Gas escape features off New Zealand: Evidence of massive release of methane from hydrates

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[1] Multibeam swath bathymetry data from the southwest margin of the Chatham Rise, New Zealand, show gas release features over a region of at least 20,000 km^2. Gas escape features, interpreted to be caused by gas hydrate dissociation, include an estimated a) 10 features, 8–11 km in diameter and b) 1,000 features, 1–5 km in diameter, both at 800–1,100 m water depth. An estimated 10,000 features, ~150 m in diameter, are observed at 500–700 m water depth. In the latter depth range sub-bottom profiles show similar gas escape features (pockmarks) at disconformities interpreted to mark past sea-level low stands. The amount of methane potentially released from hydrates at each of the largest features is ~7*10^{12} g. If the methane from a single event at one 8–11 km scale pockmark reached the atmosphere, it would be equivalent to ~3% of the current annual global methane released from natural sources into the atmosphere. **Citation:** Davy, B., I. Pecher, R. Wood, L. Carter, and K. Gohl (2010), Gas escape features off New Zealand: Evidence of massive release of methane from hydrates, *Geophys. Res. Lett.*, *37*, L21309, doi:10.1029/2010GL045184.

1. Gas Escape Features on the Sea-Floor

[2] Multi-beam swath bathymetry data collected between 1994 and 2010 covers approximately 20% of the Chatham Rise. The data reveal a >20,000 km^2 region, between 173°–180° E longitude, on the south-western Chatham Rise flank in water depths of 500 to 1,100 m, that is rich in sea floor depressions (Figure 1) [*Gohl*, 2003; *Nodder et al.*, 2009]. Sea floor pockmarks occur between 500 and 700 m depth (Figure 2). They are circular, remarkably uniformly distributed, typically 150 m in diameter, 2–8 m deep, and occupy about 1% of the sea floor. No pockmarks are identified between 700 and 800 m. Larger, irregularly shaped but dominantly ellipsoid features are estimated to occupy about 50% of the sea floor between 800 and 1,100 m (Figure 1b of Text S1 of the auxiliary material).[1] These have a pronounced rim, commonly display a central dome, are typically 1–5 km in diameter, and are 50 to 150 m deep. Amplitude washout in the sediment beneath the near-circular shallow pockmarks on seismic sections (Figure 2), and the same longitudinal range for all the sea floor depressions lead us to interpret both classes of feature as pockmarks formed by a sudden release of gas [*Judd and Hovland*, 2007]. The 1–5 km diameter structures are among the largest recorded sea floor pockmarks [*Cole et al.*, 2000; *Loncke and Mascle*, 2004].

[3] A third class of morphological features also occurs at 800–1,000 m: near circular depressions with diameters of 8–11 km. To our knowledge these are over twice the size of any known pockmarks [*Judd and Hovland*, 2007]. Two such giant features are observed in swath bathymetry (Figure 1). They are characterised by an annular ring 1,500 m wide, 80 to 100 m deep and asymmetric in cross-section. The outer ring slope is ~15°, and the inner slope ~2°. The two mapped large near-circular features have a gap in the northeast quadrant of the annular ring. A seismic reflection line [*Mobil International Oil Company*, 1979] crosses one of the 8–11 km features and shows no evidence of volcanic intrusion, deep-seated faulting, impact craters, salt tectonics, or mud diapirs that might account for their formation. This makes a sudden release of gas, perhaps coupled with slumping for the deeper two classes, a likely cause for formation of all three feature classes.

[4] Formation of gas escape features (GEF's) may be influenced by oceanographic conditions. The two classes of large GEF's lie in the Antarctic Intermediate Water (AAIW) depth range (500–1,300 m) [*McCave and Carter*, 1997] and occur south of the Sub-Tropical Front (STF). The STF position on the Chatham Rise is determined by the strength and location of zonal currents and the Chatham Rise topography. The modern STF southern zonal current, the Southland Current, intersects the Chatham Rise at c. 800 m water depth [*Chiswell*, 2002]. Most of 1–5 km and 8–11 km diameter GEF's lie immediately north of or straddle a 100–200 m high steeper slope ('R' in Figure 1) that conforms with the 1,000 m isobath. High resolution seismic data (not shown) confirm that this slope is erosional. A few isolated 1–5 km GEF's occur below 'R'.

2. Sub-Sea-Floor Gas Hydrate Features

[5] We interpret a high-amplitude reflection beneath shallow GEF's on a "Parasound" profile [*Gohl*, 2003] as a bottom simulating reflection (BSR), typical of a gas layer at the base of the gas hydrate stability zone (BGHS; Figure 2) and a key indicator of gas hydrates. The depth of the high-amplitude reflection ('BSR' Figure 2) beneath the sea floor matches the predicted depth of the BGHS using a temperature gradient of 0.04 °C/m and a sea floor temperature of

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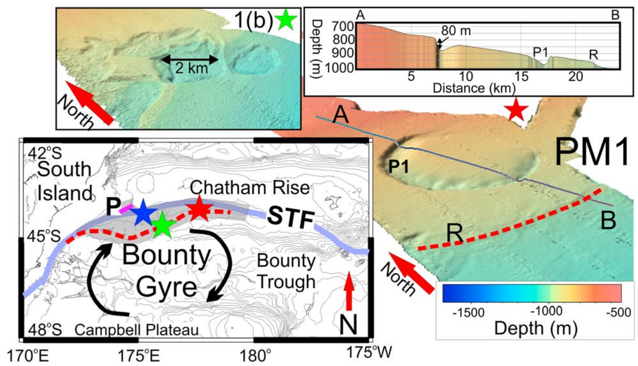

Figure 1. Perspective view of gas escape structure PM1 (red star in inset map) viewed from SW. The cross-section shows that annular pit P1 is c. 80 m deep, 1,500 m wide and has a 10 km annular diameter. Inset 1b shows intermediate-scale pockmarks (green star in inset map). STF = Subtropical front. Red dashed line marks the coincident 1,000 m contour, crest of slope 'R' and possible northern limit of STF core in glacial periods. The gray shaded area on the inset map marks the extent of GEF's mapped on the southwest Chatham Rise. Contour interval is 250 m for inset map. Line 'P' (pink) indicates the location of the Parasound profile in Figure 2. Swath data is from NZ OS2020 surveys [*Nodder et al.*, 2009].

6° C [*Chiswell*, 2002] over a water depth range >100 m, strongly suggesting that this reflection is a BSR. Gas hydrate stability is relatively sensitive to pressure at these moderate water depths and the depth of the BGHS beneath the seafloor increases significantly with increasing water depth. It would be an unlikely coincidence if a stratigraphic reflection mimicked the shape of the BGHS over a 100 m range of water depths. A thermal gradient of 0.04 °C/m is consistent with Neogene volcanic activity on this part of the Chatham Rise [*Herzer et al.*, 1989; *Wood et al.*, 1989]. The plausibility of the geothermal gradient and the coincidence of the upper depth limit of the shallow pockmark class (500 m) with the predicted upper limit of gas hydrate stability for modern ocean temperatures (550 m) provide strong indirect evidence of gas hydrates beneath the pockmarks.

3. Paleo-Pockmarks on Peak Glacial-Interglacial Transitions

[6] The "Parasound" sub-bottom profiler data also show features that we interpret as buried pockmarks. Between 600-700 m water depths these pockmarks are observed on high amplitude subsurface reflectors, some of which are unconformities. The pockmark morphology persists in the overlying sedimentary layers until the features are filled, but new GEF's are not observed on the reflection horizons between the high-amplitude reflectors.

[7] Chatham Rise carbonate content is greatest in interglacial periods, typically 40–80%, but reduces to <20% in the glacial periods [*Schaefer et al.*, 2005]. The resulting contrast in acoustic velocity between the relatively soft calcareous sediments (interglacial) and more compacted terrigenous muds (glacial) give these deposits distinctive reflection characteristics. Comparison of the history of oxygen isotope variation (Figure 2) with the amplitude variations observed on the "Parasound" sub-bottom profiler data enables matching of climate cycles over at least the last 0.6 My. We interpret the high-amplitude reflection horizons to correspond to

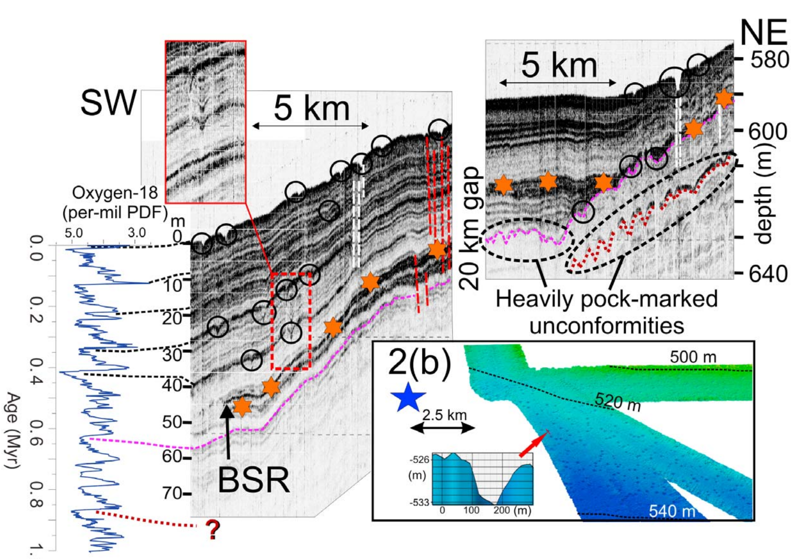

Figure 2. Segments of Parasound profile [*Gohl*, 2003] ('P' in Figure 1) and oxygen isotope record [*Hall et al.*, 2001]. Orange stars mark the predicted BGHS depth assuming sea floor temperature of 6° C and sedimentary temperature gradient 0.04° C/m. Sub-sea floor depths of the Parasound data assume a compressional-wave velocity of 1,600 m/s. New GEF's (black circles) are apparent only on disconformities. Red dashed vertical lines are faults. White vertical lines are areas of amplitude washout. A heavily pock-marked, major disconformity, correlated with the 0.62 Ma (MIS16) glaciation, is highlighted by a pink dashed line This glaciation marked the beginning of the modern period of extreme (c.120 m) sea-level fluctuations. Inset 2b shows nearby small-scale pockmarks (GEF's) on multibeam swath bathymetry data [*Nodder et al.*, 2009] (blue star in Figure 1 inset map).

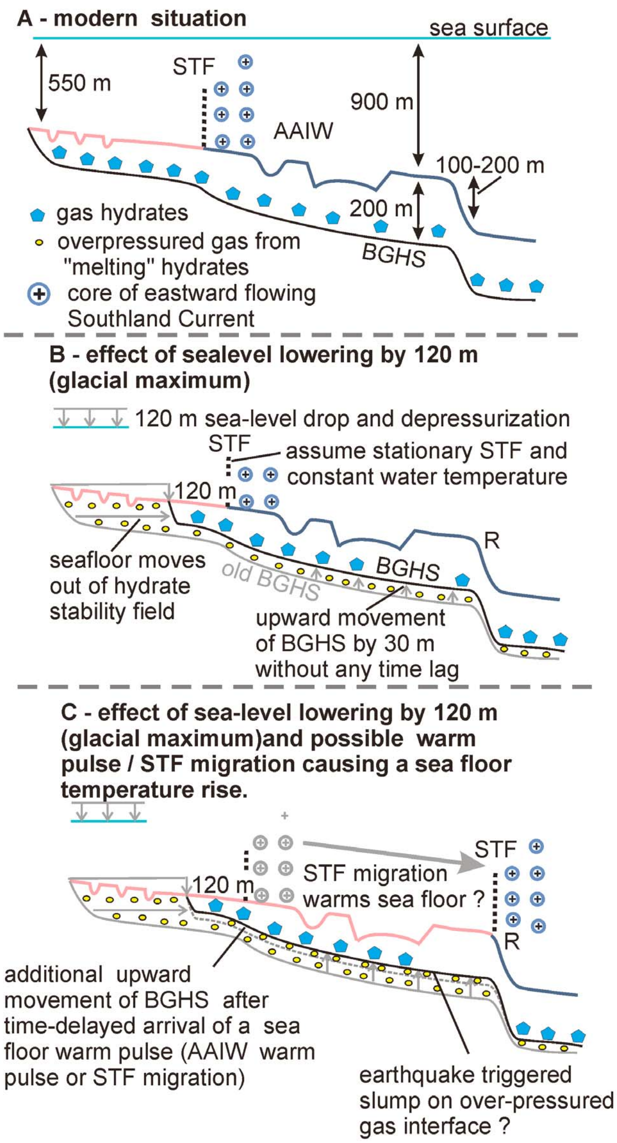

Figure 3. Concept figure of possible glacial-interglacial gas-hydrate dissociation on the southwest Chatham Rise. STF = Subtropical Front, AAIW = Antarctic Intermediate Waters, BGHS = base of gas hydrate stability. (a) The modern situation is a baseline. The bulge of the BGHS beneath the STF reflects cooler water temperatures in AAIW. (b) Sea level lowering leads to a downward movement of the top of gas hydrate stability, moving much of the sea floor in the smaller pockmark field out of the hydrate stability zone. The BGHS moves upward, adjusting immediately to pressure changes. This situation could occur during glacial maxima, but note the assumptions of constant bottom water temperatures and a stationary STF. (c) Fluctuations in the sea floor temperature due to STF migration or interglacial warming lead to an upward movement of the BGHS beneath the regions of intermediate and giant GEF's after a significant time delay. Note that the upward movement of 10 m for a 1 °C increase of water temperatures assumes a cyclic variation of period c. 15,000 years. See text and auxiliary material for details and further discussion. The over pressured gas interface could be a possible slump interface, affecting the morphology of the largest pockmarks.

peak glacial stages and subsequent glacial-interglacial transitions prior to the resumption of higher carbonate sedimentation in interglacial periods. Sedimentation rates estimated from sediment cores in the western Bounty Trough vary between 1.9–11.8 cm/ka for marine isotope stages 1 and 2 [*Carter et al.*, 2000], consistent with 2.0–9.3 cm/ka interpreted for "Parasound" profile 'P'.

4. Formation Mechanisms of GEF's

[8] We suggest that the three types of GEF's reflect different stages of gas hydrate dissociation and present three possible mechanisms for their formation (Figure 3): (1) dissociation of hydrates from the sea floor downward as a cause for small GEF's, (2) upward movement of the BGHS beneath the larger GEF's due to depressurization, and (3) upward movement of the BGHS due to bottom-water warming. Based upon 20% swath coverage we estimate total numbers of 10,000, 1000 and 10 for the smallest to largest GEF feature classes.

[9] The field of small GEF's is close to the upper limit of the top of gas hydrate stability (TGHS) in the ocean (Figure 3a). We speculate that these GEF's formed when changes in global sea level, perhaps combined with changes in ocean temperature (see discussion below), moved the gas hydrate stability zone. A ~120 m drop in sea level during major glacial stages, assuming constant bottom water temperature, would move the TGHS downward by the same amount with respect to the sea floor. This would lead to gas hydrate "melting", the release of over-pressured gas and, we propose, the formation of GEF's (Figure 3b). Alternatively, an increase of bottom water temperature by 1° C would lead to a downward movement of the TGHS by ~50 m shortly after the formation of glacial disconformities. This process is similar to active methane release west of Svalbard that has been linked to a down-slope movement of the top of gas hydrate stability since 1970 [*Westbrook et al.*, 2009]. Temperature variations at the sea floor along the Chatham Rise above 1,100 m depth are unknown, but alkenone analysis of core MD972120 (water depth 1210 m) [*Pahnke and Sachs*, 2006] indicates that glacial-interglacial sea surface temperatures along the southern Chatham Rise could have varied by 3–6° C.

[10] In the 800–1,100 m water depth range, dissociation of gas hydrates is predicted only at the BGHS. Depressurization from a ~120 m sea level drop at constant bottom water temperature would lead to an upward movement of the BGHS by ~30 m with respect to the sea floor, causing dissociation of hydrate to over-pressured gas at the BGHS [*Xu*, 2004]. Likewise, warming of bottom waters by 1° C as part of a periodic variation with a 40,000 year period would lead to a 0.65° C increase of temperatures at the BGHS, shifting it upward by 20 m (Figure 3c) (see auxiliary material).

[11] The slope 'R' (Figure 1) has likely been eroded either by the present day STF or, we speculate, by the STF core which migrated southward during glacial maxima [cf. *Carter et al.*, 2004] when currents in the Bounty Trough (e.g. Bounty Gyre - Figure 1) are expected to have been more vigorous [*McCave et al.*, 2008; *Neil et al.*, 2004]. If the latter occurred, then bottom water temperatures in the region of the giant pockmarks may have increased during glaciation (cf. 2–3° modern-day temperature difference across the STF [*Chiswell*, 2002]).

[12] Sea surface temperatures off Chatham Rise warmed abruptly by about 1° C several times between 35 and 21 ka [*Pahnke and Sachs*, 2006; *Barrows et al.*, 2007]. At depth, the benthic δ^{18}O record for AAIW also underwent episodic changes ~0.25‰ that may represent warming and cooling of ~1° C [*Pahnke and Sachs*, 2006]. The record of the underlying Circumpolar Deep Water reveals at least one prominent positive temperature change of ~1° C magnitude in the last glaciation [*Elderfield et al.*, 2010].

[13] It is important to note that there is a significant time lag between temperature changes at the sea floor and the arrival of interacting attenuated temperature pulses at the BGHS 200 m beneath the sea floor (for a 40,000-year period, the time lag is ~2,700 years; see auxiliary material). We suggest that the two types of GEF's in the 800–1,100 m depth range may have formed as the result of the interaction of two processes, 1) a pressure decrease from sea-level lowering, to which the BGHS adjusts instantaneously, and 2) bottom water temperature increases that would reach the BGHS after a significant time lag.

[14] The large size of the 8–11 km diameter GEF's and their proximity to erosional slope 'R' suggests slumping, perhaps seismically triggered and translation along the overpressured BGHS, may have contributed to their morphology (Figure 3c). However, their near-circular shape, low regional slope (0.1–1.5°), and their interior morphology are atypical for slump features [*McAdoo et al.*, 2000]. Bottom currents may, however, have modified GEF morphology and could account for the northeast gap in the largest pockmarks. The smaller (1–5 km) and more irregularly shaped GEF's extend ~20 km north from the top of slope 'R' and are therefore unlikely to be affected by any associated mass movement.

5. Gas Release Implications

[15] Release of methane, a potent greenhouse gas, from "melting" gas hydrates has long been suspected of significantly affecting climate change [*Kennedy et al.*, 2001; *Max and Dillon*, 2002]. Methane gradually released from oceanic gas hydrates is oxidized to CO_2 in the water column [*McGinnis et al.*, 2006] or sequestered in carbonates on or near the sea floor [*Zhang and Lanoil*, 2004] and thus generally only affects climate indirectly.

[16] If the giant GEF's were formed by a single, sudden release of large amounts of methane from destabilizing gas hydrates and underlying free methane, then the relatively shallow water depth and large volume of gas would favour ascent to, and release into, the atmosphere [*Kennett et al.*, 2003] and possible consequent affect on climate. To evaluate the likelihood of such an event, we conservatively estimated that the amount of methane released from a single 10 km diameter pockmark due to a 120 m drop in sea level. Assuming an average gas hydrate saturation of 5% of pore space and a porosity of 50%, similar to values measured for gas hydrate deposits on Blake Ridge [*Paull et al.*, 1996], and a diameter of 10 km, then the resulting upward movement of the BGHS by 30 m would release ~$7*10^{12}$ g of methane. This is ~3% of the current annual global methane release into the atmosphere from natural sources (see Environmental Protection Agency, Methane - Sources and emissions, available at http://www.epa.gov/methane/sources.html, 2010) (see auxiliary material for further details and further assumptions). Furthermore, we speculate that because of the sheer size of the pockmark regions, significant amounts of methane would be released during glacial cycles that might affect ocean chemistry similar to that suggested for the Arctic Ocean [*Westbrook et al.*, 2009, and references therein].

6. Conclusions

[17] A >20,000 km^2 field of sea floor depressions on the southwest flank of Chatham Rise, New Zealand provides evidence of episodic formation of GEF's during glacial-interglacial cycles. We interpret dissociating methane hydrates as the most likely cause of gas release. Furthermore, giant GEF's in this area are twice the size of the largest pockmarks known to us from the literature. If released in single events and if gas reached the atmosphere, then expulsions from these features may have injected large quantities of methane into the ocean and atmosphere.

[18] Dissociation of gas hydrates at the deep-water BGHS is dominantly the result of pressure decrease, which is greatest at peak stage glaciation, due to the accompanying ~120 m drop in sea-level. The pressure effect is potentially enhanced by the coincident arrival of warm temperature pulses at the BGHS. The low slope angle (< 1.5°) and low rates of modern sedimentation on the shallow southern Chatham Rise may have provided a stable environment that preserved the GEF's over multiple glacial-interglacial cycles. If similar features formed globally, then the cumulative release may have significantly increased the global methane supply into the ocean and atmosphere at the peak of glaciations and potentially contributed to the rapid transition to warmer post-glacial conditions (e.g. clathrate-gun hypothesis [*Kennett et al.*, 2003]).

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