Rock modeling and seismic attribute identification of the gas hydrate stability zone in New Zealand

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Summary:

This study aims to improve the imaging and detection of gas hydrate stability zones, particularly in regions that lack the presence of a Bottom Simulating Reflector (BSR) in the seismic data. Rock physics modeling techniques and a variety of seismic attribute studies have been performed in two New Zealand petroleum basins. Initial results demonstrate that far offset seismic data is critical in improving the imaging of the base of the gas hydrate stability zone.

Introduction:

A gas hydrate is solid ice that has gas molecules trapped inside of a lattice structure of water molecules. They are stable in low temperature and high pressure environments, and therefore are found only in two environments – under permafrost and in the shallow subsurface of the deepwater. Hydrates are most commonly identified in seismic data by the occurrence of a Bottom Simulating Reflector (BSR). At the base of the gas hydrate stability zone (GHSZ) there is a sharp decrease in acoustic impedance, which gives rise to this bottom simulating reflector which parallels the seafloor due to the pressure and temperature requirements for gas hydrate stability. It has been observed that BSRs are not always present in seismic data in areas where gas hydrates are present. To this extent, an improved understanding of the expected seismic response to the presence of gas hydrates is needed.

The Pegasus Basin, located southeast of the north island of New Zealand (Figure 1), yields gas hydrates and exhibits a clear BSR through most, but not all of the basin. The methods presented here aim to further investigate the seismic response of gas hydrates, namely through identifying regions of acoustic blanking, attenuation, and changes in the amplitude versus angle (AVA) response.

Acoustic blanking is a seismically transparent response at a depth/time interval above the BSR. Shipley et al. (1979) and Ojha and Sain (2009) have observed lower impedance values directly above the BSR indicative of acoustic blanking. Additionally, within this hydrate stability zone, Guerin et al. (1999) have demonstrated that hydrate-bearing sediments attenuate the seismic signal in the Outer Blake Ridge. Furthermore, in regions with a continuous BSR, Ecker et al. (1998), observed an increase of absolute amplitude with offset.

A variety of seismic attributes such as reflection strength, interval velocity analysis, and instantaneous frequency have demonstrated moderate success in validating the presence of a BSR (e.g. Lee and Dillon, 2001; Taylor et al., 2000; Berndt et al., 2004; Ojha and Sain, 2009). Although, most of these studies rely on the identification of an amplitude anomaly or frequency changes in regions that have free gas trapped beneath the base of the GHSZ, and have limited success in regions with a weak, discontinuous or non-existent BSR.

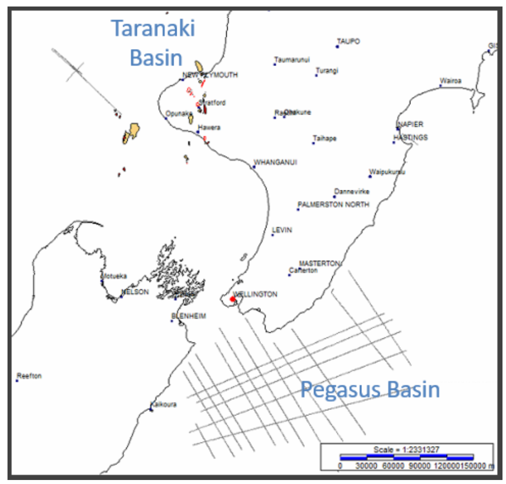

Figure 1: New Zealand study area, showing the location of 2D lines in the Pegasus Basin, as well as selected 2D lines in the Taranaki Basin. Producing petroleum fields in this resion are also denoted by yellow and red polygons.

Rock Physics Modeling Method:

The rock physics framework for the rock model was set up to represent lithologies as expected in the Pegasus Basin, although no exploration wells have been drilled there to date. It is expected that the hydrates are forming in clastic and highly unconsolidated lithologies, a soft-sand elastic medium model for unconsolidated sediments was used, as introduced by Dvorkin and Nur (1996). This model assumes that pore reduction is due to the introduction of non-cementing particles.

When introducing gas hydrates into the clastic rock framework there are two models that have been proposed.

In the first case, the hydrate acts as part of the mineral matrix, as shown in Figure 2 where the purple hydrates fill in the pore space and act as part of the clastic rock matrix. In the second model, hydrates fill in the pore space and act as part of the pore fluid.

The hydrate pore fluid model has been negated in recent years by well data that demonstrated that hydrates increase both P and S velocities (Helgerund et al., 1999; Sakai, 1999, Dvorkin et al., 2003), which would not be observed if they were not being incorporated into the rock matrix.

Moving forward under the concept that hydrates act on the rock matrix, varying hydrate saturations can be inserted into the pore space. The model then assumes that the hydrates are then incorporated into the rock matrix, resulting in a decrease of remaining pore space. Within this new system, the program then recalculated the effective elastic moduli and density of the new dry rock from using Hill's equations (Mavko et al., 2009), and Gassmann's equations (Gassmann, 1951) to incorporate fluids into the dry rock framework.

This 1D rock physics model where hydrates act on the rock matrix allows for varying the input parameters such as porosity, formation thickness, hydrate saturation, Vshale, Vquartz and recalculate the elastic parameters to output Vsh, Vs, Vp, porosity and density. The output can then be loaded into any petrophysical software to perform fluid substitutions and AVA analysis. Figure 2 shows a 4-layer model (shale with hydrate, sand with hydrate, reservoir sand, and shale), and the resultant fluid substitution with brine. In cases where the reservoir sand contains hydrocarbon, larger amplitude responses are clearly seen. The brine case results demonstrate the weak response at the BSR, as shown in the pink box. Farther offset angles are needed to image the BSR with brine present in the reservoir. Full stack seismic data will obscure evidence of the base of the GHSZ.

The rock physics modeling also demonstrates amplitude blanking in the GHSZ, as compared to beneath the BSR. Additional modeling also shows that a weak BSR can still be expected in primarily shale-rich lithologies of this high-porosity and unconsolidated sediment region of the Pegasus Basin.

Pegasus Basin 2D Seismic Data:

The Pegasus Basin wide-angle, multichannel seismic 2D profiles were collected in 2009. Figure 3 shows a portion of the 2D Line #19 of the full stack data through the Pegasus Basin. The Pegasus Basin lies between the Chatham Rise to the south, and the Opouawe Bank to the north. The Hikarungi channel can be seen in the Pegasus Basin. A high-amplitude BSR is observable throughout most of the basin, and is particularly strong beneath the Hikarungi channel and to the northwest near the Opouawe Bank. But, the BSR is discontinuous in several areas as noted by Griffin et al (2015) and highlighted by the green box in Figure 3. In this area the base of the GHSZ is not observed in the seismic data, which could result in the interpretation of gas hydrates lacking in this area.

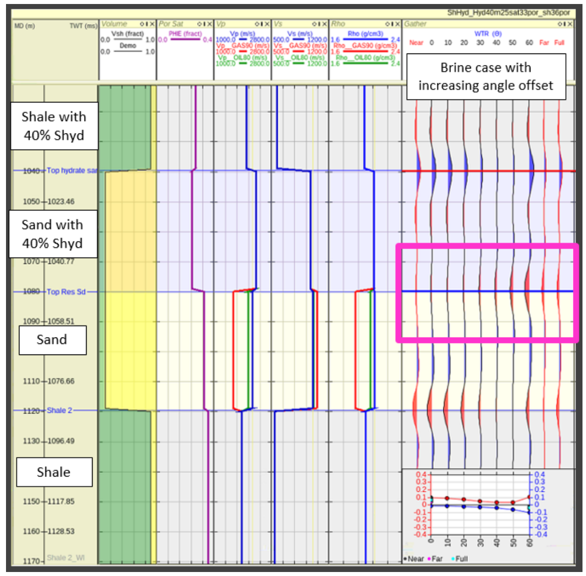

Figure 2: 4-layer rock model with amplitude vs. angle offset responses shown for a brine case. The amplitude response expected at the base of the GHSZ in a brine staurated reservoir sand is best observed at far angles.

Based on the rock physics model, the far angle stacks were analyzed and compared to the near, mid, and full stacks. Figure 4 shows a zoomed-in image of the far-stack seismic data in the green boxed region of Figure 3. In this image the high amplitude BSR likely related to free gas existing in the more quartz-rich sediments near the Hikarungi is seen to the southwest. Northwards, a stronger trough, mapped in red, appears in the region of the previously discontinuous BSR as shown in Figure 3. This presumed reflection at the base of the GHSZ runs parallel to the local stratigraphy making a clear determination of its physical cause difficult to determine. To this extent, Figure 5 displays a perpendicularly trending 2D Line #06 that cuts through this region of the discontinuous BSR. Again, a high amplitude BSR is seen beneath the Hikarungi channel where free gas is presumably being trapped beneath the GHSZ. But, the orientation of Line #06 allows the clear imaging of the BSR in the far stack data as it can be observed cross-cutting the stratigraphy, albeit with a fairly weak amplitude response.

Shipley et al. (1979), and Ojha and Sain (2009) observe amplitude blanking above the BSR, possibly where the GHSZ exists. Following the methods from Ojha and Sain (2009), we calculate the absolute reflectance as

$$A_i(dB) = 20 \log_{10} |(A_i/A_0)| \qquad (1)$$

Attribute identification of gas hydrates

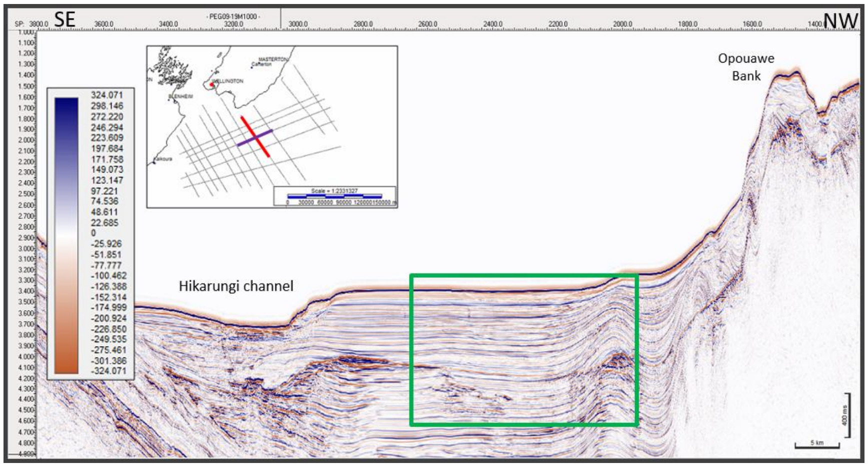

Figure 3: Pegasus Basin 2D full stack Line #19. Location map shows Line 19 location in red, and Line 06 location in purple. The green box highlights the region where the BSR at the base of the GHSZ is transparent.

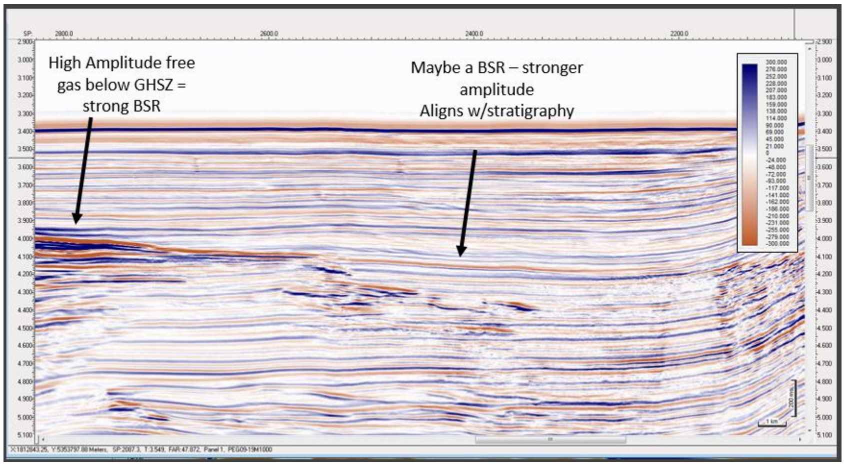

Figure 4: Pegasus Basin 2D far stack Line #19, zoomed into green box shown in Figure 3. Bottom simulating reflector is clear on the left of the seimic line where free gas is being trapped. A stronger amplitude is observed as compared to the full stack data in central region.

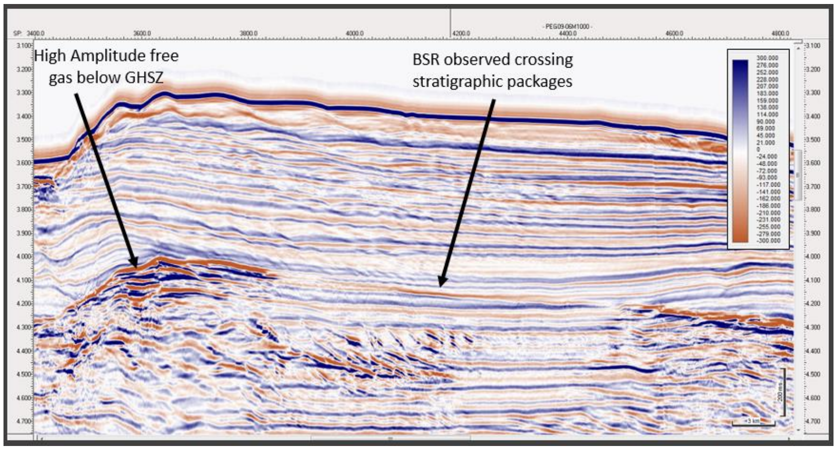

Figure 5: Pegasus Basin 2D far stack Line #06, location shown on basemap in Figure 3. Bottom simulating reflector clearly observed throughout this section as it cross cuts the stratigraphy.

where A_i is the amplitude at the sample point and A_0 is the reference amplitude. This is then plotted against time. The amplitudes being studied in the Pegasus Basin must be datumed and scaled in regards to the reference amplitude in order to accurately observe the blanking phenomena. A quick calculation of the reflectance across the BSR is shown in Figure 6. A_0 is not scaled to A_i, therefore anomalies are more prone to influence from differing lithologies. The initial study suggests that the zone of amplitude blanking is imaged.

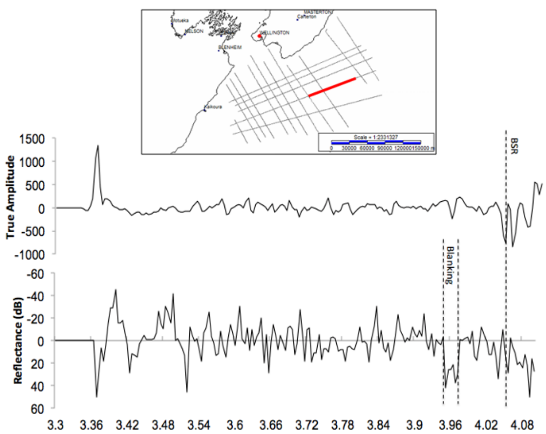

Figure 6: Initial calculated relectance values in the region of the GHSZ for Pegasus Line #08 shown as the red line in map on top of figure. The BSR and interpreted amplitude blanking zone are identified with dashed lines. A_0 was calculated at SP 3660, and A_i was calculated at SP 3172.

Within the GHSZ, Guerin et al. (1999) have demonstrated that hydrate-bearing sediments attenuate the seismic signal in the Outer Blake Ridge, and further attenuation by hydrates has been observed in the Mallik region (Wood et al., 2000). Helgerud et al. (1999) observed a higher attenuation in shear waves than in compressional waves. Should this hold true, the attenuation will be stronger on the far-angle stacks where the true amplitude trace will be more representative of the shear wave. In order to study the attenuation, wavelets are extracted from a moving time-space window along multiple traces. From each wavelet, the frequency is plotted to demonstrate changes in frequency that could be caused by attenuation within the GHSZ.

Li et al. (2016) use skewness and kurtosis to observe anomalies where attenuation exists in hydrocarbon-bearing sediments. Their method is applied within the Pegasus Basin in an attempt to investigate attenuation in the seismic data. Skewness and kurtosis were calculated along separate traces in time to observe any anomalies across the BSR in areas where the BSR is not easily observed. Higher values of these attributes are expected where attenuation is present. Initial results show that results across the traces are not consistent, yet, local maxima are observed just above the BSR. Further investigation is being performed to complete the analysis.

Taranaki Basin:

The methods that were successful in discriminating and identifying the weak acoustic impedance contrast of the base of the GHSZ in the Pegasus Basin were then applied to several 2D lines from the HOKI survey in the Taranaki Basin (Figure 1). This region was hypothesized to contain significant accumulations of gas hydrates by Kroeger et al. (2017). Unfortunately, seismic analysis has not been able to reveal the presence of a GHSZ in the seismic data through the aforementioned AVA techniques, or through the identification of amplitude blanking. Several frequency attributes have been applied in the attempt to detect the attenuation of the seismic frequency by hydrates, but have been unsuccessful thus far in the Taranaki Basin.

Conclusions:

This method of combining rock physics with seismic allows the reduction of exploration risks through the more accurate prediction of porosities and lithologies in the GHSZ, as well as identify previous unmapped gas hydrates in the subsurface.

The initial steps of creating an empirical rock physics model allows a more thorough understanding of the subsurface GHSZ response on seismic data. The rock modeling conclusions allow for a more directed analysis in improving the imaging techniques that can be used for detecting gas hydrates with seismic attributes in regions with a non-existent, weak, or discontinuous BSR. To this end, in the study area, several attributes are demonstrating an increased ability to identify previously 'unseen' BSRs at the base of the gas hydrate stability zone.

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