The Sensitivity of Seismic Responses to Gas Hydrates

Final Report

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Abstract

The sensitivity of seismic reflection coefficients and amplitudes, and their variations with changing incidence angles and offsets, was determined with respect to changes in the parameters which characterize marine sediments containing gas hydrates. Using the results of studies of ice saturation effects in permafrost soils, we have introduced rheological effects of hydrate saturation. The replacement of pore fluids in highly porous and unconsolidated marine sediments with crystalline gas hydrates, increases the rigidity of the sediments, and alters the ratio of compressional/shear strength ratio. This causes V_p/V_s ratio variations which have an effect on the amplitudes of P-wave and S-wave reflections.

Analysis of reflection coefficient functions has revealed that amplitudes are very sensitive to porosity estimates, and errors in the assumed model porosity can effect the estimates of hydrate saturation. Additionally, we see that the level of free gas saturation is difficult to determine. A review of the effects of free gas and hydrate saturation on shear wave arrivals indicates that far-offset P to S wave converted arrivals may provide a means of characterizing hydrate saturations.

Complications in reflection coefficient and amplitude modelling can arise from gradients in hydrate saturation levels and from rough sea floor topography. An increase in hydrate saturation with depth in marine sediments causes rays to bend towards horizontal and increases the reflection incidence angles and subsequent amplitudes. This effect is strongly accentuated when the vertical separation between the source and the hydrate reflection horizon is reduced. The effect on amplitude variations with offset due to a rough sea floor was determined through finite difference wavefield modelling. Strong diffractions in the waveforms add noise to the amplitude versus offset functions.

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Executive Summary

The sensitivity of seismic reflection coefficients and amplitudes, and their variations with changing incidence angles and offsets, was determined with respect to changes in the parameters which characterize deep marine sediments containing gas hydrates and associated free gas. Using the results of studies of ice saturation effects in permafrost soils, we have introduced rheological effects of hydrate saturation into the seismic modelling process. The replacement of pore fluids in highly porous and unconsolidated marine sediments with crystalline gas hydrates increases the rigidity of the sediments, and alters the ratio of compressional/shear strength of the sediments. The petrophysical alteration of the sediments caused by the hydration process changes the V_p/V_s ratio of the media and significantly affects the amplitudes of P-wave and S-wave reflections. The incorporation of parameters which characterize the petrophysical aspects of the hydration process are required to accurately model the seismic response of gas hydrates. The omission of these considerations can lead to severe miscalculation of hydrate and free gas saturation estimations.

Analysis of reflection coefficient functions has revealed that seismic amplitudes are sensitive to three key model parameters: porosity, free gas saturation level, and hydrate saturation level. Model porosity estimates, which are constrained from well log data, strongly contribute to the estimation of hydrate saturation. The presence of free gas associated with solid hydrate deposits can be determined from seismic compressional wave data, but the level of free gas saturation is difficult to estimate. Shear wave data provide little additional information to P-wave data in free gas characterization. Solid hydrate saturation levels can be robustly estimated with seismic data. Both compressional and shear wave seismic data are quite sensitive to the presence of gas hydrates and these data can be modelled to accurately characterize deep marine gas hydrate deposits.

Complications in reflection coefficient and amplitude modelling can arise from gradients in hydrate saturation levels and from rough sea floor topography. An increase in hydrate saturation with depth in marine sediments causes rays to bend towards horizontal and increases the incidence angles at the base of the hydrate zone. Saturation gradients decrease the amount of transmitted energy through the hydrate zone and therefore increase amplitudes of reflected arrivals. This effect is strongly accentuated when the vertical separation between the source and the hydrate reflection horizon is reduced. The effect on amplitude variations with offset of reflected arrivals due to a rough sea floor was determined through finite difference wavefield modelling. Strong diffractions in the waveforms add noise to the amplitude versus offset functions and can severely corrupt seismic response modelling.

In the future, finite difference modelling techniques can be used to explain the blanking phenomenon associated with several gas hydrate deposits. With this numerical technique the reduction of reflectivity in seismic data from gas hydrate saturated marine sediments can be modelled to help further constrain hydrate saturation levels.

Introduction

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 clathrates (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 $\times$ 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.

In this paper 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 used 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 paper 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 (V_p , V_s and density), we modified the simple time-term velocity relation of Pearson et al., 1986, by introducing a parameter which controls the V_p/V_s 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 from Zimmernam and King, 1986, shows that the V_p/V_s ratio in 50 % porosity, ice

saturated soil, drops dramatically from a level of 4.0 at 5% ice saturation to to a level of 1.8 at 80 % ice saturation. The reduction of the V_p/V_s 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 V_p , V_s 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 V_p/V_s 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

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 V_p , V_s 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 V_p , V_s 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 V_p/V_s 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 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 Poisson'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: $V_p = 2$ km/sec, $\rho = 1.7$ g/cc, and $\sigma = 0.1$ to represent a gas saturated sediment. Above the BSR, ρ is fixed at 1.7 g/cc, σ is fixed at 0.35 and V_p is varied from 2.0 to 3.0 km/sec. The effect of this variation in V_p 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 Poisson's ratio in the basal sediments. In this analysis we use a model 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 V_p/V_s 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 V_p/V_s 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 and variable V_p/V_s 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 V_p/V_s 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 V_p/V_s 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 V_p/V_s 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 V_p and V_s , 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 little effect on the RC. These include hydrate velocity, hydrate density, pore fluid velocity, matrix density and V_p/V_s 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 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 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 V_p/V_s ratio (2.5) above the BSR, and for a variable V_p/V_s ratio dependent on the hydrate saturation above the BSR (Figure 1). As was evident in the P-wave case, the variation of the V_p/V_s ratio with hydrate saturation has a strong effect on the offset dependence of the AVO function. When a constant V_p/V_s ratio is used (top), the absolute amplitude decrease with offset is accentuated. With a variable V_p/V_s ratio, this trend is reversed and absolute amplitudes increase with increased hydrate saturation. The strong sensitivity of converted shear wave amplitudes at offsets greater than 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 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 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 effect 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 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 13, bottom). The unstacked 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.

Conclusions:

The characteristics of RC and AVO responses of 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 is sufficient. For hydrated sediments above the BSR, we modify the simple time-term averaging technique (Pearson et al., 1986) to incorporate V_p/V_s ratio effects shown to exist in ice saturated permafrost soils by Zimmerman and King, 1986. AVO

responses are controlled mainly by the Poisson'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 for 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 than 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 V_p/V_s 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.

In the future, finite difference modelling techniques can be used to explain the blanking phenomenon associated with several gas hydrate deposits. With this numerical technique the reduction of reflectivity in seismic data from gas hydrate saturated marine sediments can be modelled to help further constrain hydrate saturation levels.

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

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

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

Figure 4. Effects of Poisson'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.

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.

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 V_p/V_s ratio.

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.

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. 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) V_p/V_s ratio models.

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.

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). AVO function for BSR is shown on bottom (no divergence correction applied).

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