formation, as well as during disintegration[6]. As such, the observations in Alaska may not be valid in other pan-Arctic regions, where different tectonic settings and petroleum systems can lead to variable responses to isostatic rebound. Nevertheless, it is clear that the ascending gas only enters the atmosphere once ice melts.

Walter Anthony *et al.* suggest that the link between cryosphere retreat and seepage makes the Arctic region a special place for gas seepage. Indeed, scaling up their findings, they estimate that seep-related methane emissions could amount to around 1–2 Tg per year in the pan-Arctic, which is considerable compared with estimates of global geological seep emissions, which amount to 3–4 Tg per year[5] (Fig. 1). Walter Anthony and colleagues also suggest that future melting of permafrost, glaciers and areas of the polar ice sheets could relax pressure on subsurface seals, and open conduits that allow the transient expulsion of further geological methane that was previously trapped by the cryosphere cap, leading to climate warming feedbacks.

Notwithstanding the large uncertainties associated with the pan-Arctic emissions estimates, the potential atmospheric impact of this terrestrial seepage could be more important than that invoked from the melting of gas hydrates in ocean bottom sediments. Present-day atmospheric methane emissions from hydrates are probably negligible; observations and model simulations indicate that the majority of the gas that escapes from melting deep-sea hydrates is dissolved in the water column, and fails to enter the atmosphere[8].

The seeps considered by Walter Anthony *et al.* are only part of a wider class of geological methane sources that include mud volcanoes, microseepage, submarine seepages, and geothermal and volcanic emissions (Fig. 1). On a global scale, geological methane emissions are thought to lie between 40 and 80 Tg per year[1,2,5], equivalent to 7–14% of global emissions. Observations indicate that around 30% of atmospheric methane is fossil in origin, which would support a geological source strength equivalent to at least half of the anthropogenic fossil source[5].

The findings of Walter Anthony and colleagues[3] indicate that geologically sourced methane emissions may well increase as ice sheets, glaciers and permafrost melt. All results obtained so far emphasize the potential significance of solid Earth geophysical processes to the atmospheric greenhouse gas budget. This effect should not be forgotten in appraisals of pre-industrial, contemporary and future methane budgets. ❐

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References

1. Anderson, B. *et al. Methane and Nitrous Oxide Emissions from Natural Sources* (US Environmental Protection Agency, 2010).
2. Reay, D., Smith, P. & van Amstel, A. *Methane and Climate Change* (Earthscan, 2010).
3. Walter Anthony, K. M., Anthony, P., Grosse, G. & Chanton, J. *Nature Geosci.* **5,** 419–426 (2012).
4. Etiope, G., Fayzullayev, A. & Baciu C. L. *Mar. Petrol. Geol.* **26,** 333–344 (2009).
5. Etiope, G., Lassey, K. R., Klusman, R. W. & Boschi, E. *Geophys. Res. Lett.* **35,** L09307 (2008).
6. Lerche, I., Yu, Z., Torudbakken, B. & Thomsen, R. O. *Mar. Petrol. Geol.* **14,** 277–338 (1997).
7. Sauber, J. M. & Molnia, B. F. *Global Planet. Change* **42,** 279–293 (2004).
8. Yamamoto, A., Yamanaka, Y. & Tajika, E. *Earth Plan. Sci. Lett.* **284,** 590–598 (2009).
9. Denman, K. L. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) Ch. 7, 499–587 (Cambridge Univ. Press, 2007).
10. Etiope, G., Nakada, R., Tanaka, K. & Yoshida, N. *Appl. Geochem.* **26,** 348–359 (2011).

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EOCENE CLIMATE

Summer rains

Today, the area north of the Arctic Circle is a challenging environment, home to only the hardiest of plants, animals and people. Beyond 66 °N, forests are sparse and primarily consist of conifers. However, 50 million years ago, during the warm Eocene epoch, the Canadian High Arctic was rife with lush forests that wouldn't seem out of place in modern temperate regions. Arctic temperatures during the early to middle Eocene were certainly more hospitable to forests — average temperatures during the coldest months probably didn't drop much below freezing, if at all — but the plants still had to cope with three months of near-total darkness.

This unusual set of growing conditions has made it difficult to identify modern analogues to these high-latitude forests. Based on average annual temperature, the amount of biomass and overall productivity, the forests of the Pacific Northwest seemed a relatively good fit. However, taking into account seasonal patterns in fossilized tree rings, Brian Schubert of the University of Hawaii,

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Honolulu, and colleagues suggest that the forests of eastern Asia may be a better match (*Geology* http://doi.org/hwr; 2012).

Unlike the brightly coloured pieces of fossil wood that decorate the walls of gem and mineral shops, some fossil wood from the Eocene Arctic was not permineralized, meaning that the original wood is intact. This includes the tree rings, which record each growing season. Using fossil wood samples from two sites, Schubert and his team divided the tree rings into subsamples of no more than 78 μm and measured the δ^{13}C values of each. The measured variability of δ^{13}C across each ring could then be used to estimate the ratio of summer to winter precipitation.

They find that summer precipitation was about three times as high as winter precipitation, with an estimated 1,130 mm of rain falling in the summer. This seasonal pattern of precipitation is similar to that of eastern Asia. However, unlike in Asia, the growing season above the Arctic Circle is tightly constrained by available sunlight. It was therefore the high summer precipitation that allowed photosynthetic organisms to flourish during the sunlit months, and supported such high productivity in such an extreme environment.

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