Benthic Mat O_2 Oases: A Modern Analog For Early Earth

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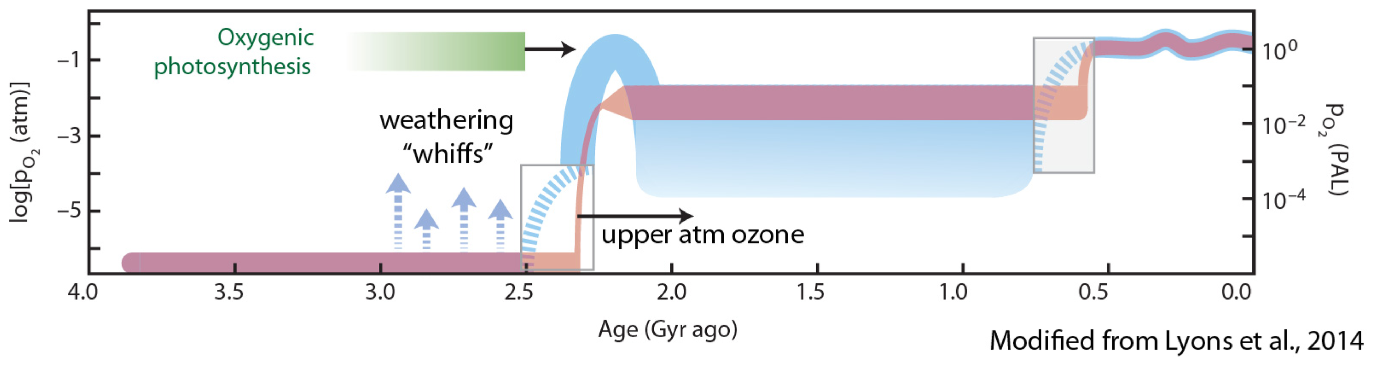
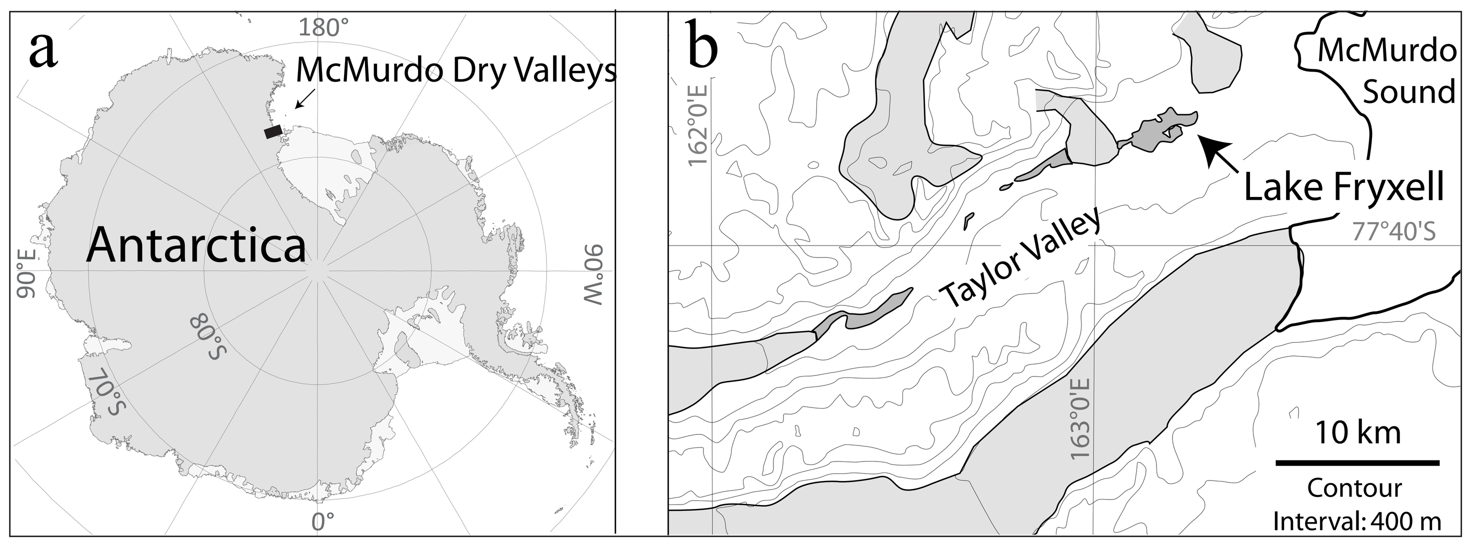


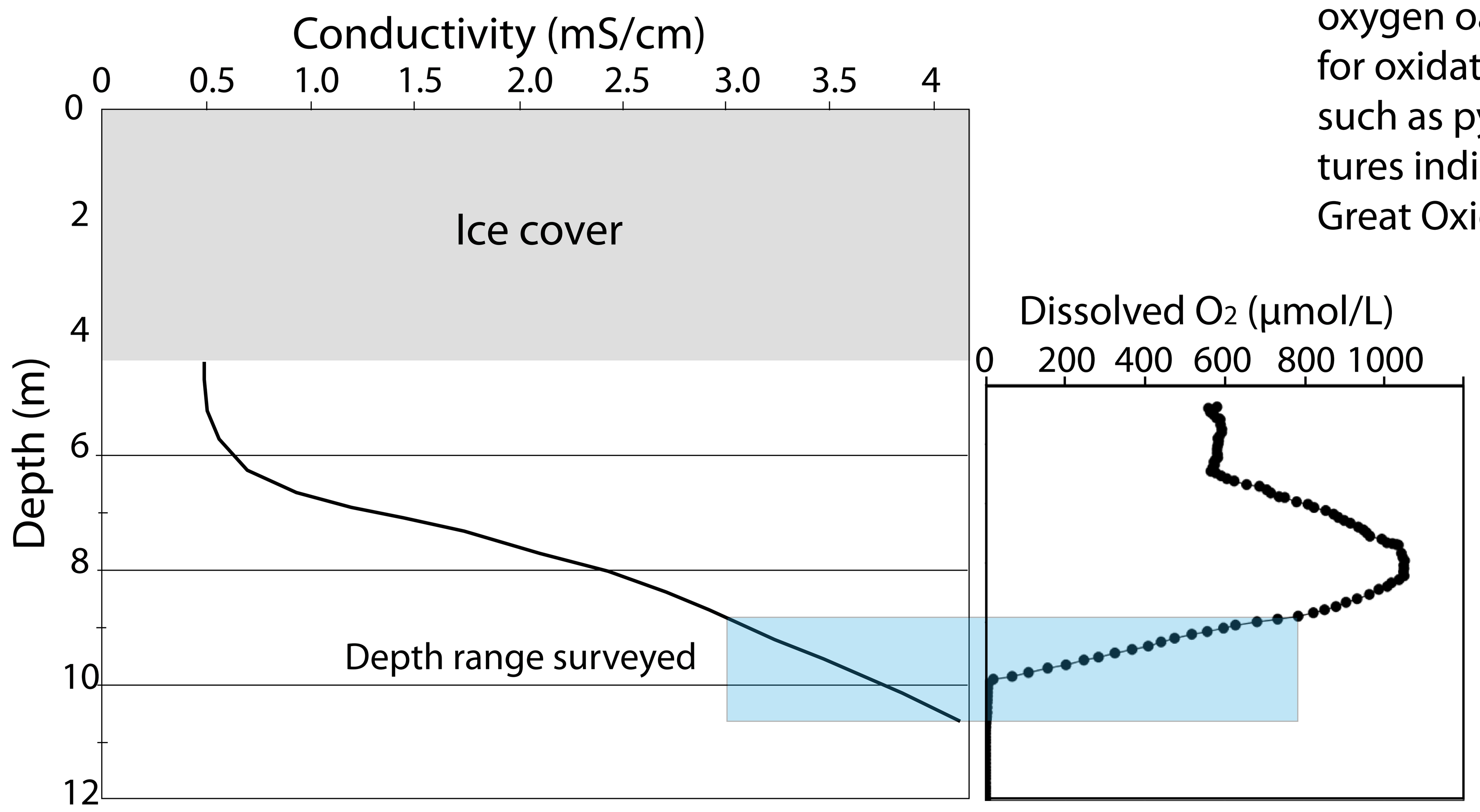
Modified from Lyons et al., 2014

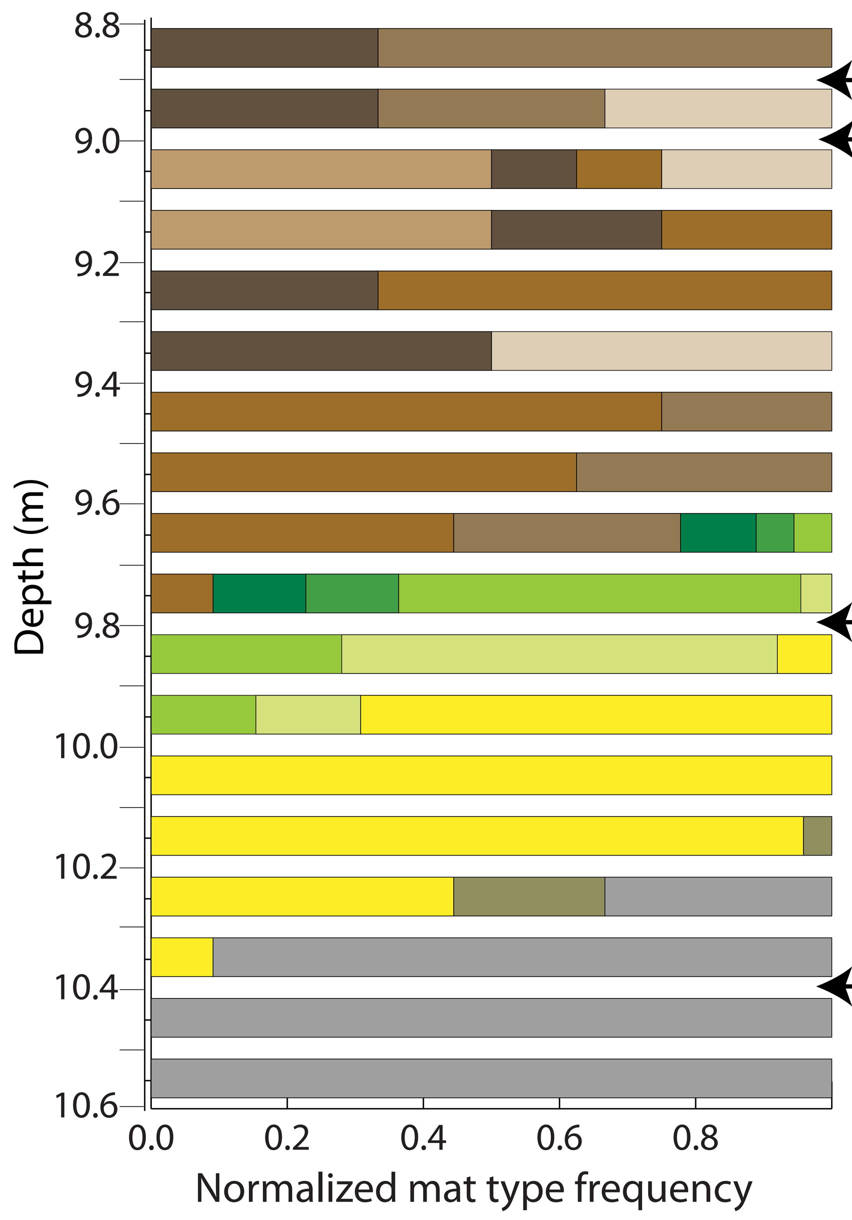
Introduction: Cyanobacterial photosynthesis produces an "oasis" of free oxygen in benthic mats below an anoxic water column in Lake Fryxell, Antarctica. Rates of photosynthesis are slow due to low irradiance, but oxygen production seasonally exceeds consumption and loss to the surrounding environment, and oxygen accumulates within the mat during summer. These transient oxygen oases provide the first known modern analog for formation of oxygen oases during Archean time, prior to oxidation of Earth's atmosphere. We hypothesize that once the first cyanobacteria evolved, they produced localized oxygen oases in benthic mats analogous to those in Lake Fryxell under a reducing atmosphere and surface waters. Then, as the efficiency and robustness of photosytem II increased, oxygen oases expanded within benthic mats and into the water column, eventually leading to oxidation of the upper oceans and the atmosphere. The presence of oxygen oases in benthic mats in terrestrial aquatic systems like those in Lake Fryxell may account for geological evidence for oxidative sulfate mineral weathering on land as early as 2.8 billion years ago.

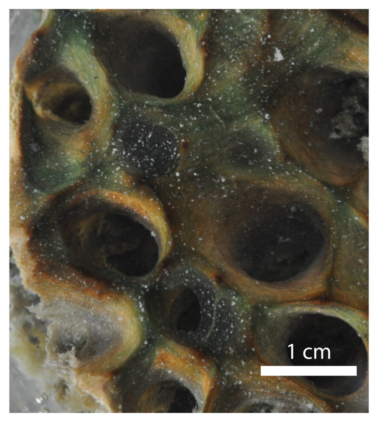


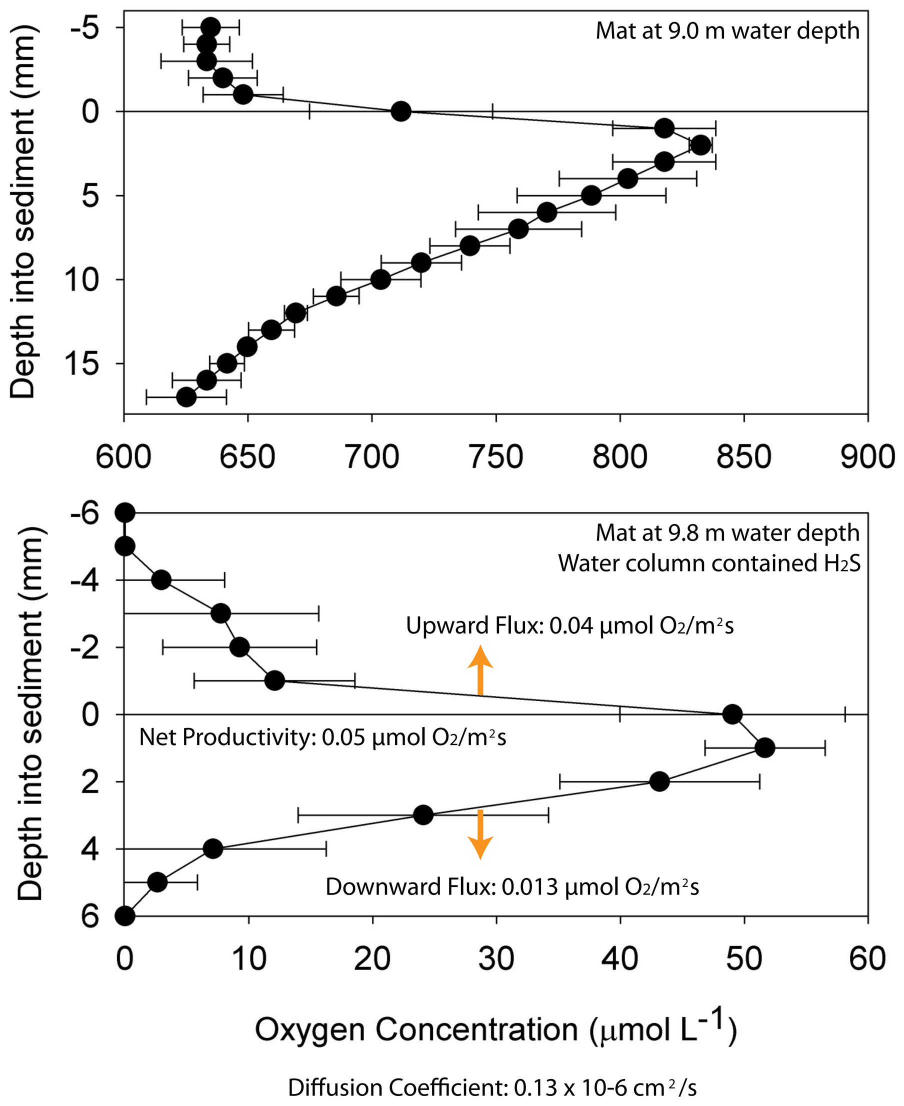
A) Location of the McMurdo Dry Valleys in Antarctica. B) Lake Fryxell at the toe of Canada Glacier within Taylor Valley.

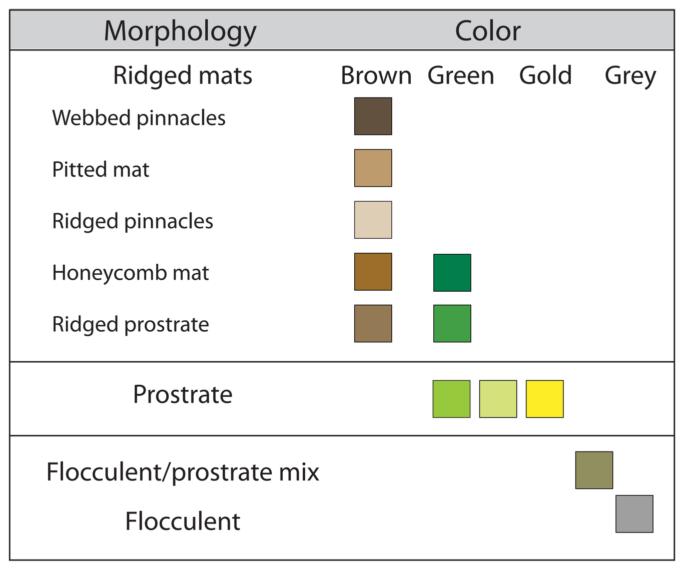
Lake Fryxell: Lake Fryxell (75°35'S, 163°35'E) is a perennially ice-covered Antarctic lake. Density stratification due to increasing salinity with depth and ice-cover inhibit mixing so that solute transport below 5 m depth is dominated by diffusion. An oxycline at ~9.5 m depth separates oxygen saturated water from deeper euxinic water. Irradiance is highly seasonal with six months of winter darkness but high irradience in the summer.





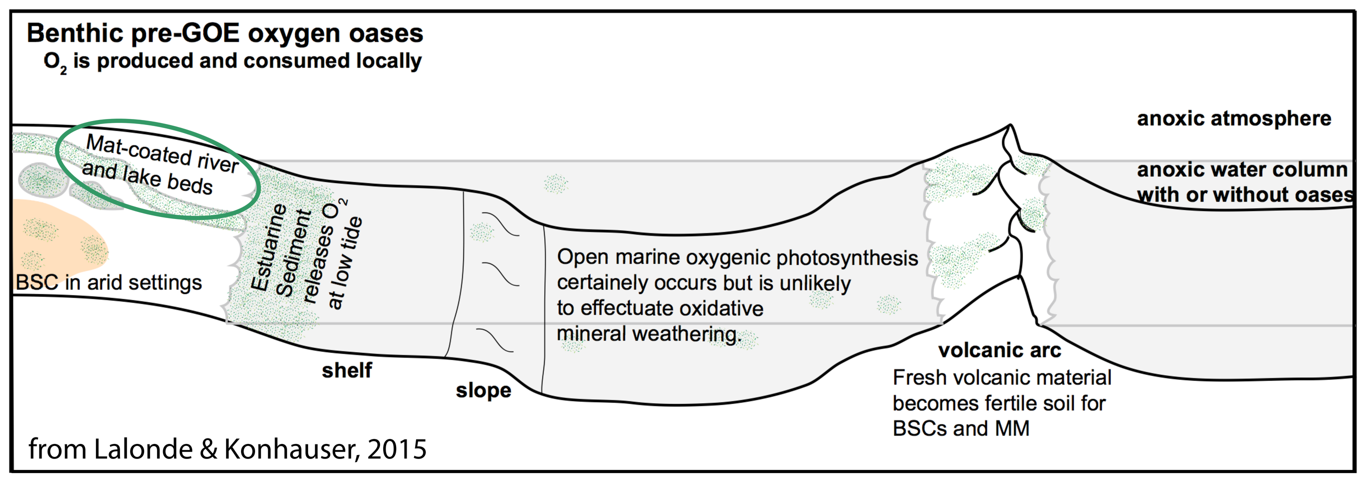


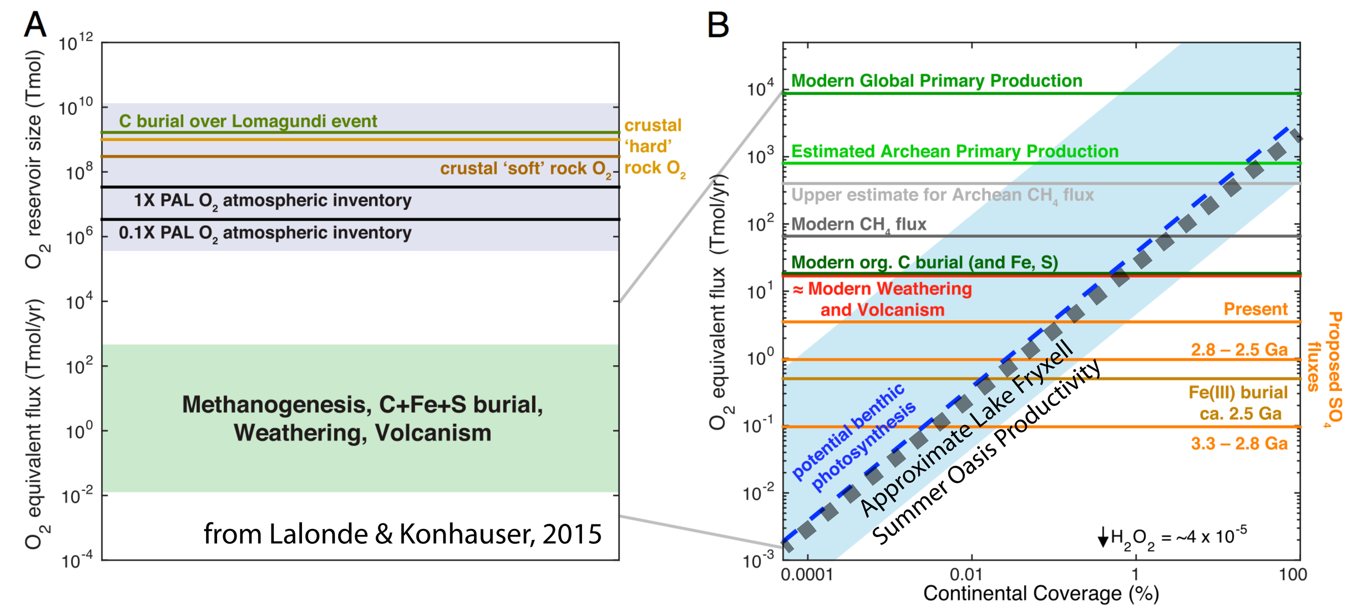




Results: In November 2012, light transmitted through the ice and water resulted in 1 µmol photons/m^{2}s (the lower limit for net photosynthesis [1]) reaching 10.4 m depth in Lake Fryxell. However, the water column transitioned from oxygen supersaturated at 9.1 m to complete anoxia below ~9.8 m. Net oxygen production in benthic mats at 9.8 m was demonstrated by a peak in oxygen at 1 mm depth in the mat . The spatial distribution of oxygen indicates a flux to the water column of 0.04 µmol O_2/m^{2}s and into the sediment of 0.013 µmol O_2/m^2 s. A net export of 0.05 µmol O_2/m^{2}s is consistent with expected local net photosynthetic rates based on productivity analysis in nearby Lake Hoare [1].

Implications: Lake Fryxell benthic mats produce transient oxygen oases that demonstrate that cyanobacteria are capable of producing sustained concentrations of ~50 µmol O_2/L without oxidizing their environment. Observed net oxygen production rates in Lake Fryxell are consistent with models for production of terrestrial benthic Archean oxygen oases as proposed by Lalonde & Konhauser (2015). Archean terrestrial environments as old as at least 2.7 Ga contained benthic mats [2]. Thus, our results suggest that similar oxygen oases may have formed prior to the oxidation of Earth's oceans and atmosphere. Benthic oxygen oases could have provided environments for oxidative weathering of continental minerals such as pyrite [3], creating the geochemical signatures indicating "whiffs of oxygen" prior to the Great Oxidation Event [4].





Geochemical model for oxygen production without oxidizing the Archean atmosphere. Continental coverage represents microbial community abundance. Modern net photosyntehetic productivity ranges shown in blue shading with the median in the dashed line. Lake Fryxell productivity added for comparison.

Acknowledgements:
The collection of field data was supported by the National Science Foundation Division of Polar Programs through grant #1115245 to the McMurdo Long Term Ecological Research project. DYS and TJM were supported by NASA Astrobiology through grant NN13AI60G. We thank both the US Antarctic Program and Antarctica NZ for logistic support.

References:
Lyons, T.W., Reinhard, C.T., and Planavsky, N.J., 2014. The rise of oxygen in Earth's early ocean and atmosphere. Nature, v. 506, p. 307-315.
[1] Hawes, I., Moorhead, D., Sutherland, D., Schmeling, J., and Schwarz, A.-M., 2001. Benthic primary production in two perennially ice-covered Antarctic Lakes: patterns of biomass accumulation with a model of community metabolism. Antarctic Science, v. 13, p. 18-27.
[2] Buick, R., 1992. The antiquity of oxygenic photosynthesis: Evidence from stromatolites in sulphate-deficient Archaean lakes. Science, v. 255, p. 74 –77.
ye, R., and Holland, H.D., 2000. Life associated with a 2.76 Ga ephemeral pond?: Evidence from Mount Roe #2 paleosol. Geology, v. 28, p. 483-486.
[3] Lalonde, S.V., and Konhauser, K.O., 2015. Benthic perspective on Earth's oldest evidence for oxygenic photosynthesis. Proceedings of the National Academy of Sciences [USA] , v. 112, p. 995-1000.
[4] Anbar, A.D., Duan, Y., Lyons,T.W., Arnold, G.L., Kendall, B., Creaser, R.A., Kaufman, A.J., Gordon, G.W., Scott, C., Garvin, J., and Buick, R., 2007. A whiff of oxygen before the great oxidation event? Science, v. 317, p.1903–1906.