DOE/MC/21181-T4

GEOEXPLORERS INTERNATIONAL, INC.
5701 EAST EVANS AVENUE DENVER, COLORADO 80222 USA TEL 303-759-2746

DR. JAN KRASON
PRESIDENT

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ANNUAL TECHNICAL PROGRESS REPORT ON "EVALUATION OF THE GEOLOGICAL RELATIONSHIPS TO GAS HYDRATE FORMATION AND STABILITY"

Period: October 1, 1984 through September 30, 1985

Reference: U.S. Department of Energy (DOE) - Morgantown Energy Technology Center (METC)
Contract No. DE-AC21-84MC21181

PERSONNEL

During the reporting period, the following staff personnel were involved in the contract's execution: Dr. Jan Krason (Principal Investigator); Dr. W. Ian Ridley (Project Geologist); Dr. Bernard Rudloff (Sr. Geologist); Mr. Mark Ciesnik (Geologist); Mr. Patrick Finley (Geologist); and Ms. Margaret Krason (Technical Assistant).

WORK ACTIVITIES

The knowledge of gas hydrates that is being developed by Geoexplorers International, Inc. is based on interpretation of public domain bathymetric maps, seismic survey data, and vast amounts of geological, geophysical, and chemical information both published and unpublished. Our data base also includes the results of direct analysis of gas hydrates, if available.

The results of our investigation are concurrently reported to DOE-METC in the Monthly Progress Reports, also summarized in the Quarterly Progress Reports. Detailed site reports (initially in draft form, then after DOE-METC's reviews and suggestions for changes, in camera-ready form) are submitted as each study region is evaluated.

So far, we have submitted four final site reports. A special report (draft) entitled "Gas Hydrates in the Russian Literature" is still in DOE-METC's review.

Since the above mentioned reports include all relevant details, the following provides some additional information pertaining to the work procedures, specifically: gathering of information and data, study and critical evaluation of data, preparation of the reports (writing text and drafting graphical illustrations), editorial organization and corrections, and preparation of the camera-ready reports.

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MASTER

Initial Phase - Data Base

During the initial phase of our research project, organizing data became an important priority because of the volume of information. To manage the information, we have prepared data files for the main topics of our study and separately for each gas hydrate site. Then we made special efforts to learn about gas hydrates. It was important to study the most recent literature and retroactively proceed with consideration of older, but still very relevant publications, especially pertaining to gas hydrate formation and stability.

In that initial work phase we have learned that the data base in most of the cases is extremely extensive, and it is a collection of information that must be accessed immediately and operated on for the determination of a specific topic needed for our study. Therefore, instead of building up a large collection of raw data, we have decided to proceed with preparation of the "site reports," which present the relevent data for each site in a concise and easily accessed format.

Also, our efforts during the initial phase of the project have been reviewing the available English language literature on geological and chemical aspects of hydrate occurrences and stability. This not only allowed us to become thoroughly familiar with both data and concepts developed by other researchers, but provided background knowledge to critically evaluate other English and Russian language literature and draw our own conclusions regarding hydrate formation and stability.

Preparation of the Gas Hydrate Site Reports

We began a critical evaluation of information available for **The Blake-Bahama Outer Ridge**, offshore of eastern United States, as our first gas hydrate site report because literature was easily available and the presence of gas hydrates in this region has been unequivocally proven. The results of our investigation have been reported concurrently with work in the Monthly Progress Reports and finally in a very extensive report (including 95 pages of text, 43 graphical illustrations and 6 tables) entitled "Basin Analysis Formation and Stability of Gas Hydrates in the Blake-Bahama Outer Ridge", which was completed and submitted to DOE-METC (2 copies plus camera-ready originals).

Some observations and conclusions are worthy of special consideration, namely:

1. The Blake - Bahama Outer Ridge developed because of an unusually high rate of deposition for the slope and rise environment. The sediment sources were the Blake Plateau and submarine margin areas north of the Blake Outer Ridge. Unusual deposition resulted from the interaction of the Gulf Stream and western boundary undercurrent.

2. Calculations based on the methane requirements of gas hydrates with the maximum possible concentration of methane molecules, indicate that those sediments having the highest organic carbon content will have 5 - 10% of pore space occupied by hydrates; the remaining pore space will contain a brine solution. Alternatively, the hydrate component may be increased proportionately if the hydrate

cages are not fully occupied by methane. Obviously, the lower the methane content of the hydrate, the less attractive becomes the hydrate as a potential resource.

3. The pore fluid has to become supersaturated with methane or other hydrate-forming gases in order to promote hydrate nucleation. The hydrate system also has to pass through a labile (unstable) stage in order to attain a stable equilibrium crystal growth stage. This can be achieved through an increase in temperature with burial. Although saturation of the pore fluid with methane is a minimum requirement for hydrate formation, it is also necessary to have available an excess volume of methane for incorporation into the hydrate cages.

4. Hydrate crystallization is promoted by the presence of "structured" versus "bulk" pore water. This ratio increases with burial depth in argillaceous sediments. Together with the increased potential for hydrate seed crystals with burial depth, this suggests that the proportion of hydrates in the pore space should increase with depth. Hydrate nucleation is promoted by large pore voids and throats. Therefore, hydrate growth may be initiated in coarser sediment intercalations and progress into finer lithologies.

5. The requirement for fluid supersaturation prior to hydrate formation is optimized near the lower hydrate boundary where an underlying zone of gas is available independent of microbial gas production. The critical factor here is the sediment permeability to upward gas migration into the hydrate zone.

6. The bottom water temperature over the Blake - Bahama Outer Ridge is sufficiently low to stabilize hydrates within the shallow sediments. Over those areas where BSRs have been located or hydrates recov- ered, the bottom water temperature is lower than 5.5°C, decreasing to about 2°C at 5,000 m water depth. Extrapolation of the bottom water/temperature depth curve for the western Atlantic Ocean suggests that the limits to hydrate stability would be at approximately 550 m water depth at a temperature of 5.5°C.

7. Class 1 BSRs occupy an area of approximately 31,000 km^2 beneath the Blake - Bahama Outer Ridge. Class 2 and 3 reflectors occupy a further 22,000 km^2. If the sediment contained 100% hydrates, i.e. all pore space filled with hydrates, then 53,000 km^2 would contain in 50 m thick zone 14 trillion cubic feet (TCF) or 400 m thick zone 66 TCF of natural gas.

Subsequently we studied the **Baltimore Canyon Trough and Environs.** The study region included offshore of New york, New Jersey, Delaware, Maryland, Virginia, and North Carolina. Also for this report the principal sources of data are seismic surveys and results from offshore exploratory drill holes.

Petroleum companies have conducted seismic and drilling studies in the region, particularly in the shallower continental shelf areas. However, much of this data remains proprietary. Government agencies and research institutions have produced a vast amount of data on the study region which is available for the public and has been used extensively for this study.

In the Baltimore Canyon Trough and environs, the gas hydrate occurrences are documented seismicly from the lower continental slope and upper continental rise, at 2,000 - 3,600 m of oceanic water. Occurrences of gas hydrates are implied from the presence of bottom simulating reflectors (BSRs). Three classes of BSRs, differing in continuity and strength of the reflection, are recognized in the study region. Strong, continuous reflectors are identified on sections from areas between the Hudson and Wilmington canyons. To the northeast and southwest of this area, more diffuse and discontinuous BSRs predominate.

Although the continental shelf areas in the study region have been extensively drilled commercially and are thus well understood, these shallow areas have limited potential for gas hydrates. The entire continental shelf is under 100 m of water, but the shelf edge is conventionally defined by the 200 m isobath. This area is not conducive for gas hydrate formation and preservation because temperatures are too high and pressures are too low.

The continental slope and upper continental rise (200 m to 3,500 m below sea level) have more potential for hydrate accumulation, but less data are available for assessment. The geological history of the continental slope and rise have a direct bearing on gas hydrate potential.

Estimates of the areal extent of gas hydrates in the study region range from 30,000 km^2 to 50,000 km^2 based on seismic evidence from areas overlain by 2,000 to 3,600 m of water. Assuming that gas hydrates occupy all of the sedimentary pore volume, a gas hydrate zone one meter thick may contain up to 2.9×10^{11} m^3 or 21 trillion cubic feet (TCF) at 0°C and one atmosphere pressure for the area underlain by BSRs.

Gas may be trapped in pore spaces below the lower limit of the gas hydrate stability zone. The thermal reequilibration of the sediments in response to sedimentation may produce relief on the lower surface of the gas hydrate zone. This relief may provide closure necessary for accumulation of gas beneath the impermeable gas hydrate. Such a reservoir beneath a gas hydrate seal with an area of one km^2 and six meters of closure could contain 10^5 m^3 or 3 MMCF of gas.

Basin analysis, the study of geological relationships to gas hydrate formation and stability, presented in the **Offshore Newfoundland and Labrador** Report, covered approximately 900,000 km^2.

Although this study is based on published literature and relevant data readily available, the study results lead to a general conclusion that offshore Newfoundland and Labrador are indeed areas with environments favorable for gas hydrate formation and stability. It can also be concluded from this study that neither offshore Newfoundland nor Labrador should presently be considered as prime gas hydrate regions. Nevertheless, with regard to both general conclusions, it should be noted that during the course of study, two major hindrances have been encountered: 1 - there is scant evidence for gas hydrate occurence; so far only one seismic bottom simulating reflector (BSR) has been reported in the literature (Taylor et al., 1979), and 2 - most of the seismic survey data are being held as proprietary.

There are also geomorphologic and bathymetric environments unfavorable for biogenic gas hydrate formation and stability since a very large area of the study region is covered by shallow shelf water (shallower than 200 m). Areas covered by shallow water include the Grand Banks of Newfoundland and the Labrador Shelf. For both, geologic information is abundant.

The sedimentary basins under the continental slope and upper rise (1,000 - 3,500 m water depth) have been poorly tested for oil and gas deposits; for these areas there is a severe lack of data.

This study shows that the eastern Canadian Continental Margin underwent epeirogenic deformation and fragmentation during Ear'y Cretaceous time. Major tectonic deformation occurred 100 m.y. after the initial rifting phase. The tectonic events led to the development of a complex sedimentary basin pattern and a major "Early Cretaceous Avalon Unconformity".

At the same time, the outer periphery of the eastern Canadian Continental Margin was affected by large scale disjunctive deformation and the foundering of large blocks of the crystalline basement at bathyal depth.

Tectonic activity influenced the present complicated configuration of the continental slope and produced a complex array of basins and highs. Also, the Labrador Shelf underwent initial rifting in Cretaceous time.

The final phase of the entire geologic evaluation of the margin is similar in its main outlines to the evaluation of the U.S. part of the Atlantic Continental Margin. The entire shelf edge from the southern Grand Banks to northern Labrador prograded steadily throughout the Tertiary and Quaternary, leading to seaward progradation by a successive development of large, steep, unstable clastic aprons over the upper part of the continental slope.

A very large amount of sand and mud was redeposited by a gravity driven process (i.e. slumping, sliding, and turbidity currents) from the shelf edge and upper slope to the deep water area of the lower slope.

In the same parts of the study region, in east Newfoundland Basin and the southernmost Labrador Shelf, the present oceanic bottom temperature and hydrostatic pressure are conducive to gas hydrate development, and turbidite slumping lithologic assemblages are regarded as especially favorable for gas hydrate formation and stability.

Because of locally highly favorable environments but insufficient data, a more confident assessment of gas hydrate potential in offshore Newfoundland and Labrador would require the following:

1. Access to proprietary seismic data.
2. Access to proprietary drilling results.
3. Detailed geologic and seismic study of slope and rise regions.
4. Industry supported research.

Then, preparation of the report on "**Basin Analysis, Formation and Stability of Gas Hydrates in the Western Gulf of Mexico**" was one of the major accomplishments in our contract work with DOE-METC. Particular emphasis was placed on examining the factors which were determined in previous studies to be critical to offshore gas hydrate formation.

The study region comprised the entire Gulf of Mexico west of 88° West longitude, an area of approximately 940,000 km^2. This huge region is subdivided into three general geologic provinces: the deep central Gulf of Mexico, the northwestern margin of the Gulf of Mexico, and the western margin of the Gulf of Mexico. The geological evolution presented in the report is a consensus distilled from the voluminous published and unpublished literature available on the region. Proprietary industry data were not included except when no comparable information was available in the public domain.

Over 40,000 km of seismic data were examined for bottom simulating reflectors and to refine geological interpretation.

Thermogenic gas hydrates were recovered from the northwestern margin of the Gulf of Mexico. Indirect evidence suggests that thermogenic gas hydrates occur on diapirs in the Campeche Knolls. Burial history reconstructions indicate that hydrocarbons in these gas hydrate deposits must have migrated at least 2,000 to 3,000 m vertically. Their association with salt structures appears to be related to the structural migrational pathways that diapirism provided. The presence of ethane through butane in the migrated thermogenic gas stabilizes these gas hydrates relative to methane hydrates, but saline pore waters due to solution of diapirs destabilize thermogenic gas hydrates.

Biogenic gas hydrates were recovered from the northwestern margin, and are inferred to have been drilled in the deep central Gulf of Mexico. Sedimentary organic matter appears to have been preserved by rapid sedimentation throughout the region. Total organic carbon content of the sediments varies from 0.2% to 3%. Large amounts of biogenic methane were generated in the deep central Gulf area from sediments with less than the accepted lower threshold of organic carbon content for microbial methanogenesis. Biogenic gas hydrates occur in a wide range of lithologies, and may show an association with volcanic detritus in host sediments. Probable gas hydrate locations in the Gulf of Mexico generally do not display the decrease in pore water salinity with depth which is often associated with gas hydrates.

Bottom simulating reflectors (BSRs) covering approximately 5,000 km^2 abound in anticlines offshore of the Mexican coast between Tampico and Veracruz. The BSRs are found in water depths of 1,200 to 2,700 m and at 400 - 600 m subbottom. Dense spacing of seismic lines permits determination of the areal extent of some BSRs and the structural closure beneath these BSRs. Some BSRs can be traced between as many as six seismic sections over distances of up to 80 km. Structural positions of the BSRs are consistent with the interpretation of free gas beneath the hydrate zone increasing the amplitude of the reflection. Thus it is likely that gas hydrates also exist in adjacent areas where no BSRs are found due to a lack of underlying free gas.

Given the very large data gaps on areal extent, vertical distribution, and degree of pore occupancy of hydrates in the Gulf of Mexico, estimates of gas contained in hydrates and as free gas beneath hydrates are speculative. However, reasonable assumptions of these parameters permits very rough estimates of in-place gas volumes at standard conditions.

Besides basin analysis and assessment of the gas hydrates in the above mentioned sites, we also have made special efforts gathering, studying, and evaluating the Russian literature pertaining to gas hydrates. As the result, in October 1985 (i.e. one month after the end of the fiscal year) we completed a very extensive report (including 154 pages of text, 51 figures and 19 tables) entitled **"Gas Hydrates in the Russian Literature."**

It would be beyond the scope of this annual progress report and the main report to discuss in detail the applicability of gas hydrate formation factors, exploration and development methods recommended by Russian professional engineers and scientists. We have made an attempt to demonstrate a great number of the Russian scientists and institutions involved in gas hydrate investigation. In spite of considerable difficulties in proper understanding of the Russian publications, we made efforts to present and evaluate without bias particularly those areas of investigation which most concerned the Russian authors and where they have specific achievements.

Perhaps as one of the most important Russian achievements should be considered the discovery, development and subsequent exploitation of the Messoiakh gas hydrate field. The peak of the gas production from this field achieved in 1972 amounted to approximately 200,000,000 CF/day. The production was continued (with difficulties) through 1977, then it was suspended until 1980, and since has been resumed and steadily increased.

Many Russian authors including highest ranking officials (e.g. E.A. Kozlovsky, the Minister of Geology, USSR) consider hydrates as an enormous energy resource. Trofimiuk et al. (1982) estimated the continental gas reserves associated with hydrates as 17.2 x 10^{14} MCF (slope), 15 x 10^{15} MCF (rise and abyssal plain). However, gas hydrate occurrences in offshore areas are poorly represented in Russian literature.

Nevertheless, the extremely large gas potential resources in the offshore and continental permafrost environments assessed by Russian authors encourages continuation of stronger efforts for either verification of already estimated gas resources or their reassessment with the highest possible level of confidence.

Editorial Review and Preparation of Camera-Ready Reports

Although we have made special efforts to prepare our draft reports in the best possible form, the editorial review and preparation of the "camera-ready reports" was extremely time consuming. Beside the DOE-METC reviews and always appreciated suggestions, the final reports (i.e. camera-ready) have been read several times and corrected; the first three reports were thoroughly restructured.

All our reports are extensively illustrated and preparation of the graphical illustrations (especially of the camera-ready quality) also takes much time. However, we believe that the graphical illustrations are the best form of data documentation and/or interpretation.

GENERAL COMMENTS

During the reported year we have enhanced our knowledge on and gained considerable experience in assessment of the gas hydrate resources in the offshore environments. Specifically, we have learned and gained experience in the following:

1. Efficiently locating data sources, including published literature and unpublished information.

2. We have established personal communication extremely critical in data accessability and acquisition.

3. We have updated information pertinent to gas hydrate knowledge, also based on thorough study and evaluation of most Russian literature and additional publications in languages other than English.

4. We have established the format of our reports which seems to be well suited for the "Evaluation of the Geological Relationships to Gas Hydrate Formation and Stability." Besides critical evaluation of widely spread literature, in many cases our reports include previously unpublished information (e.g. BSRs from tne Gulf of Mexico).

5. The assessment of the gas resources potential associated with the gas hydrates, although in most cases at a low level of confidence, appears also very encouraging for further, more detailed, study.

6. The table included in each site report containing "Summary Data of Basin Analysis, Formation and Stability of Gas Hydrates," originally suggested by Mr. Rodney Malone and developed by Geoexplorers International, may also be considered as a comprehensive form of presentation of the study topics and the results of investigation.

7. The cooperation with Ms. Kathryn Dominic, COTR, and other officers of the DOE-METC is very pleasant. We highly appreciate all comments and suggestions conveyed to us after thorough reviews of the draft reports, then once again of the final reports, and the Monthly Progress Reports.

8. We have expanded the extent of some of our reports at the request of DOE-METC. For example, the scope of our Gulf of Mexico report reflects that the study region was doubled in size and complexity to provide geological data useful in evaluating work by other DOE-METC contractors in the northwestern Gulf. Similarly, our review of the Russian gas hydrate literature for our own in-house use developed into an extended, comprehensive, separate report on the status of Soviet hydrate research.

9. "Monthly Progress Reports" are considered seriously. We do report factual work progress, providing in advance information that will be included and/or addressed in the "site report." In case our work would not be in accordance to the desire of the DOE-METC, we expect alerting comments and advice. The lack of such comments we consider as approval of the work performed and planned.

We are also confident that, because of the present reports' format, new data and a concept-oriented approach, the result of our study will be of strong interest to various industries, research institutions and numerous governmental agencies.

The study regions thus far investigated each presented an enormous amount of data to be assimilated. These sites had been the locations of countless studies resulting in volumes of publications by researchers. The proximity of these areas to the contiguous United States and this overabundance of relevant data and interpretations required that we assign far more man hours to these projects than previously projected. The study sites to be evaluated in the later phases of the project are distant from the US, and the number of relevant studies and data to be reviewed, evaluated, and incorporated will be far fewer. Thus, we believe that site reports will be produced more rapidly in the later phases of the project. If that is not the case, it is possible that the depth of coverage of these later sites may need to be reduced, or that completion of the contractual work within the estimated cost limits may be very difficult.

OUTLINE OF THE WORK PLAN

Generally, we follow the work plan as proposed in our "Amended Work Plan", dated December 31, 1984. However, because of the unexpected amount of information and particularly geophysical data which we attempt to process, there is considerable delay with regard to previously proposed "Tentative Date of the Report's Delivery." Nevertheless, because the learning period, including well established format of the site reports, and considerable experience with preparation of the "camera-ready" reports, our work is already more efficient and certainly it will improve in time. Considering all these factors, we also believe that, overall, we have already advanced the total amount of the contractual work to over 50%.

Because the remaining contractual budget the DOE-METC split for two years, and the remaining part of the subject contract has been extended for an additional 12 months (ref. DOE-METC letter of Dec. 12, 1985) the same level of efforts and the work speed will be continued until the end of December 1985. Thereafter, we do reserve more flexibility. The flexibility will concern especially the number of the professional personnel involved and/or man hours devoted to the execution of the DOE-METC project. However, our currently estimated work and cost plan is as follows (included also in the DOE Forms CR-535 and CR-533P enclosed):

Name of Gas Hydrate Site(s)	DOE-METC's Site Number	Tentative Date of the Report's Delivery
1. Blake-Bahama Outer Ridge, West Atlantic Ocean	1	Final report completed
2. Baltimore Canyon Trough and Environs, Western Atlantic Ocean	2	Final report completed
3. Offshore Newfoundland and Labrador, Atlantic Ocean	3	Final report completed
4. Western Gulf of Mexico, offshore of Mexico and US Gulf Coast	17,18	Final report completed
5. Offshore of Southern Panama, "Panama Basin"	15	January 31, 1986

6. Offshore of Panama and Colombia, "Colombia Basin"	16	January 31, 1986
7. Offshore of Mexico, Guatemala, Nicaragua and Costa Rica, Eastern Pacific Ocean	10-14	March 31, 1986
8. Offshore of Northern California, Pacific Ocean	9	March 31, 1986
9. South of Aleutian Islands, North Pacific Ocean	7,8	May 31, 1986
10. Navarin Basin, Bering Sea - Continental Slope	5	May 31, 1986
11. Norton Sound, Bering Sea, offshore of Alaska	6	December 31, 1986
12. Beafort Sea, offshore of Alaska, Arctic Ocean	4	December 31, 1986
13. Nankai Trough, offshore of Japan, Western Pacific	19	February 28, 1987
14. Timor Trough, offshore of Northern Australia	20	February 28, 1987
15. Offshore of Angola, Eastern Atlantic Ocean	21	April 30, 1987
16. Gulf of Oman, Northwestern Indian Ocean	22	June 31, 1987
17. Black Sea, offshore of Soviet Union	23	April 30, 1987
18. Offshore of New Zealand	24	June 30, 1987

END

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