INVESTIGATION OF POSSIBLE SHALLOW GAS ACCUMULATIONS ASSOCIATED WITH POCKMARKS ON THE OTAGO SLOPE SOUTHEAST OF NEW ZEALAND

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SUMMARY

High-resolution 'boomer' seismic data, together with an industrial 3D seismic dataset indicate the possible presence of shallow gas in the vicinity of the Waitaki Canyon, SE of New Zealand's South Island. Crescent-shaped seafloor depressions are abundant on the marginal extent of the Otago canyon system in water depths between 500 and 1100 m. Fluids seeping through the seabed, potentially forming pockmarks, play a crucial role in seabed ecological systems and can be used to investigate the distribution of hydrocarbons in underlying geological units. Recently acquired 3D seismic data in the Canterbury frontier basin exhibit the first indications of shallow gas in the region. Two areas with shallow high-amplitude reversed phase reflections were identified and targeted for a high-resolution 2D seismic survey. The 2D data, acquired by the University of Otago in 2017, show reduced amplitudes beneath the bright spots (as also observed in the 3D data). Above the bright spots, bathymetry data show crescent-shaped seafloor depressions, which were most likely modified by northward flowing currents. Both recent and buried seafloor depressions along the shelf exhibit the same northward facing crescent form that we associate with water current modification. Water column imaging data reveal no evidence for present-day seepage of gas through the seabed. An ongoing programme of 2D seismic and bathymetry data collection is underway. High-density velocity analysis and amplitude variations with offset (AVO) will be assessed around the bright spots using several in- and crosslines from the 3D data.

Key words: Fluid migration, pockmarks, shallow gas, AVO, chimney

INTRODUCTION

Fluid transportation through focused flow systems is a widespread phenomenon in sedimentary basins. Migration processes, fluid pathways and accumulation areas play important roles in fossil energy exploration, hazard assessment, and environmental conservation (Anka et al., 2012). On the seafloor, circular depressions – often referred to as pockmarks due to their appearance in seafloor bathymetric imagery – can be indicative of underlying acoustically transparent fluid pathways (Berndt et al., 2003; Bünz et al., 2003; Hovland et al., 2005). These depressions are caused by the removal/suspension of seabed material by escaping fluids. Fluids and gases seeping through the seabed play a crucial role in seabed ecological systems and can be used to investigate the distribution of hydrocarbon reservoirs in the underlying geological units (Berndt, 2005). Since they are likely to emit greenhouse gases, such as methane, into the oceans and the atmosphere they may also contribute to climate change (Gay et al., 2007). Identifying paleo-environmental controls on petroleum migration pathways could not only help in analysing the role of thermogenic methane leakage into the atmos/hydrosphere and its impact on the Earth's paleo-climate, but also in de-risking exploration wells.

On seismic profiles, shallow gas can be indicated by features such as enhanced reflections, acoustic turbidity or acoustic blanking (Davis, 1992). While acoustic turbidity is caused by the scattering of acoustic energy and rather characterises finely disseminated gas within impervious sediments, enhanced reflections also called bright spots correspond to gas accumulations (Judd and Hovland, 1992). These bright spots exhibit a high-amplitude reversed-phase reflection (compared to the seafloor reflection), which corresponds to a substantial decrease in impedance due to free gas in the pore space. Since the recognition of bright spots can be subjective and formations of lignite, gravel or coal can have similar low impedances and are therefore able to create bright spots in seismic data, further seismic attributes are often used to verify gas occurrence (Judd and Hovland, 1992).

The study of velocity variations in the subsurface is one of the most powerful tools available in exploration geophysics (Batzle et al., 1999). Gassmann (1951) related the bulk modulus of a rock to its grain, pore, frame and fluid properties. The bulk modulus of a gas charged sediment is significantly lower compared to water or oil charged sediments, which results in relatively low seismic velocities.

Ostrander (1984) described the influence of the Poisson's ratio on the variation of the P-wave reflection coefficient with reflection angle. He discovered an abnormally low Poisson's ratio in high-porosity gas-bearing sands, which can result in an increase in reflected P-wave energy with increasing angle. Since then, amplitude versus offset (AVO) analysis has gained a lot of attention in exploration geophysics and the seismic effects of fluid variations are considered to form a direct hydrocarbon indicator (DHI). Especially in shallow unconsolidated sediment, fluid compressibility has a more significant effect on the whole rock compressibility which makes DHI identification more likely in shallower strata (Simm and Bacon, 2014).

Pockmarks are abundant on the slope of the Canterbury basin in water depths between 500 and 1100 m. They range in diameter from 20 to 700 m and exhibit a crescent form that aligns with the north-eastward flowing Southland Current. The pockmarks occur in patches that are mainly constrained to the crests between submarine canyons and gullies. Their positions on the seafloor between depths of 500 and 1100 m are consistent with the expected extent of the gas hydrate stability zone (GHSZ) in this region. This correlation led to the interpretation that gas hydrate dissociation and resulting venting are responsible for the pockmark formation (Davy et al., 2010). Multibeam and parasound water column investigations in 2012, 2013 and 2017 revealed no evidence of active seepage on the seafloor (Bialas et al., 2013; Schneider von Deimling and Hoffmann, 2012). Water samples collected in the vicinity of Waitaki canyon show no geochemical evidence of enhanced methane concentrations on the Otago margin (Hillman et al., 2015). Since no indications for shallow hydrocarbons were present, Hillman et al. (2015) concluded that groundwater flux was likely to be the dominant formation process for pockmarks on the Canterbury basin slope.

GEOLOGY

The eastern passive continental margin of New Zealand’s South Island began to rift from Antarctica at about 80 Ma (R. M. Carter, 1988; R.M. Carter, 1988). The margin has experienced one large-scale tectonically controlled transgression-regression cycle during the Cretaceous to Recent (Fulthorpe and Carter, 1989). Post rift subsidence resulted in a transgressional phase during Late Cretaceous that terminated during the Eocene when flooding of the land mass was at a maximum (Fleming, 1962). At the end of this phase, the reduced terrigenous influx resulted in the deposition of the Amuri Limestone, which terminates the mainly terrigenoclastic, transgressive Onekakara Group (Carter, 1985; Fulthorpe et al., 2011). The Marshall paraconformity separates the Onekakara Group from the blanket-like glauconitic and bioclastic sediments of the Kekenodon Group and is thought to represent the initiation of thermohaline circulation following the separation of Australia and Antarctica ~33.7 Ma (Fulthorpe et al., 2011, 2010). Increased

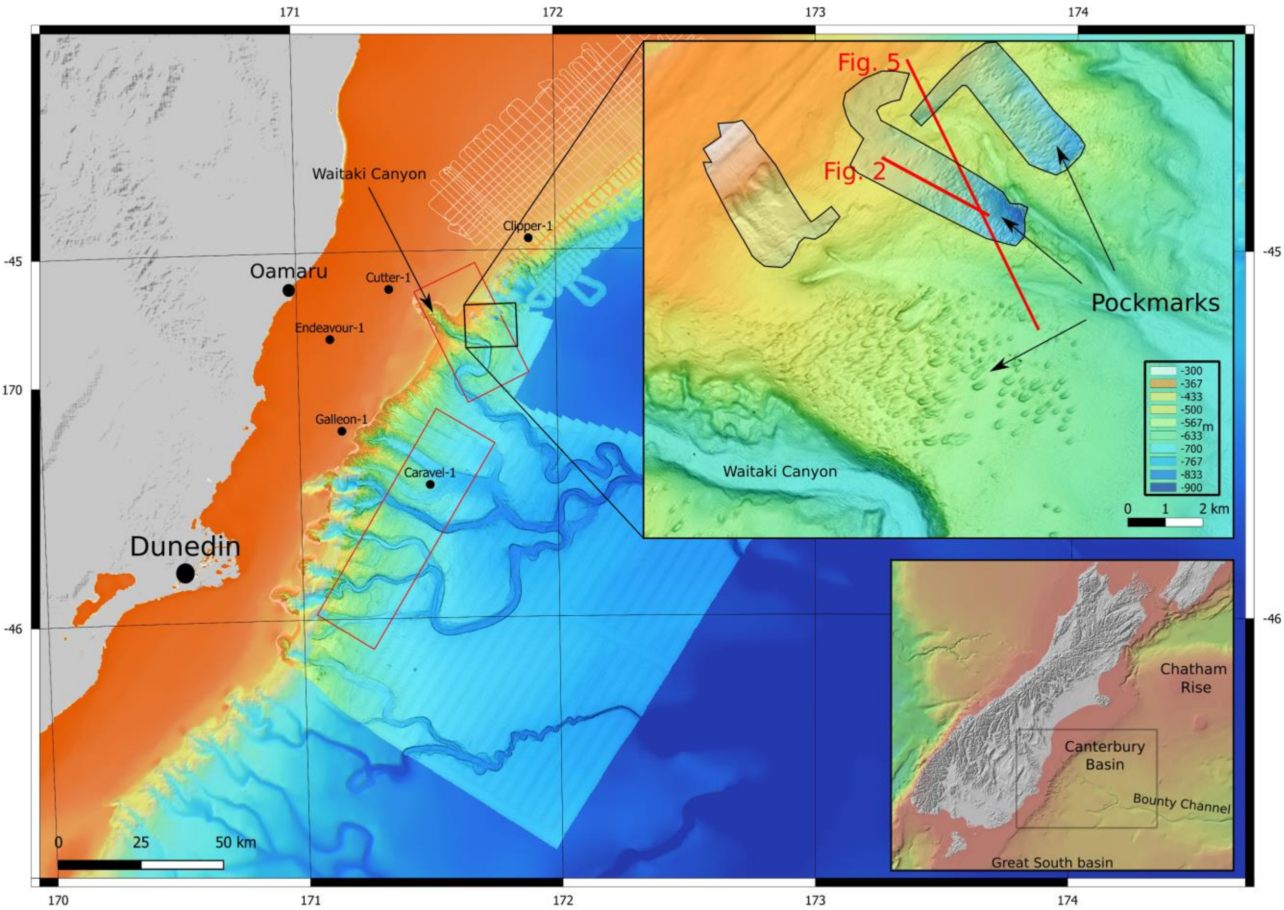

Figure 1: Bathymetric overview map of the Canterbury basin continental margin showing the two 3D datasets outlined in red and well locations used during this study. Lower right inset shows area of interest SE of New Zealand’s South Island. Upper right inset shows the location of seismic profiles (red) and newly acquired high resolution multibeam bathymetry data (outlined in black) presented in this paper. The depth legend corresponds to the newly acquired data. Data sources: NIWA, 2012, 2016

sediment supply due to initiation of movement on the Alpine Fault and corresponding uplift of the Southern Alps induced a phase of regression in the region during late Oligocene to early Miocene (Carter and Norris, 1976; Fulthorpe and Carter, 1989). During this phase of regression, the prograding clinoforms of the Otaku Group were deposited. The late Oligocene to recent Otakou Group mainly consists of quartzose fine sand and terrigenous siltstone that builds the modern continental shelf (Carter et al., 1990, 1994). The presence of large sediment drifts in this Group suggests that deeper currents parallel to the northward flowing Southland Current existed and probably strengthened during glacial periods (Carter et al., 2004a, 2004b). The Subtropical Front, currently centred roughly on the slope of the margin, represents the mixing zone between warmer and saltier Subtropical Waters to the north and cooler and fresher Subantarctic Waters to the south. The drift deposits suggest both a strengthening of currents and a basinward migration of the Subtropical Front during glacial periods (Fulthorpe et al., 2010).

The present day continental margin along the SE coast of the South Island is characterized by a very variable shelf width of 10-90 km. The continental slope in this region is highly incised by several canyons and gullies, especially south of the Waitaki River (Figure 1). The basin covers an area of ~360,000 km^2; it is confined to the north by the Chatham Rise and in the south by the Great South basin. The sedimentary history of the basin has been greatly influenced by the uplift and erosion rates of the Southern Alps (Fulthorpe et al., 2010). Also, the drainage locations of rivers, ocean currents and relative sea-level change play important roles in understanding the complex sedimentary evolution in the region (Osterberg, 2006). Up to 6 km of sediments, ranging from Cretaceous to recent, make up the continental shelf and five exploration wells have been drilled offshore between 1970 and 2014 with shows and sub-commercial discoveries of hydrocarbons in at least four of those wells (Blanke, 2015; Uruski, 2010).

METHODS & RESULTS

Recent exploration efforts by the petroleum industry in this region have involved the collection of extensive 2-D and 3-D seismic datasets. We present shallow parts of a recently acquired 3D seismic dataset, covering the Waitaki Canyon, that are complemented with high-resolution 2D seismic data acquired with the University of Otago's research vessel. We use additional targeted 2D seismic lines, in the form of CDP gathers, extracted from the 3D seismic dataset, for seismic amplitude and velocity estimations. To better constrain the pockmark distribution and their potential connection to subsurface fluid flow, we acquired high-resolution bathymetric data to supplement the seismic images (Figure 1).

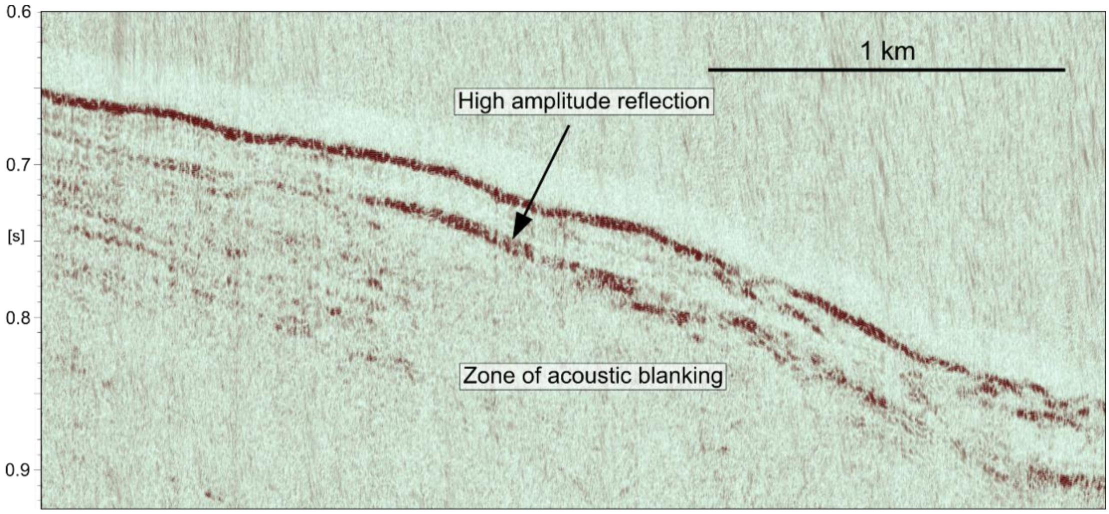

Figure 2: High resolution boomer seismic profile showing an acoustically transparent zone beneath a high-amplitude reflection while subsurface reflections are visible further up dip. (Location of seismic profile is shown in Figure 1.)

The investigation of possible fluid migration pathways connected to the pockmarks in near-surface seismic data revealed two shallow bright spots below pockmark patches on crests between gullies northeast of the Waitaki Canyon (Figure 5). The bright spots appear immediately beneath the seafloor and exhibit several strong reversed phase reflections with an acoustic curtain occurring beneath them. Detailed high-frequency boomer seismic data targeted on the bright spots reveal an acoustically blanked zone beneath a high amplitude reflection (Figure 2). Seafloor parallel subsurface reflections are visible further up the slope that disappear further out on the crest. A close line spacing allows us to accurately map out the acoustically transparent zone in the seismic data.

Semblance calculations based on velocity analysis are a standard procedure undertaken during long-offset seismic processing to determine accurate normal moveout (NMO) corrections and better constraint migration. Velocities are often picked manually in CDP gathers spaced at relatively sparse intervals along the profile and interpolated in between. For the highest spatial resolution, the semblance of every CDP can be picked. We adopted an automated high-density semblance based velocity analysis (details described by Crutchley et al. (2016) and Fraser et al. (2016)) implemented in the GLOBE Claritas seismic processing software to explore acoustic velocity behaviour in the vicinity of the shallow bright spots. For highest possible vertical resolution, the semblance along a 2D seismic line extracted from the 3D dataset was picked in 20 ms windows. The 8-km-long streamer used during acquisition of the 3D dataset provides more than sufficient offsets for this study.

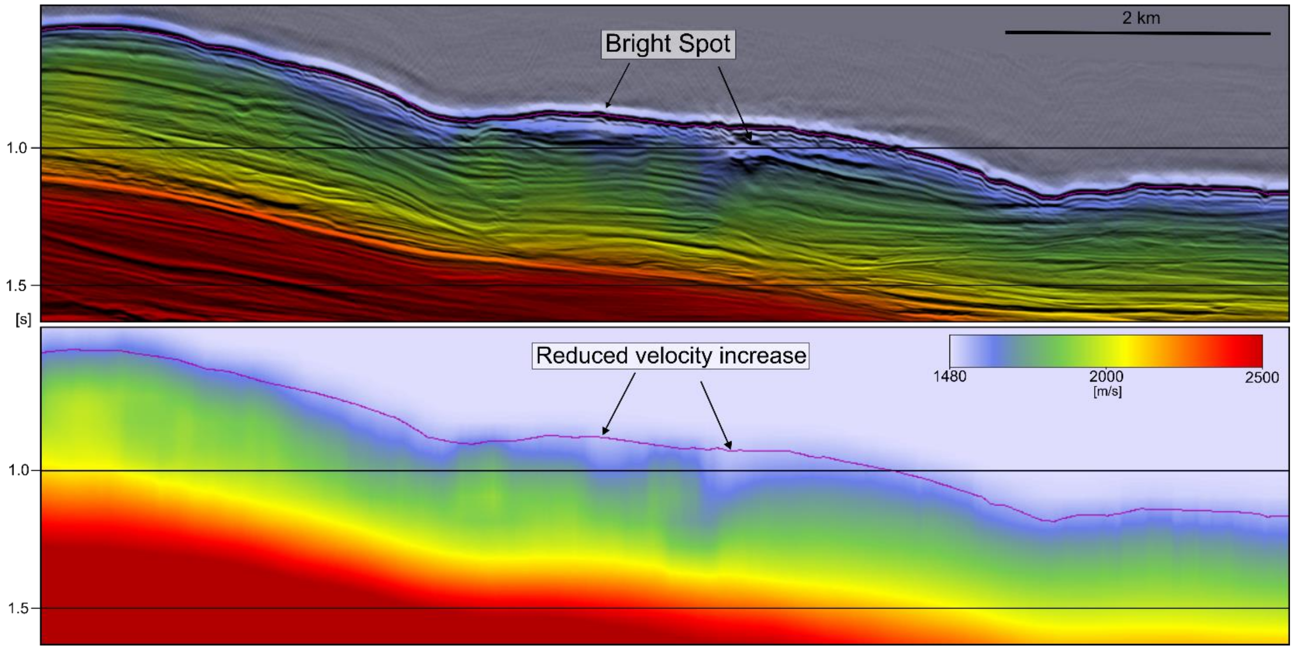

Figure 3: High-density velocity analysis of petroleum industry 2D seismic data shows patches of reduced velocity increase with depth near bright spots.

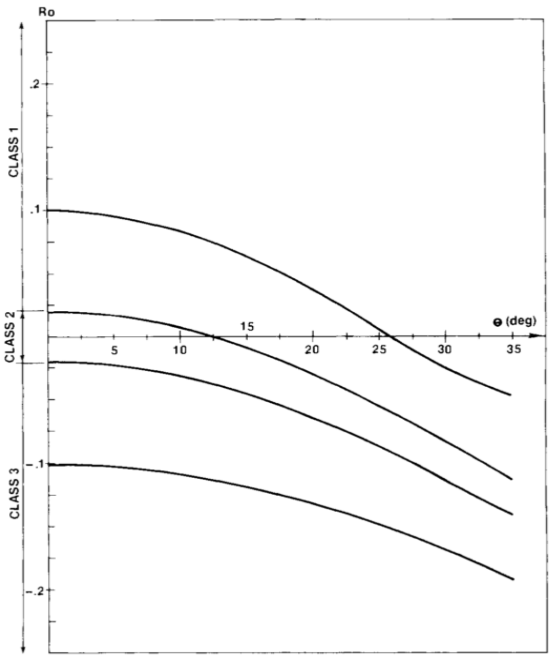

Figure 4: P-Wave reflection coefficient variations with angle for a shale-gas sand interface with different intercept values. The Poisson's ratio and density of the shale are 0.38 and 2.4 g/cm3 respectively and 0.15 and 2.0 g/cm3 for the gas sands. Three different AVO classes were observed. Adopted from Rutherford and Williams (1989)

The increase of velocity with depth around the bright spots is significantly reduced in all the 2D seismic lines processed (**Figure 3**). A distinct high velocity layer (>3500 m/s) corresponds to the most prominent reflection in the seismic sections associated with the Oligocene Marshall Paraconformity and the overlying greensands and limestones of the Kekenodon Group.

To further examine the nature of the low-velocity shallow bright spots we explored the amplitude variation with angle in the 2D seismic profiles. We used several AVO techniques including AVO gradient analysis, AVO classification by crossplotting and AVO attribute analysis. Rutherford and Williams (1989) introduced 3 classes of amplitude variation with offsets for shale-gas sand interfaces (Figure 4). Castagna and Swan (1997) proposed a fourth AVO class that represents low impedance gas sands with a negative zero offset reflection coefficient and decreasing amplitude with offset. They demonstrated how effective amplitude variations with angle can be examined by crossplotting the zero incidence reflection coefficient (intercept) and the corresponding variation of the coefficient with increasing angle (gradient). They additionally recommended the analysis of all AVO responses in the context of an expected background trend/brine saturated rock/mudrock line.

Figure 5 shows the product of intercept (A) and gradient (B). Since the product is defined as (-A)*(-B)=+AB=(+A)*(+B), positive values highlight AVO Class 3 as well as positive intercept amplitudes with a positive gradient. The bright spots exhibit a prominent AVO anomaly that is associated with a positive AVO product. Beneath the bright spots a near vertical zone between 1.5 and 3 s TWT with an AVO product close to zero is observed. The "blanked out" zone is the result of fairly small intercept values rather than gradients. While the acoustic curtain in the seismic profile is visible up to 400 ms below the bright spots, the blanked out near vertical section in the AVO attribute reaches down roughly 3 s and terminates at a reflector that exhibits several mounded structures (Figure 5).

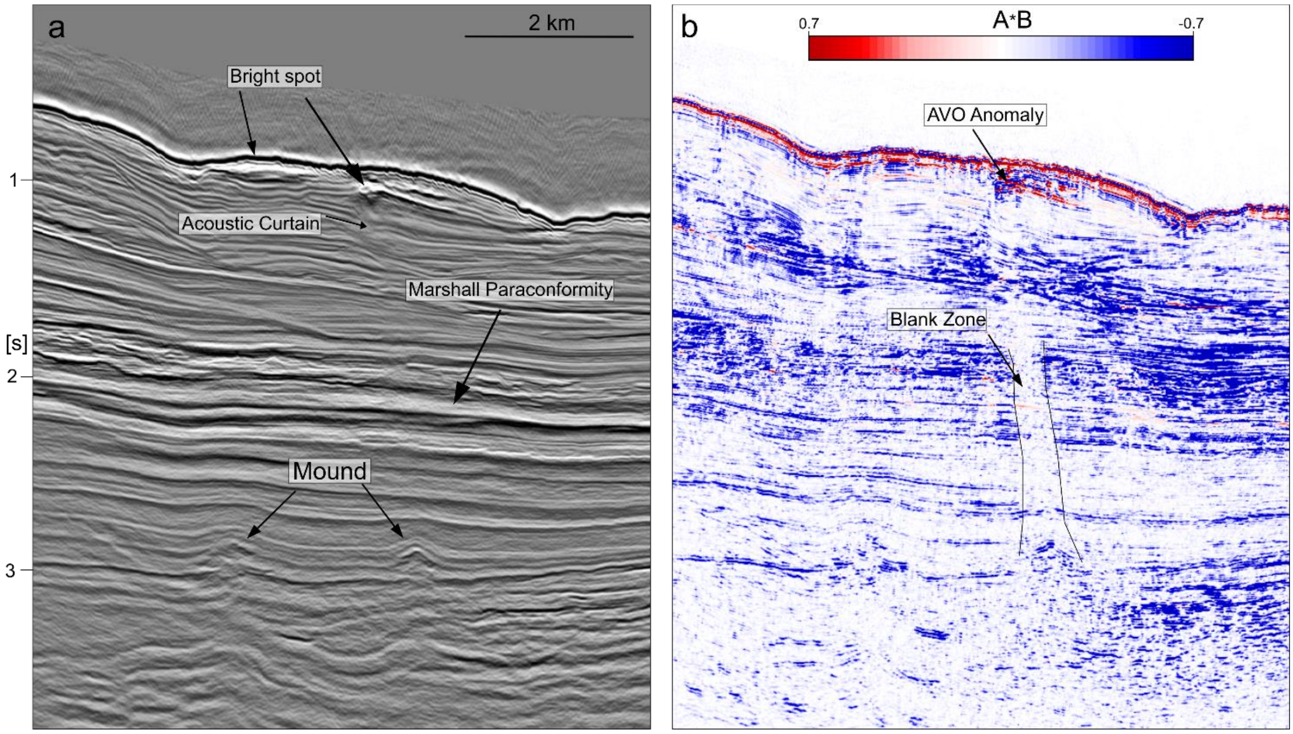

Figure 5: a) Seismic profile over bright spots showing an acoustic curtain beneath bright spots and mounded structures at ~3 s TWT. b) A corresponding AVO attribute volume showing the product of intercept and gradient indicating class 3 AVO responses in positive red colours. A near vertical blank zone connects shallow bright spots with a structurally deeper mound.

CONCLUSIONS

From the results presented we infer that gas actively accumulates – or at least has accumulated in the past – beneath the seafloor in the vicinity of the Waitaki Canyon. Reduced seismic amplitudes beneath a high-amplitude reflector observed in high-resolution boomer seismic data indicate that free gas does not reach the seafloor but rather seems to be trapped in a layer 8 to 50 m below the seafloor. No active seepage could be observed in water column imaging data above the shallow gas. The reduced velocity signal in gas bearing sediments is not as prominent as we had expected. We infer that the vertical resolution of the semblance based velocity analysis is not sufficient to resolve the low velocities directly below the seafloor. Velocities are normally picked in intervals significantly less than 100 ms because too closely spaced picks can produce unstable interval velocity calculations.

AVO analysis has not only revealed AVO Class 3 behaviour of the shallow bright spots but also a near vertical transparent zone in the AVO product volumes. In the seismic image, the acoustic curtain beneath the free gas could be indicative of local destruction of sedimentary fabric by fast flowing fluid; however most reflections appear to be fairly continuous and not chaotic or disrupted. Nevertheless, we interpret these blanked zones as recent or ancient focused fluid migration pathways feeding the shallow pockets beneath the seafloor, with only minor modification of the original sedimentary fabric. A mounded structure at ~3 s TWT seems to be the feeding location for the vertical structure. Several other mounded structures occur on the same horizon but do not show the characteristic blanked, near vertical zone above them in the AVO attribute. This either indicates that no fluid migration occurs (or has occurred) above other mounds, or an inactive stage of fluid migration pathways. The undisturbed horizons in areas where fluids are or have been migrating show that ancient fluid migration might be undetected in the seismic data.

The fact that no active seepage is observed and no enhanced methane concentrations are measured in the vicinity of shallow gas accumulations might be the result of the current sea level high stand and corresponding high pressure that keeps the gases in place. A self-sealing mechanism of marine seeps introduced by Hovland (2002) also provides explanations for no active venting. He proposed that bacterial mats form on the seafloor sealing the vents. With these bacterial mats anoxic conditions can occur even in permeable high porosity sediments if light hydrocarbons start to oxidize over time. Ultimately, the production of carbonate cement permanently plugs focused fluid migration pathways and prevents active venting.

We assume that the accumulation of shallow gas near the seafloor implies that no active groundwater flux through the seabed occurs in the vicinity of the gas forming pockmarks. Research on the timing of gas accumulation and migration will further constrain the pockmark formation processes.

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