Temporal variability of gas seeps offshore New Zealand: Multi-frequency geoacoustic imaging of the Wairarapa area, Hikurangi margin

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A B S T R A C T

Cold seeps on Opouawe Bank, situated in around 1000 m water depth on the Hikurangi Margin offshore North Island, New Zealand, were investigated using multibeam bathymetry, 75 and 410 kHz sidescan sonar imagery, and 2–8 kHz Chirp sediment echosounder data. Towed video camera observations allowed ground-truthing the various geoacoustic data. At least eleven different seep locations displaying a range of seep activity were identified in the study area. The study area consists of an elongated, northward-widening ridge that is part of the accretionary Hikurangi Margin and is well separated from direct terrigenous input by margin channels surrounding the ridge. The geoacoustic signature of individual cold-seep sites ranged from smooth areas with slightly elevated backscatter intensity resulting from high gas content or the presence of near-surface gas hydrates, to rough areas with widespread patches of carbonates at the seafloor. Five cold seeps also show indications for active gas emissions in the form of acoustic plumes in the water column. Repeated sidescan sonar imagery of the plumes indicates they are highly variable in intensity and direction in the water column, probably reflecting the control of gas emission by tides and currents. Although gas emission appears strongly focused in the Wairarapa area, the actual extents of the cold seep structures are much wider in the subsurface as is shown by sediment echosounder profiles, where large gas fronts were observed.

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1. Introduction

Although the existence of cold seeps on continental margins has been known for more than 2 decades (Paull et al., 1984; Hovland and Judd, 1988; Langseth et al., 1988) the full extent and widespread nature of the phenomenon has only been appreciated in recent years (Egorov et al., 2003; Naudts et al., 2006; Sahling et al., 2008). Systematic high-resolution geoacoustic mapping of continental margins has revealed an increasing number of cold seeps worldwide. The morphology and nature of the cold seeps, however, varies significantly from one area to another reflecting different mechanisms of fluid generation and different tectonic or stratigraphic frameworks for creating fluid pathways (Johnson et al., 2003; Huguen et al., 2004; Sager et al., 2004; Naudts et al., 2006; Klaucke et al., 2008). In addition to morphological differences and processes recent studies (Tryon et al., 1999; Leifer et al., 2004; Greinert et al., 2006) revealed a high temporal variability of the intensity of methane emissions at cold seeps.

Full appreciation of the temporal variability can only be achieved with long-term observation of the cold seeps, but this approach is spatially limited. Repeated geoacoustic mapping of the seafloor only provides snapshots of the seafloor but to a certain degree allows evaluating temporal variability. However, the actual sonar frequency used for mapping the seafloor largely determines the accuracy with which individual seeps can be imaged (Klaucke et al., 2008) and can complicate the integration of geoacoustic data and ground-truthing information. In addition to sidescan, sediment echosounder data allow imaging of subsurface features and by inference, extend estimates of seep activity to longer time frames.

In the present paper we present high and very high resolution sidescan sonar data from the continental margin of the Wairarapa area situated offshore of the southeastern margin of North Island, New Zealand (Fig. 1). During RV SONNE cruise SO191 the area was mapped repeatedly with 75 and 410 kHz sidescan sonar (Bialas et al., 2007) although with different acquisition geometry due to changing towfish altitude. The sidescan sonar data combined with video observations revealed several previously undocumented gas emissions into the water column and authigenic carbonate precipitates at the seafloor. The repeated measurements indicate high temporal variability of gas bubble streams at the sites but also suggest a strong influence of acquisition geometry of the sidescan sonar system on imaging small-scale features on the seafloor. Such bubble streams generate specific, elongate backscatter returns in the water column on echosounder and sidescan sonar data and are known as “flares” (Avdeyko et al., 1984; Obzhirov...
et al., 1989). Sediment echosounder data indicate that the extent of gas-charged sediments in the subsurface is much larger than suggested by the recorded water column flare. This suggests a strong control of sedimentary facies on the accumulation of gas in the subsurface and of erosion on the location of cold seeps.

2. Data and methods

Sidescan sonar data were obtained using the DTS-1 system, operated by IFM-GEOMAR, which consists of a modified EdgeTech dual-frequency sidescan sonar with integrated sub-bottom profiler. The DTS-1 operates with chirp signals of 75 and 410 kHz centre frequencies providing a range of 750 and 150 m, respectively. Nominal across-range resolution for these frequencies is 5.6 and 1.8 cm, respectively. However, along-track resolution is much less and determined by survey speed (2.5–3.0 knots). The 75 kHz sidescan sonar data were processed for 1.0 m pixel size whereas the 410 kHz data allowed processing for 0.25 m pixel size, in both cases slightly overestimating the along-track resolution. Unfortunately, the electronics of the 410 kHz transducers had some problems during the survey and only half of the usual swath width provided useful backscatter data or backscatter intensities are not consistent between the port and starboard channels. The DTS-1 also hosts a subbottom profiler operating with a 2–10 kHz, 20 ms pulse length signal and provide subbottom penetration of up to 40 m. Navigation of the towfish was provided by an USBL system with an accuracy of 1% of the range, but during the initial survey of the Wairarapa area (Fig. 2) the system was not operational and towfish navigation was calculated using a layback method that takes into account the survey speed. The sidescan sonar data of this survey, during which average towfish altitude was 100 m above the seafloor, were processed using the PRISM software package (Fig. 2; Le Bas et al., 1995). During subsequent surveys designed for 410 kHz sidescan sonar data the instrument was towed 15–20 m above the seafloor. 75 kHz sidescan sonar data at 750 m range were acquired simultaneously but this acquisition geometry resulted in predominantly lateral, low angle sonar incidence. These latter data were processed using the software package Carabes developed by IFREMER. Processing of the subbottom profiler data was carried out with in-house scripts based on GMT and Seismic UNIX.

Ground-truthing of the geoacoustic data in form of photographic observations of the seabed was made using two towed camera platforms: NIWA’s Deep Towed Imaging system (DTIS) during TAN0616, and the Ocean Floor Observation System (OFOS) of RV SONNE during SO191. Both platforms incorporate vertically orientated colour digital video cameras and digital stills cameras, with paired parallel red lasers for image scale. Camera platforms were towed at approximately 2 m above the seabed at speeds <0.5 m s⁻¹ and recorded continuous video footage with digital still images taken at 15 s intervals throughout each deployment. The seabed position of the camera was tracked by means of ultra short baseline (USBL) acoustic positioning systems (Simrad HPR and IXSEA Posidonia). Transects were planned, and spatially referenced observations were recorded in real time, by means of the Ocean Floor Observation Protocol (OFOP–developed by J. Greinert) software which allows ship and camera positions to be monitored against georeferenced acoustic images of the seabed. Post-voyage video analyses were also run using OFOP on smoothed (21 point running average) USBL position data splined at 1 s intervals.
Observations were allocated to 3 substratum categories and one biota category (Table 1). Because the primary aim of the surveys was to identify areas of active methane seepage and authigenic carbonate rock formation, substratum observation categories were designed to highlight the occurrence of seep-associated features. Seep sites targeted in the Wairarapa region were characterised by isolated areas of carbonate rock structures in extensive plains of soft, muddy sediments. Therefore, a simplified hierarchy of substratum descriptors was used in which the highest level category "seabed_a" distinguished simply between muddy sediments and the presence of any hard substrata, without attempting to estimate relative coverage of different substrata. Thus, an observation of "Carbonate" within the category "seabed_a" indicates only that rock of some sort was visible, even if it constituted only a small proportion of the field of view, whereas "Muddy sediments" indicates 100% cover by soft sediments. Subsequent categories refine this coarse level distinction and are set out in Table 1.

3. Geological setting and previous work

The Wairarapa area (Fig. 1) is part of the active Hikurangi Margin where the Pacific Plate subducts obliquely underneath New Zealand's North Island forming a series of accretionary ridges (Barnes and Mercier de Lépinay, 1997; Barnes et al., 2010-this volume). One of these ridges, the Opouawe Bank culminating in about 900 m water depth, is the focus of this paper and is well separated from the continental slope by erosive canyons (Fig. 1). Recent sediments on Opouawe Bank are therefore likely interbedded hemipelagic and turbidity current overspill deposits (Lewis et al., 1998). Sedimentation rates are high and include significant degrees of organic matter and coarse clastic sediments (Carter, 1992); although, sediment supply was much larger during Pleistocene times. The Hikurangi Trough bordering Opouawe Bank to the south corresponds to the deep-sea trench formed by the subduction of the Pacific Plate beneath the Australian Plate. The trench lies in only 3000 m water depth because the subducting oceanic plate is anomalously thick due to the presence of the Hikurangi Plateau. The Hikurangi Margin shows widespread indications of gas charged sediments and the presence of gas hydrates through the large distribution of bottom simulating reflectors (BSR; Katz, 1982; Townend, 1997; Henrys et al., 2003). The strength of the BSR varies significantly along the margin, which has been attributed to variable concentrations of gas hydrates in the sediments (Pecher and Henrys, 2003). However, the presence of gas and fluids is not limited to the subsurface as signs for ongoing active fluid venting...
have been found at several locations along the Hikurangi Margin including the Wairarapa area (Lewis and Marshall, 1996; Baco-Taylor et al., 2010-this volume). These signs include specific seep fauna and acoustic anomalies in echosounder and high-resolution seismic data.

4. Cold seeps in the Wairarapa area

High resolution (75 kHz) sidescan sonar data collected over Opouawe Bank (Fig. 2) indicate eleven different cold seeps which we divide into two types: high backscatter intensity patches with apparent relief, and patches that appear as areas of moderate backscatter intensity but are smooth with no apparent relief. The seeps, many of which are firstly identified and described here, have been named after New Zealand birds.

4.1. Outcrops of authigenic carbonates

The majority of the seeps are characterised by patchy distribution of high backscatter intensity and associated small shadows (Fig. 2). These characteristics, indicating relief, are particularly apparent in the 75 kHz sidescan sonar data (Fig. 3). For these profiles fish altitude was on the order of 15–25 m resulting in mostly lateral ensonification, which is known to highlight small-scale relief (Augustin et al., 1996). Individual seeps are between 250 and 500 m in diameter, but are composed of various small blocks that are up to 25 m in diameter and sometimes surrounded by small depressions (Fig. 4). These blocks have been identified as being carbonate precipitates (Fig. 5). Relief of the depressions and blocks cannot be accurately determined but does not exceed a few metres at any of the sites (Fig. 6). The cold seeps either show a distinct clustering of individual carbonate blocks with some surrounding outliers (e.g. North Tower (Fig. 4), Tui (Fig. 7)) or they are composed of more individual, loosely distributed blocks (e.g. Pukeko or Rororo seeps, Fig. 3). The latter case is likely the result of sediment burial, but could also be the effect of lower fluid venting activity. Video observations at North Tower (Fig. 4) and Tui (Fig. 7) seeps shows several central areas composed of chemoherm structures or similar massive carbonate precipitates that are surrounded by broken fragments of carbonates. In subbottom profiler records, the seep facies is characterised by high amplitude reflections with diffuse subbottom reflections (e.g. Piwakawaka and North Tower seeps; Fig. 6). The lateral extent of the seeps in the subsurface significantly exceeds the area of high backscatter intensity on sidescan sonar records and intercalates laterally with well-stratified deposits that probably represent turbidites. The impression of dispersed accumulations of gas and authigenic carbonates, characteristic of Pukeko seep, continues in the subsurface, where high amplitude reflections are less continuous than for North Tower or Piwakawaka seeps. Similar, dome-like structures with patchy high amplitude reflections are also present in the subsurface further to the southwest of Piwakawaka seep. This seep does not have a surface expression.

4.2. High backscatter areas without relief

Two cold seeps (Takahe and Takapu) show a different backscatter pattern. These seeps are characterised by relatively uniform medium backscatter intensity with no shadows that would indicate relief (Fig. 2). Both have a roughly ellipsoidal outline and are not identifiable on very high-resolution 410 kHz sidescan sonar data. Coring on Takahe revealed the presence of massive gas hydrate layers at approximately 2 m depth below seafloor (Matthias Haedckel, personal communication). The expected attenuation coefficient for 75 kHz signals (Stoll, 1985) makes signal penetration of up to 2 m rather unlikely. On the other hand, empirical data using the DTS-1 system have shown similar signal penetration (Klaucke et al., 2008) and the capability of imaging buried gas hydrates (Haedckel et al., 2008). Takahe seep is about 200 m across, both at the surface and in 25 m subbottom depth (Fig. 6). A widening of typical seep facies at depth, as for the other seeps on Opouawe Bank, is not observed.

4.3. Active gas emissions

Several of the cold seeps on Opouawe Bank (Pukeko, North Tower, South Tower, Takahe and Tui) show acoustic indications for active gas emission despite the area lying within the zone of gas hydrate stability. These acoustic indications include backscatter anomalies in the water column visible in the raw 75 kHz sidescan sonar data, which are, however, much smaller than those encountered elsewhere (e.g. eastern Black Sea; Klaucke et al., 2005), as well as more or less linear features on processed sidescan images obtained with low tow velocity (Figs. 3 and 4). Only Tui seep shows evidence of multiple gas flares that were active simultaneously. Repetitive sidescan sonar profiles, although with different acquisition geometries, indicate strong temporal variations of these flares. Four sidescan sonar profiles over North Tower seep only showed the presence of one flare emanating from the edge of the central high relief area during the last of the four crossings (Fig. 4). At Pukeko seep (Fig. 3) a large flare is present during all crossings (except for crossing C where the flare lies outside the profile area) but the direction of the flare changes. During crossings A and D the gas bubbles drift away in a southwesterly direction, while during crossing B they drift in a southerly direction. These differences are not the result of survey direction as crossing A and D were run in opposite directions. The high backscatter intensity of the feature interpreted as a gas flare suggests a high density of gas bubbles and consequently a vigorous flare. However, during the initial survey of the area several weeks earlier, no flare is visible on sidescan sonar images of Pukeko seep (Fig. 2). Interestingly, this flare observed in February 2007 emanates from the seafloor in an area that lies outside the main seep as imaged by the sidescan sonar data. One crossing of Pukeko seep (Fig. 3A) also shows the presence of a much smaller flare right at the edge of the seep. This flare is no longer visible on subsequent crossings.

4.4. Distribution of cold seeps on Opouawe Bank

Most of the seeps on Opouawe Bank are located at its southwestern margin which appears to be strongly influenced by current erosion (Figs. 2 and 6). As gas accumulation in the Wairarapa area follows stratigraphic levels, seafloor erosion appears to favour the seafloor expression of the seep structures by exposing gas-charged layers. A structural control on the emplacement of the cold seeps is not apparent within the uppermost tens of metres of sediment. A second concentration of cold seeps is found at the northeastern summit of Opouawe Bank.
The occurrence of cold seeps at the shallowest points of submarine structures is a common phenomenon and has been explained by a reduced hydraulic head at these locations (Tryon and Brown, 2001; Teichert et al., 2003; Sager et al., 2004).

5. Discussion

The Wairarapa area shows clear indications of an active hydrological system but several questions have to be addressed before any conclusions about the significance of the fluid flow pattern can be drawn, especially concerning the completeness of the inventory, the prevailing processes governing fluid seepage and their temporal variability.

The total of eleven cold seeps identified on 75 kHz sidescan sonar data is in apparent contradiction to 28 seeps identified on 2D multichannel seismic data (Netzeband et al., 2010-this volume). Sidescan sonar data provide a complete inventory of the surface expression of cold seeps and penetrate only for a few metres as a
maximum. Multichannel seismic data, on the other hand, have a vertical resolution of worse than 5–10 m. Sedimentation rates on Opouawe Bank are not known but its proximity to active turbidite channels suggests that they most likely exceed the average value of 0.4 mm/y for the Hikurangi margin (Townend, 1997). The observed mismatch in the number of seeps clearly underlines the transient nature of cold seeps at the seafloor, as sedimentation rates in excess of 2 mm/y result in cold seeps that are inactive for 1000 y being no longer visible in 75 kHz sidescan sonar data. Netzeband et al. (2010-this volume) also made a case for a two-stage hydrological system with initial gas accumulation in the subsurface and subsequent release of the gas along special pathways. Geoacoustic data and especially subbottom profiler records also show signs for seep locations emanating from a much wider gas front as shallow (about 50 m) subbottom depth (Fig. 6), but clear age relationships of individual seeps are not possible. Cold seeps without relief and patchy carbonate distribution such as Pukeko or Riroriro are not necessarily younger than those presenting high internal relief such as North and South Tower or Tui. Active gas emission is present for both types, although the most vigorous seeps appear to be outside of major carbonate accumulation. This however, could also be an acoustic

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Successive 75 kHz profiles over North Tower seep with high backscatter intensity in light tones. Profiles were obtained with 20 m towfish altitude over a period of 22 h. Note the presence of a possible gas flare at time of crossing D.}
\end{figure}
imaging effect with gas flares being more difficult to detect against a high backscatter background compared to a low backscatter background. With methane gas emanating at Opouawe Bank being of a shallow, biogenic origin (M. Haeckel, pers. comm.) gas accumulation and subsequent gas release at the seafloor appears to be mainly controlled by sedimentary processes. Coarse-grained turbidites constitute ideal reservoir facies favouring the accumulation of gas. Bedding-parallel gas fronts as shown in the vicinity of cold seeps (Fig. 6) support this interpretation. On the other hand, the location of cold seeps at the seafloor could be mainly determined by seafloor erosion that exposes these gas fronts and facilitates lateral migration of biogenic methane gas.

Gas and fluid escape at cold seeps is not a continuous process but exhibits strong variability at different time scales (Tryon et al., 1999; MacDonald et al., 2000; Leifer et al., 2004; MacDonald et al., 2005; Greinert et al., 2006). To date only little is known about amplitudes and time-scales of these variations. Tryon et al. (1999) observed low to medium variations in flow activity on Hydrate Ridge (offshore Oregon) with both outflow of gas and influx of seawater suggesting a highly dynamic, coupled hydrological system in a geological setting that is quite similar to Opouawe Bank. The same authors also showed a correlation between fluid flux and tides (Tryon and Brown, 2001). Greinert et al. (2006) documented the changes in intensity including total absence of acoustic flares over a mud volcano in the Black Sea. To date only few time-series studies of the temporal variability of seeps (e.g. Leifer et al., 2004; Greinert, 2008; Solomon et al., 2008) showing significant variations in gas fluxes on the scales of seconds to hours. Based on these observations Leifer et al. (2004) proposed a model for seep environments analogous to an electrical circuit with transistors and capacitors that fill up before releasing new bubbles. A similar behaviour can be expected for the seeps on Opouawe Bank with gas hydrates probably playing the role of capacitor. Such behaviour has been recently documented in the Gulf of Mexico, where over a period of more than 1 yr significant changes in both intensity and direction of fluid flow has been monitored and attributed to varying degrees of gas hydrate precipitation and dissolution (Solomon et al., 2008). Whether the distribution of massive carbonate pavements and chemosmmer structures at the scale of individual seeps reflect individual centres of fluid escape that are active more or less simultaneously, or whether they represent areas of shifting activity cannot be told with the present dataset. However, different degrees of backscatter between the central seep areas and some outliers such as are seen at North Tower seep (Fig. 6) on one hand, and the presence of seep facies in the very shallow subsurface next to active seeps on the other hand, suggests rapidly shifting areas of active fluid venting. The time scale of this process is not known, but carbonate crusts form at the scale of hundreds of years (Luff et al., 2004) and large chemosmmer structures appear to be active for thousands of years (Teichert et al., 2003). With total heights of the cold seep structures of several tens of metres we could speculate that they have been active for several tens of thousands of years (Liebetrau et al., 2008). While the lifetime of single seep locations is still not well constrained, fluid-venting at the Hikurangi margin is a long lasting phenomenon, as studies of fossil cold seeps in northern Wairarapa (onshore) suggest (Ledesert et al., 2003).

Accretionary margins commonly show the presence of gas hydrates and mud volcanoes in the margin wedge (Clift and Vannucchi, 2004). In contrast to the general rule, cold seeps on Opouawe bank lack indications for sediment remobilisation from depth and the wider area of the Wairarapa continental slope also lacks indications for mud volcanism. Mud volcanism has been reported from areas further to the North (Ridd, 1970; Pettinga, 2003). Fluid venting in the Wairarapa area is restricted to the circulation of methane rich fluids and their resulting bio-geochemical alterations at or near the seafloor. The methane is of biogenic origin and associated pore fluids do not show a signature for a deep source (M. Haeckel, pers. comm.). Cold seeps in the Wairarapa area in particular and the entire Hikurangi Margin in general consequently reflect processes of the overriding Australian Plate rather than
Fig. 6. 2–8 kHz subbottom profiler record crossing several seeps on southwestern Opouawe Bank seep. Older seep surfaces that are interpreted as carbonate crusts are visible in the subsurface beneath the seep and adjacent to it. For profile location refer to Figs. 1 and 2.
dewatering related to subduction processes as along erosive margins (Ranero et al., 2008). However, thrusting and the formation of accretionary ridges probably provide pathways and the driving force for fluid circulation. In this respect, the Hikurangi margin is quite similar to other accretionary margins such as the Cascadia Margin. On the other hand superficial data did not show evidence for faulting as likely fluid pathways but indicates a strong sedimentary control.

6. Conclusions

Sidescan sonar mapping of Opouawe Bank allowed imaging of eleven separate cold seep areas, which is significantly less than the number identified on seismic images from the same area (Netzeband et al., 2010-this volume)). Several seeps are actively but intermittently emitting gas bubbles into the water. Repeated passages of the sonar vehicle documented these changes on the scale of a few hours to several days. Gas emission, with probable intermediate storage of gas in gas hydrates together with authigenic carbonate precipitation are the dominant processes of fluid venting. Mobilisation of sediment in form of mud diapirism and mud volcanism is not present on Opouawe Bank and only plays a minor role at the Hikurangi margin.

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