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Combining radiocarbon and cosmogenic ages to constrain the timing of the last glacial-interglacial transition in the Uinta Mountains, Utah, USA

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ABSTRACT

Twenty lake sediment cores extracted upstream from Last Glacial Maximum terminal moraines constrain the timing of the glacial-interglacial transition in the Uinta Mountains, Utah (USA). The stratigraphy observed in the cores, and accelerator mass spectrometry ^{14}C dating of inorganic silty clay beneath gyttja, temporally constrain local deglaciation. The majority of basal ages fall within the Bølling-Allerød interval, with strong overlap at ca. 12.7 cal. (calibrated) kyr B.P. This convergence matches regional evidence of rising temperatures, increasing aridity, falling pluvial lake levels, and glacial retreat near the end of the last glacial-interglacial transition. Normalized estimates of glacier terminus retreat and elevation rise in the Uinta Mountains and elsewhere in the Rocky Mountains derived from consideration of cosmogenic ages on terminal moraines consistently average ~10%/k.y. between ca. 20 and 13 ka, implying a regionally uniform climate forcing during deglaciation. Minor variations between these rates likely reflect hypsometric effects during deglaciation. Seven lakes dammed by cirque-floor moraines have basal ages within, or slightly younger than, the Younger Dryas interval, suggesting advances of favorably located cirque glaciers before the glacial-interglacial transition was complete.

INTRODUCTION

Refining estimates of the temporal and spatial sequencing of events during the latest Pleistocene is important for elucidating how the climate system switches from glacial to interglacial modes. In the Rocky Mountains (western USA), this transition involved profound landscape-scale changes including disappearance of alpine glaciers and formation of new lacustrine environments in response to warming forced by rising insolation and greenhouse gas concentrations in the atmosphere (e.g., Shakun et al., 2015). Exactly when these and other landscape changes occurred, and how their timing varied spatially, are long-standing topics of study that can be advanced by developing chronologies for glacial retreat.

Alpine glaciers are particularly sensitive to climatic change, typically integrating shifts in winter precipitation and summer temperature over time scales of years to decades. For simple glaciers confined to bedrock valleys, climate changes that generate a shift in the equilibrium line altitude (ELA) are manifest as advance or retreat of the glacier terminus. As a result, records of glacier length variations (e.g., Oerlemans, 2005) and reconstructed ELAs (e.g., Meierding, 1982) are useful first-order archives of climatic change. However, consideration of alpine glacier behavior during the last glacial-interglacial transition is complicated by a deficit of dateable features constraining former ice positions and by the sporadic occurrence of these features in space and time.

Cosmogenic surface-exposure dating permits the calculation of ages for glacial features not otherwise directly dateable, such as moraines and striated bedrock. This approach allows tracking of the upvalley retreat of alpine glaciers from their terminal moraines and has revealed the pace of ice retreat in a small number of mountain ranges in the Rocky Mountains (e.g., Guido et al., 2007; Ward et al., 2009; Dühnforth and Anderson, 2011).

Recovery and dating of sediment cores from lakes within former glacial limits is an alternative approach for constraining deglaciation in mountain landscapes. Basal ages from these settings have been interpreted as temporal limits on the disappearance of former alpine glaciers and the onset of lacustrine conditions (e.g., Leonard and Reasoner, 1999).

Here we combine these two approaches in a heavily glaciated and centrally located mountain range of the Rocky Mountains. By compiling a large number of lacustrine basal ^{14}C ages and an extensive set of cosmogenic surface-exposure ages, we track upvalley ice retreat following the Last Glacial Maximum (LGM) and evaluate the temporal and spatial pattern of deglaciation.

METHODS

This study focuses on the Uinta Mountains, a Laramide-age uplift of Precambrian metasedimentary rocks that extends ~200 km across northeastern Utah (Fig. 1; Fig. DR1 in the GSA Data Repository[1]). Alpine glaciers are absent from the Uintas today; however, the range hosted >2000 km^2 of ice at the LGM (Munroe and Laabs, 2009). Erosion and deposition by these glaciers produced a large number of lakes surrounded by coniferous forest, alpine tundra, and felsenmeer (Atwood, 1908).

A total of 21 basal ages were obtained from 20 lakes; 14 of these are appropriate for constraining the last deglaciation (Fig. 1). Lakes were selected on the basis of reported maximum depth, accessibility, and location with the goal of ensuring broad spatial coverage (Fig. 1; Fig. DR2).

Cores were driven to refusal in the deepest part of each lake using a 7.5-cm-diameter percussion corer operated from an anchored platform. Nearly all cores penetrated the organic-inorganic transition and bottomed in dense, inorganic silty clay. Accelerator mass spectrometry (AMS) ^{14}C ages were determined for the deepest possible level in each core. Dated material included terrestrial macrofossils, *Daphnia* ephippia (a thick shell that encloses and protects the eggs), charcoal, pollen, and bulk sediment. Resulting ^{14}C ages were converted to calendar years before present (cal. yr B.P.) using OxCal 4.2 software (https://c14.arch.ox.ac.uk/oxcal.html).

Existing cosmogenic surface-exposure ages for terminal moraines (Fig. 1) and striated bedrock in the Uinta Mountains were recalculated using the Lifton-Sato-Dunai scaling (Lifton et al., 2014) and a production rate of 4.0 ± 0.1 atoms/g/yr for consistency with a recent compilation by Shakun et al. (2015). These results were compared with the basal ^{14}C ages and lake locations to determine average rates of glacier terminus retreat and terminus rise. To facilitate intercomparison, these metrics were calculated in units of percent per thousand years (%/k.y.), after normalization to maximum glacier length and elevation range. Published cosmogenic

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[1] GSA Data Repository item 2017045, supplemental Figures DR1–DR4, and Tables DR1–DR3, is available online at http://www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

GEOLOGY, February 2017; v. 45; no. 2; p. 171–174 | Data Repository item 2017045 | doi:10.1130/G38156.1 | Published online 8 December 2016

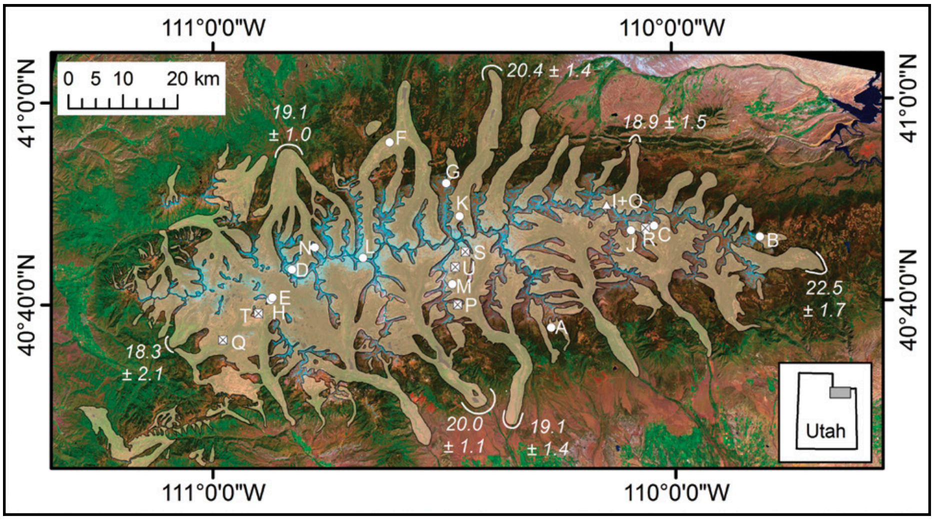

Figure 1. Locations of lakes presented over false-color Landsat 7 ETM+ (6 June 2000; http://landsat.usgs.gov/science_L7_cpf.php) image of Uinta Mountains region (Utah, USA). Solid circles represent basal ages included in composite data set; crossed circles were excluded. Two ages (I [included] and O [excluded]) were obtained from lake marked with triangle. Letters are keyed to Tables DR1 and DR2 (see footnote 1). White curves denote dated terminal moraines with associated ^{10}Be exposure ages in ka, recalculated from Laabs et al. (2009).

surface-exposure ages for other glaciated valleys in the Rocky Mountains were recalculated, as necessary, using the same approach.

RESULTS

Twenty-one (21) basal ^{14}C ages from 20 Uinta lakes range from 13,550 ± 120 ^{14}C yr B.P. (core 05-09d) to 9700 ± 80 ^{14}C yr B.P. (core 05-02) (Fig. DR3; Tables DR1 and DR2 in the Data Repository). After conversion to calendar years, this range corresponds to ca. 16.7 to ca. 11.2 cal. kyr B.P. Seven of these ages (Table DR2) are excluded from further consideration because there is reason to believe that they do not accurately constrain the timing of lake formation. These include the age from core 05-09d, which is a clear outlier (Fig. DR3). This age was determined on a concentrate of pollen that may have been contaminated with older carbon. Four ages are excluded because they were determined for material >10 cm above the core base, an elimination threshold selected to minimize reliance on extrapolation. The age from core 04-03 is dismissed because loss-on-ignition values and observed stratigraphy indicate that this core did not penetrate to the base of the lacustrine sediment. Finally, the basal age from core 05-01 is ignored because it was collected from a kettle where buried ice may have persisted for an unknown time after deglaciation.

The remaining 14 basal ages tightly constrain the timing of deglaciation in the vicinity of these lakes. When calibrated, the ages range from 14.4 to 11.2 cal. kyr B.P. (Table DR1) with a strong maximum probability ca. 12.7 cal. kyr B.P. (Fig. 2). Three of the lakes (cores 06-01, Hacking, and 04-04) have basal ages with calibration ranges that are >1000 yr older than this interval (Fig. DR3). Two of these (06-01 and Hacking) are from valleys that hosted small glaciers (<5 km long) with the two lowest-elevation headwalls (Table DR1), characteristics that likely led them to disappear early in the overall deglaciation. Core 04-04 terminated at the sediment-bedrock interface and is considered to provide a precise limit on final deglaciation in that valley.

In many valleys, existing cosmogenic ^{10}Be exposure ages (Laabs et al., 2009) for terminal moraines (Fig. 1) allow the calculation of rates of glacier terminus retreat and elevation rise (Fig. DR4; Table DR3). Glacier termini rose at rates ranging from 7.6 to 11.7%/k.y., with an average of 9.5%/k.y. Rates of terminus retreat are similar, ranging from 8.5 to 11.9%/k.y., with an average of 10.4%/k.y.

DISCUSSION

Reliability of Radiocarbon Ages

Any study involving basal ^{14}C ages must confront the reality that these ages represent minimum estimates for local deglaciation. Nonetheless, the cores in this project were driven to refusal in silty basal sediments consistent with rock flour derived from an upvalley-retreating glacier. These sediments are also inorganic, indicating that vegetation had not yet colonized the surrounding landscape. Together these inferences suggest a minimal lag time between ice retreat and lake formation. Furthermore, the data set was limited to ages obtained from within 10 cm of the base of each core, and in eight of the cores the dated material was from the actual base (Table DR1). Thus, it is reasonable to infer that these results provide close limits on the age of each lake basin.

Other issues that can yield erroneous ^{14}C ages are not of concern in this data set. Hard-water effects are unlikely given the siliciclastic bedrock of the Uintas. Radiocarbon reservoir effects are doubtful given the shallow depths (<17 m) of the lakes. Both of these issues were further avoided by dating macrofossils of terrestrial origin wherever possible. In the one core where the basal age was determined on bulk sediment (04-01), no offset was noted when paired bulk sediment and terrestrial macrofossils were dated from a higher stratigraphic level, indicating that hard-water and reservoir effects are negligible. Finally, many of the basal ^{14}C ages were replicated by analysis of additional samples isolated from the basal sediment.

The greatest strength of the data set is the large number of lakes cored. This statistical depth reduces the possibility that the pattern of ages is skewed by cores that failed to penetrate to the base of their lake basins or by erroneous ages. Thus, these ages, and their clustering, are a high-fidelity record of the temporal pattern through which the Uinta landscape deglaciated.

Rates of Deglaciation

Summing the calibration probabilities for basal ages in Uinta Mountain lakes (Fig. 2) reveals that glaciers persisted for several millennia after retreat from terminal moraines began 22.5–18.3 ka (recalculated from Laabs et al., 2009). The largest grouping of basal ages falls late in the Bølling-Allerød warm period (ca. 14.7–12.9 ka), which is consistent with other evidence of a warming and drying climate. Glaciers at multiple locations in the Rocky Mountains had retreated considerably from their LGM extents by this time (Young et al., 2011), and those in the Ruby and East Humboldt Mountains of northeastern Nevada had also retreated to <50% of their LGM lengths by ca. 15 ka (Munroe et al., 2015). Limiting ^{14}C ages from the Sawtooth Mountains (Idaho) reveal that glaciers were at their terminal positions relatively late, but nonetheless retreated after 14 cal. kyr B.P. (Thackray et al., 2004). Samples of glacially scoured bedrock in a western Uinta col (Fig. 2) yield a mean ^{10}Be exposure age of ca. 15.5 ka (Refsnider et al., 2008), suggesting that downwasting exposed high divides while active ice remained in the valleys below. Pluvial lakes

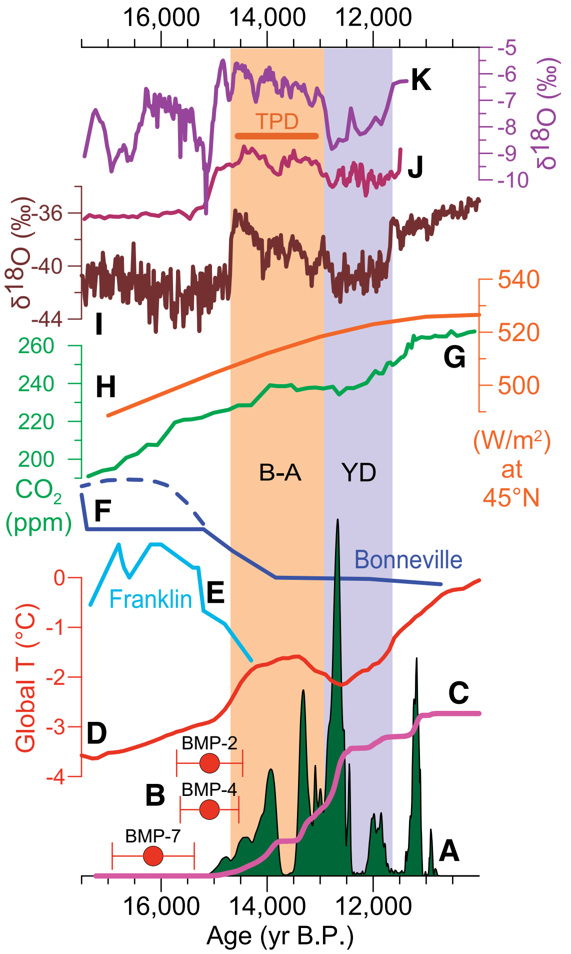

Figure 2. Calibrated Uinta Mountains (Utah, USA) basal ages compared with other paleoclimate data. A: Summed probability of all calibrated Uinta basal ages in composite data set. B: Recalculated cosmogenic surface-exposure ages for bedrock outcrops at Bald Mountain Pass (Refsnider et al., 2008). C: Cumulative probability curve for Uinta basal ages. D: Global temperature (*T*) reconstruction (Shakun et al., 2012) E,F: Lake level curves for Lake Franklin, Nevada (Munroe and Laabs, 2013) (E) and Lake Bonneville (F), dashed when overflowing (Oviatt, 2015). G: CO_2 record from European Project for Ice Coring in Antarctica (EPICA) Dome C (Lüthi et al., 2008). H: June insolation for 45°N (Berger, 1978). I: $\delta^{18}O$ record from North Greenland Ice Core Project (NGRIP) core (Rasmussen et al., 2006). J: $\delta^{18}O$ record from Cave of the Bells, Arizona (Wagner et al., 2010). K: $\delta^{18}O$ record from Fort Stanton Cave, New Mexico (Asmerom et al., 2010). TPD—terminal Pleistocene drought in southwestern United States (Polyak et al., 2012); B-A—Bølling-Allerød (B-A); YD—Younger Dryas.

in the Great Basin including Bonneville (Benson et al., 2011; Godsey et al., 2011), Lahontan (Benson et al., 2013; Adams and Wesnousky, 1998), and Franklin (Munroe and Laabs, 2013) began shrinking rapidly after ca. 15 cal. kyr B.P. (Fig. 2). Speleothems in the southwestern United States also record a marked shift toward warmer and drier conditions at ca. 15.3 ka, beginning an interval known as the terminal Pleistocene drought (Asmerom et al., 2010; Wagner et al., 2010; Polyak et al., 2012).

Recent compilation of published cosmogenic surface-exposure ages for glacial valleys in the Rocky Mountains (Shakun et al., 2015) provides additional context for the rates of ice retreat and terminus rise (~10%/k.y.) derived for the Uintas (Fig. DR4; Table DR3). Rates of terminus rise were generally similar (~6%–12%/k.y.) in the Colorado Rockies (Guido et al., 2007; Ward et al., 2009; Dühnforth and Anderson, 2011), Yellowstone Plateau (Wyoming) (Licciardi et al., 2001), and Wind River Range (Wyoming) (Gosse et al., 1995b), although values for the Jenny Lake Glacier in the Teton Range (Wyoming) (Licciardi and Pierce, 2008) may have been as high as 30%/k.y. Rates of terminus retreat were lower (~5%/k.y.) in the Middle Fork Boulder Creek (Ward et al., 2009) and Green Lake Valley (Dühnforth and Anderson, 2011), both in the Colorado Rockies, but were similar for Lake Creek, Colorado (Young et al., 2011), and the Wind River Range (Gosse et al., 1995b). Once again, the rate calculated for Jenny Lake is fastest, suggesting that this glacier retreated rapidly after a relatively late abandonment of its terminal moraine at ca. 15 ka. Such apparent differences in retreat rates may reflect filtering of climatic forcing by hypsometry to yield distinct glacier responses (Young et al., 2011).

The unusually large number of basal ^{14}C and surface-exposure ages compiled in this study provides an unprecedentedly detailed perspective on the timing of alpine glacier retreat. The strong clustering of basal ages between 13.5 and 12.5 cal. kyr B.P. reveals that Bølling-Allerød warming eliminated ice near the heads of most high-elevation valleys (Fig. 2). This impact was felt across a range of elevations (~600 m range), aspects, and glacier morphologies. Similar rates of terminus retreat and elevation rise in multiple valleys (Fig. DR4) imply a uniform climatic forcing likely paced by increasing summer insolation and atmospheric greenhouse gas concentrations (Shakun et al., 2015). Final loss of glacial ice from valley heads and formation of lakes in glacial basins represent a tremendous ecosystem transformation that occurred late in the Bølling-Allerød interval.

Evidence for Cirque Glacier Response to the Younger Dryas

A striking aspect of this data set is the suggestion of cirque glacier activity during the Late Glacial. Seven of the eight youngest basal ages are from lakes dammed by end moraines (Table DR1). Four of these align with the main cluster of ages ca. 12.7 cal. kyr B.P., whereas three others overlap ca. 11.5 cal. kyr B.P. This younger cluster is consistent with glacial advances during the Younger Dryas (YD) interval. These three lakes (cores 04-07, 05-02, and 05-08) are located at relatively high elevations (~3300 m) below tall, north-facing headwalls that would have provided optimal locations for enhanced snow accumulation.

Climatic responses to the YD in mountain regions of the western United States have been reported from a diverse array of proxies including pollen (Reasoner and Jodry, 2000; Johnson et al., 2013), chironomids (MacDonald et al., 2008), lacustrine sediments (Street et al., 2012; Yuan et al., 2013), and bat guano (Wurster et al., 2008). Glacier responses have also been proposed (Gosse et al., 1995a; Licciardi et al., 2004; Menounos and Reasoner, 1997; Armour et al., 2002), although some have challenged these interpretations (e.g., Marcott, 2011). Nonetheless, the results reported here strongly suggest that favorably located cirque glaciers in the Uintas advanced in response to the YD before the final disappearance of ice at the end of the last glacial-interglacial transition.

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