Marine Geology 272 (2010) 49–58

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

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

Ingo Klaucke [a,*], Wilhelm Weinrebe [a], C. Joerg Petersen [a,1], David Bowden [b]

[a] Leibniz Institute of Marine Scienes, IFM-GEOMAR, Wischhofstr. 1-3, 24148 Kiel, Germany
[b] National Institute of Water and Atmospheric Research, Private Bag 14 901, Kilbirnie, Wellington, New Zealand

ARTICLE INFO

Article history:
Received 10 July 2008
Received in revised form 8 December 2008
Accepted 22 February 2009
Available online 10 March 2009

Keywords:
Hikurangi Margin
cold seeps
sidescan sonar
methane
gas bubbles
temporal variability
spatial variability

ABSTRACT

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.

© 2009 Elsevier B.V. All rights reserved.

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

* Corresponding author.
E-mail address: iklaucke@ifm-geomar.de (I. Klaucke).
[1] Now at: Department of Geology, University of Tromsø, Drammsveien 201, 9037 Tromsø, Norway.

0025-3227/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2009.02.009

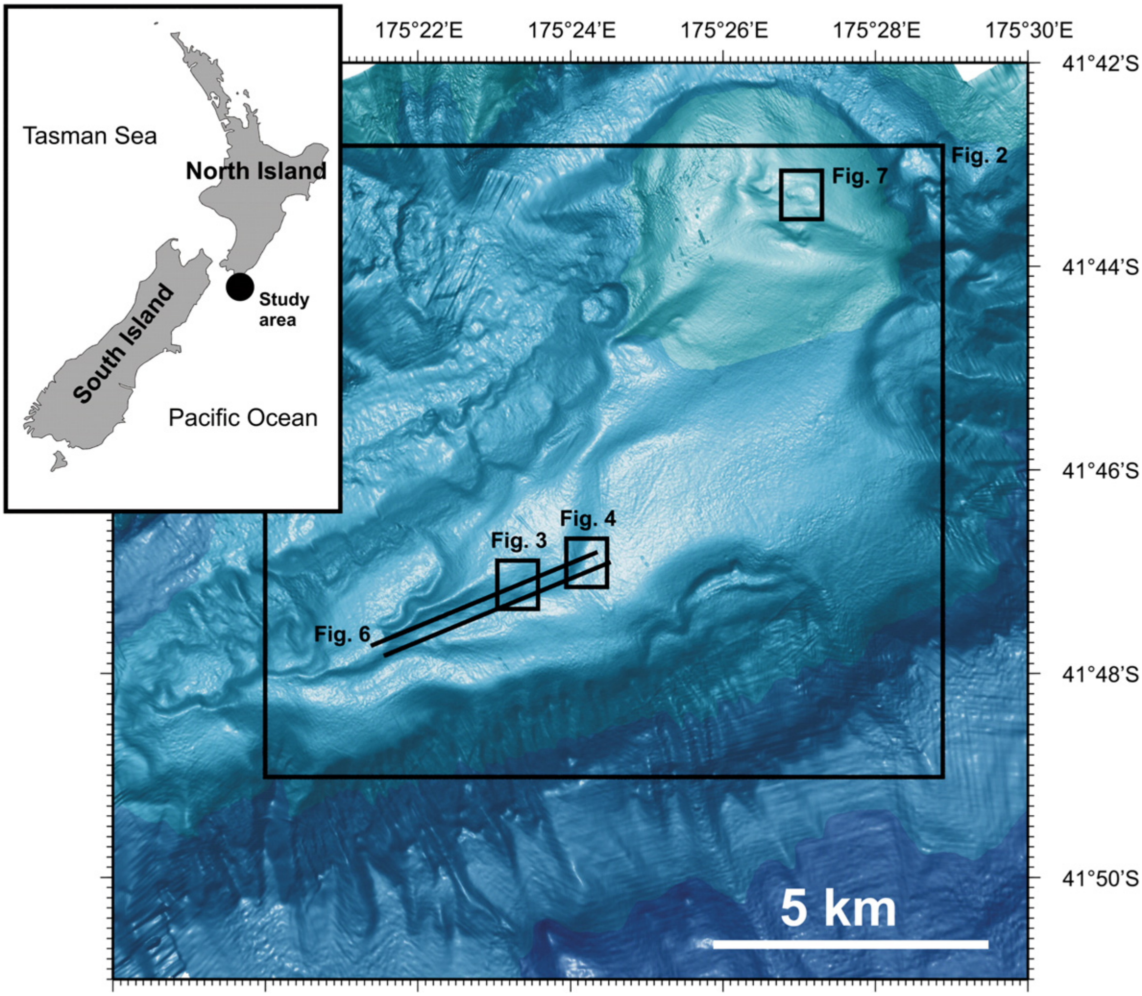

Fig. 1. Shaded bathymetric map of Opouawe Bank offshore Wairarapa showing the separation of the vent sites from the remainder of the slope by turbidite channels.

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 Caraibes 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.

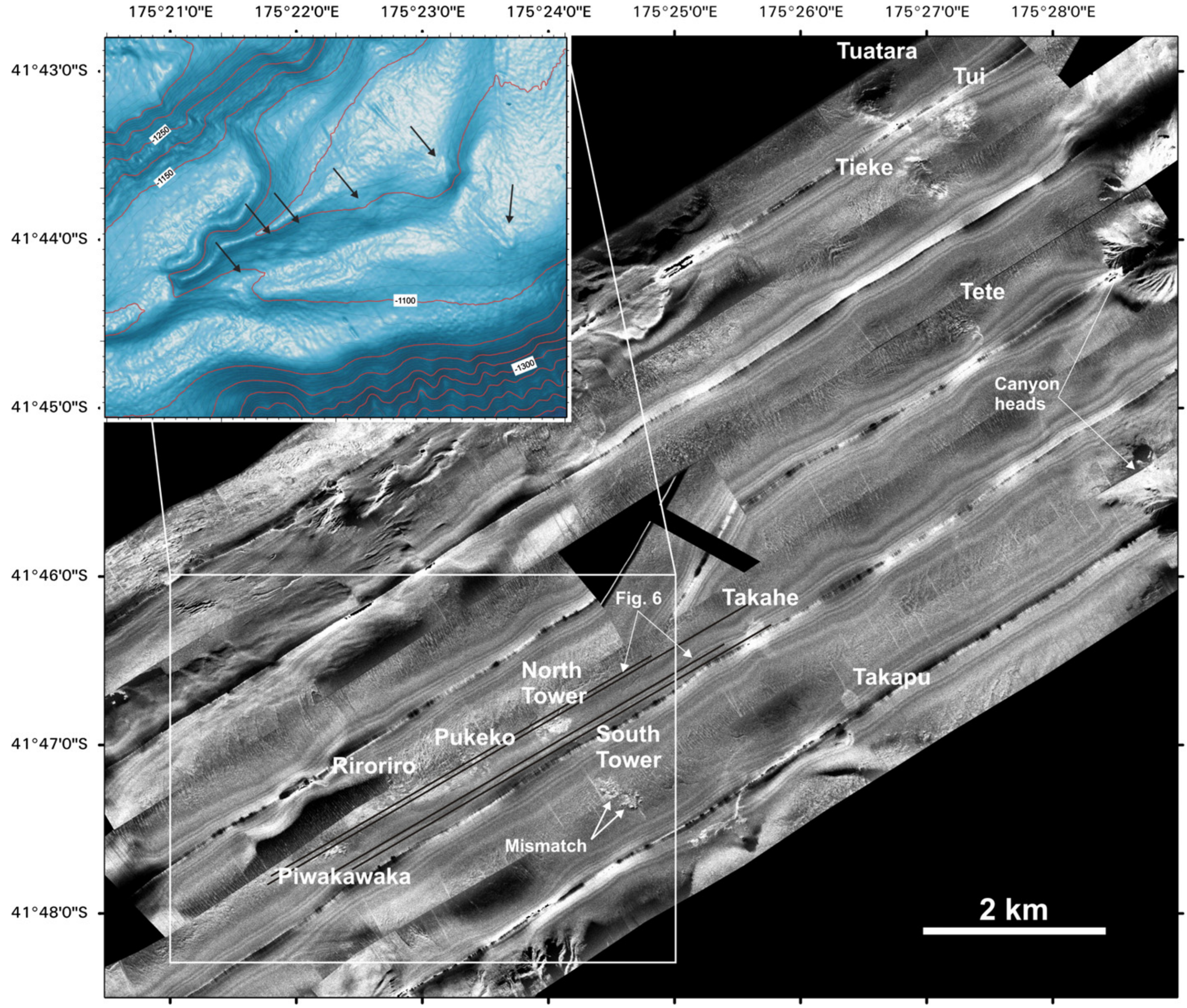

Fig. 2. Mosaic of 75 kHz sidescan sonar data of Opouawe Bank indicating eleven individual, named cold seeps. High backscatter intensity is shown in light tones. The insert shows detailed bathymetry of the southwestern margin of Opouawe Bank, where most cold seeps are located. Here seep locations are indicated by arrows.

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

Table 1
Video observations.

Category	Treatment	Observation	Description	Modifiers
Seabed_a	Fill down	Carbonate	Presence of any rock substratum	→Seabed_b →Relief,
		Muddy sediment	100% cover muddy sediments	
Seabed_b	Fill down	Outcrop	Continuous authigenic carbonate rock structures without chemosynthetic fauna	→Relief,
		Chemoherm	Continuous authigenic carbonate structures with live chemosynthetic fauna	→Relief,
		Boulders	Discrete pieces of carbonate rock >25 cm across visible above mud overlay	
		Cobbles	Discrete pieces of carbonate rock <25 cm across visible above mud overlay.	
Relief	Fill down	Low relief	Height estimated as <1 m	
		High relief	Height estimated as >1 m	
		Flat plates	Flat carbonate structures identified primarily by step edges	

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 Riroriro 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 Haeckel, 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 (Haeckel 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 towfish altitude (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

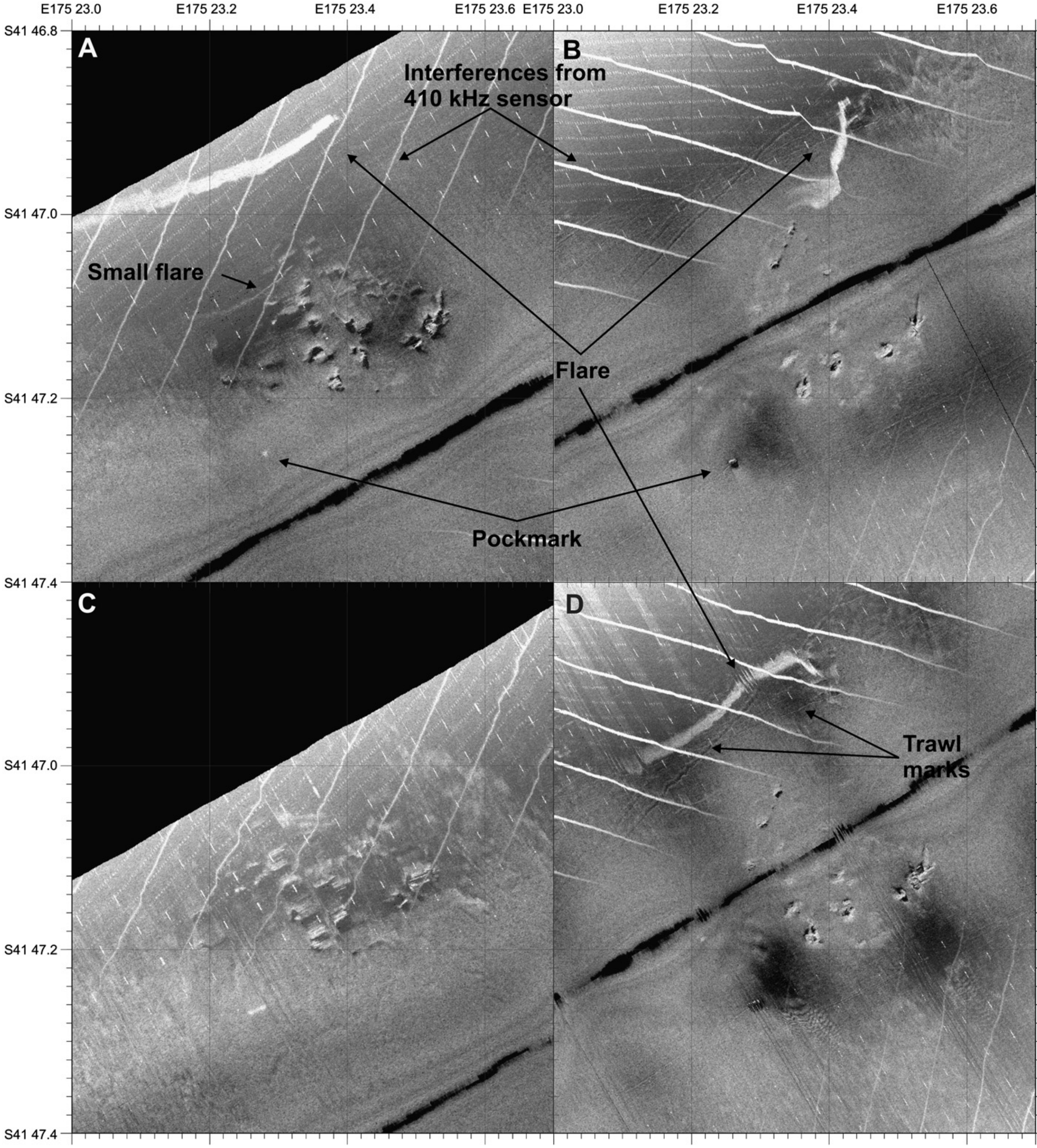

Fig. 3. Successive 75 kHz profiles over Pukeko seep with high backscatter intensity in light tones. Profiles were obtained with 20 m towfish altitude over a period of 22 h. Note the variable direction of the large gas flare and a small flare only visible on crossing A.

(Figs. 1 and 2). 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

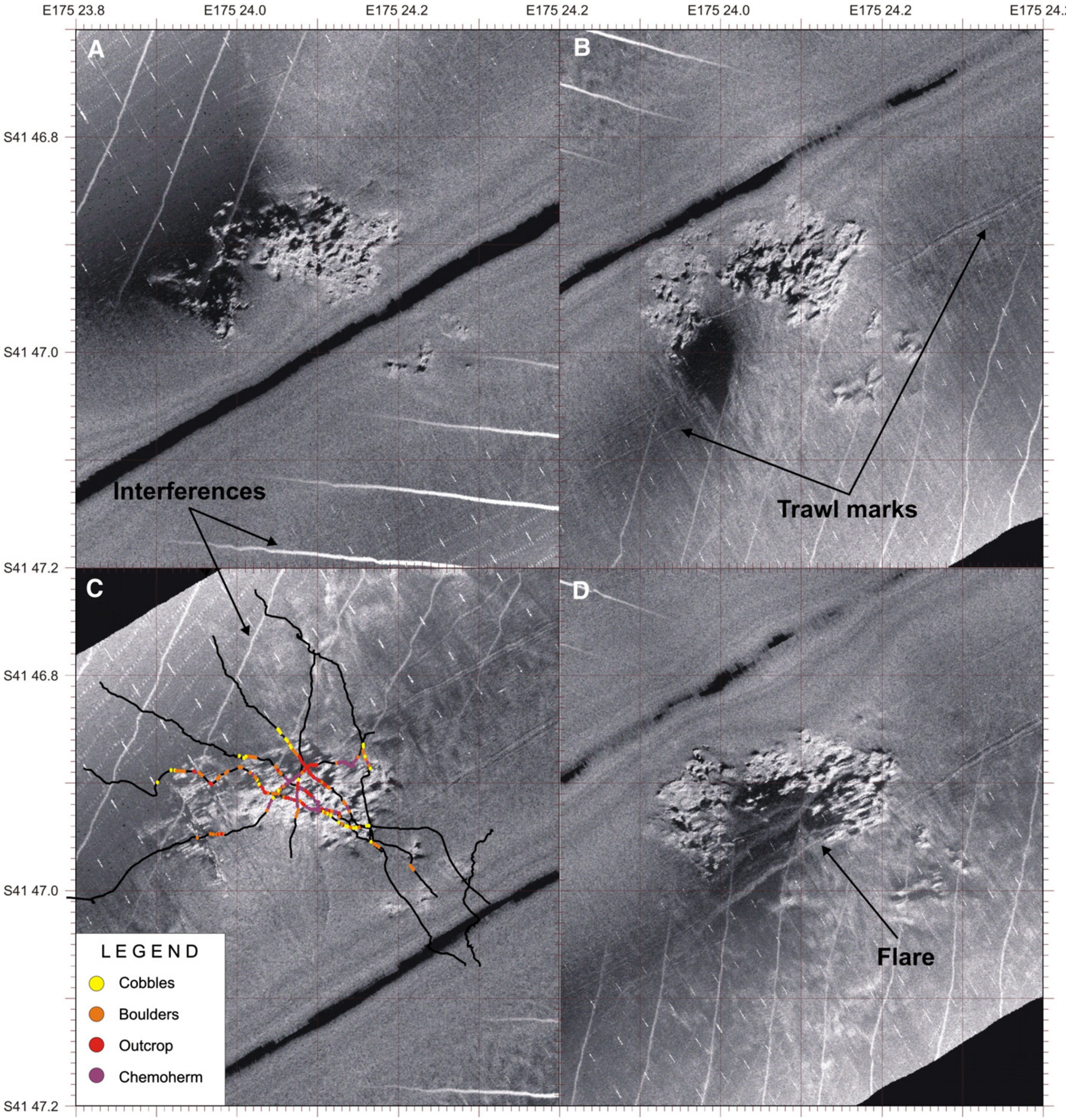

Fig. 4. Successive 75 kHz profiles over North Tower seep with high backscatter intensity in light tones. Profiles were obtained with 20 m towfish altitude over a period of 22 h. Note the presence of a possible gas flare at time of crossing D.

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

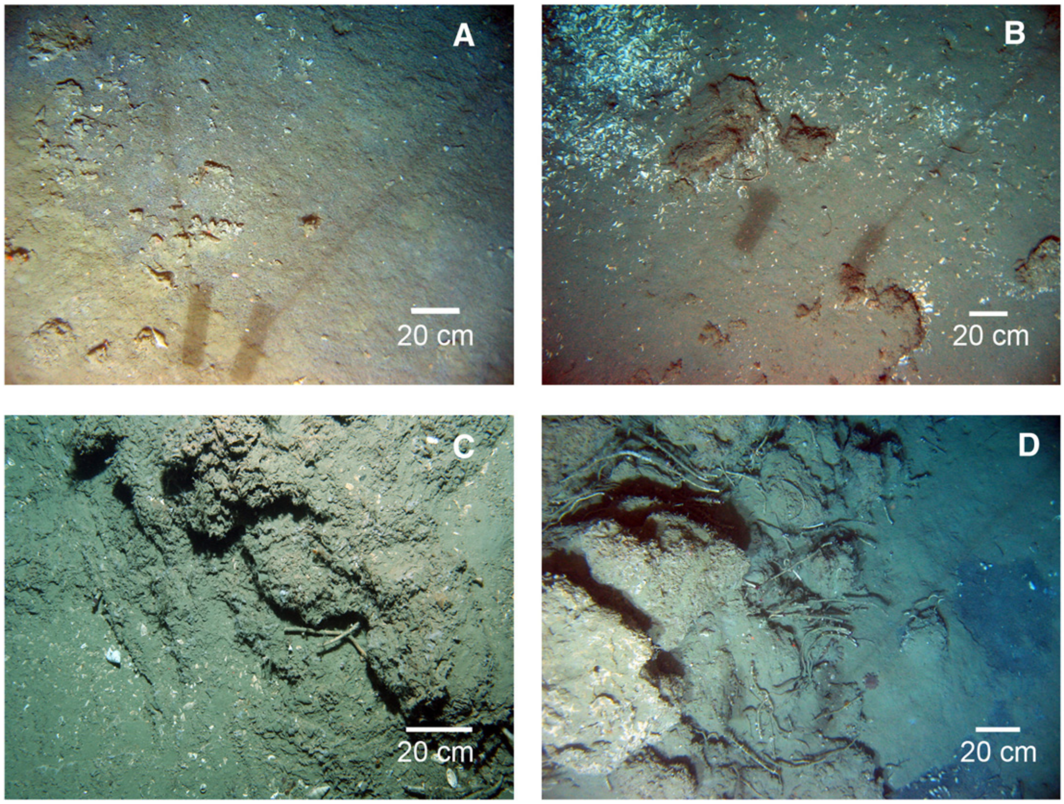

Fig. 5. Representative images illustrating the principal video substrata categories used: (A) "cobbles"; (B) "boulders"; (C) "outcrop"; (D) "chemoherm". *Calyptogena* sp. clam shells are visible in all images, especially (B), and sulphidic sediment and *Lamellibrachia* sp. tube worms are conspicuous in (D).

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 y 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 chemoherm 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 chemoherm 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

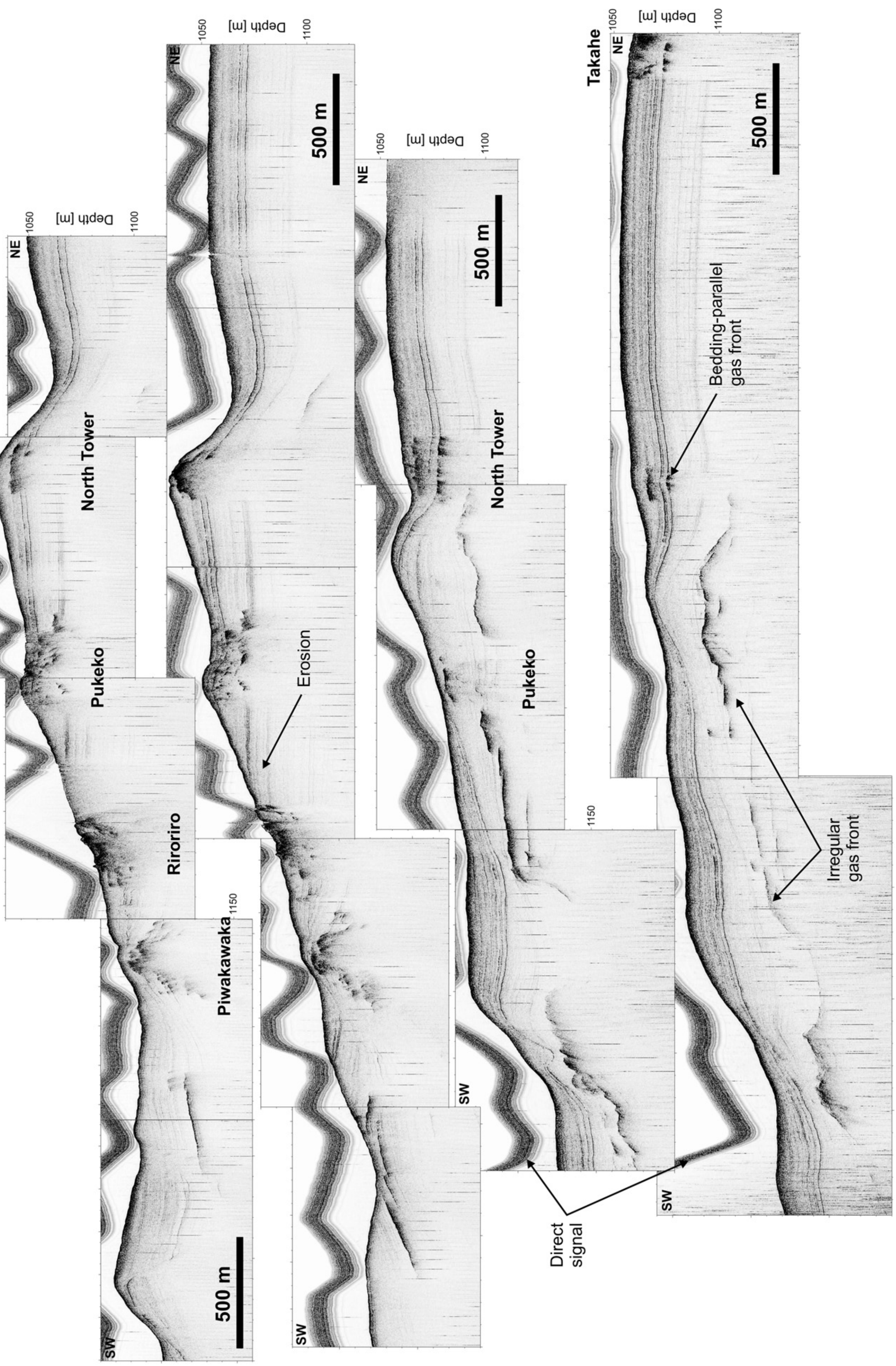

Fig. 6. 2–8 kHz subbottom profiler record crossing several seeps on southwestern Opouawe Bank seep. Older seep surfaces that are interpreted as carbonate crusts are visible in the subsurface beneath the seep and adjacent to it. For profile location refer to Figs. 1 and 2.

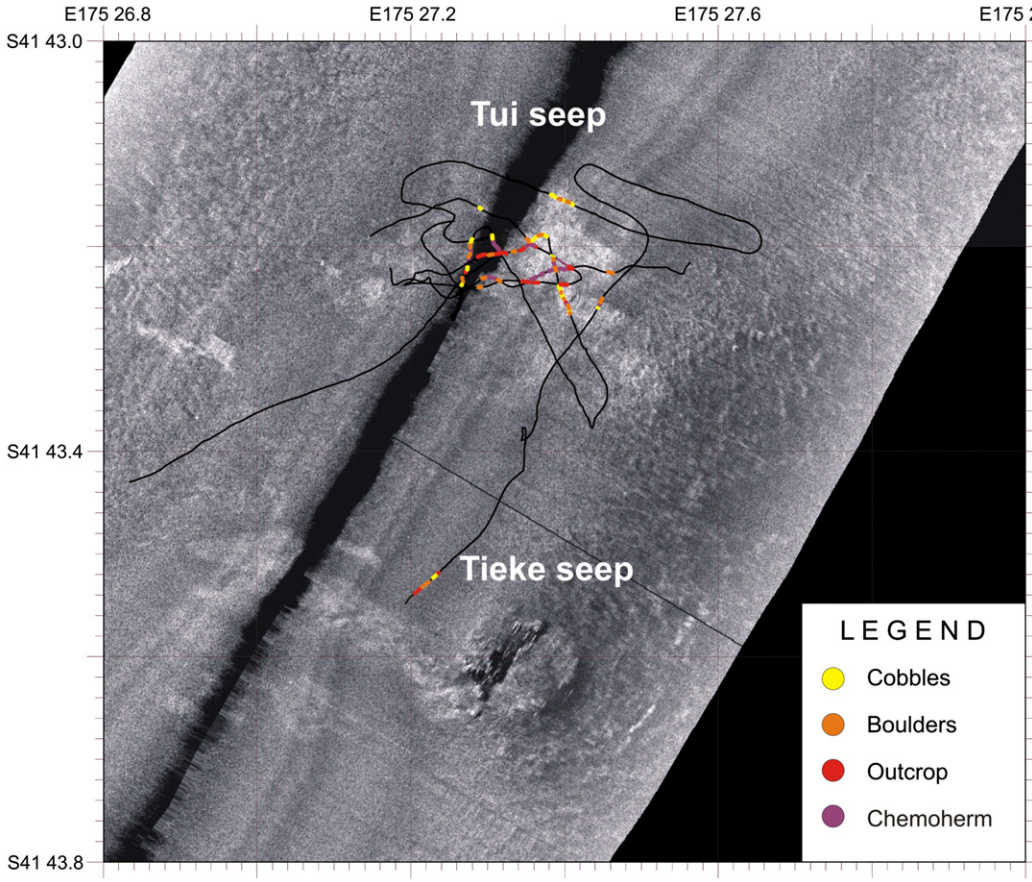

Fig. 7. 75 kHz sidescan sonar swath and geological interpretation based on video images for Tui seep. High backscatter is shown in light tones. Please note that video-tracks have been moved for "best fit" as USBL navigation was not available for sonar towfish navigation.

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.

Acknowledgements

We would like to thank masters, officers and crew of *RV Sonne* cruises SO191 for their professionalism at sea. The PIs of the RENEWZ research programme TAN0616 (Amy Baco-Taylor, Ashley Rowden, Lisa Levin, Craig Smith) are thanked for providing additional seafloor video data. This is contribution GEOTECH-1047 of the R&D-programme GEOTECHNOLOGIEN funded by the German Ministry of Education and Research (BMBF) and the German Research Foundation (DFG).

References

Augustin, J.M., Le Suavé, R., Lurton, X., Voisset, M., Dugelay, S., Satra, C., 1996. Contribution of the multibeam acoustic imagery to the exploration of the sea-bottom. Mar. Geophys. Res. 18, 459–486.
Avdeyko, G.P., Gavrilenko, G.M., Chertkova, L.V., Bondarenko, V.I., Rashidov, V.A., Guseva, V.I., Maltseva, V.I., Sazonov, A.P., 1984. Submarine gas-hydrothermal activity on the northwestern slope of Paramushir Island, Kuril Islands. Volkanologiya i Seismologiya 6, 66–81.
Baco-Taylor, A., Rowden, A.A., Levin, L.A., Smith, C.R., Bowden, D., 2010. Initial characterization of cold seep faunal communities on the New Zealand Margin. Mar. Geol. 272, 251–259 (this volume).
Barnes, P.M., Mercier de Lépinay, B., 1997. Rates and mechanics of rapid frontal accretion along the very obliquely convergent southern Hikurangi margin, New Zealand. J. Geophys. Res. 102, 24931–24952.
Barnes, P.M., Lamarche, G., Bialas, J., Henrys, S., Pecher, I., Netzeband, G.L., Greinert, J., Mountjoy, J., Pedley, K., Crutchley, G., 2010. Tectonic and geological framework for gas hydrates and cold seeps on the Hikurangi Subduction Margin, New Zealand. Mar. Geol. 272, 26–48 (this volume).
Bialas, J., Greinert, J., Linke, P., Pfannkuche, O. (Eds.), 2007. FS Sonne Fahrtbericht/Cruise report SO191 New Vents. IFM-GEOMAR Report, vol. 9. 186 p.
Carter, L., 1992. Acoustical characterisation of seafloor sediments and its relationship to active sedimentary processes in Cook Strait, New Zealand. New Zealand J. Geol. Geophys. 35, 289–300.
Clift, P., Vannucchi, P., 2004. Controls on tectonic accretion versus erosion in subduction zones: implications for the origin and recycling of the continental crust. Rev. Geophys. 42, RG2001. doi:10.1029/2003RG000127.
Egorov, V.N., Polikarpov, G.G., Gulin, S.B., Artemov, Yu, G., Stokozov, N.A., Kostova, S.K., 2003. Present-day views on the environment-forming and ecological role of the Black Sea methane gas seeps. Mar. Ecol. J. 2, 5–26 (in Russian).
Greinert, J., 2008. Monitoring temporal variability of bubble release at seeps: the hydroacoustic swath system GasQuant. J. Geophys. Res. 113, C07048. doi:10.1029/2007JC004704.
Greinert, J., Artemov, Y., Egorov, V., De Batist, M., McGinnis, D., 2006. 1300-m-high rising bubbles from mud volcanoes at 2080 m in the Black Sea: hydroacoustic characteristics and temporal variability. Earth Planet. Sci. Lett. 244, 1–15.
Haeckel, M., Reitz, A., Klaucke, I., 2008. Methane budget of a large gas hydrate province offshore Georgia, Black Sea. Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008), Vancouver, British Columbia, CANADA, July 6–10, 2008 (https://dspace.library.ubc.ca/dspace/bitstream/2429/2392/1/5366.pdf).

Henrys, S., Ellis, S., Uruski, C., 2003. Conductive heat flow variations from bottom simulating reflectors on the Hikurangi margin, New Zealand. Geophys. Res. Lett. 30, 1065–1068. doi:10.1029/2002GL015772.

Hovland, M., Judd, A.G., 1988. Seabed Pockmarks and Seepages. Impact on Geology, Biology and the Marine Environment. Graham & Trotman Ltd., London. 293 pp.

Huguen, C., Mascle, J., Chaumillon, E., Griboulard, R., Kopf, A., Woodside, J., 2004. Structural setting and tectonic control on mud volcanoes: evidences from the Central and Eastern Mediterranean Ridge from geophysical data. Mar. Geol. 209, 245–263.

Johnson, J.E., Goldfinger, C., Suess, E., 2003. Geophysical constraints on the surface distribution of authigenic carbonates across the Hydrate Ridge region, Cascadia margin. Mar. Geol. 202, 79–120.

Katz, H.R., 1982. Evidence of gas hydrates beneath the continental slope, east coast, North Island, New Zealand. New Zealand J. Geol. Geophys. 25, 193–199.

Klaucke, I., Sahling, H., Bürk, D., Weinrebe, W., Bohrmann, G., 2005. Mapping deep-water gas emissions with sidescan sonar. EOS 38, 341–346.

Klaucke, I., Petersen, C.J., Masson, D.G., Weinrebe, W., Ranero, C.R., 2008. Multi-frequency geoacoustic imaging of fluid escape features offshore Costa Rica: implications for the quantification of seep processes. Geochem. Geophys. Geosys. 9, Q04010. doi:10.1029/2007GC001708.

Langseth, M., Westbrook, G.K., Hobart, M.A., 1988. Geophysical survey of a submarine mud volcano seaward of the Barbados Ridge Accretionary Complex. J. Geophys. Res. 93, 1049–1061.

Le Bas, T.P., Mason, D.C., Millard, N.W., 1995. TOBI image processing—the state of the art. IEEE J. Ocean Eng. 20, 85–93.

Ledesert, B., Buret, C., Chanier, F., Ferriere, J., Recourt, P., 2003. Tubular structures of northern Wairarapa (New Zealand) as possible examples of ancient fluid expulsion in an accretionary prism: evidence from field and petrographical observations. Geol. Soc. Special Publ. 216, 95–107.

Leifer, I., Boles, J.R., Luyendyk, B.P., Clark, J.F., 2004. Transient discharges from marine hydrocarbon seeps: spatial and temporal variability. Env. Geol. 46, 1038–1052.

Lewis, K.B., Marshall, B.A., 1996. Seep faunas and other indicators of methane-rich dewatering on New Zealand convergent margins. New Zealand J. Geol. Geophys. 39, 181–200.

Lewis, K.B., Collot, J.-Y., Lallemant, S., 1998. The dammed Hikurangi Trough: a channel-fed trench blocked by subducting seamounts and their wake avalanches (New Zealand–France GeodyNZ Project). Basin Res. 10, 441–468.

Liebetrau, V., Eisenhauer, A., Linke, P., 2008. Cold-Seep Carbonates and Cold-Water Corals from the Hikurangi Margin, offshore New Zealand (Cruise SO-191): Growth Structures, Fluid Pathways and first Isotope Geochemical Results. Geophysical Research Abstracts 10, EGU2008-A-10760.

Luff, R., Wallmann, K., Aloisi, G., 2004. Numerical modeling of carbonate crust formation at cold vent sites: significance for fluid and methane budgets and chemosynthetic biological communities. Earth Planet. Sci. Lett. 221, 337–353.

MacDonald, I.R., Buthman, D., Sager, W.W., Peccini, M.B., Guinasso Jr., N.L., 2000. Pulsed oil discharge from a mud volcano. Geology 28, 907–910.

MacDonald, I.R., Bender, L.C., Vardaro, M., Bernard, B., Brooks, J.M., 2005. Thermal and visual time-series at a seafloor gas hydrate deposit on the Gulf of Mexico slope,. Earth Planet. Sci. Lett. 233, 45–59.

Naudts, L., Greinert, J., Artemov, Y., Staelens, P., Poort, J., Van Rensbergen, P., De Batist, M., 2006. Geological and morphological setting of 2778 methane seeps in the Dnepr paleo-delta, northwestern Black Sea. Mar. Geol. 227, 177–199.

Netzeband, G.L., Krabbenhöft, A., Zillmer, M., Petersen, C.J., Papenberg, C., Bialas, J., 2010. The structures beneath submarine methane seeps: seismic evidence from Opouawe Bank, Hikurangi Margin, New Zealand. Mar. Geol. 272, 59–70 (this volume).

Obzhirov, A.I., Kazanskiy, B.A., Melnichenko, Y.I., 1989. Effects of sound dispersion within the near-bottom waters of marginal parts of the Okhotsk Sea. Tikhookeanskaya Geol. (Pacific Geol.) 2, 119–121 (in Russian with English abstr.).

Paull, C.K., Hecker, B., Commeau, R., Freeman-Lynde, R.P., Neumann, C., Corso, W.P., Golubic, S., Hook, J.E., Sikes, E., Curray, J., 1984. Biological communities at the Florida escarpment resemble hydrothermal vent taxa. Science 226, 965–967.

Pecher, I.A., Henrys, S.A., 2003. Potential gas reserves in gas hydrate sweet spots on the Hikurangi Margin, New Zealand, GNS Report, Lower Hutt, New Zealand. 32 pp.

Pettinga, J.R., 2003. Mud volcano eruption within the emergent accretionary Hikurangi margin, southern Hawke's Bay, New Zealand. New Zealand J. Geol. Geophys. 46, 107–121.

Ranero, C.R., Grevemeyer, I., Sahling, H., Barckhausen, U., Hensen, C., Wallmann, K., Weinrebe, W., Vanucchi, P., von Huene, R., McIntosh, K., 2008. The hydrogeological system of erosional convergent margins and its influence on tectonics and interplate seismogenesis. Geochem. Geophys. Geosys. 9, Q03S04. doi:10.1029/2007GC001679.

Ridd, M.F., 1970. Mud volcanoes in New Zealand. AAPG Bull. 54, 601–616.

Sager, W.W., MacDonald, I.R., Hou, R., 2004. Sidescan sonar imaging of hydrocarbon seeps on the Louisiana continental slope. AAPG Bull 88, 725–746.

Sahling, H., Masson, D.G., Ranero, C.R., Hühnerbach, V., Weinrebe, W., Klaucke, I., Bürk, D., Brückmann, W., Suess, E., 2008. Fluid seepage at the continental margin off Costa Rica and Nicaragua. Geochem. Geophys. Geosys. 9, Q05S05. doi:10.1029/2008GC001978.

Solomon, E.A., Kastner, M., Jannasch, H., Robertson, G., Weinstein, Y., 2008. Dynamic fluid flow and chemical fluxes associated with a seafloor gas hydrate deposit on the northern Gulf of Mexico slope. Earth Planet. Sci. Lett., 270, 95–105.

Stoll, R.D., 1985. Marine sediment acoustics,. J. Acoust. Soc. Am. 77, 1789–1799.

Teichert, B.M.A., Eisenhauer, A., Bohrmann, G., Haase-Schramm, A., Bock, B., Linke, P., 2003. U/Th systematics and ages of authigenic carbonates from Hydrate Ridge, Cascadia Margin: recorders of fluid flow variations. Geochim. Cosmochim. Acta 67, 3845–3857.

Townend, J., 1997. Estimates of conductive heatflow through bottom-simulating reflectors on the Hikurangi and southwest Fjordland continental margins, New Zealand. Mar. Geol. 141, 209–220.

Tryon, M.D., Brown, K.M., 2001. Complex flow patterns through Hydrate Ridge and their impact on seep biota. Geophys. Res. Lett. 28, 2863–2866.

Tryon, M.D., Brown, K.M., Torres, M.E., Trehu, A.M., McManus, J., Collier, R.W., 1999. Measurements of transience and downward fluid flow near episodic methane gas vents, Hydrate Ridge, Cascadia. Geology 27, 1075–1078.