SESSION 3B

HYDRATES/DEEP GAS RESEARCH

GAS HYDRATE RESEARCH

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ABSTRACT

In 1983, the U.S. Department of Energy (DOE) assumed the responsibility for expanding the knowledge base and for developing methods to recover gas from hydrates. This research is part of the Unconventional Gas Recovery (UGR) program, a multidisciplinary effort that focuses on developing the technology to produce natural gas from resources that have been classified as unconventional because of their unique geologies and production mechanisms. Gas hydrate research is designed to evaluate the potential gas hydrates as a future supply of gas, to validate the extent of the resource, to estimate the potential resource, and to develop the exploration and production technology to the proof-of-concept level.

Specific objectives are:

- To determine the chemical and physical properties of both natural and synthetic gas hydrates.
- To develop the necessary geologic characterization and geologic models for the formation of and resource estimates for both onshore and offshore gas hydrates.
- To develop the necessary diagnostic techniques and methods for measuring the in-place characteristics of both onshore and offshore gas hydrates.
- To develop strategies, reservoir and stimulation models, and preliminary economics for gas hydrate production.

Logically, the approach for developing gas can be divided into (1) a better understanding of the resource which covers most R&D activities, such as laboratory experiments, geologic integration and research, diagnostics, and modeling and (2) developing a knowledge base for extraction of the resource which includes basin studies and field tests.

Laboratory experimentation on natural and man-made gas hydrate samples will provide basic data for the development of reservoir models. Basic data from

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the analysis of onshore well logs and offshore seismic records will serve to provide information on the geologic characteristics for further refinement of the reservoir models. Data base and reservoir simulations are required to develop feasible extraction/production models and to identify remaining data gaps in the knowledge base. Basin studies will provide the necessary data to evaluate the factors responsible for the formation of the various types of hydrates. Future project activities will be directed toward the hydrate zone and the gas trapped by the hydrate base in offshore areas. These activities will also evaluate the environmental and economic concerns relative to hydrate production in both the onshore and offshore regions. Field verification will provide input towards resource assessment and proof of concept for gas hydrates.

DOE project plans call for a computer simulation of a field-scale, multiple well extraction process for hydrates. This activity will include the use and/or enhancement of conventional simulation models and the application of the results of hydrate physical characterization work. With the knowledge gained thus far, the first preliminary tests were conducted on the North Slope of Alaska. These tests were focused on the measurement of gas hydrate characteristics in place using geophysical and geochemical techniques. Industry drilled wells were used for this purpose. The North Slope was chosen because of the industry drilling data that is available that can be integrated with and help validate the data obtained. Through the successful completion of these activities, the potential of gas hydrates as a natural gas resource will be assessed, and the technology for the development of the resource will become available.

DEEP SOURCE GAS RESEARCH

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ABSTRACT

Deep Source Gas research is focused on the hypothesis that natural gas is generated in sediments carried to great depths at convergent plate boundaries in the earth's crust. These deeply emplaced sediments may source gas to shallower, drillable traps through deep-fracture systems. Many areas of North America are believed to have experienced plate tectonic convergence. The western Cordilleran geologic province in particular appears to have thrust fault structures (associated with subduction and obduction) that enabled deep emplacement of hydrocarbon-generating sediments during more recent geologic ages (during the last 180 million years). The specific area of interest in this province encompasses approximately 1.5 million mi^2 (3.9 million km^2) of the western U.S. (including Alaska) and Canada; other portions of this same province extend southward into Mexico and Central and South America.

The ongoing research consists of basic studies of hydrocarbon generation, stability, and preservation at depths in excess of 30,000 feet (9,150 m) in addition to a comprehensive evaluation of the geologic structures, stratigraphy, and geochemistry of the above region.

Results to date include geologic and geophysical evidence of deeply emplaced sedimentary rock units at depths exceeding 30,000 feet (9,150 m) in Washington and south-central Alaska, a new methodology for verifying deep methane stability via fluid inclusion studies, and a preliminary gas resource estimate of 3,000 Tcf. If only a fraction of the gas thought to exist is found to be recoverable, it could have a profound influence upon the international energy industry.

DEEP INVESTIGATIVE GEOPHYSICAL STUDIES

1. INTERAGENCY AGREEMENT: DE-121-83MC20422, TASK NO. 4

AGENCY: U.S. Geological Survey
Box 25046, MS964
Denver Federal Center
Denver, CO 80225
Phone (303) 236-1328

AGENCY COORDINATOR: John Roen, USGS, Reston, VA

PRINCIPAL INVESTIGATOR: William D. Stanley, USGS, Denver

METC PROJECT MANAGER: William J. Gwilliam, DOE/METC

PERIOD OF PERFORMANCE: Continuing

2. SCHEDULE/MILESTONES: FY1989 Program Schedule

	O N D J F M A M J J A S
Complete gravity model of Coast Range, Ore-WA (C.A. Finn).	●-------●
Complete 2-D MT model of Mesozoic suture, Alaska	●--------------●
Integrate MT and seismic refraction data-Oregon	●--------------●
Assist with processing flow and preliminary interpretation of WA reflection profile	●-----------●
Add detailed MT soundings along WA reflection profile	●------●
Initiate modelling of new MT data along reflection profile and integrate models	●------●

3. OBJECTIVES:

The focus of the research under this task is the study of fossil and active subduction zones using deep investigative geophysical methods to assess the potential for methane sourced in deeply emplaced sedimentary packages. The crust of the western U.S. Cordillera is composed of sedimentary units deposited in forearc and backarc environments, components of oceanic crust, and volcanic and intrusive rocks associated with the magmatic arcs of present and past subduction zones. The subduction zone units have widely differing geophysical properties and can be mapped to locate regions favorable for the occurrence of deeply sourced methane. The electrical resistivity of the prospective sedimentary packages varies most widely of the physical properties, although components of oceanic crust associated with the forearc sedimentary rocks produce large contrasts in magnetization and densitie. Deep electromagnetic soundings using the magnetotelluric (MT) method are employed as the main tool to study the resistivities of possible deep basin rocks. Other geophysical data such as magnetic, gravity and seismic data are used in an integrated manner to define properties of identified possible deep sedimentary rocks.

5. BACKGROUND STATEMENT:

The use of MT surveys in conjunction with other geophysical data has proven to be effective in studying the accreted crust of the western Cordillera. The type of suture zone where deep source rocks might occur is generally quite complex, and in many instances, covered by volcanic rocks. We have employed deep electromagnetic soundings, using the MT method, as a mainstay in field reconnaissance. These reconnaissance surveys have been utilized where surface geologic mapping or gravity and magnetic data indicate that a structural setting favorable for deep hydrocarbon source rocks may exist. Electromagnetic (EM) methods are particularly sensitive to conductive units such as those that might be represented by a high-shale-content sedimentary complex. Normal investigations of such target areas with seismic reflection methods is inherently difficult because of complex dips associated with the suture zones and the fact that high acoustic impedance reflectors generally overly the sedimentary rocks, i.e. volcanics or crystalline units in the hanging wall of the suture-zone thrust. The large cost factor of deep, high-fold seismic reflection surveys prevents their use except in isolated instances. The sedimentary rocks in several forearc basins have been studied to typify the electrical character of these systems and the surrounding geology. Motivation for these studies was partially stimulated by the discovery of a deep conductive package in the southern Washington Cascades which is interpreted to possibly represent a compressed pre-Eocene forearc basin/accretionary prism now covered by Oligocene volcanic rocks. These proposed sedimentary rocks extend to depths of over 15 km. If these units represent carbonaceous shale facies characteristic of other forearc system studied in this project, they could be good sources for deep methane. Maturation of such rocks could have been enhanced by accretion of a large seamount complex in early Eocene time which clogged the subduction zone and forced it to jump westward. The MT, gravity, and magnetic models for this system are currently being combined with new seismic reflection data to derive an integrated geologic model. Other extensive geophysical studies have been carried out in the Methow Trough (northern Washington), in the Coast Ranges of Oregon and California, and along a major suture zone in the Alaska Range region, Alaska. Analog studies of worldwide suture zones involving compressed and deeply emplaced sedimentary systems have been made using the literature and interaction with foreign geoscientists.

6. RESULTS/ACCOMPLISHMENTS:

In the course of this project, several field surveys have been conducted in the Cordillera of the western U.S. and existing data bases have been evaluated in order to locate specific areas where subduction/accretion processes may have led to deep emplacement of hydrocarbon source rocks. Of the variety of settings studied in the Cordillera with deep geophysical methods, two have developed into reasonably mature study areas and seismic reflection methods have been utilized in the later stages. A summary of the areas studied during the course of the project and pertinent findings follows:

- Western Washington-Extensive MT surveys and modeling of these data as well as gravity and magnetic data have outlined an anomalous region in the southern Cascades that is highly conductive that we call the southern Washington Cascades conductor (SWCC). Analysis of the morphology of the conductive zone with regard to mapped structures suggest that the anomalous region may represent an Eocene suture zone with thick marine sedimentary rocks. Other possibilities for the conductive region are considered to be altered volcanic rocks, continental sedimentary rocks, or older graphitic schists (Stanley and others, 1987). Results from recently initiated deep seismic profiling across this feature will be discussed by representatives from the contractor.

- Methow Trough-MT surveys across this marine sedimentary complex in north-central Washington show that Jurassic black shales and possibly other units have been thrust beneath crystalline rocks that form the eastern margin of the structural feature (Stanley and Plesha, 1985). The MT models have been compared with COCORP seismic data in the area, but the poor quality of the seismic data made adequate integration of the two data sets impossible.

- Klamath and Blue Mountains-Fossil subduction zone systems in the Klamath Mountains of northwestern California and the Blue Mountains region of Oregon have been studied in an attempt to locate deep sedimentary complexes. Mapped Jurassic-Cretaceous marine sedimentary rocks in the Blue Mountains were proven to be of predictable section thickness and not of major interest to the deep source gas program. Analysis of MT and seismic refraction data from the Klamath Mountains suggests that subthrust sedimentary or other conductive units underlie the Klamath Mountains terrane at depths of approximately 10 km (Stanley and others, 1989).

- Oregon Cascades-Extensive MT and seismic refraction profiling completed as part of the USGS Geothermal program has recently been modeled and jointly interpreted (Stanley and others, 1989). A pseudo-horizontal conductor in the mid-crust has been mapped in the Quaternary volcanic region, largely associated with the High Cascades of Oregon. This typically horizontal conductor that occurs at depth of 12-20 km in the Cascades volcanoes region becomes shallower along the western part of the volcanic belt. Extensive two-dimensional modelling of MT data from across the area where the conductor shallows (to <6km) indicates that the shallow part of the feature dips eastward to merge with the more typically horizontal part of the conductor. The preferred interpretation for both these features is that they are caused by water released by partial melt and water from amphibolite grade mineral dehydration, an interpretation partially derived because of the high correlation of heat flow data and the depth to the conductor. COCORP seismic profiling in the same area did not produce significant results, but refraction profiling across the same area has been used to assist in development of the petrologic model. There is a possibility that the east-dipping portion of the conductive region on the boundary of the volcanic belt is a smaller, but similar feature to that mapped in the southern Washington Cascades, and may represent an expression of the same Eocene suture located in Washington.

- Mist gas field-Preliminary regional studies of the Mist gas field and northern Oregon Coast Range indicate that no thick source rocks exist beneath the Coast Range basalts which form the basement in the Mist area. Some interlayered sedimentary units were detected in basalts of the western part of the Oregon Coast Range.

- Alaska Range, Alaska-A combination of MT surveys done under the DOE deep source gas program and under the USGS Trans-Alaska-Crustal-Transect (TACT) program have found what is interpreted to be a compressed regional flysch system in the region of the central and eastern Alaska Range (Stanley, 1986; Stanley and others, 1988b). This subthrust sedimentary complex is thought to consist largely of black shales of Jurassic-Cretaceous age. Structures related the interpreted compressed flysch system mapped in MT surveys have been recently corroborated by 1000-channel deep seismic profiling (Fisher and others, 1988).

- World analogs-With funding from other programs, we have done extensive investigations of other suture zones that have possible deeply emplaced sedimentary systems and their relationship to deep methane sources. In particular, comparative geophysical studies of an Eocene suture that follows the arc of the Carpathian Mountains in eastern Europe has been instructive. It has been learned that deep conductive units (from 5 to >20 km depth) that dip toward this suture zone form the sub-basement below major gas producing zones. I have proposed that the deep, conductive rocks are Mesozoic black shales (Stanley, 1988) and recent reports from Soviet scientists indicate that this is indeed the case. Exploration wells as deep as 8 km have been drilled in this region and efforts are continuing to obtain well-log and other data for continuation of comparative studies between this suture zone and areas such as western Washington and the Alaska Range.

Deep Drilling

Although a combination of geophysical methods can outline possible deep source rocks at depths of greater than 10 km, drilling will be required to complete the research. Only recently has the concept of drilling such deep research wells been discussed as part of a national program of deep continental drilling. A consortium established to carry out a national program of deep continental drilling (DOSECC for Deep Observation and Sampling of the Earth's Continental Crust) has been able to develop several proposals and one completed deep drill hole at Cajon Pass, California. The national deep drilling program is currently in transition with NSF maintaining authority over proposal review; the funding picture is uncertain. However, it is probable that the focus for the next several years will be on drilling shallow to intermediate depth holes (1-5 km). For the deep source methane problem that we study under this project, it is impractical in the short term to think of drilling to 10 km to test hypotheses. It is more prudent and sound to find areas where the concept of deep source rocks can be tested with shallow to intermediate depth drilling. This can be done by testing geologic models and using thermal and organic geochemistry studies in such boreholes. Both the SWCC feature in Washington and the Alaska Range suture zone represent such opportunities to employ shallow to intermediate depth drilling. In particular, we have submitted preliminary proposals to both DOSECC and NSF regarding shallow to intermediate depth drilling in the area of the SWCC. This proposal (Stanley, 1987b) points out that the lithology of the SWCC core units could be tested with relatively shallow drilling (1-2 km) on the axis of either of two anticlines on the upper part of the conductive package. If this shallow drilling resulted in proving that the SWCC units are composed of sutured marine sedimentary rocks, then a deep drill hole could be sited near the Morton anticline to drill through the accretionary sediments and into hypothesized oceanic crust below. According to the MT model, this could be as shallow as 8 km beneath the Morton anticline. The recently acquired seismic reflection data may provide additional constraints on the depth to this modeled oceanic crust and details of the SWCC structure.

7. FUTURE WORK:

Future research should include continued integration of MT and seismic reflection data from Washington and similar data sets in the Alaska Range. During the 1989 field season, additional detailed MT soundings will be obtained along the Washington seismic profile; earlier MT profiles were located somewhat away from the seismic profile. Integration of the MT data and preliminary and forthcoming seismic reflection data is a long term process; extensive remodelling of the MT, gravity, and magnetic data will be undertaken to arrive at an optimal model for all of the geophysical and geological data. I will continue to work with my co-worker, Victor F. Labson, who is conducting ongoing MT survey in Alaska under the USGS TACT program to investigate areas of interest for deep source gas research in Alaska. The most active study area that is pertinent to the deep gas program is the part of the TACT study that crosses the Alaska Range along the Richardson Highway. A 1000 channel deep reflection line was completed along this segment and this data has been combined with MT data (Stanley and others, 1988). Fisher and others (1988) show several high amplitude reflectors inside a zone that we interpret to be composed of black shales. The reflections may represent pore-space anomalies within the thick shales. Fisher is continuing to process this data in order to evaluate the nature of these amplitude anomalies and I will work with him to understand their possible significance to the deep gas program.

8. REFERENCES

Fisher, M. A., W. J. Nokleberg, V. F. Labson, and W. D. Stanley, 1988, Deep crustal structure of the Alaska Range, Alaska, from coincident seismic reflection and magnetotelluric observations: (abs) EOS, Trans. Am. Geophys. Union, p. 1452.

Stanley, W. D., 1984, Tectonic study of the Cascade Range and Columbia Plateau in Washington based upon magnetotelluric soundings: Journal of Geophysical Research, v. 89, p. 4447-4460.

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Stanley, W. D., Finn, C. A., and J. L. Plesha, 1987, Tectonics and conductivity structures in the southern Washington Cascades: Journal of Geophysical Research, v. 92, p. 10179-10193.

Stanley, W. D., 1987b, Deep sampling of accreted terranes (DSAT): the role of accretionary processes in concentration of economic resources and localization of seismicity and magmatism: (Abs) Workshop on Deep Observation and Sampling of the Earth's Continental Crust, Rapid City, South Dakota, Sponsored by NSF.

Stanley, W. D., 1988, Comparison of geoelectrical/tectonic models from Mesozoic orogenic regions of the United States and Europe: are black shales a source of conductivity anomalies: in press, Physics of the Earth and Planetary Interiors.

Stanley, W. D., V. F. Labson, Bela Csejtey, Jr., W. J. Nokleberg, and C. L. Long, 1988b, Evidence for accretion and thin-skinned tectonics in the Alaska Range, Alaska: (abs) Program and Abstracts, Annual Meeting, Geological Society of America, Denver, CO.

Stanley, W. D., W. D. Mooney, and G. S. Fuis, 1989, Details of crustal structure in the Cascade Range and surrounding regions from seismic and magnetotelluric data: Proceedings of U.S. Geological Survey Conference on the Cascades, Monterey, California (in press).

DEEP SEISMIC REFLECTION STUDY ACROSS SOUTHWESTERN WASHINGTON

1. CONTRACT NUMBER: DE-AC21-87MC24155

CONTRACTOR: Geophysical Systems Corporation
2085 East Foothill Blvd
Pasadena, California 91107-3292

CONTRACTOR PROJECT MANAGER: Mr. Samuel J. Allen

PRINCIPAL INVESTIGATORS: Mr. Daniel D. Hollis
Dr. William A. Schneider
Professor Thomas V. McEvilly

METC PROJECT MANAGER: Dr. William J. Gwilliam

PERIOD OF PERFORMANCE: October 1, 1988 to September 30, 1991

2. SCHEDULE/MILESTONES:

1989 Program Schedule
S O N D J F M A M J J A S

Acquire Phase 1 of Seismic program (45 Km)

Process Phase 1

Interpretation and Analysis of Phase 1

Determine line locations for Phase 2 (105 Km)

Permitting Phase 2

Acquire Phase 2

Process Phase 2

3. OBJECTIVES:

The objective of this contract is to obtain seismic reflection data across the Southern Washington Cascades Conductor (SWCC) so as to image the structure of the SWCC and it's surrounding tectonic environment and to use the data obtained to determine the nature of the SWCC and it's possible sourcing of hydrocarbons. The survey described here is the first of a multiphase reflection seismic program over the SWCC. This seismic survey was broken down into three parts: data collection, data processing and interpretation. Data from the survey will be used to construct a structural model of the subsurface, infer rock properties within the SWCC, identify and analyze any mid-crustal bright spots and possible pathways for hydrocarbon migration. The results will be a refined geological model of the SWCC which will be used in determining source rock for hydrocarbons in the area.

4. BACKGROUND STATEMENT:

Major objectives of the DOE's Deep Source Gas Project include: (1) to establish the existence of natural gas originating from sources at depth of 30,000 feet or more below the earth's surface, and (2) to quantify deep gas resources. Southwestern Washington and the adjoining part of northwestern Oregon have known natural gas resources. The source rock for the natural gas has not been identified. Magnetotelluric soundings have identified a body of rocks of low resistivity known as the Southern Washington Cascades Conductor. See Figure 1 for a map of the SWCC. It has been theorized that the SWCC is a package of subducted marine sediments and a possible source rock for the hydrocarbons found in the area. After or during subduction of the package, organic material in the SWCC may have cooked and generated natural gas which migrated toward the surface. A reflection seismic profile across the SWCC will reveal more information on the placement and properties of the rock package. Reflection seismic profiling is a high resolution technique used for imaging subsurface structure and using bright spot analysis can indicate presences of fluids or gas that may indicate hydrocarbons.

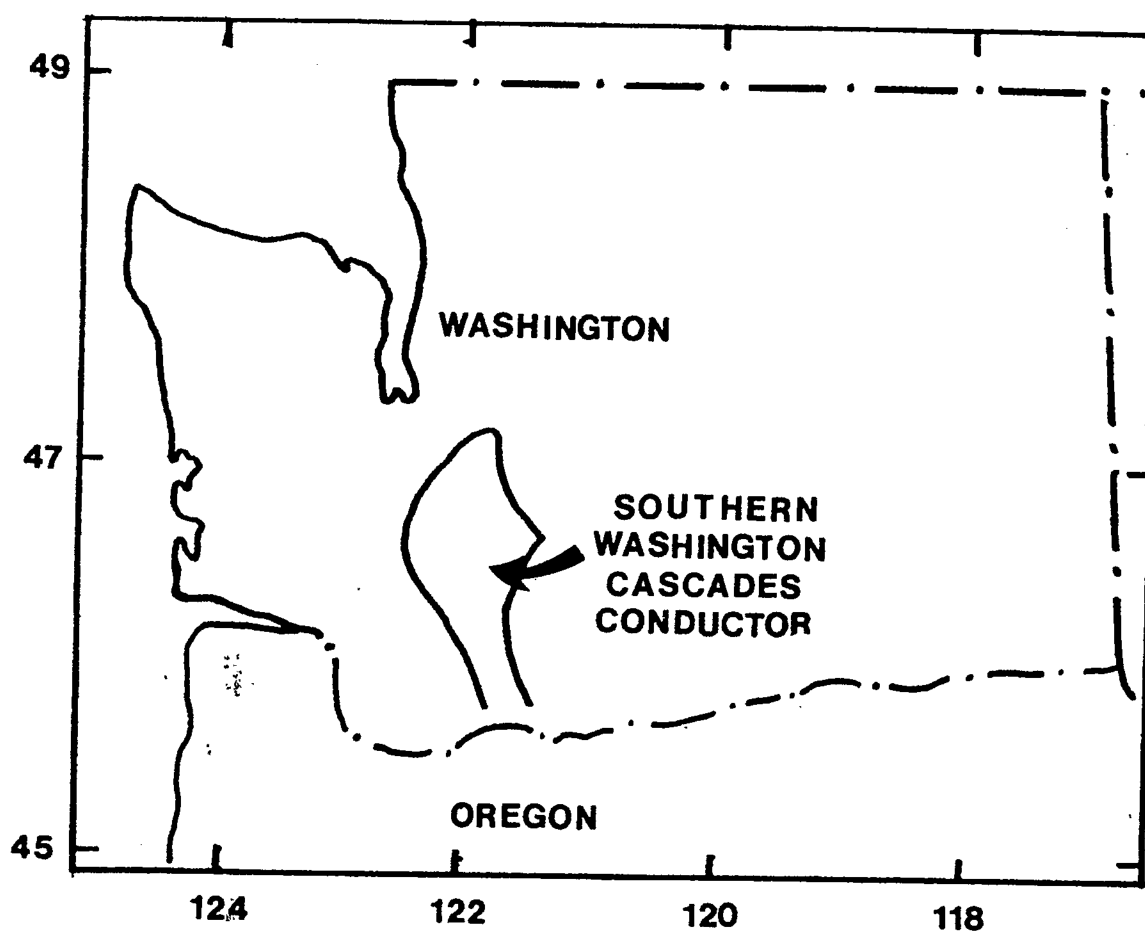

Figure 1. Map of Washington and Oregon showing areal extent of the Southern Washinton Cascades Conductor (after Cohen, 1986).

5. PROJECT DESCRIPTION:

The seismic survey across the SWCC consists of three phases: data acquisition, processing and interpretation. Data acquisition is broken down into survey line location, parameter selection and testing, and production data acquisition and data quality monitoring. Data processing takes the acquired data and reduces it to a seismic cross-section. This cross-section is analogous to a geological cross-section from which subsurface structures can be mapped. Data interpretation analyzes prominent reflectors for their structural and stratigraphic significance and identifies mid-crustal bright spots. Based on these analyzes and data from earlier studies a refined geological model is developed.

Seismic reflection surveys in this area of S.W. Washington presented a number a challenges, both geophysical and operational. Volcanic and plutonic terranes are known to be marginal data quality areas so the survey had to be designed to obtain the best data possible. There was also a broad range of geological objectives within the survey: the deep SWCC, shallow sediments and volcanics through which reflections raypaths of the deep data must pass twice, and an unknown factor of not knowing what dips of reflections were present. Operationally, there were topographic and access problems within the area. Given the nature of the targets and the surface problems, the philosophy used in designing the survey was to be as flexible as possible so that data acquisition would not limit any process in subsequent data processing that could enhance the signal-to-noise ratio of the reflections. In other words, the data should be collected in the purest form possible with the best signal-to-noise ratio and with enough statistical redundancy. This philosophy would not only give the best possible reflection data to base interpretation on but would provide a good data base on which to analyze and develop techniques to improve seismic data in volcanic and plutonic terranes.

The boundary of the SWCC was defined by previous MT work. When deciding the survey's location consideration was given to access, topography, geological structures the survey would cross and surface conditions the survey would cross. Also, there was a desire to tie into data already collected in the area. The easiest and most economical way to traverse the area was along the highways. The initial 45 kilometer line was located on Washington State Highway 12 between Mossyrock and Randle. See Figure 2 for a map of the line location. This route satisfied all the criteria outlined above. Surveying along the highway meant that there would be a higher level of traffic noise and that the seismic line would be crooked. Traffic noise is intermittent and is reduced by statical redundancy of correlation, vertical stack and CMP stack and was also reduced by the noise reduction characteristic inherent in the sign-bit transmission recording system used for the survey. The crookedness of the seismic is overcome by using crooked line stacking techniques. The crookedness of the seismic line also provides some 3-D information which may be useful later in the data interpretation phase.

In making initial choices of data acquisition parameters, flexibility of the data set was given prime consideration. Receiver array spread

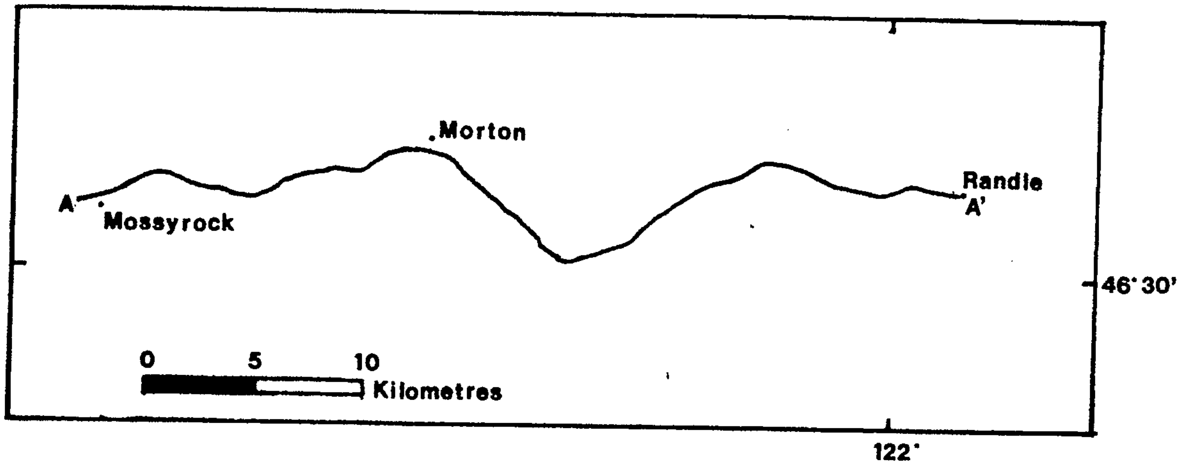

Figure 2. Map of the initial 45 kilomter seismic line along Washington State Highway 12 between Mossyrock and Randle.

offsets, receiver spacing and number of recording channels are interrelated parameters. The rule of thumb when considering far offset is that the farthest offset distance should equal the depth of the deepest objective. The depth to the SWCC package is a few kilometers to more than 25 kilometers, but to understand placement of the package and it's tectonic environment a greater depth should be used perhaps as far as the Moho which could be 30 to 45 kilometers deep. On the other hand, when considering receiver spacing, the receivers should be close enough to avoid spatial aliasing of dipping reflections, the steeper the reflection the closer spaced the receivers should be to avoid aliasing. Not knowing what the steepest reflection will be receiver spacing should be as close as possible. Between the need for long offsets and close receiver spacing means that a high channel recording system is necessary. A 1,024-channel recording system was chosen. Using a 30 meter receiver interval yielded about a 30 kilometer receiver array. The geophone array was six geophones evenly space over 30 meters. A vibroseis source consisting of 5 vibrators was used. A summary of the initial data acquisition parameters is shown in Table 1.

Before vibrator sweep parameter testing commenced the 30 kilometer receiver array was laid out. Sweep parameter tests were conducted at several different locations along the receiver array to test different surface conditions and subsurface geology. Several parameters were tested including: sweep bandwidth, sweep types (up, down, linear and non-linear), number of sweeps, vibrator drive level and the set of sweeps comprising the VARISWEEP set.

After vibrator sweep parameters were chosen production acquisition started. During production acquisition the data quality was continuously monitored. The field recording systems could correlate, composite and output the field data to tape in a trace sequential format. As each vibration point was written to tape the data was plotted. These plots were used not only to monitor the energy source and recording system but to monitor changes in surface conditions and subsurface geology that affect data quality. Further monitoring was performed by using an

Table 1. Initial Acquisition Parameters

Number of Channels	1,024.
Receiver Interval (meters)	30.
Vibrator Point Interval (meters)	120.
CMP Fold	128.
Spread Type	Split, 1,024 channels active at roll-on and roll-off.
Offsets (meters), at roll on/off	0 to 30,720.
with split spread	15,360 - 0 - 15,360.
Number of Vibrators	5.
Total Peak Force (lbs)	140,000 (5 x 28,000).
Number of Sweeps	18.
Sweep Length (sec)	15.
Sweep Type	VARISWEEP composed of 6 different linear down-sweeps.
Sweep Frequencies	24-9, 27-9, 30-10, 33-11, 36-12, 39-13.
Total Listen Time (sec)	30.
Correlated Listen Time (sec)	15.
Vibrator Array	Bumper-to-Bumper, Stationary.
Geophone Array	6 phones over 30 meters.

on-site field data processing system to produce quick look CMP stacks of the data. Based on this monitoring and additional testing, changes were made in the recording parameters as data acquisition continued. A summary of changes in data acquisition parameters is shown in Table 2.

Table 2. Summary of Acquisition Parameters

Configuration	Number of Channels	Source Interval	Receiver Interval	Number of Sweeps	Record Length
1	1024	120	30	18	15
2	1024	60	30	12	15
3	1024	40	20	12	15

After completion of data acquisition the data processing began and, as of the time this writing, is in the final stages of processing. So far, data processing has used a standard seismic data processing flow. Several non-standard processes have or will be tested on the data to determine what processes will improve data quality. Should any non-standard process improve data quality that processing was incorporated in the standard processing flow. The data processing flow is outlined in Table 3.

As of the time of this writing, there has been two processes applied to the data that were not in the original flow as outlined above. First, after refraction statics were applied, the data were summed with partial normal moveout applied to form a receiver array of 60 meters. The longer array is more effective in cancelling horizonal noise and improving the signal-to-noise ratio of the data. A 60 meter array during data

Table 3. Data Processing Flow.

Datum and Refraction Statics
Spherical Divergence and Exponential Gain Recovery
Deconvolution
Crooked Line CMP Sort
Amplitude Scaling
Velocity Analysis
Normal Moveout Corrections
Muting
Surface Consistent Residual Statics
Velocity Analysis
CMP Stack
Time Variant Filtering
Time Variant Scaling
Migration

acquisition is not the same as forming a 60 meter array during data processing. A longer array degrades or smears reflection data because of differential travel time between the elements of the array caused by near surface weathering and normal moveout across the array. These differences in travel time cause the plane wavefront to reach each element at different times and, therefore, out of phase to one another. Array forming during data processing is preferred to using longer arrays during data acquisition because weathering effects and normal moveout can be corrected between elements that form the array before summing. The second process that was not in the original flow was another pass of surface consistent residual static calculation which were performed after the second velocity analysis. The second velocity analysis resulted in a change in stacking velocities from those derived in the first round of velocity analysis which did not have the benefit of residual static corrections. The second pass of residual static calculations give better results than the first pass because of the improved velocity control.

6. RESULTS/ACCOMPLISHMENTS:

Completed 45 kilometers of seismic reflection data acquisition.

7. FUTURE WORK:

Commence interpretation and analysis of initial 45 kilometers.

Commence planning next phase of seismic survey.

8. REFERENCES:

Cohen, K.K., W.J. Gwilliam, T.H. Anderson and E. Lidiak, 1986, Deep Convergent Margin Basins of Washington State -- Past Hydrocarbon Source?: Circum-Pacific Energy and Mineral Resources Conference, 4th; Singapore, August 17-23, 1986, Transaction, Ed. by Myron K. Horn, Pp 275-284.

THERMAL HISTORY MODELING OF GEOLOGICAL BASINS

1. CONTRACT NUMBER: DE-AC21-85MC22009

   CONTRACTOR: Columbia University
   Lamont-Doherty Geological Observatory
   Palisades, NY 10964

   CONTRACTOR PROGRAM MANAGER: Charles Komar

   PRINCIPAL INVESTIGATORS: Gerard C. Bond
   Michelle A. Kominz
   Ann Grunow

   METC PROJECT MANAGER: William J. Gwilliam

   PERIOD OF PERFORMANCE: October 1, 1985 to January 31, 1989

2. SCHEDULE/MILESTONES:

1988 Program Schedule

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|                                     | J  F  M  A  M  J  J  A  S  O  N  D  |
|                                     |                                     |
| COLLECT DATA                        | +--------------------------------+  |
|                                     |                                     |
| MECHANICAL PROCESSES, ALGORITHM     | +-------------------------------+   |
|                                     |                                     |
| INITIAL, BOUNDARY CONDITIONS        | +-------------------------------+   |
| FOREARC PRISM MODEL                 |                                     |
|                                     |                                     |
| ALGORITHM FLUID FLOW                |                   +-----------+     |
|                                     |                                     |
| ALGORITHM HYDROCARBON MATURATION    |                          +-----+    |
|                                     |                                     |
| IDEALIZED FOREARC PRISM MODEL       |                   +--------------+  |
|                                     |                                     |
| APPLY FOREARC PRISM MODEL           |                          +-------->|
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3. OBJECTIVES:

The purpose of this study is to develop a generalized thermal model for forearc prisms, and to apply the model to the Oregon-Washington and southern Alaska margins. The model results are used to predict the production of significant accumulations of gas in these regions.

6. BACKGROUND STATEMENT:

Together, forearc basins and prisms comprise one of the major repositories of sediment in modern oceans, and through the process of collision and accretion they have added an immense volume of sediment to the margins of continents during the geologic past. In spite of their importance in modern oceans and their role in continental growth, the thermal and mechanical processes which control their origin and evolution are not fully understood. Recent progress has been made in understanding the physics of the mechanical processes operating in forearc prisms, while the thermal modeling of forearc prisms has not kept pace with these advances.

The thermal history of the forearc region is affected by a complex interplay of variables which include the thermal character of the underriding plate and its sediment load, the thermal character of the overriding plate, above and against which the forearc accretes, the radioactive content of the sediments, shear heating within the sediments, phase changes within the sediments and within the descending plate, and heat generated from magma emplacement behind the forearc. Additional factors that influence the thermal history of a forearc region are the effects of sediment porosity on conductivity and the advection of heat due to the motion of the sediments and the motion of water. A complete understanding of the thermal evolution of the forearc region involves a number of structural elements such as the forearc prism, the forearc basin and the arc complex itself, all of which contribute to the overall thermal regime. To include all of these structural elements together with these thermal processes is beyond the scope of this project.

5. PROJECT DESCRIPTION:

First, we have produced and applied a simple descending slab model to focus on the large scale tectonic and thermal features operating in the forearc region. Modeling indicated that the primary control on the large scale thermal regime is the age of the descending plate with subduction rate and slab friction playing a secondary role (see Kominz et al., 1987).

The forearc prism model focuses on the processes operating within the prism. Subduction processes operating in forearc prisms are complex, and many simplifying assumptions have been made in order to apply a geophysical model to the problem.

6. RESULTS/ACCOMPLISHMENTS:

- Developed a thermal model of an accretionary forearc prism including:

  - The geometry of the prism and accreting sediments -

    The angle of subduction and taper of the prism wedge are different for different prisms (e.g. Davis et al., 1983). Additionally, the amount of material entering the wedge is different for different prisms and must significantly effect the thermal history of the prisms. Our thermal model allows a range of angles and thicknesses of various elements. See Figure 1 for general geometric layout.

  - The thermal properties of the lithosphere -

    The heat capacity in the lithosphere is constant. The density is 3.33 g/cm^3 at 0°C and is decreased for higher temperatures using a thermal coefficient of expansion of $\approx 3.58 \times 10^{-5}$/°C that increases slightly with depth, following Toksöz et al., 1971. The thermal conductivity is assumed to be a function of both temperature and depth from experimental results by Schatz and Simmons, 1972.

  - The thermal properties of the sediments -

The primary control on the physical properties of the sediments is their porosity. Porosity is given by a single exponential for each of a number of domains allowing the porosity depth relation to be different for the prism sediments, the trench fill and the subducting ocean slab sediments. In each case the decay constant may be increased in an arcward direction. This allows for a porosity decrease which is observed or suggested for modern arcs (Zhao et al., 1985; Bray and Karig, 1985). The thermal properties, including density, specific heat, and radioactivity, are a direct function of the proportion of water present. The conductivity of water is temperature dependent and can be characterized by a quadratic equation (CRC Handbook of Chemistry and Physics, 1971). Also, the conductivity of the sediment/water mixture is best described by the Maxwell (dispersive) model (Beck, 1976).

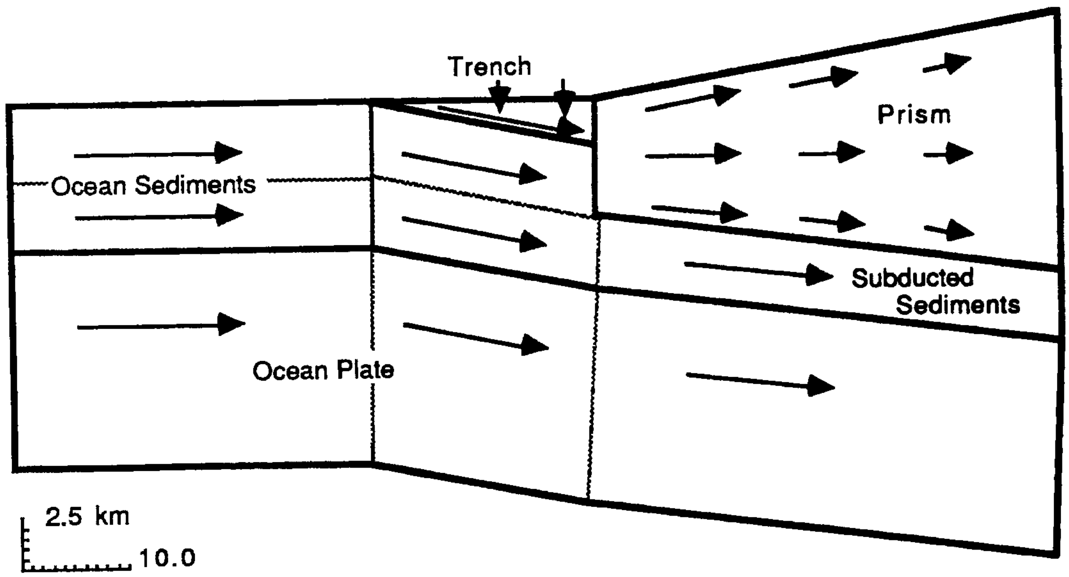

Figure 1. Prism flow and elements of grid. Diagram showing the elements of the prism model. The frontal portion of the prism, to the slope /shelf break may be included in the model. The motion of ocean plate and subducting sediments are equal to the motion of the plate perpendicular to the margin. The motion of the sediment in the trench wedge is parallel to the subducting sediment and vertically downward to fill the hole that results. The prism sediments move arcward and up or down depending on their position in the prism.

- Initial temperatures of prism and subducting slab -

A temperature distribution must be established in order to begin modeling. These initial temperatures are defined using one dimensional approximations. The thermal gradient within the ocean plate is calculated using a cooling half-space model (Turcotte and Schubert, 1982). This model determines the thermal gradient within the ocean plate and the heat flow into the base of the sediments. The temperatures within the oceanic crust are dependent on the temperature of the sediments above the plate. Initial temperatures of the ocean plate sediments are taken to be in thermal equilibrium. The surface (sediment/ocean) temperature is assumed to be 0°C (273°K) for all sediments. The one-dimensional analytical solutions of Oxburgh and Turcotte, 1971, are used to establish the initial temperatures in the prism and the trench fill. Their equations for sedimentation from the top down is used for the trench fill. Their analytical solution for sedimentation from the bottom up is used for the prism. Thus, the initial temperatures are defined by the age of the descending oceanic slab, the age of the prism sediments and the age of the trench fill sediments.

- Conductive heating -

  Two-dimensional conductive heating is calculated using the integral finite difference approach of Narasimhan and Witherspoon, 1976 & 1977.

- Sediment and water motion in the prism -

  Two two options are available to define the motion of sediments, ocean plate and pore water within the slab. The general motion pattern is shown in Figure 1. One subroutine calculates motions from a purely volumetric standpoint. This is equivalent to assuming that excess pore water is rapidly and completely removed through conduits, such as faults, within the prism. The second subroutine conserves the volume of sediment moving from one column to the next within the prism and allows excess water to move up and out through each sediment column conserving pore water space. Identical model runs utilizing the two options show that while separating the sediment and water motion results in a hotter prism, as expected, the temperature difference is negligible.

- Thermal maturation of the sediments -

  We use Waples', 1980, calibration of Lopatin's, 1971, time-temperature index of maturity (TTI) to determine the hydrocarbon maturation predicted by the thermal model in the sediments of the forearc prism model. This maturation index is calculated by assuming that maturation is directly proportional to time and exponentially related to temperature.

- Apply the forearc prism thermal model to known convergence rates in the Oregon/Washington and Alaskan margins

The thermal model was applied to the last 28 to 56 m.y. of subduction in the Oregon/Washington and Alaska margins. Results from the Kodiak margin run from Alaska and from the Oregon margin are discussed in this paper.

These two forearc prisms are similar in that they are both accretionary prisms (von Huene et al., 1987, von Huene, 1984, Snavely, 1987). That is, a considerable amount of sediment is deposited on the ocean plate adjacent to the prism and much of that sediment is actively added to and incorporated in the prism structure. From an large scale perspective, the prism can be viewed as growing as a result of the overall motion of sediments in an upward and arcward fashion (Fig. 1).

In both margins a fairly thick portion of sediment is being subducted beneath the prism wedge. It is this package of sediment which Kvenvolden and von Huene, 1985, suggest as a possible source of significant natural gas in the Aleutian prism. One to 2 km of sediment has been imaged by multichannel techniques in the Kodiak region to at least 10-20 km beyond the toe of the prism (von Huene, 1987). The presence of subducting sediments beneath Oregon and Washington margins is less well documented. Multichannel imaging indicates that subducted sediments are present 15 km beyond the toe of the accretionary prism (Snavely et al., 1986).

The age and geometry of the frontal prism wedge is different in the two regions. Detailed imaging is available to about 15 km in the Kodiak region (Kvenvolden and von Huene, 1985). The oldest sediment collected on this prism early Miocene (von Huene et al, 1987). Thus, model results are constrained by direct evidence for the last 20 m.y. in the Kodiak region. In the Oregon/Washington region extensive refraction work to 14 to 19 km, coupled with evaluation of exposures on land allow an estimate of the age of the accretionary wedge. Here, the modern accretionary prism consists of sediments of perhaps mid to early Eocene age which are truncated arcward by dexteral faults which were active mainly prior to the Late Eocene (Snavely et al., 1987; Snavely et al., 1986; Kulm et al., 1984). Thus, modeling is possible to prism depths of 14 km and for perhaps 50 m.y. The geometries of the prisms differ in terms of the angle of subduction of the slab and the taper of the prism. The slab subducts beneath the prism in southern Alaska at a fairly steep angle of $\approx$ 9-13° with a foreslope taper of $\approx$ 4-5° (von Huene et al., 1987, Davis et al., 1983). The Cascadian prism has roughly equivalent subducting plate and taper angles of 2-5° (Clowes et al., 1986; Snavely et al, 1987; Kulm et al, 1984). In the Washington/Oregon margin a well developed wedge of continentally derived trench sediments extends to $\approx$ 80 km beyond the toe of the prism. The trench is much less well defined in Alaska where it is difficult to distinguish from subducting deep sea fan deposits (von Huene, 1987; Stevenson, et al., 1983).

A particularly significant difference for understanding the overall thermal regimes of the two regions is the age of the subducting slab (von Huene et al., 1987). As we have shown (Kominz et al., 1987) a strong relation exists between prism heat flow and subducting plate age which mimics that seen in the aging of ocean plates. Thus, maintaining accurate heat flow through control over the changing ages of the subducting slab is an important modeling element. The plate age at the trench in southern Alaska today ranges from about 40 to 55 Ma implying a heat flow of $\approx$ 60-80 mW/m^2 (Parsons and Sclater, 1977). The Juan de Fuca plate which is subducting beneath the Oregon/Washington margin is about 4-9 Ma (Kulm et al., 1984) with a predicted heat flow of 140-250 mW/m^2 (Parsons and Sclater, 1977). The southern Alaskan margin has been subducting old Pacific plate formed at the Pacific/Kula spreading center prior to its cessation $\approx$ 50 Ma (Stevenson et al., 1983). For the much of the last 30 m.y. of subduction, the Aleutian trench has been subducting a plate of nearly constant age. Plate age has decreased with time at the Cascadian margin as the Farallon/Pacific, and later the Juan de Fuca ridge, approached the North American Plate margin (Engebretson et al., 1985).

Convergence rates also differ significantly in the two regions. Oblique convergence between Alaska and the Pacific plate over the last 30 m.y. has resulted in convergence rates ranging from about 4.5 to 7.5 cm/y (Engebretson et al, 1985). Convergence of the Juan de Fuca and North American plates has been more variable. Rapid subduction in excess of 10 cm/y from about 56 to 43 Ma slowed to 2.3 to 3.8 cm/y over the last 37 Ma (Engebretson et al., 1985; Stock and Molnar, 1988). These variable convergence rates coupled with changing plate ages point to the non-steady state nature of forearc accretion which our model simulates.

Thermal results from the Kodiak margin indicate that initial temperatures (at 28 Ma), using the one-dimensional models and the current age distribution of the prism, are quite high. Temperatures calculated by the two-dimensional modeling were considerably lower. In general, the thermal regime achieved at 17 Ma was maintained throughout the model run. The final temperature regime, shown in Figure 2 is quite cool. The temperatures are sufficiently low throughout the modeling procedure that no maturation of hydrocarbons was predicted. These temperatures are considerably less than those calculated to be present from observation of gas hydrate layers (Kvenvolden and von Huene, 1985).

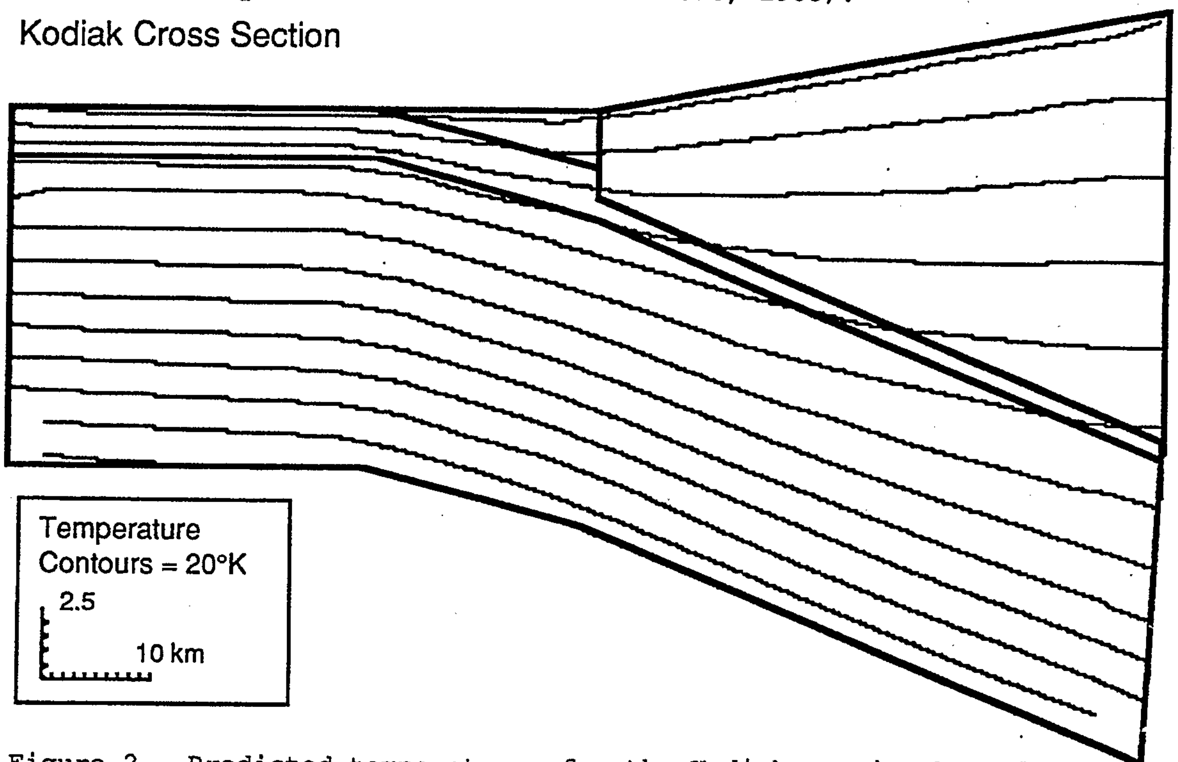

Figure 2. Predicted temperatures for the Kodiak margin thermal model simulation at 0 Ma. Decreasing heat flow and thermal gradients indicated by the increased spacing of the contours in the trench wedge and prism result from sediment motion and the rate of subduction of the oceanic plate.

The last 56 Ma of subduction was simulated for a cross section off central Oregon. In this case the prism age assumed for calculating the initial temperatures was taken to be considerably younger than the prism age today. The resulting initial temperatures are much closer to those obtained by two dimensional modeling. Model results show a general increase in temperatures throughout the modeled region as a result of the general younging of the plate and an overall decrease in subduction rates with time. The sediments substantially increase in temperature at 28 Ma, reflecting a major reduction in convergence rates at that time. The temperatures at the end of the modeling (0 Ma) are generally quite high although they do show a marked decrease towards the craton (Figure 3). The thermal gradient at the cratonic edge of the modeled region is 22°C/km and about 100°C/km at the toe of the prism. These results are consistent with observations from a number of heat flow surveys of the Cascadian prism (e.g. Lewis et al., 1988; Blackwell et al., 1982).

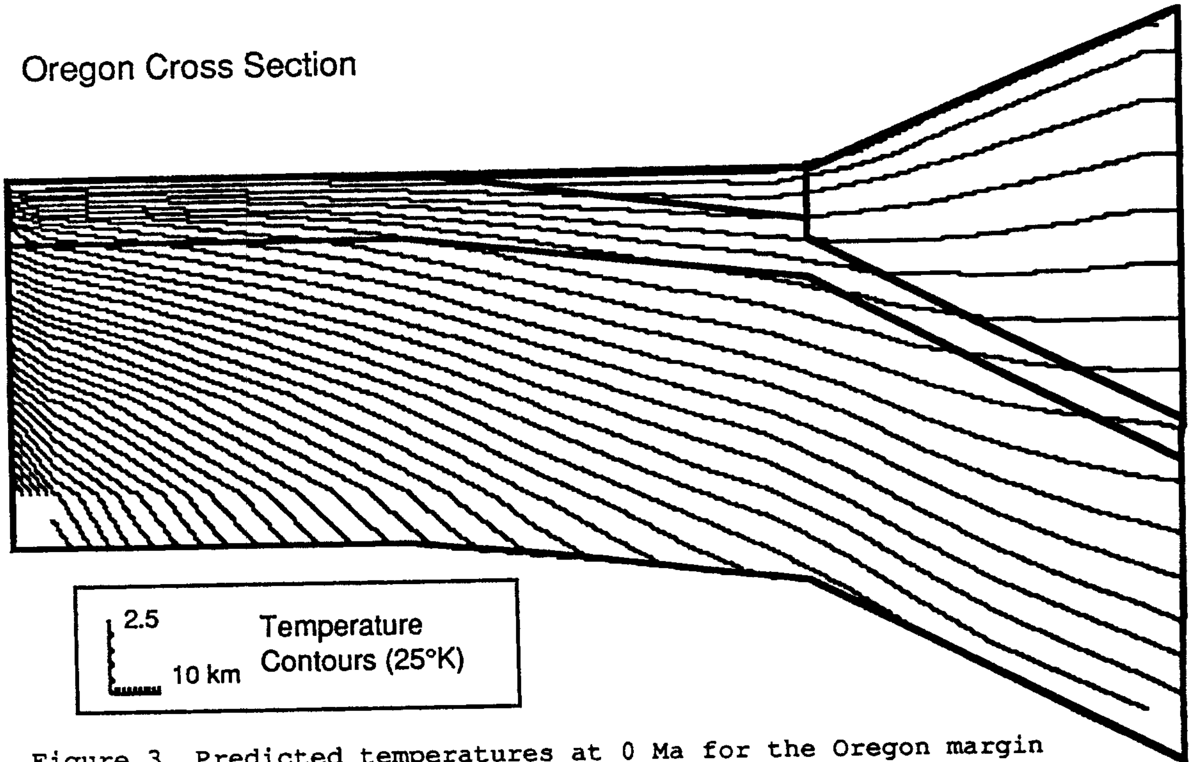

Figure 3. Predicted temperatures at 0 Ma for the Oregon margin simulation. The increasing spacing of the contours clearly indicates the decreasing heat flow from the ocean plate to the landward edge of the prism. Heavy lines give the location of the prism, the trench wedge, the oceanic sediments and the ocean plate, as shown in Figure 1. Note that the contour interval is greater than that used in Figure 2, the Kodiak results.

Thermal maturation results imply that no oil would be generated at the initiation of the Oregon model run due to the relatively old subducting plate and high rates of subduction. Oil may have generated in the prism at about 12 km and deeper at 37 Ma and at about 8 km and deeper at 17 Ma. By 0 Ma the lower portion of the prism modeled is within the 50° oil preservation window, indicating that gas has most likely generated just inboard of the modeled region. Also, sediments on the youngest portion of the ocean plate could be generating gas at 1 km depth.

Two dimensional modeling results indicate that temperatures in the prisms are lower than would be predicted by one-dimensional analyses. We have found that unless very young oceanic crust is being subducted beneath the prism (as is the case presently off Oregon and Washington) the sediments will not mature within the forearc region. As a result, vast quantities of sediments which form a portion of accreted terranes remains a potential source of hydrocarbon production. Although these sediments tend to be low in organic carbon content their sheer mass may prove a significant source for deep gas production (Kvenvolden and von Huene, 1985). However, we suggest that this production may occur later in the process of terrane accretion than was suggested by von Huene, 1987 and Kvenvolden and von Huene, 1985.

- One dimensional modeling of forearc prism accretion can be misleading. Two dimensional thermal modeling is necessary to obtain an accurate picture of the thermal history associated with forearc prism accretion.

- Temperatures predicted by two dimensional modeling are consistently lower than those predicted by one dimensional calculations.

- Temperatures of the descending ocean plate exert primary control on the temperature structure of the prism and subducting sediments.

- Secondary controls on temperature include subduction rate, radioactivity of sediments and differential motion between the water and the sediment.

- Sediments accreted to and subducted beneath the southern Alaskan margin did not form hydrocarbons while within the forearc region. Thus, they could be source rocks for generation of gas at greater depths.

- Sediments accreted to and subducted beneath the margin of Oregon and Washington from about 56 Ma to about 17 Ma did not form hydrocarbons while within the forearc region. As such, they could be source rocks for generation of gas at greater depths.

- Owing to the high temperature of Juan de Fuca plate, the model predicts that sediments accreted to and subducted beneath the margin of Oregon and Washington from about 17 Ma to the present has produced hydrocarbons within the forearc region. As such, they will not become source rocks for generation of gas at greater depths.

- Forearcs and forearc basins will only be good prospects for oil and gas generation in regions where very young ocean plate has been or is currently being subducted, unless superimposed thermal events have occurred.

- Ancient accreted terranes and deeply buried accretionary sediments will only serve as good prospects for source rocks if they were accreted in a region where mature ocean floor (=> 10 m.y.) was being subducted. Because the majority of subducting plates are "mature", accreted terranes may serve as a good prospect for sources of hydrocarbons.

6. EVALUATION OF POTENTIAL FUTURE PLANS:

Directions for future research are plentiful. These may include:

- Modification of the model to include underplating of sediments and draping of sediment on the wedge.

- Modification of the model to include cases where there is no accretion occurring or no sediment being subducted.

- Application of the current model to other very well documented prisms, such as the Caribbean prism for verification of the model.

- Application of the current model to other to very poorly known prisms for use as a tool in exploration.

- Development of a thermal model which includes the entire forearc wedge, including possible flow of material from depth upward as a result of erosion, added heat, uplift and or encountering "backstops".

• Development of a thermal model to predict hydrocarbon maturation in sediment wedges which make up portions of accreted terranes.

While the directions for further research abound, the current contract with METC is terminated.

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GEOLOGIC INTERRELATIONS RELATIVE TO GAS HYDRATES WITHIN THE NORTH SLOPE OF ALASKA

-IN SITU FIELD RESEARCH-

1. **CONTRACT NUMBER:** DE-AI21-83MC20422

CONTRACTOR: U.S. Geological Survey
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METC PROJECT MANAGER: R.D. Malone

PERIOD OF PERFORMANCE: October 1, 1983 to September 30, 1990

2. **SCHEDULE/MILESTONES:**

Task 6. Geologic Interrelations Relative To Gas Hydrates (completed 1/88)

- Map geothermal gradient and permafrost thickness (September 85).
- Map gas hydrate stability field (March 86).
- Establish geologic framework (September 86).
- Map gas hydrate occurrences (March 87).
- Develop terrestrial gas hydrate model (June 87).
- Define resources and core site (September 87).

Task 18. In Situ Field Research

- Data obtained from the well-site sampling, temperature, and borehole gravity surveys will be used to update products of Task 6 (September 90).

3. **OBJECTIVES:**

Task 6. Geologic Interrelations Relative To Gas Hydrates

- Define and evaluate possible gas hydrate reservoirs.
- Evaluate geologic/geochemical controls on gas hydrate occurrences.
- Develop model for terrestrial gas hydrate formation.
- Conduct a gas hydrate resource estimate.
- Select coring site to study gas hydrate.

Task 18. In Situ Field Research

- Collect and analyze geologic/geochemical samples relative to gas hydrates.
- Conduct precision temperature surveys to determine: 1) equilibrium formation temperatures; 2) limits of the gas hydrate stability and permafrost regions; 3) geothermal gradients and (with samples) heat flow; and 4) possible in situ thermal indications of gas hydrate occurrences.

- Conduct borehole gravity surveys to detect gas hydrate, determine reservoir porosity, and provide density measurements to better understand thermal properties.
- Characterize formation water chemistry.
- Model the seismic character of in situ gas hydrates.

4. BACKGROUND STATEMENT:

Gas hydrates are crystalline substances composed of water and gas in which a solid-water lattice accommodates gas molecules in a cage-like structure, or clathrate. Gas hydrates have been known as laboratory curiosities since about 1810. Detailed studies of hydrates and their physical properties were not undertaken until Hammerschmidt (1934) published data pertaining to the plugging of natural-gas pipelines due to gas-hydrate formation. The geologic occurrence of gas hydrates has been known since the mid-1960's, when gas-hydrate accumulations were discovered in the U.S.S.R. (reviewed by Makogon, 1981).

Pressure and temperature conditions suitable for the formation of gas hydrates are found in high latitude regions of permafrost and beneath the sea in outer continental margins and ocean basins (reviewed by Kvenvolden and McMenamin, 1980). Katz (1971) was the first to recognize that temperatures and pressures associated with permafrost may fall within the stability field of gas hydrates (fig. 1). Gas hydrates can occur not only in permafrost but also below the base of permafrost at temperatures above the freezing point of water.

Significant quantities of gas hydrates have been detected in several permafrost regions of the world, including western Siberia (Makogon, 1981), the Mackenzie Delta of Canada (Bily and Dick, 1974), and the North Slope of Alaska (Galate and Goodman, 1982; Collett, 1983; Collett and others; 1988). Estimates of worldwide gas hydrate resources in permafrost regions are as high as 10^{16} m^3 of methane (Potential Gas Agency, 1981), an estimate large enough to stimulate interest in gas hydrates as a possible energy source. Gas hydrates also may be a potential drilling hazard because they can cause sediment instability and high pressures in a bore-hole.

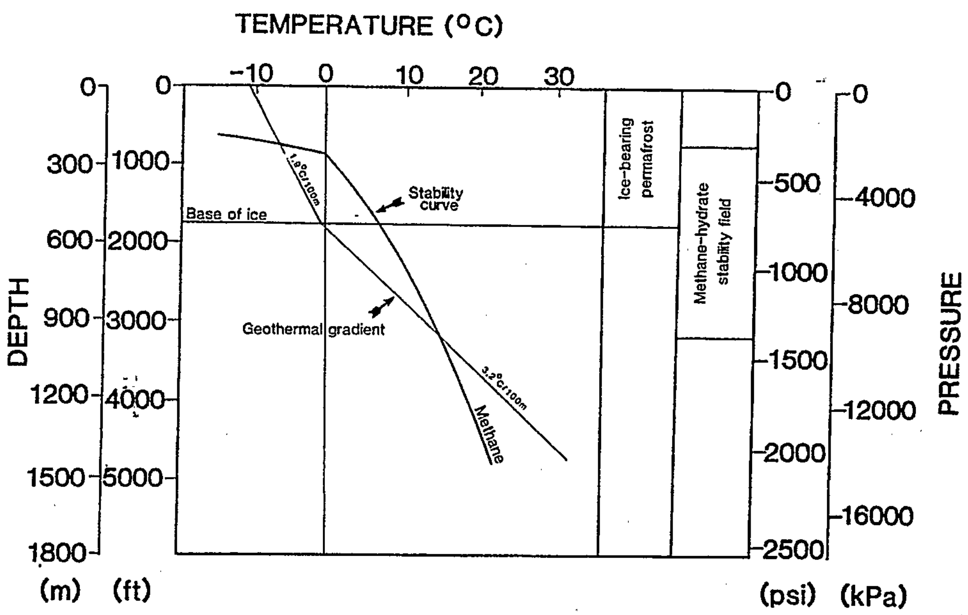

Figure 1. Gas hydrate phase diagram applied at the Northwest Eileen State-2 well on the North Slope of Alaska. The hydrate is assumed to be composed of pure methane and pure water.

5. PROJECT DESCRIPTION:

In 1983 the U.S. Geological Survey and U.S. Department of Energy developed the North Slope Alaska Gas-Hydrate Research Project. Phase I (Task 6) of this project, completed in 1988, dealt with the evaluation of existing data in an attempt to delineate gas hydrate occurrences in northern Alaska (fig. 2), and to evaluate the physical properties controlling gas hydrate distribution. Phase II (Task 18) activities are a continuation of Phase I, except that the major emphasis is to obtain new data through an active field study program. The field research includes temperature and borehole gravity surveys, formation water sampling and analysis, and geologic/geochemical sampling and analysis of wells and outcrops.

One of the primary objectives of the project is to develop a model that describes the possible origin of gas hydrate on the North Slope. Various mechanisms for gas-hydrate formation have been postulated as reviewed by Pratt (1979) and Makogon (1981). One theory suggests that gas hydrates could be part of a pre-existing gas reservoir, later solidified in place. Another theory suggests that a gas-hydrate accumulation could form by a flow of free gas into the zone of gas-hydrate stability. Migrating free gas may also be trapped at the base of the ice-bearing permafrost and converted to gas hydrate. Gas hydrates are sometimes found closely associated with decaying biomatter, such as coal, which may serve as a gas source. These various schemes of gas hydrate formation can be grouped into two end-member models.

MODEL 1. The conversion of a pre-existing gas field into a gas hydrate with a favorable change in temperature or pore-pressure (fig. 3a).

MODEL 2. Formation of gas hydrate by continuous migration of either microbial or thermogenic gas from below into the zone of gas-hydrate stability (fig. 3b).

Relatively little is known about the history of gas hydrate formation on the North Slope of Alaska. However, recent geologic and geochemical studies from the Prudhoe Bay-Kuparuk River area have provided us with new insights into the geologic parameters controlling the distribution of gas hydrates. In the following section we present a model which best describes the origin of gas hydrates in northern Alaska.

6. RESULTS/ACCOMPLISHMENTS:

GEOLOGIC SETTING

The rocks of the North Slope can be conveniently grouped into three sequences that reflect major episodes in the tectonic development of the region. Defined on the basis of source area, these sequences, proposed by Lerand (1973) and applied to northern Alaska by Grantz and others (1975) are, in ascending order, the Franklinian sequence (Cambrian through Devonian), Ellesmerian sequence (Mississippian through Jurassic), and the Brookian sequence (Cretaceous to Holocene).

The petroleum-bearing stratigraphic section in the Prudhoe Bay-Kuparuk River area includes the Ellesmerian and Brookian sequences. The Ellesmerian sequence consists of carbonate and siliciclastic rocks derived from a source terrain that was once north of the present coast line. The Prudhoe Bay oil field is the primary oil accumulation in the Ellesmerian sequence, with production from the Sadlerochit Group which also includes a 26 tcf gas cap. The Lisburne and Kuparuk River oil fields also occur within the rocks of the Ellesmerian sequence. The Brookian sequence consists of only siliciclastic rocks derived from the Brooks Range to the south. The principle oil accumulations in the Prudhoe Bay-Kuparuk River area, of the Brookian sequence, are in the (informal) West Sak and Ugnu sands. The names "West Sak sands" and "Ugnu sands" are used by ARCO to identify a series of heavy-oil bearing sandstone units in the Kuparuk River area (Werner, 1987). All of the suspected gas-hydrate occurrences are within the Brookian sequence (Collett and others, 1988).

Petroleum geochemical information and interpretation of oil types (Magoon and Claypool, 1981) and oil-source rock correlations (Seifert and others, 1979) indicate that the oil in the Prudhoe Bay-

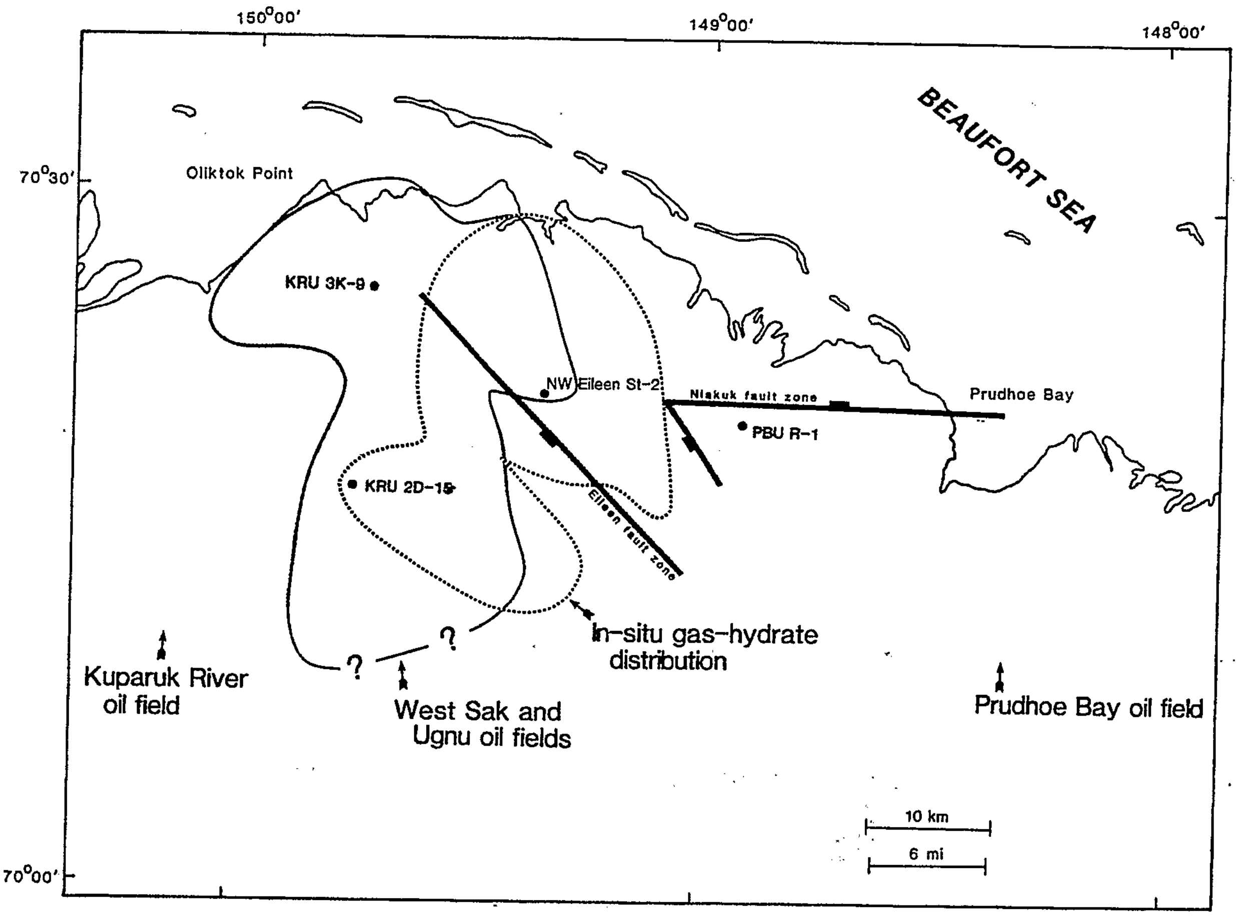

Figure 2. Distribution of the in-situ gas hydrates and oil occurrences in the Prudhoe Bay-Kuparuk River area. The lateral extent of the gas-hydrate occurrences are outlined with a dotted line. The West Sak and Ugnu oil fields are shown as a single accumulation (enclosed with a solid line, queried where inferred). The location and dip of several major fault systems are indicated by bold lines. The Prudhoe Bay and Kuparuk River oil fields are shown by shading. Oil well locations are shown by solid circles.

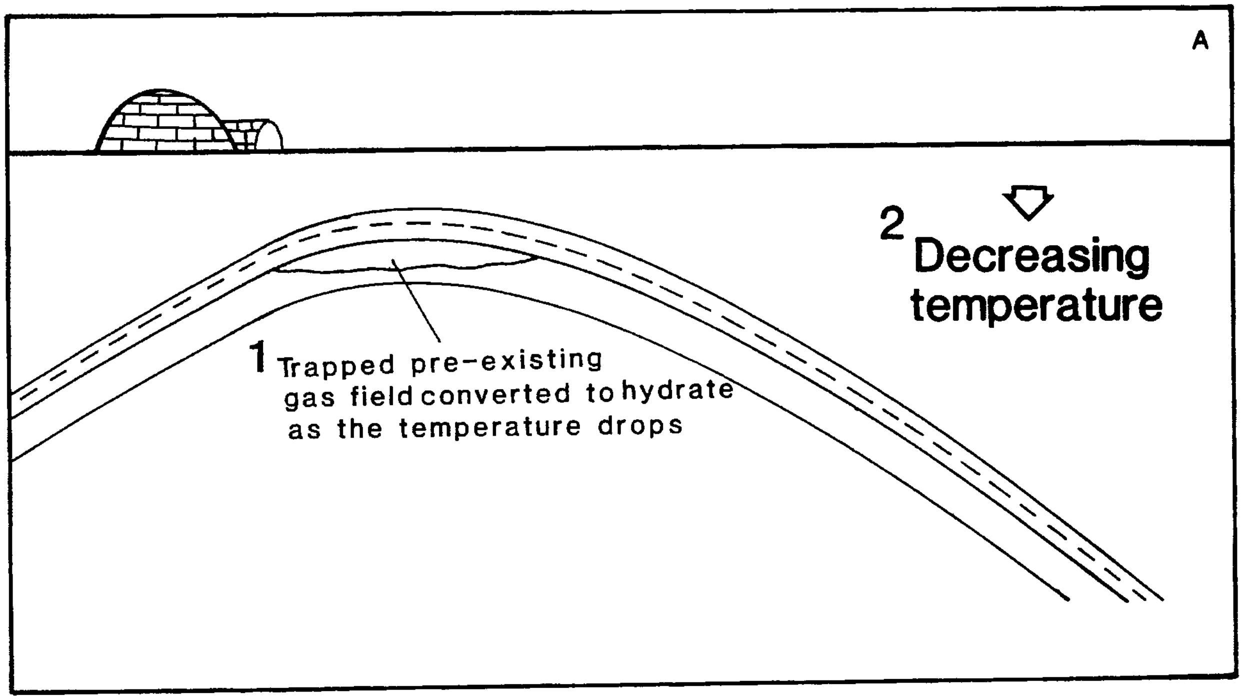

Figure 3a. Example of Model 1: The conversion of a pre-existing free-gas field, trapped within an anticlinal structure, (1) into a gas-hydrate accumulation with a decrease in temperature (2).

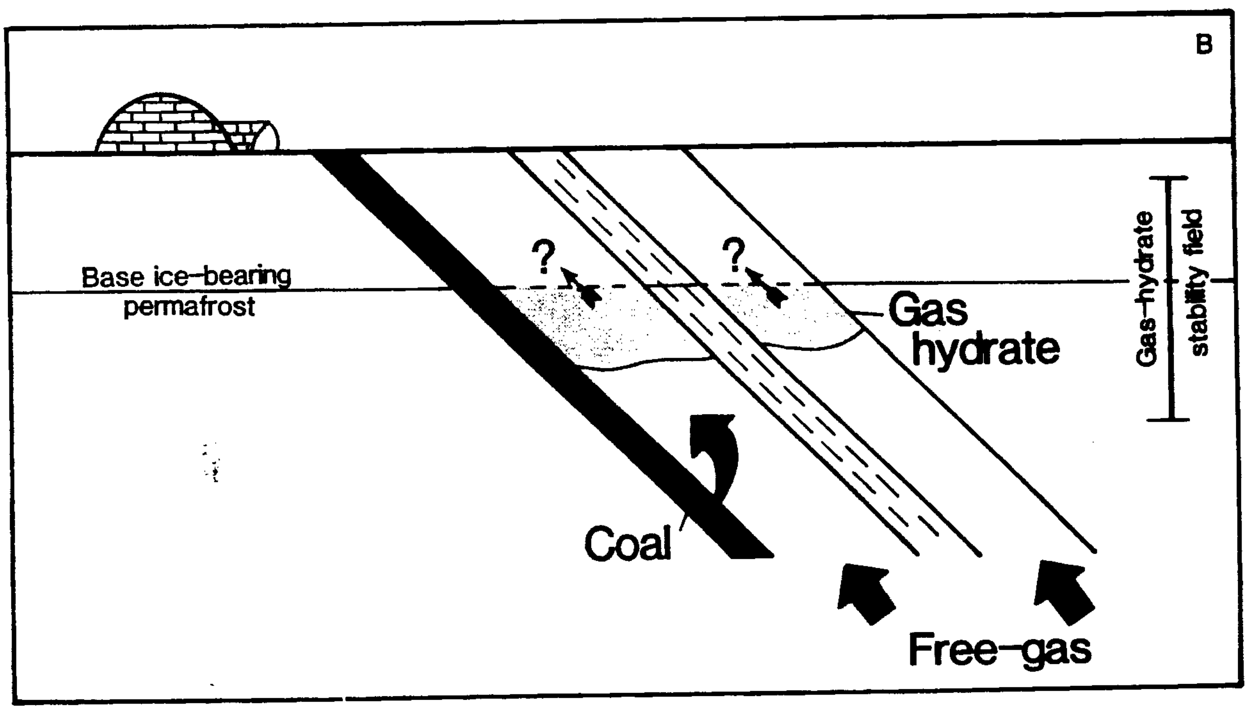

Figure 3b. Example of Model 2: Formation of gas hydrates, within monoclinal porous rock units, by migration of microbial or thermogenic gas into a pre-existing pressure-temperature regime in which gas hydrates are stable.

Kuparuk River area is from the same source rocks, the Shublik Formation, Kingak Shale, and to a lesser extent, the (informal) pebble shale unit. In late Early Cretaceous time, these source rocks were mature in the western part of the North Slope area. Maturity progressed eastward toward the Barrow Arch in the Prudhoe Bay area, a structural high during the Early Cretaceous. Oil and gas migrated to the Prudhoe Bay area and accumulated in the Prudhoe Bay, Lisburne and Endicott oil fields until middle Tertiary time. Sometime during the Tertiary, this trap was tilted to the northeast, and oil apparently migrated up faults at the west end of the Prudhoe Bay oil field into the Kuparuk River and West Sak-Ugnu reservoirs (Carman and Hardwick, 1983). The spatial relations between the major oil accumulations, the inferred gas-hydrate occurrences, and major fault systems are shown on the map in figure 2 and on the cross section in figure 4.

GAS HYDRATE OCCURRENCES

The only confirmed natural gas hydrate sample from the North Slope was obtained in 1972 in a core recovered by ARCO and Exxon (reviewed by Collett and Kvenvolden, 1987). The sample was from a depth of 666 m in the Northwest Eileen State-2 well (fig. 2), located in the Prudhoe Bay Oil Field. Indirect evidence from drillers and open-hole geophysical well logs strongly suggests the presence of numerous gas-hydrate-bearing layers in the area of the Kuparuk River and Prudhoe Bay oil fields (Collett, 1983; Collett and others, 1988).

We examined 445 North Slope wells for potential gas-hydrate occurrence. Most of the wells are from the Prudhoe Bay--Kuparuk River area; however, we also reviewed all wells from the National Petroleum Reserve in Alaska (NPRA) and most of the exploratory wells to the south and east of Prudhoe Bay. Data used included well logs, well-histories, drilling-reports, core descriptions, and production tests. This review of all available data sources revealed that gas hydrates occur in at least 39 of the surveyed wells, all from the Prudhoe Bay-Kuparuk River area. The resistivity and acoustic transit-time well logs, and the gas chromatograph on the mud log proved to be the most useful tools for identifying suspected in-situ gas hydrates.

All of the gas hydrates occur below the base of a siltstone unit that was deposited during a basin-wide marine transgression in Eocene time. All of the known and suspected gas hydrates occur in sandstone reservoirs of the Saganavirktok Formation (Brookian sequence). These sandstones were likely deposited as point- and distributary mouth-bars in a delta-plain environment (Collett and others, 1988). Most of the gas hydrates occur in six laterally continuous sandstone and conglomerate units and are geographically restricted to the east end of the Kuparuk River Oil Field and the west end of the Prudhoe Bay Oil Field (figs. 2 and 4). Many wells have multiple gas-hydrate bearing units, with individual occurrences ranging in thickness from 2 to 28 meters. Most of the gas hydrates occur below the base of ice-bearing permafrost; however, mud logs from wells in the Kuparuk River Oil Field suggest that several of the gas-hydrate bearing units extend up-dip into the ice-bearing permafrost sequence. A significant volume of oil is contained in one of the gas hydrate intervals, both in the Kuparuk River and Prudhoe Bay area. Well logs and drill-cuttings analysis have also revealed the presence of numerous thick coal seams closely associated with several of the gas-hydrate bearing units.

SOURCE OF THE GAS WITHIN THE IN-SITU GAS HYDRATES

To characterize the source of the gas trapped within the North Slope gas hydrate occurrences we have reviewed the geochemical data from the cored gas hydrate in the Northwest Eileen State-2 well. We have also collected and geochemically analyzed drill-cuttings from seven wells drilled in the Prudhoe Bay and Kuparuk River oil fields.

Gas analyses of the gas-hydrate-bearing cores from the Northwest Eileen State-2 well indicated that methane is the primary hydrocarbon gas within the cored gas hydrates (reviewed in Collett and others, 1988). Because methane was the only hydrocarbon gas detected in significant amounts, it can be assumed the the $C_1/(C_2+C_3)$ ratio of gases from the gas hydrate cores is >>1,000, suggesting the presence of mainly microbial gas. No isotopic data are available, however, to support this interpretation of source.

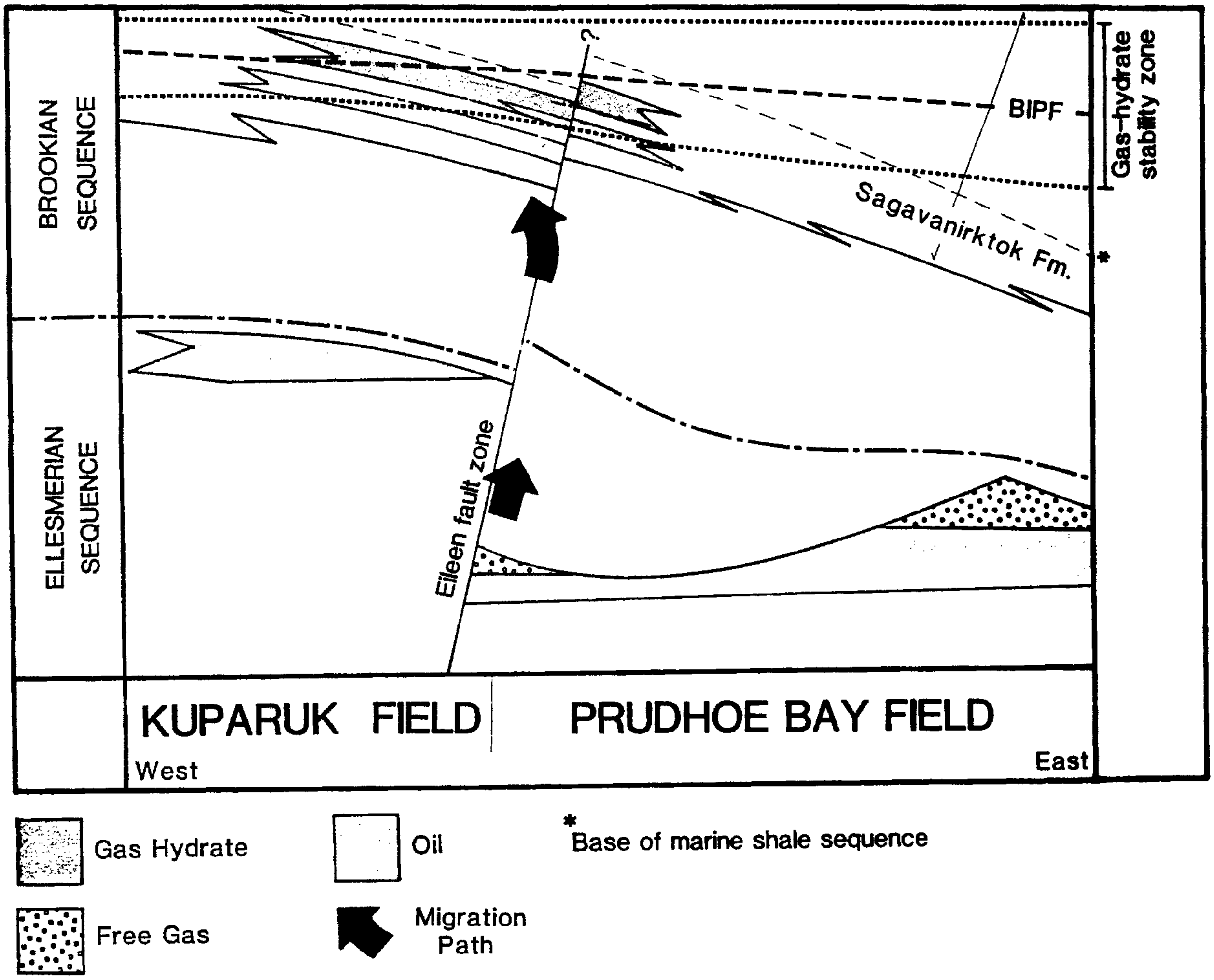

Figure 4. Generalized west to east cross section through the Prudhoe Bay-Kuparuk River area illustrating possible gas migration roots and spatial relations between gas hydrates, the Eileen fault zone, oil, base of ice-bearing permafrost (BIPF), and gas-hydrate stability field (adapted from Carman and Hardwick, 1983, fig. 13).

In the Kuparuk River Unit 2D-15 production well, one of the seven wells sampled for this project, we infer that a 30-m-thick interval contains gas hydrates (Collett and others, 1987). The occurrence of gas hydrates is suggested by the release of unusually large amounts of methane as indicated on the mud log, and an increase in transit-time velocity and electrical resistivity on the well logs. Headspace-gas analysis of canned drill-cuttings from the Kuparuk River 2D-15 well reveal methane to propane-plus-ethane ratios [$C_1/(C_2+C_3)$] typical of microbial gas, with values ranging from 3,300 to 14,500. In contrast, the carbon isotopic composition of the methane indicates the presence of thermogenic gas with C^{13}/C^{12} isotope values of approximately -49 o/oo. Stable-carbon isotopic compositions of -50 o/oo and heavier suggests that the gas was thermally generated. Vitrinite reflectance (Ro) measurements of about 0.4 percent show, that the gas-hydrate-bearing sediments have never been subjected to temperatures within the thermogenic window. Thus, the thermogenic gas must have migrated from greater depths, and the gas hydrate may contain a mixture of microbial and thermogenic gases.

NORTH SLOPE GAS HYDRATE MODEL

In developing a model for the origin of gas hydrates on the North Slope of Alaska, we must account for the following observations pertaining to the distribution of the gas hydrates: (1) All of the gas hydrates found to date occur near the eastern boundary of the Kuparuk River drilling unit and extend into the west end of the Prudhoe Bay drilling unit, an area cut by faults extending deep into the stratigraphic section; (2) gas hydrates occupy a series of sandstone units which dip gently to the northeast; (3) all of the gas hydrates occur below a relatively impermeable marine siltstone sequence; (4) gas hydrates commonly occur near coal sequences; (5) oil and tar are found within one inferred gas-hydrate-bearing interval; and (6) methane is the prominent gas in the near-surface sediments (0-1,500 m).

Carman and Hardwick (1983) postulated that oil within the West Sak and Ugnu sands migrated along faults from the underlying Prudhoe Bay Oil Field. If this theory is correct, free gas from within the Sadlerochit reservoir and dissolved gas associated with oils would also have migrated into the overlying sedimentary rocks. As shown in figures 2 and 4, most of the gas hydrates and shallow heavy-oils occur either up-dip from, or near to, the Eileen fault zone. This fault zone may have acted as a conduit for free-gas and oil migration from deeper hydrocarbon accumulations. The gas within the gas cap of the Prudhoe Bay oil field is composed primarily of methane (75 to 85 percent) along with small quantities of ethane (5 to 7 percent) and propane (2 to 4 percent). If gas within the near-surface sediments migrated from deeper structures, these shallow gases should have geochemical constituents similar to those of the deep gases. However, no significant amounts of ethane or propane were detected within the stratigraphic interval of gas-hydrate stability. The depletion of heavier hydrocarbons such as ethane and propane from gases by stripping during migration has been suggested by Schoell (1983) and Jenden and Kaplan (1986) to explain natural gases containing thermogenic methane but only minor amounts of heavier hydrocarbons. The thermogenic component of the gas within the stratigraphic interval of gas hydrate stability may have been stripped of most of it's heavier hydrocarbons. Such a process could account for the molecular and isotopic compositions observed. The presence of thermogenic gas, as indicated from the carbon isotopic analysis of drill-cuttings, supports the theory that gas has migrated into these units from the underlying accumulations, possibly along the Eileen or related faults. The presence of oil within one of the gas-hydrate-bearing units supports the theory that oil and gas must have migrated from the the underlying Prudhoe Bay or Kuparuk River oil fields. A second geochemical feature of gas hydrates that may be important is the relationship between coal and gas. Gas hydrates are known to occur in close proximity to several thick coal sequences in the Kuparuk River area. Microbial alteration of the organic matter in these coals may have supplied a significant volume of methane to the gas hydrates.

To describe the history of gas-hydrate formation, we have adapted a generalized cross-section from Carman and Hardwick (1983); (fig. 4). As gas moved up the Eileen fault and encountered relatively porous and permeable northeast-dipping sandstone units, some of the gas may have been rechannelled up-dip along these beds. The up-dip migrating gas may have collected in structural or stratigraphic traps where subsequent temperature changes deepened the permafrost sequence and converted the trapped gas into hydrate. Conversely, the up-dip migrating gas may have converted to gas hydrate upon entering the pressure-temperature regime of gas-hydrate stability, thus forming its own trap. Because so little is known about the history of temperatures on the North Slope and the presence of traps for free gas in this area, either of these scenarios are plausible. However, we speculate that gas hydrates presently occur more than 160 m above the base of ice-bearing permafrost which is assumed to be impermeable (Collett and others, 1988). Therefore, when gas migrated into these upper horizons, the base of the ice-bearing permafrost must have been at least 160 m shallower than today.

Since the onset of gas migration into these near-surface horizons (middle Tertiary time), temperatures have fluctuated significantly. Regional temperature changes during the last 2 to 3 million years have been great enough to repeatedly thicken and thin the zone of gas-hydrate stability; however, the magnitude of these changes is not known. It is known that a surface water-body of depth sufficient to prevent complete freezing inhibits or prevents the formation of permafrost (Lachenbruch, 1957). Therefore, we must consider the paleo-positions of the coastline of the Arctic Ocean. Certainly more work is needed to establish the history of subsurface temperatures on the North Slope.

An additional observation which strengthens the idea that migrating gas was involved with gas-hydrate formation is that all of the gas hydrates occur regionally below a marine siltstone sequence. This relatively impermeable rock sequence may act as a barrier to vertical gas migration, thus controlling the distribution of gas hydrate. This potential vertical gas migration barrier may explain why no gas hydrates are present in the eastern part of the Prudhoe Bay drilling unit. Because of the regional northeastward dip, all potential gas hydrate-bearing units in the Prudhoe Bay area occur below the zone of gas-hydrate stability. Thus, a limited supply of gas to the zone of gas hydrate stability prevents hydrate formation.

CONCLUSION

Given our present understanding, two possible explanations for the origin of the gas hydrates in the Prudhoe Bay-Kuparuk River area are recognized. (1) Thermogenic solution- and free-gas from reservoirs of the Prudhoe Bay oil field migrates upward along the Eileen and other fault zones into the overlying shallow sedimentary rocks. In these rocks in-situ microbial gas, mixes with the thermogenic gas, causing total gas concentrations to reach amounts that trigger gas hydrate formation within the zone of gas-hydrate stability. (2) Concentration of in-situ and migrated gas in shallow traps which initially were outside the zone of gas-hydrate stability, but moved into that zone in response, for example, to climate cooling, causing gas hydrates to form both within and beneath permafrost.

7. FUTURE WORK:

In keeping with DOE emphasis on projects that promise immediate and near-term benefits, we have focused our research efforts on the known occurrences of gas hydrates in the Prudhoe Bay--Kuparuk River area of the Alaskan North Slope. We believe that the proposed work is a necessary precursor to a gas hydrate coring and production testing program.

The focus of the North Slope Gas Hydrate Project during 1989 will be in two primary directions. Most of our work will consist of examining the newly-discovered gas-hydrate occurrences in the so-called West End of the Prudhoe Bay Unit. The other aspects of our proposed work includes the review and updating of products from the first four years of the gas hydrate project, such as the North Slope gas-hydrate distribution maps, in light of new data from the West End and other areas.

Recent drilling and geologic sampling in the West End of the Prudhoe Bay Unit have confirmed the occurrence on in situ gas hydrates in three to four distinct stratigraphic units. Development drilling in the West End and technical support from BP Exploration have provided us with a wealth of new data. These new data should provide us with new insight into the geologic parameters controlling the distribution of the in situ gas hydrates on the North Slope and also appear to present us with a gas-hydrate/free-gas contact within several reservoirs-a situation analogous to the Russian Messoiakh hydrate gas accumulation.

New log data from exploratory and development wells recently drilled in the Kuparuk River Unit, have shown that several of the previously mapped gas hydrate occurrences are more extensive than originally mapped. Therefore, the existing gas hydrate distribution maps and the gas hydrate resource estimates will be updated.

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EVALUATION OF GEOLOGICAL RELATIONSHIPS TO GAS HYDRATE FORMATION AND STABILITY

CONTRACT NUMBER: DE-AC21-84MC21181

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PERIOD OF PERFORMANCE: October 1984 - September 1989

2. SCHEDULE/MILESTONES

	FY 89											
	O	N	D	J	F	M	A	M	J	J	A	S
Regional Studies	-	-	-	-	-	-	-	-	-	-|		
Project Summary	-	-	-	-	-	-	-	-	-	-	-	-|

3. BACKGROUND STATEMENT

Gas hydrates are a potential gas resource which may supplement U.S. energy supplies in the future. Research into the formation and stability of gas hydrates and applicable recovery technology is necessary to define and quantify this resource.

Understanding of the geological environments controlling gas hydrate occurrence is fundamental to their eventual exploitation. Much of the current knowledge of natural gas hydrate occurrence was obtained indirectly. Geophysical and geological data collected for purposes other than gas hydrate study indicated gas hydrate presence. Thorough review and analysis of all available geological data is necessary to assess the regional extent of known gas hydrate occurrences. The systematic study of geological environments of identified gas hydrate occurrences provides the basic data to determine the relationships of geological environments to gas hydrate formation and stability.

4. OBJECTIVES

Determination of the relationships of geological environments of gas hydrate formation and stability is one of the major tasks of the research project performed by Geoexplorers International, Inc. for the U.S. Department of Energy, Morgantown Energy Technology Center (DOE-METC). Assessment of the gas resource potential of gas hydrates is an ultimate study objective.

5. PROJECT DESCRIPTION

The project investigates the relationship of geological environments on gas hydrate formation and stability by basin analysis of gas hydrate sites. Basin analyses are performed on 21 offshore locations with direct or indirect evidence of gas hydrates. The gas hydrate sites included in this study, located in various parts of the world, have been predesignated by DOE. Extensive geological investigations are conducted for each study region comprising one or more gas hydrate locations (Figure 1). Sediment composition, provenance, and depositional history are documented for each study region. Structural development of the sedimentary basin is determined using drilling results and seismic reflection profiles. Potential for generation of biogenic methane and conventional thermogenic hydrocarbons is assessed by analysis of existing geochemical data and by thermal modeling. All available seismic data, both published and unpublished, are examined for evidence of gas hydrates. Bottom simulating reflectors (BSRs) and other seismic anomalies are mapped. Drilling evidence of possible gas hydrates is reviewed. Based on the limited available information, conditional assessments of gas resources are derived. Quantities of gas contained both in the gas hydrate and possibly trapped beneath the gas hydrate stability zone are estimated.

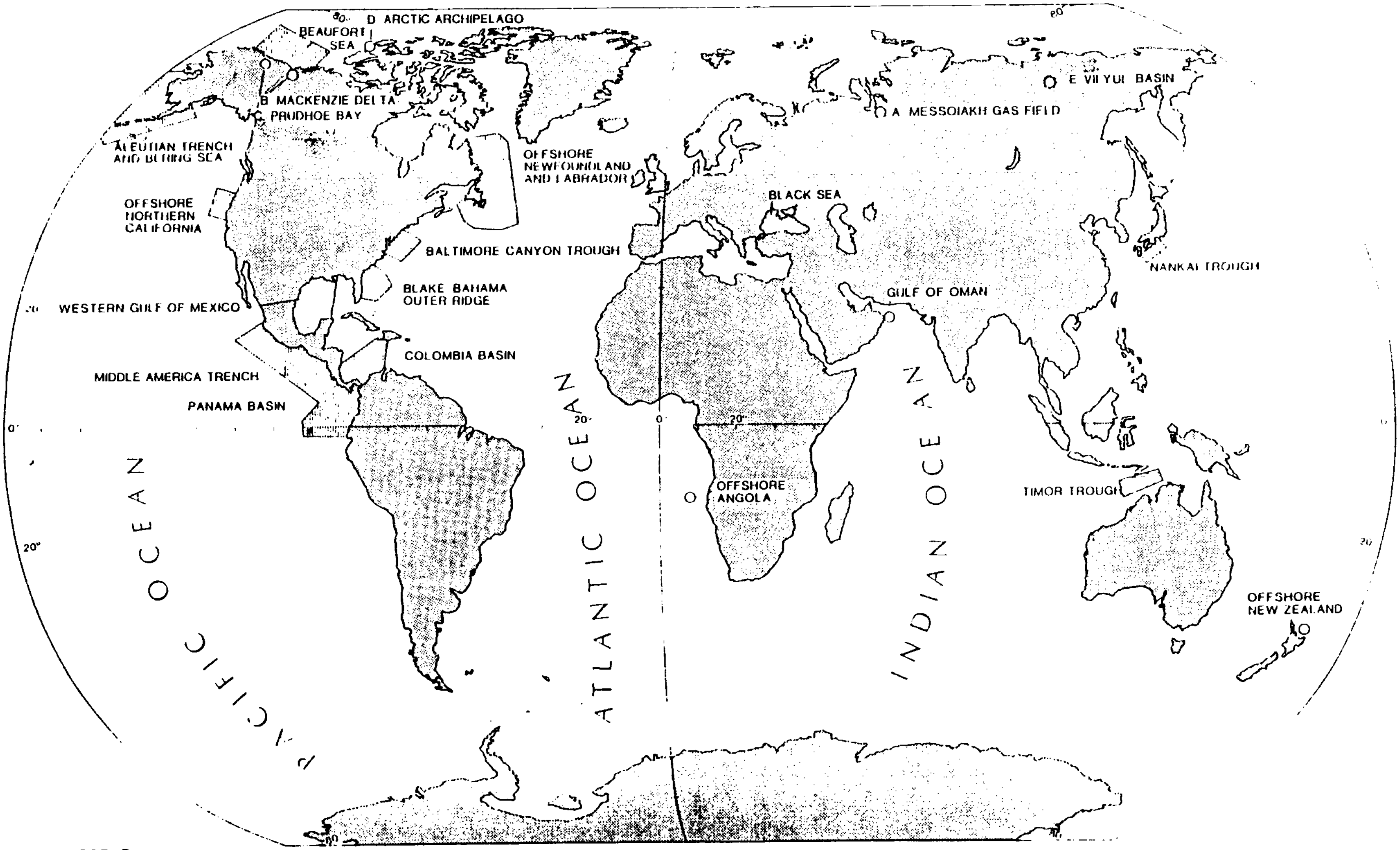
6. RESULTS/ACCOMPLISHMENTS

Detailed results of ten regional basin analysis studies of gas hydrate locations have been published by DOE-METC (Figure 1). Five of these study regions are located on passive continental margins: offshore of Newfoundland and Labrador, Canada (Krason and Rudloff, 1985), the Baltimore Canyon Trough (Krason and Ridley, 1985a) and Blake-Bahama Outer Ridge (Krason and Ridley, 1985b) offshore of the eastern United States, the western Gulf of Mexico (Krason et al., 1985), and the Black Sea (Ciesnik and Krason, 1987). Five of the regions for which the results have been published in detail are on active continental margins: the Colombia Basin (Finley and Krason, 1986a) on the Caribbean margin of South and Central America, the Panama Basin (Krason and Ciesnik, 1986a), and the Middle America Trench (Finley and Krason, 1986b), offshore of northern California (Krason and Ciesnik, 1986b), and the Aleutian Trench and Bering Sea (Krason and Ciesnik, 1987) all on the Pacific Margins of North and Central America. Results from these studies were summarized at DOE contractors meetings in 1985, 1986, and 1987. Brief discussions of the studies on these 10 regions were included in the respective proceedings volumes (Krason and Ridley, 1985c; Krason et al., 1986; Krason et al., 1987).

Reports presenting the detailed results of basin analyses of two study regions were in progress when execution of the contract was interrupted in 1987: the Beaufort Sea offshore of the north slope of Alaska (Finley and Krason, 1988) and the Nankai Trough offshore of Japan (Ciesnik and Krason, 1988). Work on these two regions and the Timor Trough (Finley and Krason, 1989a) region is progressing. Brief discussions of results from studies from the Nankai Trough and the Timor Trough are presented below. A final report summarizing the findings of the regional reports is also in preparation (Finley and Krason, 1989b).

Nankai Trough:

The Nankai Trough is located beneath the western Pacific, south of the Japanese islands Shikoku and central Kyushu (Figure 1). The trough strikes in a northeast-southwest direction. The southern flank of the central and western trough displays a smooth transition into the abyssal plain of the Shikoku Basin. The eastern limit of the study region is the



LEGEND:

- REGIONAL STUDY COMPLETED
- REGIONAL STUDY IN PROGRESS
- ○ PROJECTED STUDY SITES

Figure 1. GAS HYDRATES STUDY LOCATIONS

After U.S. Department of Energy

Zenisu ridge. The Kyushu-Palau ridge constitutes the western limit of the Nankai Trough. The eastern area of the trough ends in the vicinity of the Nishishichto Ridge which strikes north to south. This ridge is also known as Izu-Bonin Ridge. The entire area as outlined above is approximately 450 km long with the width varying from 20 to 60 km.

Nankai Trough jointly with the landward slope constitute the continental margin of southwest Japan. This continental margin includes the areas east of Kyushu, south of Shikoku, and the Kii peninsula of the Honshu island (Nankai), as well as east of the Kii peninsula. A narrow continental shelf is found offshore of southwest Japan. Periodic seismic uplifts of coastal promontories, in conjunction with the subsidence of the sea floor, have resulted in deep embayments of the shoreline. Two geomorphologically distinct sections of the continental slope are easily discernible in the area adjacent to the Nankai Trough. The upper and lower slope sections are separated by a discontinuous series of flat-surfaced terraces. The terraces occur at a sea depth between 200 and 1,200 m. The upper slope section has a mostly uniform and only a slightly geomorphologically differentiated surface, but the lower slope displays a more diverse relief. The most noticeable feature of the lower landward slope area along the Nankai Trough is the presence of a series of ridges parallel to the trough. The ridges emerge along thrusts rooted in the basal detachment beneath the slope, and thus appear to be structurally controlled.

Tectonically the Nankai Trough is part of a complex area of active margins marked by a well developed system of trenches. Although its western and eastern limits are delineated by ridges, the Nankai Trough continues to the southwest as Ryuku trench. In an eastern direction it merges at the triple junction with the Japan trench from the north and the Mariana-Izu trench from the south. The system of trenches mentioned above, south and east of the Japan islands, separates three major tectonic plates in the region, the Pacific plate, the Eurasia plate, and the Philippine plate.

Two principal types of sedimentation have been discerned on the basis of lithological profiles, both in deformed and undeformed sediments of the Nankai Trough. The turbidite sequences, represented by interbedded sandstone and shale with turbidite sedimentary structures, appear to form the upper 500 m of the sedimentary profile. The lower sedimentary unit consists predominantly of hemipelagic muds.

Adequate organic carbon for bacterial methanogenesis exists in the few drilled holes on the continental slope of the Nankai Trough study region. Sediments within the gas hydrate stability zone are immature with respect to thermogenic methane formation.

Seismic recordings from the Nankai Trough in the public domain feature BSRs related to gas hydrates. Migrated seismic lines 54K-1-2, 55N-1, and 55N-3-1 obtained by Japan Petroleum Exploration from the ship Kaiyo Maru show very well developed BSRs. Despite the fact that structural features are obscure in many sections, distinct and mostly continuous BSRs occur in lower sections of the continental slope.

Based on areal extent of BSRs potential gas resources contained in gas hydrates were estimated at between 10^{11} m^3 (4 tcf) and 10^{13} m^3 (400 tcf) depending on the thickness assumed for the gas hydrate bound sediment layer causing the BSR

Timor Trough:

The Timor Trough separates the Indonesian island of Timor from the Australia continental margin (Figure 1). Timor is located some 700 km northwest of Darwin Australia. The Timor Trough extends in a northeast-southwest direction for about 600 km and averages 150 km across. Water depths range to 2,300 m in the axis of the trough

The origin and tectonic history of the Timor Trough is controversial. The trough is part of the outer Banda Arc, separated from the inner Banda Arc by the narrow Wetar Strait located north of Timor. Convergence between the Australia-India and the Eurasian plates is occurring at about 8 cm/year. Some authors have mapped the plate boundary coincident with the axis of the Timor Trough. However, recently Timor and the Timor Trough have been interpreted to be the northern boundary of the Australian-Indian plate. The more recent interpretation places the convergent plate boundary north of Timor beneath the Wetar Strait. The tectonism which formed the Timor trough is interpreted as simple back-arc thrusting rather than plate collision.

Deep Sea Drilling Project (DSDP) Site 262 was drilled on the Australia flank of the Timor Trough about 2 km from the axis. A 442 m sediment section ranging in age from Holocene to Pliocene was recovered. A well-lithified calcarenite at the base of the hole and an overlying dolomitic mud totalling 31 m were deposited under very shallow water. A 76 m section of thick nannofossiliferous ooze records very rapid deepening of the sea in late Pliocene time. Overlying Pleistocene and Holocene units were deposited beneath water depths very similar to present depths. The sediments contained and average of 0.8% total organic carbon. Cores recovered from subbottom depths of 5 m to the bottom of the hole released biogenic methane gas.

The Timor Trough study region was included in this study of gas hydrate locations based on geochemical work performed on the recovered cores from DSDP Site 262 by McKirdy and Cook (1980). No hydrates were recovered from sediments at DSDP Site 262. Gas emission from the recovered cores increased the core volume by about 25%. However, simple exsolution methane dissolved in pore water could account for a similar degree of core expansion without hydrates being present.

Gas hydrates were proposed by McKirdy and Cook (1980) to rectify an apparent paradox in pore water geochemical data from Site 262. High alkalinity values for the upper 250 m of the hole indicated active bacterial degradation of organic carbon to carbon dioxide. The alkalinity of the pore water reached a peak of about 100 meq/l at 50 m subbottom depth and decreased to 5 meq/L at 275 m. The salinity of the pore water increased through the interval from 37 ppt to 40 ppt. The salinity of the pore water increased rapidly to the bottom of the hole, reaching 54 ppt at 441 m subbottom, presumably indicating diffusion from an underlying evaporate bed. McKirdy and Cook (1980) proposed that the alkalinity peak in the pore water geochemical profile of Site 262 was a relict feature which indicated past levels of bacterial activity. However, diffusion of pore-water constituents evidenced by the increase of salinity with depth would be expected to have obliterated any such relict alkalinity enrichment. McKirdy and Cook (1980) proposed that gas hydrate in the sediment section at Site 262 "reduces the effective permeability to zero, thus blocking fluid migration in the top 300 m of the section." McKirdy and Cook (1980) postulated the presence of gas hydrates to reconcile the observed diffusion-controlled salinity profile below 300 m subbottom depth and a relict alkalinity peak in the shallower sediments.

We disagree with McKirdy and Cook (1980) that the geochemistry of the pore water at DSDP Site 262 indicates hydrate presence. McKirdy and Cook (1980) rejected the possibility that the alkalinity profile reflected ongoing bacterial activity. McKirdy and Cook (1980) concluded that the alkalinity of the pore water throughout the hole was fixed by carbon dioxide produced by sulfate reducing bacteria in the upper 5 m of sediment. We suggest that the alkalinity values of the pore water in the sediment section below the sulfate reduction zone depends not only on the carbon dioxide inherited from sulfate reduction. Carbon dioxide is also generated in deeper sediments by direct fermentation of organic matter and by consumption of carbon dioxide by methanogenic bacteria. The alkalinity curve from Site 262 is not anomalous. The alkalinity curve of DSDP Site 262 is a result of normal bacterial action on sediment organic matter; gas hydrate presence is not required to explain the alkalinity variation down hole.

While there is no direct geochemical evidence of gas hydrate presence in the sediments of the Timor Trough study region, we have discovered seismic evidence of hydrates in the region. Bottom simulating reflectors indicating the base of the gas hydrate stability zone are widespread on seismic lines from the north flank of the Timor Trough. In addition to the strong discordance of the BSR and sediment reflectors, a decided velocity anomaly exists above some of the reflectors. We have mapped the occurrence of such hydrate reflectors all along the north flank of the trough.

Based on the seismic lines reviewed and the proven gas generating potential of the sediments of the Timor Trough, we are confident that hydrates exist in the study region. We estimate that 1×10^{11} to 6×10^{12} m^3 (4 to 200 tcf) of gas is trapped in hydrates in sediments the north flank of the Trough. We estimate a most probable potential gas resource figure of 1×10^{12} m^3 (35 tcf) for the region. Structural gas traps formed at the base of the gas hydrate stability zone beneath bathymetric highs could potentially contain 1.5×10^{12} m^3 (20 tcf) of free gas.

Summary

Regional basin analyses document that potentially economic accumulations of gas hydrates can be formed in both active and passive margin settings. The principal requirement for gas hydrate formation in either setting is abundant methane. Passive margin sediments with high sedimentation rates and sufficient sedimentary organic carbon can generate large quantities of biogenic methane for hydrate formation. Similarly, active margin locations near a terrigenous sediment source can also have high methane generation potential due to rapid burial of adequate amounts of sedimentary organic matter. Many active margins with evidence of gas hydrate presence correspond to areas subject to upwelling. Upwelling currents can enhance methane generation by increasing primary productivity and thus sedimentary organic carbon.

Structural deformation of the marginal sediments at both active and passive sites can enhance gas hydrate formation by providing pathways for migration of both biogenic and thermogenic gas to the shallow gas hydrate stability zone. Additionally, conventional hydrocarbon traps may initially concentrate sufficient amounts of hydrocarbons for subsequent gas hydrate formation. Based on studies completed and released thus far, diapirs of salt or shale appear to enhance gas hydrate formation along passive margins. On active margins, evidence of gas hydrates has been correlated with imbricate thrust fault zones on the continental slope. Strike-slip faulting in conjunction with pure compressional thrusting further increases the likelihood of gas hydrate presence on active margins. The few instances of diapirism on active margins likewise show a possible connection with gas hydrates.

In addition to the basin analysis and assessment of gas hydrates in the above mentioned regions, we have also completed a very extensive study and published a separate report entitled "Gas Hydrates in the Russian Literature" (Krason and Ciesnik, 1986b). Our report includes a large amount of the most up-to-date information presented for the first time in English. Many Russian authors consider gas hydrates as an enormous energy resource. However, Russian research programs have been mostly oriented toward the engineering aspects of gas hydrates. Geological environments of gas hydrate formation have not been thoroughly documented in the Russian work.

7. FUTURE WORK

The final report currently in preparation will summarize the major findings from our regional studies and present our conclusions on the geological factors which control gas hydrate formation and stability. Based on these conclusions we will recommend further research concerning gas hydrates as:

- Potential unconventional energy sources
- Pathfinders for conventional oil and gas deposits
- Aids in interpreting the thermal and tectonic history of offshore regions

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