“Measurements for Assessment of Hydrate Related Geohazards”

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Abstract

Natural gas hydrate deposits are found in deep offshore environments. In some cases these deposits overlay conventional oil and gas reservoirs. There are concerns that the presence of hydrates can compromise the safety of exploration and production operations [*Hovland and Gudmestad,* 2001]. Serious problems related to the instability of wellbores drilled through hydrate formations have been document by *Collett and Dallimore,* 2002]. A hydrate-related incident in the deep Gulf of Mexico could potentially damage the environment and have significant economic impacts.

Borehole and seafloor stability models are needed to predict potentially hazardous conditions. The inputs to those models will be provided by measurements. The purpose of this paper is to propose measurement schemes that are likely to be relevant to the safety problem. This survey is a starting point. It is anticipated that measurement requirements will co-evolve with our knowledge of hydrate deposits and our ability to model relevant aspects of them.

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1.0 Introduction

Natural gas hydrate deposits are found in deep offshore environments. In some cases these deposits overlay conventional oil and gas reservoirs. There are concerns that the presence of hydrates can compromise the safety of exploration and production operations [*Hovland and Gudmestad*, 2001]. Serious problems related to the instability of wellbores drilled through hydrate formations have been documented by *Collett and Dallimore,* [2002]. A hydrate-related incident in the deep Gulf of Mexico could potentially damage the environment and have significant economic impacts.

Borehole and seafloor stability models are needed to predict potentially hazardous conditions. The inputs to those models will be provided by measurements. The purpose of this paper is to propose measurement schemes that are likely to be relevant to the safety problem. This survey is a starting point. It is anticipated that measurement requirements will co-evolve with our knowledge of hydrate deposits and our ability to model relevant aspects of them.

Measurements will be needed during exploration, evaluation, and monitoring phases. The requirements during these phases are distinct from one another, and can be treated separately.

2.0 Executive Summary

The exploration phase is mainly characterized by survey measurements of large areas, usually but not always conducted from the sea surface. Performance can often be improved by use of deep towed systems, submersible robots, or seafloor sensors.

The principal technique employed during the exploration phase is the seismic survey [*Prior and Hooper*, 1999; *Pecher and Holbrook*, 2000]. Seismic acquisition techniques are by now well advanced. Deep towed high frequency arrays [*Chapman et al.*, 2002; *NRLSSC*, 2003] and ocean bottom seismographs (OBS) [*Tinivella and Accaino*, 2000; *Bunz et al.*, 2002] are in use, at least in limited areas. *Miles* [2000] provides an overview of practical systems. Optimization of acquisition should recognize that hydrate deposits are limited by the geothermal gradient to depths no greater than a few hundred meters below the sea floor.

Unconsolidated seafloor sediments are very weak in shear, and hydrate has a significant strengthening effect. Thus it is to be expected that shear wave imaging will be of more importance in hydrate reservoirs than in conventional seismic targets. In fact, acquisition and processing of shear wave data has been shown to be useful [*Pecher and Holbrook*, 2000; *Mallick et al.*, 2000]. There is broad agreement that four-component (4C) OBS acquisition is highly desirable for characterization of hydrate deposits.

Whereas seismic surveys explore the subsurface, high frequency acoustic multibeam systems focus on the seafloor [*Orange et al.*, 1999; *Miles*, 2000]. The primary output is a bathymetric map. With some additional effort in acquisition and processing, the amplitude of backscattered waves can be analyzed for mechanical properties. Spatial resolution on the order of 10 m is feasible from the sea surface; efficient acquisition permits 100% coverage over hundreds of square kilometers per day. Deep towed systems have also been employed [*Paull et al.,* 1995].

Although multibeam mapping is not sensitive to the typical subseafloor hydrate deposit, it can be valuable for locating hydrates that breach the seafloor, and for secondary evidence of deeper hydrates. It is sensitive to free gas in the water column, and to seafloor expressions of gas venting, such as pockmarks, authigenic carbonate masses, and hard-shell chemosynthetic communities [*Paull et al.*, 1995].

Electrical methods are frequently neglected in conventional hydrocarbon exploration campaigns. This is unsurprising because targets can be thousands of meters below the surface and may only be tens of meters thick. However, when hydrate deposits are immediately beneath the seafloor, and hundreds of meters thick, deep tow electrical surveys may be useful to roughly estimate hydrate saturations prior to drilling.

Electrical methods are a good complement to seismic surveys. Whereas the seismic survey (often) accurately locates the bottom of a hydrate deposit, it is often not useful for estimating hydrate saturation. Even rough average saturation information provided by electrical methods can be a significant aid in evaluating drilling prospects. Moreover, electrical sounding provides an alternate method of locating hydrate in the absence of a BSR [*Yuan and Edwards*, 2000], which is particularly significant in the Gulf of Mexico where BSRs are frequently absent in hydrate bearing provinces.

Although forward and inverse modeling of the electrical survey is reasonably mature, acquisition techniques can be developed further. It would appear that even modest research investments could bring significant returns.

Gravity waves on the sea surface produce small changes of hydrostatic pressure on the seafloor. These pressure variations produce very small deformations of near-seafloor sediments, and the resulting elevation changes can be sensed by a seafloor gravity meter. The seafloor compliance (ratio of the deformation response to the pressure drive) is sensitive to elastic properties of sediments hundreds of meters below the seafloor [*Willoughby and Edwards*, 1997], i.e. coincident with the GHSZ. The success of this seemingly improbable method depends on exquisitely sensitive (but commercially available) field-deployable gravimeters, and averaging times of several hours per site [*Willoughby and Edwards*, 2000].

Methane in the water column, where the water depth is more than 500 meters, is a strong indicator that methane hydrate is either being accumulated [*Roberts and Carney*, 1997], depleted [*Hutnak et al.*, 1999; *Sasaki et al.*, 2002], and/or redistributed [*Paull et al.*, 1995] within the sediments below. Any of these situations can affect seafloor stability.

Hydrate deposits are frequently associated with dramatic methane seeps, particularly in the Gulf of Mexico [*Roberts*, 2001; *Sassen et al.*, 2001]. However, even subtle indications of methane can be significant. For example, the Blake Ridge deposit, which is situated on a quiescent passive margin, has a fault system extending from below the base of the bottom simulating reflector to almost the seafloor. These faults are believed to constitute efficient conduits for transport of methane [*Rowe and Gettrust*, 1994; *Booth et al.*, 1998]. Time-resolved measurements appear to be valuable in at least some locations [*Hutnak et al.*, 1999; *Tryon et al.*, 1999].

Logging while drilling (LWD) systems deliver real-time or near-real-time formation evaluation information. Combined with directional drilling technology [*Cooper*, 1994] LWD is used to actively steer the drill bit in response to geological or petrophysical properties of earth formations [*Luthi*, 2001]. Nearly a full suite of formation evaluation measurements is available in the LWD format. These include electrical resistivity, electrical imaging of the borehole, γ-γ density, neutron porosity, sonic wave speed, vertical seismic profiles, and magnetic resonance [*Bargach et al.*, 2000].

Borehole imaging and sonic wave speed measurements are most important for geohazard assessment. Electrical conductivity images of the borehole wall are useful for identifying hydrate lenses and nodules. They are also excellent indicators of open fractures, which are sensitive to the local stress state [*Bratton et al.*, 1999; *Rezmer-Cooper et al.*, 2001; *Zoback et al.*, 2003]. The status of sonic logging while drilling is somewhat less satisfactory. Although compressional wave speed can be determined, measurement of shear speed in very porous, unconsolidated, shallow marine sediments is problematical. Quadruple sonic tools [*Freitag*, 2003] hold out some promise for the future.

Wireline logging is an established technique for evaluating hydrate formations [*Collett*, 1998a; *Collett*, 1998b; *Dallimore et al.*, 1999; *Collett*, 2001; *Akihisa et al.*, 2002]. Deep water exploration wells are generally drilled without a riser, putting a premium on tools that can be deployed through drillpipe [*Stoller et al.*, 1997].

The stiffening effect of hydrate in sediment causes acoustic velocities to increase, but quantitative evaluation depends on the pore scale morphology of hydrate [*Collett*, 1998a], which is, in general, unknown. With respect to nuclear tools, hydrate has properties nearly identical to water, so those tools give reliable measurements of porosity irrespective of the presence of hydrate. Quantitative wireline interpretation of hydrate relies on combining magnetic resonance and density-porosity measurements [*Takahashi et al.*, 2001; *Kleinberg et al.*, 2004]. Resistivity measurements are less sensitive to borehole rugosity than density and magnetic resonance measurements, so electric logs are also useful in quantitative determinations.

The stability of a hydrate-affected formation is controlled by its temperature and pressure. Thus these quantities, which have only ancillary roles in conventional oil and gas reservoir characterization, are of prime importance for monitoring hydrate deposits.

Permanently implanted temperature sensors behind casing are becoming increasingly widespread [*Brown et al.*, 2000; *Tolan et al.*, 2001; *Brown and Hartog*, 2002]. Fiber optic distributed temperature sensing (DTS) systems are capable of continuously measuring temperature profiles with 0.3°C accuracy and 0.1°C precision at a spatial resolution of 1 m [Carnahan 1999]. Experimental fiber Bragg grating systems are about an order of magnitude more precise. It should be noted that there are considerable technical challenges in deploying subsea fiber optic sensor systems [Eriksson, 2002].

The industry is familiar with a number of reservoir-related hazards, such as subsidence and shallow water flows. However, it has little experience with seafloor and reservoir-scale hazards related to the presence of hydrates. Hydrate-related seafloor slide scars have been studied on the United States Atlantic margin [*Booth et al.,* 1994] and off Norway [*Bugge et al.*, 1988], but these features are typically thousands of years old, and knowledge of their precursors and causative factors, while advancing [see e.g. *Paull et al.*, 2000], is still limited.

Sensor suites should be chosen based on the most probable causes and precursors of seafloor slope failure. Hydrate stiffens sediments in which it exists, and this semi-consolidated mass overlies the highly fluidized and frequently gassy silts and muds at the base of the gas hydrate stability zone (GHSZ).

Since free gas has several important roles in the destabilization of hydrate deposits, seismic measurements are likely to be the most valuable inputs to a seafloor monitoring program. Time-lapse measurements will benefit from four component (three-component geophone plus hydrophone) receivers permanently installed in fixed positions at the seafloor. Such systems have been deployed in many areas. *Entralgo and Spitz* [2001] warn against operations in depths greater than 1,000 ft (300 m), but others have been successful in much deeper water [*Tinivella and Accaino*, 2000; *Bunz et al.*, 2002]. Since seismic sources are energy intensive, they may visit the site only occasionally, possibly in a deep-tow system [*Chapman et al.*, 2002; *NRLSSC*, 2003].

The seafloor monitoring project most closely related to the hydrate hazard problem is being planned at the Center for Marine Resources and Environmental Technology at the University of Mississippi [*McGee and Woolsey*, 1999; *McGee and Woolsey*, 2000]. Sensors will be placed in an area of active gas vents in the Gulf of Mexico. The emphasis of this project is on passive seismic detection of earth motions, as well as time-lapse monitoring of seismic reflectors in the subsurface. Acoustic sensors will monitor the temperature of the water column, important for understanding the behavior of hydrate outcrops. Electromagnetic and chemical sensors are also being considered.

3.0 Results and Discussion

3.1 Exploration Phase

The exploration phase is mainly characterized by survey measurements of large areas, usually but not always conducted from the sea surface. Performance can often be improved by use of deep towed systems, submersible robots, or seafloor sensors. Several short review articles on the exploration geophysics of hydrate deposits are available [*Max and Miles*, 1999; *Spence et al*., 2000].

3.1.1 Seismic Surveys

The principal technique employed during the exploration phase is the seismic survey [*Prior and Hooper*, 1999; *Pecher and Holbrook*, 2000]. Seismic acquisition techniques are by now well advanced. Deep towed high frequency arrays [*Chapman et al.*, 2002; *NRLSSC*, 2003] and ocean bottom seismographs (OBS) [*Tinivella and Accaino*, 2000; *Bunz et al.*, 2002] are in use, at least in limited areas. *Miles* [2000] provides an overview of practical systems. Optimization of acquisition should recognize that hydrate deposits are limited by the geothermal gradient to depths no greater than a few hundred meters below the sea floor.

Typically, the appearance of the bottom simulating reflector (BSR) is taken as a marker of hydrate presence. However, it is becoming increasingly evident that the absence of a BSR does not imply the absence of hydrate. A "control" borehole, drilled into Blake Ridge offshore South Carolina, encountered hydrate even though no BSR was present on the seismic section in that area [*Collett and Ladd*, 2000]. This and similar observations have been explained by an upward flux of methane inadequate to maintain a stratum of free gas beneath the gas hydrate stability zone (GHSZ) [*Ruppel and Kinoshita*, 2000]. Thus, more sophisticated screening techniques for hydrate occurrence are needed.

Characterization of hydrate reservoirs is critical to predicting their behavior. Hydrate saturations tend to be very heterogeneous. Both intergranular and massive morphologies are common, with prominent nodules and lenses present in many formations. Unfortunately, seismic measurements are poor indicators of either average or patchy hydrate saturation in the GHSZ. Above the BSR the seismic signal sometimes appears blanked. It has been theorized that the blanking itself provides some information about hydrate distribution [*Lee and Dillon*, 2001], but this is controversial [*Pecher and Holbrook*, 2000].

Even when good travel-time inversions can be performed, hydrate saturation determination is elusive. Sediment porosity is a major influence on acoustic wave speeds. The presence of free gas [*Ecker et al.*, 2000; *Tinivella and Carcione*, 2001] or permafrost can be major complications. The intergranular growth habit of hydrate is an important influence [*Dvorkin et al.*, 2000; *Helgerud*, 2001] that remains controversial and may depend on the mechanism of accumulation [*Kleinberg et al.*, 2003b]. However, as knowledge of hydrate microstructure increases, estimates of hydrate distributions can be refined [Dai *et al*., 2004].

Unconsolidated seafloor sediments are very weak in shear, and hydrate has a significant strengthening effect. Thus it is to be expected that shear wave imaging will be of more importance in hydrate reservoirs than in conventional seismic targets. In fact, acquisition and processing of shear wave data has been shown to be useful [*Pecher and Holbrook*, 2000, *Mallick et al.*, 2000]. There is broad agreement that four-component (4C) OBS acquisition is highly desirable for characterization of hydrate deposits.

3.1.2 Multibeam Mapping

Whereas seismic surveys explore the subsurface, high frequency acoustic multibeam systems focus on the seafloor [*Orange et al.*, 1999; *Miles*, 2000]. The primary output is a bathymetric map. With some additional effort in acquisition and processing, the amplitude of backscattered waves can be analyzed for mechanical properties. Spatial resolution on the order of 10 m is feasible from the sea surface; efficient acquisition permits 100% coverage over hundreds of square kilometers per day. Deep towed systems have also been employed [*Paull et al.*, 1995].

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3.1.3 Electrical Surveys

Electrical methods are frequently neglected in conventional hydrocarbon exploration campaigns. This is unsurprising because targets can be thousands of meters below the surface and may only be tens of meters thick. However, when hydrate deposits are immediately beneath the seafloor, and hundreds of meters thick, deep tow electrical surveys may be useful to roughly estimate hydrate saturations prior to drilling.

Although the electrical survey on land is a classical technique of geophysics [*Allaud and Martin*, 1977], one may wonder whether it is applicable to the seafloor, where the upper half space is conductive seawater. However, the theory of electrical sounding of marine gas hydrate formations is well developed [*Edwards*, 1997]. Low frequency (Hz), long baseline measurements are capable of giving not only half-space resistivities of the seabed, but also crude depth profiles. The method has been implemented with apparent success on the Cascadia margin [*Yuan and Edwards*, 2000].

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A variety of methods are used to detect and investigate marine seeps. Free gas is efficiently detected by sonar [*Merewether et al.*, 1985], though this method is not quantitative or specific. Chromatography [*Cynar and Yayanos*, 1992] gives more precise information on water samples obtained from bottles, sniffers, or cores. Electrochemical sensors [*Whitfield and Jagner*, 1981; *Bussell et al.*, 1999] are also species-specific and have the advantage of being easily deployable on submersible systems. Interpretation of the data both depends on and contributes to understanding the geological setting [*Schumacher and Abrams*, 1994].

3.2 Evaluation Phase

The evaluation of gas hydrate deposits occurs during and immediately after the drilling of boreholes. Typically, the earliest information comes from logging while drilling tools. After the well is drilled to its total depth, wireline tools are used to acquire more complete information. Some wells may be cored, with the recovered sediment or rock cores carefully examined and subsampled in the laboratory. These methods have been compared by *Hutchinson* [1991].

3.2.1 Logging While Drilling

Logging while drilling (LWD) systems deliver real-time or near-real-time formation evaluation information. Combined with directional drilling technology [*Cooper*, 1994] LWD is used to actively steer the drill bit in response to geological or petrophysical properties of earth formations [*Luthi*, 2001]. Nearly a full suite of formation evaluation measurements is available in the LWD format. These include electrical resistivity, electrical imaging of the borehole, γ-γ density, neutron porosity, sonic wave speed, vertical seismic profiles, and magnetic resonance [*Bargach et al.*, 2000].

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A primary purpose of LWD is to make measurements where wireline logging and coring are impractical. Hydrate shares the near-seafloor environment with unconsolidated sand and mud. In the Gulf of Mexico the upper part of the well is normally cased as quickly as possible to reduce the risk of collapse. Sometimes the only opportunity to characterize hydrate-bearing sediment is to use LWD tools. Thus the technique of logging-while-coring [*Goldberg et al.*, 2003], introduced on Ocean Drilling Program Leg 204, is a significant advance, enabling the recovery of core while acquiring borehole data.

A limitation of LWD tools is that they are designed to operate in a limited range of hole sizes [*Bargach et al.*, 2000]:

Tool Collar Size (in.)	Maximum Bit Size (in.)
4.75	6.25
6.75	9.875
8.25	12.25

Unlike wireline tools, some of which are useful in very large boreholes because they are run eccentered, few LWD tools are capable of operating in boreholes very much larger than the tool collar size. Since typical deepwater Gulf of Mexico drilling operations prescribe several hundred feet of 36 inch borehole followed by several thousand feet of 20 inch borehole [*Jenkins et al.*, 1999], it is unlikely that a full suite of LWD logs can be obtained in the upper sections of conventional exploration and production wells. Therefore, characterization of hydrate reservoirs using LWD tools require drilling special wells into the hydrate reservoir.

3.2.2 Wireline Logging

Wireline logging is an established technique for evaluating hydrate formations [*Collett*, 1998a; *Collett*, 1998b; *Dallimore et al.*, 1999; *Collett*, 2001; *Akihisa et al.*, 2002]. Deep water exploration wells are generally drilled without a riser, putting a premium on tools that can be deployed through drillpipe [*Stoller et al.*, 1997].

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When water, free gas, and hydrate are present simultaneously in the pore space, neutron porosity [*Ellis*, 1987] is a useful measurement. The neutron log responds to all protons, whether in water or hydrate; the proton density of hydrate is only 6% higher than that of water. Thus the neutron-density combination can be used to estimate free gas content, irrespective of the presence of hydrate. The neutron log responds anomalously to clay, and this must be corrected by other tools.

The problem of evaluation of hydrate in the presence of permafrost is a significant problem in well log interpretation. Their stability ranges are different, so temperature and pressure measurements can remove the ambiguity in some situations. However there are depth intervals in which both are stable. Most physical properties of ice and methane hydrate are very similar [*Dvorkin et al.*, 2000]. Permafrost and hydrate responses to density, neutron, resistivity, sonic and NMR logging tools are indistinguishable for all practical purposes. The small differences in the relevant bulk properties are masked by modest uncertainties in porosity and saturation. Dielectric constant measurements may be useful in distinguishing hydrate from permafrost, but dielectric logging tools are not broadly deployed. Ice has a thermal conductivity almost four times larger than water or gas hydrate. Thus, once the porosity and water saturation of a formation are determined, thermal conductivity measurements may prove useful in distinguishing ice from hydrate in formations in which they can coexist.

Wireline logging provides more and better tools for geohazard assessment than LWD does. Shear wave logging in soft, slow formations is superior, and electrical borehole imaging tools have higher resolution. Fluid sampling tools can be used to conduct mini-fracture tests [*Bell*, 2003; *Zoback et al.*, 2003].

3.3 Monitoring Phase

Exploration phase measurements indicate the presence of gas hydrate deposits, and evaluation phase measurements are essential for defining the exact quantities and locations of hydrate within those deposits. These measurements warn of the possibility of drilling hazards, and provide inputs to wellbore stability and seafloor stability models that help predict whether the deposits will become hazards during production. However the predictive power of these stability models is still untested. Moreover, even after more experience has been acquired with them, the models are unlikely to provide totally reliable predictions of hazard events.

Offshore platforms, wellheads and pipelines are very costly assets, and the environmental risks associated with disruption of hydrocarbon production in deep water are considerable. Therefore prudent engineering practice dictates that potential hazard conditions be monitored, possibly over the lifetime of the reservoir. Sensor systems can be installed in well bores and on the seafloor. To gain broadest acceptance, these systems should be continuous, permanent, inexpensive, and in some cases widely dispersed.

3.3.1 Permanent Monitoring of the Well Bore

Hydrate-associated well bore hazards have been documented by *Collett and Dallimore* [2002]. As warm fluid is produced from underlying conventional reservoirs, near-wellbore hydrates can decompose. This results in flows of gas and water outside of casing due to loss of hydraulic isolation, and in extreme cases damage to the casing itself.

The stability of a hydrate-affected formation is controlled by its temperature and pressure. Thus these quantities, which have only ancillary roles in conventional oil and gas reservoir characterization, are of prime importance for monitoring hydrate deposits.

Permanently implanted temperature sensors behind casing are becoming increasingly widespread [*Brown et al.*, 2000; *Tolan et al.*, 2001; *Brown and Hartog*, 2002]. Fiber optic distributed temperature sensing (DTS) systems are capable of continuously measuring temperature profiles with 0.3°C accuracy and 0.1°C precision at a spatial resolution of 1 m [*Carnahan*, 1999]. Experimental fiber Bragg grating systems are about an order of magnitude more precise. It should be noted that there are considerable technical challenges in deploying subsea fiber optic sensor systems [*Eriksson*, 2002].

Permanently installed pressure gauges are also now relatively routine; quartz gauges are both very precise and very stable over time [*Tibold et al.*, 2000]. Combined temperature and pressure sensor systems based on fiber optics are now at the leading edge of technology [*Kragas et al.*, 2001; *Schroeder et al.*, 2002]. Although the fiber optic pressure measurement is not as precise as that available from the quartz gauge, this technology has the potential for providing low cost multisensor arrays. Perhaps the most sophisticated borehole permanent monitoring system installed to date, including temperature, pressure, and resistivity arrays, has been used in a reservoir control system [*Bryant et al.*, 2002].

3.3.2 Permanent Monitoring of Reservoir

3.3.2.1 Nature of the Hazards

The industry is familiar with a number of reservoir-related hazards, such as subsidence and shallow water flows. However, it has little experience with seafloor and reservoir-scale hazards related to the presence of hydrates. Hydrate-related seafloor slide scars have been studied on the United States Atlantic margin [*Booth et al.,* 1994] and off Norway [*Bugge et al.*, 1988], but these features are typically thousands of years old, and knowledge of their precursors and causative factors, while advancing [see e.g. *Paull et al.,* 2000], is still limited.

Sensor suites should be chosen based on the most probable causes and precursors of seafloor slope failure. Hydrate stiffens sediments in which it exists, and this semi-consolidated mass overlies the highly fluidized and frequently gassy silts and muds at the base of the gas hydrate stability zone (GHSZ). The setting is reminiscent of avalanche conditions on a snow-covered mountain. Thus, as a general principle, either creation or dissociation of hydrate can cause problems, though dissociation is the more immediately worrisome condition because it can lead to a loss of shear strength and an increase in pore pressure.

An increase in the amount of free gas within or below the GHSZ is perhaps the most important indicator of potential problems. Although gas is not thermodynamically stable in the GHSZ, it has been observed to exist there, presumably due to the kinetic limitations of hydrate formation [*Sloan*, 1998]. Indeed, hydrates are frequently associated with natural gas vents and seeps in the Gulf of Mexico [*Roberts,* 2001; *Sassen et al.*, 2001] and elsewhere.

The presence of free gas in the GHSZ leads to two different problems with respect to hydrate thermodynamic stability. First, it reduces the lithostatic pressure by decreasing the density of the sediment column. Secondly, and probably more importantly, it steepens the geothermal gradient due to its small thermal conductivity. Because the seafloor constitutes a nearby heat reservoir of essentially infinite capacity, steepening the gradient causes the temperature at the base of the GHSZ to increase. Both pressure and temperature effects tend to destabilize the hydrate deposit. These problems can be exacerbated by a pore-filling growth habit [*Kleinberg et al.*, 2003b].

Accumulation of gas under the base of the GHSZ, due to destabilization of hydrate there or migration from below, is also clearly problematic. Increasing gas saturation reduces the shear strength of the formation.

There is limited information about the times scales over which gas moves in the subsurface [*Hutnak et al.*, 1999; *Tryon et al.*, 1999]. While it has been observed that gas hydrate outcrops change in size and shape in less than a year, and possibly on time scales of days to weeks [*McDonald et al.*, 1994; *Roberts*, 1999], this appears to be correlated to ocean temperatures, not fluctuations of gas supply. However it has recently been found that the spatial patterns of upward gas migration are much more complicated than had been thought [*Wood et al.*, 2002], and this insight may lead to a more detailed understanding of the variability of gas flows over time.

Several other hazard conditions should be monitored. Subsidence or steepening of the seabed are clearly hazard warnings. Submarine landslides have been observed to occur on surprisingly gentle slopes: 1°-7° is typical [*Hampton*, 1996], though a triggering event such as an earthquake may be required. Sediment warming around pipelines and other production facilities is another potential hazard indicator.

3.3.2.2 Sensor Systems and Methods

Since free gas has several important roles in the destabilization of hydrate deposits, seismic measurements are likely to be the most valuable inputs to a seafloor monitoring program. Time-lapse measurements will benefit from four component (three-component geophone plus hydrophone) receivers permanently installed in fixed positions at the seafloor. Such systems have been deployed in many areas. *Entralgo and Spitz* [2001] warn against operations in depths greater than 1,000 ft (300 m), but others have been successful in much deeper water [*Tinivella and Accaino*, 2000; *Bunz et al.*, 2002]. Since seismic sources are energy intensive, they may visit the site only occasionally, possibly in a deep-tow system [*Chapman et al.*, 2002; *NRLSSC*, 2003].

Heat flow sensors are indicators of thermal changes in the subsurface [*Ruppel*, 2000; *Grevemeyer and Villinger*, 2001]. It should be noted that hydrate and water have almost equal thermal conductivities, with free gas providing the only significant contrast.

Chemical and/or bubble sensors may find a place in the seafloor sensor suite. Dissolved or free natural gas in the water column in deep water suggests that hydrate is either being formed or being dissociated; both conditions are of concern to the reservoir manager.

Tiltmeters and seismographs can passively monitor subtle or sudden seafloor motions. Seafloor pressure sensors can be used to measure subsidence [*Mes*, 1988].

To use sensor systems to best advantage, they should be in place before wells are drilled. The drilling operation is a perturbation of the reservoir, and time lapse measurements during and immediately after drilling may prove valuable.

3.3.2.3 Survey of Seafloor Observatories

The seafloor monitoring project most closely related to the hydrate hazard problem is being planned at the Center for Marine Resources and Environmental Technology at the University of Mississippi [*McGee and Woolsey*, 1999; *McGee and Woolsey*, 2000]. Sensors will be placed in an area of active gas vents in the Gulf of Mexico. The emphasis of this project is on passive seismic detection of earth motions, as well as time-lapse monitoring of seismic reflectors in the subsurface. Acoustic sensors will monitor the temperature of the water column, important for understanding the behavior of hydrate outcrops. Electromagnetic and chemical sensors are also being considered.

The Monterey Bay Aquarium Research Institute (MBARI) is undertaking a major effort to instrument Monterey Bay, California [MBARI, 2003]. In 2002 MBARI received a $7 million National Science Foundation grant to start work on the Monterey Accelerated Research System (MARS). The initial objective is to install 62 km of submarine cable with a power capacity of 10 kW and a data capacity of 100 megabits per second. This cable will service one node with four docking ports. A variety of sensors will be designed to interchangeably dock at the node. The system is connected to a shore station via copper and fiber optic submarine cable.

The MARS project is a steppingstone toward the much more ambitious NEPTUNE system, planned for the Juan de Fuca Plate, offshore British Columbia, Washington, and Oregon [*Howe, et al.,* 2001; *Neptune,* 2003]. This plan envisions 30 instrumented nodes on a 3,000 km cable backbone. The system is sized to carry 100 kW of power and 10 gigabits per second of telemetry. The design lifetime is 30 years. Each node will accept a variety of interchangeable sensors, which can include borehole sensor strings.

VENUS (Victoria Experimental Network Under Sea) [*Tunnicliffe and Dewey*, 2001], managed by the University of Victoria, British Columbia, is a spin-off of NEPTUNE. The VENUS consortium will build and operate sensors compatible with the NEPTUNE backbone. The existence of nascent user communities such as VENUS is an indication of the flexibility that the seafloor observatory architects aim to build into their systems.

Of particular interest to the hydrate community is the proposal to use the NEPTUNE system to monitor seawater chemistry and ground motions at Hydrate Ridge in the Cascadia subduction zone offshore Oregon [*Suess et al.,* 1999]. The proposed sensors are:

- Photography at active vent and bubble sites.
- Conductivity, temperature and depth (CTD) sensor package.
- Chemical sensors:
  methane, hydrogen sulfide, oxygen, iron, pH and pCO_2.
- Doppler current records.
- High-precision hydrostatic pressure readings.
- Three-component seismometers.
- Geodetic observations; tilt meters.

The full-featured NEPTUNE system is a reasonably costly proposition [*Neptune*, 2000]. It is estimated that the design and planning tasks will cost roughly $13 million, and constructing and installing the infrastructure (including cable and shore stations) will cost close to $90 million. User-group sensor construction and installation is estimated to cost in the range of $100 million. Operating expenses will approximate $10 million per year. It can be anticipated that a system narrowly focused on hydrate hazard monitoring, in a defined geographical area, using mass produced sensors, would cost considerably less.

4.0 Experimental

No experimental work was conducted for this report.

5.0 Conclusions

Measurements will be needed during exploration, evaluation, and monitoring phases. The requirements during these phases are distinct from one another, and can be treated separately.

Characterization of hydrate reservoirs is critical to predicting their behavior. Hydrate saturations tend to be very heterogeneous. Both intergranular and massive morphologies are common, with prominent nodules and lenses present in many formations. Unfortunately, seismic measurements are poor indicators of either average or patchy hydrate saturation in the GHSZ.

Unconsolidated seafloor sediments are very weak in shear, and hydrate has a significant strengthening effect. Thus it is to be expected that shear wave imaging will be of more importance in hydrate reservoirs than in conventional seismic targets.

Although multibeam mapping is not sensitive to the typical subseafloor hydrate deposit, it can be valuable for locating hydrates that breach the seafloor, and for secondary evidence of deeper hydrates. It is sensitive to free gas in the water column, and to seafloor expressions of gas venting, such as pockmarks, authigenic carbonate masses, and hard-shell chemosynthetic communities [*Paull et al.*, 1995].

Electrical methods are a good complement to seismic surveys. Whereas the seismic survey (often) accurately locates the bottom of a hydrate deposit, it is often not useful for estimating hydrate saturation. Even rough average saturation information provided by electrical methods can be a significant aid in evaluating drilling prospects. Moreover, electrical sounding provides an alternate method of locating hydrate in the absence of a BSR [*Yuan and Edwards*, 2000], which is particularly significant in the Gulf of Mexico where BSRs are frequently absent in hydrate bearing provinces.

Although forward and inverse modeling of the electrical survey is reasonably mature, acquisition techniques can be developed further. It would appear that even modest research investments could bring significant returns.

The seafloor compliance (ratio of the deformation response to the pressure drive) is sensitive to elastic properties of sediments hundreds of meters below the seafloor [*Willoughby and Edwards*, 1997], i.e. coincident with the GHSZ. The success of this seemingly improbable method depends on exquisitely sensitive (but commercially available) field-deployable gravimeters, and averaging times of several hours per site [*Willoughby and Edwards*, 2000].

A variety of methods is used to detect and investigate marine seeps and can be used to infer hydrates. Free gas is efficiently detected by sonar [*Merewether et al.*, 1985], though this method is not quantitative or specific. Chromatography [*Cynar and Yayanos*, 1992] gives more precise information on water samples obtained from bottles, sniffers, or cores. Electrochemical sensors [*Whitfield and Jagner*, 1981; *Bussell et al.*, 1999] are also species-specific and have the advantage of being easily deployable on submersible systems. Interpretation of the data both depends on and contributes to understanding the geological setting [*Schumacher and Abrams*, 1994].

Logging while drilling (LWD) systems deliver real-time or near-real-time formation evaluation information. Combined with directional drilling technology [*Cooper*, 1994], LWD is used to actively steer the drill bit in response to geological or petrophysical properties of earth formations [*Luthi*, 2001]. Nearly a full suite of formation evaluation measurements is available in the LWD format. These include electrical resistivity, electrical imaging of the borehole, γ-γ density, neutron porosity, sonic wave speed, vertical seismic profiles, and magnetic resonance [*Bargach et al.*, 2000].

Borehole imaging and sonic wave speed measurements are most important for geohazard assessment. Electrical conductivity images of the borehole wall are useful for identifying hydrate lenses and nodules. They are also excellent indicators of open fractures, which are sensitive to the local stress state [*Bratton et al.*, 1999; *Rezmer-Cooper et al.*, 2001; *Zoback et al.*, 2003]. The status of sonic logging while drilling is somewhat less satisfactory. Although compressional wave speed can be determined, measurement of shear speed in very porous, unconsolidated, shallow marine sediments is problematical. Quadruple sonic tools [*Freitag*, 2003] hold out some promise for the future.

Wireline logging provides more and better tools for geohazard assessment than LWD does. Shear wave logging in soft, slow formations is superior, and electrical borehole imaging tools have higher resolution. Fluid sampling tools can be used to conduct mini-fracture tests [*Bell*, 2003; *Zoback et al.*, 2003]. However, the use of wireline tools is limited because of well bore stability concerns in shallow sediments.

The stability of a hydrate-affected formation is controlled by its temperature and pressure. Thus these quantities, which have only ancillary roles in conventional oil and gas reservoir characterization, are of prime importance for monitoring hydrate deposits.

Permanently implanted temperature sensors behind casing are becoming increasingly widespread [*Brown et al.*, 2000; *Tolan et al.*, 2001; *Brown and Hartog*, 2002]. Fiber optic distributed temperature sensing (DTS) systems are capable of continuously measuring temperature profiles with 0.3°C accuracy and 0.1°C precision at a spatial resolution of 1 m [Carnahan 1999]. Experimental fiber Bragg grating systems are about an order of magnitude more precise. It should be noted that there are considerable technical challenges in deploying subsea fiber optic sensor systems [Eriksson, 2002].

Permanently installed pressure gauges are also now relatively routine; quartz gauges are both very precise and very stable over time [*Tibold et al.*, 2000]. Combined temperature and pressure sensor systems based on fiber optics are now at the leading edge of technology [*Kragas et al.*, 2001; *Schroeder et al.*, 2002]. Although the fiber optic pressure measurement is not as precise as that available from the quartz gauge, this technology has the potential for providing low cost multisensor arrays. Perhaps the most sophisticated borehole permanent monitoring system installed to date, including temperature, pressure, and resistivity arrays, has been used in a reservoir control system [*Bryant et al.*, 2002].

The industry is familiar with a number of reservoir-related hazards, such as subsidence and shallow water flows. However, it has little experience with seafloor and reservoir-scale hazards related to the presence of hydrates. Hydrate-related seafloor slide scars have been studied on the United States Atlantic margin [*Booth et al.*, 1994] and off Norway [*Bugge et al.*, 1988], but these features are typically thousands of years old, and knowledge of their precursors and causative factors, while advancing [see e.g. *Paull et al.*, 2000], is still limited.

An increase in the amount of free gas within or below the GHSZ is perhaps the most important indicator of potential problems. Although gas is not thermodynamically stable in the GHSZ, it has been observed to exist there, presumably due to the kinetic limitations of hydrate formation [*Sloan*, 1998]. Indeed, hydrates are frequently associated with natural gas vents and seeps in the Gulf of Mexico [*Roberts*, 2001; *Sassen et al.*, 2001] and elsewhere.

The presence of free gas in the GHSZ leads to two different problems with respect to hydrate thermodynamic stability. First, it reduces the lithostatic pressure by decreasing the density of the sediment column. Secondly, and probably more importantly, it steepens the geothermal gradient due to its small thermal conductivity. Because the seafloor constitutes a nearby heat reservoir of essentially infinite capacity, steepening the gradient causes the temperature at the base of the GHSZ to increase. Both pressure and temperature effects tend to destabilize the hydrate deposit. These problems can be exacerbated by a pore-filling growth habit [*Kleinberg et al.*, 2003b].

Since free gas has several important roles in the destabilization of hydrate deposits, seismic measurements are likely to be the most valuable inputs to a seafloor monitoring program. Time-lapse measurements will benefit from four component (three-component geophone plus hydrophone) receivers permanently installed in fixed positions at the seafloor.

6.0 References

Akihisa, K. et al., Well Log Evaluation of Gas Hydrate Saturation in the MITI Nankai Trough Well, Offshore East Japan, SPWLA 43rd Annual Logging Symposium, Paper BB, 2002.

Allaud, L.A. and M. Martin, *Schlumberger, History of a Technique*, Wiley, New York, 1977.

Bargach, S., et al., Real-time LWD: Logging for drilling, *Oilfield Review 14*(3), 58-78, Autumn 2000.

Bell, J.S., Practical methods for estimating in situ stresses for borehole stability applications in sedimentary basins, *Journal of Petroleum Science and Engineering 38*, 111-119 (2003)

Booth, J.S., W.J. Winters, and W.P. Dillon, Circumstantial Evidence of Gas Hydrate and Slope Failure Associations on the United States Atlantic Continental Margin, in *Annals of the New York Academy of Sciences, vol 715: Natural Gas Hydrates*, edited by E.D. Sloan, J. Happel, and M.A. Hnatow, pp. 283-305, New York Academy of Sciences, New York, 1994.

Booth, J.S., W.J. Winters, W.P. Dillon, M.B. Clennell and M.M. Rowe, Major occurrences and reservoir concepts of marine clathrate hydrates: Implications of field evidence, in *Geological Society Special Publication No. 137: Gas Hydrates, Relevance to World Margin Stability and Climatic Change*, edited by J.-P. Henriet and J. Mienert, pp. 113-127, The Geological Society, London, 1998.

Bratton, T., T. Bornemann, Q. Li, D. Plumb, and J. Rasmus, Logging-while-drilling images for geomechanical, geological and petrophysical interpretations, SPWLA 40th Annual Logging Symposium, Paper JJJ, 1999.

Brown, G.A., B. Kennedy, and T. Meling, Using fiber optic distributed temperature measurements to provide real time reservoir surveillance data on Wytch Farm field horizontal extended reach wells, SPE 62952, Society of Petroleum Engineers, Dallas, 1-4 October 2000.

Brown, G.A. and A. Hartog, Optical fiber sensors in upsteam oil and gas, *J. Petrol. Tech. 54*(11), 63-65, November 2002.

Bryant, I.D. et al., Real time monitoring and control of water influx to a horizontal well using advanced completion equipped with permanent sensors, SPE 77522, Society of Petroleum Engineers, San Antonio, 29 September - 2 October, 2002.

Bugge, T., R.H. Belderson, and N.H. Kenyon, The Storegga Slide, *Phil. Trans. Roy. Soc. London A325*, 357-388, 1988.

Bünz, S., J. Mienert and K. Andreassen, Gas hydrate reservoir characterization using multi-component wide-angle and ocean bottom cable seismic data, "Gashydrate im Geosystem", Statusseminar zum GEOTECHNOLOGIEN-Forschungsschwerpunkt, GEOMAR Forschungszentrum, Kiel, Germany, 6-7 May 2002.

Bussell et al., Application of the METS methane sensor to the in-situ detection of methane over a range of time scales and environments, American Geophysical Union Fall Meeting, San Francisco, Dec. 13-17, 1999.

Carnahan, B.D., R.W. Clanton, K.D. Koehler, G.O. Harkins, and G.R. Williams, Fiber optic temperature monitoring technology, SPE 54599, Society of Petroleum Engineers Western Regional Meeting, Anchorage, 26-28 May 1999.

Chapman, N.R., J.F. Gettrust, R. Walia, D. Hannay, G.D. Spence, W.T. Wood and R.D. Hyndman, High-resolution, deep-towed, multichannel seismic survey of deep-sea gas hydrates off western Canada, *Geophysics 67*, 1038-1047, 2002.

Collett, T.S., Well Log Evaluation of Gas Hydrate Saturations, SPWLA 39th Annual Logging Symposium, Paper MM, 1998a.

Collett, T.S., Well Log Characterization of Sediment Porosities in Gas-Hydrate-Bearing Reservoirs, Society of Petroleum Engineers Paper SPE 49298, 1998b.

Collett, T.S. and J. Ladd, Detection of gas hydrate with downhole logs and assessment of gas hydrate concentrations (saturations) and gas volumes on the Blake Ridge with electrical resistivity log data, in *Proceedings of the Ocean Drilling Program, Scientific Results, Leg 164*, edited by C.K. Paull et al., chap. 19, Ocean Drilling Program, College Station, 2000.

Collett, T.S., A Review of Well-Log Analysis Techniques Used to Assess Gas Hydrate Bearing Reservoirs, in *Natural Gas Hydrates: Occurrence, Distribution and Detection, Geophysical Monograph 124,* edited by C.K. Paull and W.P. Dillon, pp. 87-98, American Geophysical Union, Washington, 2001.

Collett T.S. and S.R. Dallimore, Detailed Analysis of Gas Hydrate Induced Drilling and Production Hazards, *Proceedings of the Fourth International Conference on Gas Hydrates*, Yokohama, 19-23 May 2002

Cooper, G.A., Directional drilling, *Sci. Am.* May, 1994.

Cynar, F.J. and A.A. Yayanos, The distribution of methane in the upper waters of the southern California bight, *J. Geophys. Res. C 97*, 11269-11285, 1992.

Dai, J., H. Xu, F. Snyder, and N. Dutta, Detection and estimation of gas hydrates using rock physics and seismic inversion: Examples from the northern deepwater Gulf of Mexico, *Leading Edge 23*, 60-66, 2004

Dallimore, S.R. T. Uchida, and T.S. Collett, *Geological Survey of Canada Bulletin 544: Scientific Results from JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada*, Geological Survey of Canada, Ottawa, 1999.

Dickens, G.R., C.K. Paull, and P. Wallace, Direct measurement of *in situ* methane quantities in a large gas hydrate reservoir, *Nature 385*, 426-428, 1997

Dvorkin, J., M.B. Helgerud, W.F. Waite, S.H. Kirby and A. Nur, Introduction to physical properties and elasticity models, in *Natural Gas Hydrate in Oceanic and Permafrost Environments*, edited by M.D. Max, pp. 245-260, Kluwer, Dordrecht, 2000.

Ecker, C., J. Dvorkin and A.M. Nur, Estimating the amount of gas hydrate and free gas from marine seismic data, *Geophysics 65*, 565-573, 2000.

Edwards, R.N., On the resource evaluation of marine gas hydrate deposits using sea-floor transient electric dipole-dipole methods, *Geophysics 62*, 63-74, 1997.

Ellis, D.V., *Well Logging for Earth Scientists*, Elsevier, New York, 1987.

Entralgo, R. and S. Spitz, The Challenge of Permanent 4-C Seafloor Systems, *Leading Edge 20*, 614-620 (2001).

Eriksson, K., C. Baggs, and M. Theobald, Fiber optic downhole sensors for subsea wells: Remaining problems, OTC 14198, Offshore Technology Conference, Houston, 6-9 May, 2002.

Freitag, H.-C., Tool provides p-, s-wave measurements, Hart's E&P, July 2003, pg 56-57.

Goldberg, D., G. Myers, K. Grigar, T. Pettigrew, S. Mrozewski, C. Arceneaux, T. Collins, and Shipboard Scientific Party ODP Leg 204, Logging-while-coring - New technology advances scientific drilling, SPWLA 44th Annual Logging Symposium, Paper CC, 2003.

Graber, K.K., E. Pollard, B. Jonasson and E. Schulte, Overview of Ocean Drilling Program engineering tools and hardware, *ODP Tech. Note 31*, 2002.

Grevemeyer, I. and H. Villinger, Gas Hydrate Stability and the Assessment of Heat Flow through Continental Margins, *Geophys. J. Int. 145*, 647-660 (2001)

Hampton, M.A., Submarine Landslides, *Rev. Geophys. 34*, 33-59 (1996).

Helgerud, M.B., Wave speeds in gas hydrate and sediments containing gas hydrate: A laboratory and modeling study, Ph.D. Dissertation, Stanford University, 2001.

Hovland, M. and O.T. Gudmestad, Potential influence of gas hydrates on seabed installations, in *Natural Gas Hydrates: Occurrence, Distribution and Detection, Geophysical Monograph 124*, edited by C.K. Paull and W.P. Dillon, pp. 307-315, American Geophysical Union, Washington, 2001.

Howe, B.M., H. Kirkham, A.D. Chave, A.R. Maffei and S. Gaudet, Wiring the Juan de Fuca Plate for Science: The NEPTUNE System, Oceanography International Conference, Miami, 3-5 April 2001.

Hutchinson, M.W., Comparisons of MWD, wireline and core data from a borehole test facility, SPE 22735, Society of Petroleum Engineers 66th Annual Technical Conference, Dallas, Oct. 6-9, 1991.

Hutnak, M., M.E. Torres, H.P. Johnson and R.W. Collier, Periodic negative heat flow on southern Hydrate Ridge: Implications for the destabilization of gas hydrate, American Geophysical Union Fall Meeting, San Francisco, Dec. 13-17, 1999.

Jenkins, R.W., J.F. Greenip, and B.A. Adams, Case history: Utilizing 5-1/2" drill pipe in a deepwater Gulf of Mexico drilling program, SPE/IADC 52769, SPE/IADC Drilling Conference, Amsterdam, 9-11 March 1999.

Kvenvolden, K.A., L.A. Barnard, and D.H. Cameron, Pressure core barrel: Applications to the study of gas hydrates, Deep Sea Drilling Project Site 533, Leg 76, *Initial Reports of the Deep Sea Drilling Project, Leg 76*, 367-375, 1983.

Lee, M.W. and W.P. Dillon, Amplitude blanking related to the pore-filling of gas hydrate in sediments, *Marine Geophys. Res. 22*, 101-109, 2001.

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

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

Kleinberg, R.L., C. Flaum, and T.S. Collett, Magnetic resonance log of Mallik 5L-38: Hydrate saturation, growth habit, and relative permeability. In: S.R. Dallimore and T.S. Collett (Editors), Scientific Results from the Mallik 2002 Gas Hydrate Production

Research Well, Mackenzie Delta, Northwest Territories, Canada, Bulletin 585. Geological Survey of Canada, Ottawa, 2004.

Kragas, T.K., B.A. Williams, and G.A. Myers, The optic oil field: Deployment and application of permanent in-well fiber optic sensing systems for production and reservoir monitoring, SPE 71529, Society of Petroleum Engineers, New Orleans, 30 September – 3 October 2001.

Kvenvolden, K.A., L.A. Barnard, and D.H. Cameron, Pressure core barrel: Applications to the study of gas hydrates, Deep Sea Drilling Project Site 533, Leg 76, *Initial Reports of the Deep Sea Drilling Project, Leg 76,* 367-375, 1983.

Luthi, S.M., *Geological Well Logs,* chap. 3.5, Springer, Berlin, 2001.

MacDonald, I.R., N.L. Guinasso Jr., R. Sassen, J.M. Brooks, L. Lee, and K.T. Scott, Gas Hydrate that Breaches the Sea Floor on the Continental Slope of the Gulf of Mexico, *Geology 22,* 699-702, 1994.

Mallick, S., X. Huang, J. Lauve and R. Ahmad, Hydbrid seismic inversion: A reconnaissance tool for deepwater exploration, *Leading Edge 19*, 1230-1237, 2000.

Max, M.D. and P.R. Miles, Marine survey for gas hydrate, OTC 10769, Offshore Technology Conference, Houston, May 3-6, 1999.

MBARI, Monterey Accelerated Research System, 2003
http://www.mbari.org/mars/

McGee, T.M. and J.R. Woolsey, An installation in the northern Gulf of Mexico for monitoring interactions between the water column and seafloor sediments containing gas hydrates, OTC 10771, Offshore Technology Conference, Houston 3-6 May 1999.

McGee, T.M. and J.R. Woolsey, A remote station to monitor gas hydrate outcrops in the Gulf of Mexico, in *Gas Hydrates: Challenges for the Future, Annals of the New York Academy of Sciences vol. 912*, edited by G.D. Holder and P.R. Bishnoi, pp. 527-532, New York Academy of Sciences, New York, 2000.

Merewether, R., M.S. Olsson and P. Lonsdale, Acoustically detected hydrocarbon plumes rising from 2-km depths in Guaymas Basin, Gulf of California, *J. Geophys. Res. B 90*, 3075-3085, 1985.

Mes, M.J., Measuring offshore subsidence with seabed pressure gauges, SPE 18182, Society of Petroleum Engineers, Houston, 2-5 October 1988.

Miles, P.R., Geophysical sensing and hydrate, in *Natural Gas Hydrate in Oceanic and Permafrost Environments,* edited by M.D. Max, pp. 261-274, Kluwer, Dordrecht, 2000.

Neptune, Real Time, Long Term Ocean and Earth Studies at the Scale of a Tectonic Plate: NEPTUNE Feasibility Study, 2000.
http://www.neptune.washington.edu/pub/documents/low-qual_feas_study/low-res.pdf

Neptune, NEPTUNE: A Fiber Optic Cable to Inner Space, 2003
http://www.neptune.washington.edu/

NRLSSC, Deep towed acoustics/geophysics system (DTAGS), Naval Research Laboratory Stennis Space Center web site:
http://www.nrlssc.navy.mil/~hydrates/dtags.htm, 2003

Orange, D.L., M. Angell and D. Lapp, Applications of multibeam mapping to exploration and production: Detecting seeps, mapping geohazards, and managing data overload with GIS, *Leading Edge 18*, 495-501, 1999.

Paull, C.K., W. Ussler III, W.S. Borowski and F.N. Spiess, Methane-rich plumes on the Carolina continental rise: Associations with gas hydrates, *Geology 23*, 89-92, 1995.

Paull, C.K., W. Ussler III and W.P. Dillon, Potential role of gas hydrate decomposition in generating submarine slope failures, in *Natural Gas Hydrate in Oceanic and Permafrost Environments*, edited by M.D. Max, pp. 149-156, Kluwer, Dordrecht, 2000.

Pecher, I.A. and W.S. Holbrook, Seismic methods for detecting and quantifying marine methane hydrate / free gas reservoirs, in *Natural Gas Hydrate in Oceanic and Permafrost Environments*, edited by M.D. Max, pp. 275-294, Kluwer, Dordrecht, 2000.

Prensky, S, A review of gas hydrates and formation evaluation of hydrate-bearing reservoirs, SPWLA 36th Annual Logging Symposium, Paper GGG, 1995.

Prior, D.B. and J.R. Hooper, Sea floor engineering geomorphology: recent achievements and future directions, *Geomorphology 31*, 411-439, 1999.

Rezmer-Cooper, I., T. Bratton, and H. Krabbe, The use of resistivity-at-the-bit images and annular pressure while drilling in preventing drilling problems, *SPE Drilling and Completion*, March 2001, pg 35-42.

Roberts, H.H. and R.S. Carney, Evidence of episodic fluid, gas and sediment venting on the northern Gulf of Mexico continental slope, *Econ. Geol. 92*, 863-879, 1997.

Roberts, H.H., W.J. Wiseman Jr., J. Hooper, and G.D. Humphrey, Surficial gas hydrates of the Louisiana continental slope - Initial results of direct observations and in situ data collection, OTC 10770, Offshore Technology Conference, Houston 3-6 May 1999.

Roberts, H.H., Fluid and gas expulsion on the northern Gulf of Mexico continental slope: Mud-prone to mineral-prone responses, in *Natural Gas Hydrates: Occurrence,* *Distribution and Detection, Geophysical Monograph 124,* edited by C.K. Paull and W.P. Dillon, pp. 145-161, American Geophysical Union, Washington, 2001

Rowe, M.M. and J.F. Gettrust, Methane hydrate content of Blake Outer Ridge sediments, in *International Conference on Natural Gas Hydrates, Annals of the New York Academy of Sciences vol. 715*, edited by E.D. Sloan, J. Happel and M.A. Hnatow, pp. 492-494, New York Academy of Sciences, New York, 1994.

Ruppel, C., Thermal State of the Gas Hydrate Reservoir, in *Natural Gas Hydrate in Oceanic and Permafrost Environments*, edited by M.D. Max, pp. 29-42, Kluwer, Dordrecht, 2000.

Ruppel, C. and M. Kinoshita, Fluid, methane, and energy flux in an active margin gas hydrate province, offshore Costa Rica, *Earth Planet. Sci. Lett. 179,* 153-165, 2000.

Sasaki, M., N. Endo, N. Ohashi and E. Tsukahara, Dissociation of methane hydrate in the Sea of Okhotsk - Survey of dissolved methane concentration in seawater and sea ice, Proceedings of the Fourth International Conference on Gas Hydrates, Yokohama, May 19-23, 2002.

Sassen, R., S.L. Losh, L. Cathles III, H.H. Roberts, J.K. Whelan, A.V. Milkov, S.T. Sweet, D.A. DeFreitas, Massive vein-filling gas hydrate: relation to ongoing gas migration from the deep subsurface in the Gulf of Mexico, *Marine Petrol. Geol. 18,* 551-560, 2001.

Schroeder, R.J., R.T. Ramos, T. Yamate, and E. Udd, Fiber optic sensors for oilfield services, in *Handbook of Optical Fiber Sensing Technology*, edited by J.M. Lopez-Higuera, pp. 671-686, John Wiley & Sonds, Ltd., 2002.

Schumacher, D. and M.A. Abrams, *Hydrocarbon Migration and its Near-Surface Expression, AAPG Memoir 66*, American Association of Petroleum Geologists, Tulsa, 1996

Sloan, E.D., *Clathrate Hydrates of Natural Gases*, Marcel Dekker, New York, 1998.

Spangenberg, E., Modeling of the influence of gas hydrate content on the electrical properties of porous sediments", *J. of Geophys. Res. B 106,* 6535-6548, 2001.

Spence, G.D., R.D. Hyndman, N.R. Chapman, M. Riedel, N. Edwards and J. Yuan, Cascadia Margin, Northeast Pacific Ocean: Hydrate distribution from geophysical investigations, in *Natural Gas Hydrate in Oceanic and Permafrost Environments,* edited by M.D. Max, pp. 183-198, Kluwer, Dordrecht, 2000.

Stoller, C., H.L. Darling, T. DasGupta, B.M. Jorion, R.A. Perchonok, O.G. Philip, and N.I. Wijeyesekera, Density logging in slim holes with a novel array density tool, Society of Petroleum Engineers Paper 38650 (1997).

Suess, E., et al., Subduction Zone Processes: Fluid Venting and Gas Hydrates at the Cascadia Convergent Margin, Neptune Science White Paper #5, 1999, http://www.neptune.washington,edu/pub/documents/documents.html

Takahashi, H., T. Yonezawa and Y. Takedomi, Exploration for natural hydrate in Nankai Trough wells offshore Japan, Offshore Technology Conference paper 13040, 2001.

Tibold, M.P., S. Simonian, M. Chawla, and M. Akbar, Well testing with a permanent monitoring system, SPE 63079, Society of Petroleum Engineers, Dallas, 1-4 October 2000.

Tinivella, U. and F. Accaino, Compressional velocity structure and Poisson's ratio in marine sediments with gas hydrate and free gas by inversion of reflected and refracted seismic data (South Shetland Islands, Antarctica), *Marine Geology 164*, 13-27 (2000).

Tinivella, U. and J.M. Carcione, Estimation of gas-hydrate concentration and free-gas saturation from log and seismic data, *Leading Edge 20*, 200-203, 2001.

Tolan, M., M. Boyle, and G. Williams, The use of fiber optic distributed temperature sensing and remote hydraulically operated interval control valves for management of water production in the Douglas field, SPE 71676, Society of Petroleum Engineers, New Orleans 30 Sept-3 Oct 2001.

Tryon, M.D. et al., Measurements of transience and downward fluid flow near episodic methane gas vents, Hydrate Ridge, Cascadia, *Geology 27*, 1075-1078, 1999.

Tunnicliffe, V., and R. Dewey, VENUS: Victoria Experimental Network Under Sea, Proposal Submitted to the Canadian Foundation for Innovation, 2001.

Whitfield, M. and D. Jagner, *Marine Electrochemistry: A Practical Introduction*, Wiley, New York, 1981.

Zoback, M.D., C.A. Barton, M. Brudy, D.A. Castillo, T. Finkbeiner, B.R. Grollimund, D.B. Moos, P. Peska, C.D. Ward, and D.J. Wiprut, Determination of stress orientation and magnitude in deep wells, *International Journal of Rock Mechanics & Mining Sciences 40*, 1049-1076 (2003).

Willoughby, E.C. and R.N. Edwards, On the resource evaluation of marine gas hydrate deposits using seafloor compliance methods, *Geophys. J. Int. 131*, 751-766, 1997.

Willoughby, E.C. and R.N. Edwards, Shear velocities in Cascadia from seafloor compliance measurements, *Geophys. Res. Lett. 27*, 1021-1024, 2000.

Wood, W.T., J.F. Gettrust, N.R. Chapman, G.D. Spence, and R.D. Hyndman, Decreased stability of methane hydrates in marine sediments owing to phase-boundary roughness, *Nature 420*, 656-660, 2002.

Yuan, J. and R.N. Edwards, The assessment of marine gas hydrates through electrical remote sounding: Hydrate without a BSR?, *Geophys. Res. Lett. 27*, 2397-2400, 2000.