Multiple generations of interglacial lake sediment preserved beneath the Laurentide Ice Sheet

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ABSTRACT

It is generally assumed that regions glaciated by continental ice sheets offer little promise for long paleoenvironmental records due to erosional processes associated with glaciation. We show that beneath portions of the northeastern Laurentide Ice Sheet, characterized by cold-based glaciation, sediment sequences representing multiple interglaciations have been preserved within extant lake basins. Radiocarbon and optically stimulated luminescence dating confirm the antiquity of the sediments, thereby extending the terrestrial paleoenvironmental record of the Canadian Arctic by hundreds of thousands of years. The lake sediment record presented here corroborates numerous recent cosmogenic exposure dating studies indicating complex patterns of erosion beneath polar ice sheets. It also demonstrates that the presence of intact interglacial sediments does not demand unglaciated refugia. Similarly ancient sediments may be preserved in many regions formerly covered by Pleistocene ice sheets.

Keywords: Arctic, lake sediments, Laurentide Ice Sheet, cold-based ice, glacier erosion, paleoclimate, interglaciation.

INTRODUCTION

It is increasingly apparent that polar regions play a disproportionate role in the global climate system. Strong positive feedbacks, largely modulated by cryospheric processes, have amplified climate sensitivity on historic (Overpeck et al., 1997; ACIA, 2005), Holocene (Kaufman et al., 2004; CAPE Members, 2001) and glacial-interglacial (CAPE Last Interglacial Project Members, 2006) time scales relative to global or hemispheric averages. Ice sheets, in particular within the North Atlantic sector, have been directly implicated in altering global oceanic circulation (Broecker, 1994), driving abrupt climate change (Alley et al., 2003), and causing rapid sea-level rise (Alley et al., 2005). Placing ongoing and future changes in the Arctic into a geologic context is critical for understanding processes and rates of climate change in these sentinel regions, especially given the limited nature of the instrumental climate record in remote, high-latitude regions. However, few archives of pre-Holocene environments exist from the arctic terrestrial realm (e.g., Brigham-Grette et al., 2007), in large part because erosive ice sheets have repeatedly overrun vast areas of the Arctic. Although ice cores provide invaluable assessments of past climate and atmospheric composition (North Greenland Ice Core Project (NGRIP) Members, 2004), they do not address attendant terrestrial processes and ecological responses to climate change. Furthermore, the longest ice core records from the Northern Hemisphere extend only part way through the last interglaciation (North Greenland Ice Core Project Members, 2004).

Recent discoveries from the beds of former ice sheets hint at the potential for preservation of long sedimentary archives in glaciated portions of the Arctic. Relict landscapes that predate the last glacial cycle have been identified in a number of regions within the margins of the Laurentide and Fennoscandian Ice Sheets (Dyke, 1993; Kleman and Hättestrand, 1999; Briner et al., 2006a), attesting to the heterogeneous nature of subglacial erosion. In these examples, delicate landforms of subaerially weathered bedrock are often preserved intact, typically in conjunction with a drape of erratics that are demonstrably younger, based on cosmogenic exposure dating (Fabel et al., 2002; Briner et al., 2006b; Davis et al., 2006). Cosmogenic isotope inheritance and the degree of disequilibrium between cosmogenic ^{10}Be and ^{26}Al in samples from these regions attest to minimal ice sheet erosion (0–2 m) over long time scales (Bierman et al., 1999; Stroeven et al., 2002; Briner et al., 2006b), which has allowed the preservation of weathered preglacial landforms such as tors, and organic lake sediments deposited during successive interglacial periods.

Lake sediments predating the Last Glacial Maximum (LGM) have been identified in a number of extant lake basins on eastern Baffin Island (Fig. 1A; Miller et al., 2002), near the northeastern margin of the Laurentide Ice Sheet. These records have enabled climate reconstructions for the last interglaciation (Fréchette et al., 2006; Francis et al., 2006), and were initially interpreted as evidence for unglaciated refugia situated on weathered uplands (Wolfe, 1996; Steig et al., 1998). In this study we present a new and longer lake sediment sequence that refines this model, in addition to extending the temporal scope (≥200 k.y.) of lake sediments in the Canadian Arctic. These sediments represent a valuable target for future studies aimed at understanding late Quaternary climate variability, and provide new information on glacial processes at the margins of polar ice sheets.

NEW LONG LACUSTRINE RECORD FROM BAFFIN ISLAND

The Clyde foreland, a wide coastal lowland on northeastern Baffin Island (Fig. 1B), was occupied by a cold-based portion of the Laurentide Ice Sheet during the last glaciation, until deglaciation ca. 12 ka (Briner et al., 2005). Ice-marginal and proglacial meltwater channels (Fig. 1B) and scattered erratic boulders provide the only evidence of late Pleistocene ice cover; these are superimposed on intact marine shorelines, ice-contact glacial-marine deltas, and delicate fluvial channels that were formed before the LGM (e.g., Davis et al., 2006). A large database of cosmogenic exposure ages on erratic boulders reveals a polymodal age distribution for the foreland (Fig. 1C; Briner et al., 2005).

We cored Lake CF8 (informal name) on the Clyde foreland (70°33′22.10″N, 68°57′8.23″W; Fig. 1B) to test the hypothesis that pre-LGM lacustrine sediments are preserved within the glacierized fringe of northeastern Baffin Island. Lake CF8 has a surface area of 0.3 km^2, a maximum depth of 10 m, and is 195 m above sea level. The lake is in a small catchment (1.1 km^2) that contains an abandoned lateral meltwater channel, similar to dozens of others in the region, which attests to the cold-based nature of the Laurentide Ice Sheet when it covered this region. Seven cores collected with a percussion coring system range from 1.8 to 2.5 m long, and penetrated as much as 3.3 m beneath the mud-water interface (some cores purposely bypassed the upper ~1 m of sediment). The cores contain alternating units of stratified organic-rich mud

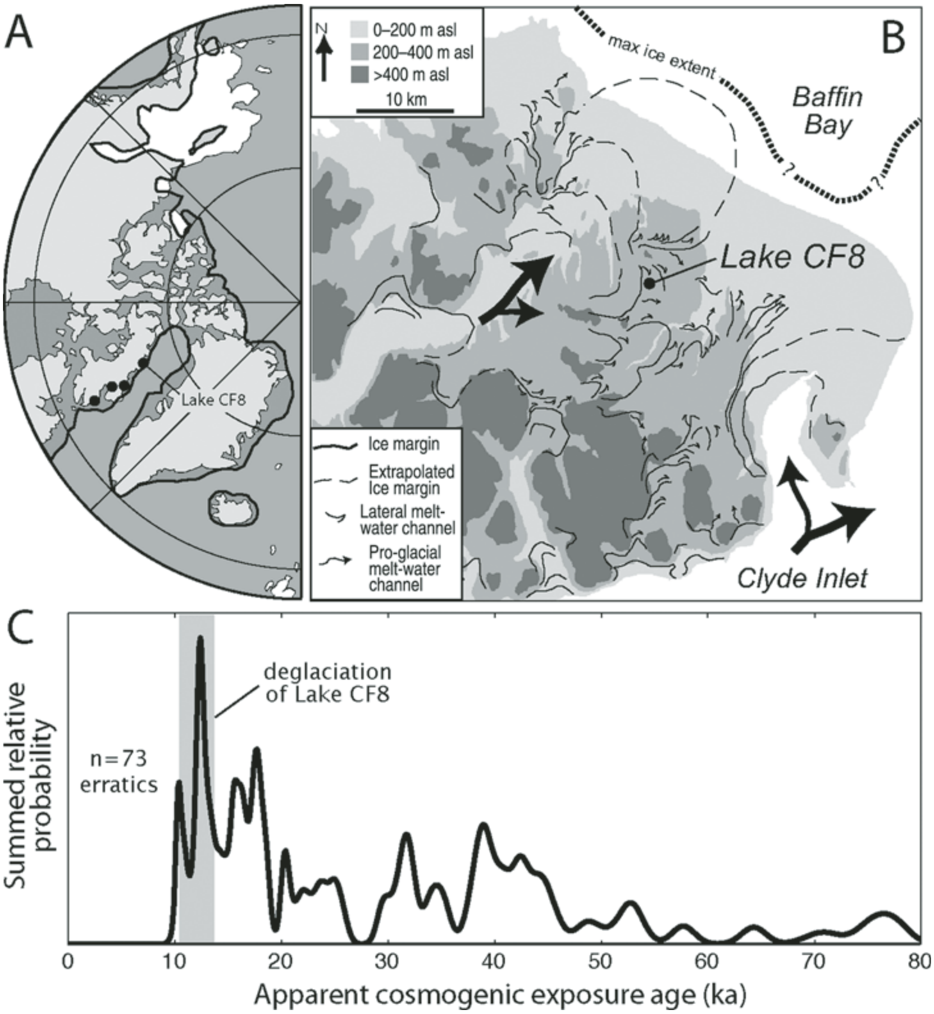

Figure 1. A: Location maps showing sites where pre-Holocene organic sediments have been recovered (black dots) within glaciated North America (black line), including Lake CF8. B: Lake CF8 and surrounding glacial-geologic features on the Clyde foreland. Large arrows indicate former flow directions of the Laurentide Ice Sheet, which deposited erratics across the landscape (asl—above sea level). C: Summed relative probability distribution of 73 erratics from relict landscape near Lake CF8 dated by ^{10}Be and ^{26}Al exposure dating (from Briner et al., 2005) reveals several modes, the youngest of which represents last deglaciation. Multiple modes illustrate prevalence of cosmogenic radionuclide inheritance in terrains formerly covered by cold-based ice.

(gyttja) and faintly laminated medium to coarse sand. A composite sediment stratigraphy was constructed from the individual cores (Fig. 2). Sediment organic matter and magnetic susceptibility were measured using standard protocols (Last and Smol, 2001). From top to bottom, units I, III, V, and VII are composed of gyttja with high organic content and low magnetic susceptibility, whereas units II, IV, and VI are composed of sand with low organic content and elevated magnetic susceptibility (Fig. 2).

The upper two organic-rich units in Lake CF8 (units I and III) were dated with accelerator mass spectrometry ^{14}C measurements on aquatic bryophyte remains. The ^{14}C results indicate that unit I represents continuous organic sedimentation over the past ~12 k.y. (Axford, 2007). Three bryophyte samples from unit III yielded nonfinite ^{14}C ages (Fig. 2; GSA Data Repository Table DR1[1]).

We used optically stimulated luminescence (OSL) to date sediments beyond the range of ^{14}C dating following the methodology outlined by Forman et al. (2007) for lake sediments (see footnote 1). Samples of organic-rich sediments were collected from 5 or 10 cm core increments. All OSL measurements were obtained via the multiple-aliquot regenerative dose method (Jain et al., 2003), which was used to excite the silt-sized fraction sequentially under infrared light (IR, 920 nm) and blue light (BL, 470 nm; Table DR2; see footnote 1). To test for complete zeroing of the luminescence signal, two samples from radiocarbon-dated unit I were dated by OSL. The OSL age from near the top of unit I is 1.5 ± 0.1 ka (BL), where sediments are radiocarbon dated to ca. 5 ka B.P. A second sample from the base of unit I yields an age of ca. 10.3 ± 0.3 ka, which is an average of three OSL ages obtained from the same level via different methods (BL, IR, and BL/IR). The corresponding ^{14}C age for this level is ca. 10.5 ka B.P. (Fig. 2). The general coherence of Holocene OSL and ^{14}C ages in the upper part of the sequence (Fig. 2) verifies that full solar resetting has occurred, and that OSL is an appropriate dating technique in this depositional setting. The OSL ages from the top and bottom of unit V are 101.3 ± 5.8 ka (average of 97.2 ± 1.0 ka [BL] and 105.4 ± 9.9 ka [IR]) and 121.7 ± 12.1 ka (BL), respectively. The OSL age from unit VII is older than 194.1 ± 18.9 ka (BL); this is a minimum age due to saturation of the luminescence signal.

GENETIC STRATIGRAPHY OF LAKE CF8

We propose a sedimentological model that accommodates the stratigraphic succession and geochronological data obtained from Lake CF8 (Fig. 3). During interglaciations with climate similar to or warmer than present, Lake CF8 is ice free in summer, and the catchment is stabilized by tundra vegetation. Organic-rich lake sediments are produced at these times, integrating the products of aquatic and terrestrial biological activity. As climate cools during the inception of glaciations, Lake CF8 crosses a climatic threshold beyond which it becomes perennially frozen. Given analogs from both the Canadian High Arctic (Blake, 1989; Doran et al., 1996) and Antarctica (Hodgson et al., 2006), we envisage that such conditions are encountered once mean annual temperatures are consistently <–15 °C, or when mean summer temperatures do not exceed 0 °C for prolonged periods. At such times, lake sedimentation ceases because hydrological and biological systems are essentially shut down. The lake may remain in this quiescent state for millennia prior to the encroachment of glacier ice (Fig. 3B). When this occurs, lake ice may play a crucial role in protecting underlying sediments from disruption by the passage of glacier ice, as even cold-based glaciers are potentially erosive (Cuffey et al., 2000).

Following the interval of glacial cover and the associated hiatus of sedimentation over tens of millennia (Fig. 3C), lake sedimentation resumes during regional deglaciation as the hydrological cycle is reactivated. Deglaciation is recorded by layers of stratified sandy sediments in Lake CF8

[1]GSA Data Repository item 2007221, luminescence methods and Tables DR1 and DR2, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

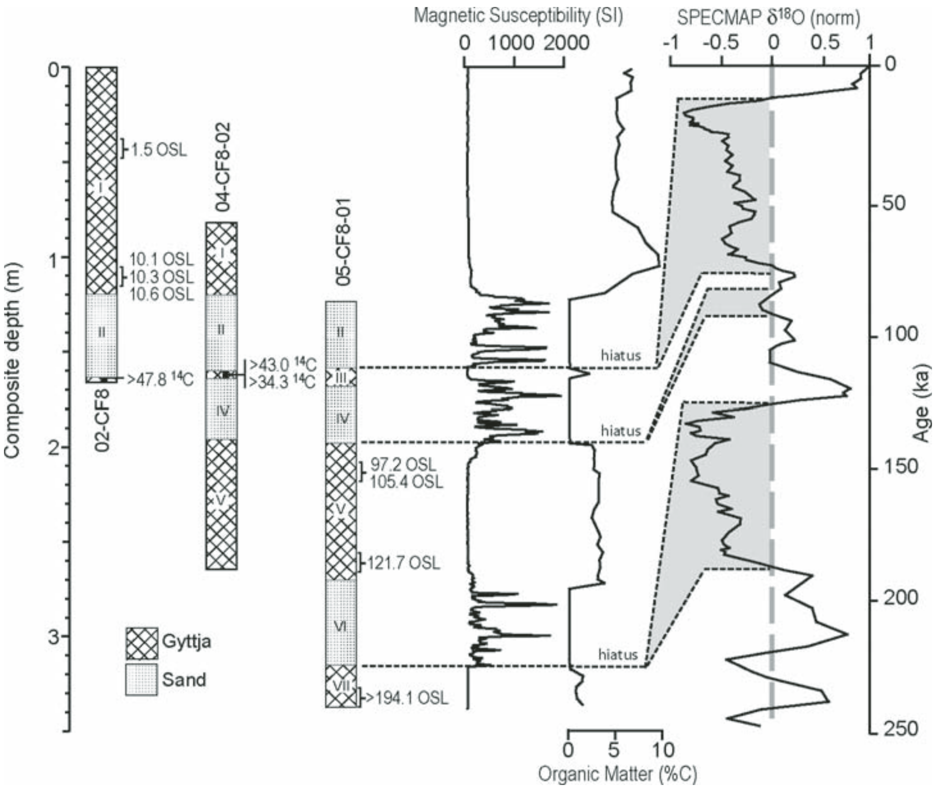

Figure 2. Stratigraphic context of 14C and optically stimulated luminescence (OSL) ages, shown in thousands of years B.P. 14C ages from unit III are given in Table DR1, and OSL ages are given in Table DR2 (see footnote 1). Composite magnetic susceptibility (MS) and organic matter (OM) content were generated by splicing MS and OM content from individual cores using unit contacts as tie points. The global ice volume proxy, normalized oceanic $\delta^{18}O$, is from Martinson et al. (1987).

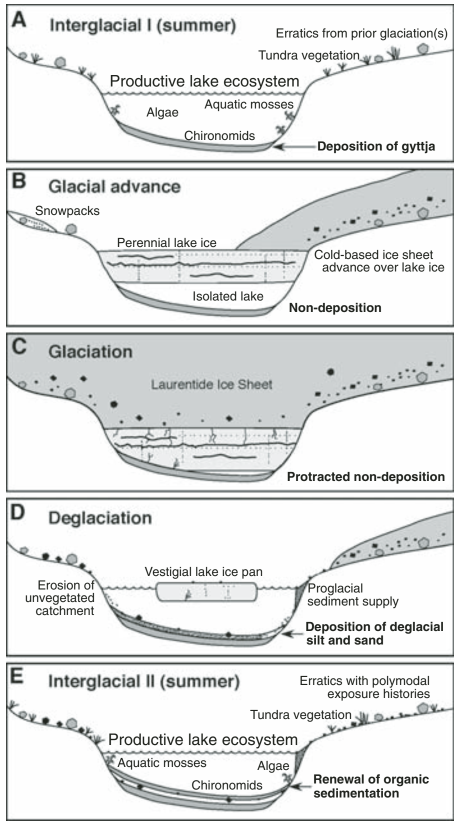

Figure 3. Model for sedimentation in Lake CF8 throughout complete glacial cycle, showing formation and preservation of consecutive interglacial units, depositional hiatuses during glacial intervals, and deposition of deglacial minerogenic sediments.

cores (units II, IV, and VI) that were presumably deposited by rapid proglacial sedimentation during the brief intervals when the Laurentide Ice Sheet margin fed the lateral meltwater channel in Lake CF8's small drainage basin (Fig. 3D). Once the Laurentide Ice Sheet disappears from the catchment, and aquatic production resumes, a new cycle of organic sedimentation begins. Thus far, we have retrieved four such organic sequences (units I, III, V, and VII) to which this model can be applied. We note that core lengths thus far have been limited technically and not by impenetrable lithology; thus the complete record from Lake CF8 may be considerably longer than reported here.

The OSL results assign an age older than 194 ka to the lowest organic unit retrieved (unit VII). Because an interglacial climate state is required to produce this sediment, by correlation we ascribe this sediment to warm intervals within marine isotope stage (MIS) 7 (Fig. 2). Following nondeposition during MIS 6 glaciation, unit VI was produced as the basin was deglaciated. The OSL ages on unit V constrain its deposition to early MIS 5. These ages imply that MIS 5e, a time that is recognized as having been as much as 5 °C warmer than present at high latitudes (North Greenland Ice Core Project (NGRIP) Members, 2004; CAPE Last Interglacial Project Members, 2006), is well represented in Lake CF8 sediments. Nonfinite 14C ages from the thin organic-rich unit III (Fig. 2) and its superposition over unit V imply that it is older than 48 ka B.P., but younger than the last interglaciation (MIS 5e). We therefore correlate unit III with interstadial conditions following peak warmth of the last interglaciation, which likely occurred during MIS 5c or MIS 5a. We favor an MIS 5a age for unit III sediments (Fig. 2) because this interval underwent peak summer high-latitude insolation of the past 100 k.y. (Berger and Loutre, 1991). Thus, we ascribe the underlying minerogenic unit IV to deglacial sedimentation following a regional ice sheet advance in the MIS 5d–5b interval (Miller and de Vernal, 1992). Unit II was deposited after a protracted interval of glacial cover during MIS 4–2. Unit I represents Holocene sedimentation following the last deglaciation (unit II), which occurred ca. 12 ka at this site.

CONCLUSION

Temporally long lacustrine sequences preserved within the margin of the Laurentide Ice Sheet on eastern Baffin Island demonstrate that glaciation does not universally erase the record of preglacial organic sedimentation. Given the presence of extensive tracts characterized by cold-based glaciation and relict landscapes (e.g., Kleman and Hättestrand, 1999; Briner et al., 2006a), such records may prove to be widespread around the high-latitude North Atlantic region. Lake CF8 sediments record at least three interglacial periods (MIS 7, MIS 5, MIS 1) and compose the longest lake-sediment record thus far recovered from within the limits of continental glaciation. This record challenges the assumption that only sites distal to glacial margins are useful for reconstructing pre-Holocene environmental changes. Because only nonglacial intervals of maximum warmth are preserved, these records provide valuable targets for understanding the dynamics of arctic landscapes and ecosystems during periods as warm or warmer than present, in absence of enhanced greenhouse gas forcing. Comparisons of these interglacial sediments to recent (postindustrial) counterparts may assist in differentiating the consequences of natural versus anthropogenic warming in the Arctic.

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Data Repository Items

Luminescence methods

Luminescence dating of lake sediments was completed on the fine-grained (4-11 μm) polymineral and quartz fractions. All samples were dated by the multiple aliquot regeneration dose procedures, using the component-specific dose normalisation (CSDN) method (Jain et al., 2003). This method compensates for sensitivity changes from irradiation and subsequent preheating, rendering robust equivalent dose values. Initially, the CSDN procedure determined equivalent dose with infrared (IR) stimulation, and then subsequently with blue light excitation. This sequence of analysis (IR followed by blue excitation) preferentially measures feldspar-sourced and then quartz-sourced emissions. The resultant blue emissions were measured at ~ 25º C by a photomultiplier tube coupled with one 3-mm-thick Schott BG-39 and one 3-mm-thick Corning 7-59 glass filter; these emissions are the most suitable as a chronometer (e.g. Balescu and Lamothe, 1994; Lang et al., 2002). The background count rate for measuring emissions was <100 counts/s, with a signal-to-noise ratio of >20. A sample was excited for 90s, and the resulting emissions was recorded in 1s increments.

A critical analysis for luminescence dating is the dose rate, which is an estimate of the sediment exposure to ionizing radiation during the burial period. Most ionizing radiation in sediment is from the decay of isotopes in the U and Th decay chains and ^{40}K, which was measured by inductively coupled plasma-mass spectrometry. A small cosmic ray component is included in the estimated dose rate (Prescott and Hutton, 1994). Dose rate for each sample was adjusted for measured moisture, organic and biogenic silica content.

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Data Repository Table 1

Data Repository Table 1. Radiocarbon ages from Lake CF8.

Lab number[a]	Core name	Depth in core section (cm)	Stratigraphic unit	Material	$\delta^{13}C$	Fraction modern	^{14}C age (^{14}C yr B.P.)
AA60641	02-CF8	31	I	aquatic moss	-26.6	0.6766±0.0052	3140±60
AA60642	02-CF8	50	I	aquatic moss	-29.1	0.5596±0.0028	4660±40
CURL-6954	02-CF8	107	I	aquatic moss	-30.5	0.3133±0.0017	10490±190
NSRL-13843	04-CF8-02a	80	III	aquatic moss	-22.1	0.00474 ±0.00063	43000 ±1070
AA60649	04-CF8-02a	81	III	aquatic moss	-23.9	0.0140±0.0010	34290 ±570
NSRL-13322	02-CF8	164	III	aquatic moss	-22.3	0.00260 ±0.00020	47810 ±400

[a]NSRL/CURL = The INSTAAR Laboratory for AMS Radiocarbon Preparation and Research; AA = The NSF - Arizona Accelerator Mass Spectrometry (AMS) Laboratory.

Data Repository Table 2

Table 2: Optically stimulated luminescence ages from Lake CF8 sediments.

Sediment core ID and depth	Lab #	Equiv. dose (Gy)[d]	U (ppm)[e]	Th (ppm)[e]	K_20 (%)[e]	A-value	H_2O (%)	Organic & $BSiO_2$ (%)	Cosmic[e] dose (Gy/ka)	Dose rate (Gy/ka)	OSL age (ka)
02-CF8-01 40.5-50.5 cm	UIC1683BL[a]	7.14 ± 0.46	3.1 ± 0.1	54.7 ± 0.1	1.14 ± 0.01	0.13 ± 0.01	80 ± 10	32 ± 5	0.08 ± 0.01	4.82 ± 0.29	1.48 ± 0.14
02-CF8-01 108-118 cm	UIC1684BL	44.70 ± 0.66	3.5 ± 0.1	38.4 ± 0.1	2.79 ± 0.01	0.10 ± 0.01	70 ± 10	32 ± 5	0.07 ± 0.01	4.44 ± 0.28	10.07 ± 0.88
02-CF8-01 108-118 cm	UIC1684BL-IR[b]	45.62 ± 0.64	3.5 ± 0.1	38.4 ± 0.1	2.79 ± 0.01	0.10 ± 0.01	70 ± 10	32 ± 5	0.07 ± 0.01	4.44 ± 0.28	10.28 ± 0.89
02-CF8-01 108-118 cm	UIC1684IR[c]	47.03 ± 0.51	3.5 ± 0.1	38.4 ± 0.1	2.79 ± 0.01	0.10 ± 0.01	70 ± 10	32 ± 5	0.07 ± 0.01	4.44 ± 0.28	10.59 ± 0.92
05-CF8-01 90-95 cm	UIC1682BL	425.07 ± 2.40	2.0 ± 0.1	35.1 ± 0.1	2.23 ± 0.01	0.13 ± 0.01	60 ± 10	25 ± 5	0.05 ± 0.01	4.38 ± 0.28	97.15 ± 0.91
05-CF8-01 90-95 cm	UIC1682IR	460.94 ± 2.95	2.0 ± 0.1	35.1 ± 0.1	2.23 ± 0.01	0.13 ± 0.01	60 ± 10	25 ± 5	0.05 ± 0.01	4.38 ± 0.28	105.35 ± 9.85
05-CF8-01 140-145 cm	UIC1685BL	899.77 ± 8.28	3.8 ± 0.1	66.0 ± 0.1	1.97 ± 0.01	0.12 ± 0.01	60 ± 10	12 ± 3	0.04 ± 0.01	7.39 ± 0.41	121.71 ± 12.08
05-CF8-01 213-218 cm	UIC1681 BL	(>)1260.44 ± 7.45	2.4 ± 0.1	37.3 ± 0.1	3.78 ± 0.04	0.12 ± 0.01	50 ± 10	4 ± 2	0.04 ± 0.01	6.49 ± 0.35	(>)194.12 ± 18.92

[a]Excitation under blue light (470 nm).
[b]Excitation under infrared light (920 nm) with subsequent blue light excitation.
[c]Excitation under infrared light.
[d] Multiple aliquot regenerative dose method following normalization procedures of Jain et al. (2003)
[e]U, Th and K_20 content by ICP-MS; includes a cosmic ray dose rate from calculations of Prescott and Hutton (1994)
All errors are at one sigma. Analyses by the Luminescence Dating Research Laboratory, University of Illinois at Chicago.