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Title: First evidence of widespread active methane seepage in the Southern Ocean, off the sub-Antarctic island of South Georgia

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Abstract: An extensive submarine cold-seep area was discovered on the northern shelf of South Georgia during R/V Polarstern cruise ANT-XXIX/4 in spring 2013. Hydroacoustic surveys documented the presence of 133 gas bubble emissions, which were restricted to glacially-formed fjords and troughs. Video-based sea floor observations confirmed the sea floor origin of the gas emissions and spatially related microbial mats. Effective methane transport from these emissions into the hydrosphere was proven by relative enrichments of dissolved methane in near-bottom waters. Stable carbon isotopic signatures pointed to a predominant microbial methane formation, presumably based on high organic matter sedimentation in this region. Although known from many continental margins in the world's oceans, this is the first report of an active area of methane seepage in the Southern Ocean. Our finding of substantial methane emission related to a trough and fjord system, a topographical setting that exists commonly in glacially-affected areas, opens up the possibility that methane seepage is a more widespread phenomenon in polar and sub-polar regions than previously thought.

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To the

Editor of Earth and Planetary Science Letters,
Prof. Dr. Gideon Henderson

Submission of a revised manuscript to 'Earth and Planetary Science Letters'

Dear Prof. Dr. Gideon Henderson,

Thank you very much for the processing of our manuscript and your decision letter from June 8, 2014. Our revised manuscript along with a track-changed copy and a detailed response letter is enclosed herewith. We gratefully acknowledge the very constructive comments and suggestions of all three reviewers, which helped to improve the quality of the manuscript. We highly appreciate your evaluation that the manuscript is of sufficient interest to a broad scientific community.

As you will see from our response letter and the track-changed copy, we agree with most of the changes suggested by reviewer #1 and #2. All wording suggestions and the reference suggestions have been implemented.
In acknowledgment of the concern of reviewer #3, we did several changes not to extrapolate unreasonably from our study site and not to oversell the broader significance of our results. We modify the title to state upfront the location of the study; however we disagree with reviewer #3 in that South Georgia might not be located in the Southern Ocean. To clarify, we included in the text (introduction) the commonly accepted oceanographic definition of the Southern Ocean as including the water masses south of the Polar Front, and support this with references. We do nonetheless also mention the seep findings offshore Chile, New Zealand and Australia, even though these are not located in Southern Ocean, as defined above.

We hope that the manuscript is now acceptable for publication in Earth and Planetary Science Letters and are looking forward to hearing from you soon.

Yours sincerely,

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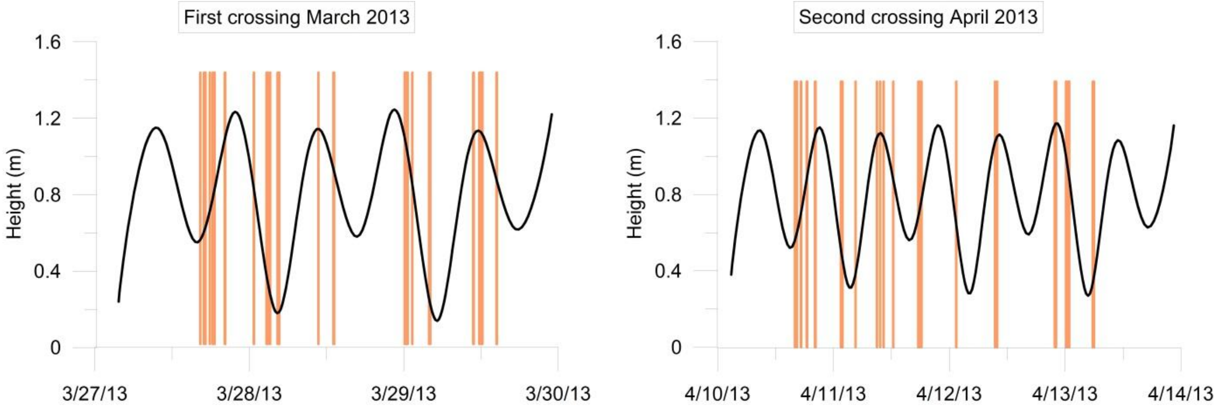
Response Letter

Reviewer #1

Questions:

Line 190 - You mention that flares only appear intermittently. Are these appearances tidally related? Did you check if the appearance of the flares was related to the tidal stage?

→ This is a very interesting point and it would be great if we could show a tidal correlation. However, our two short surveys do not really allow for such an analysis as they were not systematically conducted for that purpose. Now that we are aware of how flares are distributed, future studies can actually nicely add to answer this question. Nevertheless, we plotted the times of flare observations (red bars in the figure below) in combination with the tides in a time-series (tidal information downloaded from http://tides.mobilegeographics.com/, Station Leith Harbor at South Georgia). Although not to be seen as a systematic correlation, a convincing correlation would probably also show up if flares have been restrictedly detected during the same tidal phases. However, this is apparently not the case as illustrated in the figure below. In order to clearly state that this is still an open question we added a sentence in the discussion chapter (lines 408-412): 'Due to the nature of our surveys, we are not able to resolve possible factors modulating the discharge (e.g. tides, earthquakes, storms events, bottom currents, decomposition of subsurface gas hydrates), as documented in more intensively investigated seep areas such as Hydrate Ridge (Kannberg et al., 2013), Coal Oil Point (Boles et al., 2001), Bush Hill (Solomon et al., 2008), or at seeps at the Northern Cascadia Margin (Lapham et al., 2013).' and expanded the respective sentence in the Conclusion and Outlook chapter (lines 460-462): 'Detailed surveys are required to determine further distribution, variability, and total abundance of such methane seep sites,..'



Line 225 - 228. Consider combining figure 5 with figure 6a & b. I think it would be easier to read.

→ We prefer to separate these figures due to the fact that the geometry of three figures makes it difficult to combine them without wasting space and to arrange them with the maximum sizes needed for the reader to see the important features.

Comments in the annotated pdf:

Line 48: we deleted 'at'

Line 65: Maybe better as ...possible contributor to atmospheric methane concentrations. → we changed accordingly the wording

Line 91-92: We deleted accordingly
Line 97: we deleted ‘recognized’
Line 154-156: we deleted accordingly and changed the wording
Line 185: changed to ‘did not’
Line 190: changed to ‘surveyed’
Line 198: changed to ‘were’
Line 253: We added a reference to Fig. 7
Line 268: the reference had to be changed to chapter 4.1 to make sense
Line 268: ‘Strong’ was changed to ‘Significant’
Line 343-344: The Reviewer suggested deleting ‘whereas thermogenic light hydrocarbons by non-selective hydrocarbon cracking are not affected by significant isotope fractionation effects’, however, we think it is not redundant to mention just once the thermogenic methane characteristics, as we discuss the source of gas in this chapter.
Line 346: we changed to ‘are’
Line 403: changed to ‘agree’
Line 628: we deleted ‘to the’
Line 629: we use the expression combining, because actually two echograms of different frequencies are manually combined in one.
Line 633: we deleted ‘Map showing the’
Line 648: we deleted ‘up’
Line 649: we deleted ‘accordingly’ and changed the wording to ‘demonstrating’
Line 655: we changed to ‘suggested’
Line 662: we deleted ‘acquired’
Fig 4a: ‘m’ was changed to ‘mbsl’

Highlights:

Instead of the suggested change of bullet point: ‘Gas analysis resulted a composition of predominantly methane of microbial origin’ to ‘Gas analyses suggests methane of microbial origin’, we decided to also include the high organic matter sedimentation: ‘High input of organic matter leads to high rates of formation and emission of methane’.

Reviewer #2

Abstract Mention the bacterial matts. Also mention hypothesis that fjords have high deposition rates driving the seepage.
→ We included now the findings of bacterial mats ('Video-based sea floor observations confirmed the sea floor origin of the gas emissions and spatially related microbial mats.') and the hypothesis that high deposition rates drive the seepage (…, presumably based on high organic matter sedimentation in this region') .

45 – later was revisited (split verb)
→ changed
49 also have been found (split verb)
→ changed
53 can be explained partly (split verb)
→ changed
53 no comma after exploration
→ changed
55 not really. More numbers does not indicate its importance. Emissions estimates do.
→ We agree and changed 'locations discovered' to 'emission estimates'

59 Mau et al 2012 is not deep sea and thus not relevant to the deep sea. Delete. McGinnis does not talk about oxidation. Choose another citation for the oxidation. Also put the citation near the process, not at the end of the sentence.
→ We changed the citation to (Reeburgh, 2007; Valentine et al., 2001) for the oxidation process and cited (McGinnis et al., 2006) after mentioning the dissolution process.

58-63 – run on sentence. Split in two.
→ changed to two sentences

Schneider is not really a good reference for transport to the atmosphere from shallow water – the thermocline in the North Sea is rather unique. ESAS or COP seep field are better. Also, Schneider does not talk about storms except in terms of their relationship to the thermocline, which is a separate process. Again a poor citation. Shakhova et al. 2013 specifically measures the mass transfer from a storm on accumulated seepage methane in shallow waters.
→ We deleted the citation of Schneider v. Daimling and mentioned instead the paper by Shakhova et al., 2013, here and in the reference list.

Schmale et al does not talk about storms at all and notes that non-negligible transport only occurs for z<100 m, but their shallowest seep is 90 m, so this also seems a poor citation.
→ citation deleted

63 Westbrook argues no methane from their seeps in 2009 reach the atmosphere. Bad reference. Gentz is okay. The most extensive literature on shallow seepage is for the Coal Oil point seep field. Cite.
→ The citation Westbrook et al., 2009 was deleted. We included the Coal Oil Point seep field with appropriate references: (e.g. Clark et al., 2010; Mau et al., 2012).

Organization section 1. Since the geology comes before the seepage, why mention seepage first? Not saying you cant, but adding two or three sub headings and a little introductory paragraph to introduce the manuscript flow would be helpful. Specifically, the introductory paragraph should explain why someone not a “seepologist” should care. Maybe something about fluid migration, hydrocarbon accumulation indicators, important to chemosynthetic communities, and global warming (you are talking about methane getting to the atmosphere in the intro, but never mention that it is a greenhouse gas. Maybe cite IPCC.
→ We agree that the Introduction can be subdivided and structured the introduction as followed: general introduction (as suggested), 1.1 Marine methane seepage in the Southern Ocean, and 1.2 Regional setting of South Georgia.
→ We already mentioned that methane is a greenhouse gas, but we agree to emphasize the importance to better constrain the sources of the atmospheric methane inventory here and wrote a new paragraph in the first part of the Introduction and cited the IPCC.

In fact, having finished reading the manuscript, the conclusion also notes a number of questions of broader interest. I suggest you set the stage for your conclusion in a paragraph here.
→ We indeed reordered and reworded the introduction in order to strengthen the broader interest.

Also, add an intro sentence to each of the sub sections.
→We agree to start sub sections with an intro sentence, however also feel that each sub section is already nicely introduced.

85 use while in cases with a time sense. Change to although
→ changed
96 why are you mentioning warming here? The reader does not know. Suggest moving to the end of the paragraph and adding a sentence indicating why this is important to know for the reader.
→ We deleted the sentence entirely, because this information is actually not of much importance for the reader.

104 suddenly mentioning flares! Define. Also, distinct from bubble section. The manuscript is a report (or presentation or discussion, or …) on what you did, not what you did.
→We agree: the term ‘flare’ appears without definition. We added an explanation and definition in Line 55-56. In addition, we added a half sentence as well in the method section (lines 152-154) to explain the correlation between gas bubbles and high backscatter producing flares visible in echograms.

Again, here is where you explain why should the reader care. In this paragraph you can explain (extending our understanding of seep processes in the north to southern oceans, suggesting the need to re-examine overall budgets, whatever you like), just give the reader something….
→ We reworded the paragraph and added the suggested description about extending our understanding of seep processes. However, in order to not oversell our results as described by reviewer #3, we neglected stating something that extents too much.

115 define acronyms, please.

→ We added some more description for each software package, however, ATLAS, CARIS HIPS and SIPS and ESRI ArcMap are the official software names and not acronyms.

130 What is the OFOS? It sounds like a towed camera sled. Are there other instruments on it? CTD? I am wondering why you are calling it a system if it is just a camera on a sled? Do you have live video feed?
→ The OFOS is indeed an acronym, which is in the first sentence introduced (Ocean Floor Observation System). The name is not invented by us, but used for this specific sled and is called a system because it includes besides the camera two flash lights (iSiTEC UW-Blitz 250, TTL driven), three Laser, four LED lights and a Tritech Altimeter attached to the steel frame as well as the (USBL) Posidonia transponder. It has indeed a live video feed, which is not clearly mentioned but now included in this paragraph (lines 160-161). However, the live video could not be archived and, thus, the pictures were taken for post-cruise analyses.

140: to confirm, does the transmissometer record the SBE43?
→ No, the transmissometer records the beam transmission and the SBE 43 sensor records the oxygen concentration. We revised the sentence for more clarity.

145: Were samples analyzed onboard or back at the laboratory? If back at the lab, were the samples poisoned?
→ Samples were analyzed directly after recovery onboard, and have not been poisoned. We added 'onboard' for clarification.

183: "had no connection to the" to "were disconnected with the seafloor"
→ changed accordingly

184: primarily temporal variability - spatial implies either a mobile sediment bed, or close connectivity between vents such that flow through one vent shifted to another between vents in and out of the beams seafloor footprint. Please note footprint site here if you want to include the spatial explanation. My suggestion is to simply note temporal emission variability.
→ We agree, in this context spatial variability makes no sense, thus, we deleted this assumption.

184 Pulsing. I suggest transient. Given that the bubble trains are 20% of the water column depth, if "pulses", they are quite disparate. Moreover, do you have any indication they are cyclical on short time scales? That the vents are precisely the same? Etc.? Your footprint is fairly large, so it could be different vents in the same area. OR the same.
→ We agree and changed the expression to transient. The interpretation of correlation and timing of single pulses of bubble trains is indeed difficult due to the large footprint and we agree that we cannot definitely state if these pulses are sourced from the same sea-floor location.
→ As discussed above by the question of Reviewer #1 we are unfortunately not able with our dataset to discuss cyclical behavior in time scales of hours. Nevertheless, we did a first correlation of our seep findings with the tidal cycle (figure shown in the response to Reviewer #1) indicating the activity was no limited to a specific tidal stage. However, the surveys need to be done systematically in order to get a reliable conclusion.

204 “were also found” to “also were found”
→ changed
206 “The northern shelf was passed for hydroacoustic surveys twice in a roughly two week interval and” to “The northern shelf was surveyed with hydroacoustics twice in a roughly two week interval and”
→ changed
207 comma after investigations
→ changed

217 acoustic chimney – I agree that they could be sites for gas migration; however, this merits a citation, either here, in the discussion, or best, in the introduction – add a sentence at line 104
→ We agree and added a sentence in the introduction (lines 56-59): ‘… They often correlate with sub-seafloor anomalies characterized by blanking in the echograms. Such anomalies in the sediment can be caused by upward migrating fluids transporting light hydrocarbons and, thus, may represent gas chimneys fueling the seafloor seepage sites (Judd and Hovland, 1992).’

226 “inspections were thus performed with an” to “thus inspections were performed at an”
→ changed
234-235: “single gas bubbles emanating from” to “gas bubbles emanating singly”
→ changed

237 I am confused. How to 2 or 3 bubbles emanate singly over a minute? Were they pulses?
→ we indeed found that difficult to describe. Gas bubbles emanated either singly or in few times 2 or 3 close together. We thought 2 or 3 bubbles are not enough to describe them as a pulse and wrote therefore ‘small groups of 2 or 3 bubbles’. We changed it as suggested to: ‘…where a single bubble or pulses of 2 or 3 bubbles close together rose from the seabed.’

246 “was slightly elevated” to “was elevated slightly”
→ changed
248 “were located” They may not be there any more…
→ We agree and changed
305 mats, (add comma)
→ changed

318-357 I know this section is essentially indicating that a geologic structure (fjords) is controlling the location of seeps, but I think it would be beneficial if you could comment on whether smaller geologic structures also are controlling locations, aka as noted in Naudts et al 2006, as such structures are also important to ensure fluxes are larger than the microbial filter. This section also should be broken in two. One section is the source (high sedimentation rates) and a second section is geologic control – where, not why.
→We agree to include a short paragraph about smaller geologic structures and to mention the work by Naudts et al., 2006. We attached the paragraph following the part about the source to not change the flow of the discussion (lines 386-395). As we do not have seismic information, we are further limited in sub-surface interpretation of geologic structures and therefore briefly comment on morphological features observed in the bathymetric data within the fjord.

369 I think you could posit that it is likely that they change seasonally and annually (rather than just may be possible). State as a hypothesis, if you like.
→ we changed the wording to 'it is likely..'

371-379 – should acknowledge that you also may have been there at a time when it was relatively senescent. See Bradley et al. 2010 showing how lower emissions were in the SB Seeps in 1995 than currently. See comment above.
→ This is an important point we should definitely add at the end of the paragraph (line 422-425): 'In addition, it is conceivable that our observations occurred in a period of minor seepage activity. For example, observations made for the Coal Oil Point seep field revealed interannual changes between 1990 and 2008, which have been related to internal geological processes (Bradley et al., 2010).' And added Bradley et al., 2010 in the reference list.

377 change to non–negligible quantities of methane, or define more clearly what you mean by significant.
→ We agree and changed

388 Wuest et al has nothing to do with seep bubbles, but is purely air bubbles, so this citation has nothing to do with replacement of methane. Other citations fine.
→ We deleted the citation, here and in the reference list

389 Rise velocity
→ changed
402 bottom-water consumption (not sea floor consumption)
→ changed

Reviewer #3

The title "First evidence of widespread active methane seepage in the Southern Ocean" is technically not correct as the respective research area is not beyond 60° latitude being the boundary criterion of the Southern Ocean. Neither should the seepage along a 100nm spanning survey area be classified as "widespread" when being set in relation to the huge Southern Ocean.

→ We discussed about both expressions and although disagreeing with the reviewer, we extended the title to not oversell our study: 'First evidence of widespread active methane seepage in the Southern Ocean, off the sub-Antarctic island of South Georgia'.

→ However, we acknowledge that the 'Southern Ocean' needs to be defined in our manuscript when we use the expression of a first finding. Although the political boundary is set to 60° S, in our opinion the geographic definition using the oceanographic setting is much more common in scientific studies dealing with the water masses. Therefore, the Southern Ocean is defined to extent south of the Polar Front, which marks a strong separation in water masses and currents. We added a short definition in the Introduction chapter for clarification (lines 79).

Consider that there are virtually no land masses in the Sub-Antarctic region, hitherto missing finding of methane seepage in this part of the planet is not very surprising. If the authors would include e.g. New Zealand or Chile as a sub-antartic region as well, then their "first" finding is not true anymore.

→ We agree to mention the seep findings offshore Chile, New Zealand and Australia. Nevertheless, all of these seeps are located far more north and the respective geographic regions are classified as "temperate zone" and do not belong to the Sub-Antarctic (see table and figure below). We mentioned those additional findings in the Introduction chapter (lines 91-93).

Geographic region	**Area**	**Latitude (S)**	**Citation**
Antarctica	Weddell Sea, Larsen B	65.5°	Domack et al., 2005 Niemann et al., 2009
Sub-Antarctic	South Georgia	54.5° - 53.5°	This study
Temperate zone	New Zealand, Chatham Rise	45°	Davy et al., 2010
Temperate zone	Offshore Chile	45° - 35°	Oliver and Sellanes, 2005; Sellanes et al., 2008
Subtropical zone	New Zealand, Hikurangi margin	42°- 40°	Several
Temperate zone	Australia, Bass Strait	40°	Logan et al. 2010 and references therein

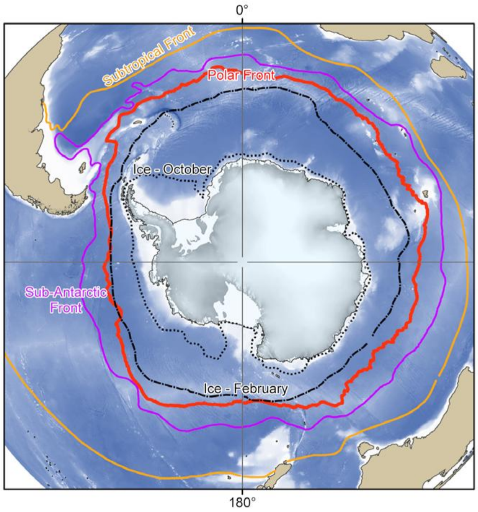


Figure from Griffiths, 2010

I understand the remote research area is difficult to be assessed, but this criterion should not lead to overestimating the scientific significance of finding gas seepage here. The authors provide references in the article manifesting high and rapid organic input in this part of the ocean (line 100). The consequence is there is no big surprise about methane seepage. If seepage would be a surprise, the authors should provide supporting arguments for that e.g. are the organic compounds for methanogenesis substantially different in this part of the world, why? But this question was not scope of their sampling and the authors conducted a standard work similar to many previous field studies.

→ Seepage was not known around South Georgia and such a widespread occurrence was actually surprising. Furthermore, only due to the isotopic measurements we could state it was biogenetically sourced. It could also well be to infer migration of deeper thermogenetically sourced methane (which is also not absolutely ruled out as stated in the conclusion).

One could speculate about the potentials in the southern ocean in general providing similar settings (with high C-Org fluxes), but this is not covered by this study. Neither the authors present a discussion about the huge Antarctic continental shelves dominating the Southern Ocean.

→ We agree that areas with high organic matter input and generally also the Antarctic shelves should be mentioned when discussing similar settings, which we now caught up for in the Conclusion and Outline chapter (lines 466-471).

Overall, this work has to be considered a local study about yet another methane seepage site. No new or unexpected seepage related processes have been identified. The conclusions about seepage processes drawn here were reported before in methane seepage related publications, except for the fact that benthic seep communities in the Southern Ocean may be different. However, this statement lacks on a data base and was not focus of the study as only 400m seafloor observation were conducted.

→ Our manuscript is a report on a local study, but due to the findings we want to emphasize the possibility of further seep areas in this area/related to similar geological settings. However, we do not want to extrapolate too much, but just want to enable future expeditions focusing on fluid flow in such areas to be aware about this possible relation between geological setting and seep distribution.

There are still a lot of uncertainties if and how submarine gas seepage contributes to the atmospheric methane budget. Exploration in remote areas and observations of gas emissions where none have been reported before are, therefore, of great value. Our study confirms that indeed if there is sufficient organic material, seepage occurs even in areas that are ocean dominated. Future research of the new seeps will identify if there are any differences between these ‘southern’ seeps in contrast to the ‘northern’ seeps in the Arctic, our work is thus of relevance to all geoscientist studying seep sites.

One of the authors highlights is: "Seepage might be more common in polar and sub-polar regions than previously thought"

I can not see how the authors can conclude that from their local study and the fact, that the Southern Ocean is very poor in continental slopes (except Antarctica, which is not being discussed).

→ As stated above, we agree on the one hand that we should mention the continental slopes around Antarctica (lines 466-471). On the other hand we still believe we can state the hypothesis that there might be numerous other seep areas both in southern but also (maybe even more due to the correct point that there are more extensive continental margins with extensive shelves) in northern polar and sub-polar regions, related to similar -glacially influenced- settings.

Due to the more local finding of methane seepage and the non-surprising results and conclusions the authors should move to another Journal. Their work was thoroughly conducted and is valuable as a base for future work. The paper is well written and structured, but does not fulfill the requirements for an EPSL publication from a scientific perspective. Moving this manuscript to another Journal could be conducted straight forward. Below I further list some shortcomings that should be considered for a re-submission to another Journal.

Details

L 59: in an introduction I would expect more classical citing instead of self-citations

→ We agree that only appropriate and accepted publications should be cited in the introduction and it should not be used for self-citations. Actually, we cited only a few times publications where one of the authors was the leading author as well, but, they were not chosen for self-representing: Graham et al., 2009 is essential to mention as this publication forms the base of our study with the description of the shelf morphology and Bohrmann et al., 1999 is the first description of the hydrothermal vents in the Bransfield Strait. We deleted Römer et al., 2012b and Mau et al., 2012.

L117-118: remove

→ We deleted the half-sentence mentioning the plotting of additional data

L214: as mentioned above the authors have to be more careful on the interpretation of their acoustic subbottom records

From Fig. 4c flares may indicate shallow gas below, but the acoustic blanking rather looks like being caused from the topography and subsurface morphology (especially on the right side of the picture). The seismic record is of moderate quality and gas pockets can not un-ambiguously be identified here.

→ We disagree. The subbottom single-beam echograms are from our experience of a very good quality and show nicely the subsurface structures and anomalies. The blanking is quite convincing to be caused by enhanced gas content, also reviewer #2 agrees on that point. Nevertheless, we state this interpretation now more carefully and as Reviewer #2 suggested, we defined and cited the occurrence of subbottom blanking and 'gas chimneys' now in the introduction (Lines 56-59).

L285-293: this is just a summary of the results! Delete

→ The first paragraph of the discussion is dedicated to mention all indications for active seepage together. All statements were indeed described in the result chapter individually but not in combination to demonstrate the convincing coalescence of all indicators. It also forms the base for the following discussion.

L359: this again is just a summary of the results, delete

→ See above

L377: I would term the low nano-molar concentrations "weak" in relation to other seepage sites worldwide. By the way, without presenting water current data the concentration values can hardly be interpreted in terms of seepage intensity.

→ Indeed, for real quantitative interpretation a more comprehensive investigation is needed and water current data should be discussed. As also suggested by reviewer #1 and #2 earlier, we changed the wording 'strong enrichment' to 'significant enrichment' and 'significant quantities' to 'non-negligible quantities'

L393: inappropriate citations: delete Greinert and McGinnes, 2006; delete Römer et al. 2012, instead include more classical papers, e.g. Leifer…

→ we changed the citation to: Leifer and Patro, 2002; McGinnis et al., 2006; Rehder et al., 2002

L414: "This finding is to our knowledge only the second cold seep detected in the (sub-)Antarctic region so far and the first observation" : No , see New Zealand, Chile…..

→ As stated above, we agree to mention the seeps discovered offshore New Zealand, Chile and Australia (Lines 91-93); however, they are not located in the sub-Antarctic region.

L415: I would not talk about "first observation in the Southern Ocean" as the research area is beyond 60°S. If the authors include e.g. New Zealand as a (sub-)Antarctic region as well there finding is not the second

→ As explained above, the study area is indeed located north of the political boundary of 60°S, but by conducting a scientific study we chose the oceanographic definition of the Southern Ocean to be south of the Polar Front, which covers our study area. Actually numerous publications about South Georgia even state in the title, that it is an island in the Southern Ocean:

- Borrione, I., & Schlitzer, R. (2013). Distribution and recurrence of phytoplankton blooms around South Georgia, Southern Ocean. Biogeosciences, 10(1), 217–231;
- Jones, E. M., Bakker, D. C. E., Venables, H. J., & Watson, A. J. (2012). Dynamic seasonal cycling of inorganic carbon downstream of South Georgia, Southern Ocean. Deep Sea Research Part II: Topical Studies in Oceanography, 59-60, 25–35;
- Murphy, E. J., Hofmann, E. E., Watkins, J. L., Johnston, N. M., Piñones, a., Ballerini, T., … Fretwell, P. (2013). Comparison of the structure and function of Southern Ocean regional ecosystems: The Antarctic Peninsula and South Georgia. Journal of Marine Systems, 109-110, 22–42.
- Whitehouse, M. J., Meredith, M. P., Rothery, P., Atkinson, a., Ward, P., & Korb, R. E. (2008); Rapid warming of the ocean around South Georgia, Southern Ocean, during the 20th century: Forcings, characteristics and implications for lower trophic levels. Deep Sea Research Part I: Oceanographic Research Papers, 55(10), 1218–1228.
- Young, E. F., Meredith, M. P., Murphy, E. J., & Carvalho, G. R. (2011). High-resolution modelling of the shelf and open ocean adjacent to South Georgia, Southern Ocean. Deep Sea Research Part II: Topical Studies in Oceanography, 58(13-16), 1540–1552.

In both definitions New Zealand is not located in the Southern Ocean.

First evidence of widespread active methane seepage in the Southern Ocean, off the sub-Antarctic island of South Georgia

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Abstract

An extensive submarine cold-seep area was discovered on the northern shelf of South Georgia during R/V Polarstern cruise ANT-XXIX/4 in spring 2013. Hydroacoustic surveys documented the presence of 133 gas bubble emissions, which were restricted to glacially-formed fjords and troughs. Video-based sea floor observations confirmed the sea floor origin of the gas emissions and spatially related microbial mats. Effective methane transport from these emissions into the hydrosphere was proven by relative enrichments of dissolved methane in near-bottom waters. Stable carbon isotopic signatures pointed to a predominant microbial methane formation, presumably based on high organic matter sedimentation in this region. Although known from many continental margins in the world's oceans, this is the first report of an active area of methane seepage in the Southern Ocean. Our finding of substantial methane emission related to a trough and fjord system, a topographical setting that exists commonly in glacially-affected areas, opens up the possibility that methane seepage is a more widespread phenomenon in polar and sub-polar regions than previously thought.

Keywords: Cold seeps, gas bubble emissions, methane seepage, South Georgia

1. Introduction

As methane is a potent greenhouse gas, considerable research efforts have been made to comprehend its sources and sinks (Intergovernmental Panel on Climate Change (IPCC), 2007). A large part of the methane in the ocean is generated in anoxic marine sediments by methanogens (e.g. Whiticar, 1999; Hinrichs and Boetius, 2002), but sedimentary methane is also formed by thermal breakdown of organic matter occurring at high temperature and pressure. The methane generated in the sediments is influenced by several processes limiting the amount of methane reaching the sediment–water interface. Methane can be removed by hydrate formation in the gas hydrate stability zone (e.g. Hyndman and Davis, 1992). At or near the sediment surface, up to 80% of the methane is utilized in reduced sediments as a result of the anaerobic oxidation of methane (AOM) (e.g. Barnes and Goldberg, 1976; Knittel and Boetius, 2009). Finally, aerobic methane-oxidizing bacteria at the sediment surface and/or in the water column oxidize methane that has bypassed the anaerobic microbial filter (Hanson and Hanson, 1996; Murrell, 2010). Although the methane flux to the ocean is reduced by these processes, a fraction of methane is injected into the water column. This methane can either be emitted dissolved in fluids or, in case of over-saturation, in form of gas bubbles. Gas bubble emissions are hydroacoustically detectable and are commonly called flares due to their flame-shape appearance in echograms. They often correlate with sub-seafloor anomalies characterized by blanking in the echograms. Such anomalies in the sediment can be caused by upward migrating fluids transporting light hydrocarbons and, thus, may represent gas chimneys fueling the seafloor seepage sites (Judd and Hovland, 1992).

The expanding numbers of seep emission estimates worldwide highlights the importance of methane seepage for the global carbon cycle, and its potential contribution to the oceanic and atmospheric methane inventory, where - in the latter case - methane acts as a potent greenhouse gas. Although the total global atmospheric methane budget is constrained reasonably well (580 Tg yr^{-1}; IPCC, 2007), estimates by source sector vary considerably (Dlugokencky et al., 2011). In particular, global estimations of methane fluxes from geological sources in the marine realm such as natural gas seeps are highly uncertain. At deep-water seep sites most gas bubbles dissolve during ascent through the water column (e.g. McGinnis et al., 2006) and the dissolved methane is further oxidized by microbes (Reeburgh, 2007; Valentine et al.,2001). In contrast, a fraction of gas emitted from shallow water environments may transgress the sea-atmosphere boundary, especially in storm seasons (Shakhova et al., 2013). Therefore, shelf and upper slope areas such as off Spitsbergen (Gentz et al., 2013), in the Black Sea (Greinert et al., 2010), at the Coal Oil Point seep field (Clark et al., 2010; Mau et al., 2012) and off East Siberia (Shakhova et al., 2010) are of particular interest when considering the role of marine methane seepage as possible contributor to atmospheric methane concentrations.

1.1 Marine methane seepage in the Southern Ocean

Sea-floor hydrocarbon seepage occurs at numerous sites on the world's ocean margins, from the continental shelves to the abyssal depths, in a variety of geological settings (Judd and Hovland, 2007; Suess, 2010). Notwithstanding several decades of global methane seep exploration, examples in the Southern Ocean, defined to comprise the water masses south of the Polar Front (Griffiths, 2010), are almost unknown. First videographic evidence of an Antarctic cold seep was obtained by Domack et al. (2005) from the seafloor beneath the collapsed Larsen B ice shelf, western Weddell Sea, located in the trough of the Evans and Crane glacier. This site later was revisited by Niemann et al. (2009), who classified the seepage as inactive, based on the presence of dead shells of seep-associated chemosymbiotic clams (*Calyptogena* sp.), a geochemical sea floor analysis, and the lack of hydroacoustically detectable gas emissions. Apart from this single extinct cold seep site, naturally occurring chemosynthetic organisms (Van Dover et al., 2002) also have been found in the Southern Ocean at hydrothermal vents in the Bransfield Straight (Aquilina et al., 2013; Bohrmann et al., 1999) and the South Sandwich back-arc (Rogers et al., 2012), and at a whale fall from the Kemp Caldera (Amon et al., 2013). The paucity of records of chemosynthesis-based communities in the Southern Oceans can be explained partly by a lack of exploration due to the challenging and remote conditions in this region (Rogers and Linse, 2014). The biogeographic relation to chemosynthetic-based communities at seeps north of the Polar Front, e.g. New Zealand (Davy et al., 2010), offshore Chile (Sellanes et al., 2004) and Australia (Logan et al, 2010), is however largely unknown (Rogers and Linse, 2014).

1.2 Regional setting of South Georgia

South Georgia belongs to the crustal blocks forming the North Scotia Ridge (Fig. 1a), which were once part of the continental connection between South America and the Antarctic Peninsula (Cunningham et al., 1998; Dalziel and Dott, 1975). These crustal blocks were moved during the Cenozoic by backarc spreading and subsequent eastward growth of the Scotia Sea (Cunningham et al., 1998; Forsyth, 1975). There is evidence for active convergence along the western side of the North Scotia Ridge, but convergence has now ceased along its eastern section, which includes the South Georgia block (Cunningham et al., 1998; Ludwig and Rabinowitz, 1982). However, analyses of an earthquake with its epicenter located south of the South Georgia block (see Fig. 1b) indicates nearly pure thrust faulting, interpreted to represent thrusting of the Scotia Plate beneath South Georgia (Pelayo and Wiens, 1989). This tectonic framework shows that South Georgia is part of an isolated microcontinental block, divided by the W-E trending Cooper Bay Shear Zone that crosses the Island (Fig. 1b). This is the major tectonic boundary that displaces the late Jurassic to early Cretaceous basement complexes exposed on South Georgia (Curtis et al., 2010).

In contrast to the geologic and tectonic evolution of South Georgia, the shelf and upper slope area surrounding the Island have been less well studied. However, a recent comprehensive bathymetric compilation aimed at elucidating the paleo-ice sheet drainage of the island has greatly improved our knowledge of the continental shelf morphology of South Georgia (Graham et al., 2008). These researchers described large eroded troughs linked to the recent fjords around South Georgia (Fig. 1b; for the purpose of this study numbered 1-10), and they proposed that these cross-shelf troughs were formed during glacial times and represent former pathways of outlet glaciers and ice streams. Although probable Mesozoic sedimentary and volcanic rocks extend beneath the inner shelf of South Georgia, Cenozoic sediments form the outer parts of the continental shelf (Graham et al., 2008; Simpson and Griffiths, 1982).

South Georgia is located in the path of the Antarctic Circumpolar Current (ACC). The Polar Front is located to the north and the southern ACC front loops anticyclonically around the island from the south before retroflecting to the east (Thorpe et al., 2002). The shelf waters of South Georgia are often markedly different from the open waters, indicating that local processes are important in dictating shelf water mass characteristics (Young et al., 2011). Various shelf-specific processes have been observed, or inferred at South Georgia, and significant interannual variability of the oceanographic conditions on the shelf are known (Meredith et al., 2005; Young et al., 2011). In general, the special oceanographic conditions around South Georgia result in a rich ecosystem, with large phytoplankton blooms and related strong atmospheric carbon drawdown (Borrione and Schlitzer, 2013; Jones et al., 2012), as well as high organic matter sedimentation on the shelf. The seasonally occurring blooms are particularly intense on the northern shelf area of South Georgia and within the adjacent Georgia Basin (Borrione and Schlitzer, 2013).

Seepage of methane has not been reported so far near South Georgia. During Polarstern cruise ANT-XXIX/4 we explored the northern shelf of South Georgia to identify any seeps that might originate from the high organic matter load on the continental shelf. We first performed a comprehensive hydroacoustic survey to detect gas seepage, which we subsequently investigated by visual seafloor observation and correlated with methane analysis in the sediments and water column that together extend our understanding of methane-related processes taking place in the local hydrosphere.

2. Methods

2.1 Hydroacoustic systems

The data used for this study were acquired during R/V Polarstern cruise ANT-XXIX/4 in March and April 2013 (Bohrmann, 2013). Bathymetric mapping was performed using an ATLAS Hydrosweep Deep-Sea 320-beam echosounder operating at a frequency of ~15 kHz and covering a swath width about four times the water depth. Raw data were processed with the commercially available hydrographic processing systems CARIS 7.0 HIPS and SIPS and the open source seafloor mapping software MB (MultiBeam)-System (Caress et al., 2012). The grids produced were visualized with the geographic information system ESRI ArcMap 10.0. The cleaned Hydrosweep data were gridded with a cell size of 25 m. We combined our results with additional data from earlier cruises of the British Antarctic Survey (Fretwell et al., 2008) (available at http://www.antarctica.ac.uk/bas_research/data/online_resources/sgbd/) and the GEBCO dataset (http://www.gebco.net/).

We used the ship-mounted parametric single beam echosounder (SBES) ATLAS PARASOUND for shallow subbottom imaging. The secondary low frequency (SLF) of about 4 kHz was recorded and processed online with the software ATLAS PARASTORE. The resulting PS3-files were imported to

SENT (H. Keil, University of Bremen) and the data plotted. In addition, the SBES ATLAS PARASOUND was used for imaging of rising gas bubbles (‘flare detection’) that show up as backscatter anomalies in echograms using the primary high frequency (PHF) of about 18 kHz (Fig. 2a). The transducer opening angle was 4°, resulting in a footprint size of about 7% of the water depth. PARASOUND data as well as metadata are available at the PANGAEA data repository.

2.2 Seafloor observations

The Ocean Floor Observation System (OFOS), a towed underwater system equipped with a high-resolution digital camera (ISITEC, CANON EOS 1Ds Mark III), was used to visually inspect the sea floor at an altitude of about 1.5 – 2 m relative to the seabed in areas where flares were detected. In addition to the provided live feed, the camera was programmed to take high-resolution (21 megapixels) photographs of the sea floor every 30 seconds. Underwater-navigation was achieved using the shipboard IXSEA Posidonia ultra short baseline system, with an accuracy of 5 – 10 m, and these data were used to establish the OFOS tracks and the positions of each photograph taken.

2.3 Water column analyses

Water column properties were investigated deploying a 24-Niskin water bottle rosette to which a CTD-unit was attached (Seabird, SBE 911+). Using the sensors of the CTD-unit, salinity, temperature, and pressure data were measured. In addition, a Sea-Tech transmissometer and a SBE 43 sensor was used to record beam transmission and concentrations of dissolved oxygen, respectively. For quantification of methane concentrations in the water column, 750 ml of sampled seawater were transferred from the Niskin bottles into pre-evacuated 1000 ml glas bottles immediately after recovery. Gas was extracted from these samples using the modification of the vacuum degassing method described by Rehder et al. (1999). The extracted gas was analyzed onboard with a 6890N gas chromatograph (Agilent Technologies) equipped with a capillary column and connected to a Flame Ionization Detector, as described in Pape et al. (2010). Calibrations and performance checks of the analytical system were conducted regularly using commercial pure methane standards. The coefficient of variation determined for the analytical procedure was less than 2%.

2.4 Stable carbon isotope signatures

Three sediment gas samples were extracted from two gravity cores taken close to flare origins (GC-1: station PS81/280-1 in cross-shelf Trough 6, Fig. 3a; GC-2: station PS81/284-1 in Cumberland Bay, Fig. 3b) were analyzed for stable carbon isotope ratios of methane. The samples were obtained from depths between 6 and 9 meters below sea floor (mbsf), which was below the depth of the sulfate-methane transition (Chapter 9 in Bohrmann, 2013), and therefore should not have been influenced by potential anaerobic methane oxidation. Sediment (3 ml) was sampled from the bottom of each of the freshly cut core sections were taken immediately after core recovery using cut-off syringes and transferred into 20 ml glass vials prefilled with 5 ml of 1 M NaOH. The headspace gas was sampled for onboard methane concentration analyses (Pape et al., 2014) and a subsample was used shortly after arrival at the home laboratory for shore-based measurements of its stable isotope signature. Analysis of stable C isotope signatures of CH_4 was conducted at the commercial GEO-data GmbH laboratory (Garbsen, Germany). Stable C isotope ratios are reported in δ-notation in parts permil (‰), relative to the Vienna PeeDee Belemnite (V-PDB) standard. The reproducibility of stable carbon isotope determinations is estimated at ±0.1‰.

3. Results

3.1 Hydroacoustic observations

Hydroacoustic surveys revealed the presence of numerous gas emission sites at water depths between 130 and 390 meters below sea level (mbsl) on the northern shelf of South Georgia in spring 2013. The gas emissions appeared as ‘flares’ in the echograms due to the high impedance contrast of free gas emanating as bubbles through the water column, which produce a high-backscatter signal (Fig. 2a). The flares were composed of vertically arranged oblique reflections that image the up-rising individual bubbles or groups of bubbles, and make them discernible from fish schools. In total, at least 133 individual flares were detected during our study (Figs. 3a and b, supplementary table S1). The flares showed largely straight and vertical orientation (e.g. the 170-m high ‘Cumberland Bay Flare’, Fig. 4c), indicating a lack of strong currents that would be expected to deflect the bubbles during their rise through the water column. Roughly 75 % of the flares were less than 100 m high, with an average of ~70 m (supplementary table S1). However, three flares extended from the sea floor to a height of at least 25 mbsl. The uppermost part of the echograms was disturbed by acoustic noise that hampered differentiation of gas bubbles from plankton and/or fish. In general, the real flare height was difficult to determine using Parasound recordings, as the small ~4° opening angle and a coherent narrowing footprint with decreasing depth impeded the detection of the uppermost part of the flares when the ship did not pass exactly through the center of the bubble train.

Many flares detected were discontinuous or were disconnected from the sea floor (Figs. 4a and b). This observation can be attributed to horizontal deflections of a bubble stream that moves in and out of the conical Parasound beam, or to transient gas bubble streams where the emissions are temporally variable. The latter explanation seems to be more likely in this case, as the tall flares appeared vertical and did not show strong lateral deflections; however, variable current regimes cannot be ruled out entirely.

The temporal variability of the flares was examined by imaging a given location more than once. Four flares became visible at the same location two times within ca. 14 days, whereas eight other flares appeared only once, although surveyed twice (supplementary table S2). The observations of the flare appearance and the repeated surveys show that most flares probably are temporally variable on scales of minutes to weeks.

The detected flares were not randomly distributed along the northern South Georgia margin. They occurred either within the Cumberland Bay fjord system or within the other incised cross-shelf troughs that cut through the broad shelf surrounding the island (Fig. 3a). Two fjord systems were inspected for the occurrence of flares during cruise ANT-XXIX/4: Cumberland Bay was investigated intensively (Fig. 3b), whereas Possession Bay was entered once and inspected only along two survey lines. While numerous flares were observed in the Cumberland Bay region, no indication of gas emissions were found in Possession Bay. In total, more than 75 flares were detected in both branches of Cumberland Bay and within the cross-shelf to which the fjord system connects (designated as Trough 5 in Fig. 3b). Flares were distributed close to the fjord-mouth and within the fjord itself, but were not detected in the innermost parts of the bay close to the glaciers that discharge into the fjord at the coast. A few flares were found within the ~10 km area seaward of the fjord mouth, and one flare was detected as far as ~30 km from land. In addition to cross-shelf Trough 5, gas emissions also were found in four of the seven troughs defined by Graham et al. (2008) on the northern shelf of South Georgia (Fig. 3a). The northern shelf was hydroacoustically surveyed twice in a roughly two week interval, and during both investigations, flares were observed to be restricted to the troughs. No flares were detected on the shallower banks between the cross-shelf troughs and, with the exception of Troughs 2 and 7, all of the troughs surveyed showed gas emissions.

Sedimentary strata were not visible in subbottom Parasound SLF profiles of the shallow shelf banks (Fig. 4b), but the troughs were characterized by reflections indicating sediment accumulations of up to ~40 m in their centers (Figs. 4a). The reflections were sub-parallel to the sea floor and presumably reflect accumulations of sediment transported from the fjords to the shelf, and deposition within the cross-shelf troughs. Numerous zones of acoustic blanking or acoustically-transparent chimneys that pierced the horizontal reflections were observed for all of the sediment infills within the troughs (Figs. 2b, 4a, b and c), which might be caused by upward gas migration at these sites. The acoustic chimneys were positioned directly underneath the acoustic flares in the water column in several areas, giving credence to the suggestion that the chimneys are the conduits for channeling free gas through the sediments towards the sea floor, where gas bubbles escape into the water column and form the flares imaged in the Parasound PHF echograms (Figs. 2b, 4a, b and c).

3.2 Visual sea floor observations at the ‘Cumberland Bay Flare’

An OFOS deployment was conducted at a flare site designated as the ‘Cumberland Bay Flare’ in order to visually confirm the sea floor origin of the gas flares recorded hydroacoustically (Fig. 4c), and the nature of the surrounding sediments. The sea floor was inspected along an approx. 400 m long track (Fig. 5). The flat sea floor was composed of unconsolidated sediments and detached kelp fronds (Figs.

6a and b), many of which were partially buried. The observed epibenthic invertebrate megafauna included cidaroid and echinoid sea urchins, asteroid starfish, holothurians, hexactinellid sponges, and fish (Fig. 6a).

Numerous centimetre-sized holes were visible in the sea floor along the OFOS track, which were probably produced by endobenthic organisms or may represent the orifices of emanating gas bubbles. Rising gas bubbles were observed at two seep sites during the OFOS deployment, which was guided by flare observations in the water column. Our observations document gas bubbles emanating singly from the sea floor without forming continuous bubble streams. During an observation period of about 40 minutes at the southeastern located seep site (Figs. 5 and 6a), we documented more than 50 events (roughly about each minute), where a single bubble or pulses of 2 or 3 bubbles close together rose from the seabed. We observed individual rising gas bubbles again at a northwestern seep site, which is located ~50 m distant from the other and corresponded to a different water column flare (Figs. 5 and 6b).

At both seep sites the sea floor was covered by centimeter to decimeter-sized, subcircular, whitish material (Fig. 6a and b), occurring either as coherent patches or as collections of several smaller patches (Figs. 5 and 6a). These patches most probably represent microbial mats indicative of fluid flow from below. However, we did not see taxonomically higher chemosymbiotic organisms typically associated with cold seeps in other regions, such as bathymodiolin mussels or vesicomyid clams. The sea floor in two locations where whitish material was observed was elevated slightly and formed topographic mounds up to a few decimeters high (Fig. 6a). Fig. 5 illustrates that the whitish material was restricted to two areas a few meters in extent, both of which were located at the central foci of the two flares detected hydroacoustically.

3.3 Water column characteristics in Cumberland Bay

Three hydrocasts revealed a general water column stratification and specific differences in hydrological conditions in Cumberland Bay (station CTD-1 close to the ‘Cumberland Bay Flare’; CTD-2 close to the ‘Grytviken Flare’; see Fig. 3b) and a station seaward of the fjord (CTD-3; Fig. 7). A pronounced surface layer (upper ~20 mbsl) was present at stations CTD-1 and CTD-2 in Cumberland Bay, characterized by relatively low salinities (<33 PSU), temperatures (<2.8 °C) and beam transmissions (<80 %). These characteristics suggest that this water mass (not observed at the seaward station CTD-3; Figs. 7, supplementary Fig. S3) is affected by mixing with freshwater originating from the melting marine terminating glaciers (Fig. 3b). Physico-chemical properties varied only slightly with increasing depth throughout the midwater section. The lower limit of this water mass was found at ~165 mbsl for CTD-2 (located relatively deep within the fjord) and at ~190 mbsl for CTD-1 (located close to the fjord mouth), suggesting that its vertical extent is spatially variable and may reflect topographically-controlled circulation patterns. Similar water characteristics at all three investigated stations indicate water exchange between Cumberland Bay and the shelf area of South Georgia. The lowermost water mass within and outside Cumberland Bay was characterized by relatively low temperatures (~2.4 – 1.7°C) and relative depletions in dissolved oxygen concentrations (6.5 – 5.2 mL/l), but with the highest salinities (up to 34.2 PSU). A markedly lower beam transmission (as low as 80% at the bottom) recorded for the near-bottom water mass within the bay, if compared to that at the outer shelf station, might be the result of a higher particulate matter load (see also chapter 4.1).

Significant enrichments in dissolved methane of up to 25.4 nmol/l and 55.6 nmol/l, respectively, were measured in the lowermost water mass characterized by low-beam transmission at the two CTD stations taken in close proximity to the ‘Cumberland Bay Flare’ and the ‘Grytviken Flare’ (Figs. 3b and 7). At these stations concentrations of dissolved methane decreased significantly with decreasing depth within the lower 100-120 meters of the water column down to ca. 5 nmol/l (Fig. 7), which is still slightly elevated in contrast to the atmospheric equilibrium (3-3.3 nmol/l). At the outer shelf station, where flares were not detected, dissolved methane concentrations of <5 nmol/l were measured though the whole water column.

3.4 Stable carbon isotopic composition of methane

Stable carbon isotopic analysis of methane in the gas samples extracted from the two sediment cores taken in close proximity to flares (GC-1 within cross-shelf Trough 6; GC-2 in the Cumberland Bay; Figs. 3a and b) revealed strong depletions in ^{13}C, with $\delta^{13}C\text{-}CH_4$ values ranging between –80.2 and –88.9‰ (V-PDB). The greatest depletion came from a methane sample extracted at ~6.5 mbsf from the sediment core GC-2 at the 'Grytviken Flare'.

4. Discussion

4.1 Gas seeps at the northern shelf of South Georgia

We detected 133 gas flares at the northern shelf of South Georgia (Fig. 3a) during R/V Polarstern cruise ANT-XXIX/4 in 2013. Visual sea-floor inspections with the high-resolution video camera of the OFOS system confirmed active seepage at the 'Cumberland Bay Flare' in the form of rising gas bubbles and white sea-bed patches (Figs. 6a and b) interpreted as microbial mats fueled by methane emission. Hydroacoustically-imaged flares originated from sea floor locations that showed acoustically-blanked chimneys in the underlying sediments. In addition, water samples taken in bottom waters within two flares showed elevated concentrations of dissolved methane (Fig. 7), that proved methane transport by gas bubbles from the sea floor into the hydrosphere.

This new finding of methane seepage adds to the long and steadily growing list of seep areas in the world's oceans (Campbell, 2006; Judd and Hovland, 2007; Suess, 2010). At high latitudes, seeps are known in the Arctic and sub-Arctic, which have recently sparked particular scientific interest because of their links to permafrost settings (Shakhova et al., 2010) with potential global warming effects (Westbrook et al., 2009). Hydrothermal vents and cold seeps are known to host specialized faunal communities which are based on chemosynthesis (Bachraty et al., 2009; Van Dover et al., 2002). In the Southern Ocean to date only a few chemosynthetic ecosystems are known (Rogers and Linse, 2014), including the presently inactive cold seep in the western Weddell Sea, hydrothermal vent fields and a natural whale fall (Amon et al., 2013; Aquilina et al., 2013; Bohrmann et al., 1999;

Domack et al., 2005; Niemann et al., 2009; Rogers et al., 2012). The epibenthic invertebrate megafauna observed in the Cumberland Bay area comprises species commonly found around South Georgia (Hogg et al., 2011; James E. McKenna Jr., 1991; Jones et al., 2008). Except for the inferred microbial mats, chemosynthetic organisms usually found at cold seep sites were not found at the seeps investigated in this study. This might be because of the relatively shallow water depth (~250 mbsl), since the typical animals obligate at cold seeps (e.g. species of vesicomyid clams, bathymodiolin mussels and siboglinid tubeworms) are restricted to aphotic habitats. Explanations for their absence on the continental shelves include the abundance of predators in shallower waters, or competitive exclusion by primary consumers limiting the presence of species dependent on chemoautotrophic symbionts (Sahling et al., 2003). The exact depth limit is not precisely resolved (Little et al., 2002), but the shallowest seep communities with the typical obligate species found so far are reported from the Eel River basin, offshore California in ~350 mbsl (Orange et al., 2002) and in the Sea of Okhotsk in ~370 mbsl (Sahling et al., 2003). In our study we detected gas bubble seepage using hydroacoustics in the same depth range (ca. 380 mbsl), but did not investigate these sites visually. Thus, it remains a possibility that typical obligate cold seep animals are present on the deeper shelves around South Georgia.

As noted above, the flares detected during ANT-XXIX/4 along the northern shelf of South Georgia are not randomly distributed, but are restricted to the fjords and glacial troughs along the shelf (Fig. 3a), the latter accounting for ~15% of the total shelf area surrounding the island of South Georgia. A similar observation was made in a hydrocarbon seep area on the Baffin Bay shelf region, where oil and gas seeps were found within glacially-formed troughs seaward of fjord systems (Grant et al., 1986; Levy and Ehrhardt, 1981). In addition, seepage was inferred to occur in fjords in Spitsbergen (Forwick et al., 2009) and Norway (Judd and Hovland, 2007), based on the presence of sea floor pockmarks. Fjords generally appear to represent favorable settings for methane seepage as they are commonly characterized by high sedimentation rates due to high input from inflowing glaciers or meltwater streams. In addition, in some cases shallow water sills hamper water exchange with open seawater areas and ventilation, favouring anoxic conditions and protecting organic material from rapid microbial decomposition under aerobic conditions, which finally leads to large accumulations of refractory organic matter in the sediments (Judd and Hovland, 2007). During our study we observed various sill structures in the high-resolution bathymetric maps of the South Georgia fjords, probably representing fjord moraines (Hodgson et al., 2014). However, these do not appear to fully restrict flow (Fig. 3b), as temperature, salinity and concentrations of dissolved oxygen are indeed lower in the bottom waters than in overlying water masses, but the values where similar in magnitude for all three stations, both within and outside the fjord. Therefore, there is no apparent isolation of the deep waters in Cumberland Bay (Figs. 7, supplementary Fig. S3). Bottom water oxygen concentrations within and outside the bay were ~5 mL/l (corresponding to ~220 µmol/l), indicating well-oxygenated conditions.

For Cumberland Bay, Platt (1979) estimated the sedimentation rate at 2.8 × 10^3 g m^{-2} yr^{-1} and an organic matter input of 60 g carbon m^{-2} yr^{-1}, providing an ideal setting for shallow biogenic methane production. A biogenic methane source is proven by $\delta^{13}C$-CH_4 values <–80 ‰ (V-PDB) for all gas samples collected from the two sediment cores we investigated. Methanogens preferentially consume substrates depleted in ^{13}C, whereas thermogenic light hydrocarbons by non-selective hydrocarbon cracking are not affected by significant isotope fractionation effects (Claypool and Kvenvolden, 1983). For a microbial hydrocarbon formation and accumulation both high sedimentation rate and the presence of sufficient amount of organic matter in the sediments are required. South Georgia lies in the eastward flowing Antarctic Circumpolar Current (ACC), creating a morphological high in the largest meander modifying the Southern ACC front (Meredith, 2003; Thorpe et al., 2002). Due to this particular hydrographic configuration, intensive and regular phytoplankton blooms develop in the area north and northwest of the South Georgia shelf (Borrione and Schlitzer, 2013), leading to both a rich food web (Atkinson et al., 2001), and a high carbon production, which is either exported (Schlitzer, 2002) or ultimately deposited at the sea floor. Although there is no indication for deeply buried reservoirs of thermogenic gas fueling the gas emission sites investigated in this study, thermogenic hydrocarbon migration through deep-rooted faults cannot be entirely excluded as the fjords and connecting cross-shelf troughs may have established along lines of structural weakness that could have evolved in association to faults zones (Graham et al., 2008). Unfortunately, there are currently no seismic data imaging the deeper structure of the South Georgia block to test such a hypothesis. Lacking those data, we are also limited in discussion whether smaller geologic structures are controlling the seep distribution, such as those documented by Naudts et al. (2006) for the widespread seepage at the northwestern Black Sea margin. There, seeps were preferentially found in elongated pockmarks above margins of filled channels, along crests of sedimentary ridges, related to canyons or scarps of submarine landslides. In our study we discovered several flares rooted at morphological structures within the Cumberland Bay fjord, which were interpreted by Hodgson et al. (2014) as remnant or partially-preserved outer moraines and might support sub-surface channeling of migrating fluids. Other small-scale morphological features described by Hodgson et al. (2014), which include iceberg scours and pits or glacial debris, do not appear to be related to seepage.

4.2 Intensity of gas seepage and fate of methane in the water column

Most of the imaged flares during our surveys were not centered directly under the vessel, thus, precluding a quantitative assessment of their intensities. However, our observations revealed that (1) most flares are only few tens of meters high, (2) flares often appear episodically and are characterized by discharge in pulses, and (3) flares indicative for individual bubbles or bubble groups are occasionally tilted, so that their sea floor origin could not always be traced (Figs. 4a and b). These data suggest that most of the flares are rather weak and represent discontinuous releases of gas bubble emissions. Visual inspection of the ‘Cumberland Bay Flare’, one of the most intense flares we imaged (Fig. 4c), showed sporadic gas bubble discharge from the projected flare origin, but also indicated that the sporadic release of individual gas bubbles was sufficient to cause a relatively intense signature in the corresponding echogram. Our data demonstrate that the flares are temporally variable over minutes to weeks and it is likely that the activity and intensity of the gas emissions may also change seasonally or annually. Due to the nature of our surveys, we are not able to resolve possible factors modulating the discharge (e.g. tides, earthquakes, storms events, bottom currents, decomposition of subsurface gas hydrates), as documented in more intensively investigated seep areas such as Hydrate Ridge (Kannberg et al., 2013), Coal Oil Point (Boles et al., 2001), Bush Hill (Solomon et al., 2008), or at seeps at the Northern Cascadia Margin (Lapham et al., 2013).

The quantity of bubbles and the intensity of seepage on the northern shelf of South Georgia seems to be rather weak in comparison to other seep areas, e.g. Hydrate Ridge (Heeschen et al., 2005; Torres et al., 2002), the Makran continental margin (Römer et al., 2012b), Santa Barbara channel (Hornafius, 1999), as well as several seepage areas in the Black Sea (Greinert et al., 2006; Naudts et al., 2006; Nikolovska et al., 2008; Pape et al., 2010; Römer et al., 2012a), where vigorous gas bubble emissions and/or strong flares have been documented. However, the large number of emission sites as revealed from our flare imaging, in combination with the significant enrichments in dissolved methane, suggests injection of non-negligible quantities of methane into the bottom water in fjords and the cross-shelf troughs of South Georgia, even though each individual seep may contribute only a small amount of methane. In addition, it is conceivable that our observations occurred in a period of minor seepage activity. For example, observations made for the Coal Oil Point seep field revealed interannual changes between 1990 and 2008, which have been related to internal geological processes (Bradley et al., 2010).

Our hydroacoustic data additionally indicate that most gas bubbles released into the water column probably did not reach the upper water layer and atmosphere, but instead dissolved entirely during their ascent. With three exceptions, all 133 flares detected disappeared from the SBES echograms well below the sea surface. Although the geometric limitation of the SBES coverage, particularly at shallow depths, has to be considered, the fraction of methane transported as gas bubbles is not limited only by the maximum bubble rising height, but mainly depends on the effectiveness of gas exchange processes taking place when entering the hydrosphere, due to concentration differences. The proportion of methane initially contained in the bubble is rapidly replaced by dissolved nitrogen and oxygen from the ambient water (Leifer and Patro, 2002; McGinnis et al., 2006). The rapidity of this process strongly depends on the bubble size, the rise velocity, as well as the composition and conditions of the surrounding medium and the presence of upwelling flows (Leifer and Judd, 2002). Several studies have demonstrated that methane escapes the bubbles well before final bubble dissolution (Leifer and Patro, 2002; McGinnis et al., 2006; Rehder et al., 2002). Our suggestion that most of the methane discharged from the South Georgia northern shelf does not reach the upper water column is additionally strengthened by the relatively low concentrations of dissolved methane (about 5 nmol/l) in the intermediate to uppermost water masses at two hydrocast stations, deliberately acquired close to recorded flares in the Cumberland Bay area (Figs. 3b and 8). Most probably, the strong stratification of the water column, as evidenced by the T-S diagram (supplementary Fig. S3), impedes a regular vertical mixing within Cumberland Bay and the released methane therefore remains within the bottom water, leading to the observed profiles. A fraction of this methane may be oxidized through microbial activity (Reeburgh, 2007; Valentine et al., 2001), so the measured concentrations reflect a balance between methane input and bottom-water consumption within Cumberland Bay and water exchange with the outer shelf water. It is hard to directly correlate water column data with flare strength, but our data agree with our assumption that the methane transported via gas bubbles rapidly dissolves in the water body, so that most of the dissolved methane remains in the bottom water. Bubbles producing the hydroacoustic flares visible at that sites and reaching 50 m higher into the water column may have been depleted in methane.

5. Conclusion and Outlook

Hydroacoustic surveys and physico-chemical investigations of the water column in combination with visual sea floor inspections and analysis of sedimentary gas conducted on the northern shelf of South Georgia revealed the presence of widespread methane seepage from the sea floor into the water column. Flares occur restricted to the fjords and within glacial troughs along the shelf surrounding the island of South Georgia, which we confirmed has a biogenic source through isotopic analyses. This finding is to our knowledge the second cold seep detected in the (sub-)Antarctic region so far and the first observation of a widespread and active area of seepage in the Southern Ocean. Detailed surveys are required to determine further distribution, variability, and total abundance of such methane seep sites, which is probably significantly higher than the 133 flares we detected during the detailed but still spatially-limited surveys of R/V Polarstern cruise ANT-XXIX/4.

We argue that the seepage around South Georgia is spatially related to the glacial trough and fjord system, a setting often occurring in sub-Antarctic regions that need further exploration to characterize the nature, distribution and magnitude of hydrocarbon seepage in this region. Because of the high organic matter input and presumed available methane reservoirs in the largely unexplored margins surrounding the Antarctic Peninsula (Murphy et al., 2013; Schlitzer, 2002; Wadham et al., 2012), and in the glacially-influenced shelves of various sub-Antarctic islands (Dickens et al., accepted), natural seepage in the Southern Ocean might be more common than previously thought.

Research questions arising from our methane seepage finding around South Georgia include: 1) unraveling the relationships between seepage, , rates of sediment accumulation, and the type and amount of organic carbon that sustain the methane reservoirs; 2) evaluating the potential contribution of thermogenic gas; 3) documenting the role of methane input on the biosphere and associated biogeochemical processes; 4) establishing whether some of the deeper seeps support chemosynthetic fauna, and, if present, determining whether they serve as ‘stepping stones’ for larval distribution of chemosynthesis-based organisms in the Southern Ocean; 5) constructing a carbon budget for the region, which includes source and consumption terms as well as the effect of circulation within and outside the fjords, and the circumstances under which this methane may reach the atmosphere.

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Figure captions

Fig. 1 a) Plate tectonic overview with the South Georgia microplate (SG) located at the eastern part of the North Scotia Ridge. SAM: South American Plate, SCO: Scotia Plate, SAN: Sandwich Plate, ANT: Antarctic Plate (modified after Cunningham et al., 1998). b) Map of the main tectonic structures of the South Georgia crustal block (after MacDonald and Storey, 1987). The shelf morphology is characterized by at least ten cross-shelf troughs sourcing at the fjords of the island (yellow areas; Graham et al., 2008).

Fig. 2 a) Echogram recorded with the single beam echosounder (SBES) illustrating a flare composed of numerous oblique high-backscatter traces representing uprising gas bubbles. The footprint of the SBES at a water depth of ~380 mbsl corresponds to ~30 m width of the flare signal at the sea floor (white line). b) SBES echogram combing the water column data and the subbottom information (using 18 and 3.5 kHz frequencies, respectively). Gas emission sites are characterized by acoustic blanking in the subsurface (gas chimneys) and emissions of free gas in the water column causing hydroacoustic flares. For locations see Figs. 3a and b.

Fig. 3 a) Shelf bathymetry with its characteristic cross-shelf troughs in combination with the ship track (black line) and flare positions (red dots) detected during R/V Polarstern cruise ANT-XXIX/4. Cross-shelf Troughs 1-7 at the northern shelf have been crossed in order to detect free gas in the subbottom and water column. Additionally, two fjords were investigated: the Possession Bay, where Trough 4 is sourced, and the Cumberland Bay, which is directly connected to Trough 5. b) Detailed map of the Cumberland Bay with the processed bathymetric data acquired during cruise ANT-XXIX/4. More than 75 flares were detected during the surveys within the fjord system.

Fig. 4 Three profiles recorded with SBES combining subbottom (3.5 kHz) and water column (18 kHz) information. Flares are repainted in red. For locations see Figs. 3a and b. a) Profile 1 shows an echogram crossing the cross-shelf Trough 4. Several flares were detected with the majority showing a discontinuous pattern most probably caused by pulsing gas bubble emissions. b) Profile 2 shows an echogram at cross-shelf Trough 6. In contrast to the shallow banks lacking visible sediment strata in the subbottom, the troughs are characterized by sediment accumulation. c) Profile 3 shows an echogram recorded during entering of the Cumberland Bay and crossing the ‘Cumberland Bay flare’. Several acoustic chimneys characterized by vertical blanking zones illustrate rising free gas in the subbottom (red outlines with arrows) and three flares demonstrating the emission of gas bubbles into the water column.

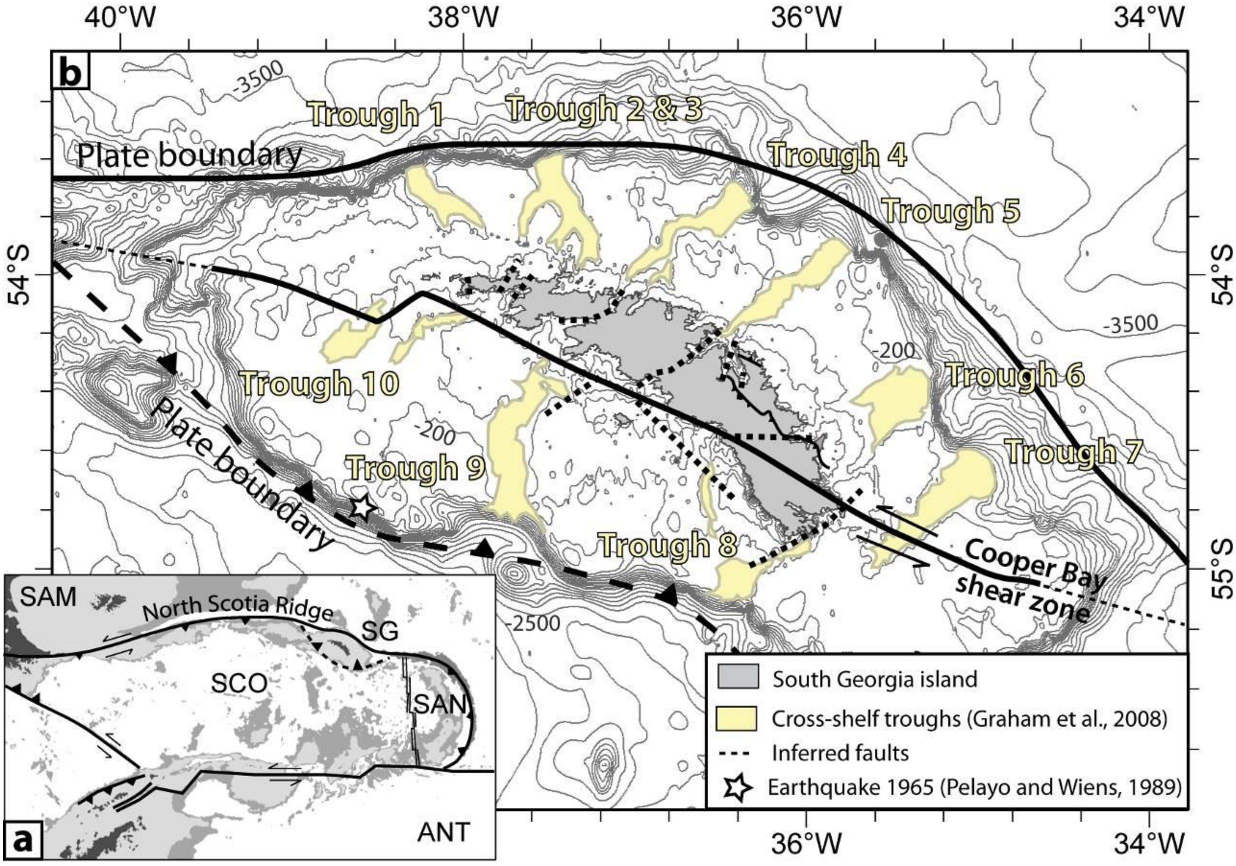
Fig. 5 a) Bathymetric map from ship-based swath echosounder recordings with the dive track of the Ocean Floor Observation System (OFOS; station PS81/285-1) passing two areas, where hydroacoustic investigations indicated gas bubble emissions from the sea floor (light red circles). Rising gas bubbles were recognized in both areas and whitish patches on the sea floor additionally suggested the position of the seep sites (white dots).

Fig. 6 a) Sea floor picture taken at the Cumberland Bay Flare with the high-resolution video camera mounted on the frame of the Ocean Floor Observation System (OFOS) and showing an elongated mounded structure at the sea floor characterized by whitish color, probably representing microbial mats. b) Sea floor image taken at the northwestern flare area demonstrates the occurrence and intercalation of white colored and additionally dark grey colored patches. For locations see Figs. 3b and 5.

Fig. 7 Water column profile illustrating selected data recorded during three CTD casts. Stations CTD-1 (colored dashed lines) and CTD-2 (colored solid lines) were located within the Cumberland Bay and CTD-3 (black lines) seaward the fjord mouth (see Fig. 3b). Elevated methane concentrations were measured in particular in the lowermost ~100 m at the two Cumberland Bay stations taken close to hydroacoustically detected flares. Bottom waters at that depth were characterized by low temperatures, beam transmissions and dissolved oxygen concentrations.

Supplementary Fig. S3 Temperature-Salinity diagram of the data from the three CTD stations during ANT-XXIX/4. T-S condition in surface waters at stations CTD-1 and CTD-2 located in the Cumberland Bay clearly differed from those at station CTD-3 positioned seaward (for locations see Fig. 3b).

Fig. 1



40°W
38°W
36°W
34°W
54°S
55°S
b
-3500
-200
-2500
Trough 1
Trough 2 & 3
Trough 4
Trough 5
Trough 6
Trough 7
Trough 8
Trough 9
Trough 10
Plate boundary
Plate boundary
Cooper Bay shear zone
South Georgia island
Cross-shelf troughs (Graham et al., 2008)
Inferred faults
Earthquake 1965 (Pelayo and Wiens, 1989)
a
SAM
North Scotia Ridge
SG
SCO
SAN
ANT

Fig. 2

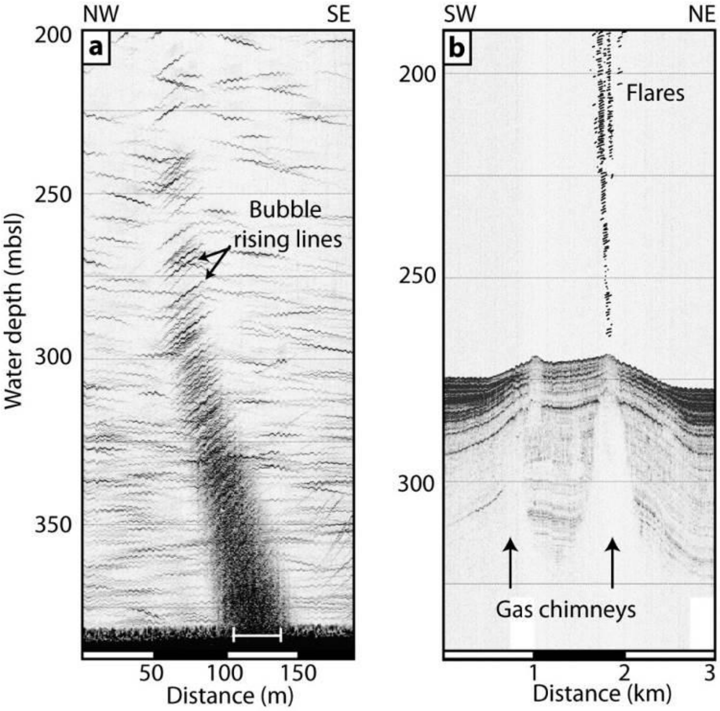

NW
SE
a
Water depth (mbsl)
200
250
300
350
Bubble rising lines
50
100
150
Distance (m)
SW
NE
b
200
250
300
Flares
Gas chimneys
1
2
3
Distance (km)

Fig. 3

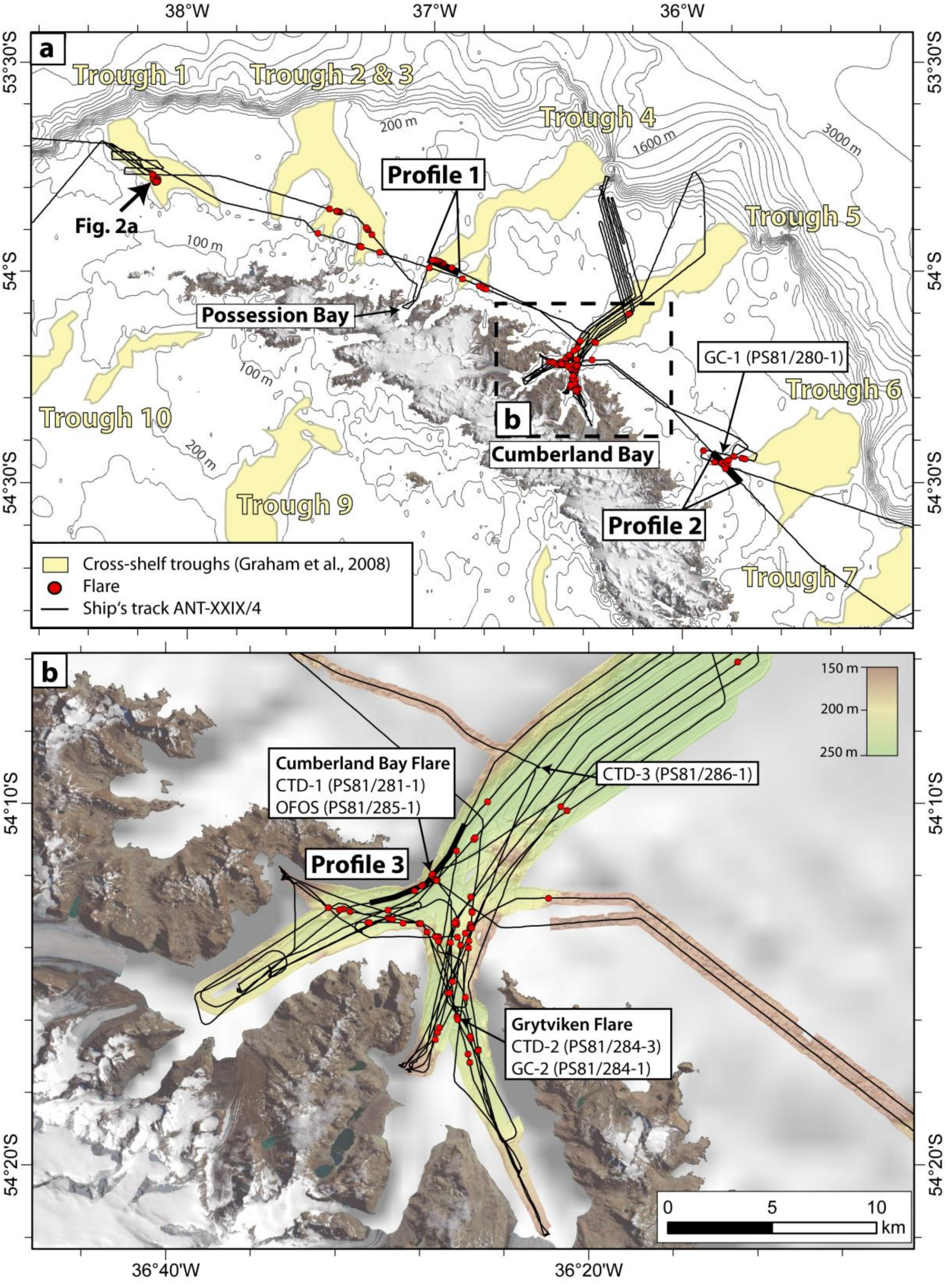

a
38°W
37°W
36°W
53°30'S
54°S
54°30'S
Trough 1
Trough 2 & 3
Trough 4
Trough 5
Trough 6
Trough 7
Trough 9
Trough 10
200 m
1600 m
3000 m
100 m
100 m
200 m
Profile 1
Fig. 2a
Possession Bay
GC-1 (PS81/280-1)
b
Cumberland Bay
Profile 2
Cross-shelf troughs (Graham et al., 2008)
Flare
Ship's track ANT-XXIX/4
b
150 m
200 m
250 m
Cumberland Bay Flare
CTD-1 (PS81/281-1)
OFOS (PS81/285-1)
CTD-3 (PS81/286-1)
Profile 3
Grytviken Flare
CTD-2 (PS81/284-3)
GC-2 (PS81/284-1)
0
5
10
km
54°10'S
54°20'S
36°40'W
36°20'W

Fig. 4

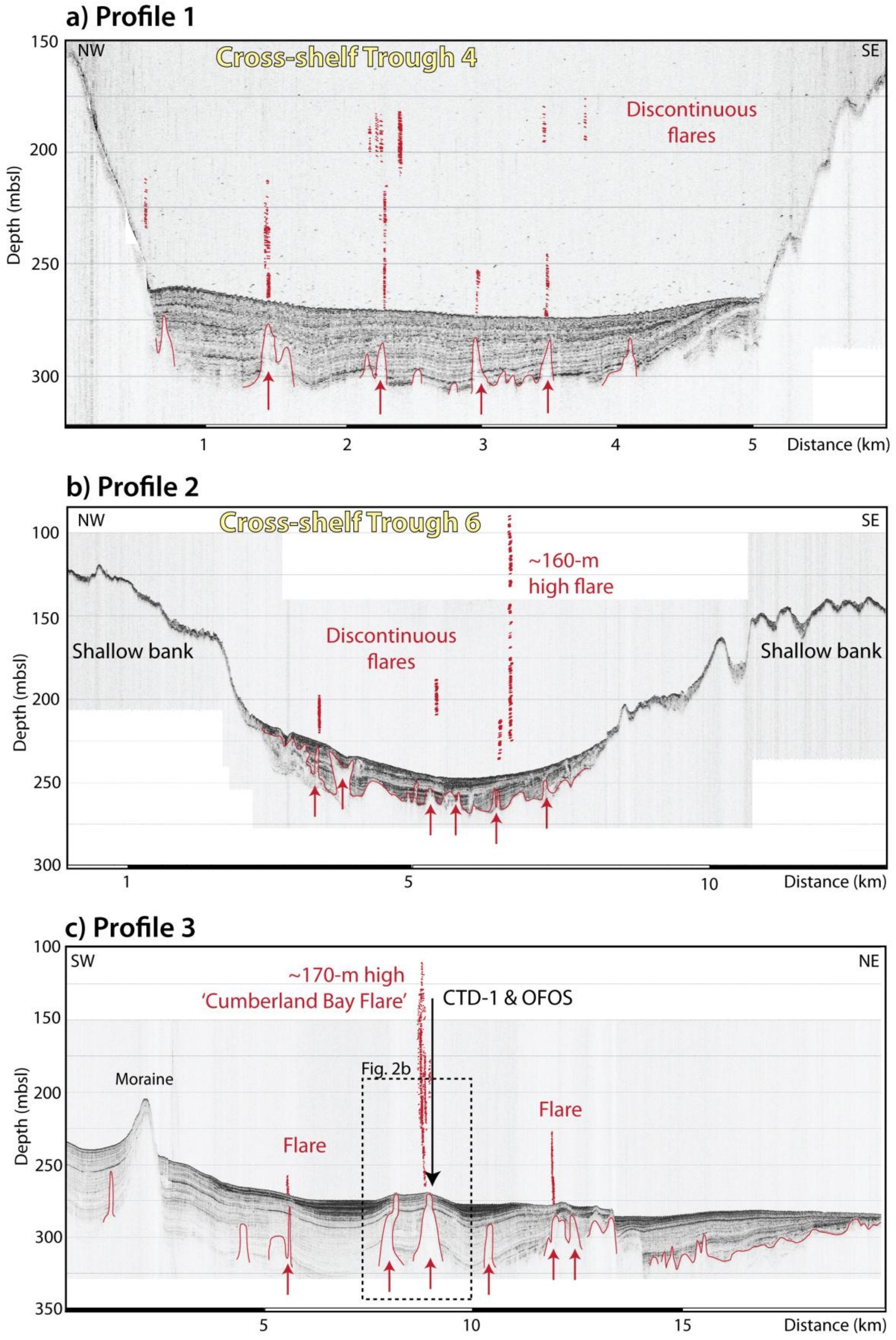

a) Profile 1
Cross-shelf Trough 4
NW
SE
Discontinuous flares
Depth (mbsl)
150
200
250
300
1
2
3
4
5
Distance (km)
b) Profile 2
Cross-shelf Trough 6
NW
SE
~160-m high flare
Shallow bank
Discontinuous flares
Shallow bank
Depth (mbsl)
100
150
200
250
300
1
5
10
Distance (km)
c) Profile 3
SW
NE
~170-m high 'Cumberland Bay Flare'
CTD-1 & OFOS
Moraine
Fig. 2b
Flare
Flare
Depth (mbsl)
100
150
200
250
300
350
5
10
15
Distance (km)

Fig. 5

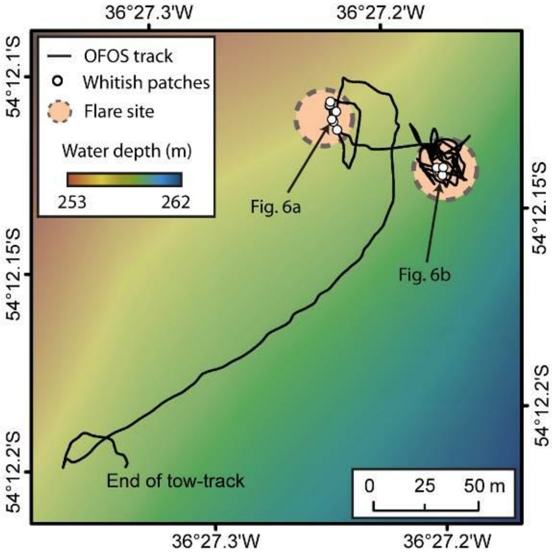

36°27.3'W
36°27.2'W
54°12.1'S
54°12.15'S
54°12.2'S
OFOS track
Whitish patches
Flare site
Water depth (m)
253
262
Fig. 6a
Fig. 6b
End of tow-track
0
25
50 m

Fig. 6

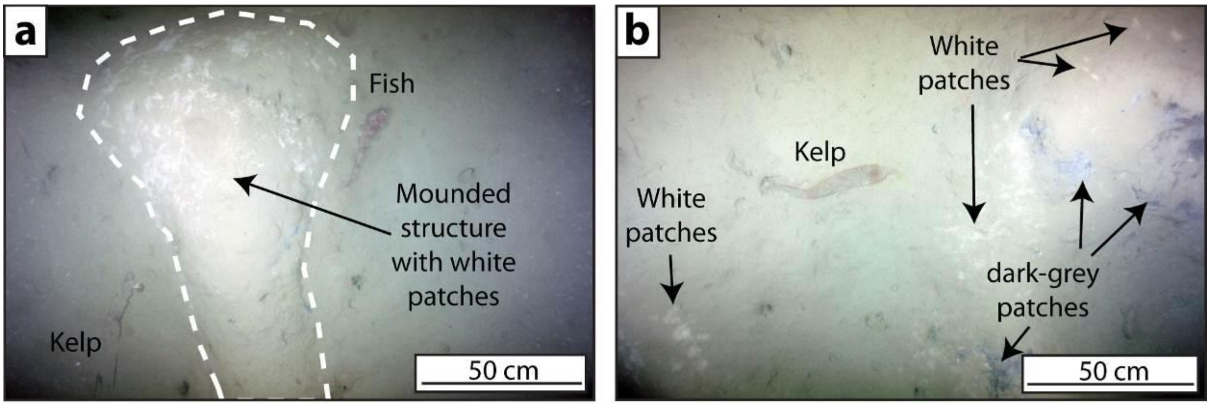
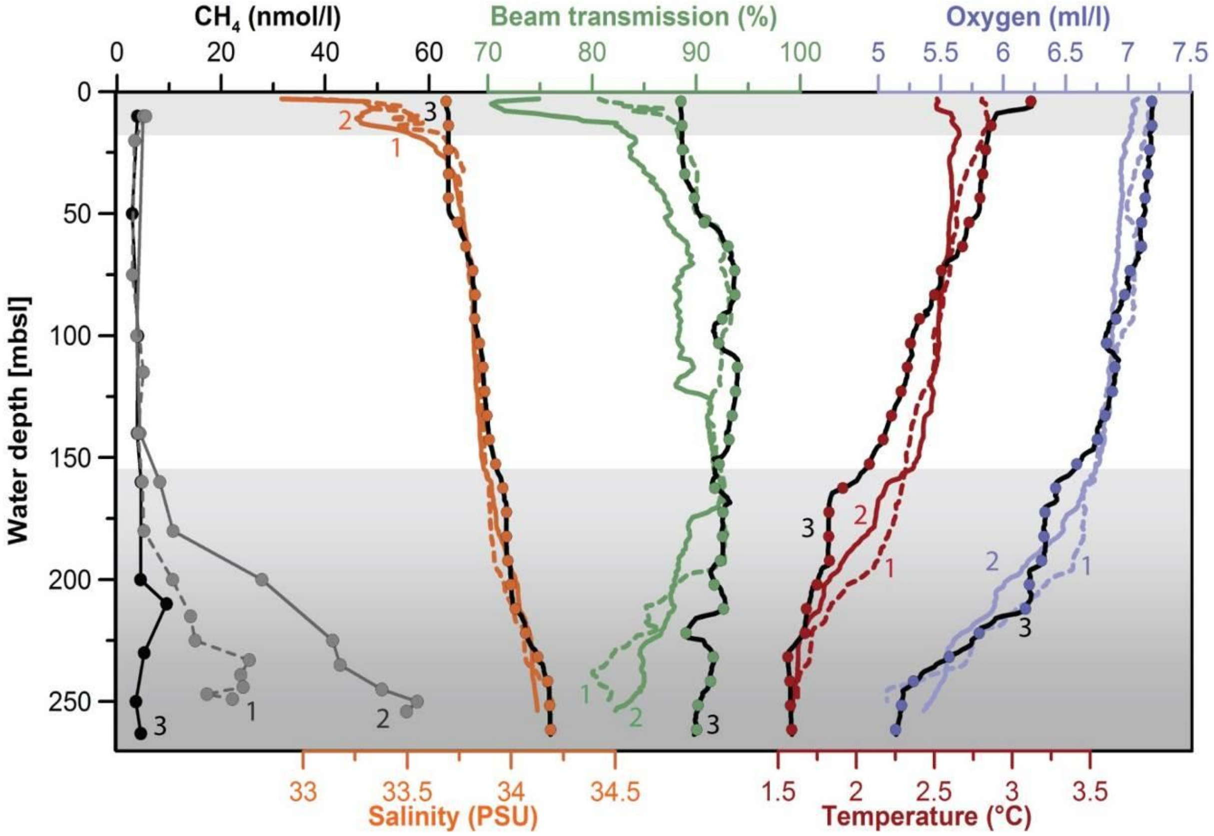

a
Fish
Mounded structure with white patches
Kelp
50 cm
b
White patches
Kelp
White patches
dark-grey patches
50 cm

Fig. 7



CH_4 (nmol/l)
0
20
40
60
Beam transmission (%)
70
80
90
100
Oxygen (ml/l)
5
5.5
6
6.5
7
7.5
Water depth [mbsl]
0
50
100
150
200
250
1
2
3
33
33.5
34
34.5
Salinity (PSU)
1.5
2
2.5
3
3.5
Temperature (°C)

First evidence of widespread active methane seepage in the Southern Ocean, off the sub-Antarctic island of South Georgia

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Abstract

A~~ new~~n extensive submarine cold-seep area was discovered on the northern shelf of South Georgia during R/V Polarstern cruise ANT-XXIX/4 in spring 2013. Hydroacoustic surveys ~~and video-based sea floor observations~~ documented the presence of 133 ~~individual~~ gas bubble emissions, which were restricted to glacially-formed fjords and troughs. Video-based sea floor observations confirmed the sea floor origin of the gas emissions and spatially related microbial mats. Effective methane transport from these emissions into the hydrosphere was proven by relative enrichments of dissolved methane in near-bottom waters. Stable carbon isotopic signatures ~~of the methane~~ pointed to a predominant microbial ~~origin~~methane formation, presumably based on high organic matter sedimentation in this region. Although known from many continental margins in the world's oceans, this is the first report of an active area of methane seepage in the Southern Ocean. Our finding of substantial methane emission related to a trough and fjord system, a topographical setting that exists commonly in glacially-affected areas, opens up the possibility that methane seepage is a more widespread phenomenon in polar and sub-polar regions than previously thought.

Keywords: Cold seeps, gas bubble emissions, methane seepage, South Georgia

1. Introduction

As methane is a potent greenhouse gas, considerable research efforts have been made to comprehend its sources and sinks (Intergovernmental Panel on Climate Change (IPCC), 2007). A large part of the methane in the ocean is generated in anoxic marine sediments by methanogens (e.g. Whiticar, 1999; Hinrichs and Boetius, 2002), but sedimentary methane is also formed by thermal breakdown of organic matter occurring at high temperature and pressure. The methane generated in the sediments is influenced by several processes limiting the amount of methane reaching the sediment–water interface. Methane can be removed by hydrate formation in the gas hydrate stability zone (e.g. Hyndman and Davis, 1992). At or near the sediment surface, up to 80% of the methane is utilized in reduced sediments as a result of the anaerobic oxidation of methane (AOM) (e.g. Barnes and Goldberg, 1976; Knittel and Boetius, 2009). Finally, aerobic methane-oxidizing bacteria at the sediment surface and/or in the water column oxidize methane that has bypassed the anaerobic microbial filter (Hanson and Hanson, 1996; Murrell, 2010). Although the methane flux to the ocean is reduced by these processes, a fraction of methane is injected into the water column. This methane can either be emitted dissolved in fluids or, in case of over-saturation, in form of gas bubbles. Gas bubble emissions are hydroacoustically detectable and are commonly called flares due to their flame-shape appearance in echograms. They often correlate with sub-seafloor anomalies characterized by blanking in the echograms. Such anomalies in the sediment can be caused by upward migrating fluids transporting light hydrocarbons and, thus, may represent gas chimneys fueling the seafloor seepage sites (Judd and Hovland, 1992).

The expanding numbers of seep emission estimates worldwide highlights the importance of methane seepage for the global carbon cycle, and its potential contribution to the oceanic and atmospheric methane inventory, where - in the latter case - methane acts as a potent greenhouse gas. Although the total global atmospheric methane budget is constrained reasonably well (580 Tg yr^{-1}; IPCC, 2007), estimates by source sector vary considerably (Dlugokencky et al., 2011). In particular, global estimations of methane fluxes from geological sources in the marine realm such as natural gas seeps are highly uncertain. At deep-water seep sites most gas bubbles dissolve during ascent through the water column (e.g. McGinnis et al., 2006) and the dissolved methane is further oxidized by microbes (Reeburgh, 2007; Valentine et al.,2001). In contrast, a fraction of gas emitted from shallow water environments may transgress the sea-atmosphere boundary, especially in storm seasons (Shakhova et al., 2013)~~(Schmale et al., 2010; Schneider Von Deimling et al., 2011)~~. Therefore, shelf and upper slope areas such as off Spitsbergen (Gentz et al., 2013), in the Black Sea (Greinert et al., 2010), at the Coal Oil Point seep field (Clark et al., 2010; Mau et al., 2012) and off East Siberia (Shakhova et al.,

2010) are of particular interest when considering the role of marine methane seepage as possible contributor to atmospheric methane concentrations.

1.1 Marine methane seepage in the Southern Ocean

Sea-floor hydrocarbon seepage occurs at numerous sites on the world's ocean margins, from the continental shelves to the abyssal depths, in a variety of geological settings (Judd and Hovland, 2007; Suess, 2010). Notwithstanding several decades of global methane seep exploration, examples in the Southern Ocean, defined to comprise the water masses south of the Polar Front (Griffiths, 2010), are almost unknown. First videographic evidence of an Antarctic cold seep was obtained by Domack et al. (2005) from the seafloor beneath the collapsed Larsen B ice shelf, western Weddell Sea, located in the trough of the Evans and Crane glacier. This site later was ~~later~~ revisited by Niemann et al. (2009), who classified the seepage as inactive, based on the presence of dead shells of seep-associated chemosymbiotic clams (*Calyptogena* sp.), a geochemical sea floor analysis, and the lack of hydroacoustically detectable gas emissions. Apart from ~~at~~ this single extinct cold seep site, naturally occurring chemosynthetic organisms (Van Dover et al., 2002) also have ~~also~~ been found in the Southern Ocean at hydrothermal vents in the Bransfield Straight (Aquilina et al., 2013; Bohrmann et al., 1999) and the South Sandwich back-arc (Rogers et al., 2012), and at a whale fall from the Kemp Caldera (Amon et al., 2013). The paucity of records of chemosynthesis-based communities in the Southern Oceans can be explained partly ~~explained~~ by a lack of exploration~~,~~ due to the challenging and remote conditions in this region (Rogers and Linse, ~~2012~~2014). The biogeographic relation to chemosynthetic-based communities at seeps north of the Polar Front, e.g. New Zealand (Davy et al., 2010), offshore Chile (Sellanes et al., 2004) and Australia (Logan et al, 2010), is however largely unknown (Rogers and Linse, 2014).

~~The expanding numbers of seep locations discovered worldwide highlights the importance of methane seepage for the global carbon cycle, and its potential contribution to the oceanic and atmospheric methane inventory, where - in the latter case - methane acts as a potent greenhouse~~

~~gas. In contrast to deep-water seep sites, where most bubbles dissolve during ascent through the water column and the dissolved methane is oxidized by microbes (Mau et al., 2012; McGinnis et al., 2006; Römer et al., 2012b), a fraction of gas emitted from shallow water environments may transgress the sea-atmosphere boundary, especially in storm seasons (Schmale et al., 2010; Schneider Von Deimling et al., 2011). Therefore, shelf and upper slope areas such as off Spitsbergen (Gentz et al., 2013; Westbrook et al., 2009), in the Black Sea (Greinert et al., 2010), and off East Siberia (Shakhova et al., 2010) are of particular interest when considering the role of methane seepage as a possible contributor to concentrations of methane in the atmosphere.~~

1.2 Regional setting of South Georgia

South Georgia belongs to the crustal blocks forming the North Scotia Ridge (Fig. 1a), which were once part of the continental connection between South America and the Antarctic Peninsula (Cunningham et al., 1998; Dalziel and Dott, 1975). These crustal blocks were moved during the Cenozoic by backarc spreading and subsequent eastward growth of the Scotia Sea (Cunningham et al., 1998; Forsyth, 1975). There is evidence for active convergence along the western side of the North Scotia Ridge, but convergence has now ceased along its eastern section, which includes the South Georgia block (Cunningham et al., 1998; Ludwig and Rabinowitz, 1982). However, analyses of an earthquake with its epicenter located south of the South Georgia block (see Fig. 1b) indicates nearly pure thrust faulting, interpreted to represent thrusting of the Scotia Plate beneath South Georgia (Pelayo and Wiens, 1989). This tectonic framework shows that South Georgia is part of an isolated microcontinental block, divided by the W-E trending Cooper Bay Shear Zone that crosses the Island (Fig. 1b). This is the major tectonic boundary that displaces the late Jurassic to early Cretaceous basement complexes exposed on South Georgia (Curtis et al., 2010).

In contrast to ~~the knowledge of~~ the geologic and tectonic evolution of South Georgia, the shelf and upper slope area surrounding the Island have been less well studied. However, a recent comprehensive bathymetric compilation aimed at elucidating the paleo-ice sheet drainage of the

~~Island~~ island has greatly improved our knowledge of the continental shelf morphology of South Georgia (Graham et al., 2008). ~~Graham et al. (2008)~~ These researchers described large eroded troughs linked to the recent fjords around South Georgia (Fig. 1b; for the purpose of this study numbered 1-10), and they proposed that these cross-shelf troughs were formed during glacial times and represent former pathways of outlet glaciers and ice streams. ~~While~~ Although probable Mesozoic sedimentary and volcanic rocks extend beneath the inner shelf of South Georgia, Cenozoic sediments form the outer parts of the continental shelf (Graham et al., 2008; Simpson and Griffiths, 1982).

South Georgia is located in the path of the Antarctic Circumpolar Current (ACC). The Polar Front is located to the north and the southern ACC front loops anticyclonically around the island from the south before retroflecting to the east (Thorpe et al., 2002). The shelf waters of South Georgia ~~often show oceanographic properties that~~ are often markedly different from the open waters, indicating that local processes are important in dictating shelf water mass characteristics (Young et al., 2011). Various shelf-specific processes have been observed, or inferred at South Georgia, and significant interannual variability of the oceanographic conditions on the shelf are known (Meredith et al., 2005; Young et al., 2011). ~~Whitehouse et al. (2008) reported a surface water warming of up to 2.3°C in 81 years around South Georgia, however, this warming was not recognized in waters deeper than 200 m.~~ In general, the special oceanographic conditions around South Georgia result in a rich ecosystem, with large phytoplankton blooms and related strong atmospheric carbon drawdown (Borrione and Schlitzer, 2013; Jones et al., 2012), as well as high organic matter sedimentation on the shelf. The seasonally occurring blooms are particularly intense on the northern shelf area of South Georgia and within the adjacent Georgia Basin (Borrione and Schlitzer, 2013).

Seepage of methane has not been reported so far near South Georgia. During Polarstern cruise ANT-XXIX/4 we explored the northern shelf of South Georgia to identify any seeps that might originate from the high organic matter load on the continental shelf. We first performed a comprehensive hydroacoustic survey to detect gas seepage, which we subsequently investigated by visual seafloor observation and correlated with methane analysis in the sediments and water column that together extend our understanding of methane-related processes taking place in the local hydrosphere.

~~In this study we performed a comprehensive hydroacoustic survey along the northern shelf of South Georgia, detecting numerous gas flares and analyzing their distribution. Subsequent sea floor visual observations of two of these flares revealed a detailed view of the seep sites. These data were correlated with oceanographic parameters and methane analyses in water column samples that together illustrate methane-related processes taking place in the local hydrosphere. In addition, gas samples taken from sediment cores from the seep sites were analyzed for their stable carbon isotopic composition, which allowed us infer the source of the methane fueling them.~~

2. Methods

2.1 Hydroacoustic systems

The data used for this study were acquired during R/V Polarstern cruise ANT-XXIX/4 in March and April 2013 (Bohrmann, 2013). Bathymetric mapping was performed using an ATLAS Hydrosweep Deep-Sea 320-beam echosounder operating at a frequency of ~15 kHz and covering a swath width about four times the water depth. Raw data were processed with the commercially available hydrographic processing systems CARIS 7.0 HIPS and SIPS and the open source seafloor mapping software MB (MultiBeam)-System ~~software~~ (Caress et al., 2012)~~and~~. ~~the~~ The grids produced were visualized with the geographic information system ESRI ArcMap 10.0~~, which allowed for inclusion of additional relevant data to be plotted (e.g. track lines, locations of gas emissions)~~. The cleaned Hydrosweep data were gridded with a cell size of 25 m. We combined our results with additional data from earlier cruises of the British Antarctic Survey (Fretwell et al., 2008) (available at http://www.antarctica.ac.uk/bas_research/data/online_resources/sgbd/) and the GEBCO dataset (http://www.gebco.net/).

We used the ship-mounted parametric single beam echosounder (SBES) ATLAS PARASOUND for shallow subbottom imaging. The secondary low frequency (SLF) of about 4 kHz was recorded and processed online with the software ATLAS PARASTORE. The resulting PS3-files were imported to

SENT (H. Keil, University of Bremen) and the data plotted. In addition, the SBES ATLAS PARASOUND was used for ~~flare detection and~~ imaging of rising gas bubbles (‘flare detection’) that show up as backscatter anomalies in echograms~~,~~ using the primary high frequency (PHF) of about 18 kHz (Fig. 2a). The transducer opening angle ~~is~~ was 4°, resulting in a footprint size of about 7% of the water depth. PARASOUND data as well as metadata are available at the PANGAEA data repository.

2.2 Seafloor observations

The Ocean Floor Observation System (OFOS), a towed underwater system equipped with a high-resolution digital camera (ISITEC, CANON EOS 1Ds Mark III), was used to visually inspect the sea floor at an altitude of about 1.5 – 2 m relative to the seabed in areas where flares were detected. In addition to the provided live feed, ~~T~~the camera was programmed to take high-resolution (21 megapixels) photographs of the sea floor every 30 seconds~~ at an altitude of about 1.5 – 2 m relative to the seabed~~. Underwater-navigation was achieved using the shipboard IXSEA Posidonia ultra short baseline system, with an accuracy of 5 – 10 m, and these data were used to establish the OFOS tracks and the positions of each photograph taken.

2.3 Water column analyses

Water column properties were investigated deploying a 24-Niskin water bottle rosette to which a CTD-unit was attached (Seabird, SBE 911+).~~Water column properties were studied by repeated hydrocasts with a 24-Niskin water bottle rosette and a CTD (Seabird, SBE 911+).~~ Using the sensors of the CTD-unit, salinity, temperature, and pressure data were measured. ~~and, i~~In addition, a Sea-Tech transmissometer and a SBE 43 sensor was used to record~~ed~~ beam transmission and ~~a SBE 43 sensor~~ concentrations of dissolved oxygen, respectively. For quantification of methane concentrations in the water column, 750 ml of sampled seawater were transferred from the Niskin bottles into pre-evacuated 1000 ml glas bottles immediately after recovery~~,~~. ~~followed by gas extraction according to~~Gas was extracted from these samples using the modification of the vacuum degassing method described by ~~-~~Rehder et al. (1999). The extracted gas ~~samples were~~was analyzed onboard with a 6890N gas chromatograph (Agilent Technologies) equipped with a capillary column and connected to a Flame Ionization Detector, as described in Pape et al. (2010). Calibrations and performance checks of the analytical system were conducted regularly using commercial pure methane standards. The coefficient of variation determined for the analytical procedure was less than 2%.

2.4 Stable carbon isotope signatures

Three sediment~~ary~~ gas samples ~~each~~ were extracted from two gravity cores taken close to flare origins (GC-1: station PS81/280-1 in cross-shelf Trough 6, Fig. 3a; GC-2: station PS81/284-1 in Cumberland Bay, Fig. 3b) were analyzed for stable carbon isotope ratios of methane. The samples were obtained from depths between 6 and 9 meters below sea floor (mbsf), which was below the ~~actual~~ depth of the sulfate-methane transition (Chapter 9 in Bohrmann, 2013), and therefore~~, thus,~~ should not have been influenced by potential anaerobic methane oxidation ~~of methane processes~~. Sediment (3 ml) was sampled from the bottom of each of the freshly cut core sections were taken immediately after core recovery using cut-off syringes and transferred into 20 ml glass vials prefilled with 5 ml of 1 M NaOH. The headspace gas was sampled for onboard methane concentration analyses (Pape et al., 2014) and a subsample was used shortly after arrival at the home laboratory for shore-based measurements of its stable isotope signature. Analysis of stable C isotope signatures of CH$_4$ was conducted ~~in~~ at the commercial GEO-data GmbH laboratory (Garbsen, Germany). Stable C isotope ~~signatures~~ ratios are reported in δ-notation in parts permil (‰), relative to the Vienna PeeDee Belemnite (V-PDB) standard ~~for carbon isotopes~~. The reproducibility of stable carbon isotope determinations is estimated at ±0.1‰.

3. Results

3.1 Hydroacoustic observations

Hydroacoustic surveys revealed the presence of numerous gas emission sites at water depths between 130 and 390 meters below sea level (mbsl) on the northern shelf of South Georgia in spring 2013. The gas emissions appeared as 'flares' in the echograms due to the high impedance contrast of free gas emanating as bubbles through the water column, which produce a high-backscatter signal (Fig. 2a). The flares ~~are~~ were composed of vertically arranged oblique reflections that image the up-rising individual bubbles or groups of bubbles, and make them discernible from fish schools. In total, at least 133 individual flares were detected during our study (Figs. 3a and b, supplementary table S1). The flares showed largely straight and vertical orientation (e.g. the 170-m high ‘Cumberland Bay Flare’, Fig. 4c), indicating a lack of strong currents that would be expected to deflect the bubbles during their rise through the water column. Roughly ~~≃~~75 % of the flares were less than 100 m high, with an average of ~70 m (supplementary table S1). However, three flares extended from the sea floor to a height of at least 25 mbsl. The uppermost part of the echograms was disturbed by acoustic noise that hampered differentiation of gas bubbles from plankton and/or fish. In general, the real flare height was difficult to determine using Parasound recordings, as the small ~4° opening angle and a coherent narrowing footprint with decreasing depth impeded the detection of the uppermost part of the flares when the ship did not pass exactly through the center of the bubble train.

Many flares detected were discontinuous or ~~had no~~were disconnected ~~connection to~~from the sea floor (Figs. 4a and b). This observation can be attributed to horizontal deflections of a bubble stream that moves in and out of the conical Parasound beam, or to ~~pulsing~~ transient gas bubble streams where the emissions are ~~spatially and~~ temporally variable. The latter explanation seems to be more likely in this case, as the tall flares appeared vertical and ~~didn’t~~ did not show strong lateral deflections~~,~~; ~~although~~ however, variable current regimes cannot be ruled out entirely.

The temporal variability of the flares was examined by imaging a given location more than once. Four flares became visible at the same location two times within ca. 14 days, whereas eight other flares appeared only once, although ~~crossed~~ surveyed twice (supplementary table S2). The observations of the flare appearance and the repeated surveys show that most flares probably are temporally variable on scales of minutes to weeks.

The detected flares were not randomly distributed along the northern South Georgia margin. They occurred either within the Cumberland Bay fjord system or within the other incised cross-shelf troughs that cut through the broad shelf surrounding the island (Fig. 3a). Two fjord systems were inspected for the occurrence of flares during cruise ANT-XXIX/4: Cumberland Bay was investigated intensively (Fig. 3b), whereas Possession Bay was entered once and inspected only along ~~only~~ two survey lines. While numerous flares were observed in the Cumberland Bay region, no indication of gas emissions ~~was~~ were found in Possession Bay. In total, more than 75 flares were detected in both branches of Cumberland Bay and within the cross-shelf to which the fjord system connects (designated as Trough 5 in Fig. 3b). Flares were distributed close to the fjord-mouth and within the fjord itself, but were not detected in the innermost parts of the bay close to the glaciers that discharge into the fjord at the coast. A few flares were found within the ~10 km area seaward of the fjord mouth, and one flare was detected as far as ~30 km from land. In addition to cross-shelf Trough 5, gas emissions also were ~~also~~ found in four of the seven troughs defined by Graham et al. (2008) on the northern shelf of South Georgia (Fig. 3a). The northern shelf was ~~passed for~~ hydroacoustically ~~surveys~~ surveyed twice in a roughly two week interval, and during both investigations, flares were observed to be restricted to the troughs. No flares were detected on the shallower banks between the cross-shelf troughs and, with the exception of Troughs 2 and 7, all of the troughs surveyed showed gas emissions.

Sedimentary strata were not visible in subbottom Parasound SLF profiles of the shallow shelf banks (Fig. 4b), but the troughs were characterized by reflections indicating sediment accumulations of up to ~40 m in their centers (Figs. 4a). The reflections were sub-parallel to the sea floor and presumably reflect accumulations of sediment transported from the fjords to the shelf, and deposition within the cross-shelf troughs. Numerous zones of acoustic blanking or acoustically-transparent chimneys that pierced the horizontal reflections were observed for all of the sediment infills within the troughs (Figs. 2b, 4a, b and c), ~~suggesting~~ which might be caused by upward gas migration at these sites. The acoustic chimneys were positioned directly underneath the acoustic flares in the water column in several areas, ~~strongly~~ giving credence to the ~~suggesting~~ suggestion that the chimneys are the conduits for channeling free gas through the sediments towards the sea floor, where gas bubbles escape into the water column and form the flares imaged in the Parasound PHF echograms (Figs. 2b, 4a, b and c).

3.2 Visual sea floor observations at the 'Cumberland Bay Flare'

An OFOS deployment was conducted at a flare site designated as the 'Cumberland Bay Flare' in order to visually confirm the sea floor origin of the gas flares recorded hydroacoustically (Fig. 4c), and the nature of the surrounding sediments. The sea floor was inspected along an approx. 400 m long track (Fig. 5). ~~Visibility during the OFOS deployment was limited to a few meters because of the highly turbid and sediment-rich meltwater in the fjord and inspections were thus performed with an altitude of ~2 m.~~ The flat sea floor was composed of unconsolidated sediments and detached kelp fronds (Figs. 6a and b), many of which were partially buried. The observed epibenthic invertebrate megafauna included cidaroid and echinoid sea urchins, asteroid starfish, holothurians, hexactinellid sponges, and fish (Fig. 6a).

Numerous centimetre-sized holes were visible in the sea floor along the OFOS track, which were probably produced by endobenthic organisms or may represent the orifices of emanating gas bubbles. Rising gas bubbles were observed at two seep sites during the OFOS deployment, which was guided by flare observations in the water column. Our observations document ~~single~~ gas bubbles emanating singly from the sea floor without forming continuous bubble streams. During an observation period of about 40 minutes at the southeastern located seep site (Figs. 5 and 6a), we documented more than 50 events (roughly about each minute), where a single bubble or ~~small groups~~pulses of 2 or 3 bubbles close together rose from the seabed. ~~-~~We observed individual rising gas bubbles again at a northwestern seep site, which is located ~50 m distant from the other and corresponded to a different water column flare (Figs. 5 and 6b).

At both seep sites the sea floor was covered by centimeter to decimeter-sized, subcircular, whitish material (Fig. 6a and b), occurring either as coherent patches or as collections of several smaller patches (Figs. 5 and 6a). These patches most probably represent microbial mats indicative of fluid flow from below. However, we did not see taxonomically higher chemosymbiotic organisms typically associated with cold seeps in other regions, such as bathymodiolin mussels or vesicomyid clams. The sea floor in two locations where whitish material was observed was ~~slightly~~ elevated slightly and formed topographic mounds up to a few decimeters high (Fig. 6a). Fig. 5 illustrates that the whitish material ~~is~~ was restricted to two areas a few meters in extent, both of which ~~are~~ were located at the central foci of the two flares detected hydroacoustically.

3.3 Water column characteristics in Cumberland Bay

Three hydrocasts revealed a general water column stratification and specific differences in hydrological conditions in Cumberland Bay (station CTD-1 close to the 'Cumberland Bay Flare'; CTD-2 close to the 'Grytviken Flare'; see Fig. 3b) and a station seaward of the fjord (CTD-3; Fig. 7). A pronounced surface layer (upper ~20 mbsl) was present at stations CTD-1 and CTD-2 in Cumberland Bay, characterized by relatively low salinities (<33 PSU), temperatures (<2.8 °C) and beam transmissions (<80 %). These characteristics suggest that this water mass (not observed at the seaward station CTD-3; Figs. 7, supplementary Fig. S3) ~~represents plumed meltwater and~~is affected by mixing with freshwater ~~originates~~ originating from the melting marine terminating glaciers ~~that feed the bay~~ (Fig. 3b). Physico-chemical properties varied only slightly with increasing depth throughout the midwater section. The lower limit of this water mass was found at ~165 mbsl for CTD-2 (located relatively deep within the fjord) and at ~190 mbsl for CTD-1 (located close to the fjord mouth), suggesting that its vertical extent is spatially variable and may reflect topographically-controlled circulation patterns. Similar water characteristics at all three investigated stations indicate water exchange between Cumberland Bay and the shelf area of South Georgia. The lowermost water mass within and outside Cumberland Bay was characterized by relatively low temperatures (~2.4 – 1.7°C) and relative depletions in dissolved oxygen concentrations (6.5 – 5.2 mL/l), but with the highest salinities (up to 34.2 PSU). A markedly lower beam transmission (as low as 80% at the bottom) recorded for the near-bottom water mass within the bay, if compared to that at the outer shelf station, might be the result of a higher particulate matter load (see also chapter 4.~~2~~1).

~~Strong~~ Significant enrichments in dissolved methane of up to 25.4 nmol/l and 55.6 nmol/l, respectively, were measured in the lowermost water mass characterized by low-beam transmission at the two CTD stations taken in close proximity to the 'Cumberland Bay Flare' and the 'Grytviken

Flare' (Figs. 3b and 7). At these stations concentrations of dissolved methane decreased significantly with decreasing depth within the lower 100-120 meters of the water column down to ca. 5 nmol/l (Fig. 7), which is still slightly elevated in contrast to the atmospheric equilibrium (3-3.3 nmol/l). At the outer shelf station, where flares were not detected, dissolved methane concentrations of <5 nmol/l were measured though the whole water column.

3.4 Stable carbon isotopic composition of methane

Stable carbon isotopic analysis of methane in the gas samples extracted from the two sediment cores taken in close proximity to flares (GC-1 within cross-shelf Trough 6; GC-2 in the Cumberland Bay; Figs. 3a and b) revealed strong depletions in ^{13}C, with $\delta^{13}C\text{-}CH_4$ values ranging between –80.2 and –88.9‰ (V-PDB). The greatest depletion came from a methane sample extracted at ~6.5 mbsf from the sediment core GC-2 at the 'Grytviken Flare'.

4. Discussion

4.1 Gas seeps at the northern shelf of South Georgia

We detected 133 gas flares at the northern shelf of South Georgia (Fig. 3a) during R/V Polarstern cruise ANT-XXIX/4 in 2013. Visual sea-floor inspections with the high-resolution video camera of the OFOS system confirmed active seepage at the 'Cumberland Bay Flare' in the form of rising gas bubbles and white sea-bed patches (Figs. 6a and b) interpreted as microbial mats fueled by methane emission. Hydroacoustically-imaged flares originated from sea floor locations that showed acoustically-blanked chimneys in the underlying sediments. In addition, water samples taken in bottom waters within two flares showed elevated concentrations of dissolved methane (Fig. 7), that proved methane transport by gas bubbles from the sea floor into the hydrosphere.

This new finding of methane seepage adds to the long and steadily growing list of seep areas in the world's oceans (Campbell, 2006; Judd and Hovland, 2007; Suess, 2010). At high latitudes, seeps are known in the Arctic and sub-Arctic, which have recently sparked particular scientific interest because of their links to permafrost settings (Shakhova et al., 2010) with potential global warming effects

(Westbrook et al., 2009). Hydrothermal vents and cold seeps are known to host specialized faunal communities which are based on chemosynthesis (Bachraty et al., 2009; Van Dover et al., 2002). In the Southern Ocean to date only a few chemosynthetic ecosystems are known (Rogers and Linse, ~~2012~~2014), including the presently inactive cold seep in the western Weddell Sea, hydrothermal vent fields and a natural whale fall (Amon et al., 2013; Aquilina et al., 2013; Bohrmann et al., 1999; Domack et al., 2005; Niemann et al., 2009; Rogers et al., 2012). The epibenthic invertebrate megafauna observed in the Cumberland Bay area comprises species commonly found around South Georgia (Hogg et al., 2011; James E. McKenna Jr., 1991; Jones et al., 2008). Except for the inferred microbial mats, chemosynthetic organisms usually found at cold seep sites were not found at the seeps investigated in this study. This might be because of the relatively shallow water depth (~250 mbsl), since the typical animals obligate at cold seeps (e.g. species of vesicomyid clams, bathymodiolin mussels and siboglinid tubeworms) are restricted to aphotic habitats. Explanations for their absence on the continental shelves include the abundance of predators in shallower waters, or competitive exclusion by primary consumers limiting the presence of species dependent on chemoautotrophic symbionts (Sahling et al., 2003). The exact depth limit is not precisely resolved (Little et al., 2002), but the shallowest seep communities with the typical obligate species found so far are reported from the Eel River basin, offshore California in ~350 mbsl (Orange et al., 2002) and in the Sea of Okhotsk in ~370 mbsl (Sahling et al., 2003). In our study we detected gas bubble seepage using hydroacoustics in the same depth range (ca. 380 mbsl), but did not investigate these sites visually. Thus, it remains a possibility that typical obligate cold seep animals are present on the deeper shelves around South Georgia.

As noted above, the flares detected during ANT-XXIX/4 along the northern shelf of South Georgia are not randomly distributed, but are restricted to the fjords and glacial troughs along the shelf (Fig. 3a), the latter accounting for ~15% of the total shelf area surrounding the island of South Georgia. A similar observation was made in a hydrocarbon seep area on the Baffin Bay shelf region, where oil and gas seeps were found within glacially-formed troughs seaward of fjord systems (Grant et al., 1986; Levy and Ehrhardt, 1981). In addition, seepage was inferred to occur in fjords in Spitsbergen (Forwick et al., 2009) and Norway (Judd and Hovland, 2007), based on the presence of sea floor pockmarks. Fjords generally appear to represent favorable settings for methane seepage as they are commonly characterized by high sedimentation rates ~~(~~due to high input from inflowing glaciers or meltwater streams~~)~~. In addition, in some cases shallow water sills hamper water exchange with open seawater areas and ventilation, favouring anoxic conditions and protecting organic material from rapid microbial decomposition under aerobic conditions, which finally leads to large accumulations of refractory organic matter in the sediments (Judd and Hovland, 2007). During our study we observed various sill structures in the high-resolution bathymetric maps of the South Georgia fjords, probably representing fjord moraines (Hodgson et al., ~~subm.~~2014). However, these do not appear to fully restrict flow (Fig. 3b), as temperature, salinity and concentrations of dissolved oxygen are indeed lower in the bottom waters than in overlying water masses, but the values where similar in magnitude for all three stations, both within and outside the fjord. Therefore, there is no apparent isolation of the deep waters in Cumberland Bay (Figs. 7, supplementary Fig. S3). Bottom water oxygen concentrations within and outside the bay were ~5 mL/l (corresponding to ~220 µmol/l), indicating well-oxygenated conditions.

For Cumberland Bay, Platt (1979) estimated the sedimentation rate at 2.8 × 10^3 g m^{-2} yr^{-1} and an organic matter input of 60 g carbon m^{-2} yr^{-1}, providing an ideal setting for shallow biogenic methane production. A biogenic methane source is proven by $\delta^{13}C\text{-}CH_4$ values <–80 ‰ (V-PDB) for all gas samples collected from the two sediment cores we investigated. Methanogens preferentially consume substrates depleted in ^{13}C, whereas thermogenic light hydrocarbons by non-selective hydrocarbon cracking are not affected by significant isotope fractionation effects (Claypool and Kvenvolden, 1983). For a microbial hydrocarbon formation and accumulation both high sedimentation rate and the presence of sufficient amount of organic matter in the sediments ~~is~~ are required. South Georgia lies in the eastward flowing Antarctic Circumpolar Current (ACC), creating a morphological high in the largest meander modifying the Southern ACC front (Meredith, 2003;

Thorpe et al., 2002). Due to this particular hydrographic configuration, intensive and regular phytoplankton blooms develop in the area north and northwest of the South Georgia shelf (Borrione and Schlitzer, 2013), leading to both a rich food web (Atkinson et al., 2001), and a high carbon production, which is either exported (Schlitzer, 2002) or ultimately deposited at the sea floor. Although there is no indication for deeply buried reservoirs of thermogenic gas fueling the gas emission sites investigated in this study, thermogenic ~~gas~~ hydrocarbon migration through deep-rooted faults cannot be entirely excluded as the fjords and connecting cross-shelf troughs may have established along lines of structural weakness that could have evolved in association to faults zones (Graham et al., 2008). Unfortunately, there are currently no seismic data imaging the deeper structure of the South Georgia block to test such a hypothesis. Lacking those data, we are also limited in discussion whether smaller geologic structures are controlling the seep distribution, such as those documented by Naudts et al. (2006) for the widespread seepage at the northwestern Black Sea margin. There, seeps were preferentially found in elongated pockmarks above margins of filled channels, along crests of sedimentary ridges, related to canyons or scarps of submarine landslides. In our study we discovered several flares rooted at morphological structures within the Cumberland Bay fjord, which were interpreted by Hodgson et al. (2014) as remnant or partially-preserved outer moraines and might support sub-surface channeling of migrating fluids. Other small-scale morphological features described by Hodgson et al. (2014), which include iceberg scours and pits or glacial debris, do not appear to be related to seepage.

4.2 Intensity of gas seepage and fate of methane in the water column

~~Due to the nature of our survey, m~~Most of the imaged flares during our surveys were not centered directly under the vessel, thus, precluding a quantitative assessment of their intensities. However, our observations revealed that (1) most flares are only few tens of meters high, (2) flares often appear episodically and are characterized by discharge in pulses, and (3) flares indicative for individual bubbles or bubble groups are occasionally tilted, so that their sea floor origin could not always be traced (Figs. 4a and b). These data suggest that most of the flares are rather weak and represent discontinuous releases of gas bubble emissions. Visual inspection of the ‘Cumberland Bay Flare’, one of the most intense flares we imaged (Fig. 4c), showed sporadic gas bubble discharge from the projected flare origin, but also indicated that the sporadic release of individual gas bubbles was sufficient to cause a relatively intense signature in the corresponding echogram. ~~Because o~~Our data demonstrate that the flares are temporally variable over minutes to weeks and it ~~may be possible~~is likely that the activity and intensity of the gas emissions may also change seasonally or annually. Due to the nature of our surveys, we are not able to resolve possible factors modulating the discharge (e.g. tides, earthquakes, storms events, bottom currents, decomposition of subsurface gas hydrates), as documented in more intensively investigated seep areas such as Hydrate Ridge (Kannberg et al., 2013), Coal Oil Point (Boles et al., 2001), Bush Hill (Solomon et al., 2008), or at seeps at the Northern Cascadia Margin (Lapham et al., 2013).

The quantity of bubbles and the intensity of seepage on the northern shelf of South Georgia seems to be rather weak in comparison to other seep areas, e.g. Hydrate Ridge (Heeschen et al., 2005; Torres et al., 2002), the Makran continental margin (Römer et al., 2012b), Santa Barbara channel (Hornafius, 1999), as well as several seepage areas in the Black Sea (Greinert et al., 2006; Naudts et al., 2006; Nikolovska et al., 2008; Pape et al., 2010; Römer et al., 2012a), where vigorous gas bubble emissions and/or strong flares have been documented. However, the large number of emission sites as revealed from our flare imaging, in combination with the ~~strong ~~significant enrichments in dissolved methane, suggests injection of ~~significant ~~non-negligible quantities of methane into the bottom water in fjords and the cross-shelf troughs of South Georgia, even though each individual seep may contribute only a small amount of methane. In addition, it is conceivable that our observations occurred in a period of minor seepage activity. For example, observations made for the Coal Oil Point seep field revealed interannual changes between 1990 and 2008, which have been related to internal geological processes (Bradley et al., 2010).

Our hydroacoustic data additionally indicate that most gas bubbles released into the water column probably did not reach the upper water layer and atmosphere, but instead dissolved entirely during their ascent. With three exceptions, all 133 flares detected disappeared from the SBES echograms well below the sea surface. Although the geometric limitation of the SBES coverage, particularly at shallow depths, has to be considered, the fraction of methane transported as gas bubbles is not limited only by the maximum bubble rising height, but mainly depends on the effectiveness of gas exchange processes taking place when entering the hydrosphere, due to concentration differences. The proportion of methane initially contained in the bubble is rapidly replaced by dissolved nitrogen and oxygen from the ambient water (Leifer and Patro, 2002; McGinnis et al., 2006)~~; Wüest et al., 1992)~~. The rapidity of this process strongly depends on the bubble size, the ~~rising~~ rise velocity, as well as the composition and conditions of the surrounding medium and the presence of upwelling flows (Leifer and Judd, 2002). Several studies have demonstrated that methane escapes the bubbles well before final bubble dissolution (~~Greinert and McGinnis, 2009; Greinert et al., 2006;~~ Leifer and Patro, 2002; McGinnis et al., 2006; Rehder et al., 2002~~; Römer et al., 2012a~~). Our suggestion that most of the methane discharged from the South Georgia northern shelf does not reach the upper water column is additionally strengthened by the relatively low concentrations of dissolved methane (about 5 nmol/l) in the intermediate to uppermost water masses at two hydrocast stations, deliberately acquired close to recorded flares in the Cumberland Bay area (Figs. 3b and 8). Most probably, the strong stratification of the water column, as evidenced by the T-S diagram (supplementary Fig. S3), impedes a regular vertical mixing within Cumberland Bay and the released methane therefore remains within the bottom water, leading to the observed profiles. A fraction of this methane may be oxidized ~~by~~ through microbial activity (Reeburgh, 2007; Valentine et al., 2001), so the measured concentrations reflect a balance between methane input and ~~sea-floor~~bottom-water consumption within Cumberland Bay and water exchange with the outer shelf water. It is hard to directly correlate water column data with flare strength, but our data agree~~s~~ with our assumption that the methane transported via gas bubbles rapidly dissolves in the water body, so that most of the dissolved methane remains in the bottom water~~ and that~~ . ~~b~~Bubbles producing the hydroacoustic flares visible at that sites and reaching 50 m higher into the water column may have been depleted in methane.

5. Conclusion and Outlook

Hydroacoustic surveys and physico-chemical investigations of the water column in combination with visual sea floor inspections and analysis of sedimentary gas conducted on the northern shelf of South Georgia revealed the presence of widespread methane seepage from the sea floor into the water column. Flares occur restricted to the fjords and within glacial troughs along the shelf surrounding the island of South Georgia, which we confirmed has a biogenic source through isotopic analyses. This finding is to our knowledge ~~only~~ the second cold seep detected in the (sub-)Antarctic region so far and the first observation of a widespread and active area of seepage in the Southern Ocean. Detailed surveys are required to determine further distribution ~~and~~, variability, and total abundance of such methane seep sites, which is probably significantly higher than the 133 flares we detected during the detailed but still spatially-limited surveys of R/V Polarstern cruise ANT-XXIX/4.

We argue that the seepage around South Georgia is spatially related to the glacial trough and fjord system, a setting often occurring in sub-Antarctic regions that need further exploration to characterize the nature, distribution and magnitude of hydrocarbon seepage in this region. Because of the high organic matter input and presumed available methane reservoirs in the largely unexplored margins surrounding the Antarctic Peninsula (Murphy et al., 2013; Schlitzer, 2002; Wadham et al., 2012), and in the glacially-influenced shelves of various sub-Antarctic islands (Dickens et al., accepted), natural seepage in the Southern Ocean might be more common than previously thought.

Research questions ~~about~~ arising from our methane seepage finding around South Georgia ~~following from our study~~ include: 1) unraveling the relationships between seepage, ~~methane sources and~~, rates of sediment accumulation, ~~as well as~~and the type and amount of organic carbon that sustain the methane reservoirs; 2) evaluating the potential contribution of thermogenic gas ~~in some areas~~; 3) ~~documentation~~ documenting ~~of~~ the role of methane input on the biosphere and associated biogeochemical processes ~~supported by the methane input~~; 4) establishing whether some of the deeper seeps support chemosynthetic fauna, and, if present, ~~do~~ determining whether they serve as 'stepping stones' for larval distribution of chemosynthesis-based organisms in the Southern Ocean; 5) constructing a carbon budget for the region, which includes source and consumption terms as well as the effect of circulation within and outside the fjords, and the circumstances under which this methane may reach the atmosphere.

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Figure captions

Fig. 1 a) Plate tectonic overview with the South Georgia microplate (SG) located at the eastern part of the North Scotia Ridge. SAM: South American Plate, SCO: Scotia Plate, SAN: Sandwich Plate, ANT: Antarctic Plate (modified after Cunningham et al., 1998). b) Map of the main tectonic structures of the South Georgia crustal block (after MacDonald and Storey, 1987). The shelf morphology is characterized by at least ten cross-shelf troughs sourcing at the fjords of the island (yellow areas; Graham et al., 2008).

Fig. 2 a) Echogram recorded with the single beam echosounder (SBES) illustrating a flare composed of numerous oblique high-backscatter traces representing uprising gas bubbles. The footprint of the SBES at a water depth of ~380 mbsl corresponds to ~30 m ~~to the~~ width of the flare signal at the sea floor (white line). b) SBES echogram combing the water column data and the subbottom information (using 18 and 3.5 kHz frequencies, respectively). Gas emission sites are characterized by acoustic blanking in the subsurface (gas chimneys) and emissions of free gas in the water column causing hydroacoustic flares. For locations see Figs. 3a and b.

Fig. 3 a) ~~Map showing the shelf~~ Shelf bathymetry with its characteristic cross-shelf troughs in combination with the ship track (black line) and flare positions (red dots) detected during R/V Polarstern cruise ANT-XXIX/4. Cross-shelf Troughs 1-7 at the northern shelf have been crossed in order to detect free gas in the subbottom and water column. Additionally, two fjords were investigated: the Possession Bay, where Trough 4 is sourced, and the Cumberland Bay, which is directly connected to Trough 5. b) Detailed map of the Cumberland Bay with the processed bathymetric data acquired during cruise ANT-XXIX/4. More than 75 flares were detected during the surveys within the fjord system.

Fig. 4 Three profiles recorded with SBES combining subbottom (3.5 kHz) and water column (18 kHz) information. Flares are repainted in red. For locations see Figs. 3a and b. a) Profile 1 shows an echogram crossing the cross-shelf Trough 4. Several flares were detected~~, but~~ with the majority ~~showed~~ showing a discontinuous pattern most probably caused by pulsing gas bubble emissions. b) Profile 2 shows an echogram at cross-shelf Trough 6. In contrast to the shallow banks lacking visible sediment strata in the subbottom, the troughs are characterized by sediment accumulation. c) Profile 3 shows an echogram recorded during entering of the Cumberland Bay and crossing the ‘Cumberland Bay flare’. Several acoustic chimneys characterized by vertical blanking zones illustrate ~~up-~~rising free gas in the subbottom (red outlines with arrows) and ~~additionally,~~ three flares ~~prove~~ demonstrating the emission of gas bubbles into the water column.

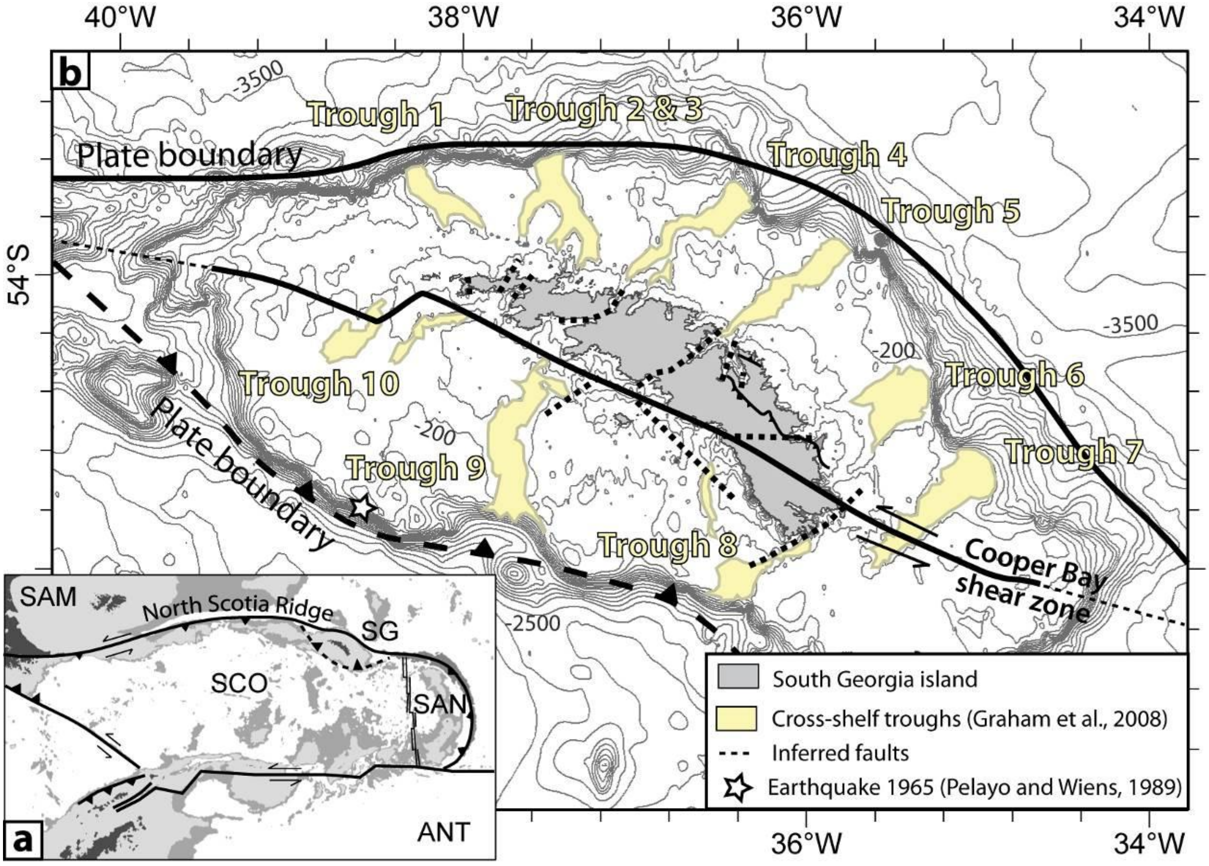
Fig. 5 a) Bathymetric map from ship-based swath echosounder recordings with the dive track of the Ocean Floor Observation System (OFOS; station PS81/285-1) passing two areas, where hydroacoustic investigations indicated gas bubble emissions from the sea floor (light red circles). Rising gas bubbles were recognized in both areas and whitish patches on the sea floor additionally ~~proved~~ suggested the position of the seep sites (white dots).

Fig. 6 a) Sea floor picture taken at the Cumberland Bay Flare with the high-resolution video camera mounted on the frame of the Ocean Floor Observation System (OFOS) and showing an elongated mounded structure at the sea floor characterized by whitish color, probably representing microbial mats. b) Sea floor image taken at the northwestern flare area demonstrates the occurrence and intercalation of white colored and additionally dark grey colored patches. For locations see Figs. 3b and 5.

Fig. 7 Water column profile illustrating selected data recorded during three CTD casts ~~acquired~~. Stations CTD-1 (colored dashed lines) and CTD-2 (colored solid lines) were located within the Cumberland Bay and CTD-3 (black lines) seaward the fjord mouth (see Fig. 3b). Elevated methane concentrations were measured in particular in the lowermost ~100 m at the two Cumberland Bay stations taken close to hydroacoustically detected flares. Bottom waters at that depth were characterized by low temperatures, beam transmissions and dissolved oxygen concentrations.

Supplementary Fig. S3 Temperature-Salinity diagram of the data from the three CTD stations during ANT-XXIX/4. T-S condition in surface waters at stations CTD-1 and CTD-2 located in the Cumberland Bay clearly differed from those at station CTD-3 positioned seaward (for locations see Fig. 3b).

Fig. 1


40°W
38°W
36°W
34°W
54°S
55°S
b
-3500
Trough 1
Trough 2 & 3
Trough 4
Trough 5
Trough 6
Trough 7
Trough 8
Trough 9
Trough 10
Plate boundary
Plate boundary
-200
-2500
Cooper Bay shear zone
South Georgia island
Cross-shelf troughs (Graham et al., 2008)
Inferred faults
Earthquake 1965 (Pelayo and Wiens, 1989)
a
SAM
North Scotia Ridge
SG
SCO
SAN
ANT

815

Fig. 2

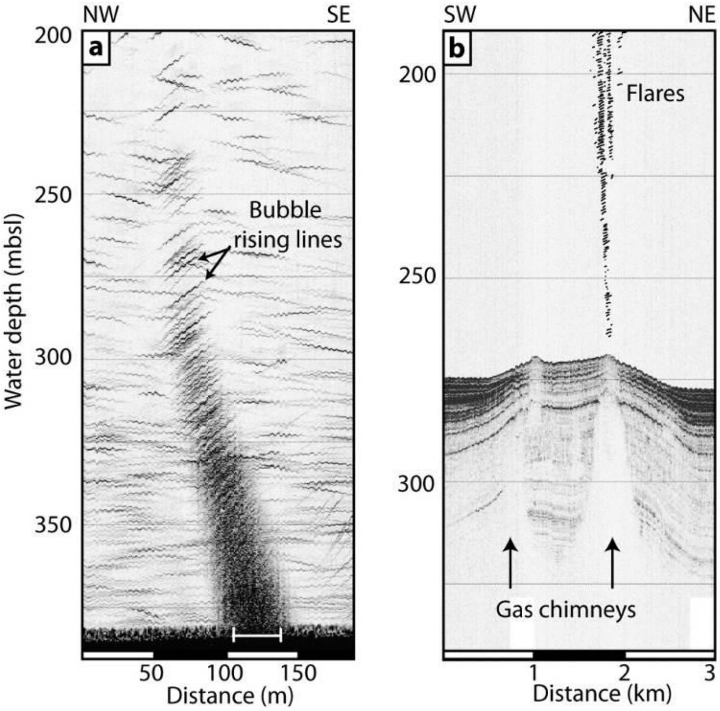
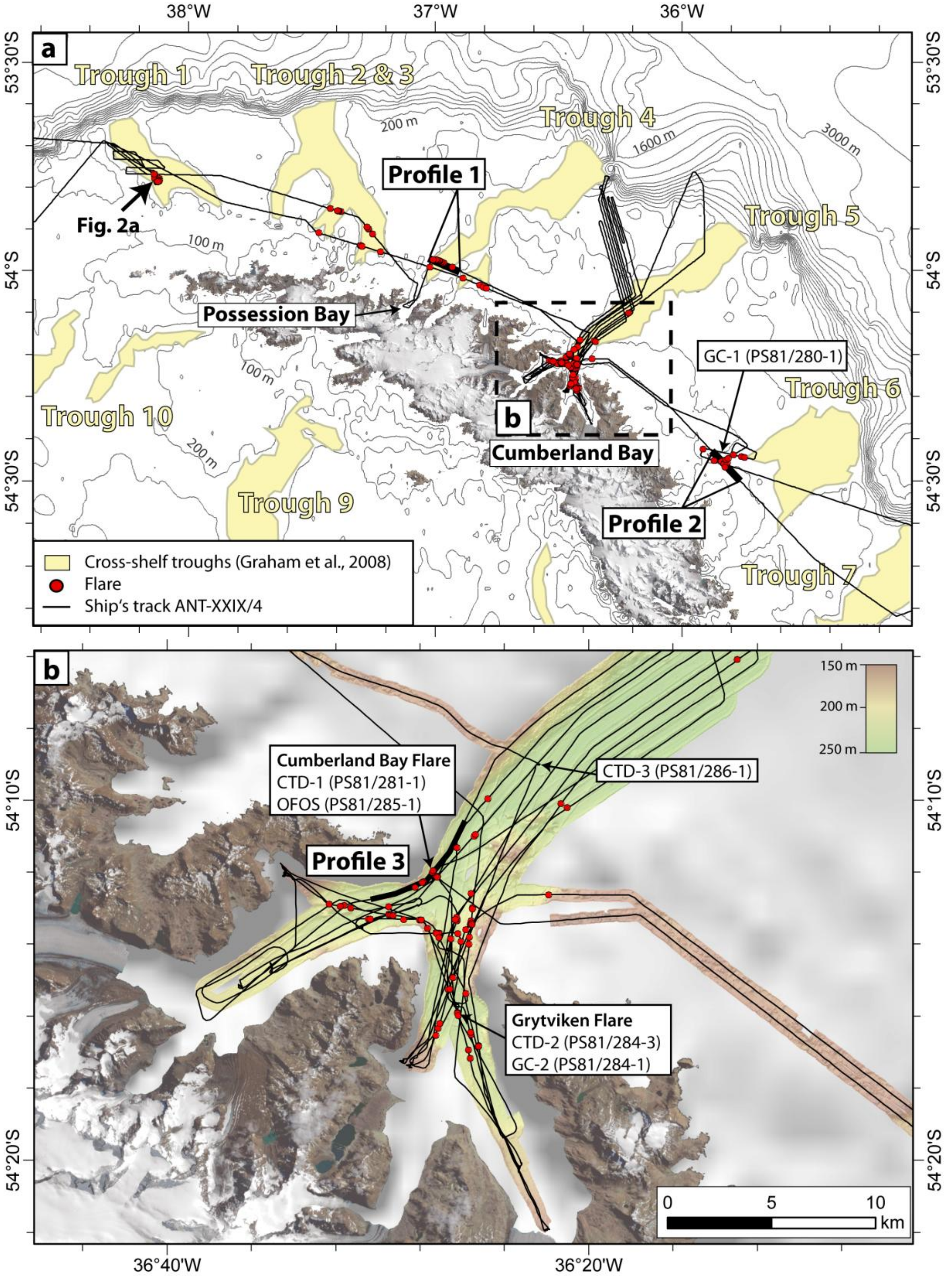

NW
SE
a
200
250
300
350
Water depth (mbsl)
Bubble rising lines
50
100
150
Distance (m)
SW
NE
b
200
250
300
Flares
Gas chimneys
1
2
3
Distance (km)

Fig. 3



a
38°W
37°W
36°W
53°30'S
54°S
54°30'S
Trough 1
Trough 2 & 3
Trough 4
Trough 5
Trough 6
Trough 7
Trough 9
Trough 10
200 m
1600 m
3000 m
100 m
100 m
200 m
Profile 1
Profile 2
Fig. 2a
Possession Bay
Cumberland Bay
GC-1 (PS81/280-1)
b
Cross-shelf troughs (Graham et al., 2008)
Flare
Ship's track ANT-XXIX/4
b
150 m
200 m
250 m
54°10'S
54°20'S
36°40'W
36°20'W
Cumberland Bay Flare
CTD-1 (PS81/281-1)
OFOS (PS81/285-1)
CTD-3 (PS81/286-1)
Profile 3
Grytviken Flare
CTD-2 (PS81/284-3)
GC-2 (PS81/284-1)
0
5
10
km

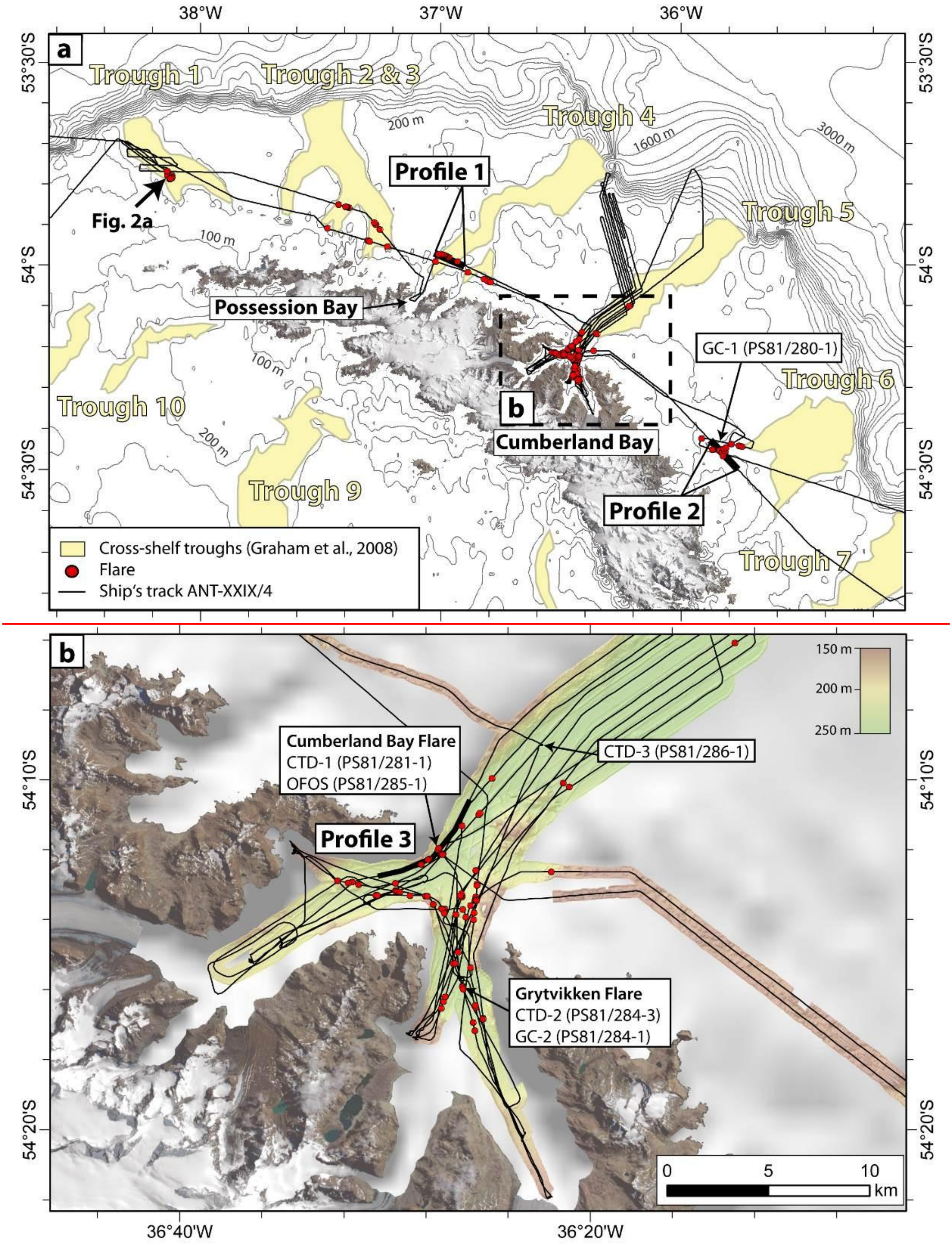
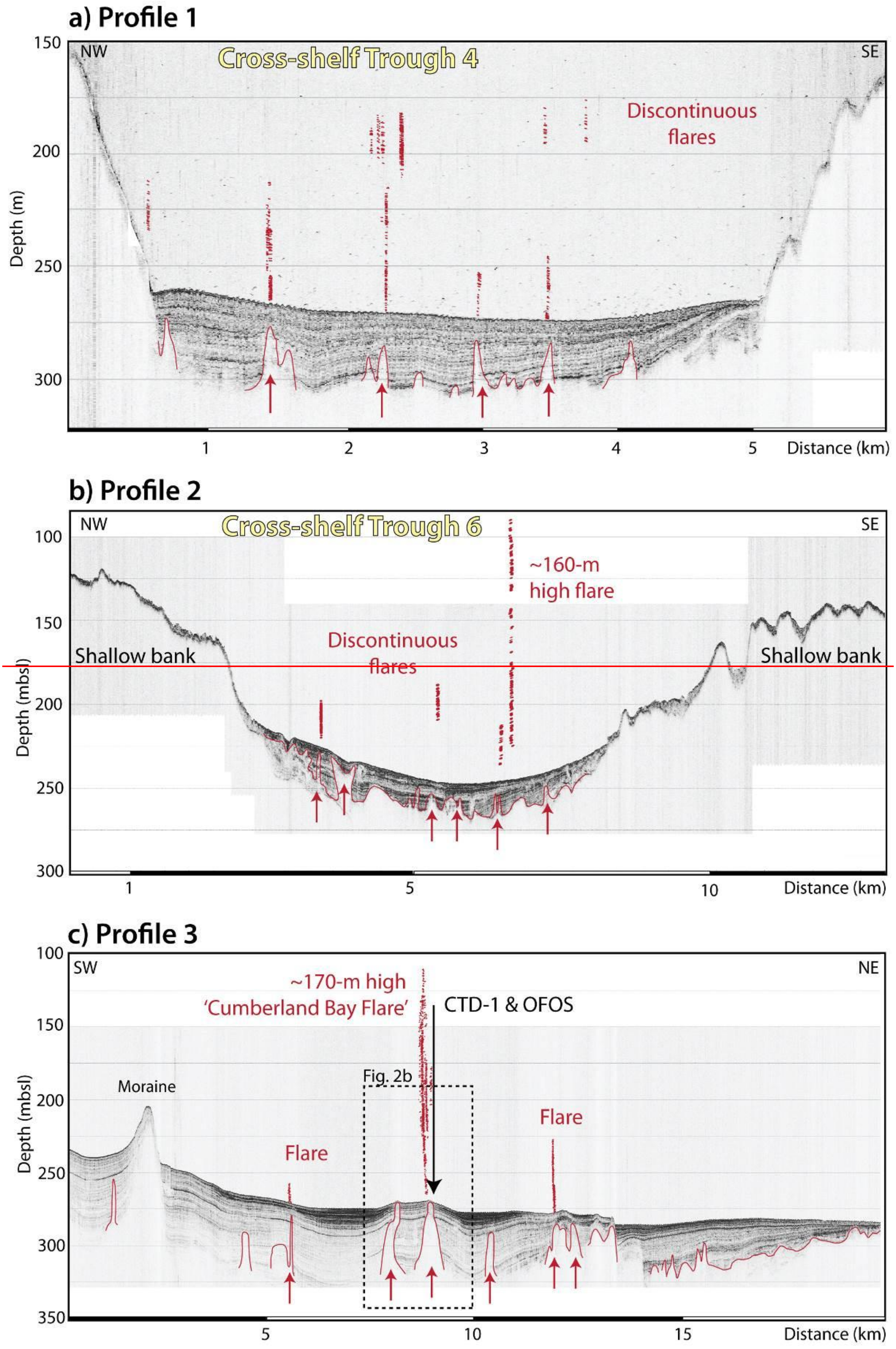
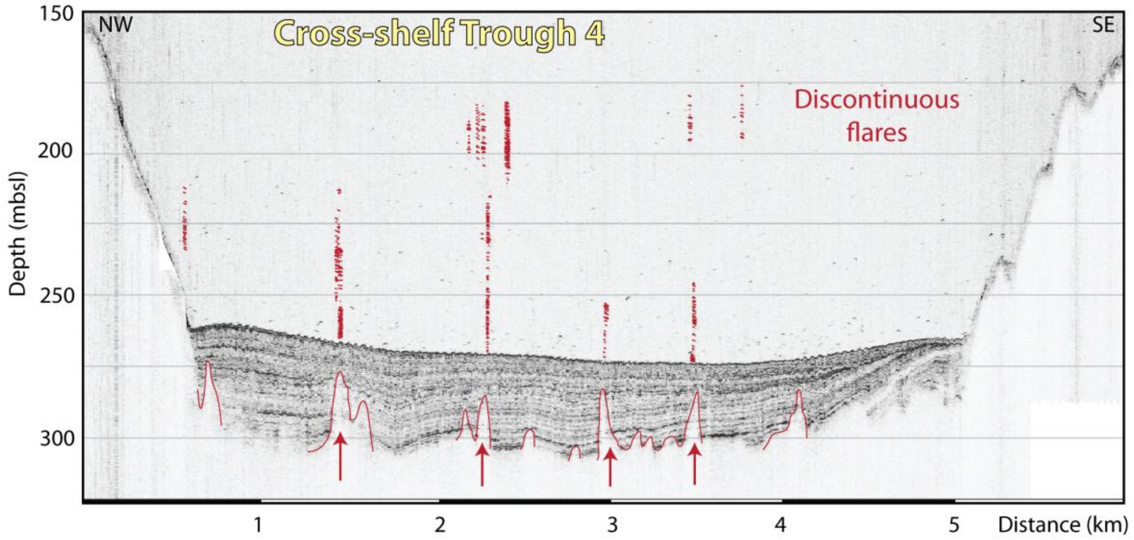

a
38°W
37°W
36°W
53°30'S
54°S
54°30'S
Trough 1
Trough 2 & 3
Trough 4
Trough 5
Trough 6
Trough 7
Trough 9
Trough 10
200 m
1600 m
3000 m
100 m
100 m
200 m
Profile 1
Profile 2
Fig. 2a
Possession Bay
Cumberland Bay
GC-1 (PS81/280-1)
b
Cross-shelf troughs (Graham et al., 2008)
Flare
Ship's track ANT-XXIX/4
b
150 m
200 m
250 m
CTD-3 (PS81/286-1)
Cumberland Bay Flare
CTD-1 (PS81/281-1)
OFOS (PS81/285-1)
Profile 3
Grytvikken Flare
CTD-2 (PS81/284-3)
GC-2 (PS81/284-1)
54°10'S
54°20'S
36°40'W
36°20'W
0
5
10
km

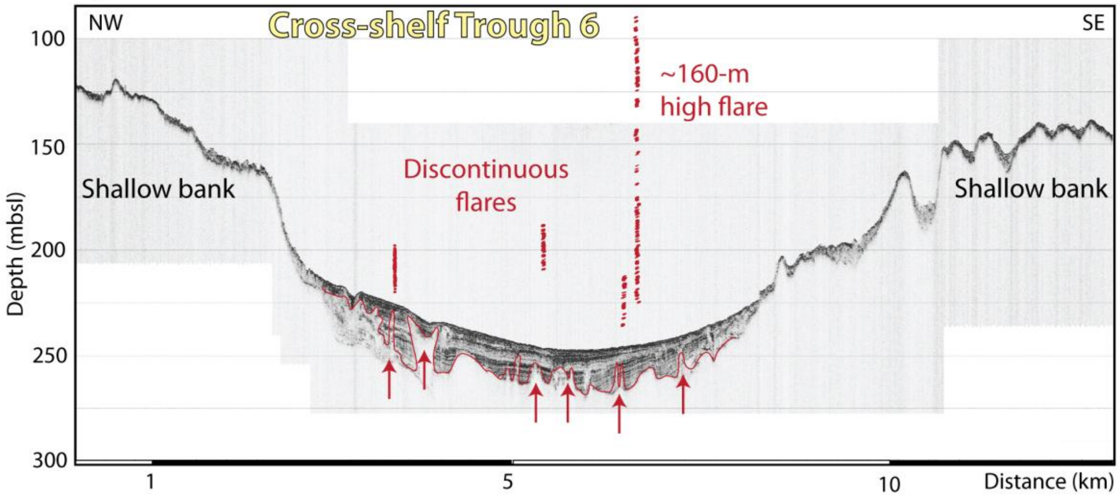
Fig. 4


a) Profile 1
NW
SE
Cross-shelf Trough 4
Discontinuous flares
Depth (m)
150
200
250
300
1
2
3
4
5
Distance (km)
b) Profile 2
NW
SE
Cross-shelf Trough 6
~160-m high flare
Shallow bank
Discontinuous flares
Shallow bank
Depth (mbsl)
100
150
200
250
300
1
5
10
Distance (km)
c) Profile 3
SW
NE
~170-m high 'Cumberland Bay Flare'
CTD-1 & OFOS
Fig. 2b
Moraine
Flare
Flare
Depth (mbsl)
100
150
200
250
300
350
5
10
15
Distance (km)

a) Profile 1



b) Profile 2



c) Profile 3

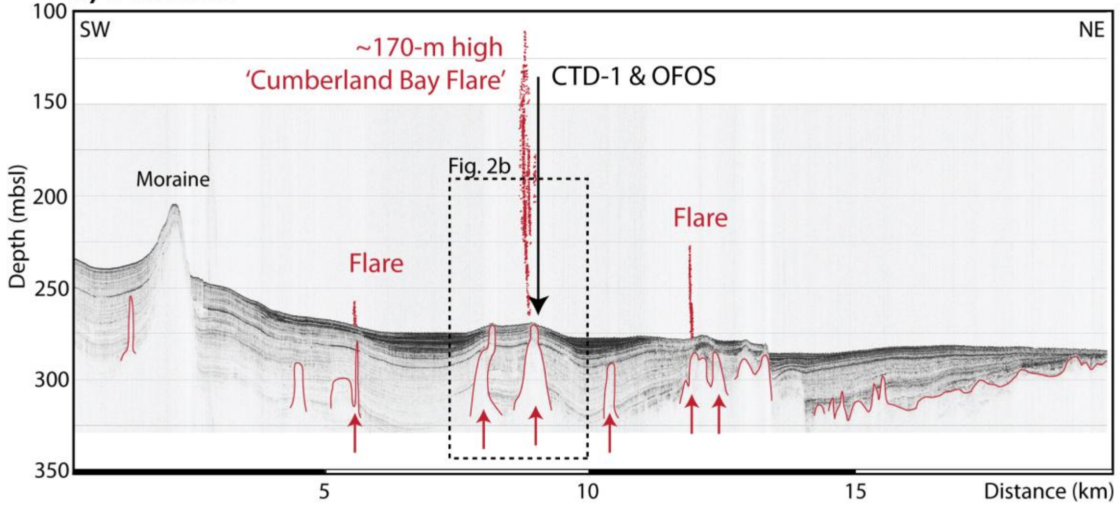


Fig. 5

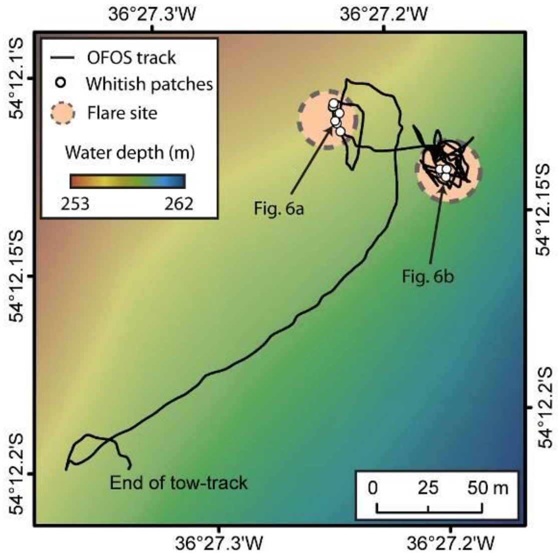

36°27.3'W
36°27.2'W
54°12.1'S
54°12.15'S
54°12.2'S
54°12.15'S
54°12.2'S
OFOS track
Whitish patches
Flare site
Water depth (m)
253
262
Fig. 6a
Fig. 6b
End of tow-track
0
25
50 m
36°27.3'W
36°27.2'W

Fig. 6

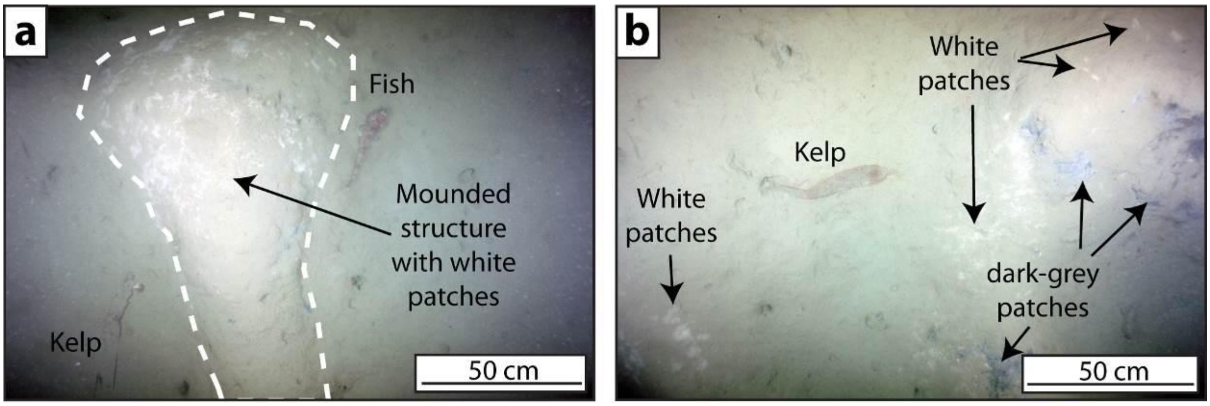
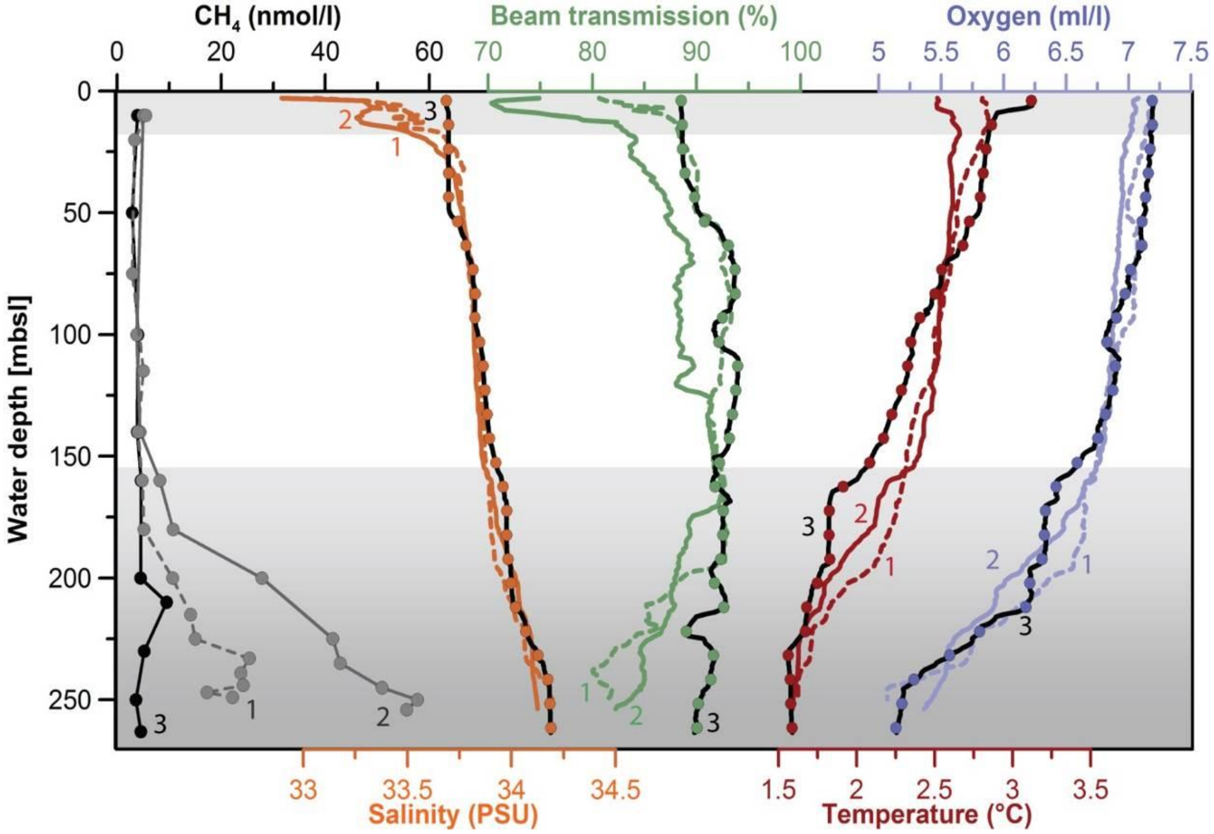

a
Fish
Mounded structure with white patches
Kelp
50 cm
b
White patches
Kelp
White patches
dark-grey patches
50 cm

Fig. 7



CH$_4$ (nmol/l)
0
20
40
60
Beam transmission (%)
70
80
90
100
Oxygen (ml/l)
5
5.5
6
6.5
7
7.5
Water depth [mbsl]
0
50
100
150
200
250
1
2
3
33
33.5
34
34.5
Salinity (PSU)
1.5
2
2.5
3
3.5
Temperature (°C)

Highlights:

- An extensive active seepage area was discovered north of South Georgia
- High input of organic matter leads to high rates of formation and emission of methane
- Gas emissions were restricted to glacially-formed fjords and cross-shelf troughs
- Seepage might be more common in polar and sub-polar regions than previously thought