

This discussion paper is/has been under review for the journal Biogeosciences (BG).
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Technical Note: Disturbance of soil structure can lead to release of methane entrapped in glacier forefield soils

P. A. Nauer, E. Chiri, J. Zeyer, and M. H. Schroth

Institute of Biogeochemistry and Pollutant Dynamics (IBP), ETH Zurich, Zurich, Switzerland

Received: 2 August 2013 – Accepted: 26 August 2013 – Published: 6 September 2013

Correspondence to: M. H. Schroth (martin.schroth@usys.ethz.ch)

Published by Copernicus Publications on behalf of the European Geosciences Union.

BGD

10, 14815–14834, 2013

Methane release in glacier forefield soils

P. A. Nauer et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Abstract

Investigations of sources and sinks of atmospheric CH₄ are needed to understand the global CH₄ cycle and climate-change mitigation options. Glaciated environments might play a critical role due to potential feedbacks with global glacial meltdown. In an emerging glacier forefield, an ecological shift occurs from an anoxic, potentially methanogenic subglacial sediment to an oxic proglacial soil, in which soil-microbial consumption of atmospheric CH₄ is initiated. The development of this change in CH₄ turnover can be quantified by soil-gas profile analysis.

We found evidence for CH₄ entrapped in glacier forefield soils when comparing two methods for the collection of soil-gas samples: a modified steel rod (SR) designed for one-time sampling and rapid screening (samples collected ~ 1 min after hammering the SR into the soil), and a novel multi-level sampler (MLS) for repetitive sampling through a previously installed access tube (samples collected weeks after access-tube installation). In glacier forefields on siliceous bedrock, sub-atmospheric CH₄ concentrations were observed with both methods. Conversely, elevated soil-CH₄ concentrations were observed in calcareous glacier forefields, but only in samples collected with the SR, while MLS samples all showed sub-atmospheric CH₄ concentrations. Time-series SR soil-gas sampling (additional samples collected 2, 3, 5, and 7 min after hammering) confirmed the transient nature of the elevated soil-CH₄ concentrations, which were decreasing from ~ 100 μL L⁻¹ towards background levels within minutes. This hints towards the existence of entrapped CH₄ in calcareous glacier forefield soil that can be released when sampling soil-gas with the SR.

Laboratory experiments with miniature soil cores collected from two glacier forefields confirmed CH₄ entrapment in these soils. Treatment by sonication and acidification resulted in a massive release of CH₄ from calcareous cores (on average 0.3–1.8 μg CH₄ (g d.w.)⁻¹); release from siliceous cores was 1–2 orders of magnitude lower (0.02–0.03 μg CH₄ (g d.w.)⁻¹). Clearly, some form of CH₄ entrapment exists in calcareous

BGD

10, 14815–14834, 2013

Methane release in glacier forefield soils

P. A. Nauer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ous glacier forefield soils, and to a much lesser extent in siliceous glacier forefield soils. Its nature and origin remain unclear and will be subject of future investigations.

1 Introduction

Methane in the atmosphere contributes significantly to global climate change (Forster et al., 2007). The total global CH₄ budget is relatively well-constrained, but uncertainties in estimates of individual source and sink contributions remain high (Bousquet et al., 2006; Bridgman et al., 2013). About 70% of CH₄ are from microbial sources (Conrad, 2009); other sources comprise fossil fuel extraction and mining (~18%) and biomass burning (~7%). There is still much debate about the contribution of plant-derived CH₄ (Bruhn et al., 2012), and recently, geologic sources (natural CH₄ emissions related to hydrocarbon reservoirs or geothermal areas) have also been proposed to contribute significantly to the global budget (Etiope and Klusman, 2002, 2010; Milkov et al., 2003). Only three sinks of atmospheric CH₄ have been identified: photochemical oxidation by OH radicals (>80%), losses to the stratosphere, and oxidation by methane-oxidizing bacteria in unsaturated soils (Crutzen, 1991; Dutaur and Verchot, 2007).

In the wake of global change, glaciers and ice sheets have been subject to extensive investigations, resulting in the recognition of subglacial microbial life (Sharp et al., 1999; Skidmore et al., 2000; Skidmore et al., 2005). In this context, certain observations fuelled speculations about widespread methanogenesis under ice, e.g. prevalent anoxic conditions under glaciers (Wadham et al., 2004), elevated CH₄ concentrations in ice-cores (Price and Sowers, 2004; Miteva et al., 2009), molecular evidence of the presence of methanogenic archaea (Miteva et al., 2009) and long-term incubation experiments (Boyd et al., 2010; Stibal et al., 2012). Potential climate feedbacks are subject of an ongoing debate, as the produced CH₄ might be released with glacial meltdown (Wadham et al., 2008, 2012; Boyd et al., 2010).

BGD

10, 14815–14834, 2013

Methane release in glacier forefield soils

P. A. Nauer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Methane release in glacier forefield soils

P. A. Nauer et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Areas in front of receding glaciers, termed glacier forefields, are the first ecosystems directly affected by glacial meltdown. With the ice melt causing a dramatic shift from a subglacial (anoxic, constantly cold, dark) to a proglacial habitat (oxic, temperature fluctuations, UV-light), organisms are forced to adapt. As exposure of subglacial sediments to the atmosphere occurs gradually, forming a well-defined soil chronosequence, glacier forefields are ideal environments to investigate soil development and microbial succession (Stevens and Walker, 1970; Sigler and Zeyer, 2002; Duc et al., 2009; Lazzaro et al., 2009, 2012). However, little is known on CH₄ cycling in these environments.

Recently, microbial oxidation of atmospheric CH₄ has been confirmed in glacier forefield soils in Greenland and Switzerland (Bárcena et al., 2010, 2011; Nauer et al., 2012). Methods employed to estimate soil-CH₄ oxidation in the field included flux chambers and soil-CH₄ profiles, respectively. Flux chambers should be inserted at least 5-10 cm into the soil to minimize lateral gas flux (Rochette and Bertrand, 2007; Rochette and Eriksen-Hamel, 2008). In the stony soil of a glacier forefield, finding locations where this is possible can be challenging and time-consuming. Hence, for the first survey on soil-CH₄ oxidation in glacier forefields in the Swiss Alps (Nauer et al., 2012), the soil-CH₄ profile method was employed using a steel rod (SR) designed for rapid soil-gas extraction in stony soils. Yet, repetitive sampling at the same location was not possible with this device. Consequently, a novel multi-level sampler (MLS) was developed for repeated soil-gas sampling at multiple depths (Nauer et al., 2013). Remarkably, elevated CH₄ concentrations previously observed in SR samples from glacier forefields on calcareous bedrock could not be detected in samples from the MLS during initial tests.

Hence, our objectives for this study were (i) to compare the two sampling instruments (MLS and SR) side by side at three locations in a siliceous and a calcareous glacier forefield to confirm the disagreement with respect to elevated CH₄ concentrations; (ii) to examine the possibility of temporary CH₄ release during SR sampling by performing time-series sampling; and (iii) to provide a first quantitative assessment of

potentially entrapped CH₄ in glacier forefield soils by disturbing miniature soil cores in the laboratory using sonication and acidification.

2 Materials and methods

2.1 Field sites

5 Soil-gas samples and miniature soil cores were collected in two glacier forefields that were part of the initial survey on CH₄ oxidation in the Swiss Alps (Nauer et al., 2012): the Damma glacier forefield (DAM) on siliceous bedrock, and the Griessfirn glacier forefield (GRF) on calcareous bedrock. Details on their soil-physical and -chemical properties can be found in the literature (Lazzaro et al., 2009; Bernasconi et al., 2011; Nauer et al., 2012). In summary, soils in both glacier forefields ranged from barren glacial till to poorly-developed Leptosols (IUSS Working Group WRB, 2006) with dominating sand and gravel fractions. Organic carbon and nutrient contents were low, but increasing with soil age. In each glacier forefield we sampled at three locations with increasing distance to the glacier. Location A was ice-free for < 20 yr, location B for ~ 40-50 yr, and location C for ~ 50–70 yr. Soils around location A at both sites and location B at GRF were largely devoid of vegetation, with occasional pioneer species such as *Cerastium uniflorum* at DAM, and *Linaria alpina* and *Saxifraga aizoides* at GRF. At location C at GRF we observed patchy ground cover of mainly *Salix retusa* and other creeping *Salix* spp. Location B and C at DAM came to lie in the “intermediate age section” as described in Bernasconi et al. (2011), and therefore exhibited similar vegetation cover and soil properties.

2.2 Soil-gas sampling

Collection of soil-gas samples was accomplished using the SR (Nauer et al., 2012) and the MLS as part of a newly developed sampling system (Nauer et al., 2013). A graphical overview of both instruments is given in the supporting information. The SR

Methane release in glacier forefield soils

P. A. Nauer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Methane release in glacier forefield soils

P. A. Nauer et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

is a 2-cm-diameter rod with an inner capillary to extract soil gas. It is hammered into the soil in user-defined increments, and from each depth one soil-gas sample is collected, typically within ~ 1 min after hammering ceased. Conversely, the MLS is designed as an insert for perforated access tubes installed at least 2 weeks prior to soil-gas sampling.

5 With the MLS, up to 20 depths down to 1 m can be sampled through the access tubes' wall, while an inflatable packer system seals the 5-cm interspace between the sampled depths.

The access tubes for the MLS were installed on 12 July 2012 at the GRF locations, and on 8 and 13 July 2012 at the DAM locations. Actual soil-gas sampling with the MLS 10 took place on 25 July and 17 September 2012 at GRF, and on 31 July and 25 September 2012 at DAM. On the sampling days in September we subsequently sampled soil gas with the SR within ~ 0.5 m distance from the installed access tubes at all locations (except for DAM C due to a sudden rain event). In addition to the typically-collected single sample from each depth, we left the SR in place and collected another four soil-gas 15 samples in sequence at $t_n = 2, 3, 5$ and 7 min, respectively, after hammering ceased. Hence, a time-series of total $n = 5$ samples were collected at each of the 3-4 selected depths (up to 65 cm). The first samples from each depth at t_1 (~ 1 min after hammering ceased) were used for comparison with the MLS data, as they represented profiles equivalent to typically-performed one-time sampling with the SR.

20 The procedure of soil-gas sampling was identical for both instruments. At the respective valve of the instrument we collected 15 mL soil gas with a plastic syringe (after discarding the respective dead volume) and injected it into previously evacuated 10-mL glass vials. Air from 2 m above ground was sampled in similar fashion. Pressure was measured with a manometer (LEO 1, Keller AG, Winterthur, Switzerland) to account for 25 dilution and altitude-related concentration differences. Methane from all soil-gas samples was measured on a GC-FID as described in Nauer and Schroth (2010), while oxygen in selected samples was measured on a GC-TCD according to Urmann et al. (2007).

2.3 Miniature-soil-core experiments

To test soils from both glacier forefields in the laboratory for potentially entrapped CH₄, we collected miniature soil cores on the day after respective sampling with the SR. At each of the SR sampling locations, a 60–70-cm deep and ~50-cm wide soil profile was excavated. Soil cores were collected at 24–30 arbitrary spots along the profile using a small steel tube of 10 mm i.d. and 80 mm length, which was horizontally driven 2–5 cm into the soil. We checked for compaction by comparing the insertion depth outside and core length inside the tube; compacted cores were discarded on the spot. Quasi-undisturbed cores were immediately transferred into a 20-mL autosampler glass vial and sealed by crimped butyl rubber stoppers. To prevent microbial oxidation of potentially released CH₄ we added 0.4 mL acetylene (C₂H₂) as inhibitor, resulting in a C₂H₂ gas concentration of approximately 2 vol%. After transfer to the laboratory, 4–5 mL of N₂ was added to each vial to create an overpressure, and the cores were stored at 8 °C until further treatment.

To disturb the soil structure, cores in glass vials were subjected to two different treatments (addition of water with sonication, and acidification). Pressure and CH₄ concentrations were measured before and immediately after each treatment to determine the mass difference of CH₄ (Δ CH₄) in the vials' headspace. The initial mass of CH₄ after closure in the field (0-value field) was estimated using ambient pressure, temperature and CH₄ concentrations in air on the day of sampling. The mass of CH₄ in the headspace determined before the first treatment was denoted as 0-value lab. Five mL of ultrapure H₂O was then added to each vial, followed by vigorous shaking of the vial for 30 s to suspend the soil core and to dissolve any water-soluble soil structure. Preliminary experiments showed that this had only marginal effects on CH₄ concentrations, therefore, the Δ CH₄ was determined after the following sonication treatment. For this the vials were submerged in an ultrasonic bath (USC500D, VWR International, Radnor, Pennsylvania, USA) and sonicated for 5 min at the highest level (45 kHz, 100 W), to disrupt any loosely-bound colloids or organic aggregates. Finally, we added 1 mL of

BGD

10, 14815–14834, 2013

Methane release in glacier forefield soils

P. A. Nauer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



6 N HCl to each vial to dissolve carbonate minerals and potential carbonate precipitates. The cores from GRF immediately released CO₂; however, the acid was largely buffered within minutes. During the reaction, the headspace was connected to a 60-mL syringe, and the additionally produced gas volume was transferred to two empty and pre-evacuated 20-mL vials. Pressure and CH₄ concentrations were determined together with the original vials to calculate total mass of released CH₄. Five vials each of laboratory air and air with 2 vol% of C₂H₂ served as control and underwent the same treatments. Temperature was approximately 20 °C during all laboratory experiments. Methane was determined as described above, but with additional runtime to allow for C₂H₂ elution.

3 Results and discussion

3.1 Comparison of MLS and SR profiles

In both glacier forefields, all CH₄ concentrations measured in samples from the MLS were below atmospheric values (Fig. 1). The profiles from July and September generally agreed well and displayed no major discrepancies. Concentrations of CH₄ showed a gradual decrease with depth, typical for soils with a stable soil-CH₄ sink and no inherent CH₄ source. Lowest CH₄ concentrations were around 1 μL L⁻¹ in young soils (A locations), and tended to decrease to 0.5 μL L⁻¹ in older soil (B and C locations). In contrast, SR samples collected ~ 1 min after hammering ceased (*t*₁; Fig. 1) showed elevated CH₄ concentrations up to 130 μL L⁻¹ at all GRF locations. These samples depict profiles comparable with one-time sampling with the SR (Nauer et al., 2012). Concentrations increased with depth, and highest values were reached at deepest sampling points. On the other hand, SR samples from DAM showed atmospheric or sub-atmospheric CH₄ concentrations at all times (Fig. 1). In all SR samples O₂ concentrations were between 98–100 % of ambient air (not shown).

BGD

10, 14815–14834, 2013

Methane release in glacier forefield soils

P. A. Nauer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Methane release in glacier forefield soils

P. A. Nauer et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Clearly, elevated CH_4 concentrations at GRF could not be explained by sample handling or analytical procedures, as for both sampling instruments the actual extraction of soil gas, storage and CH_4 measurement were identical. Sub-atmospheric CH_4 concentrations from siliceous sites showed that the SR did not “generate” CH_4 by an unknown mechanism. Furthermore, we are confident that sampling with the MLS reflected steady-state situations, as suggested by various tests with the instrument (Nauer et al., 2013). Using the MLS the soil is not disturbed during sampling through access tubes; disturbance occurs only once when the access tubes are installed (weeks earlier). Hence, the most probable explanation for the elevated CH_4 concentrations in GRF soil is the momentary release of entrapped CH_4 when hammering the SR into the soil.

3.2 Time-series sampling with the SR

At all GRF locations, elevated CH_4 concentrations were decreasing exponentially within minutes when sampling several times at the same depth before hammering the SR to the next sampling depth (Fig. 1). This is likely a consequence of the incremental dilution due to sampling, as well as diffusive gas transport away from the release source (depicted in the insert of Fig. 1 with samples from GRF A at 60 cm depth). Possibly, concentrations immediately after hammering were even higher. This clearly shows that the elevated CH_4 concentrations were transient and released by the act of sampling with the SR.

Time-series samples from DAM remained sub-atmospheric, with one exception at DAM A, t_3 (Fig. 1). However, CH_4 concentrations tended to slightly increase with depth and decrease with time in the deepest samples. The variability of soil- CH_4 concentrations between samples from the same depth was likely caused by soil heterogeneity and the increasing volume of soil gas extracted during repeated sampling. In GRF samples potential variability was likely masked by the released CH_4 . However, it cannot be excluded that even in siliceous soils, small amounts of CH_4 could be released by sampling with the SR.

With no additional information, the shape of the SR profiles t_1 from GRF might suggest a deep-soil CH_4 source (Nauer et al., 2012), similar to what has been observed in landfills or peat bogs (Fechner and Hemond, 1992; Urmann et al., 2007; Schroth et al., 2012). However, given the transient nature of the elevated CH_4 concentrations in samples from the SR, a steady-state interpretation of such soil-gas profiles involving a continuous source has to be rejected. More likely, as suggested by results from the MLS, glacier forefield soils on both bedrock types appear to be stable sinks for atmospheric CH_4 . Nonetheless, the performed time-series sampling provided strong indications that additional CH_4 from sources other than the atmosphere are retained in these fully oxic soils, whereby the amount present appears to be orders of magnitude larger in GRF compared with DAM soils. Considering the clear pattern reported in Nauer et al. (2012), where all SR samples from five calcareous glacier forefields showed elevated CH_4 concentrations ($10\text{--}1000 \mu\text{L L}^{-1}$), the phenomenon of entrapped CH_4 might be more widespread in these environments.

3.3 Miniature-soil-core experiments

For a first quantitative assessment of entrapped CH_4 , miniature soil cores enclosed in vials in the field were disturbed by different treatments in the laboratory, and the released CH_4 was measured (Fig. 2). The average amount of CH_4 released from cores of each location increased significantly during the course of the experiment, while in the control vials containing laboratory air or air + C_2H_2 it remained constant and even decreased marginally after acidification (decrease not visible in Fig. 2). Hence, cores from all locations contained some CH_4 that was released with either sonication or both sonification and acidification.

However, the average amounts of CH_4 released from calcareous soil cores were much higher than from siliceous cores (Fig. 2). Some of the GRF cores already released CH_4 during transport from the field to the laboratory. It is unlikely that methanogenesis was ongoing in these cores as they were closed under oxic conditions. Rather we believe that CH_4 was released when part of the core structure was disturbed. The

Methane release in glacier forefield soils

P. A. Nauer et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

addition of water itself had only a negligible effect (preliminary experiments, not shown), but sonication of the suspended cores released significant amounts of CH_4 from DAM and GRF cores (2–5 times more from the latter; Fig. 2). This is a first indication that at least part of the CH_4 could be entrapped in soil colloids or cemented particles that can be suspended by ultrasound. Acidification almost exclusively affected calcareous cores, for which the average amount of CH_4 in the vials increased again by an order of magnitude or more (Fig. 2). Similar CH_4 concentrations in the headspace of the vial containing the core and in the vials containing the excess gas volume showed that CH_4 was released together with CO_2 during acidification only. As the acid affects all calcareous minerals, it is unclear from which particle fraction this massive CH_4 increase originated. Likely, the acid foremost affected the smaller particle fractions in suspension, and only the surface of larger particles, before it was completely buffered. Although calcareous gravel (2–5 mm fraction) from another glacier forefield (Griessen glacier; Nauer et al., 2012) and a quarry showed CH_4 release during acidification, total release was in the range of DAM cores (data not shown). This indicates that the bulk mass of CH_4 in GRF samples may be entrapped in the finer soil fractions, e.g. in cemented particles. Clarification of this issue will require further investigation, which was beyond the scope of this study.

On a mass basis, CH_4 in the vials from GRF increased on average by a factor of 45–270 compared to the originally enclosed air. This is roughly the same order of magnitude as the increase in soil-gas concentrations when sampling with the SR in the field. For DAM, the mass increase in the vials was in the range of 4–7, although no substantial increase in CH_4 concentrations was observed with the SR in the field. Reasons for this are unclear; it might be attributed to the 1-min delay between disturbance (hammering) and sampling with the SR, which could be sufficient to dilute potentially released CH_4 to ambient levels. However, it may also point towards a different nature of entrapment in siliceous versus calcareous soils.

When considering individual cores, cumulative amounts of released CH_4 showed considerable variability (Fig. 3). Amounts released from GRF cores ranged from 0.12–

Methane release in glacier forefield soils

P. A. Nauer et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

7.5 $\mu\text{g CH}_4$ (g d.w.)⁻¹, which was 1–2 orders of magnitude higher than the 0.002–0.16 $\mu\text{g CH}_4$ (g d.w.)⁻¹ from DAM cores. For the latter, the increase of CH_4 in some vials was smaller than the estimated CH_4 originating from the enclosed air. In contrast, all GRF cores released substantial amounts of CH_4 , but some “hotspots” were responsible for the most pronounced increase. However, we could not observe a clear pattern of the released CH_4 with respect to the sampling depth of the cores, with the exception of GRF B and C, where highest amounts of CH_4 were released from samples collected around 30–40 cm depth (Fig. 3). Furthermore, there was no obvious correspondence with bulk-density classes. However, it is remarkable that the only sample with an exceptionally low bulk density released the highest amount of CH_4 from all cores (Fig. 3, GRF C). At present, we lack a conclusive explanation for this observation.

3.4 Implications for further studies

In summary, we can state that there is CH_4 entrapped in both the GRF and DAM soils, but the former retains orders of magnitude more CH_4 . In light of previous results (Nauer et al., 2012) our findings suggest that CH_4 entrapment might be a common feature of glacier forefield soils, in particular on calcareous bedrock. At present, we can only speculate about the origin of released CH_4 and the nature of entrapment. The observation that the bulk mass of CH_4 appears to be entrapped in the finer soil fraction or aggregates could hint towards a potential role of secondary carbonate precipitates of glacial origin (Ford et al., 1970; Fairchild et al., 1993; Lacelle, 2007). Water films existing at the base of temperate glaciers can refreeze due to pressure changes while calcite precipitates and cements particles together (Fairchild et al., 1993; Carter et al., 2003). Methane produced by subglacial methanogenesis may get entrapped in closed-off pores or fissures. Such a mechanism would partially prevent or delay the outgassing of any subglacially-produced CH_4 after glacial meltdown. Secondary carbonate precipitates have also been reported from environments on siliceous bedrock (Carter et al., 2003; Lacelle et al., 2007). However, it is unlikely that such precipitates

would be preserved in the DAM soil with pH of 4–5 (Bernasconi et al., 2011). Here, other types of aggregates might be responsible for CH₄ entrapment. In both glacier forefields, CH₄ might also originate from recent methanogenesis in sealed microsites.

For calcareous glacier forefields we cannot exclude the possibility that the CH₄ is entrapped in the bedrock itself. In this case the likely origin of the CH₄ would be thermogenic. Sampled calcareous glacier forefields in Nauer et al. (2012) lie on late jurassic or early cretaceous limestones as part of the Helvetic nappes (Geological Atlas 1 : 500 000, Federal Office of Topography swisstopo, Wabern, Switzerland). The occurrence of these limestones partially overlaps with a zone where fluid inclusions in quartz-filled fissures are dominated by thermogenic CH₄ (Mullis et al., 1994; Tarrantola et al., 2007). In some adjacent marls in the Helvetic nappes, CH₄-dominated fluid inclusions in calcite-filled fissures have also been documented (Gautschi et al., 1990).

Further insights in the nature of these CH₄ entrapments require additional experiments with fresh samples, including initial separation of grain-size classes, and complete dissolution of calcareous minerals to establish a total mass balance. Radiocarbon age determination and auxiliary stable isotope measurements may shed light on the origin of entrapped CH₄. Furthermore, given the relative ease of how entrapped CH₄ was released, its potential bioavailability should be addressed. Particularly in glacier forefields, CH₄ diffusing from such entrapments could represent an additional source of carbon in an otherwise oligotrophic environment.

Supplementary material related to this article is available online at
**[http://www.biogeosciences-discuss.net/10/14815/2013/
bgd-10-14815-2013-supplement.pdf](http://www.biogeosciences-discuss.net/10/14815/2013/bgd-10-14815-2013-supplement.pdf)**

Acknowledgements. Funding for this study by the Swiss National Science Foundation (grant no. 200021-137721) and by ETH Zurich (grant no. TH-20 06-3) is gratefully acknowledged. Thanks go to Isolde Erny and Martin Vogt for their invaluable help with field work. Further-

BGD

10, 14815–14834, 2013

Methane release in glacier forefield soils

P. A. Nauer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



more, we acknowledge the valuable inputs from Helmut Weissert, Dept. of Earth Sciences, ETH Zurich.

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BGD

10, 14815–14834, 2013

Methane release in glacier forefield soils

P. A. Nauer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Methane release in glacier forefield soils

P. A. Nauer et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Methane release in glacier forefield soils

P. A. Nauer et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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Methane release in glacier forefield soils

P. A. Nauer et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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Methane release in glacier forefield soils

P. A. Nauer et al.

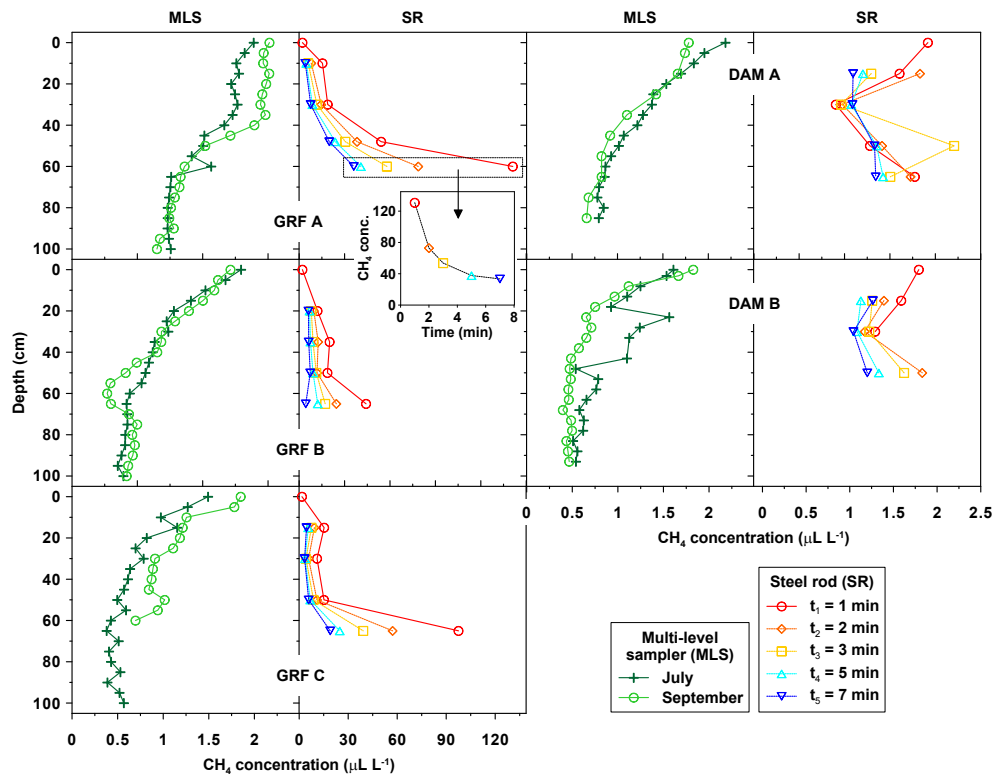


Fig. 1. Soil-CH₄ profiles obtained from the MLS and the SR time-series soil-gas samples. The red SR samples (t_1) can be directly compared to profiles for which each depth is sampled only once. Note the different scales of the x axis for the SR profiles in GRF and DAM graphs.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Methane release in glacier forefield soils

P. A. Nauer et al.

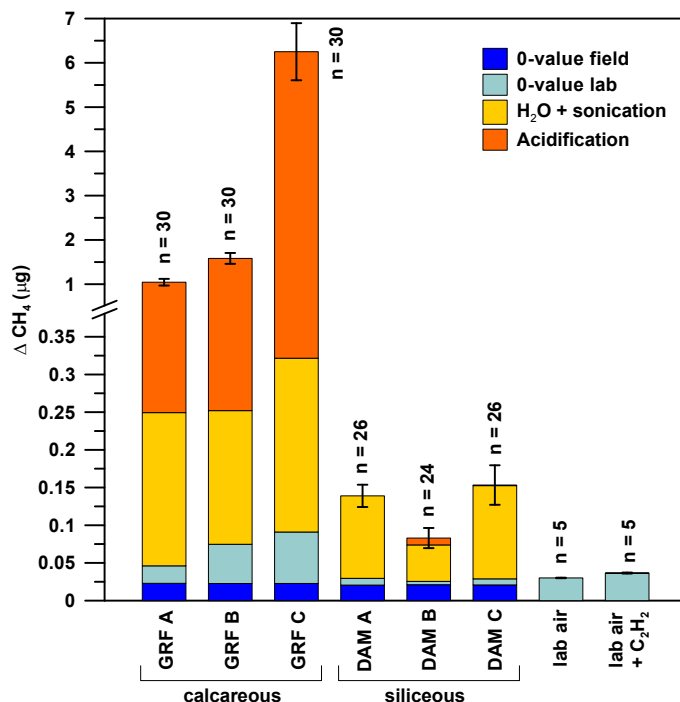


Fig. 2. Cumulative, average amount of CH₄ released from miniature soil cores after treatments to disturb the soil structure. Note the break and variable scaling of the y axis. Zero-values in the field represent the estimated amount of CH₄ contained in enclosed ambient air; 0-values in the lab represent the (additional) amount of CH₄ released during transport and storage. Error bars denote standard deviation of the mean of the total amount of CH₄ in the vials.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Methane release in glacier forefield soils

P. A. Nauer et al.

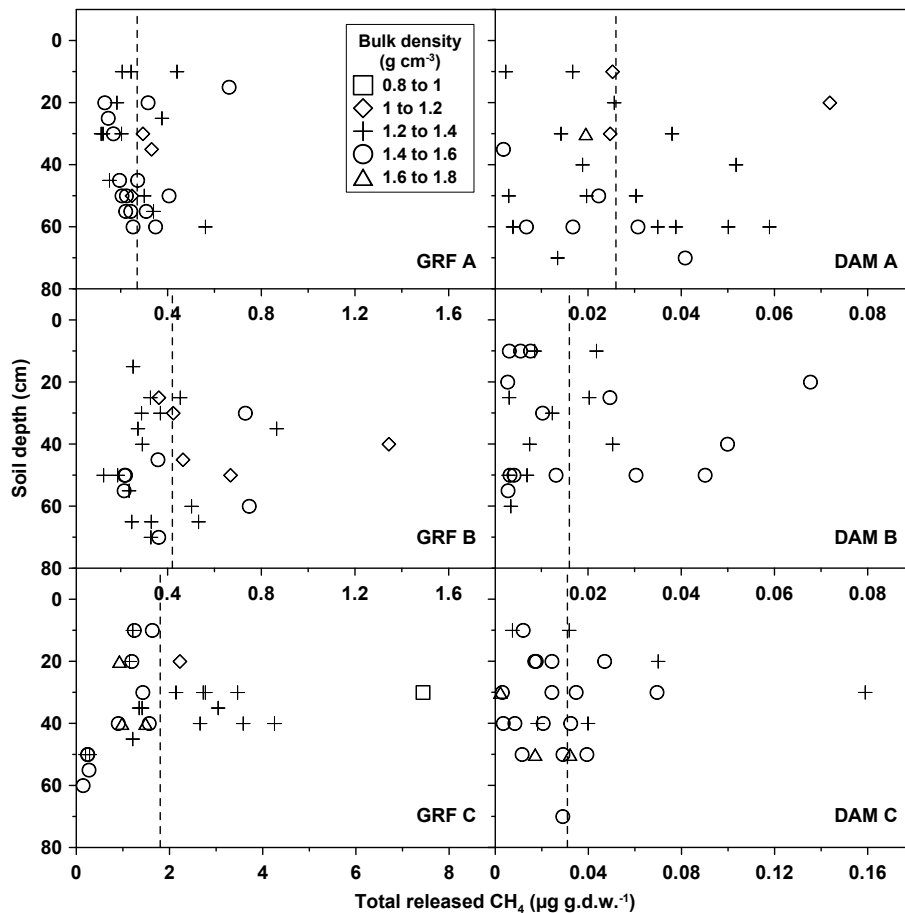


Fig. 3. Depth distribution and cumulative CH_4 released from individual miniature soil cores. The different symbols denote bulk-density classes of individual cores. Vertical dashed lines indicate the average cumulative CH_4 release for each location.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

