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## Technical Note: Disturbance of soil structure can lead to release of methane entrapped in glacier forefield soils

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### Abstract

Investigations of sources and sinks of atmospheric CH<sub>4</sub> are needed to understand the global CH<sub>4</sub> 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 CH<sub>4</sub> is initiated. The development of this change in CH<sub>4</sub> turnover can be quantified by soil-gas profile analysis.

We found evidence for CH<sub>4</sub> 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 CH<sub>4</sub> concentrations were observed with both methods. Conversely, elevated soil-CH<sub>4</sub> concentrations were observed in calcareous glacier forefields, but only in samples collected with the SR, while MLS samples all showed sub-atmospheric CH<sub>4</sub> 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-CH<sub>4</sub> concentrations, which were decreasing from ~ 100 μL L<sup>-1</sup> towards background levels within minutes. This hints towards the existence of entrapped CH<sub>4</sub> 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 CH<sub>4</sub> entrapment in these soils. Treatment by sonication and acidification resulted in a massive release of CH<sub>4</sub> from calcareous cores (on average 0.3–1.8 μg CH<sub>4</sub> (g d.w.)<sup>-1</sup>); release from siliceous cores was 1–2 orders of magnitude lower (0.02–0.03 μg CH<sub>4</sub> (g d.w.)<sup>-1</sup>). Clearly, some form of CH<sub>4</sub> entrapment exists in calcareous

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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 CH<sub>4</sub> 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 CH<sub>4</sub> 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 CH<sub>4</sub> (Bruhn et al., 2012), and recently, geologic sources (natural CH<sub>4</sub> 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 CH<sub>4</sub> 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 CH<sub>4</sub> 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 CH<sub>4</sub> might be released with glacial meltdown (Wadham et al., 2008, 2012; Boyd et al., 2010).

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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 CH<sub>4</sub> cycling in these environments.

Recently, microbial oxidation of atmospheric CH<sub>4</sub> 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-CH<sub>4</sub> oxidation in the field included flux chambers and soil-CH<sub>4</sub> 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-CH<sub>4</sub> oxidation in glacier forefields in the Swiss Alps (Nauer et al., 2012), the soil-CH<sub>4</sub> 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 CH<sub>4</sub> 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 CH<sub>4</sub> concentrations; (ii) to examine the possibility of temporary CH<sub>4</sub> release during SR sampling by performing time-series sampling; and (iii) to provide a first quantitative assessment of

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potentially entrapped CH<sub>4</sub> 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 CH<sub>4</sub> oxidation in the Swiss Alps (Nauer et al., 2012): the Damma glacier forefield (DAM) on siliceous bedrock, and the Griesstfirn 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

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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. 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 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 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.

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 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 CH<sub>4</sub>, 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 CH<sub>4</sub> we added 0.4 mL acetylene (C<sub>2</sub>H<sub>2</sub>) as inhibitor, resulting in a C<sub>2</sub>H<sub>2</sub> gas concentration of approximately 2 vol%. After transfer to the laboratory, 4–5 mL of N<sub>2</sub> 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 CH<sub>4</sub> concentrations were measured before and immediately after each treatment to determine the mass difference of CH<sub>4</sub> ( $\Delta$ CH<sub>4</sub>) in the vials' headspace. The initial mass of CH<sub>4</sub> after closure in the field (0-value field) was estimated using ambient pressure, temperature and CH<sub>4</sub> concentrations in air on the day of sampling. The mass of CH<sub>4</sub> in the headspace determined before the first treatment was denoted as 0-value lab. Five mL of ultrapure H<sub>2</sub>O 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 CH<sub>4</sub> concentrations, therefore, the  $\Delta$ CH<sub>4</sub> 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

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6 N HCl to each vial to dissolve carbonate minerals and potential carbonate precipitates. The cores from GRF immediately released CO<sub>2</sub>; 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 CH<sub>4</sub> concentrations were determined together with the original vials to calculate total mass of released CH<sub>4</sub>. Five vials each of laboratory air and air with 2 vol% of C<sub>2</sub>H<sub>2</sub> 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 C<sub>2</sub>H<sub>2</sub> elution.

## 3 Results and discussion

### 3.1 Comparison of MLS and SR profiles

In both glacier forefields, all CH<sub>4</sub> 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 CH<sub>4</sub> showed a gradual decrease with depth, typical for soils with a stable soil-CH<sub>4</sub> sink and no inherent CH<sub>4</sub> source. Lowest CH<sub>4</sub> concentrations were around 1  $\mu$ L L<sup>-1</sup> in young soils (A locations), and tended to decrease to 0.5  $\mu$ L L<sup>-1</sup> in older soil (B and C locations). In contrast, SR samples collected ~ 1 min after hammering ceased ( $t_1$ ; Fig. 1) showed elevated CH<sub>4</sub> concentrations up to 130  $\mu$ L L<sup>-1</sup> 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 CH<sub>4</sub> concentrations at all times (Fig. 1). In all SR samples O<sub>2</sub> concentrations were between 98–100 % of ambient air (not shown).

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Clearly, elevated CH<sub>4</sub> 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<sub>4</sub> measurement were identical. Sub-atmospheric CH<sub>4</sub> concentrations from siliceous sites showed that the SR did not “generate” CH<sub>4</sub> 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<sub>4</sub> concentrations in GRF soil is the momentary release of entrapped CH<sub>4</sub> when hammering the SR into the soil.

### 3.2 Time-series sampling with the SR

At all GRF locations, elevated CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> concentrations tended to slightly increase with depth and decrease with time in the deepest samples. The variability of soil-CH<sub>4</sub> 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<sub>4</sub>. However, it cannot be excluded that even in siliceous soils, small amounts of CH<sub>4</sub> could be released by sampling with the SR.

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With no additional information, the shape of the SR profiles  $t_1$  from GRF might suggest a deep-soil CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub>. Nonetheless, the performed time-series sampling provided strong indications that additional CH<sub>4</sub> 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<sub>4</sub> concentrations (10–1000  $\mu\text{L L}^{-1}$ ), the phenomenon of entrapped CH<sub>4</sub> might be more widespread in these environments.

### 3.3 Miniature-soil-core experiments

For a first quantitative assessment of entrapped CH<sub>4</sub>, miniature soil cores enclosed in vials in the field were disturbed by different treatments in the laboratory, and the released CH<sub>4</sub> was measured (Fig. 2). The average amount of CH<sub>4</sub> 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<sub>2</sub>H<sub>2</sub> it remained constant and even decreased marginally after acidification (decrease not visible in Fig. 2). Hence, cores from all locations contained some CH<sub>4</sub> that was released with either sonication or both sonification and acidification.

However, the average amounts of CH<sub>4</sub> released from calcareous soil cores were much higher than from siliceous cores (Fig. 2). Some of the GRF cores already released CH<sub>4</sub> 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<sub>4</sub> was released when part of the core structure was disturbed. The

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addition of water itself had only a negligible effect (preliminary experiments, not shown), but sonication of the suspended cores released significant amounts of CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> in the vials increased again by an order of magnitude or more (Fig. 2). Similar CH<sub>4</sub> concentrations in the headspace of the vial containing the core and in the vials containing the excess gas volume showed that CH<sub>4</sub> was released together with CO<sub>2</sub> during acidification only. As the acid affects all calcareous minerals, it is unclear from which particle fraction this massive CH<sub>4</sub> 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<sub>4</sub> release during acidification, total release was in the range of DAM cores (data not shown). This indicates that the bulk mass of CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> showed considerable variability (Fig. 3). Amounts released from GRF cores ranged from 0.12–

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7.5 μg CH<sub>4</sub> (g d.w.)<sup>-1</sup>, which was 1–2 orders of magnitude higher than the 0.002–0.16 μg CH<sub>4</sub> (g d.w.)<sup>-1</sup> from DAM cores. For the latter, the increase of CH<sub>4</sub> in some vials was smaller than the estimated CH<sub>4</sub> originating from the enclosed air. In contrast, all GRF cores released substantial amounts of CH<sub>4</sub>, but some “hotspots” were responsible for the most pronounced increase. However, we could not observe a clear pattern of the released CH<sub>4</sub> with respect to the sampling depth of the cores, with the exception of GRF B and C, where highest amounts of CH<sub>4</sub> 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 exceptionally low bulk density released the highest amount of CH<sub>4</sub> 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<sub>4</sub> entrapped in both the GRF and DAM soils, but the former retains orders of magnitude more CH<sub>4</sub>. In light of previous results (Nauer et al., 2012) our findings suggest that CH<sub>4</sub> 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<sub>4</sub> and the nature of entrapment. The observation that the bulk mass of CH<sub>4</sub> 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<sub>4</sub> 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

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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 CH<sub>4</sub> entrapment. In both glacier forefields, CH<sub>4</sub> might also originate from recent methanogenesis in sealed microsites.

For calcareous glacier forefields we cannot exclude the possibility that the CH<sub>4</sub> is entrapped in the bedrock itself. In this case the likely origin of the CH<sub>4</sub> 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 CH<sub>4</sub> (Mullis et al., 1994; Tarantola et al., 2007). In some adjacent marls in the Helvetic nappes, CH<sub>4</sub>-dominated fluid inclusions in calcite-filled fissures have also been documented (Gautschi et al., 1990).

Further insights in the nature of these CH<sub>4</sub> 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 CH<sub>4</sub>. Furthermore, given the relative ease of how entrapped CH<sub>4</sub> was released, its potential bioavailability should be addressed. Particularly in glacier forefields, CH<sub>4</sub> 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>.**

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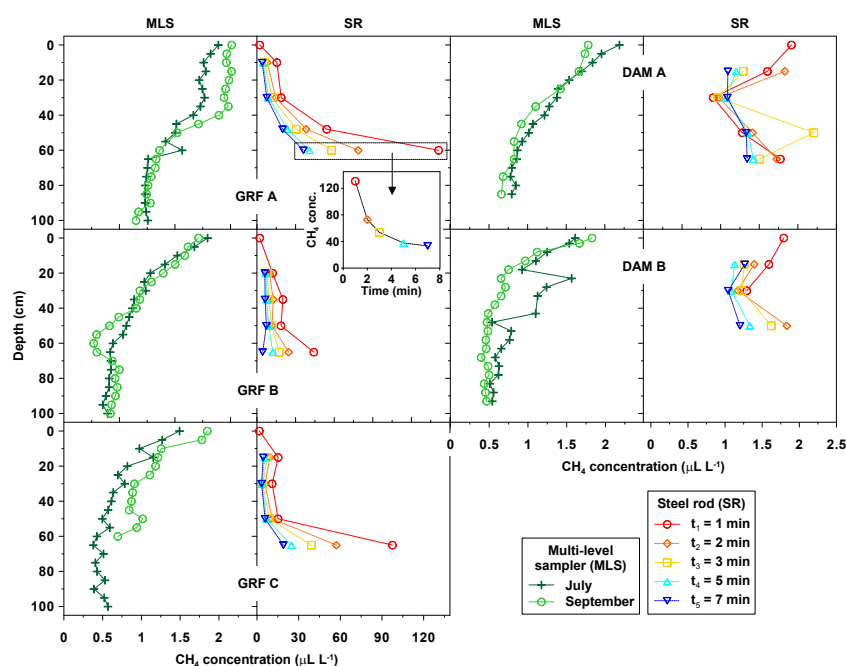
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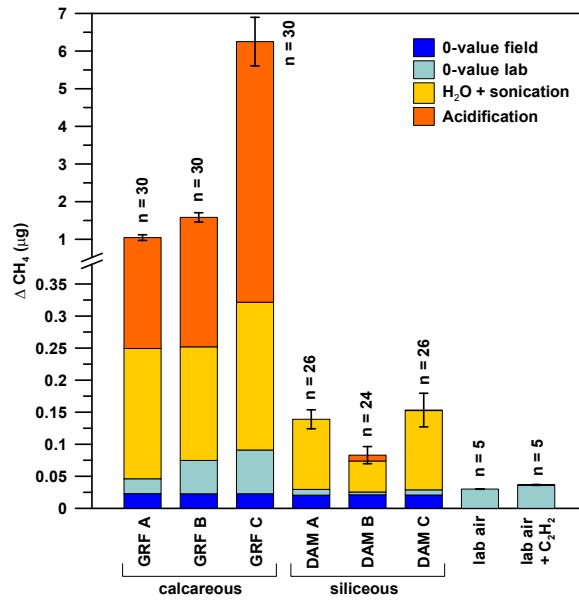
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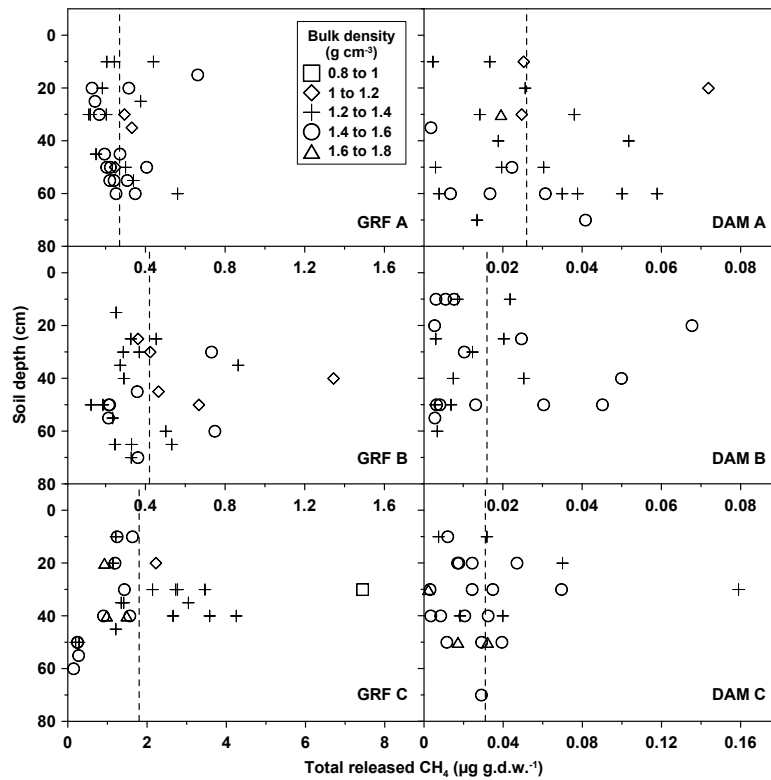
**Fig. 1.** Soil- $\text{CH}_4$  profiles obtained from the MLS and the SR time-series soil-gas samples. The red SR samples ( $t_1$ ) can be directly compared to profiles for which each depth is sampled only once. Note the different scales of the x axis for the SR profiles in GRF and DAM graphs.

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**Fig. 2.** Cumulative, average amount of CH<sub>4</sub> 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 CH<sub>4</sub> contained in enclosed ambient air; 0-values in the lab represent the (additional) amount of CH<sub>4</sub> released during transport and storage. Error bars denote standard deviation of the mean of the total amount of CH<sub>4</sub> in the vials.

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**Fig. 3.** Depth distribution and cumulative CH<sub>4</sub> released from individual miniature soil cores. The different symbols denote bulk-density classes of individual cores. Vertical dashed lines indicate the average cumulative CH<sub>4</sub> release for each location.

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