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# Holocene glacier fluctuations inferred from lacustrine sediment, Emerald Lake, Kenai Peninsula, Alaska

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ABSTRACT

Physical and biological characteristics of lacustrine sediment from Emerald Lake were used to reconstruct the Holocene glacier history of Grewingk Glacier, southern Alaska. Emerald Lake is an ice-marginal threshold lake, receiving glaciofluvial sediment when Grewingk Glacier overtops the topographic divide that separates it from the lake. Sub-bottom acoustical profiles were used to locate core sites to maximize both the length and resolution of the sedimentary sequence recovered in the 4-m-long cores. The age model for the composite sequence is based on 13 $^{14}$C ages and a $^{210}$Pb profile. A sharp transition from the basal inorganic mud to organic-rich mud at 11.4 ± 0.2 ka marks the initial retreat of Grewingk Glacier below the divide of Emerald Lake. The overlaying organic-rich mud is interrupted by stony mud that records a re-advance between 10.7 ± 0.2 and 9.8 ± 0.2 ka. The glacier did not spill meltwater into the lake again until the Little Ice Age, consistent with previously documented Little Ice Ages advances on the Kenai Peninsula. The retreat of Grewingk Glacier at 11.4 ka took place as temperature increased following the Younger Dryas, and the subsequent re-advance corresponds with a climate reversal beginning around 11 ka across southern Alaska.

## Introduction

Evidence for the growth of mountain glaciers during the early Holocene (following the Younger Dryas at ~11.7 ka and prior to ~8.2 ka) is sparse in western North America (reviewed by Davis et al., 2009). The growth of glaciers at high northern latitudes during the early Holocene is somewhat unexpected because orbitally driven summer insolation was higher than at present. Glacier growth during the early Holocene implicates changes in dynamical aspects of ocean–atmospheric circulation, possibly a synoptic-scale increase in winter precipitation.

Using geomorphic evidence to infer early Holocene glacier growth is difficult because discerning between moraines that represent a pause during overall retreat versus a true re-advance is impossible without super-positional or cross-cutting relations. A pause in glacier retreat during the early Holocene might be expected as deglaciation leads to uplift of a glacier's accumulation zone, or as a glacier retreats to a sheltered position within a valley and regains equilibrium. In contrast, a re-advance requires a millennial-scale climate reversal. We use the term “re-advance” to emphasize the distinction from an “advance”, a term that is commonly misused when referring to former glacier extent based on end moraines, even though they might be recessional moraines and therefore do not represent an expansion of a glacier from a previously less-extensive position.

Sedimentary sequences from proglacial lakes, including threshold lakes, often provide a more complete record of Holocene glacier fluctuations than do ice-marginal landforms. In this study, we report evidence for a well-defined multi-centennial interval during the early Holocene (10.7–9.8 ka) when Grewingk Glacier in south-central Alaska expanded beyond its 20th century extent. The re-advance is recorded in the sedimentary sequence from Emerald Lake, which provides a continuous Holocene record for the re-advance and for the Little Ice Age (LIA), which is represented by complementary evidence provided by well-preserved moraines in the forefield of Grewingk Glacier (Wiles and Calkin, 1994).

## Study site

Emerald Lake (59°03′N, 151°37′W) is located 25 km east of Homer, Alaska, in the Kenai Mountains, which separate Cook Inlet from the Gulf of Alaska (Figure 1). Grewingk Glacier, the largest outlet of the Grewingk–Yalik Ice Complex, is located 2.1 km from Emerald Lake, but does not currently flow into the lake. Emerald Lake is an ice-marginal threshold lake; it receives meltwater and clastic sediment when Grewingk Glacier expands to overtop the topographic divide of the lake. The present-day divide between the lake and the glacier is occupied by a prominent 3-km-long, 5-m-high lateral moraine that formed during the LIA (Figure 2). Emerald Lake spans 0.5 km$^2$ at 445 m asl, with a maximum depth of 52 m at its center (Figure 3).

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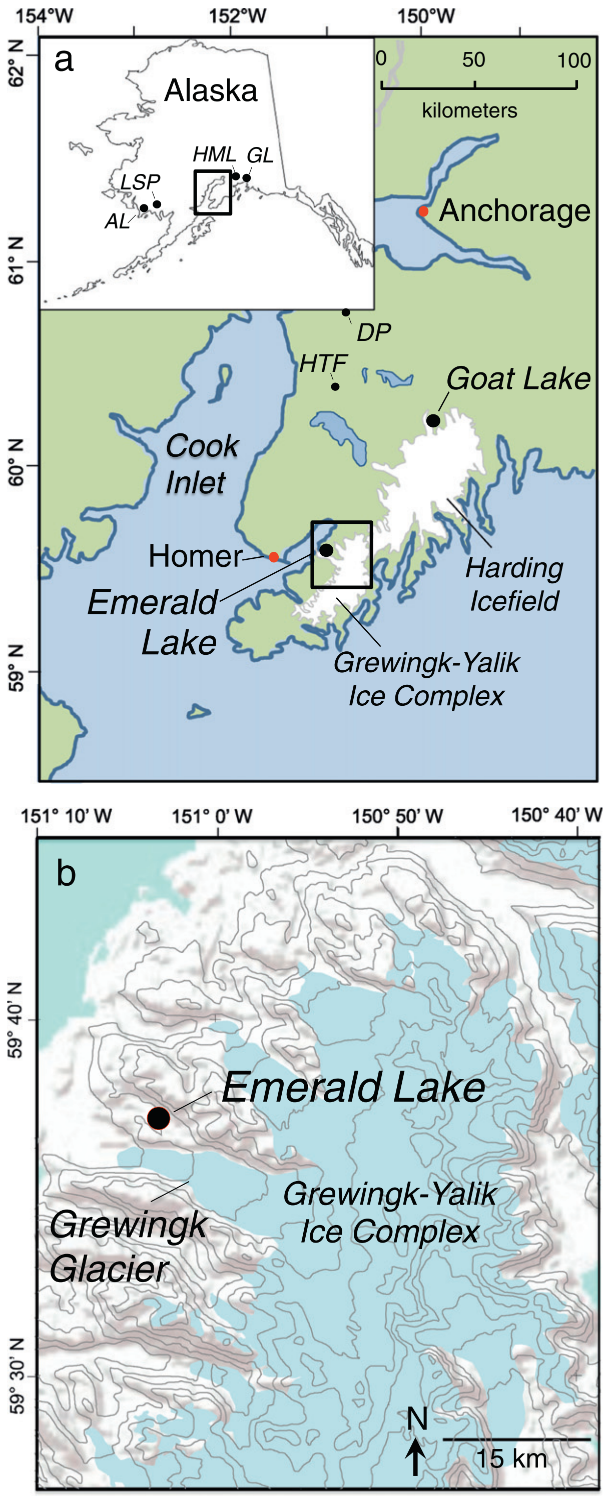

**Figure 1.** Maps of the study area. (a) Cook Inlet region, and (b) southwest Kenai Peninsula. Locations of paleo-records shown in Fig. 6 as follows: AL = Arolik Lake; LSP = Lone Spruce Pond; HML = Hundred Mile Lake; GL = Greyling Lake; HTF = Horse Trail Fen; DP = Discovery Pond.

## Methods

### Lake coring and core processing

Sediment cores were extracted from Emerald Lake during August 2012 following a survey of sub-bottom stratigraphy using a Knudsen 320BP acoustic profiler (12 and 200 kHz). Two core sites were chosen: one with low sedimentation rate and one with high sedimentation rate to maximize both the length and resolution of the sedimentary sequence recovered in the 4-m-long, single-drive percussion core barrels. In addition, a surface corer was used to collect the sediment–water interface. The sediment density was measured on the whole cores using gamma-ray attenuation at 0.5-cm intervals with a Geotek multi-sensor core logger at LacCore, University of Minnesota. The cores were then split, photographed with line-scan imaging, and measured for magnetic susceptibility (MS) and other properties at 0.5-cm intervals. The sediments, including tephra beds, were described by their sedimentary structures and textures. The organic content of the sediment was analyzed at centimeter scale using two bulk-sediment indicators: (1) visible-range scanning reflectance spectroscopic data to infer the chlorophyll content (including degradation products) based on the relative-absorption-band-depth algorithm developed by Rein and Sirocko (2002); and (2) loss on ignition to determine the weight percent of organic-matter (OM) content lost following combustion at 550°C for 5 h.

### Geochronology

The chronology for the sedimentary sequence from Emerald Lake was based on 13 $^{14}$C ages and a $^{210}$Pb profile. The upper 13 cm of the high-sedimentation rate core (Site 3) was dated by $^{210}$Pb. The surface core was sampled in 1-cm intervals and analyzed by Flett Research Ltd, Manitoba, Canada, using alpha-spectrometry measurements of $^{210}$Po, which attains secular equilibrium with $^{210}$Pb within two years, and $^{226}$Ra activity was measured on two samples by $^{222}$Ra emanation. Rather than errors based only on analytical precision, we assume more realistic uncertainties based on the differences between the known (varve) ages and $^{210}$Pb ages from the same profiles as determined by Binford (1990), and approximated using an exponential equation for which the age uncertainty increases for $\pm 2$ years at AD 2000 to $\pm 50$ yr at AD 1860.

Fourteen $^{14}$C ages were analyzed by the Keck Carbon Cycle AMS Facility, University of California at Irvine, to date ~0.3 mg of macrofossils spaced relatively equally downcore. To prepare samples for $^{14}$C dating, approximately 3 cm$^3$ of sediment were rinsed through a 100 μm sieve and dried under laminar flow. Vegetation bits of all types were picked, photographed, and weighed. $^{14}$C ages were calibrated using CALIB 7.0 (Stuiver and Reimer, 1993) and reported as the median of the probability density function of the calibrated age. Errors are reported as ± one half of the $1\sigma$ calibrated age range. All ages are reported in calendar years prior to 1950 (BP) or thousands of calendar years (ka). Ages reported as AD are rounded to the nearest decade.

The age–depth relation (age model) for the sedimentary sequence was developed using the program CLAM v2.0 (Blaauw, 2010) using $^{14}$C and $^{210}$Pb ages and the age of the sediment–water interface (AD 2012). The routine generates Monte Carlo age–depth fits through the age–probability distribution of the $^{14}$C calibration to derive the best-fit age–depth curve using 10,000 iterations. The age model for each of the two core sites was separated into two segments (upper and lower) to accurately capture the abrupt changes in sedimentation rates, and the two segments were spliced together. The ages were fit with a smooth spline (type = 4) with different smoothing values (Core 3 upper = 0.58, lower = 0.22; Core 2 upper = 0.17, lower = 0.15) so that the spline intersected nearly all of the $1\sigma$ calibrated age ranges. Tephra beds, assumed to have been deposited instantly, were removed from the model using the “slump” function.

## Results

### Composite sequence

Core EMD-3A is from the deepest part of the lake (52.0 m) where sedimentation rate, and therefore sample resolution, is highest. Core