**Geologic Methane seeps along boundaries of Arctic permafrost thaws and melting glaciers.**


**Objectives:**

- This study documents the first evidence of widespread geological methane seepage along boundaries of cryosphere retreat.
- The study focused on the release of $^{14}$C-depleted methane from abundant gas seeps concentrated along boundaries of permafrost thaw and receding glaciers in Alaska and Greenland.
- The authors combined a new method of aerial survey and ground truth to identify seep-induced melt-holes in ice covered water bodies in order to quantify methane seeps in Alaska, to confirm the occurrence of anomalous seeps in Greenland, and to document for the first time the widespread occurrence of $^{14}$C-depleted methane seeps along boundaries of permafrost thaw and melting glaciers in the terrestrial Arctic.
- Ground surface survey data and *in situ* measurements (ebullition flux measurements, gas collection and isotope analyses) were used to map the occurrence of superficial and subcap methane seeps along a north/south transect in Alaska; in West Greenland, seeps were quantified only by ground survey.
- Over 150,000 seeps were mapped in Alaska and Greenland.

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- Seeps were characterized by anomalously high methane fluxes, and in Alaska by ancient radiocarbon ages and stable isotope values that matched those of coal bed and thermogenic methane accumulations.
- In Greenland, younger seeps were associated with zones of ice-sheet retreat since the Little Ice Age.
- Examination of 6,700 lakes across Alaska revealed the occurrence of 77 previously undocumented subcap seep sites containing >150,000 highly ebullient macroseep vents.
- Survey results increased the number of previously documented geologic seep-site occurrences in Alaska four fold. In some regions, this discovery increased previous ecosystem-based lake methane emission estimates by 80-350%.
Most of these cryosphere-cap seeps were observed in lakes along the boundaries of permafrost thaw and moraines, and fjords of retreating glaciers.

Geospacial and geochemical field data support the hypothesis that cryosphere degradation leads to the release of $^{14}$C-depleted methane previously trapped by the cryosphere.

The study showed that cryosphere-cap methane seeps are prevalent in highy latitude terrestrial environments along steep thaw gradients in permafrost and in association with wasting glaciers, often through activated faults.

**Significance**

In the Arctic, permafrost and glaciers form a cryosphere cap that traps large reservoirs of geologic methane ($\text{CH}_4$) in coal beds, in natural gas deposits and as hydrates.

With a carbon store of over 1,200 Pg, the Arctic geologic methane reservoir is large when compared with the global atmospheric methane pool (about 5 Pg). As such, the Earth’s climate is sensitive to release of even a small fraction of this methane.

Many hypotheses and model predictions suggest that warming of the cryosphere cap will result in an increase in methane seepage, but there is a dearth of field evidence for an increase in natural geologic methane seepage as direct result of cryosphere disintegration.

The mechanisms, timescales and rates of exchange of this fossil ($^{14}$C-dead) pool with the atmosphere are not well determined.

The findings in this study imply that in a warming climate, disintegration of permafrost, wastage of glaciers and parts of the polar ice sheets could facilitate the transient expulsion of $^{14}$C-depleted methane trapped by the cryosphere cap, and lead to a significant transitional degassing of subcap methane.

While it is possible that methane oxidation processes could temper future subcap emissions, at the very least, an injection of methane carbon due to cryosphere degradation will increase surface carbon cycling.

The geospacial association of methane seeps with cryosphere boundaries in Alaska and Greenland suggests that, in other regions where sedimentary basins are at present capped by permafrost, glaciers and ice sheets, such as northern West Siberia (where intense permafrost degradation has been predicted by 2100), a very strong increase in methane carbon cycling will result, with potential significant implications for climate warming feedbacks.
**Figure 1.** The effect on lake ice formation of subcap and superficial seeps. 

- **a-c.** Photographs showing examples of the largest superficial seeps (a) and small (b) and large (c) subcap macroseeps. Even the strongest superficial seeps are ice-covered in late winter. Further, ebullition does not occur simultaneously among superficial seeps (a). In contrast, bubbles breaking the surface of all open holes indicate high, simultaneous ebullition among subcap seeps (b). 

- **d.** Clustering of subcap seeps is apparent in the aerial photograph. Photographs were taken near Fairbanks, interior Alaska (a). Cook Inlet, southcentral Alaska (b) at Atqasuk, northern Alaska (c,d) one, eight and three weeks, respectively, following freeze-up.
Figure 6. Subcap seep methane stable isotopes and radiocarbon age in relation to faults in the Lake Eyak region of southcentral Alaska. a–d. The relationship between subcap seep δ^{13}C_{CH4} and 14C content (pmC, \( r^2=0.91 \)) (a) and δD_{CH4} (b), and proximity to known faults near Lake Eyak (c) and in lakes extending east 100 km to Katalla (d), where oil and gas were first discovered in Alaska in 1902, suggests that deep, 14C-dead, thermogenic methane escapes through faults, whereas gas seeping through smaller fractures and fissures mixes with microbial methane in shallower, 14C-enriched organics. The neotectonic fault data (d) were provided by T. L. Pavlis (personal communication, May 14, 2010 and ref. 48), but not all faults and surface ruptures are known. Black lines are mapped faults; white dots are unsampled, mapped seep fields.