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Gas migration through Opouawe Bank at the Hikurangi margin offshore New Zealand

Stephanie Koch[1] · Henning Schroeder[1] · Matthias Haeckel[1] · Christian Berndt[1] ·
Joerg Bialas[1] · Cord Papenberg[1] · Dirk Klaeschen[1] · Andreia Plaza-Faverola[2]

Abstract This study presents 2D seismic reflection data, seismic velocity analysis, as well as geochemical and isotopic porewater compositions from Opouawe Bank on New Zealand's Hikurangi subduction margin, providing evidence for essentially pure methane gas seepage. The combination of geochemical information and seismic reflection images is an effective way to investigate the nature of gas migration beneath the seafloor, and to distinguish between water advection and gas ascent. The maximum source depth of the methane that migrates to the seep sites on Opouawe Bank is 1,500–2,100 m below seafloor, generated by low-temperature degradation of organic matter via microbial CO_2 reduction. Seismic velocity analysis enabled identifying a zone of gas accumulation underneath the base of gas hydrate stability (BGHS) below the bank. Besides structurally controlled gas migration along conduits, gas migration also takes place along dipping strata across the BGHS. Gas migration on Opouawe Bank is influenced by anticlinal focusing and by several focusing levels within the gas hydrate stability zone.

✉ Stephanie Koch
skoch@geomar.de

1 GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstraße 1-3, 24148 Kiel, Germany

2 CAGE-Centre for Arctic Gas Hydrate, Environment, and Climate, Department of Geology, UiT The Arctic University of Norway, 9037 Tromsø, Norway

Introduction

Cold seeps and associated gas migration through marine sediments occur worldwide on continental margins (e.g., Hovland and Judd 1988; Sibuet and Olu 1998; Cartwright et al. 2007), and are often linked to gas hydrate deposits. Investigation of the processes related to gas migration and accumulation in marine sediments is driven by different motivations, such as the general understanding of chemosynthetic metabolism, its role in the subduction zone factory, and also economic interest in the exploitation of gas and gas hydrate resources. The global gas hydrate reservoir contains a huge amount of methane, and thereby represents an alternative energy resource (e.g., Kvenvolden 1988; Milkov and Sassen 2002; Wallmann et al. 2012; Pinero et al. 2013).

Furthermore, determining the fluid flow system of a convergent continental margin is a key to understanding the spatial and temporal variations of geological processes associated with the subduction system (e.g., Hensen et al. 2004; Klaucke et al. 2008; Ranero et al. 2008). For this, it is important to identify the origin of gas to decide if seeps can be used as a window into deep-seated processes, and whether subduction zone mechanisms can be derived from the study of seep sites (Hensen et al. 2004). Combining geochemical information and seismic reflection images is an effective way to investigate the nature of gas migration beneath the seafloor (e.g., Brooks et al. 2000).

Gas migration is often accompanied by anomalous high-amplitude reflections, as well as by acoustic blanking or turbidity of the seismic signal. Columnar zones of seismic blanking and turbidity, referred to as chimneys or pipes, are caused by absorption and scattering of acoustic energy by gas-charged sediments (Gay et al. 2007; Løseth et al. 2009; Cartwright and Santamarina 2015). Highly focused and energetic fluid flow can lead to suppressed reflectivity, as migrating fluids

physically destroy the stratified fabric of the sediments through which they migrate (Wood and Gettrust 2001; Gorman et al. 2002). High-amplitude anomalies can occur, for example, when gas is present in the sediments, reducing the seismic velocity and increasing the impedance contrast to the adjacent sediments (Løseth et al. 2009), or they may result from a strong acoustic impedance contrast by hydrocarbon-related diagenetic zones (O'Brien and Woods 1995).

Fluid flow toward seep sites in marine sediments often has to penetrate and migrate through the gas hydrate stability zone (GHSZ). The specific seismic anomalies at the base and within the GHSZ provide useful information on the processes involved in transporting fluids through the hydrate stability zone. The most widespread and easily recognized gas hydrate-related reflection in marine sediments is the bottom simulating reflection (BSR), a high-amplitude reflection with a negative impedance contrast. The BSR marks the base of the GHSZ, as partially gas hydrate saturated sediments overlie sediments containing free gas (Holbrook et al. 1996). Variations in the appearance of the BSR can indicate disturbances in the hydrate system for example, gas chimneys penetrating the base of gas hydrate stability (BGHS), shoaling of the BSR due to locally increased heat flow, or gas migration along sedimentary layering that transects the BSR (e.g., Pecher et al. 2010; Crutchley et al. 2014).

Cold vent ecosystems at the sediment surface are fuelled primarily by methane generated from buried organic matter either thermo-catalytically at temperatures above 80 °C or microbially at lower temperatures. This methane is transported to the seafloor by upward migration of the buoyant gas phase or dissolved in upward advecting porefluids driven by overpressures created through subduction-compaction or mineral dewatering reactions, and combinations of these (e.g., Kastner et al. 1991; Berndt 2005). While geophysical investigations can identify the methane escape routes in the subsurface, the geochemical characteristics of the rising porefluids and gases are helpful in deciphering their origin and genesis (e.g., Hensen et al. 2004; Haffert et al. 2013).

For the southern Hikurangi margin, Crutchley et al. (2015) demonstrated that free gas zones of up to ~500 m thickness exist beneath the BSR, constituting the source for focused gas migration into the GHSZ. Fluid migration into the hydrate stability zone is inferred along conduits (Netzeband et al. 2010; Krabbenhoeft et al. 2013; Plaza-Faverola et al. 2014) and for sedimentary layers crossing the BSR (Crutchley et al. 2010, 2015).

This study presents a combination of geophysical data from Opouawe Bank and geochemical data from Opouawe Bank, Omakere Ridge, and Rock Garden, accretionary ridges at the Hikurangi margin offshore New Zealand. It shows that Opouawe Bank and the Hikurangi margin feature gas-only seeps and provide an insight on how gas migration may affect the gas hydrate system. The study discusses the shallow

biogenic origin of the gas seeps as well as the migration pathways and focusing levels of the ascending gas, and thereby assesses if the seeps on Opouawe Bank can be used as a window to deep-seated processes of the subduction zone.

Geological setting

The Opouawe Bank (Fig. 1) is located at the narrowest part of the active Hikurangi margin, the southernmost expression of
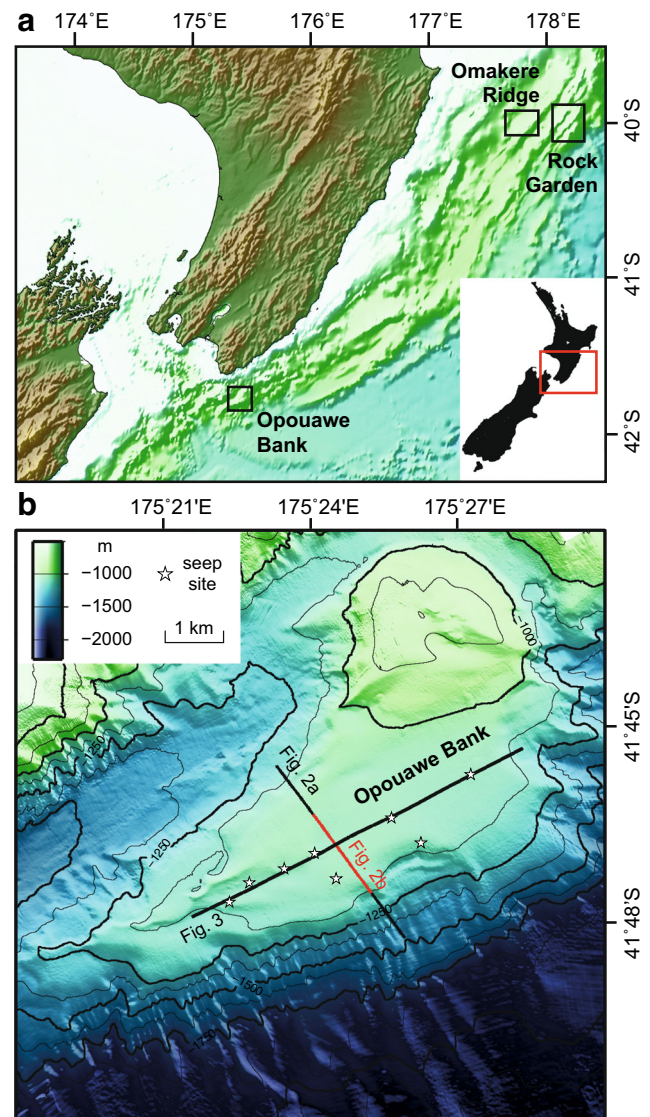
Fig. 1 a Overview of the study area offshore New Zealand, with Opouawe Bank, Omakere Ridge, and Rock Garden. Geochemical analyses were carried out on material from gravity corer and video-guided multiple corer in all three areas (for locations, see Table S1 in the online electronic supplementary material). b Bathymetric map of Opouawe Bank, displaying the locations of the seep sites. The marked profiles are the 2D Nemesys line (Fig. 3), a segment of the 2D Pegasus line (Pegasus_19, Fig. 2a), and a section from the 3D P-Cable Cube (Fig. 2b)

the Tonga-Kermadec-Hikurangi subduction zone. Dominated by the east–west oriented oblique subduction of the Pacific Plate underneath New Zealand's North Island, this part of the margin formed by accretion of 500–2,000-m-thick marine sediments of the Hikurangi Plateau (Davy and Wood 1994; Barnes et al. 2010). Subduction started approximately 24 Ma ago and, at present, the subduction rate is 49 mm/year at 37°S and declines southward to 40 mm/year at 42°S (DeMets et al. 1994; Collot et al. 1996; Barnes et al. 2010).

Subduction has led to the formation of a series of anticlinal accretionary ridges parallel to the margin. Opouawe Bank, a SW–NE trending oval-shaped bathymetric high, is situated in 900–1,100 m water depth (Barnes et al. 2010) and associated with active methane seepage (Greinert et al. 2010). The NW flank of the ridge is characterized by translational landslide scars and the SE flank by gullies (Law et al. 2010). Opouawe Bank is separated from the continental slope by erosional canyons (Lewis et al. 1998), and is bordered in the south by the Hikurangi Trough (Barnes et al. 2010).

The tectonic structure of the area is dominated by three major sub-parallel fault systems (Barnes et al. 2010), which underlie the bathymetric highs on which the seeps are located. Eight seep sites (Fig. 1) were investigated in this study. They are located in the southwestern part of the Opouawe Bank, and have formed on the hanging wall of the Pahaua Fault (Barnes and Mercier de Lépinay 1997). Six seep sites are aligned along the crest of the ridge, whereas two are located farther south on the ridge.

Materials and methods

Geophysical data

High-resolution seismic data (P-Cable system, Fig. 2) and 2D multi-channel seismic (MCS) data (Fig. 3) were acquired during the Nemesys Project in 2011 from aboard the research vessel R/V SONNE (cruise SO214). The 2D MCS data were recorded using a 200-m-long streamer with 128 channels and a group spacing of 1.5 m. The 3D data were recorded using a P-cable system consisting of 16 streamers, each with 8 channels and a group distance of 1.5 m covering an area of 3 by 8 km. A single GI-gun with a volume of 210 cubic inches was operated in harmonic mode at a shot interval of 5 s. The MCS and P-Cable datasets both have a bandwidth of 50–300 Hz.
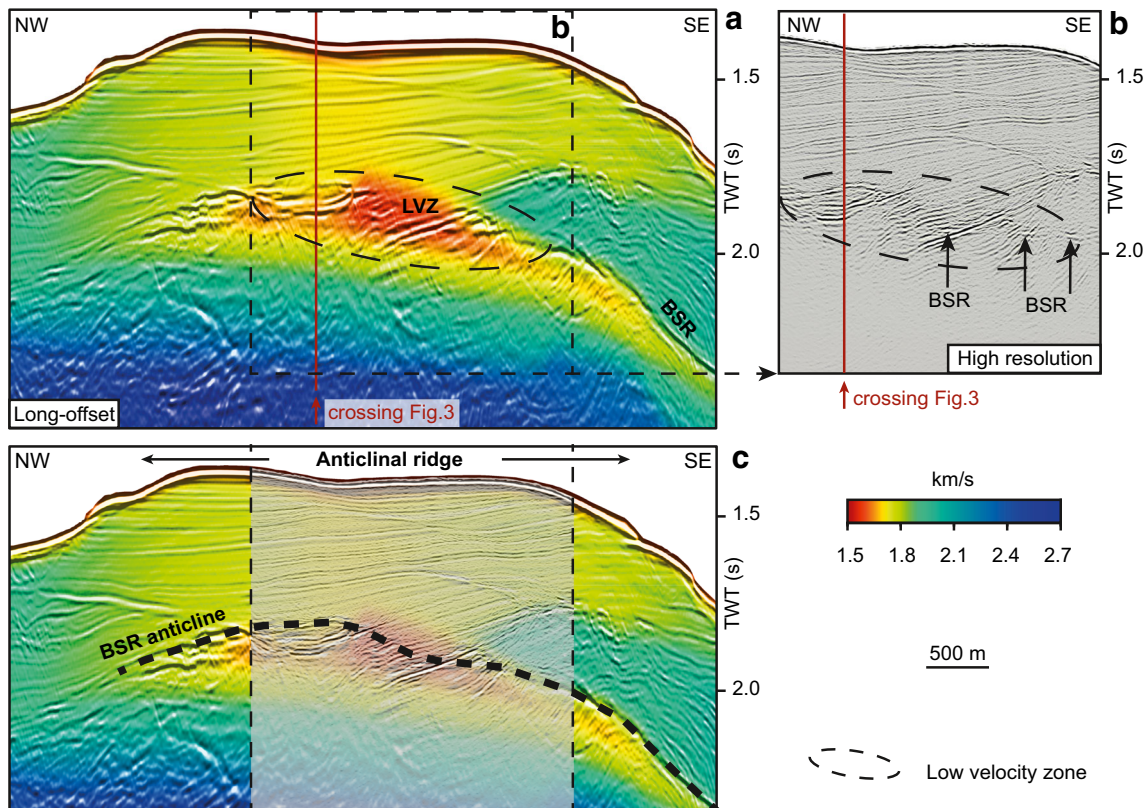
Fig. 2 a Long-offset 2D Pegasus line and b corresponding cross section of the 3D Cube across the ridge. The plot in a displays the migrated depth section and the velocity distribution, with a low velocity zone (*LVZ*) underneath Opouawe Bank. Northwest dipping high-amplitude reflections occur in both sections at the location of the LVZ. c Merged section of a and b, illustrating the connection between the anticlinal structure of the ridge, the LVZ, and dipping high-amplitude reflections. The latter occur above and below the BSR
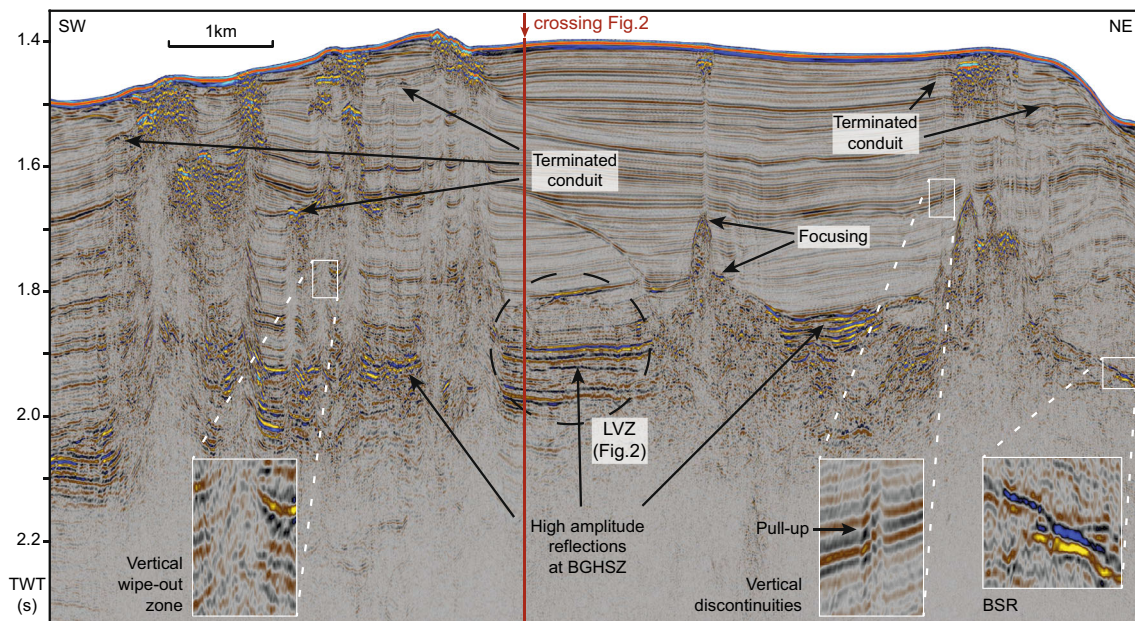
Fig. 3 2D Nemesys line along the Opouawe Bank crossing the seep structures aligned along the ridge. The vertical conduits display several focusing levels, and some conduits terminate within the sediments. The interface of Figs. 2 and 3 illustrates the spatial distribution of the high-amplitude reflections at the base of the gas hydrate stability zone (*BGHSZ*), where the LVZ is located

The main processing steps of the high-resolution 3D P-Cable seismic data included navigation correction for the source and the 16 streamers, trace editing, frequency filtering, and binning to a regular 3D grid with a cell size of 6.25×6.25 m. Due to insensitivity of moveout velocities, a water velocity stack was the input to 3D Kirchhoff time migration. The 3D velocity model for the migration was seafloor depth dependent interpolated and extrapolated from a 2D velocity profile crossing the 3D area.

The 2D single-streamer data processing included navigation processing, trace editing, frequency and velocity filtering, and a crooked line binning with cell size of 1.5 m. After water velocity stack, a post-Kirchhoff time migration with a representative velocity function below the seabed was applied.

Velocity information (Fig. 2a) was extracted from 2D MCS data originating from the PEGASUS survey (Ministry of Economic Development of New Zealand in 2009). A 31.5-km-long northern segment of line Pegasus_19 (Plaza-Faverola et al. 2012) was reprocessed with special attention to the upper 1 km of sediments at Opouawe Bank for optimizing velocity analysis and pre-stack depth migration. The data were collected with a 10-km-long streamer consisting of 800 channels with a group spacing of 12.5 m. Their dominant frequency of 25 Hz (zero-phase wavelet) leads to a vertical resolution (one-quarter of the dominant wavelength) of 8–10 m for a velocity range of 1,500–2,100 m/s. Frequency and wave number-domain filtering, deconvolution, and attenuation of seafloor and interbed multiples were applied using WesternGeco's Omega software during reprocessing at GEOMAR. The Kirchhoff pre-stack depth migration was done with Sirius by GX-Technology. The depth velocity field was iteratively determined from top to bottom by semblance and residual moveout analysis of pre-stack migrated common depth point (cdp) gathers. Five iterations resulted in a velocity error of less than 2.4%.

Geochemistry

Sediments of the Hikurangi margin from Opouawe Bank, Rock Garden, and Omakere Ridge (for geographic locations, see Table S1 in the online electronic supplementary material) were retrieved with a gravity corer and a video-guided multiple corer during expedition SO191 with RV SONNE in 2007. Porewater was extracted from ca. 2-cm-thick slices of sediment using a low-pressure squeezer (argon gas at 3–5 bar) at approximately in situ temperatures (4–8 °C) in the cold room onboard the research vessel. Upon squeezing, the porewater was filtered through 0.2 µm cellulose acetate Nuclepore filters and collected in recipient vessels. Onboard, the collected porewater samples were analyzed for their contents of dissolved Cl and SO_4 by ion chromatography, dissolved hydrogen sulfide by photometry, and dissolved total alkalinity by HCl titration (see Haffert et al. 2013 for analytical details and errors). Subsamples were taken for shore-based analyses of dissolved B, Li, Ca, Sr, and K concentrations using an atomic emission spectrometer, particulate organic carbon and calcium carbonate content using an element analyzer, and the isotopic composition of the water, i.e., $\delta^{18}O$ and δD, using an isotope ratio mass spectrometer (see Haffert et al. 2013 for analytical details and errors).

For later headspace methane and higher hydrocarbon gas analyses, 3 ml of wet sediment were collected and suspended in 3 ml of 10% KCl solution. Gas concentrations were measured by gas chromatography and the isotopic composition, i.e., $\delta^{13}C$, of the methane gas was determined by coupled gas chromatography and combustion isotope ratio mass spectrometry (Nuzzo et al. 2009). Undissociated gas hydrate samples from the cores were stored in liquid nitrogen containers, and the chemical and isotopic compositions were analyzed by the same procedures as the headspace gas samples.

Results

Seismics

Most seeps of Opouawe Bank align along the ridge crest. Their principal gas migration structure is discernible on the 2D Nemesys line (Fig. 3) crossing along the ridge. Vertically it can be subdivided into three parts, starting at the base of the gas hydrate stability zone (BGHSZ), which is characterized by a band of high-amplitude reflections. This reflection band is terminated by blanking or by chaotic reflections with high-amplitude anomalies in the lower part of the migration structures. At the base and within the GHSZ, the gas migration structures converge into vertical conduits characterized by pull-ups in combination with reduced amplitudes or wipe-out zones with weak reflections. The conduits cut vertically through the sub-horizontal strata, and some terminate at various stratigraphic levels. In the shallow sub-seafloor the conduits terminate as rounded structures at the seafloor with various amplitude anomalies, in some cases accompanied by gas-controlled doming of the seabed sediments (Koch et al. 2015).

The 2D Pegasus line (Fig. 2a) and a corresponding high-resolution seismic section (Fig. 2b) across the ridge connect seismic observations with the superimposed velocity field. At the center of Opouawe Bank, a low velocity zone (LVZ, Fig. 2a) is located underneath the anticline of the ridge, in about 320 mbsf (meter below seafloor). The seismic velocity decreases from about 1,715 m/s to about 1,575 m/s at the BGHSZ. Northwest dipping high-amplitude reflections crossing the BSR exist in the LVZ. These show the typical thickness variations and limited lateral extent of the seismic facies associated with contourite deposits. This is supported by the undulating interfaces approximately 200 ms below the seafloor, which are interpreted as boundaries between sediment waves. The crosscutting BSR in the Pegasus line has reversed polarity on both flanks of the anticline, whereas it is not a proper reflector at the apex. Apart from the crosscutting BSR, there are no other crosscutting seismic reflectors, suggesting that out-of-plane reflections do not significantly affect the seismic imaging. Patches of high-amplitude reflections and patches of reduced reflectivity occur also at the peak of

the LVZ on the Pegasus line (Fig. 2a). Beneath the LVZ, the Pegasus line displays subdued reflections and low seismic resolution as consequence of low frequencies.

Further distinct reduction of seismic velocities occurs beneath the clearly visible oblique BSR down the southeastern flank, and thus situated deeper than the LVZ. The BSR crosscuts folded strata underneath this part of the ridge. Northwest of the LVZ, the BGHSZ is characterized by chaotic high-amplitude reflections of reversed polarity. No distinct BSR reflection is present under the northwestern flank of the ridge and, in contrast to the southeastern flank, a distinct reduction of seismic velocities is not observed.

Geochemistry

In samples retrieved from different seeps at Opouawe Bank, there are only slight variations in the isotopic composition of porewater, dissolved chloride concentrations, carbon isotopic composition of the dissolved methane, and the gas composition (Fig. 4). This is in line with data from other seep areas of the Hikurangi margin, such as Rock Garden and Omakere Ridge (cf. Fig. 4). Porewater isotope signatures and chloride concentrations show typical seawater values (δD of -4 to -2‰ SMOW, $\delta^{18}O$ of -0.5 to $+0.5$‰ VPDB, and Cl of 540 to -570 mM), with possibly small influences of near-surface formation of gas hydrates and the corresponding artifact caused by the dissociation of gas hydrates during core retrieval (Fig. 4a, b; for a detailed discussion on this issue, see Haeckel et al. 2004). Boron and lithium concentrations have similar trends, i.e., B of 0.3 to -0.5 mM and Li of 15 to -25 µM (see Fig. S2 in the online electronic supplementary material).

The dissolved seep gas is composed primarily of methane (C_1/C_{2+} ratio >500), and the methane is isotopically enriched in light ^{12}C, thus carrying a $\delta^{13}C$ of -60 to -80‰ VPDB (Fig. 4c). The gas bound in near-surface gas hydrates at the Takahe seep is naturally even more enriched in methane (C_1/C_{2+} of 11,000 to $-23,000$). This methane has isotopic signatures of $\delta^{13}C$ of -65 to -66‰ VPDB and δ^2H of -126 to -145‰ VSMOW (Fig. 4d).

Discussion

Gas focusing

The strong decrease of seismic velocities at the LVZ from 1,715 to 1,575 m/s, which coincides precisely with the base of the GHSZ, suggests gas accumulation in sediments of Opouawe Bank at about 320 mbsf. The shape of the LVZ at the BGHSZ indicates trapping of upward migrating gas under the anticlinal structure of the ridge, which forms a trap due to the reduction of permeability in the hydrate sediments (Bünz et al. 2003). This entrapment
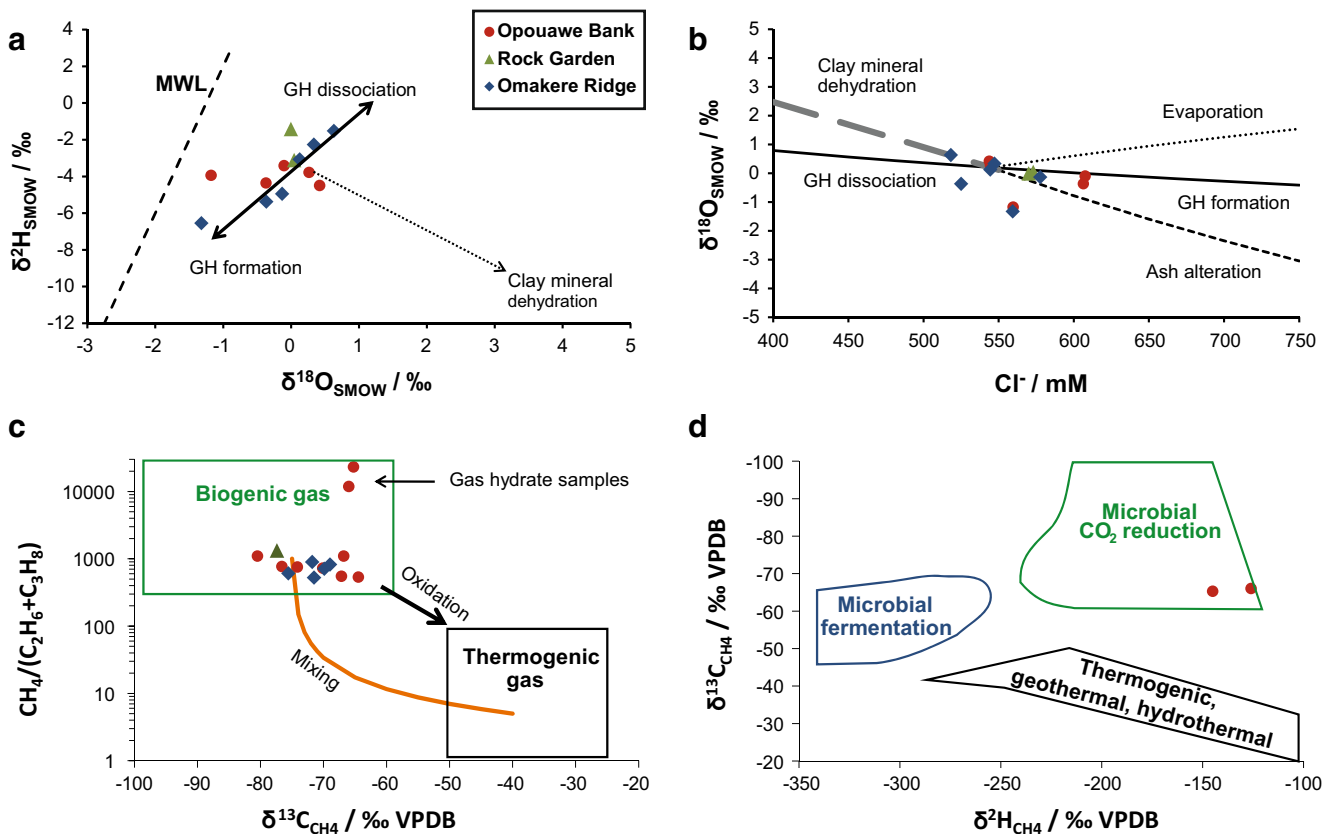
Fig. 4 Geochemical characterization of the porefluid and gas composition as well as gas hydrates in surface sediments of cold seeps at the Hikurangi margin (Opouawe Bank, Rock Garden, and Omakere Ridge). **a** Porewater isotopic composition and typical trends from gas hydrate formation and dissociation (*solid line*), clay mineral dehydration (*dotted line*), and meteoric water mixing (*dashed line*; *MWL* meteoric water line). **b** Porewater oxygen isotopes versus chloride concentration, and influences from typical diagenetic processes. **c** Bernard plot indicating the biogenic or thermogenic origin of the gas. For comparison, the theoretical mixing line between biogenic and thermogenic methane as well as the trend for oxidation are indicated. **d** Isotopic composition of methane in the recovered gas hydrate pieces from the Takahe seep, and process-related fields (according to Whiticar et al. 1986)

has been observed for many gas hydrate provinces (Bünz et al. 2003; Crutchley et al. 2013). The coincidence of the LVZ with the BSR argues against other possible interpretations such as underconsolidation or lithological variations, as these would have to be located at this depth and dipping strata coincidentally. Decreased seismic velocities underneath the oblique BSR and the inclined base of the LVZ (Fig. 2) indicate ascending gas toward the LVZ at the southeastern flank of the ridge. This suggests that free gas originates from deeper parts of the sediments, and is not generated at the depth of the LVZ.

The LVZ extends upward beyond the BSR depth (Fig. 2). It corresponds to a band of near-horizontal high-amplitude reflections in between the seep structures (Fig. 3) and where the BSR is highly attenuated or inexistent (Fig. 2). The observed BSR gap corresponds with an area where the LVZ reaches up into the GHSZ, suggesting that there is no sharp impedance contrast across the BGHSZ, as gas is migrating upward into the GHSZ. Similar observations have been documented in the proximity of thrust ridges at the southern Hikurangi margin

(Crutchley et al. 2015) and for the Gulf of Mexico (Boswell et al. 2012).

The formation of migration pathways under the ridge structure and the alignment of most seep sites along the ridge crest are most likely linked to anticlinal focusing (Johnson et al. 2003). As the Opouawe Bank is an anticlinal structure (Barnes et al. 2010; Law et al. 2010), the BSR also adopts an anticlinal shape. At the BGHSZ the gas hydrate constitutes a permeability contrast (Hornbach et al. 2004). Bünz et al. (2003) showed that the decreased permeability enables gas accumulation, which probably generates overpressure and particular high overpressure below an anticlinal BSR leads to the formation of fluid migration pathways. This overpressure is at least partly due to buoyancy forces, but can be augmented by dynamic flow processes (Crutchley et al. 2014). Thus, subsequent fracturing may lead to focusing of gas migration into the GHSZ.

The 2D Nemesys line (Fig. 3) reveals several focusing levels for the ascending gas. This is reflected by the seismically distinguishable parts of the gas migration structures, first at the BGHSZ where gas migration from the LVZ into the GHSZ is accompanied by blanking or by chaotic reflections.

Successive focusing occurs within the GHSZ, which in some parts is visible as a cone-like shape with high-amplitude anomalies, to vertical narrow conduits characterized by pull-ups in combination with reduced amplitudes or wipe-out zones with weak, deteriorated reflections.

The conduits exhibit no specific stratigraphic level at which their tops cluster, which indicates a long record of gas migration through Opouawe Bank. This is supported by different evolutionary stages of the gas migration structures observed in the upper 100 m in the shallow sediments (Koch et al. 2015) and the different phases of intensified seep activity, which Liebetrau et al. (2010) inferred from geochemical analysis of authigenic carbonate samples.

Gas source

At the Hikurangi margin, porewater oxygen and hydrogen isotopic signatures from subsurface sediment cores (uppermost 6 m) concomitantly show a positive correlation, i.e., δD values increase with increasing $\delta^{18}O$ values (Fig. 4a), whereas $\delta^{18}O$ values are negatively correlated with Cl concentrations (Fig. 4b). Both trends are indicative for currently active in situ gas hydrate formation in the sediments, as well as dissociation of gas hydrates due to depressurization of the retrieved cores (see Haeckel et al. 2004 for detailed discussion). This is, however, the complete opposite of what is to be expected if fluid advection would be driven by clay mineral dewatering reactions, i.e., smectite–illite transformation occurring at temperatures of 60–190 °C (cf. dotted arrow in Fig. 4a and dashed line in Fig. 4b). In accordance with this observation, porewaters are not enriched in boron and lithium, as would be the case if upward fluid flow driven by smectite–illite dewatering took place (e.g., Hensen et al. 2004, 2007; Haffert et al. 2013). Instead, Li and B concentrations decrease downcore (see Fig. S1 in the online electronic supplementary material), which is a typical result from uptake during ash alteration (e.g., Kastner and Rudnicki 2004; Scholz et al. 2010).

In line with the above observations, also the seeping gas does not show any indications for a deep origin, i.e., a thermogenic imprint caused by temperatures above 80 °C. The expelled gas as well as the one bound in near-surface gas hydrates is composed primarily of methane, generated from organic matter degradation via metabolic CO_2 reduction (Fig. 4c, d). Considering the observed margin-wide heat flow (Henrys et al. 2003), the source depth of the methane is at maximum 1,500–2,100 m below the seafloor and may shoal below seeps, such as Takahe, to 600 m sediment depth due to increased heat flow (Schwalenberg et al. 2010a). Thus, the methane at Opouawe Bank and in the other investigated seep areas at the Hikurangi margin is largely generated below the GHSZ (Uruski and Bland 2011; Kroeger et al. 2015), as is expected (Wallmann et al. 2006, 2012).

In addition, the 2D seismic lines do not reveal possible focused gas migration pathways in greater depths underneath the BGHSZ (Fig. 3) and underneath the LVZ (Fig. 2b). However, some of the conduit structures might be of a deeper origin than the BSR level. Coherent reflections are not present below the LVZ, and thus it is not clear if there are focused fluid migration pathways. Therefore, the origin of the upward migrating gas below the LVZ cannot be determined in the seismic data at Opouawe Bank.

Thus, the present study does not document any evidence for fluid seepage through the deep thrust faults underlying Opouawe Bank, as hypothesized by Plaza-Faverola et al. (2012). Migration of thermogenic gas is postulated along the décollement into the sediments of the Pegasus Basin (Kroeger et al. 2015), but does not appear to have a connection to the seeps further upslope, such as Opouawe Bank.

Further evidence that the methane transport is dominated by gas migration through the surface sediments is provided by the ubiquitous occurrence of S-shaped profiles of dissolved porewater constituents (Schwalenberg et al. 2010a, 2010b). Boudreau et al. (2005) have established that gas bubbles rise through soft, muddy surface sediments by linear elastic fracture mechanics, thereby creating tubular rise paths, and Haeckel et al. (2007) have demonstrated that this results in irrigation-like mixing of bottom water solute concentrations several meters into the sediments. In contrast, upward porewater advection would lead to concave-shaped solute profiles.

Conclusions

This study demonstrates the strength of linking geochemical and geophysical data in order to discriminate between gas ascent and the upward advection of water. The analyses clearly show that the cold vents at Opouawe Bank (as well as at the Hikurangi margin in general) are fueled by the seepage of biogenic methane gas. Bubble-induced irrigation-type porewater profiles, strongly enhanced methane fluxes, and the absence of any signal of mineral dewatering reactions provide the main geochemical evidence. Hence, seepage at Opouawe Bank appears not to be driven by the compaction-subduction process, but by upward migration of microbial gas. The source depth of the methane is at maximum 1,500–2,100 mbsf, considering the average margin-wide heat flow, which does not allow microbial gas production at greater depth.

The combination of MCS data and velocity analysis shows that gas migration through Opouawe Bank is a continuous process. Trapping of upward migrating gas under the anticlinal structure of the bank and the alignment of most of the seeps along the ridge crest document anticlinal focusing of the ascending gas. In addition to gas migration along focused pathways through the gas hydrate stability zone, high-

amplitude reflection segments indicate migration of gas along layers crossing the bottom simulating reflection.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest with third parties.

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