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EROSION OF SEAFLOOR RIDGES AT THE TOP OF THE GAS HYDRATE STABILITY ZONE, HIKURANGI MARGIN, NEW ZEALAND – NEW INSIGHTS FROM RESEARCH CRUISES BETWEEN 2005 AND 2007

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ABSTRACT

It was proposed that erosion of subsea ridges on the Hikurangi margin may be linked to a fluctuating level of the top of gas hydrate stability in the ocean. Since publication of this hypothesis, three field campaigns were conducted in the study area. Here we summarize relevant results from these cruises. We found that water temperature fluctuations occur at lower frequencies and higher amplitudes than previously thought, making it more likely that temperature changes reach sub-seafloor gas hydrates. Dredge samples encountered numerous consolidated mudstones. We speculate that gas hydrate "freeze-thaw" cycles may lead to dilation of fractures in mudstones due to capillary forces, weakening the seafloor. Ubiquitous gas pockets beneath the ridge may lead to overpressure that may also contribute to seafloor fracturing.

Keywords: gas hydrates, seafloor stability, New Zealand

NOMENCLATURE

BGHS: Base of gas hydrate stability
BSR: Bottom simulating reflection
TGHS: Top of gas hydrate stability
ZIS: Zone of intermittent gas hydrate stability

INTRODUCTION

Gas hydrates have long been implicated in seafloor instability [1-3]. Two conceptual mechanisms are often considered for linking gas hydrates to seafloor weakening. "Melting" (dissociation) of frame-bearing or cementing gas hydrate may weaken the strength of the sediment frame. Furthermore, release of gas during hydrate dissociation leads to net-volume expansion potentially causing overpressure. Overpressure from dissociating gas hydrates at the base of gas hydrate stability (BGHS) has been cited as a potential cause for triggering or facilitating submarine slides [2, 4]. While these mechanisms appear intuitively feasible, there is to our knowledge, no clear evidence yet for a significant role of gas hydrates in seafloor instability. In 2003, we have discovered two ridges on the Hikurangi margin offshore of New Zealand, eastern Rock Garden and western Ritchie Banks, with flattened crests flanked by pinchouts of bottom simulating reflections (BSRs; Figures 1

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and 2), which we interpreted as evidence for seafloor erosion at the top of gas hydrate stability (TGHS) in the ocean [5]. Since then, three research campaigns have been conducted to the study area. We present an overview of relevant results from these surveys and discuss their implications.

PROPOSED HYPOTHESIS

The hypothesis linking seafloor erosion and the TGHS in the ocean [5] is based on two key observations.

1. Seismic data acquired during sea trials of the U.S. *RVIB N.B. Palmer* (NBP0304D) in 2003 [6] show BSR pinchouts at ~630 m water depth on the edges of the plateau-like crests of eastern Rock Garden and western Ritchie Banks (Ridge RB1 in Figures 1 and 2). Ridge RB2 (formerly labeled eastern Ritchie Banks) however, beneath which BSRs appear to be absent, crosses these depths without any break in its slope (Figure 2).
2. Historic CTD data [7-10] from a radius of ~150 km around Rock Garden indicate water temperature fluctuations of ±0.9 °C (Figure 3) likely to be caused by mixing of the warm East Cape and cold Wairarapa Coastal Current.

Rock Garden and Ritchie Banks are about 30 km apart. A regional tectonic origin for erosion, i.e., uplift, sub-aerial and/or wave erosion, followed by subsidence to current depths, was considered unlikely because of the smooth flanks of ridge RB2 across ~600 m water depth. Regional uplift should have exposed this ridge to subaerial erosion and hence, a change of slope dip would be expected. Likewise current-related erosion above ~600 m water depth as an alternative regional erosion mechanism should also affect this ridge, leading to a change of slope dip.

The coincidence of BSR pinchouts, marking the TGHS in the ocean, with the edge of the flattened ridge crests led to the suggestion that seafloor erosion was most likely linked to the TGHS. Two potential mechanisms were proposed: An upward migrating BGHS with respect to the seafloor caused by depressurization during ridge uplift may lead to gas hydrate dissociation, release of gas, volume expansion of the pore fill, overpressure, seafloor weakening and ultimately, sliding – a variation of the mechanism proposed for linking gas hydrates to submarine slides. After sliding, water depth and hence, hydrate stability, increases again and the process may repeat itself during continued uplift. Evidence from bathymetric and

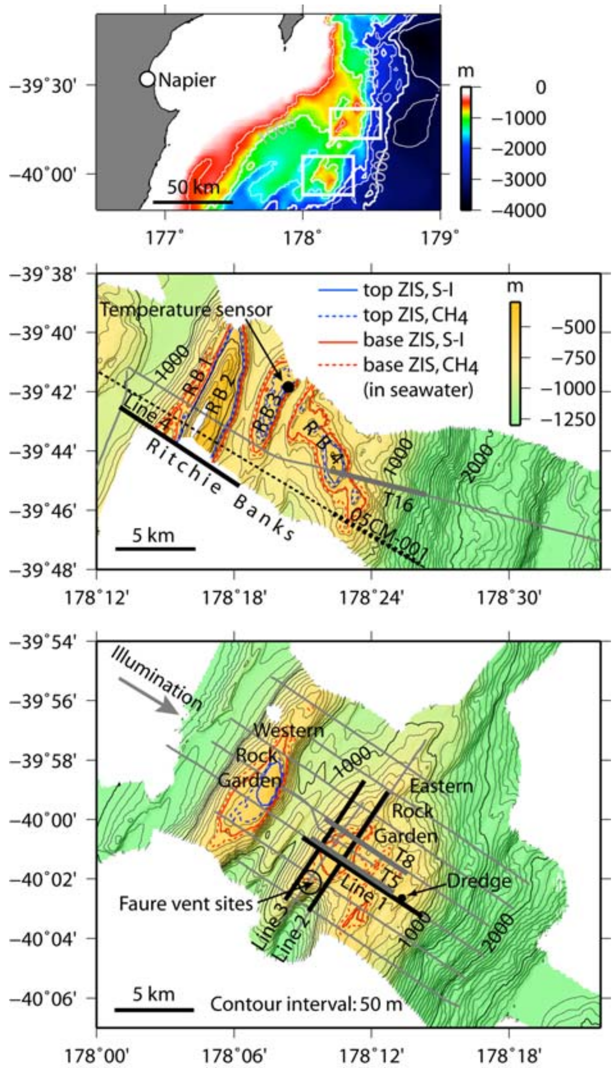

Figure 1. Location map (top) with study areas (while rectangles) shown below. Bathymetry of Ritchie Banks (center) and Rock Garden (bottom). Black lines mark NBP0403 seismic sections shown in Figure 2. Thin grey lines mark seismic tracks during TAN0607, thick lines are sections shown in Figures 5 and 7. The dashed line marks 05CM-001, thick part shown in Figure 5. Ridge RB1 was previously named western Ritchie Banks, RB2 eastern Ritchie Banks. The Faure vent sites are located at the slump in Line 2 (Figure 2). Samples from the dredge are shown in Figure 6. The zone of intermittent hydrate stability (ZIS) is calculated for a gas mix forming Structure-I hydrate (S-I, without propane, see text) and methane hydrate (CH_4) using the new temperature range in Figure 3.

seismic data supports the presence of small slides on the edges of the plateau (Figure 2). However,

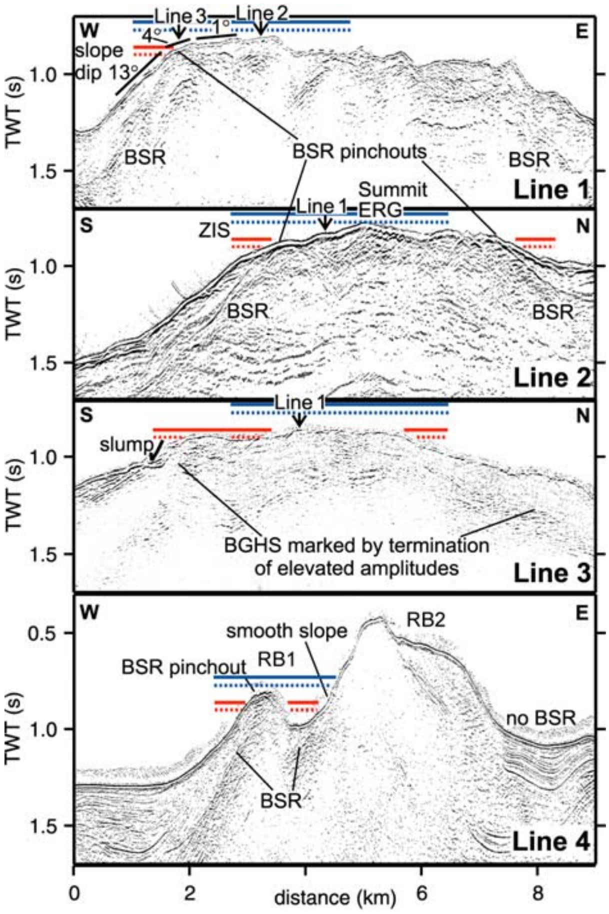

Figure 2. Seismic profiles from NBP0403D, after ref. [5]. ZIS as in Figures 1 and 3.

for this mechanism to be efficient, the ridge crest must remain within the gas hydrate stability field, which seems to contradict the presence of BSR pinchouts marking the TGHS. It was therefore proposed that repeated dissociation and formation of gas hydrates on the ridge crests caused by water temperature fluctuations may contribute to seafloor weakening. During warm-water periods, gas hydrates would dissociate leading to net pore-volume expansion whereas pore volume would contract during gas hydrate formation in cold-water periods. It was hypothesized that repeated pore volume contraction and expansion could cause weakening of the seafloor. Weakened sediments would then slide down the steep ridge flanks, perhaps aided by water currents.

Several issues remained unresolved when presenting this hypothesis:

- *Range and frequency of temperature fluctuations:* It is conceivable that the historic CTD data did not sample the entire range of water temperature fluctuations. More importantly, no data were available on the frequency of these fluctuations, which is a key factor for determining down to which depth temperature fluctuations affect the seafloor (for modeling, ref. [5] used an arbitrary wavelength of 160 days, within typical mesoscale timescales for mixing of currents).

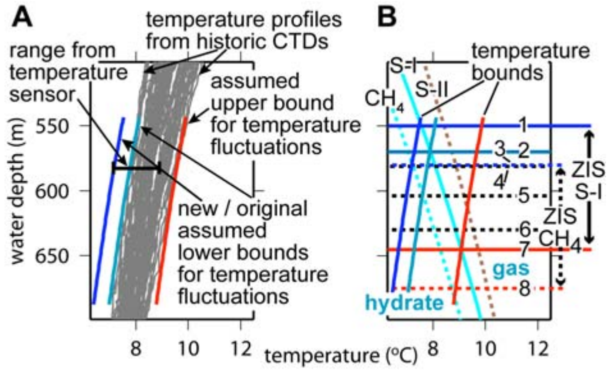

Figure 3. A: Range of temperature profiles from historic CTD data compared to that from temperature sensor (Figure 4).
B: Phase boundaries for natural gas (S-I, Structure-I forming mix of 96.3% CH_4, 2.6% CO_2, 1.1% ethane; S-II: Structure-II forming mix of 96.0% CH_4, 2.6% CO_2, 1.1% ethane, 0.3% propane) compared to pure methane hydrate (CH_4), in seawater [11, 12]. Depth levels: 1: Top of ZIS, S-I forming gas mix with new lower bound in temperature range in A. 2: Top of ZIS, S-I forming gas, original temperature bounds from [5]. 3: Top of ZIS, new temperature range, pure methane hydrate. 4: Summit of eastern Rock Garden. 5: Summit of RB1 (western Ritchie Banks). 6: Level of BSR pinchouts, eastern Rock Garden. 7: Base of ZIS, S-I forming gas mix. 8: Base of ZIS, methane hydrate.

- *Top of gas hydrate occurrence:* Because of anaerobic methane oxidation linked to sulfate reduction beneath the seafloor, gas hydrates rarely crop out at the seafloor. The base of the sulfate reduction zone is typically located several tens of centimeters to tens of meters beneath the seafloor – the top of gas hydrate occurrence even deeper. It was therefore not clear whether the temperature fluctuations would reach gas-hydrate-bearing layers at all. On the other hand, BSR pinchouts suggest that gas and, by inference, hydrates are present close to the seafloor within the resolution of the seismic data.
- *Gas hydrate phase boundary.* The only relevant data available on gas composition were from onshore seeps [13]. An average composition

from these seeps (96.3% CH_4, 2.6% CO_2, 1.1% ethane, mole fractions), without Structure-II forming propane, was used for calculating the phase boundary. The omission of propane was justified by the fact that the fraction of propane was negligible in 16 of the 21 onshore vents. Using the average propane concentration over all 21 vents (0.3%) would already lead to forming a considerably more stable Structure-II hydrate (Figure 3). It was noted that with the above gas mix, the ridge crests would conveniently be within the ZIS where hydrates on the seafloor are predicted to repeatedly form and dissociate – using pure methane hydrate in seawater would shift the ZIS down such that the ridge summits would (just) be located above the ZIS.

- *Fate of gas:* Most models of gas hydrate formation in sediments predict that considerable time, in the order of 1000s to 100,000s of years, is required to form significant gas hydrate deposits “from scratch”, i.e., starting with methane-depleted sediments [14]. During freeze-thaw cycles, much of the gas released after dissociation, must therefore remain in the sediments to be available for hydrate formation. It was noted however, that gas at low concentrations is often less mobile than water.
- *Rock type:* The steep ridge flanks (~13°) suggest the presence of fairly indurated rocks, consistent with exhumation of older, consolidated rocks during erosion. However, this assumption was only based on indirect observation – no rocks had been sampled from this area.
- *Erosion or non-sedimentation:* Crustal seismic data [15] show that layers that are deeply buried further to the west are being exhumed on Rock Garden. Hence, the ridge is likely to have been eroded at some stage. However, it is not clear that erosion is still taking place or whether Rock Garden is now an area of non-sedimentation rather than erosion.

Three major marine research campaigns were carried out between 2005 and 2007 in the study area (Table 1). In addition, further evaluation of already existing data and modeling were conducted to elucidate possible mechanisms of seafloor erosion at the TGHS.

M/V Pacific Titan, 05CM, 3/2005: • Multichannel seismic, 12-km streamer, 4000 cu-in airgun array (only Line 05CM-001 used here)
R/V Tangaroa, TAN0607, 20/6-2/7/06: • High-resolution seismic, 600-m streamer, 45-105 cu-in Generator/Injector ® gun • Multibeam • Echosounder (3.5 kHz and higher) • Pore-water chemistry • Water chemistry • Microbiology • Carbonates • Dredging • Recovery of temperature probe
R/V Sonne, SO191, 11/1-23/3/07: • Sidescan, multibeam • Parasound ® echosounder • Heatflow • ROV • Water chemistry • Seafloor sampling with various equipment • (and others)

Table 1. Summary of relevant research cruises since 2005, with experiments on Rock Garden and Ritchie Banks.

NEW FINDINGS

Temperature record

The 15-month time series of a temperature sensor deployed at 580 m water depth on Ritchie Banks (frequent bottom trawling prevented us from deploying a sensor on Rock Garden) shows that the wavelength of temperature fluctuations is larger than the time series (Figure 4), and much larger than the 160-day cycles assumed by ref. [5] for modeling the penetration of the temperature signal into the seafloor. Combined with the historic records, the peak-to-peak amplitude range of temperature fluctuations increases from 1.8ºC to 2.4ºC (Figure 3).

Heatflow measurements during SO191 at a location on Rock Garden show a negative temperature gradient immediately below the seafloor [16, 17], which is consistent with recent warming of bottom-waters.

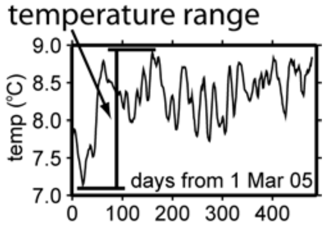

Figure 4. Temperature record, 7-day running-average filter. The cold-water event in the first few days is not an artifact.

Eastern edge of Ritchie Banks

Line 05CM-001 was commissioned in 2005 as part of a regional survey to encourage hydrocarbon exploration. The line crossed Ritchie Banks. A BSR pinchout may be present at the eastern edge of this system (Figure 5). From bathymetric data, it appears that this possible BSR pinchout occurs at the edge of a plateau to the North (Figure 1). Subsequently we acquired high-resolution Line T16 during TAN0607 which almost crossed the summit of the ridge. While a BSR is present in this line, no pinchout could be identified. The summit of this ridge lies above the ZIS; however from bathymetry, it appears that large parts of the ridge are within the ZIS.

Seafloor composition

Dredge samples from eastern Rock Garden recovered during TAN0607 consisted of authigenic carbonates, consolidated mudstones, and sandstones (Figure 6) [18]. Mudstones were prevalent and appear to be the "country rock" of eastern Rock Garden, assuming that authigenic carbonates are limited to the near-seafloor.

Numerous samples and bottom observations with cameras and an ROV during SO191 revealed ubiquitous carbonates, often as flat pavements [19].

Near-seafloor gas pockets

Wide-spread high-amplitude reflections were identified in the seismic data acquired during TAN0607. These reflections are interpreted as gas near the seafloor (Figure 7). Most of these gas pockets in the deeper part of the ridge seem to terminate against the BGHS (Line T8, eastern part). In the shallower parts, where the seafloor is predicted to be situated in the ZIS, there appears to be a sub-horizontal upper level of the gas pockets (Lime T5, western part). However, it is not obvious what controls that level.

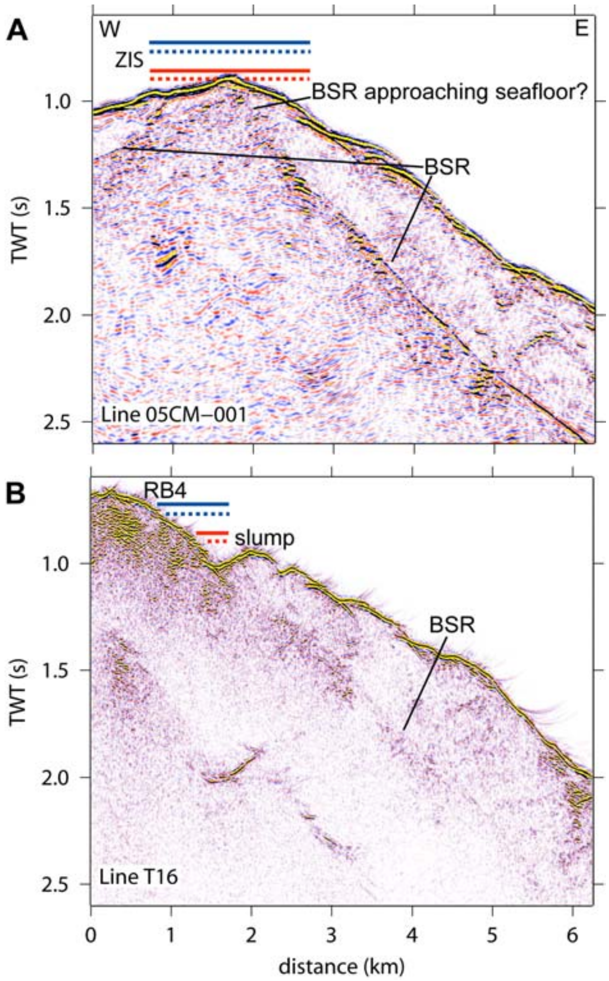

Figure 5. Eastern edge of Ritchie Banks (RB4).
A: Seismic profile 05CM-001 collected with industry vessel. ZIS as in Figure 3.
B: Line T16, acquired with high-resolution system during TAN0607.

Figure 6. Rock samples from dredge, eastern Rock Garden, mudstone (left), sandstone (center), and carbonates.

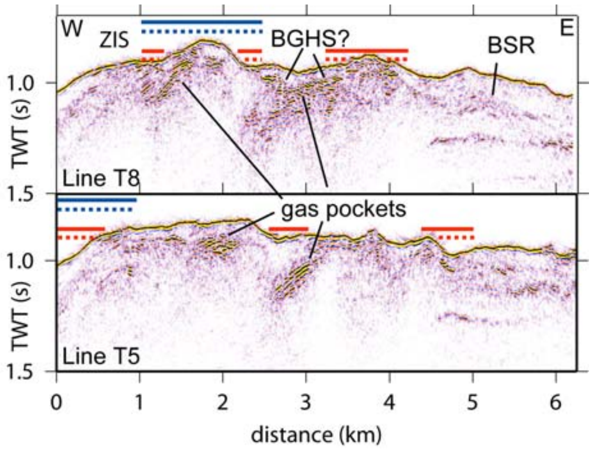

Figure 7. Examples of high-amplitude events near the seafloor that we interpret as gas pockets. ZIS as in Figure 3.

Phase boundary and gas composition

The gas composition used by ref. [5] was somewhat arbitrarily based on that from on-shore vent sites [13]. Ref. [20] calculated thermal gradients from the depth of BSRs along one of the NBP0403 seismic lines on Rock Garden's flanks. Using the average gas composition of ref. [5] without Structure-II forming propane leads to a slight increase of the thermal gradient towards the ridge crest. This could e.g., be explained by advective heatflow caused by fluid flow focusing. This increase is more pronounced if assuming a Structure-II forming gas mix. Using pure methane hydrate in seawater however, results in a decrease of the thermal gradient towards the ridge crest, which would be difficult to explain.

Porewater chemistry from shallow sediment cores on the other hand suggests that the by far dominant gas at most locations along this margin is methane [21, 22].

Slumping and vent sites

Analysis of bathymetric data confirmed that the step observed in the seismic data [5] (see Line 3 in Figure 2) is indeed the head of a slump [20]. Furthermore, elevated methane concentration in the water column indicated the presence of seafloor venting. During TAN0607 and SO191, numerous vent sites were discovered [18, 21].

Black sediment spots were found near seep sites. Pore water profiles from these spots show very shallow depths of the sulfate reduction zone in the order of several centimeters [23] indicative of high methane flux rates.

Modeling of possible erosion mechanisms

Modeling of gas hydrate formation and dissociation near the seafloor is still ongoing. We are addressing the question if during gas hydrate dissociation, sufficient pore pressure can build up to cause hydrofracturing of the sediments. We use a 1-D model for gas hydrate formation [24] and predict pore pressure development [25]. Initial results suggest that repeated gas hydrate dissociation only builds significant pressure during dissociation in a limited range of methane fluxes and wavelengths of the temperature fluctuations. Our models encountered two key challenges (S. Ellis, pers. comm., 2008):

1. It was difficult to model the formation of near-seafloor hydrates. For shorter wavelengths, the 160-day cycles assumed by ref. [5], the models suggests that it is unlikely that temperature fluctuations reach significant gas hydrate deposits
2. For longer wavelengths leading to deeper penetration into the seafloor, there is sufficient time for pressure to dissipate so that no significant overpressure is predicted to build up.

DISCUSSION AND CONCLUSIONS

First, we acknowledge that we still don't have any direct evidence that eastern Rock Garden and Ritchie Banks RB1 are *currently* being eroded. However, past erosion followed by current non-sedimentation would still leave open the question why both ridges happen to flatten out in the depth range of the current ZIS.

Ritchie Banks

RB4's crest is most likely above the ZIS but the bathymetric data show a large area with relatively low dip within the ZIS. This morphology is similar to that of western Rock Garden with a peak "sticking out" over a larger, flatter area within the ZIS. Furthermore, RB3 also displays a relatively flat, large area within the ZIS, depending on the choice of phase boundary, with a small peak above it (Figure 1). It is therefore possible that seafloor erosion close to the TGHS takes place at other ridges, albeit with less convincing evidence than for eastern Rock Garden and ridge RB1 (western Ritchie Banks).

Unlike Rock Garden, the eastern flanks of Ritchie Banks are not smooth – they show several slump blocks that appear to slide as whole blocks. Modeling is currently under way to investigate if the BGHS may be involved in facilitating these slides [26].

Temperature fluctuations

The increased wavelengths and amplitudes of the temperature fluctuations makes it more likely that repeated dissociation and formation of gas hydrate takes place beneath the ridge crests. Temperature fluctuations over 450-day cycles are predicted to penetrate the seafloor down to ~6 m (Figure 8), compared to the ~3 m for 160-day cycles [5]. This makes it more likely that the temperature signal reaches gas-hydrate-bearing layers in particular close to the seep sites where shallow sulfate reduction zones indicate high methane flux and by inference, shallow gas hydrate occurrence.

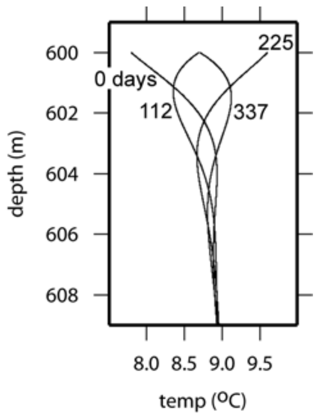

Figure 8: Penetration of temperature signal into the seafloor assuming a 450-day sinusoidal bottom-water temperature signal with an amplitude of ±1.2 ºC. Seafloor at 600 m water depth. Temperature profiles after 0, 112, 225, and 337 days. Rock properties as in ref. [5].

Gas hydrate formation in mudstones?

The link between repeated gas hydrate "freeze-thaw" cycles and seafloor weakening may need to be re-considered. Most current models of gas hydrate formation focus on porous media with reasonable porosities and permeabilities. Should mudstone be prevalent beneath Rock Garden, these models may not be appropriate. Mudstones display little primary permeability; however, if fractured, they tend to exhibit significant secondary (or structural) permeability. The importance of structural permeability on pore pressure along the Hikurangi margin has been documented by earthquake-related studies [27]. Gas hydrate formation in consolidated mudstones still needs to be understood. Capillary forces during gas hydrate formation in pores are thought to be similar to those of water ice. To minimize interfacial free energy (or surface tension), the surfaces of hydrate or ice crystals in narrow pores tend to be curved, "preferring" larger spherical forms (Figure 9). These capillary forces are significant, and are understood to result in displacement of grains in soft, fine-grained sediments [28-31]. We now speculate that capillary forces in consolidated mudstones could lead to fracturing and/or dilation of existing fractures, ultimately decreasing the strength of the seafloor. In this case, the ice-like growth of hydrate crystals during *formation* would push aside the walls of thin fractures as opposed to overpressure from volume expansion caused by the release of gas during *dissociation* in the original model [5]. Dissipation of overpressure during gas hydrate dissociation would not affect this process. On the other hand, capillary forces are also linked to hysteresis – in fine-grained sediments, gas hydrate formation may require up to several degrees Celsius cooler temperatures than its dissociation – and both curves lie below the phase boundary in water [30, 31]. Significant hysteresis would make repeated dissociation and formation of gas hydrates less likely because large temperature fluctuations would be required. It is particularly tempting to implicate capillary forces during gas hydrate "freeze-thaw" cycles in fracturing of mudstones because repeated freezing is an established laboratory procedure for disaggregating mudstones [32].

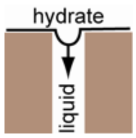

Figure 9: Conceptual model of hydrate growth into cylindrical pore throats. The capillary forces that need to be overcome for growth of the hydrate crystal depend on its curvature (geometries for hydrate dissociation are different; after ref. [30]). We speculate that similar processes take place for hydrate growth in fractures, which may ultimately "push away" the walls of the fractures.

Carbonates and sand layers

Rock composition still remains a wild card for understanding possible erosion mechanisms on Rock Garden. The apparent abundance of carbonates that "cement" the crest of Rock Garden would be predicted to strengthen the ridge. On the other hand, if carbonates are equally prevalent on the ridge flanks, the argument is a relative one – all that our hypothesis requires is weakening of the ridge crests compared to the flanks. It is possible however that even if mudstones are dominant on Rock Garden, sand layers control the supply of methane for gas hydrate formation, similar to Horizon A, an ash layer on Southern Hydrate Ridge that is thought to provide much of the more deeply sourced gas for hydrate formation [33].

Gas columns

The ubiquitous presence of seismic high-amplitude regions that we interpret as shallow gas pockets beneath eastern Rock Garden adds another possible mechanism for seafloor weakening. Gas in hydraulically interconnected pores (or fractures) can build up significant pressure due to its buoyancy. Such gas columns beneath the BGHS have e.g., been implicated in the dilation of microfractures in soft sediments on the Blake Ridge opening pathways into the gas hydrate stability zone [34, 35]. We are currently conducting modeling to estimate whether similar processes may take place in the consolidated rocks on Rock Garden. A key question for this process to be feasible on eastern Rock Garden is what determines the sub-horizontal top of the gas columns in particular beneath the western part of the ridge (e.g., Figure 7, Line T5, 0.8-2.2 km) where the seafloor is predicted to be within the ZIS and a well-defined BGHS should not exist above the gas layers.

Escape of gas

We do no longer think that an escape of gas after dissociation leading to a lack of gas for subsequent hydrate formation is a conceptual problem [5]: Gas hydrate deposits are quasi-steady-state systems, with methane loss into the ocean being compensated by supply from below. Repeated hydrate formation and dissociation would simply superimpose a periodically open “valve” onto the steady-state flow of methane through hydrates. Methane is released episodically while dissociating during warm-water periods whereas the “valve” would be shut during cold-water periods. In other words, even if all of the methane close to the seafloor escaped into the ocean during dissociation, it would be replenished from below – the gas hydrate system does not need to be re-formed “from scratch”.

Finally, we speculate that such a “valve” related to cooling and warming of water temperatures may lead to ephemeral release of methane on vent sites of Rock Garden, a question that would require long-term monitoring for testing. A discussion on this topic is beyond the scope of this paper.

Conclusions

The coincidence between BSR pinchouts and flattened crests of two, possibly three, ridges lets us implicate the TGHS in the ocean in seafloor erosion. Two mechanisms have previously been suggested for linking the TGHS and seafloor weakening [5] – repeated slumping at the BGHS during uplift and repeated pore volume expansion and contraction due to the release of gas during gas hydrate dissociation. We here add two other possible causes for seafloor weakening, capillary forces during hydrate formation and dilation of fractures above overpressured gas columns. Many of the data from those cruises are still being evaluated and we expect more insights into the processes that shape Rock Garden and Ritchie Banks in the future.

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