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The Sensitivity of Seismic Responses to Gas Hydrates

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CONTRACT IMFORMATION

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Schedule and Milestones

This project was designed to be completed in six months. In October and November, 1991, we gathered background material dealing with seismic modelling of gas hydrates and developed a working model to parameterize hydrate saturated sediments. In December, 1992 we made modifications to numerical processing software to test our model of hydrated sediments. During January, February and March, 1992, we tested the sensitivity of seismic velocity and waveform amplitudes to model parameters in gas hydrate deposits and compiled our results.

OBJECTIVES

The primary goal of this project was to determine the sensitivity of seismic responses to gas hydrate and associated free gas saturation within marine sediments. The development of a model to predict the physical properties of sediments containing hydrates was required. This model was used as the basis for predicting the sensitivity of P and S wave seismic velocities and waveform amplitudes to variations in hydrate and free gas saturation. Secondary goals of the project included: assessment of the usefulness of seismic shear waves in characterizing hydrate saturation and a review of potential complications in seismic modelling procedures.

BACKGROUND INFORMATION

Strong seismic reflections, occurring hundreds of meters below the sea floor, are commonly found within the unconsolidated and highly porous sediments of some continental margin environments. These seismic markers have the distinct characteristic of following, or simulating, the topography of the sea floor, and are thus termed bottom simulating reflectors, or BSRs. It is believed that these features represent the bottom of a zone of accumulated gas clatherates (commonly referred to as gas hydrates) which develop when water forms a cage-like structure around smaller molecules, most commonly methane. These crystalline structures form in a narrow pressure/temperature zone within the sediments and are associated with rapid depositional regimes (Sloan, 1990).

Large amplitudes associated with reflections from these sediments, indicate that a strong impedance (velocity x density) contrast exists at the base of the gas hydrates saturated sediments. Furthermore, it has been suggested that the variation of amplitudes of seismic reflections with increasing offset indicates that free gas deposits may exist beneath the solid hydrate zone, trapped by the accumulated crystalline hydrates above. Direct evidence of gas hydrates has come primarily from the results of the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP): Shipley and Didyk, 1982; Kvenvolden and Barnard, 1983; Mathews and von Huene, 1985; Suess et al., 1988.

Various seismic techniques have been used to characterize hydrate deposits. Interval velocity estimations (Stoll 1974; Tucholke, et al., 1977; Dillon Paull, 1983; Sheridan et al., 1983) have been used to estimate hydrate saturation levels based on an equation (Pearson et al., 1986) which relates bulk interval velocity with porosity and saturation. Amplitude and reflection coefficient modelling has also been used to determine hydrate saturation levels (e.g. Minshull and White, 1989; Max, 1990; Miller et al, 1991). Blanking effects, where a dramatic decrease in reflectance often precedes the BSR (Shipley et al., 1979, Lee et al., 1992) have been modeled to infer hydrate saturation levels.

PROJECT DESCRIPTION

In this project we examine the nature of the reflection coefficient (RC), and the variation of the RC with incidence angle, of seismic reflections coming from hydrated sediments lying above marine sediments which may contain free gas. It is important to determine the effectiveness of seismic modelling techniques in characterizing gas hydrate and free gas saturated deposits, because direct evidence of these marine sedimentary features is sparse and difficult and expensive to acquire. An understanding of physical properties of sediments above and below the BSR is required to model hydrated sediments. The accurate representation of the changes in the elastic parameters brought about by rheological modification of the sediments caused by gas hydrate and free gas accumulation is important if seismic data is to be use in characterizing hydrate and free gas volumes. Knowledge of the seismic response of these sediments, as well as the sensitivity of the response to changes in key parameters in the model, is essential.

Recent emphasis in the oil and gas exploration industry on the amplitude versus offset (AVO) response of gas saturated sands has prompted research into the nature of AVO functions from BSRs. However, AVO modelling is intrinsically difficult due to the sensitivity of AVO functions to model parameter variations, as well as the dependence of

AVO analysis on accurate and true seismic amplitudes. Complications can arise in true amplitude processing of seismic data, and from the distortions in amplitudes due to heterogeneities in the sediments.

This report is divided into three sections: first, we discuss the development of a numerical model for hydrate and free gas saturated sediments; second, we examine the sensitivity of RC functions to variations in important parameters characterizing BSRs; and third, the complications in RC and AVO functions due to gradients in hydrate saturation and from the effects of rough sea floor topography are presented.

Model Construction

In order to model RC and AVO effects in seismic data recorded in sediments saturated with solid hydrate or free gas deposits associated with BSRs, a physical model which allows for the effects of hydrate saturation to sediments is required. We introduce below a model of hydrated sediments; first for the solid hydrated sediments above the BSR, then second for the sediments below the BSR which may contain some level of free gas.

Hydrated Sediments above the BSR. The process of hydrate saturation above the BSR involves the replacement of pore fluid with solid methane hydrate. The mechanics of this replacement process are not fully understood (e.g. Claypool and Kaplan, 1984; Sloan, 1990,), and the subsequent effect on the bulk physical parameters of the saturated sediments is not well documented. Analysis of samples taken from wells cored in hydrated sediments indicates that hydrate in the sediments can exist in several different forms, from highly disseminated deposits with low saturation levels to massive deposits of pure solid methane hydrate. Marine sediments in which hydrate nucleates generally are unconsolidated and have porosities ranging from 20 to 65 % with hydrate saturation levels between 0 and 30 % (see Sloan, 1990 for a review of compiled data).

To quantify the bulk elastic parameters which characterize hydrated sediments (Vp, Vs and density), we modified the simple time-term velocity relation of Pearson et al., 1986, by introducing a parameter which controls the Vp/Vs ratio of the sediments as a function of the hydrate saturation level. This procedure takes advantage of the theoretical and experimental results of soil rheology studies in permafrost areas. In these areas, it has been demonstrated (Timur 1968; Zimmernam and King, 1986) that the rigidity of the soils increases with increased ice saturation. Figure 1, taken

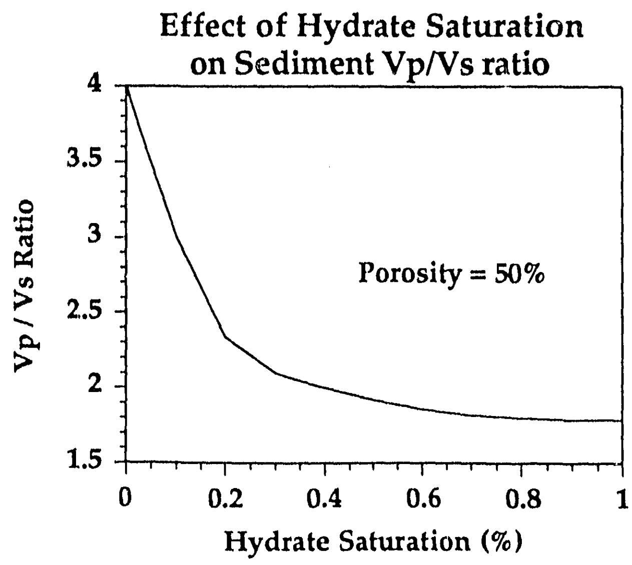

Figure 1. Effects of ice saturation in permafrost soils on Vp/Vs ratio. Soil has 50% porosity. This model is used in determining Vp/Vs ratios in hydrated sediments. Taken from Zimmerman and King, 1986.

from Zimmernam and King, 1986, shows that the Vp/Vs ratio in 50 % porosity, ice saturated soil, drops dramatically from a level of 4.0 at 5% ice saturatior to to a level of 1.8 at 80 % ice saturation. The reduction of the Vp/Vs ratio, (and Poission's ratio) is due to the increased shear strength of the frozen, ice saturated soils. Hydrated sediments are parameterized to have shear strength characteristics similar to those of permafrost soils. The effect of this parameterization on RC and AVO functions is demonstrated below.

Figure 2 shows the effect of free gas and solid hydrate saturation on the elastic parameters Vp, Vs and density , below and above the BSR for a 60% porosity sediment. On the right side of the graph we see that an increase of saturation of hydrate above the BSR increases compressional velocities steadily. Shear wave velocities are plotted for constant and variable Vp/Vs ratios. It is evident that in the range of 0 to 30% saturation, the model with which the shear wave velocity is determined is quite important

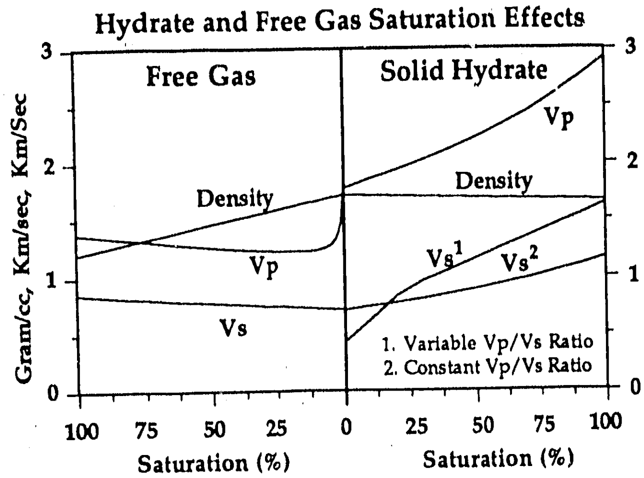

Figure 2. Elastic parameters Vp, Vs and density for hydrates and free gas saturated sediments. On left the effect of gas saturation below the BSR is shown. Vp (and the Vp/Vs ratio) rapidly decreases due to a small amount of free gas. Above the BSR (right), a Vs is determined using a constant and variable Vp/Vs ratio model, the implications of which are discussed in the text.

Free Gas Saturated Sediments below the BSR. Since Ostrander's 1984 papers on the effect of Poission's ratio on reflection coefficients, AVO signatures have been used to help determine if free gas is present below observed reflection horizons . Questions regarding free gas are of particular importance in the study of hydrate deposits in marine sediments, where strong BSRs exist on numerous seismic data (see Sloan 1990 for a catalog of BSR observations). If free gas is trapped in basal marine sediments, a potentially important energy resource may exist.

In order to answer fundamental questions regarding the existence of free gas in the sediment below a BSR, a parameterized model of the sediments below the BSR, which allows for variations in elastic moduli due to gas saturation is required. We use the generalized zero frequency form of Biot's equation presented by Domenico, 1977 (equivalent to Gassman's equation), in which Vp, Vs and density are dependent on constituent compressibilities and densities, as well as the sediment porosity and the shear modulus of the reservoir frame.

Figure 2 (left) shows the effect of free gas on the elastic parameters Vp, Vs and density below the BSR using this formulation. From this figure we see that below the BSR a small percentage of gas saturation (< 10% of the 60 % reference porosity) dramatically reduces compressional wave velocity. This drop is due to the strong increase in the bulk compressibility of the media caused by the introduction of the gas. The shear velocity increases slightly, and more significantly, the Vp/Vs ratio increases abruptly.

Modelling Techniques

In order to examine the effects of hydrate and free gas saturation in marine sediments we, parameterized with the model described above, we utilize three different modelling techniques: reflection coefficient modelling; ray modelling and finite difference wavefield modelling. Reflection coefficient modelling consists of an application of the Zoeppritz equations (e.g.. Telford et al., 1976) to partition incident P wave energy at planar interface in to reflected P wave and converted S wave arrivals, at all angles of incidence. With ray modelling the amplitudes of particular rays traveling through an an elastic model containing smoothly varying interfaces are determined at a set of source - receiver offsets. With finite difference modeling a model for hydrate and free gas saturated sediments is established numerically on a two dimensional grid, which allows for heterogeneous model representation. Seismic wavefields are calculated with this technique, from which amplitude features can be extracted.

Parameter Sensitivity Analysis

The primary goal AVO and RC analysis of BSRs is to determine estimates of key parameters which characterize the media; the hydrate saturation above the BSR and the free gas saturation below the BSR. The amplitude of P and S wave reflections from a BSR and their variations with incidence angle can be a useful tool in characterizing the elastic parameters of the sediments. The reflection coefficients of a plane wave impinging onto a simple elastic interface, are primarily controlled by two factors; the impedance contrast across the interface, and the Poission's ratio contrast across the interface. Figure 3 shows the effect of the variations in the impedance contrast at an interface for a reflected P-wave. In this example we fix the basal parameters to be: Vp = 2 km/sec, ρ = 1.7 g/cc, and σ = 0.1 to represent a gas saturated sediment. Above the BSR, ρ is fixed at 1.7 g/cc, σ is fixed at 0.35 and Vp is varied from 2.0 to 3.0 km/sec. The effect of this variation in Vp is to increase the impedance in the sediments above the BSR and therefore increase (negatively) the RC. The overall variation in shape of the RC function with increasing angle is not significantly changed.

Figure 4 demonstrates the effects of variations in Poission's ratio in the basal sediments. In this analysis we use a model

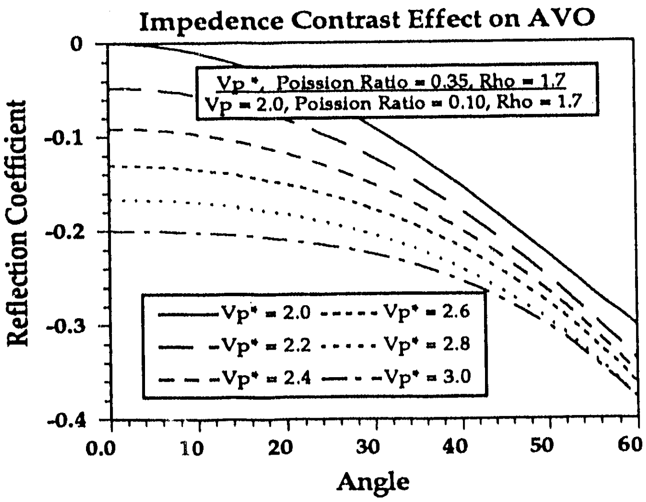

Figure 3. Effect of the impedance contrast on reflection coefficient variations with incident angle. Increases in Vp above the interface increase the absolute reflection coefficient at vertical incidence, but have diminished effects with increased angles.

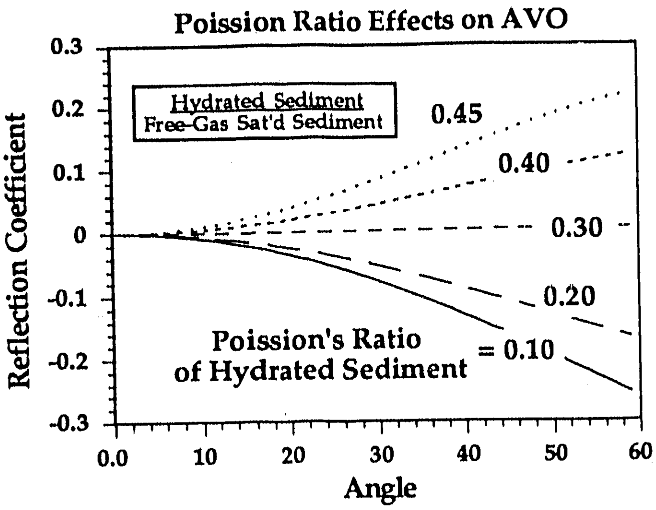

Figure 4. Effects of Poission's ratio in basal sediments on reflection coefficient functions. Sediments above BSR have σ of 0.3. Decrease in σ (from introduction of free gas) causes a negative amplitude increase with increasing incidence angle.

of a hydrated sediment above a gas saturated sediment similar to that of the previous example. Here we see that when σ below the BSR is changed from 0.3 (the value of σ above the BSR), a strong variation in RC is induced. A change of σ to 0.4 sharply increases the RC and a reduction of σ to 0.2 sharply decreases the RC. For this representative hydrate saturated reference model, an increase in negative amplitude is only possible when σ below the BSR is decreased.

We have seen that both above the BSR and below the BSR a mechanism exists to reduce the Vp/Vs ratio. Above the BSR the replacement of pore fluid with solid hydrate increases the rigidity of the high porosity sediments and therefore increases the efficiency of shear wave propagation. Below the BSR the addition of highly compressible free gas drops the bulk compressibility of the sediments and therefore reduces the efficiency of P-wave propagation and subsequently increases the Vp/Vs ratio. These two factors drive the σ contrast in the same direction and complicate the AVO and RC modelling process.

In order to demonstrate the importance of properly characterizing the rheological effects of hydrate saturation above the BSR, a series of AVO functions were calculated for models with constant

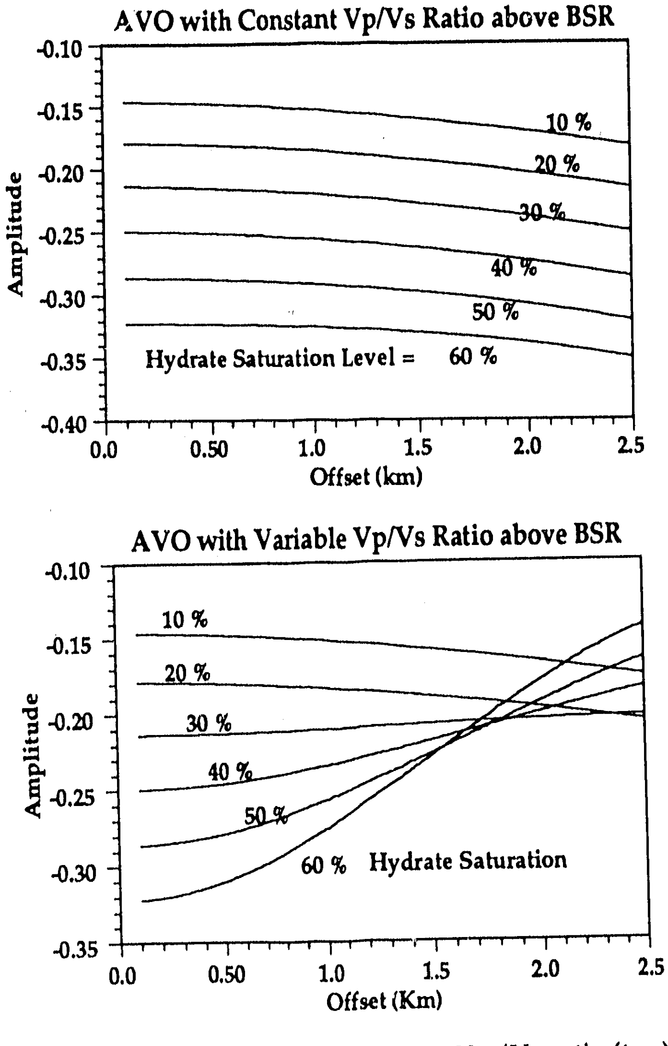

Figure 5. Effects of using constant Vp/Vs ratio (top) and variable Vp/Vs ratio (bottom) when characterizing sediments saturated with gas hydrates. With a variable Vp/Vs ratio model, absolute amplitudes decrease with offset for high saturation levels due to increased shear strength of the hydrated sediments.

and variable Vp/Vs ratios. Figure 5 has 2 graphs which demonstrate the change in the AVO functions with variation in hydrate saturation. In the upper plot the AVO functions are calculated to an offset of 2.5 km using a fixed Vp/Vs ratio of 2.5 above the BSR. The only significant change in the curves is in the magnitude of the negative amplitude. In the lower plot the AVO functions are calculated using the variable Vp/Vs function derived from permafrost soils (Zimmerman and King, 1986) which is shown in Figure 1. At zero offset the curves are quite similar to those of the constant Vp/Vs case, but at greater offsets the high saturation cases (30 % saturation and greater) the magnitude of the amplitude decreases sharply with offset.

Partial Derivatives - Sensitivity Analysis. In order to quantify the relative effects of variations in the parameters which characterize hydrate and free gas saturated sediments, partial derivatives of the RC versus offset function with respect to perturbation of each parameter were calculated (Figure 6). The RC sensitivity functions are calculated using a relaxation technique in which a single parameter in the model is perturbed in a positive and then negative sense, while all other parameters are fixed. RC functions are calculated at each + and - perturbation and the derivative of the RC with respect to the relaxed parameter is determined. The reference model has $\phi = 0.60$, σ above the BSR= 0.3, σ below the BSR = 0.1, hydrate saturation = 30% and free gas saturation = 9%. It is clear from Figure 6 that three parameters control the sensitivity of the RC response for this reference model; hydrate saturation, free gas saturation and porosity. This graph shows that a positive increase in porosity (given that all other parameters remain fixed) increases the RC and that the porosity increase has the greatest effect at low angles. Since this model produces a negative P-wave RC, an increase in ϕ actually reduces the negative amplitude of the reflection. The level of free gas saturation also has positive partial derivative, with little angular dependence. We showed in Figure 2 that gas saturation levels above 10% have little effect on Vp and Vs, so this result is expected at the reference point from which the derivative was taken (9% gas saturation). At lower saturation (3%, for example) the sensitivity of the AVO to free gas saturation is greater. Hydrate saturation above the BSR has the reverse effect as porosity; an increase in hydrate saturation will decrease the RC (produce a larger negative amplitude). Perturbations in any of the remaining parameters used to characterize this model have have little

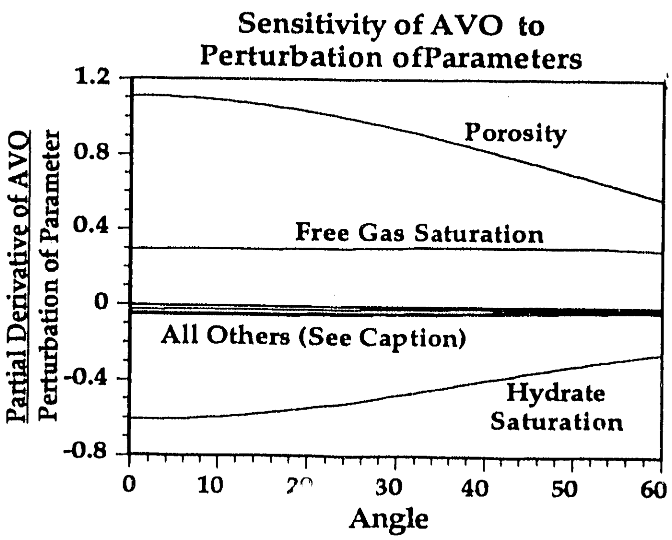

Figure 6. Partial derivatives of reflection coefficient functions. Model from which derivatives was taken has 60 porosity, with 30% hydrate saturation and 9% free gas saturation. Near zero derivatives are from parameters: hydrate velocity, hydrate density, pore fluid velocity, matrix density and Vp/Vs ratio.

effect on the RC. These include hydrate velocity, hydrate density, pore fluid velocity, matrix density and Vp/Vs ratio.

BSR Sensitivity to Free Gas. Two obvious and important questions regarding the modelling of free gas deposits associated with BSRs are: 1. Can we determine if free gas exists below a BSR? and more specifically, 2. Can we determine how much gas exists below a BSR? As with many seismic modelling questions, the answer is yes; provided that sufficient data with sufficient signal quality exists. Figure 7 shows the RC functions for 4 different free gas saturation levels below a BSR (0, 3, 6 and 9%). We see that a very strong negative increase in RC exists between 0 and 3 % saturation, but that difference between 6 and 9 % is relatively insignificant. From this result we conclude that the existence of gas can be validated from RC (or AVO) analysis, but given the general difficulties of true-amplitude processing (Hyndman and Davis, 1992) as well as the non linear nature of the AVO and RC functions, the amount of free gas can not be readily determined. The porosity sensitivity plot of Figure 6 supports this conclusion; a small negative error in porosity estimation can be incorrectly modelled as a large free gas saturation.

If the level of gas saturation is difficult to uniquely determine from the AVO features of a BSR, one is left with the question: Does a BSR require free gas? To answer this question RC functions for a set of hydrate saturated sediments without free gas were calculated. Figure 8 shows these results. We see that at steep angles (< 20 degrees) all levels of hydrate saturation produce RC functions which decrease in absolute amplitude. However, at more oblique incidence (greater offsets), the RC increases in amplitude. This result demonstrates that an unambiguous polarity determination is important in post critical angle AVO analysis.

Shear Waves. Up to this point we have shown the effects of parameter

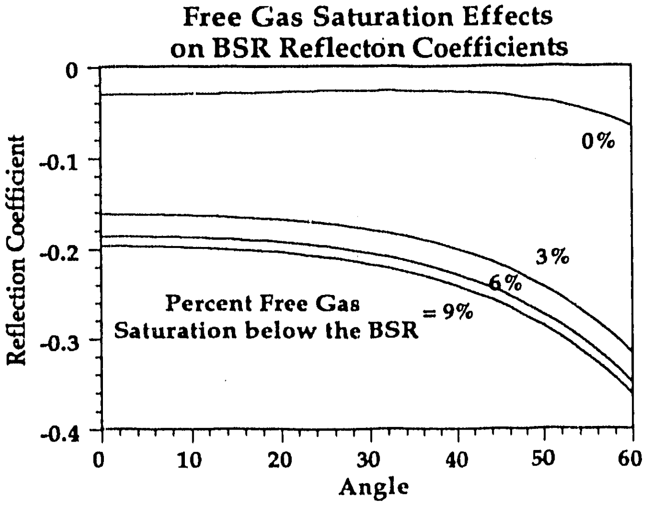

Figure 7. Free gas saturation effect on reflection coefficient functions. Model has 30% hydrate saturation (60% porosity) above the BSR. Increased gas saturation (above 9%) shows little effect.

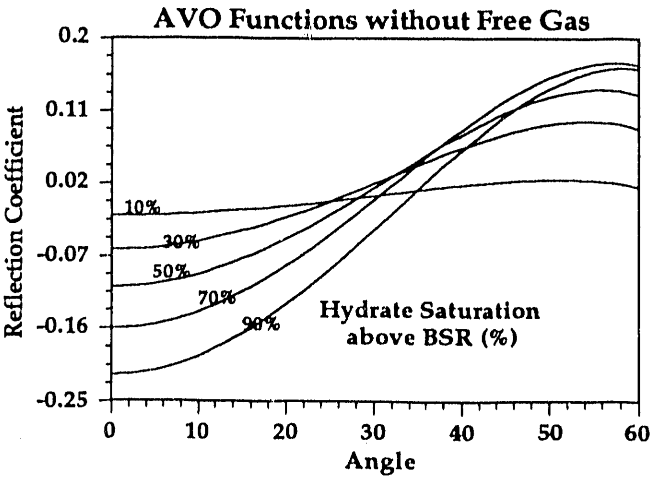

Figure 8. Reflection coefficient functions without free gas. Increasing the hydrate saturation increases the vertical incidence reflection coefficient. At large angles reflection coefficients become positive.

variations on P-wave reflection coefficients. In this section the variations in shear wave reflection coefficients are discussed. Figure 9 shows the effect of gas saturation on shear wave reflections and compressional wave to shear wave conversions off of the hydrate - gas interface. This figure should be contrasted against Figure 7 where compressional wave RC results are presented. There are two main features in the shear wave RC plot. First, there is a strong angular dependence of the RC from the compressional to shear wave conversion, which grows from zero, at vertical incidence, to a maximum of -0.02 at 40 degrees. The functional dependence of this RC is strongly dependent on gas saturation levels. Second, the magnitude of the RC is very small in comparison to those of the compressional wave case. The largest RC on either shear wave case is about 4 times less than the smallest compressional RC. These facts indicate that the use of shear wave arrivals as gas saturation indicators is limited.

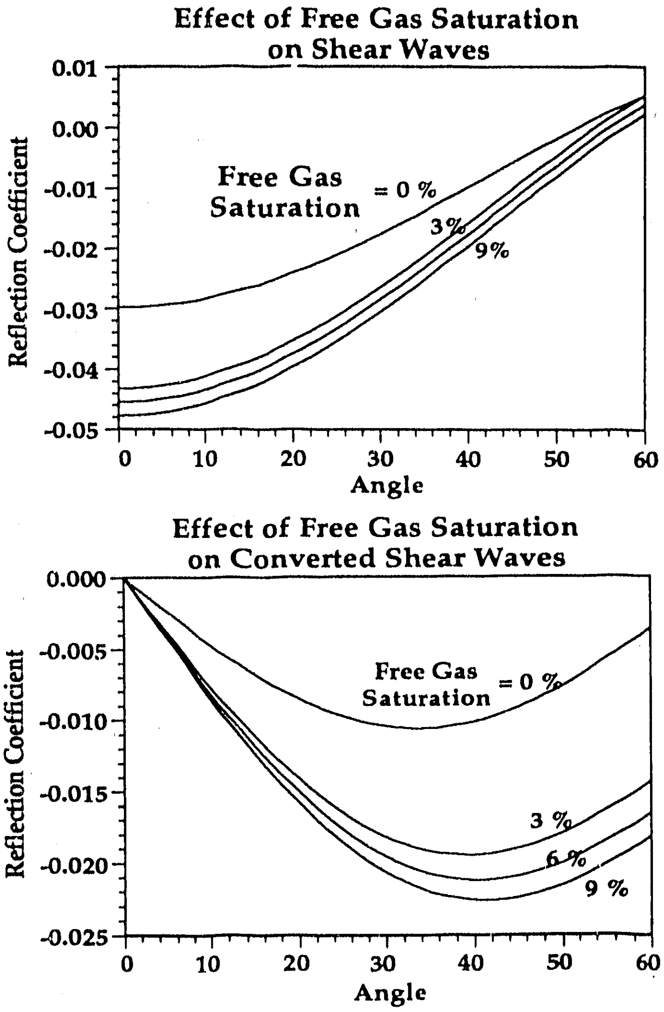

Figure 9. Effects of free gas saturation on shear wave reflection coefficients for reflected shear waves (top) and P to S conversions (bottom). Sensitivity to small variations in gas saturation above 3% is small. The overall magnitude of the reflection coefficients is about 4 time less than corresponding P waves.

Figure 10 shows the effects of different hydrate saturation levels on the AVO response of a BSR containing 9% gas saturation in the basal sediments. Amplitudes for converted P to S waves generated on the BSR are plotted for the case of constant Vp/Vs ratio (2.5) above the BSR, and for a variable Vp/Vs ratio dependent on the hydrate saturation above the BSR (Figure 1). As was evident in the P-wave case, the variation of the Vp/Vs ratio with hydrate saturation has a strong effect on the offset dependence of the AVO function. When a constant Vp/Vs ratio is used (top), the absolute amplitude decrease with offset is accentuated. With a variable Vp/Vs ratio, this trend is reversed and absolute amplitudes increase with increased hydrate saturation. The strong sensitivity of converted shear wave amplitudes at offsets greater that 1 km may be useful in hydrate saturation estimation.

Complications in AVO Applications

Thus far we have presented AVO and RC modelling results where calculations were made using models

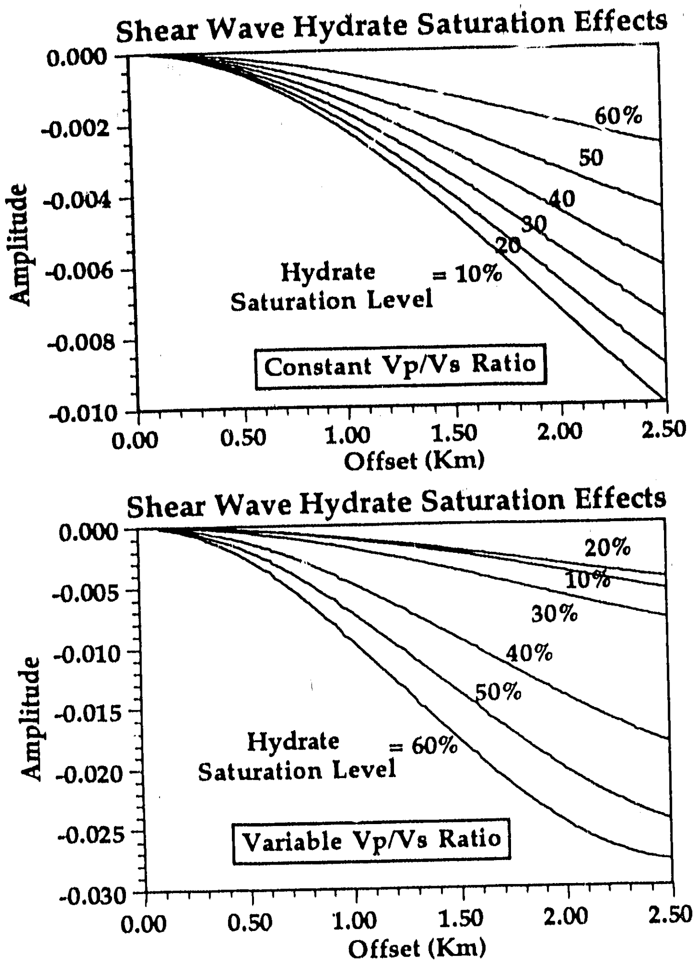

Figure 10. Shear wave AVO functions (P to S conversions) for various levels of hydrate saturation above a 9% free gas saturated BSR for constant (top) and variable (bottom) Vp/Vs ratio models.

constructed with simple homogeneous layers which have step discontinuities in velocity. In this section we examine two factors which complicate this simplified approach. First, the effects of gradients in hydrate concentrations are investigated, and second, the effects of diffractions associated with rough sea floor topography are examined.

Velocity Gradients. There are several indications that hydrates in marine sediments exist in some gradational form. Although direct evidence is sparse, analysis of well logs collected from wells drilled in hydrated sediments indicates that a sharp and sustained increase in hydrate saturation does not generally exist in the vicinity of BSRs (e.g. Mathews and von Huene, 1985). Indirect evidence of hydrate saturation levels above a BSR, from seismic data, support the idea of a gradational hydrate saturation model with saturation increasing with depth to a maximum at

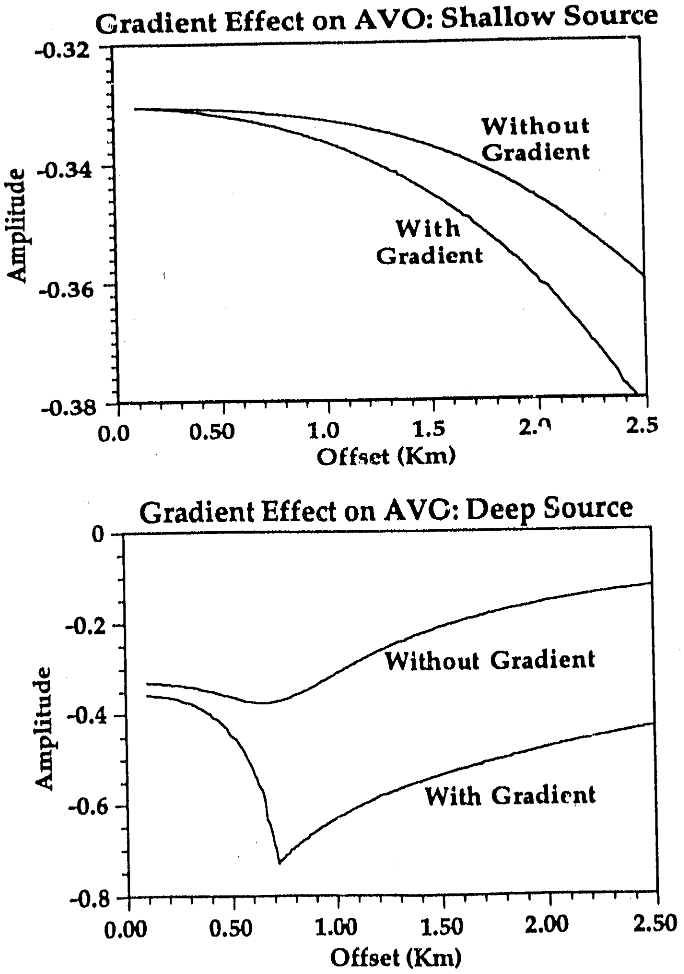

Figure 11. Effect on AVO functions due to gradients in hydrate saturation for shallow source & receiver geometry (top) and deep source & receiver geometry (bottom). Turning rays are seen at 0.70 km in the second case.

the BSR. Indirect evidence includes: first, the absence of a pre-BSR reflection which would exist if a step discontinuity in saturation existed above the BSR. Second, a reduction in reflectance is often observed above the BSR (referred to as a blanking effect). This phenomenon is attributed to a homogenization of the impedance within the sediments above the BSR, effectively removing sources of reflectivity before the BSR arrival (Lee et al., 1992) Third, large amplitudes are recorded at far offsets indicating that rays are being bent towards the horizontal by a gradient above the BSR (Hyndman and Davis, 1992). In steep gradients rays can be turned before arriving at the BSR resulting in strong positive amplitudes. To demonstrate this effects two models were generated, one with a gradient in hydrate saturation and one with a uniform level of hydrate saturation. The models have $\sigma = 0.3$ in the hydrates sediments above the BSR and $\sigma = 0.1$ in the sediment below the BSR to simulate gas saturated sediments. The AVO functions (Figure 11, top) show that the introduction of a gradient has little effect at small offsets (low angles) and increases with increased offset. The increase in absolute amplitude with offset is caused by the gradient effect on the incidence angle. This effect will be accentuated when the vertical distance between the source and the BSR is reduced: when deep towed sources are used, ocean bottom recordings are collected , or when hydrate deposits are shallow. To demonstrate the extreme effects of this phenomenon, AVO functions were calculated, using the same model as in the previous example, with the source 25 meters above the sea floor and receivers on the sea floor. The results (Figure 11, bottom) show a dramatic increase in absolute amplitude with offset as the incidence angles approach 90 degrees (at about 0.7 km).

Rough Sea floor Effects. Lateral heterogeneities in marine sediments can cause diffractions in the wavefield not modelled with ray based AVO and RC techniques. In this section we examine the variations in BSR reflection amplitudes brought about by rough sea floor topography. Wavefields are calculated using a 2D finite difference program for a series of models with progressively rougher sea floor. Figure 12 shows the base model used in the calculations. A rough sea floor is introduced into the model by randomly perturbing the sea floor depth at each offset in the model with the depth of the sea floor constrained between a minimum and maximum value. Next, the rough sea floor is smoothed over some horizontal distance to obtain a vertical/horizontal roughness ratio. Additionally, the model is defined to have a gradient in hydrate concentration above the BSR. Figure 13 (top) shows the vertical component

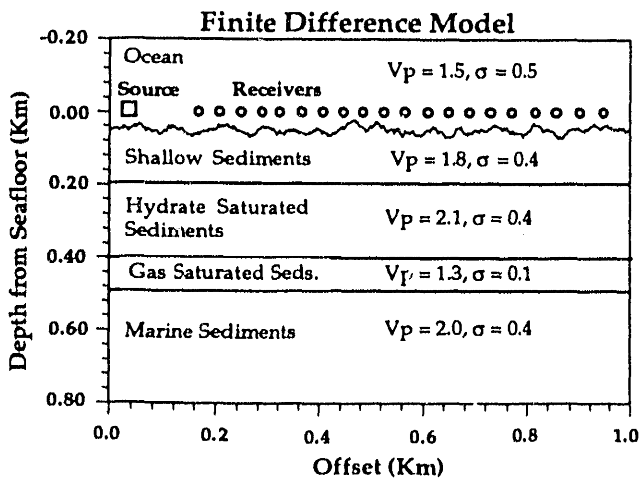

Figure 12. Model used for finite difference waveform modelling. A smooth sea floor is replace with one with a rough topography.

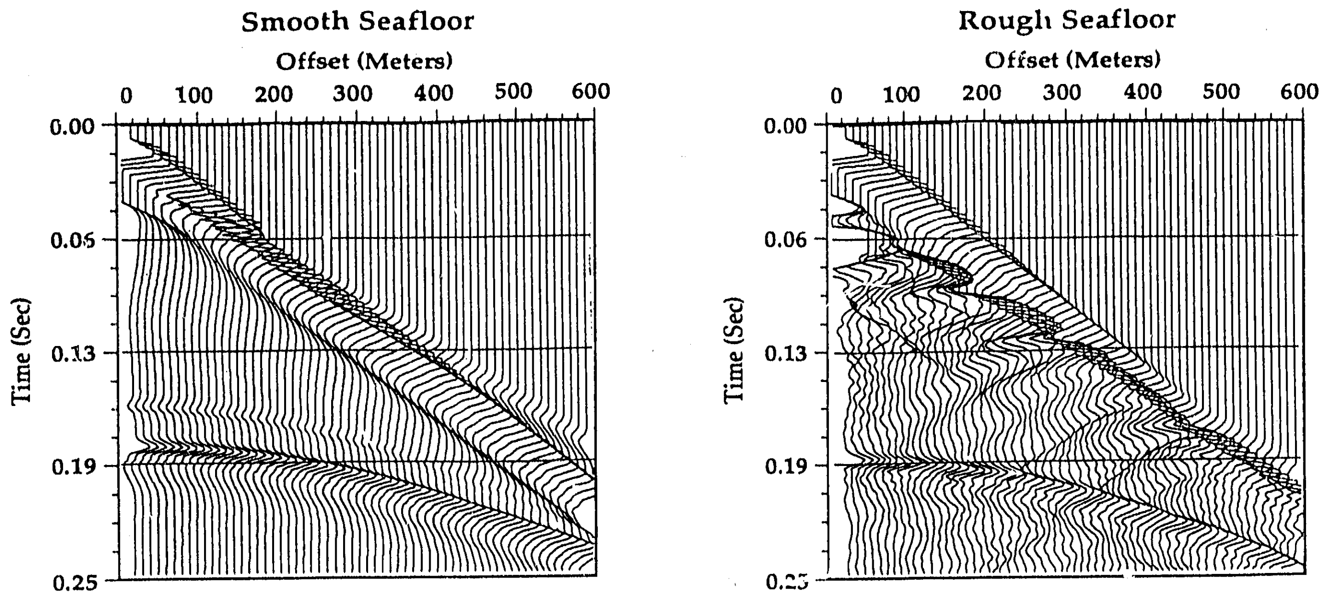

Figure 13. Wavefields for a smooth sea floor (left) and a rough sea floor (right).

wavefields for the reference model (with a flat sea floor) and a model with vertical roughness of 30 m and horizontal smoothing of 30 m. The smooth wavefield has a clear, simple BSR with amplitude steadily increasing with offset (to 600 m). These wavefields are presented without a divergence correction. The rough sea floor introduces strong diffractions into the wavefield which corrupt the AVO function (Figure 14). The un-stacked AVO for the rough sea floor model has standard deviation of 60.8 when the AVO values of the reference model are used as the expected values (which has a standard deviation of 6.1). This indicates that if the noise is randomly distributed, a 100 fold stack is required to remove this noise from this AVO.

RESULTS

The characteristics of reflection coefficient (RC) and amplitude-verse-offset (AVO) responses of bottom simulating reflections (BSRs), their sensitivity to key parameters, and complications in determining these functions are presented. We have shown that the model parameterization used to describe the saturation of sediments with hydrates or free gas deposits should allow for the changes in shear strength of the sediments. For free gas saturated sediments, Domenico's 1977 formulation

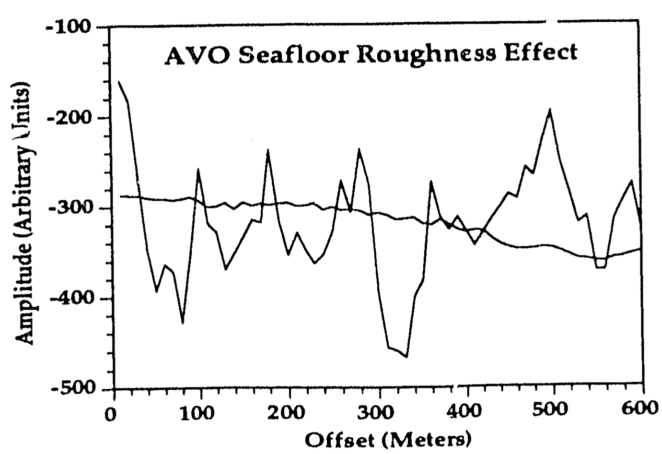

Figure 14. AVO functions for smooth and rough seafloor models (no divergence correction applied).

is sufficient. For hydrated sediments above the BSR, we modify the simple time-term averaging technique (Pearson et al., 1986) to incorporate Vp/Vs ratio effects shown to exist in ice saturated permafrost soils by Zimmerman and King, 1986. AVO responses are controlled mainly by the Poission's ratio contrast at the gas saturated sediment interface (Ostrander, 1984; Figure 4), and therefore we see large variations in the AVO responses when a hydrate saturation dependent parameterization is used (see Figures 5 and 10).

An analysis of the sensitivity of RC functions to perturbations in parameters characterizing hydrate and free gas saturated sediments, has shown that there are three important parameters which control BSR reflectivity: porosity, free gas saturation, and hydrate saturation (Figure 6). Increases in both porosity and free gas saturation (at this reference model) tend to increase amplitudes (decrease negative amplitudes), and increases in hydrates saturation tend to further decrease negative amplitudes. These results are particular to the reference used, and in general, we find that sensitivity function are quite non-linear. This implies that AVO and RC data can not easily be inverted of parameter estimates.

Free gas saturation below the BSR has a strong effect on the amplitude and angular dependence of AVO and RC functions. Figure 7 shows that there is little sensitivity of the RC function to free gas saturation levels above 6%, and implies that BSR analysis will not be able to robustly estimate the levels of free gas saturation. A review of RC functions, calculated at various hydrate saturation levels, for models containing no free gas, shows that at angles greater that about 25 degrees increases in positive RCs occur. This result shows the obvious need for accurate polarity determinations.

Shear wave RC analysis (Figure 9) indicates that shear waves are not more sensitive than P-waves, to free gas saturation, and will not be superior to P-wave analysis as a discriminant of free gas. Above the BSR we see that the use of a variable Vp/Vs ratio has an important effect on subsequent converted shear wave AVO functions (Figure 10) and that at far offsets (> 1 km) converted shear waves are quite sensitive to hydrate saturation levels.

Complications in AVO and RC modelling due to gradients in hydrate saturation levels above the BSR and due to a rough sea floor topography were investigated. Positive gradients in hydrate saturation with depth cause rays to turn towards horizontal, which increases the BSR angles of incidence and RCs (Figure 11). This effect is increased when the source to BSR distance is reduced. Roughness on the sea floor topography causes diffractions in the wavefield which may significantly contaminate AVO functions.

FUTURE WORK

The results of this brief project have been very positive. We have constructed a model of marine sediments which can characterize the elastic parameters of hydrate and free gas saturated sediments. Preliminary results regarding the sensitivity RC and AVO functions to saturation parameters, and the description of complications which may arise in modelling seismic data, indicate that seismic reflection and converted wave data may be used to characterize hydrate deposits. We intend to follow this completed project with a more comprehensive study which includes extensive modelling of field data and finite difference wavefield modelling of heterogeneous hydrate saturation and rough interface effects.

REFERENCES

Claypool, G.E. and I.R Kaplan. 1974. The Origin and Distribution of Methane in Marine Sediments. *Natural Gases in Marine Sediments,* ed. I.R. Kaplan, 99-139. New York: Plenum Press.

Dillon, W.P. and C.K. Paull. 1983. *Natural Gas Hydrates: Properties, Occurrence and Recovery.* Boston: Butterworth Publishing.

Domenico, S.N. 1977. Elastic Properties of Unconsolidated Porous Sand Reservoirs. *Geophysics* 42: 1339-1368.

Hyndman, R.D. and E.E. Davis. In Preparation. A Mechanism for the Formation of Methane Hydrate and Sea Floor Bottom Simulating Reflectors by Vertical Fluid Expulsion. In *Journal of Geoph. Research.*

Kvenvolden, K.A. and L.A. Barnard. 1983. Hydrates of Natural Gas in Continental Margins. *Studies in Continental Margin Geology,* ed. J.S. Watkins and C.L. Drake, 631-640. Am. Assoc. Petrol.Geol. Memoir 34.

Lee, M.W., W.P. Dillon, D.R. Hutchinson, J.J. Miller, W.F. Agena, and B.A. Swift. Submitted 1991. A Method of Estimating the Amount of In-Situ Gas Hydrates in Deep Sea Marine Sediments. In *Journal of Geoph. Res.*

Mathews, M.A. and R. von Huene. 1985. Site 570 Methane Hydrate Zone. In *Init. Repts. Deep Sea Drilling Project,* 773-790. Washington: U.S. Gov't. Printing Office.

Max, M.D. 1990. *Gas Hydrate and Acoustically Laminated Sediments: Potential Environmental Cause of Anomalously Low Acoustic Bottom Loss in Deep-Ocean Sediments.* NRL Report 9235. Washington D.C.: Naval Research Laboratory.

Miller, J.J., M.W. Lee, and R. von Huene. 1991. An Analysis of a Seismic Reflection from the Base of a Gas Hydrate Zone, Offshore Peru. *Am. Assoc. Petrol. Geol. Bull.* 75: 910-924.

Minshull, T., and R. White. 1989. Sediment Compaction and Fluid Migration in the Makran Accretionary Prism. *J. Geophys. Res.* 94: 7387-7402.

Ostrander, W.J. 1984. Plane-Wave Reflection Coefficients for Gas Sands at Non-Normal Angles of Incidence. *Geophysics* 49: 1637-1648.

Pearson, C., J. Murphy, and R. Hermes. 1986. Acoustic and Resistivity Measurements on Rock Samples Containing Tetrahydrofuran Hydrates: Laboratory Analogue to Natural Gas Hydrate Deposits. *J. Geophys. Res.* 91(14): 132-138.

Shipley, T.H., M.H. Houston, R.T. Buffler, F.J. Shaub, K.J. McMillen, J.W. Ladd, and J.L. Worzel. 1979. Seismic Evidence for Widespread Possible Gas Hydrate Horizons on Continental Slopes and Rises. *Am. Assoc. Petrol. Geol. Bull.* 63 (12): 2204-2213.

Shipley, T.H. and B.M. Didyk. 1982. Occurence of Methane Hydrates Offshore Southern Mexico. In *Initial Reports of the Deep Sea Drilling Project,* ed. J.S. Watkins et al, 547-555. Washington D.C.: U.S. Gov't Printing Office.

Sheridan, R.B. F.M. Gradstein, et al. 1983. *Initial Reports of the Deep Sea Drilling Project,* Vol 76. 35-80.

Sloan, E.D. 1990. *Clathrate Hydrates of Natural Gases.* New York: Marcel Dekker, Inc.

Stoll, R.D. 1974. Effects of Gas Hydrates in Sediments. In *Natural Gases in Marine Sediments,* ed. I.R Kaplan, 235-248. New York: Plenum.

Suess, E.R., et al. 1988. *Proceedings of the Ocean Drilling Program, Initial Reports.* v. 112. 873-931.

Telford, W.M., L.P. Geldart, R.E. Sheriff and D.A. Keys, 1976, *Applied Geophysics.* Cambridge University Press, Cambridge.

Timur, A. 1968. Velocity of Compressional Waves in Porous Media at Permafrost Temperatures. *Geophysics* 33: 621-645.

Tucholke, B.E., G.M. Bryan, and J.I. Ewing. 1977. Gas Hydrate Horizons Detected in Seismic-Profiler Data from the Western North Atlantic. *Am. Assoc. Petrol. Geol.* 61: 698-707.

Zimmerman, R.W. and M.S. King. 1986. The Effects of the Extent of Freezing on Seismic Velocities in Unconsolidated Permafrost. *Geophysics* 51 (6): 1285-1290.

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