gamma with an API cut off of 55 API shaded, resistivity, sonic) and the depth intervals used as training samples for each output class. A total of 1,142 discrete patterns were used for ANN3. Each input pattern consists of three depth samples for each type of log. So, each training sample uses a 1.5 foot window of data. The window is shifted 0.5 foot downhole and the next 1.5 foot window is captured for training. An example of an input training pattern is shown in Table 4. Depth information is not included in the input pattern vector used by the neural network. Once the neural network is trained, the connection weights are held fixed and data from any well can be processed by the network to produce a fluid and lithologic classification.

Table 4: Three sample input training pattern vectors for ANN3.

Well	Depth	Gamma1	Gamma2	Gamma3	Resist1	Resist2	Resist3	Sonic1	Sonic2	Sonic3
MPA-01	1948	43.105	41.73	43.823	52.875	56.094	56.844	138.568	138.101	137.635
	1948.5	41.73	43.823	42.667	56.094	56.844	56.656	138.101	137.635	137.168
	1949	43.823	42.667	42.667	56.844	56.656	57.906	137.635	137.168	136.701

The second training set, ANN5, uses 5 log curves: gamma, resistivity, sonic, density, and neutron porosity. The wells used for training samples in ANN5 are shown in Figure 32. Similar to ANN3, ANN5 classifies hydrate, coal, sand, and, with the addition of the density and neutron porosity, can also classify gas. Since the density and neutron porosity logs typically have a starting depth deeper than the hydrate stability zone for many of the wells in our area of interest, the training samples for gas hydrate are more limited. This training set is primarily a refinement for coal classification and for identification of free gas. A total of 896 discrete patterns were used for ANN5. Results from ANN5 tend to classify fewer coal and gas hydrate intervals relative to ANN3. The addition of density porosity information refines the coal classification. Future improvement of ANN5 would incorporate more samples of coal-bearing intervals. Variations of ANN5 remove individual logs from training to accommodate interpretation of wells that are missing one or more types of logs. For example, if a well has a density log but not a neutron porosity log, the neural network is simply retrained, excluding the neutron porosity data as input. The neural network training results are sensitive to the selection of logs used as input in addition to the selection of depth intervals used to typify each lithologic or fluid class.

5.6.3.7 Neural Network Classification Application

The three or four output classes used by the neural network represent a very limited vocabulary and hence are non-unique under some situations. Once trained, the connection weights in the neural network are held constant and data from any well can be processed to produce a lithologic or fluid classification. Figures 33-34 show the ANN3 and ANN5 results superimposed on the cross sections from figures 19 and 20. The length of the bar for each depth interval represents a confidence in the classification from 0 to 1 (longer the bar, the more confident the interpretation). The NWEileen-02 well was tested by ANN3 in figure 35. The results for the NWEileen-02 well show very good correlation between the interpreted gas hydrate occurrence, the ANN classification of gas hydrate, and the expert system identification of gas hydrate. The first three tracks show the intervals classified as hydrate, coal or sand. The next tracks compare the expert system predictions for this well. The differences in predictor 2 and 3 are the exact thresholds used to determine each class (see Figure 30 for general criteria in the expert system). The cored hydrate intervals are also shown in Figure 35. The results for the NWEileen-02 well show a very good correlation between the known gas hydrate occurrence, the ANN classification of gas hydrate, and the expert system identification of gas hydrate. The confidence of the ANN classification is indicated by the length of the bar for each 0.5 foot interpreted interval. The expert system calculates percentage of gas hydrate in the interval from 0 to 1.

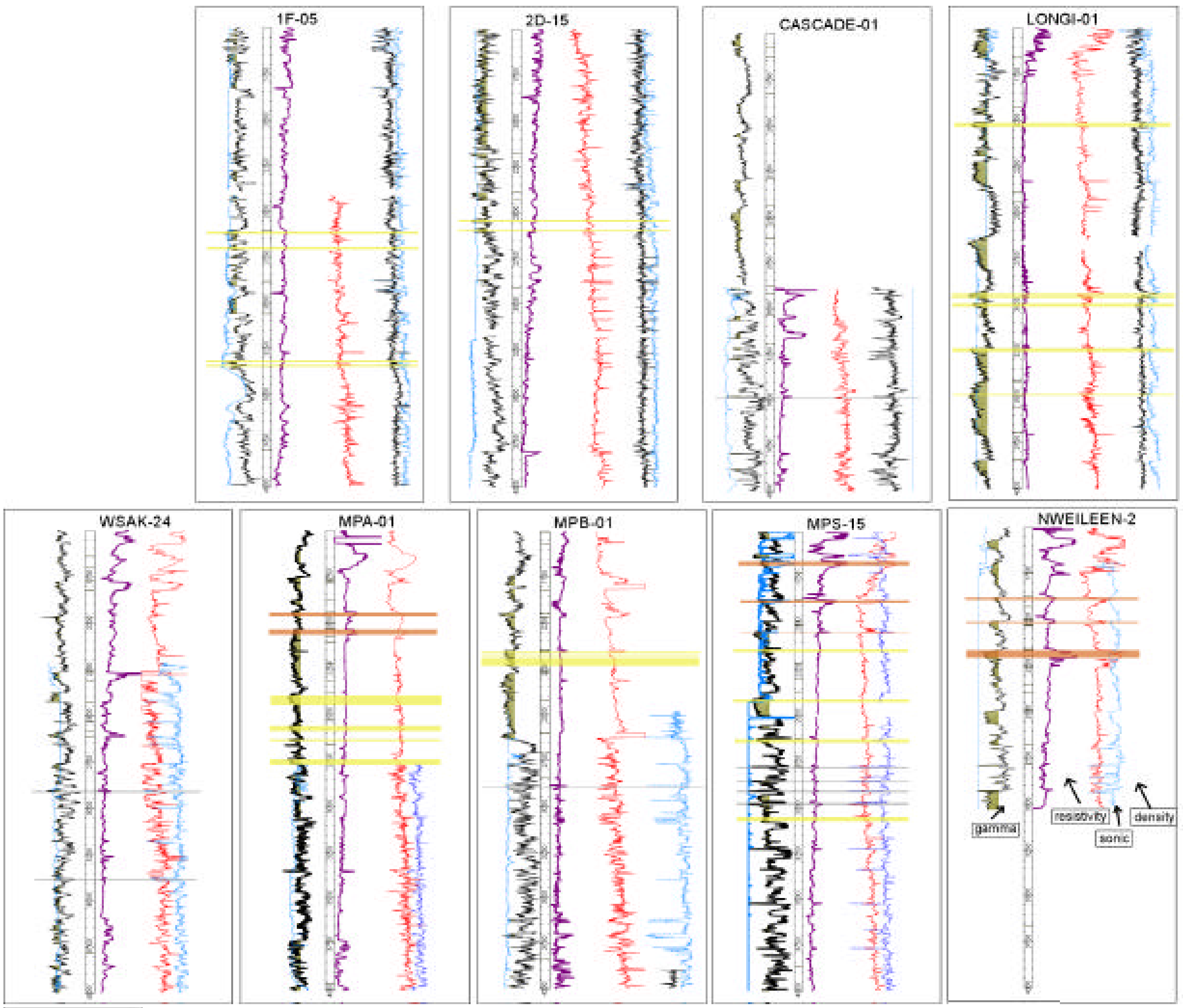


Figure 31: Log curves for wells in AOI used for ANN3 training. Intervals from which training samples for each output class were extracted are highlighted. ANN3 used gamma, resistivity, and sonic curves for training.

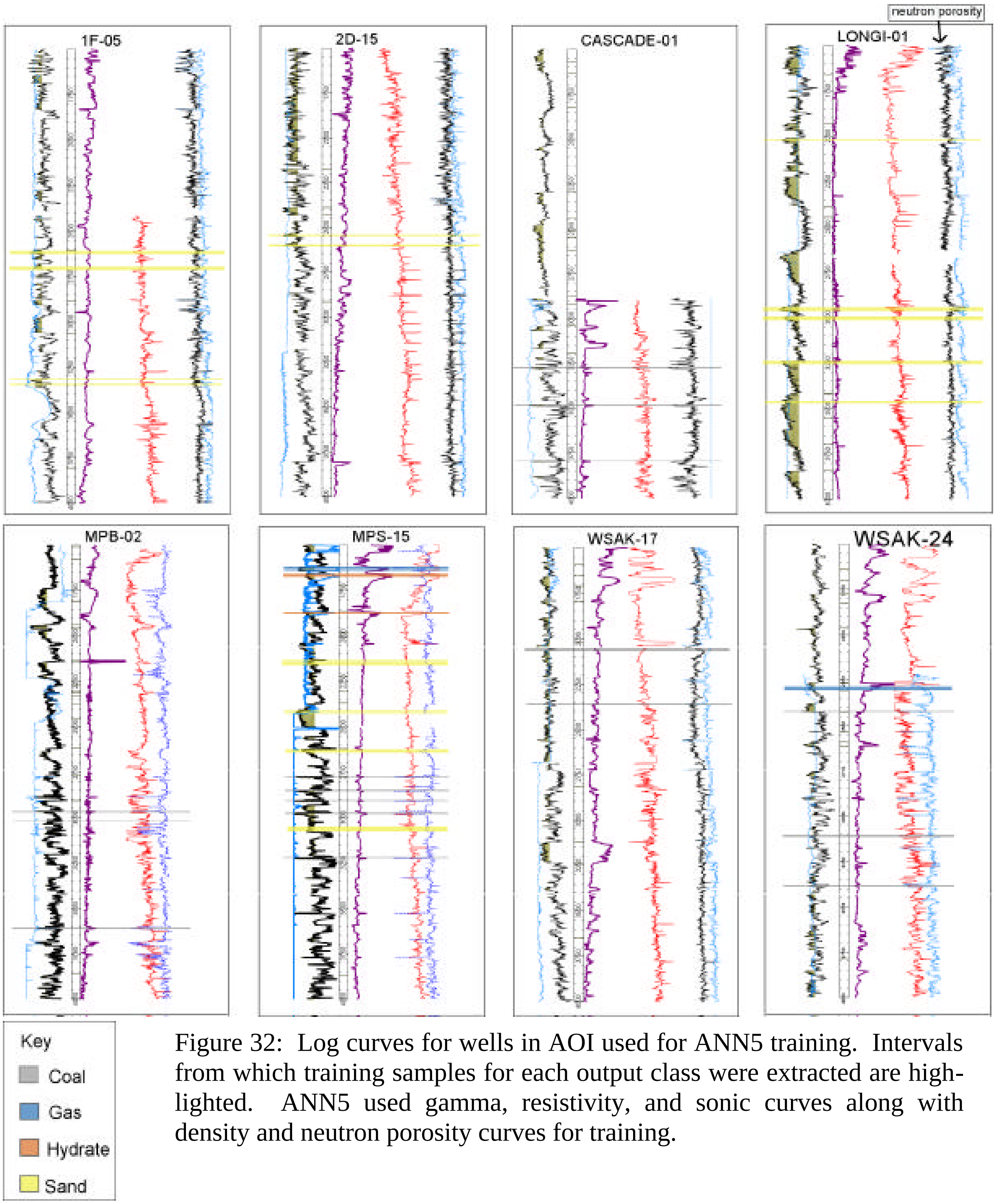


Figure 32: Log curves for wells in AOI used for ANN5 training. Intervals from which training samples for each output class were extracted are highlighted. ANN5 used gamma, resistivity, and sonic curves along with density and neutron porosity curves for training.

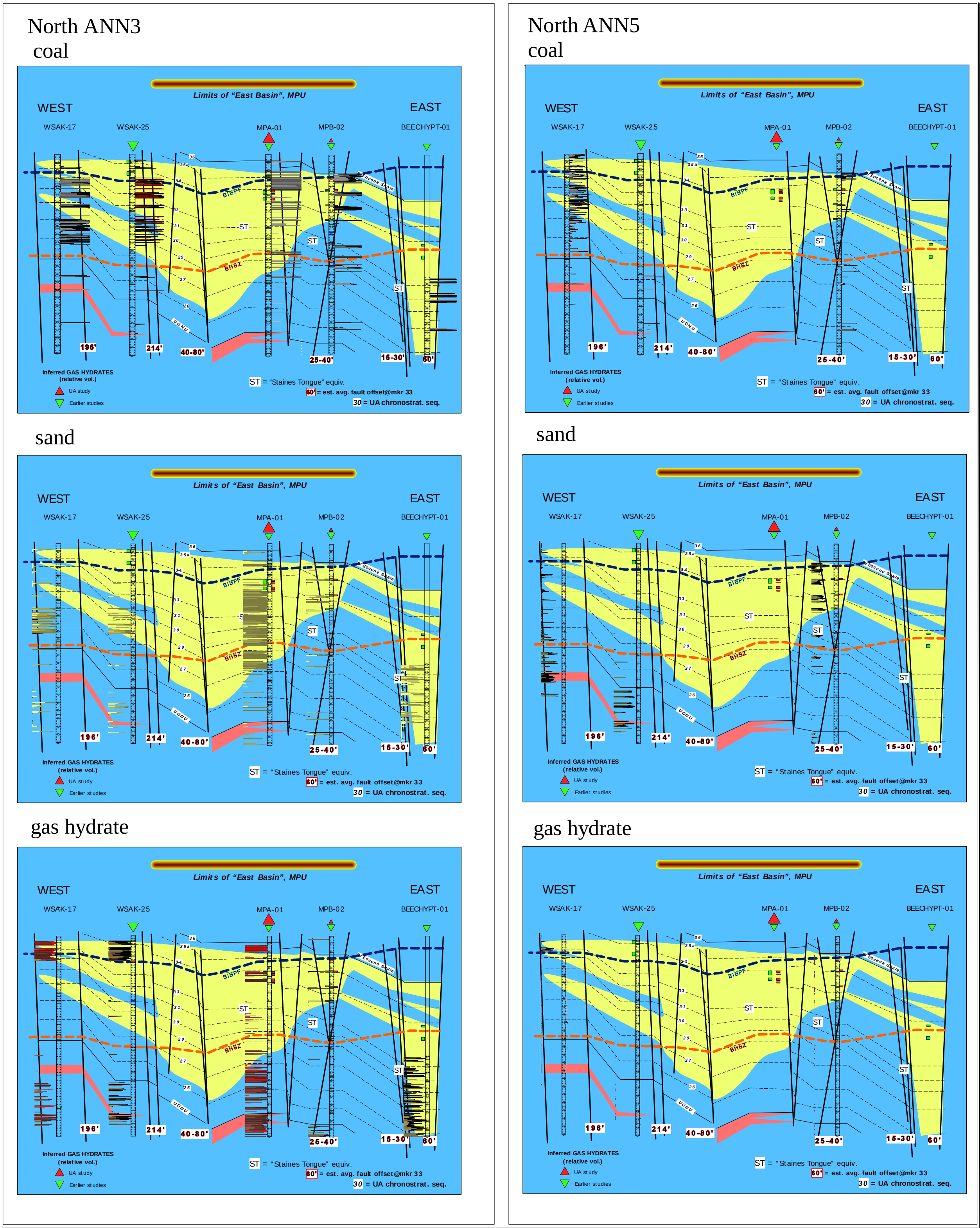


Figure 33: ANN3 and ANN5 results for wells north of cross section in Figure 7 superimposed on the conceptual basin of figures 19 and 20. Length of bar for each depth interval indicates level of confidence in the interpretation. ANN3 uses gamma, resistivity and sonic logs. ANN5 uses these logs plus density and neutron porosity.

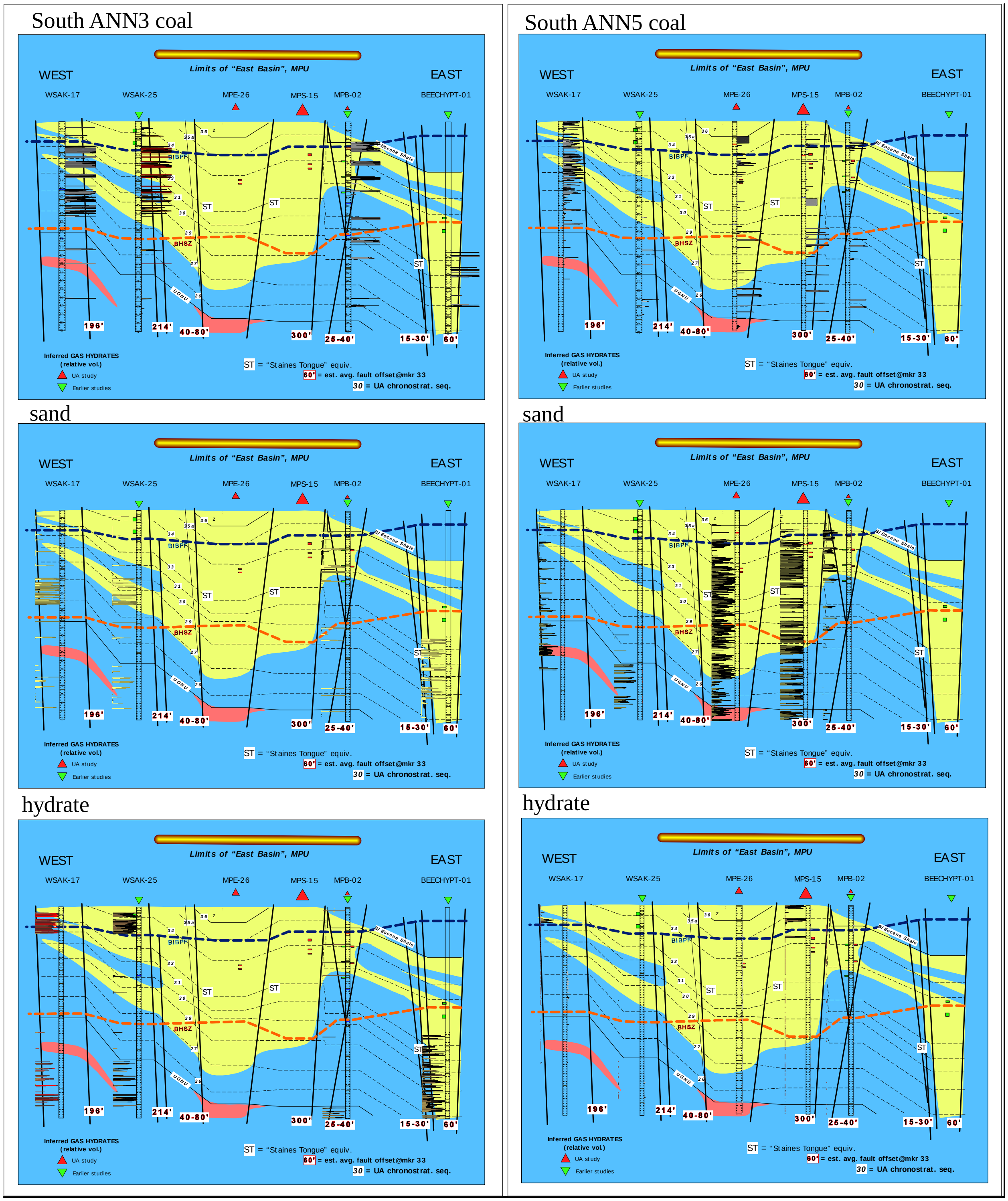


Figure 34: ANN3 and ANN5 results for wells south of cross section in Figure 7 superimposed on the conceptual basin of figures 19 and 20. Length of bar for each depth interval indicates level of confidence in the interpretation. ANN3 uses gamma, resistivity and sonic logs. ANN5 uses these logs plus density and neutron porosity.

When a well is tested, the process first screens the individual depth samples by the gamma API count. Any depth sample with a count greater than 55 API units is excluded from testing because it is considered a shale class. Hence, only samples with a gamma API less than or equal to 55 API units are ever processed by the neural network.

The classification system does not distinguish between the gas hydrate stability zone and the permafrost zone within the logged interval when testing a well with a neural network, although it could certainly restrict testing to any interval. Hence, the neural network will identify gas hydrate within the permafrost based on well log training signatures from below the permafrost but cannot ensure with any certainty that such depth intervals are really gas hydrate and not permafrost. Similarly, the network will identify gas hydrate below the base of the hydrate stability zone if such signatures match that of gas hydrate within the stability zone. These gas hydrate picks usually correlate with an oil phase. Future work may add an oil class to ANN5.

The network can only name patterns one of four names: gas hydrate, coal, sand, or gas. In some cases, a sample will have a gamma API count less than 55 API units but will not resemble a signature for any of these four classes. In such cases, the neural network outputs all negative numbers indicating a pattern that does not fit. In some cases, the sample will be close enough to a training signature to generate a positive output for a particular class, but the value is closer to 0 than to 1.0. Classifications with an output less than 0.5 for a particular class are deemed low confidence and generally not reliable. Classification values that are close to 1.0 are very confident and therefore strongly resemble the typical patterns used for training. Visual examination reveals confidence level by the length of the bar for each depth sample (i.e. short bars from left to right are low confidence).

Therefore, the interpretation should be viewed as "hydrate-like", "coal-like", "sand-like", or "gas-like" based on characteristics of the suite of well logs used for training. Non-unique data lead to non-unique classification results. Geological context then becomes important in validating the classification.

5.6.3.8 Conclusions and Future Work

The neural network and expert system classifications are consistent with the preliminary geological interpretation of a basin by Casavant et al. (2004). More fine-tuning of the thresholds used in the expert system and the training samples used in the neural network will result in more accurate calculations of coal thickness, net sand thickness, and gas hydrate- and gas-bearing reservoir thickness. Future work may include tying the interpreted well logs to the seismic volume and seismic waveforms analyses by the neural network corresponding to gas hydrate, gas, sand, coal, and oil. A self-organizing map neural network may be used to refine the volumetric estimates of gas and gas hydrate from the seismic data.

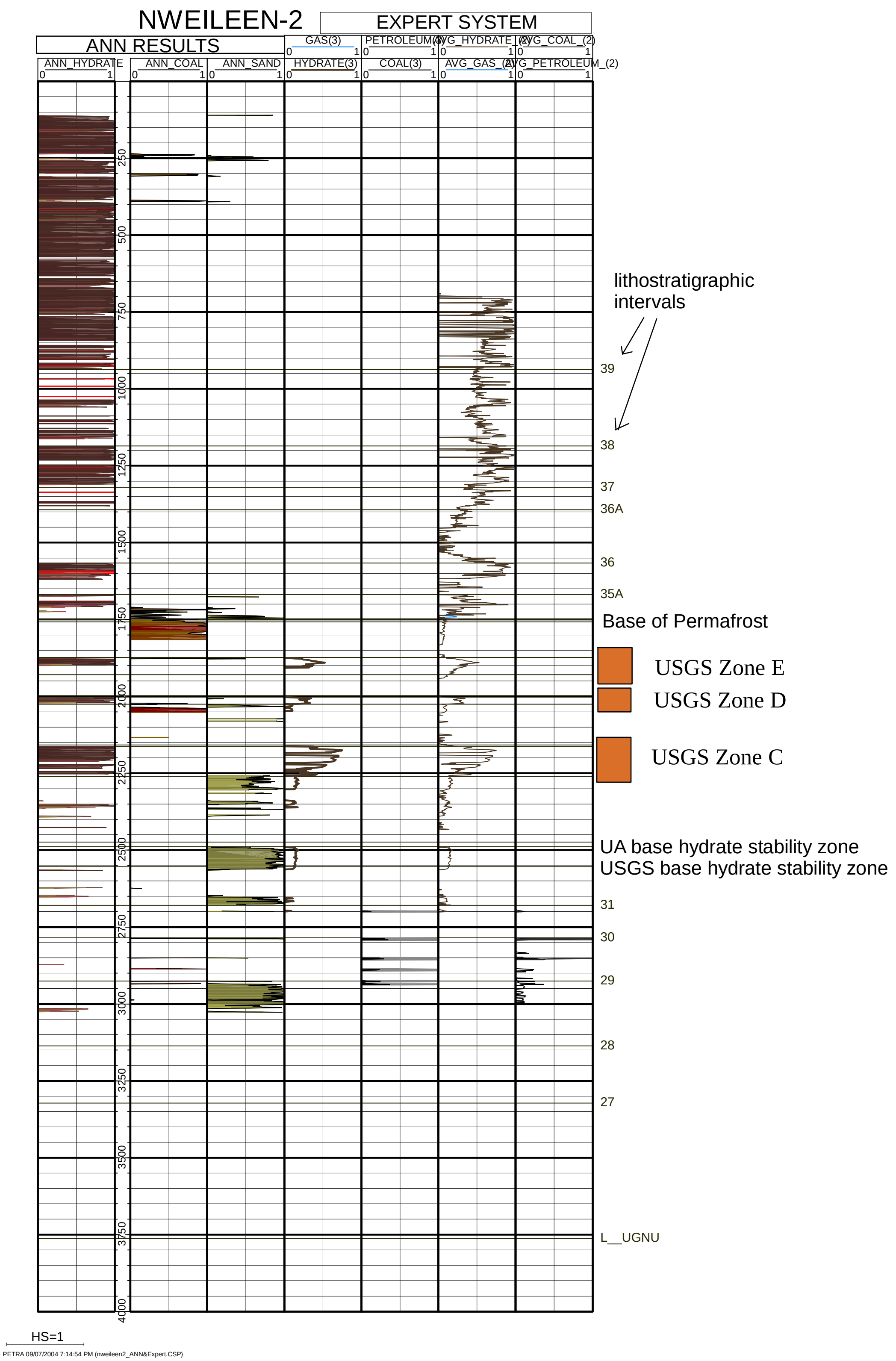


Figure 35: ANN3 test of NWEileen-02 well. Log curve displays from GeoPlus Corp. software.

5.7 TASK 7.0: Lab Studies for Drilling, Completion, and Production Support – UAF

University of Alaska Fairbanks
UAF Principle Investigator: Shirish Patil
UAF Co-Principle Investigator: Abhijit Dandekar
UAF Research Professional: Narender R Nanchary
UAF Graduate Students: *Jason Westervelt, Stephen Howe,* Namit Jaiswal, and Prasad Kerkar
UAF Undergraduate Student Assistant: Phillip Tsunemori

5.7.1 Subtask 7.1: Characterize Gas Hydrate Equilibrium

Prior accomplished work documented in previous quarterly reports was compiled into a poster presentation for the September AAPG Hedberg Gas Hydrate Research Conference in Vancouver.

5.7.2 Subtask 7.2: Relative Permeability Studies

Prior accomplished work documented in previous quarterly reports was compiled into a poster presentation for the September AAPG Hedberg Gas Hydrate Research Conference in Vancouver.

5.7.2.1 Future Work

1. Gas-water relative permeability data experiments for gas hydrate systems used reconstituted sediment samples. Actual field samples from the Sagavanirktok reservoir interval within MPU are unavailable at this time. Sediment samples from actual field areas would help refine the results of procedures pioneered in these experiments. Input from potential future experiments run with actual field samples would be used to help refine the reservoir simulation work with important gas-water relative permeability measurements.
2. The dynamics of growth and dissociation of gas hydrates in presence of fluid flow are not yet fully known. Therefore, additional experimental measurements are recommended to help predict these relative permeability curves for the formation, distribution, and dissociation of gas hydrate within the pore structure of porous media. Conducting the laboratory displacements in a fully scaled model of the field-scale displacement may help enable prediction of the functional relationship between permeability, porosity, pore structure discontinuities, tortuosity, and fluid parameters such as viscosity and dissociation in-stability.
3. Additional relative permeability tests should be performed at different temperature conditions, which could significantly improve understanding of the relative permeability characteristics of gas hydrate-bearing petroleum systems.

5.8 TASK 8.0: Evaluate Drilling Fluids and Assess Formation Damage

5.8.1 Subtask 8.1: Design Integrated Mud System for Effective Drilling, Completion and Production Operation

Objectives for subtask 8.1 include: 1. design fully integrated mud system for permafrost and gas hydrate bearing reservoirs, 2. determine mud contamination and formation damage risk, and 3. evaluate mud chiller system.

5.8.2 Subtask 8.2, Assess Formation Damage: Testing, Analysis and Interpretation

Progress on this task was limited during the reporting period due to delays in obtaining various mud samples. Reconstituted samples may be substituted for actual mud samples.

5.9 TASK 9.0: Design Cement Program

No work on this task was performed during the reporting period. A related study to determine the efficacy of Argonne National Laboratory's Ceramicrete cement for completion operations was funded as discussed in Section 2.3. Ceramicrete may provide a viable alternative to current permafrost cements used in Alaska North Slope drilling operations.

5.10 TASK 10.0: Study Coring Technology

No work on this task was performed during the reporting period.

5.11 TASKS 11.0 and 13.0: Reservoir Modeling and Project Commerciality and Progression Assessment – UAF, BP, LBNL, Ryder Scott

Significant reservoir simulation progress was made from June through December in studying predicted productivity sensitivities by evaluating effects of changing reservoir parameters including heat flux, aquifer influx, permeabilities, and gas, gas hydrate, and water saturations within both gas hydrate-only and gas hydrate-free gas-bearing prospect evaluations. Undersaturated-with-respect-to-gas-hydrate reservoirs were evaluated; contribution of in-situ depressurization from production of mobile connate waters coexisting with gas hydrate within porous media was considered. The results were analogous to coalbed methane production mechanisms. Much uncertainty remains, including data on gas hydrate-bearing reservoir saturations, absolute and relative reservoir permeabilities, and other factors influencing potential gas hydrate-bearing reservoir productivity.

5.11.1 Reservoir Modeling Review

Preliminary modeling results were presented in the June 2004 Quarterly Report and at the September 2004 AAPG Hedberg Gas Hydrate Research Conference in Vancouver. Additional work accomplished during this reporting period included investigations of varying reservoir parameters including heat flux, aquifer influx, permeabilities, and gas, gas hydrate, and water saturations to predict effects on reservoir productivity. These studies helped determine importance of key variables and identify areas in which additional data acquisition could help mitigate productivity uncertainty.

Figure 36 illustrates heat flux variation. An issue in the modeling of gas production from gas hydrate-bearing reservoirs involves temperature recovery during depressurization and potential for formation of ice and/or reformation of hydrate during production operations. In-situ temperature behavior is a variable with significant uncertainty and range of expectations. Field observations of reservoir temperatures in shut-in producing wells indicate a return toward ambient temperature over a period of days rather than weeks or years. If the thermal mass is large and different from the ambient condition, temperature recovery typically takes longer to recover since the "disturbed" volume is larger. On the other hand, the disturbed area is also larger, with more rock volume contributing to help reestablish ambient temperature, giving what may be a non-linear relation. The third non-linear dimension would occur during production, when the system includes dissociated water and gas moving away from the gas hydrate dissociation source. This would likely cause temperature decrease up the wellbore (gas) or downstructure (water).

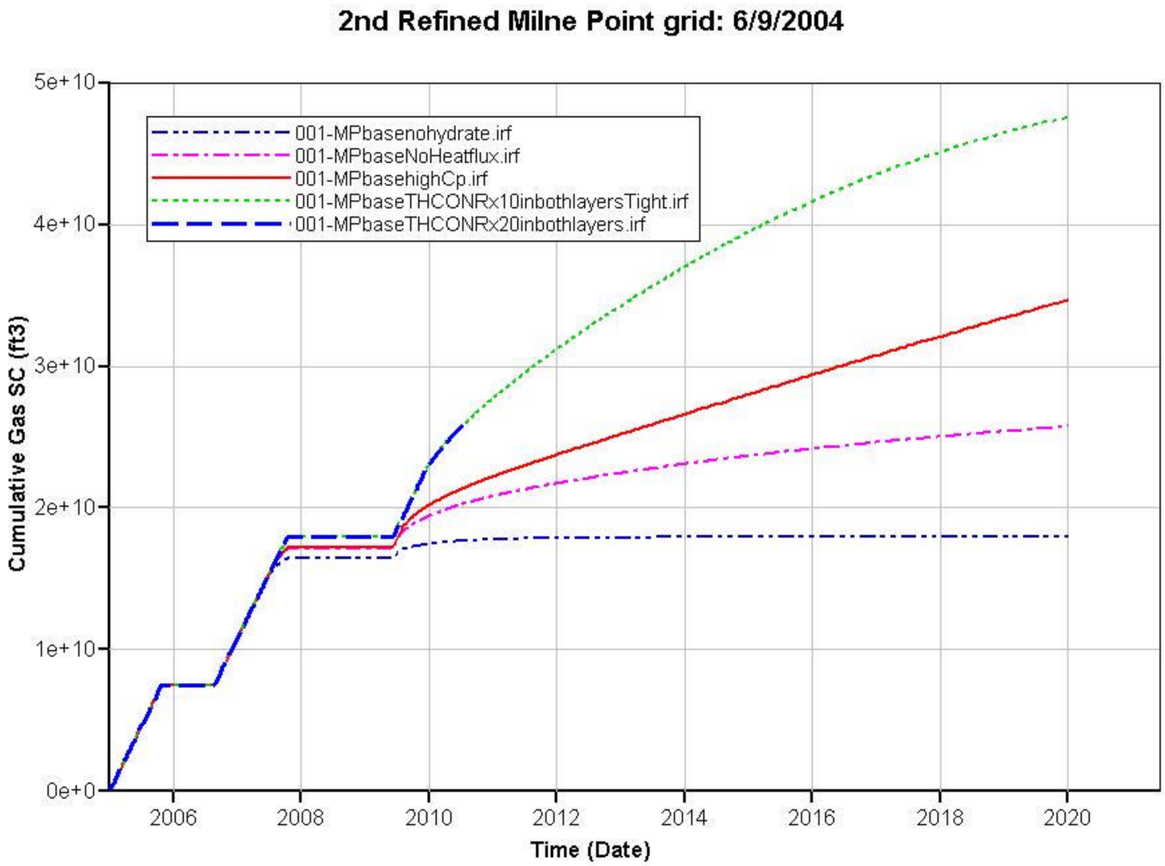


Figure 36: Sensitivity to Conductive Heat Flux variation. The Mallik matched value = 2.4e5 J/(m-day-C) from Wright et al, 2003. The Silica Reference value = 6.6e5 J/(m-day-C) from STARS Reference.

Figure 37 illustrates a plot of a gas storage observation well that was put on flow test and then shutin for build-up in St. James Parish, Louisiana on December 2, 2004. Normally, very little adiabatic temperature drop is observed in a flow test on a normal producing well. However, this well has a severe restriction at the wellbore due to only a few perforations being shot for observation purposes. While flowing first at 1.7 MMCF/d then 2.8 at MMCF/d, the pressure bomb across from the perforations caused a temperature drop of almost 10 degrees Fahrenheit and it appears as though the well was trying to reach a steady state condition below ambient temperature.

The rapid (< 4 days) temperature recovery to near-ambient conditions seems to confirm empirical observations of reservoir temperatures returning toward ambient in days rather than in weeks or years. One reason this example is so dramatic is that it was probably a point source with localized impact. Other observations from this potential analog include: 1. Reservoir temperature nearly 200 degrees, 2. Field was shutin for 6 months prior to these measurements from this observation well, 3. The reservoir sand interval is approximately 84 feet, 4. Reservoir permeability (398 md) is comparable to Sagavanirktok sands, and 5. Calculated skin factor is 543 (limited perforation of 5 feet and severe drawdown) which may be comparable to a gas hydrate-bearing reservoir.

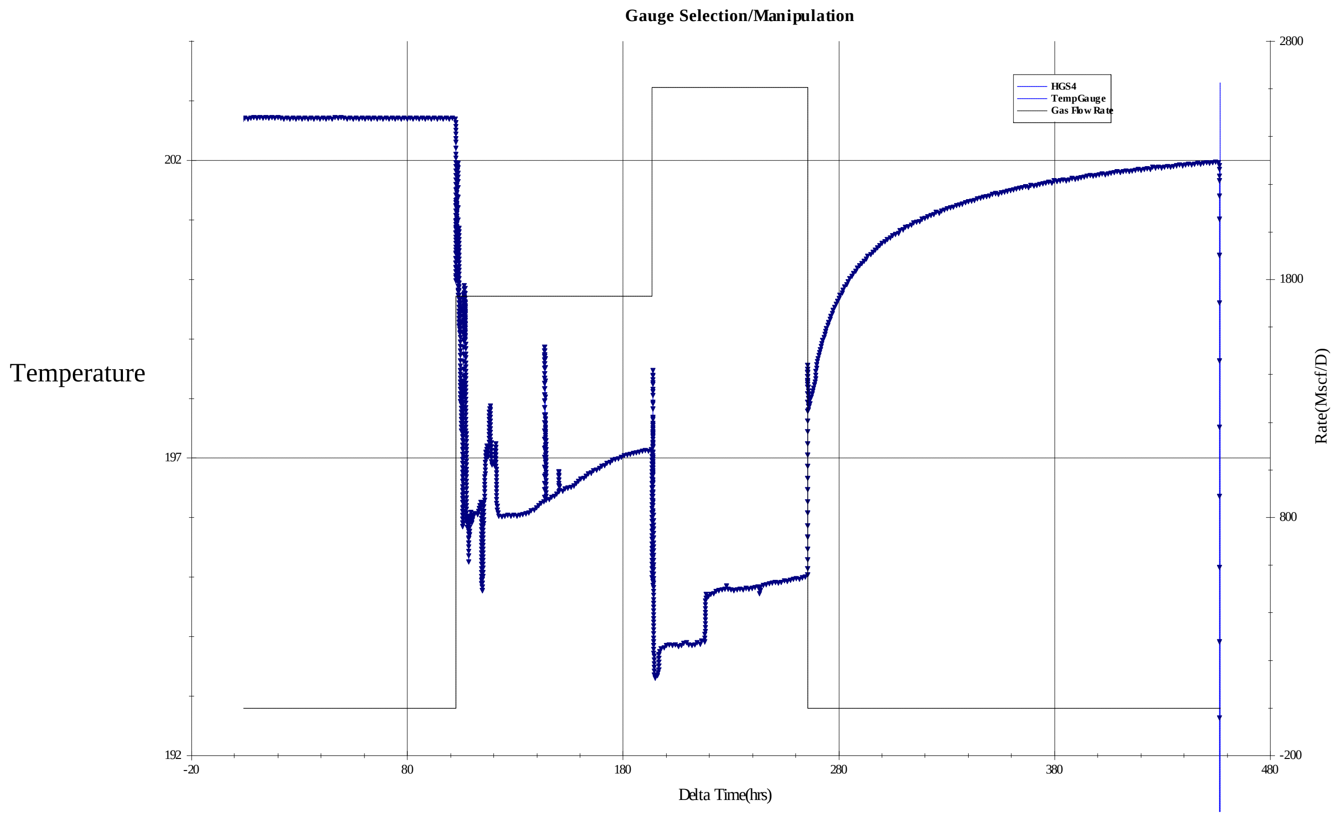


Figure 37: Potential Temperature Recovery Analog.

Figure 38 illustrates a second temperature recovery example from the Safah A reservoir interval. This example shows an interval of high inflow (Safah A) and the zone at the bottom of the wellbore where no inflow occurred.

Gas, gas hydrate, and water saturations also significantly influence modeling of gas dissociation from a gas hydrate-bearing reservoir. Figure 39 illustrates how a gas hydrate-bearing reservoir containing a 20% saturation of movable connate waters can enable depressurization and gas dissociation from gas hydrate. Undersaturation with respect to gas hydrate could occur, possibly due to the gas volume reduction occurring when what was originally a free gas-bearing reservoir is transformed into gas hydrate in the presence of water within the gas hydrate stability zone.

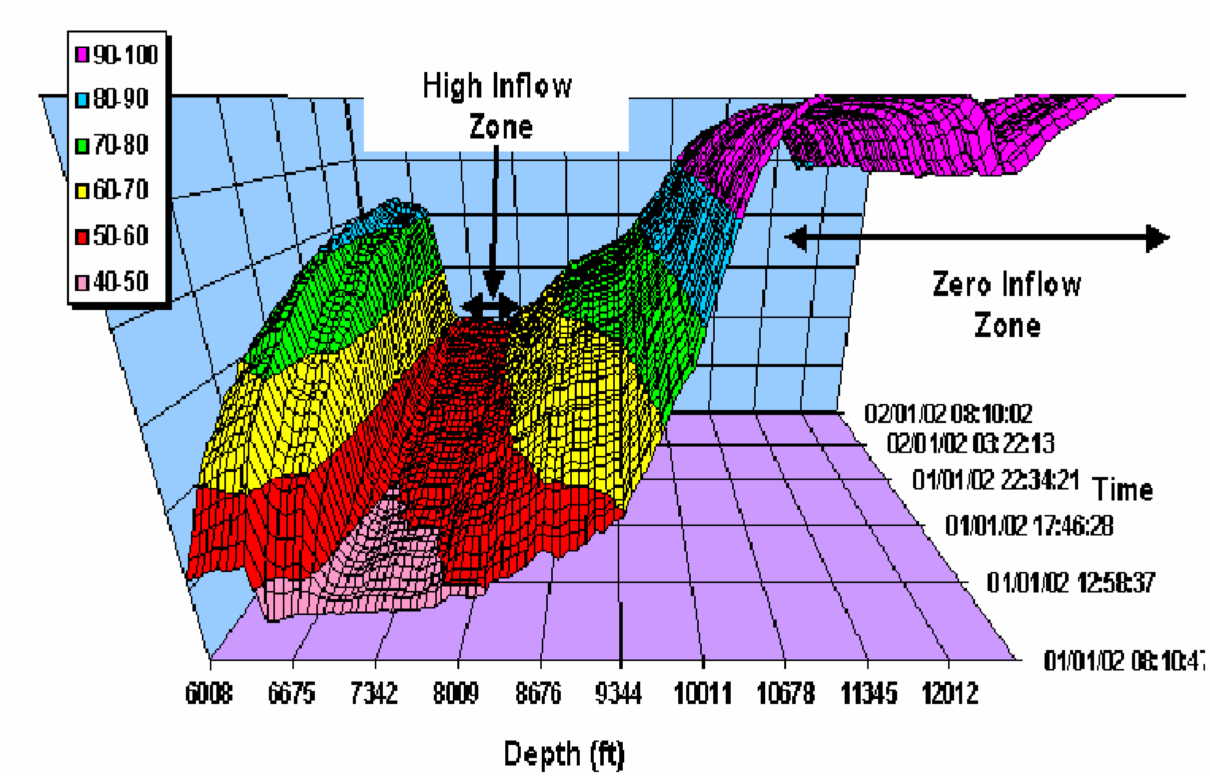


Figure 38: Temperature recovery example from the Safah A reservoir interval (Brown, Storer, and McAllister, 2003).

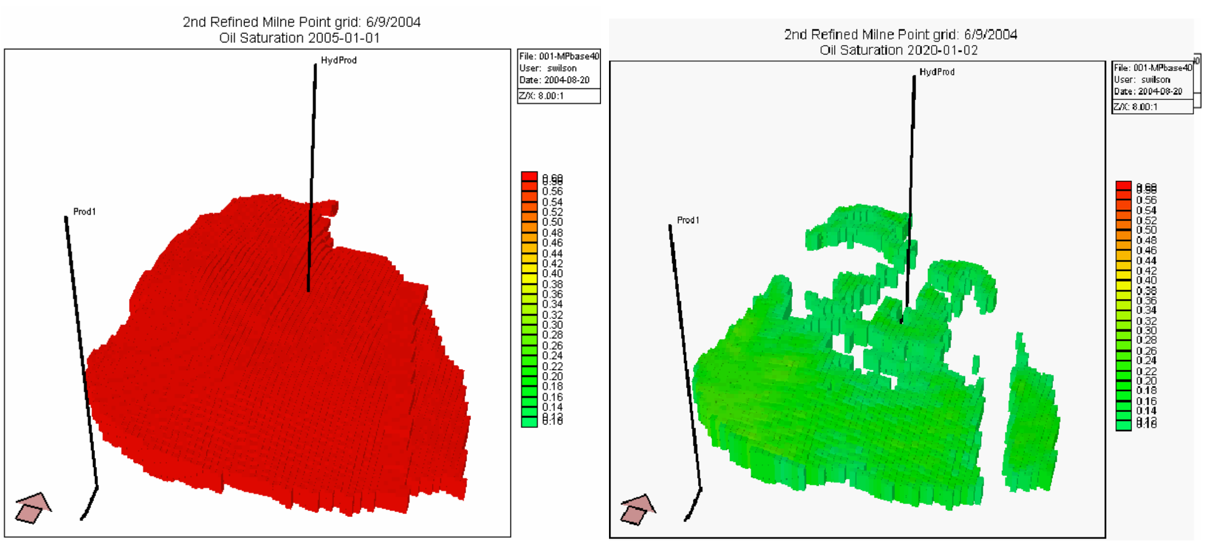


Figure 39: Production history showing gas saturation at time 0, 2005 (left) and gas saturation at end-model run, 2020 (right) after 15-year gas production from an under-saturated gas hydrate-bearing reservoir containing 20% mobile connate water saturation.

Figure 40 compares the gas production rates from a gas hydrate-bearing reservoir for various permeabilities in an under-saturated gas hydrate-bearing reservoir with 20% mobile connate water saturation and 20% irreducible water saturation (upper plot) and in a fully-saturated gas hydrate-bearing reservoir with only 20% irreducible water saturation (lower plot).

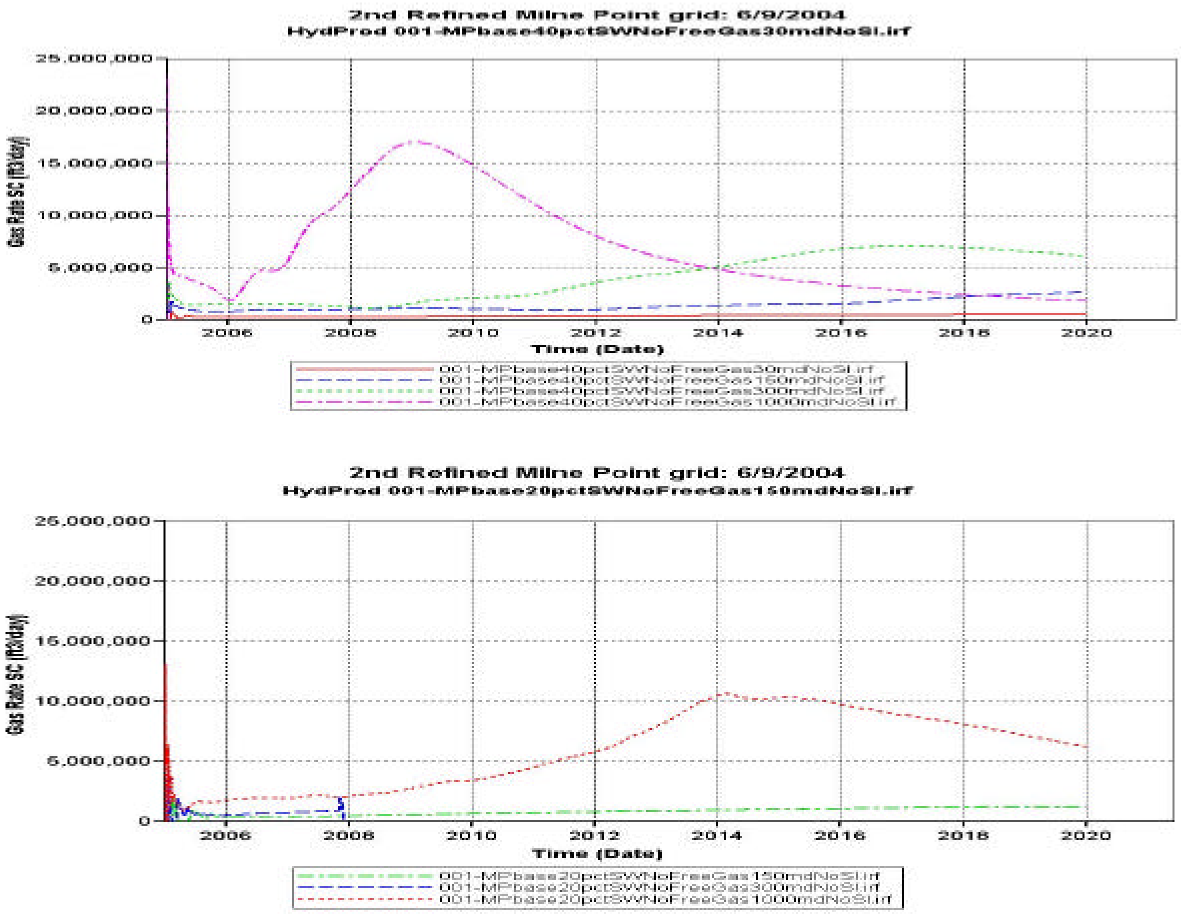


Figure 40: Gas production rate comparisons for various permeabilities for an under-saturated gas hydrate-bearing reservoir (upper plot) and for a fully-saturated gas hydrate-bearing reservoir (lower plot).

Figure 41 illustrates example associated water production rates during depressurization method of production for an under-saturated gas hydrate-bearing reservoir with 20% mobile connate water saturation and 20% irreducible water saturation (blue) and for a fully-saturated gas hydrate-bearing reservoir with only 20% irreducible water saturation (red). Note that the mobile connate water saturation enables much quicker depressurization of the gas hydrate due to higher-rates of associated water production.

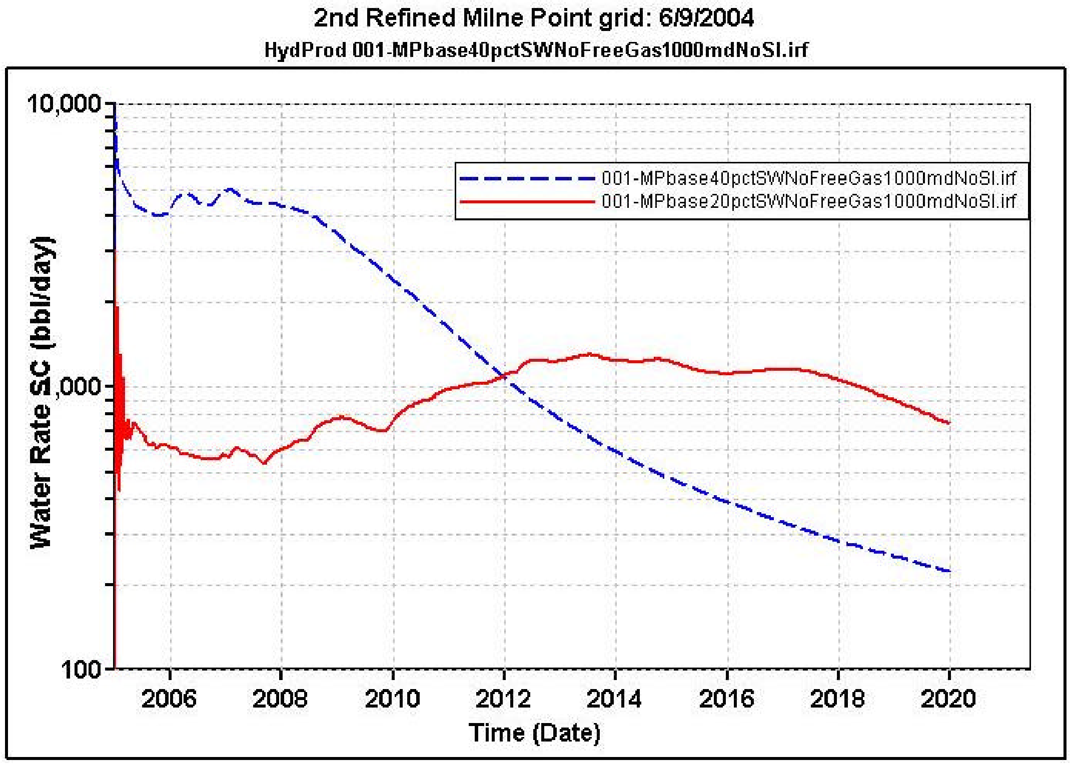


Figure 41: Water production rates for an under-saturated gas hydrate-bearing reservoir with 20% mobile connate water saturation and 20% irreducible water saturation (blue) and for a fully-saturated gas hydrate-bearing reservoir with only 20% irreducible water saturation (red).

Figure 42 shows a potential gas hydrate production analog from a coalbed methane production well in Drunkards Wash. Note that water offtake depressurizes the gas held in the cleats of the coal and allows gas production to start at a later date. Gas hydrate-bearing reservoirs with a mobile water component might exhibit a similar relation of gas production following water offtake.

Figure 43 illustrates how permeability effects pressure propagation, which in turn effects gas dissociation from gas hydrate (Figure 44). If the permeabilities to the flowing phases of gas and water, are low (left diagram of figures 43-44), then a steep pressure profile will prevent dissociation over large distances and restrict the ability of the dissociation front to move away from the producer to access significant new reservoir. If, however, a higher net permeability exists (right diagram of figures 43-44), then the dissociation front could move outward fairly quickly. Higher permeability can result from either higher native rock permeability or higher flowing phase relative permeability caused by lower hydrate saturations and higher mobile phase (water or gas) saturations. The complementary behavior of a radial temperature profile is shown in the tight formation on the left side of figure 44. On the right side of figure 44, the high permeability case shows an interesting temperature "shadow" which remains as the hydrate dissociates in the accumulation and then the pressure propagates beyond that illustrated in comparison to the low permeability case. If this behavior is real, not only pressure, but temperature reduction below ambient could be used as an indicator of partly or completely dissociated hydrates in observation wells or in newly drilled wells. Observation wells offsetting a pilot well would "see" both a temperature and pressure reduction; the pressure reduction would be the leading indicator since it initiates the gas dissociation reaction that causes the associated endothermic temperature reduction.

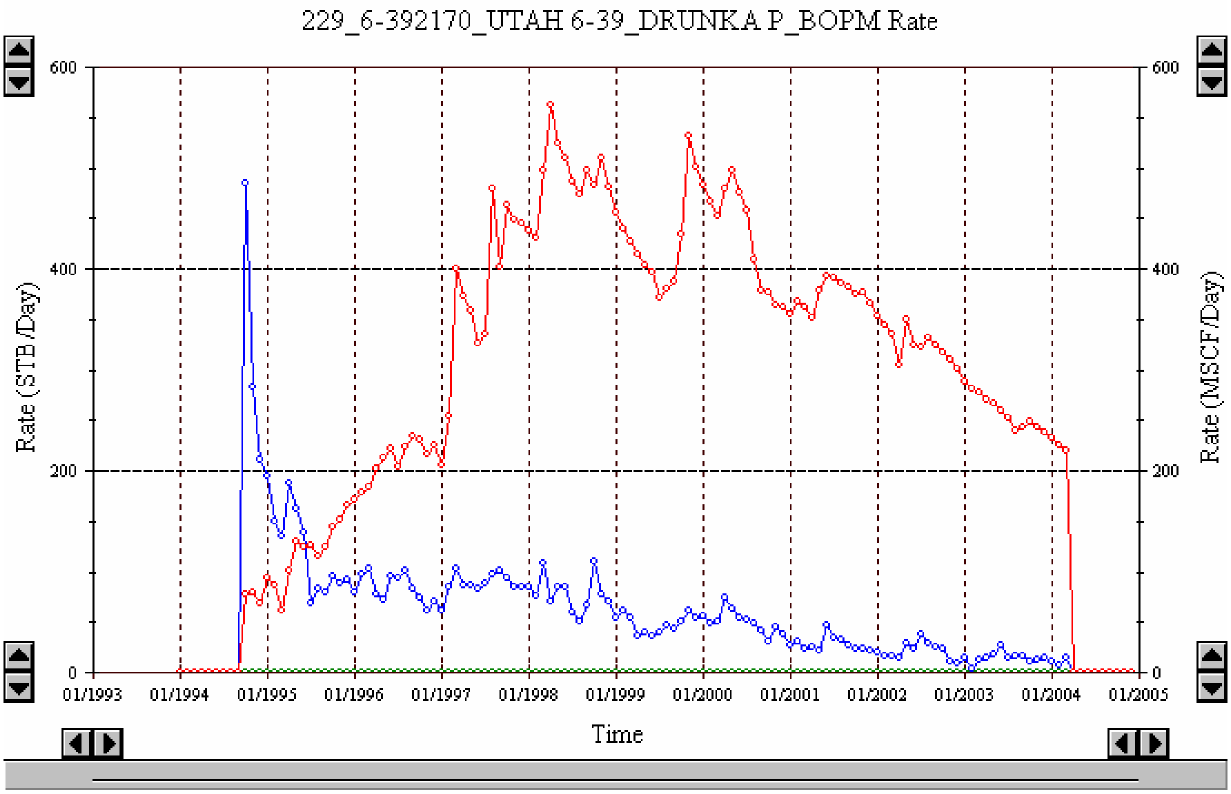


Figure 42: Potential gas hydrate production analog from a coalbed methane production well from Drunkards Wash. Gas rate is shown in red (right scale) and water rate is shown in blue (left scale).

Figure 45 illustrates that aquifer influx does not significantly affect gas hydrate dissociation rate over a modeled 15-year production history.

5.12 TASK 12.0: Select Drilling Location and Candidate – BP, UA, USGS

Reservoir and fluid characterization studies in Task 6.0, investigation of seismic technologies in tasks 5.0 and 6.0, and reservoir and economic modeling studies in tasks 11.0 and 13.0 helped to identify prospective areas within MPU for possible future gas hydrate data acquisition and/or production testing operations. The associated project study by USGS as funded primarily by the regional ANS BLM-USGS research has identified seismic attribute anomalies potentially associated with changes in pore fluid types (water, free gas, and gas hydrate) within reservoir (sand-prone) intervals. Multiple gas hydrate-bearing prospects from these studies were evaluated and comparatively ranked (Table 1).

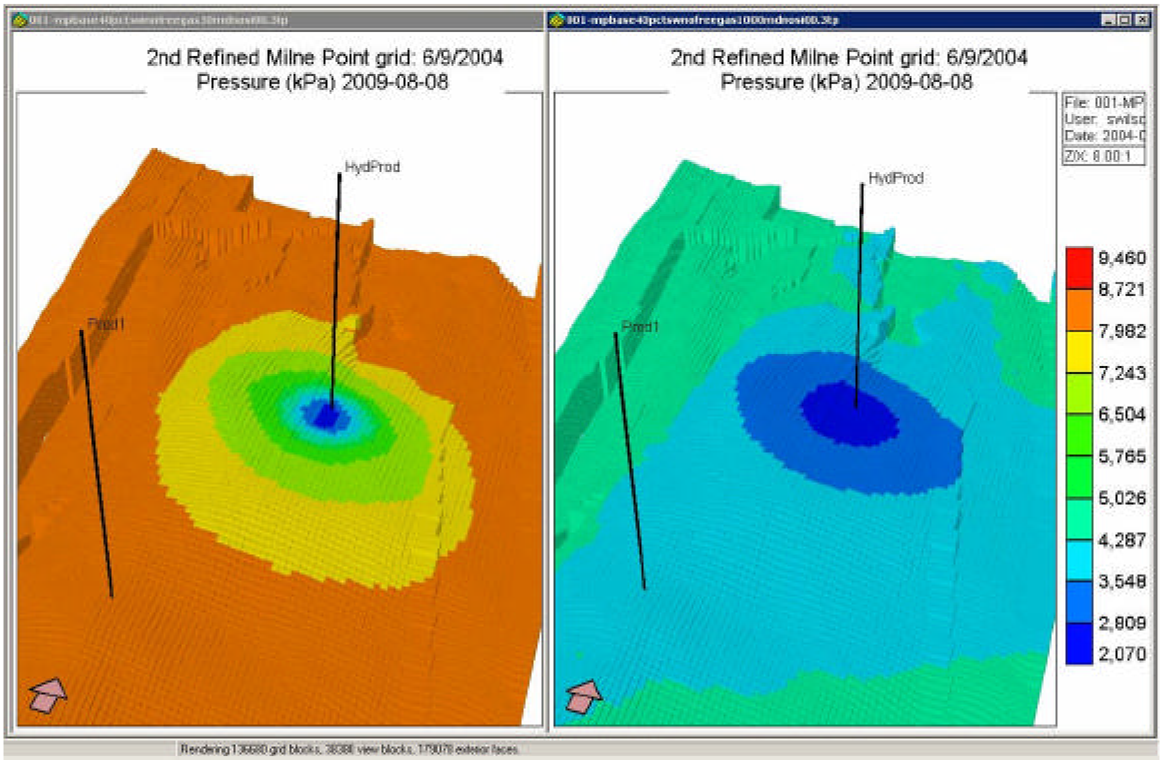


Figure 43: Pressure conditions during gas dissociation from gas hydrate after 4-year production history. Low permeability case on left; High permeability case on right.

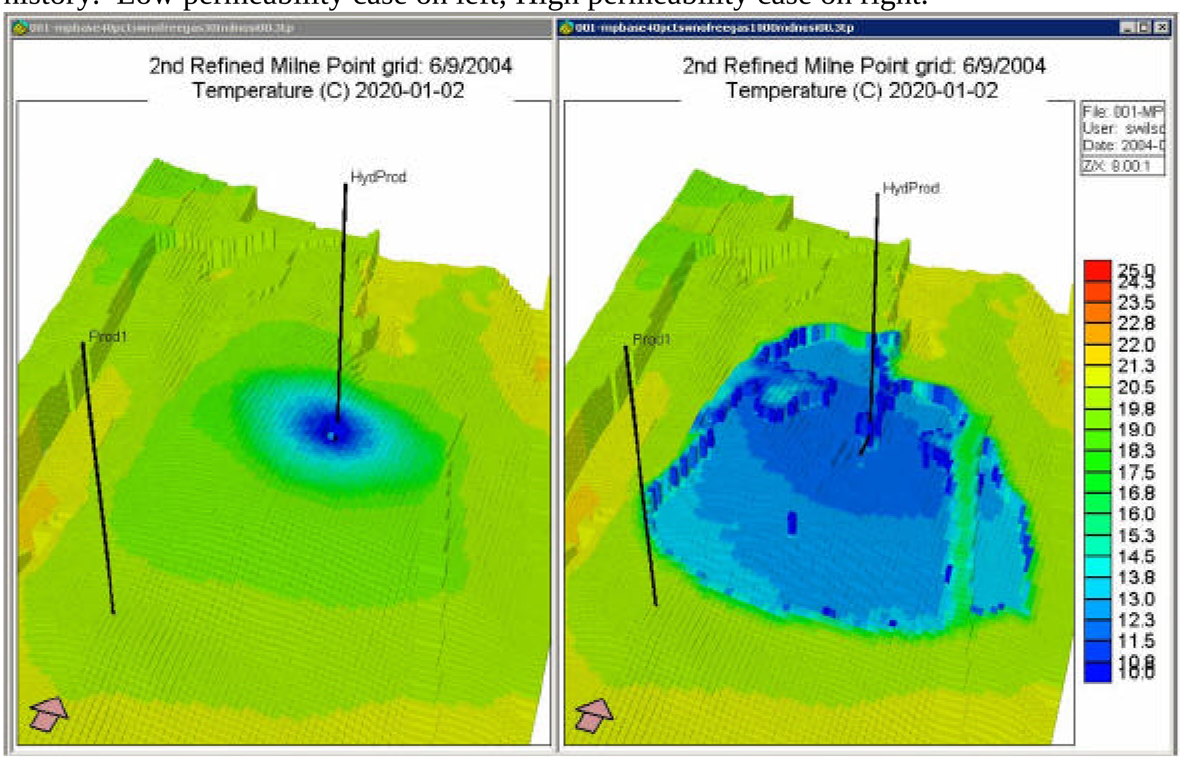


Figure 44: Temperature cooling from gas dissociation from gas hydrate after 15-year production under pressure conditions shown in Figure 43. Low permeability case on left; High permeability case on right.

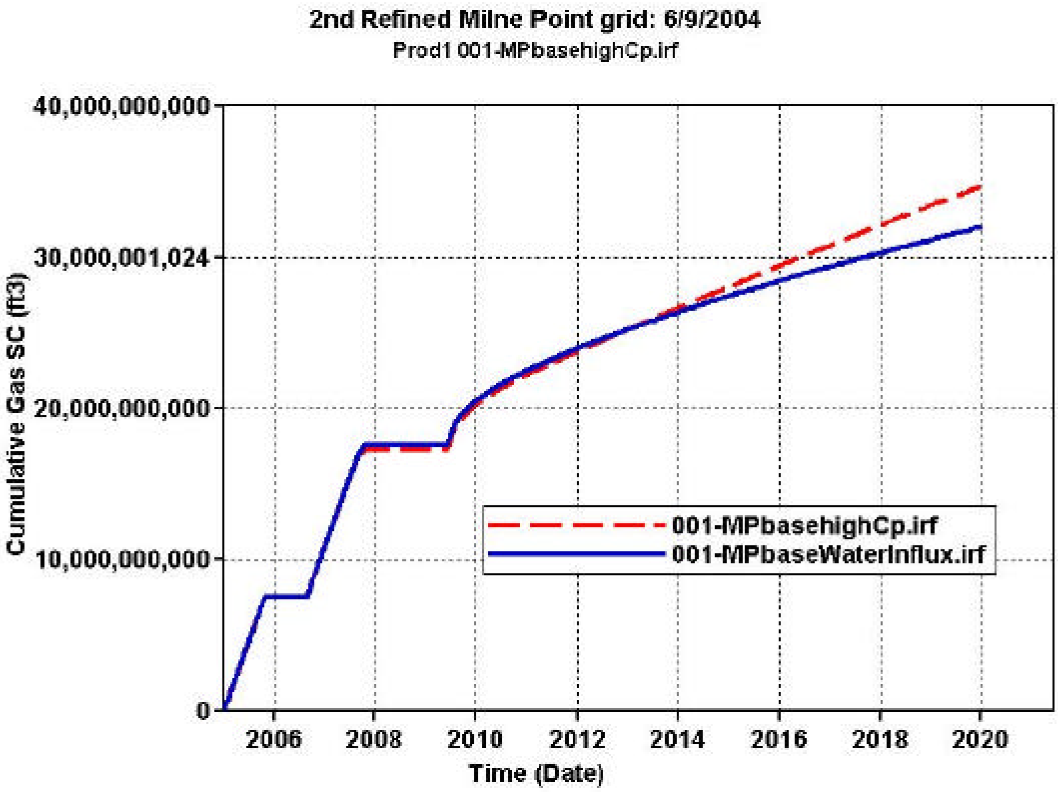


Figure 45: Comparison of gas production with (blue) and without (red) adjacent aquifer influx.

6.0 CONCLUSIONS

Interim conclusions are presented at this stage in the research program. The first dedicated gas hydrate coring and production testing well, NW Eileen State-02, was drilled in 1972 within the Eileen gas hydrate trend by Arco and Exxon. Since that time, ANS methane hydrates have been known primarily as a drilling hazard. Industry has only recently considered the resource potential of conventional ANS gas during industry and government efforts in working toward an ANS gas pipeline. Consideration of the resource potential of conventional ANS gas created the industry – government alignment necessary to reconsider the resource potential of the potentially large (44 – 100 TCF in-place) unconventional ANS methane hydrate accumulations beneath or near existing production infrastructure. Studies show this in-place resource is compartmentalized both stratigraphically and structurally within the petroleum system.

The BPXA – DOE collaborative research project is designed to enable industry and government to make informed decisions regarding the resource potential of this ANS methane hydrate petroleum system through comprehensive regional shallow reservoir and fluid characterization utilizing well and 3D seismic data, implementation of methane hydrate experiments, and design of techniques to support potential methane hydrate drilling, completion, and production operations.

The potential to induce gas hydrate dissociation across a broad regional contact from adjacent free gas depressurization is demonstrated by the results of the collaborative BPXA-LBNL pre-

Phase 1 scoping reservoir model (presented in the March 2003 Quarterly report and technical conferences) and corroborated by the results of continued UAF and Ryder Scott Co. reservoir model research as presented in Section 5.9 of the December 2003 Quarterly report and herein. The possibility to induce in-situ gas hydrate dissociation through producing connate waters from within an under-saturated gas hydrate-bearing reservoir establishes saturation and permeability as key variables which, when better understood, could help mitigate productivity uncertainty.

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c. Hagbo, C., and Johnson, R. A., 2003, Use of seismic attributes in identifying and interpreting onshore gas-hydrate occurrences, North Slope, Alaska, Eos Trans. AGU, 84, Fall Meet.
d. Hennes, A., and R. Johnson, 2004, Structural character and constraints on a shallow, gas-hydrate-bearing reservoir as determined from 3-D seismic data, North Slope, Alaska, 2004 Univ. of Arizona Dept. Geosciences Annual GeoDaze Symposium

7.2.2 Professional Posters

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8.0 LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Denotation
2D	Two Dimensional (seismic or reservoir data)
3D	Three Dimensional (seismic or reservoir data)
AAPG	American Association of Petroleum Geologists
AETDL	Alaska Energy Technology Development Laboratory
ANL	Argonne National Laboratory
ANN	Artificial Neural Network
ANS	Alaska North Slope
AOGCC	Alaska Oil and Gas Conservation Commission
AOI	Area of Interest
AVO	Amplitude versus Offset (seismic data analysis technique)
ASTM	American Society for Testing and Materials
BLM	U.S. Bureau of Land Management
BP	British Petroleum (commonly BP Exploration (Alaska), Inc.)
BPXA	BP Exploration (Alaska), Inc.
DOI	U.S. Department of Interior
DGGS	Alaska Division of Geological and Geophysical Surveys
DNR	Alaska Department of Natural Resources
EM	Electromagnetic (referencing potential in-situ thermal stimulation technology)
ERD	Extended Reach Drilling (commonly horizontal and/or multilateral drilling)
GEOS	UA Department of Geology and Geophysics
GOM	Gulf of Mexico (typically referring to Chevron Gas Hydrate project JIP)
GR	Gamma Ray (well log)
GTL	Gas to Liquid
GSA	Geophysical Society of Alaska
HP	Hewlett Packard

JBN	Johnson-Bossler-Naumann method (of gas-water relative permeabilities)
JIP	Joint Industry Participating (group/agreement), ex. Chevron GOM project
JNOC	Japan National Oil Corporation
JOGMEC	Japan Oil, Gas, and Metals National Corporation (reorganized from JNOC 1/04)
KRU	Kuparuk River Unit
LBNL	Lawrence Berkeley National Laboratory
LNG	Liquefied Natural Gas
MGE	UA Department of Mining and Geological Engineering
MPU	Milne Point Unit
NETL	National Energy Technology Laboratory
ONGC	Oil and Natural Gas Corporation Limited (India)
PBU	Prudhoe Bay Unit
PNNL	Pacific Northwest National Laboratory
Sag	Sagavanirktok formation
SPE	Society of Petroleum Engineers
TCF	Trillion Cubic Feet of Gas at Standard Conditions
TCM	Trillion Cubic Meters of Gas at Standard Conditions
UA	University of Arizona (or Arizona Board of Regents)
UAF	University of Alaska, Fairbanks
USGS	United States Geological Survey
USDOE	United States Department of Energy
VSP	Vertical Seismic Profile
WOO	Well-of-Opportunity

9.0 APPENDICES

9.1 APPENDIX A: Project Task Schedules and Milestones

9.1.1 U.S. Department of Energy Milestone Log, Phase I, 2002-2004

Program/Project Title: DE-FC26-01NT41332: Resource Characterization and Quantification of Natural Gas-Hydrate and Associated Free-Gas Accumulations in the Prudhoe Bay - Kuparuk River Area on the North Slope of Alaska

Identification Number	Description	Planned Completion Date	Actual Completion Date	Comments
Task 1.0	Research Management Plan	12/02 – 12/06*	12/02 and Ongoing	Subcontracts Completed Research Management
Task 2.0	Provide Technical Data and Expertise	MPU: 12/02 PBU: ** KRU: **	MPU: 12/02 PBU: ** KRU: **	Ongoing, See Technical Progress Report
Task 3.0	Wells of Opportunity Data Acquisition	Ongoing	Ongoing	Ongoing, See Technical Progress Report
Task 4.0	Research Collaboration Link	Ongoing	Ongoing	Ongoing, See Technical Progress Report
Subtask 4.1	Research Continuity	Ongoing	Ongoing	

Task 5.0	Logging and Seismic Technology Advances	Ongoing		Ongoing, See Technical Progress Report
Task 6.0	Reservoir and Fluids Characterization Study	12/06*		Interim Results presented, 2004 Hedberg Conference
Subtask 6.1	Characterization and Visualization	12/06*		Interim Results presented, 2004 Hedberg Conference
Subtask 6.2	Seismic Attributes and Calibration	12/06*		Interim Results presented, 2004 Hedberg Conference
Subtask 6.3	Petrophysics and Artificial Neural Net	12/06*		Interim Results presented, 2004 Hedberg Conference
Task 7.0	Laboratory Studies for Drilling, Completion, Production Support	6/04	6/04	
Subtask 7.1	Characterize Gas Hydrate Equilibrium	6/04	6/04	Results presented, 2004 Hedberg Conference
Subtask 7.2	Measure Gas-Water Relative Permeabilities	6/04	6/04	Results presented, 2004 Hedberg Conference
Task 8.0	Evaluate Drilling Fluids	12/04		
Subtask 8.1	Design Mud System	11/03		
Subtask 8.2	Assess Formation Damage	9/05		
Task 9.0	Design Cement Program	12/04		
Task 10.0	Study Coring Technology	2/04	2/04	
Task 11.0	Reservoir Modeling	12/06*		Interim Results presented, 2004 Hedberg Conference
Task 12.0	Select Drilling Location and Candidate	9/05		Topical Report submitted, June 2005
Task 13.0	Project Commerciality & Progression Assessment	9/05		BPXA and DOE decision

* Date dependent upon project continuation into latter phases
** Date dependent upon industry partner agreement for seismic data release

9.1.2 U.S. Department of Energy Milestone Log, Phase II-III, 2005-2006

Program/Project Title: DE-FC26-01NT41332: Resource Characterization and Quantification of Natural Gas-Hydrate and Associated Free-Gas Accumulations in the Prudhoe Bay - Kuparuk River Area on the North Slope of Alaska

Identification Number	Description	Planned Completion Date	Actual Completion Date	Comments
Task 1.0	Research Management Plan	1/05 – 12/06*	3/05 and Ongoing	Subcontracts Completed Research Management
Task 2.0	Provide Technical Data and Expertise	MPU: 12/02 PBU: ** KRU: **	MPU: 12/02 PBU: ** KRU: **	Ongoing, See Technical Progress Report; Industry Support more feasible?
Task 3.0	Wells of Opportunity Data Acquisition	Ongoing	Ongoing	Ongoing, See Technical Progress Report
Task 4.0	Research Collaboration Link	Ongoing	Ongoing	Ongoing, See Technical Progress Report
Subtask 4.1	Research Continuity	Ongoing	Ongoing	
Task 5.0	Logging and Seismic Technology Development and Advances	Ongoing		Ongoing, See Technical Progress/Topical reports
Task 6.0	Reservoir and Fluids Characterization Study	12/06*		
Subtask 6.1	Structural Characterization	12/06*		
Subtask 6.2	Resource Visualization	12/06*		
Subtask 6.3	Stratigraphic Reservoir Model	12/06*		
Task 7.0	Laboratory Studies for Drilling, Completion, Production Support	12/06*		
Subtask 7.1	Design Mud System	12/05*		
Subtask 7.2	Assess Formation Damage Prevention	1/06*		
Subtask 7.3	Measure Petrophysical and Other Physical Properties	9/06*		
Task 8.0	Completion & Production Testing	12/06*		Planning for Potential operations underway
Task 9.0	Field Operations and Data Acquisition Program	12/06*		Planning for Potential operations underway
Task 10.0	Reservoir Modeling and Project Commercial Evaluation	12/06*	Ongoing	Regional Resource Review & Development Planning

* Date dependent upon project continuation into latter phases
** Date dependent upon industry partner agreement for seismic data release

9.1.3 U.S. Department of Energy Milestone Plans

(DOE F4600.3)

DOE F 4600.3#

U.S. DEPARTMENT OF ENERGY FEDERAL ASSISTANCE MILESTONE PLAN, Phase I

1. Program/Project Identification No. DE-FC26-01NT41332	2. Program/Project Title Resource Characterization and Quantification of Natural Gas-Hydrate and Associated Free-Gas Accumulations in the Prudhoe Bay - Kuparuk River Area on the North Slope of Alaska
3. Performer (Name, Address) BP Exploration (Alaska), Inc., 900 East Benson Blvd, P.O. Box 196612, Anchorage, Alaska 99519-6612	4. Program/Project Start Date 10/22/02* 5. Program/Project Completion Date 12/31/06 (through Phase 3)

6. Identification Number	7. Planning Category (Work Breakdown Structure Tasks)	8. Program/Project Duration (Currently illustrates 2002-2004) O N D J F M A M J J A S O N D J F M A M J J A S-D	9. Comments (Primary work Performer)
Task 1.0	Research Management Plan	>>!>	BPXA
Task 2.0	Technical Data and Expertise	>>>>>>----->>>>------>>>>>>>>------------>>>>>>>>-------->>>>>>>>-->>>>>>>>--!-	BPXA
Task 3.0	Wells of Opportunity - Data	------>>>>>--------------->>>>>--------->>>>>>>>>>>>>>>---------->>>>>>>>>>>>>>>>!-	BPXA
Task 4.0	Research Collaboration Link	>>!>	BPXA, USGS, UAF, UA
Task 5.0	Logging/Seismic Technology	>>>!	USGS, BPXA
Task 6.0	Characterize Reservoir/Fluid	------->>>!>>	UA
Task 7.0	Lab Studies: Ph Behav, Rel k	-- ----->>!----------	UAF
Task 8.0	Evaluate Drilling Fluids	------->>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>--->>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>	UAF
Task 9.0	Design Cementing Program	------->>>>>>>>>>>>>>>>>>>>>>>>>>>>>	UAF
Task 10.0	Study Coring Techniques	-------->>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>- --	UAF
Task 11.0	Reservoir Modeling	>>>>------------------------>>>>>>>>>----------------->>>>>>>>>>>>>>>>>>>>>>!>>>	UAF, RyderScott
Task 12.0	Drilling Candidate Selection	>>>------ ----->>>>>>------>>>>>>>>>>>>---->>>>>>>>>>>>!	BPXA, UA, USGS, RyderScott
Task 13.0	Commerciality Assessment	>>>>>>--------------------------------->>>>>>>>---------------->>>>>>>----->>>>>>>>>	BPXA, UAF, Ryder Scott

10. Remarks * Official Contract Date 10/22/02; Funded reduced-cost pre-Phase 1 from 10/01-10/02. Phase 1 project from 10/02 through 12/04.
Explanation of Symbols: (> = Major Task Work); (- = Minor Task Work); (! = Milestones).
Additional significant milestones presented in Quarterly Technical Progress Reports.

11. Signature of Recipient and Date	12. Signature of U.S. Department of Energy (DOE) Reviewing Representative and Date

DOE F 4600.3#

U.S. DEPARTMENT OF ENERGY FEDERAL ASSISTANCE MILESTONE PLAN, Phase II-III

1. Program/Project Identification No. DE-FC26-01NT41332	2. Program/Project Title Resource Characterization and Quantification of Natural Gas-Hydrate and Associated Free-Gas Accumulations in the Prudhoe Bay - Kuparuk River Area on the North Slope of Alaska
3. Performer (Name, Address) BP Exploration (Alaska), Inc., 900 East Benson Blvd, P.O. Box 196612, Anchorage, Alaska 99519-6612	4. Program/Project Start Date 10/22/02* 5. Program/Project Completion Date 12/31/06 (through Phase 3)

6. Identification Task Number	7. Planning Category (Work Breakdown Structure Tasks)	8. Program/Project Duration (Currently illustrates Phases 2-3, 2005 - 2006) ← Planning/Analysis → ← DECISION → ←Planning→←---------POTENTIAL IMPLEMENTATION ---------→ J F M A M J J A S O N D J F M A M J J A S O N D	9. Comments (Primary work Performer)
Task 1.0	Contracts and Research Management Planning	>>>>>>>!>>>--->>>>>!-->>>>>>>>>>!>>>>>>>>---------------------------->>-!>>>>>>>	BPXA, AES
Task 2.0	Technical Data and Expertise	-->>>>>>----->>>>--!---->>>>>>>>!----------->>>>>>>>-------->>>>>>>-->!>>>>>>--	BPXA, AES
Task 3.0	Wells of Opportunity - Data	------------->>>>>-!------------!>>>>--------->>>>>>>>>>>>>>>----------!>>>>>>>>	BPXA, AES
Task 4.0	Research Collaboration Link	---------->>>>>>>>>!---------->>!>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>!>>>>>>>>	BPXA, USGS, AES, UAF,UA
Task 5.0	Logging/Seismic Technology	>>>>>>>>>>>>>>>>>>>>!>>>>>>>>>>>>!>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>!>>>>>>>>	USGS, BPXA
Task 6.0	Characterize Reservoir/Fluid	------->>>>>>>>>>>>>!---------->>!>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>!>>>>>>>>	UA, USGS
Task 7.0**	Lab Studies: Drilling, Completion, Production	------------>>>>>>>!---------->>!>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>!>>>>>>>>	UAF
Task 8.0**	Production Test Design: 2005 and Implementation: 2005-06	-->>>>>>>>>>>>!>>>----->>>>!>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>!--->>>>>	APA, BPXA, AES, UAF
Task 9.0**	Field Operations Plans: 2005 and Implementation: 2005-06	---->>>>>>>>>>!>>>------->>!>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>!--->>>>>	APA, BPXA, AES, UAF
Task 10.0**	Reservoir Modeling and Commercial Evaluation	----->>>>>>>>>>>>>>>!>>>>>>>>>>>>!>>>>--------------------------->>>>>>>!>>>>>>>>	RS, AES, BPXA, UAF

10. Remarks * Official Contract Date 10/22/02; Funded reduced-cost pre-Phase 1 from 10/01-10/02. Phase 1 project from 10/02 through 12/04. Phase 2 project from 1/05 through 9/05. Phase 3 project would be from 10/05 through 12/06 and would require approval of both BPXA and DOE. Explanation of Symbols: >> Major Task Work; -- Minor Task Work; ! Milestone. Significant technical work and milestones presented in Quarterly Technical Progress and Topical Reports. **Note new (Phase 2-3) Task numbers.

11. Signature of Recipient and Date	12. Signature of U.S. Department of Energy (DOE) Reviewing Representative and Date