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Zimov, SA
Voropaev, YV
Semiletov, IP
et al.

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North Siberian Lakes: A Methane Source Fueled by Pleistocene Carbon

S. A. Zimov, Y. V. Voropaev, I. P. Semiletov, S. P. Davidov, S. F. Prosiannikov, F. S. Chapin III,* M. C. Chapin, S. Trumbore, S. Tyler

The sizes of major sources and sinks of atmospheric methane (CH$_4$), an important greenhouse gas, are poorly known. CH$_4$ from north Siberian lakes contributes $\sim$1.5 teragrams CH$_4$ year$^{-1}$ to observed winter increases in atmospheric CH$_4$ concentration at high northern latitudes. CH$_4$ emitted from these lakes in winter had a radiocarbon age of 27,200 years and was derived largely from Pleistocene-aged carbon.

The highest concentration and greatest seasonal amplitude of atmospheric CH$_4$ occurs at 65° to 70°N. Concentrations are highest in March to April and lowest in summer (1). Photochemical oxidation of CH$_4$ contributes to the low summer levels (2) but does not explain why the seasonal amplitude of atmospheric CH$_4$ is twice as high as in the Northern as in the Southern Hemisphere, given large summer effluaxes from North American bogs and tundra (3, 4) and modest CH$_4$ fluxes from Siberian wetlands (5). Between August and April, 5.8 Tg (1 Tg = 10$^{12}$ g) of CH$_4$ accumulates in the atmosphere north of 60°N (6). High-latitude winter fluxes measured in a muskeg and a peatland were only 10 to 12% of the annual total (4, 7), an insufficient flux to explain a winter maximum in atmospheric CH$_4$. Here we provide evidence for a large winter CH$_4$ source from Siberian lakes.

In the Pleistocene, most of the northern Siberian plains were unglaciated and accumulated $\sim$400,000 Tg of organic C in sediments (8) (mainly derived from plant roots), similar to the total C in the terrestrial biosphere (9). These sediments contained abundant ice (40 to 70% of soil volume) (10–12), which began melting during the Holocene to form thermokast (thaw) lakes that now make up $\sim$30% of the landscape. These lakes migrated across the north Siberian plains during the Holocene (10), releasing to the atmosphere an average of 170 to 220 g C m$^{-2}$ year$^{-1}$, including $\sim$16 g CH$_4$ m$^{-2}$ year$^{-1}$; we estimate that half of this CH$_4$ was derived from Pleistocene C (13). Siberian lake sediments produce CH$_4$ bubbles in lakes throughout the year (14), particularly near shores with active erosion. During winter, the bubbles form koshkas, which are flat bubbles of CH$_4$ in lake ice separated by ice films that periodically sublime and release CH$_4$ to the atmosphere. In areas where CH$_4$ ebullition (bubbling) is most active, channels through the ice remain open all winter.

To evaluate the significance of this source, we incubated Pleistocene sediments from an eroding lakeshore with lake water. The yield was 65 ± 3 mg CH$_4$ g$^{-1}$ sediment at 15°C (mean ± SE, n = 3) over 12 months, equivalent to 5% of the C originally present in the soil; 26 ± 2 mg CH$_4$ g$^{-1}$ were emitted at 3.5°C, and 19 ± 2 mg CH$_4$ g$^{-1}$ were emitted at 0°C. These data indicate that the C in Pleistocene sediments is sufficiently labile to support methanogenesis and that, although methanogenesis is temperature-sensitive, it occurs at substantial rates at 0°C. To determine whether methanogenesis in lake sediments is currently fueled by Pleistocene-aged organic matter, we measured stable and radiocarbon isotopes of CH$_4$ emitted by ebullition from two representative thaw lakes near Cherskii, Republic of Sakha (Yakutia), Russia (69°N, 161°E). CH$_4$ collected from these lakes in winter (April) had an average $^{13}$C age of 27,200 years (Table 1). This age indicates that Pleistocene sediments deposited 20,000 to 40,000 years ago (11) contributed 68 to 100% of CH$_4$ flux from these lakes. In contrast, CH$_4$ emitted in the summer (July) had an average $^{13}$C age of 9,200 years, indicating that Pleistocene C fueled 23 to 46% of summer methanogenesis and thus that more CH$_4$ was produced in the younger surface sediments, which are warmer in summer than winter (10). Thus, about half of current annual methanogenesis is fueled by Pleistocene C. In contrast, CH$_4$ from Alaskan lakes was only 200 years old (15) because Alaska lacks extensive Pleistocene sediments.

The $^\delta^{13}$C value of CH$_4$ collected from Siberian lakes was $-71$ to $-73$ (Table 1). This value is less than that produced in summer by Alaskan tundra lakes ($^{13}$C = $-61$ ± 2) (15) or North American wet tundra ($^{13}$C = $-66$ to $-63$) (15, 16). These values imply that the Siberian winter-collected CH$_4$ was not as oxidized as in these other environments, or that there was an isotopic difference in substrate or a different pathway of methanogenesis (17). The hydrogen isotopic composition of the CH$_4$ was variable, but most samples from the Siberian lakes were low ($\deltaD$ = $-370$), indicative of a biotic source for CH$_4$, low oxidation rates in the water column, and CH$_4$ production by fermentation (17, 18). We measured CH$_4$ ebullition fluxes from two thaw lakes using large funnels suspended beneath the ice (19). CH$_4$ fluxes were generally highest from October to January (Fig. 1), when deep sediments had their annual thermal maximum (10). Fluxes were highly variable within a season; fluxes were highest at

Table 1. Isotopic data for CH$_4$ collected from sediments in two thaw lakes in Pleistocene sediments in the Kolyma lowlands. Results are given as percent modern C, or 100 times the ratio of $^{13}$C/12C in the sample divided by the $^{14}$C/12C ratio in 1895 wood (corrected for $^{13}$C/12C differences) (27, 28).

| Lake no. | Lake depth (m) | $^{13}$C | $^{14}$CH$_4$ age | Modern C (% of CH$_4$-C) | $\deltaD$ |
|----------|----------------|--------|-----------------|--------------------------|-------|
| Summer  |
| 13       | 5              | $-69.5$ | 11,731 ± 360    | 23.2 ± 1.0               | $-369$ |
| 13       | 10             | $-69.6$ | 8,200 ± 240     | 35.3 ± 1.0               | $-317$ |
| 13       | 10             | $-71.8$ | 8,370 ± 180     | 35.1 ± 0.8               | $-317$ |
| 13       | 10             | $-71.8$ | 8,430 ± 100     | 35.3 ± 0.4               | $-317$ |
| Average  | $-70.8$ ± 0.7  | 9,200 ± 800 | 32 ± 3           | $-317$ |
| Winter   |
| 13       | 10             | $-75.1$ | 38,000          | 0.2                      | $-390$ |
| 13       | 10             | $-80.0$ | 27,670 ± 850    | 2.8                      | $-479$ |
| 14       | 41             | $-72.7$ | 27,200 ± 730    | 3.4                      | $-391$ |
| Average  | $-73.3$ ± 3.1  | 27,200 ± 4700 | 5 ± 3            | $-370$ ± 70 |

†Subsamples analyzed separately.

*S. A. Zimov, S. P. Davidov, S. F. Prosiannikov, North-East Scientific Station, Pacific Institute for Geography, Far-East Branch, Russian Academy of Sciences, Republic of Sakha, Yakutia, 678800 Cherskii, Russia.
†S. F. Prosiannikov and I. P. Semiletov, Pacific Oceanographic Institute, Far-East Branch, Russian Academy of Sciences, Vladivostok, Russia.
‡F. S. Chapin III and M. C. Chapin, Department of Integrative Biology, University of California, Berkeley, CA 94720–3140, USA.
S. Trumbore and S. Tyler, Department of Earth System Sciences, University of California, Irvine, CA 92697–3100, USA.

*To whom correspondence should be addressed. E-mail tschapin@socrates.berkeley.edu.

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times of low atmospheric pressure, as in northern temperate lakes (20). The average CH₄ ebullition flux in centers of lakes (80% of the lake area) was 4.7 ± 2.3 mg CH₄ m⁻² day⁻¹ (90 measurements). Near eroding lake shores, fluxes were so high that they frequently overtopped the collection funnels; the flux (2 cm², min⁻¹, n = 25; 90% CH₄) emitted from open holes in the ice (300 ha⁻¹) was 56 mg CH₄ m⁻² day⁻¹. In addition to open holes, there were koshkas (400 to 1000 ha⁻¹) containing 1 to 100 liters of 50% (25 to 75%) CH₄ (n = 8) that vent CH₄ several times each winter and provide an additional unquantified CH₄ source. Sediments in these lakes released 22 g CH₄ m⁻² (38 ± 12 liter m⁻² of 80% CH₄, n = 3) in September, when we disturbed the sediments (15), but <3 g CH₄ m⁻² a month later. This large CH₄ release over 1 month provides independent evidence for a large CH₄ ebullition flux.

CH₄ can also move to the atmosphere in winter in overflow, when the weight of winter snow pushes the ice below the equilibrium water level of the lake. The CH₄ concentration in overflow water decreases from 1.7 mg CH₄ liter⁻¹ (21) to <0.01 mg CH₄ liter⁻¹. The 30 cm of overflow that typically accumulate on lakes of the forest zone would thus release 0.52 g of dissolved CH₄ m⁻² year⁻¹.

The average summer diffusive flux measured in 19 lakes along a climate transect inland from the Arctic Ocean was 7.6 ± 1.4 mg CH₄ m⁻² day⁻¹ (60 measurements) (21), a value similar to that in Alaskan lakes (6.8 ± 1.3 mg m⁻² day⁻¹) (22). The 19 lakes had 3.1 ± 0.7 mg m⁻² of dissolved CH₄ in March, indicating that winter accumulation of CH₄ is typical of north Siberian lakes.

We estimate the total annual flux of CH₄ for the lakes in our study region to be at least 7 g CH₄ m⁻² year⁻¹ (Table 2), ~50% of the potential flux we estimated (16 g CH₄ m⁻² year⁻¹) from regional C inputs to lakes. Approximately 75% of this flux occurs in winter. If these fluxes are typical of Siberian lakes, these lakes would emit ~1.5 Tg CH₄ in winter (2 Tg CH₄ annually). This is small relative to global sources (18) but is 25% of the high-latitude winter accumulation of CH₄ in the atmosphere. If high-latitude warming trends continue, thawing of permafrost would increase, and methane flux from Siberian thaw lakes would act as a positive feedback to climate warming.

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Sizes and Ages of Seamounts Using Remote Sensing: Implications for Intraplate Volcanism

Paul Wessel

Satellite altimetry was used to identify and characterize Pacific intraplate seamounts. The gravimetric amplitudes of seamounts appear to be related to the age difference between the sea floor and seamounts; by inverting this relation, pseudo ages can be obtained for undated seamounts. These pseudo ages imply that excursions in seamount volcanism generally correlate with times of formation of large oceanic plateaus.

The Pacific plate may support more than 50,000 seamounts taller than 1 km, yet 50-70% of these undersea volcanoes are uncharted because of sparse bathymetric coverage (1, 2). Even fewer (<1%) have been sampled for radiometric dating (3), making assessment of temporal fluctuations in intraplate volcanism uncertain. Because electromagnetic sensing devices cannot penetrate the oceans, we are unable to image the seafloor remotely and instead must rely on surface ships equipped with sonar. At the present rate of data acquisition, complete bathymetric coverage may take centuries. However, the density contrast between seawater and the sea floor basalt gives rise to gravity anomalies. These minute variations in Earth’s gravitational pull cause seawater to be attracted to seamounts, leading to a sea surface (which approximates the geoid) whose shape reflects these underlying features (4). Thus, since the early 1980s, satellite altimetry has provided broad coverage of the sea surface or geoid undulations (5).

Recently, the U.S. Navy declassified its Geosat satellite altimetry, which has been combined with the European Space Agency's SeaSat altimeter to produce a high-resolution gravity dataset. This information provides unique insights into the distribution and temporal variability of seamount volcanism in the Pacific plate. The results challenge previous notions of intraplate volcanism, which were based on sparse and partial data. By using satellite altimetry, we are able to map seamounts with unprecedented detail, allowing us to evaluate the role of seamount volcanism in the geological history of the Pacific plate.