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HIGH-RESOLUTION AGE MODEL BASED ON AMS RADIOCARBON AGES FOR KETTLE LAKE, NORTH DAKOTA, USA

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ABSTRACT. A high-resolution age model was developed for Kettle Lake, North Dakota, USA, from a series of 53 accelerator mass spectrometry (AMS) radiocarbon ages calibrated with Bayesian statistical methods, which provide a monotonically increasing series of calibrated ages with depth. Evident in the sediment are several slumps, debris flows, or landslides, which are confirmed by ^{14}C dating. Removal of these facies produces a continuous sedimentary sequence for the past 13,000 yr with exception of one ~260-yr hiatus associated with a 1.5-m-thick slump deposit. All ages except one are on terrestrial macrofossils and charcoal. A test age on aquatic organic detritus shows a hardwater effect of 600 yr at ~2000 cal BP. Two ages from the same level on herbaceous charcoal and *Chenopodium* seeds are statistically the same, which further demonstrates the suitability of charcoal from grassland environments for AMS ^{14}C age control. However, 2 specimens of wood charcoal are too old relative to bracketing ages and glacial geologic history. These ages confirm the sedimentary interpretation of redeposition and provide a caution about the longevity of wood charcoal in the environment and its suitability for age control in lacustrine sediments.

INTRODUCTION

Studies of microfossils, charcoal, geochemistry, and stable isotopes from lakes in the northern Great Plains (NGP) of North America show that lake chemistry and vegetation are highly responsive to decadal- and century-scale climate change, particularly precipitation variations (Fritz et al. 1994, 2000; Laird et al. 1996a,b, 1998a,b; Valero-Garcés et al. 1997; Yu and Ito 1999; Clark et al. 2001, 2002; Grimm 2001; Yu et al. 2002; Umbanhowar 2004; Brown et al. 2005). In this sub-humid to semi-arid region, closed-basin lakes are particularly sensitive to moisture variations. Lake levels fluctuate in response to moisture variability, and salinity varies as lake volume and groundwater input change. Salinity may be a function of water volume (Laird et al. 1996a, 1998a; Valero-Garcés et al. 1997; Yu and Ito 1999; Yu et al. 2002), and carbonate precipitation may vary as a function of groundwater input of dissolved carbonate (Brown et al. 2005; Donovan and Grimm 2007). Changes in lake chemistry are recorded in diatom and ostracode assemblages and in sediment geochemistry. The prairie vegetation is highly responsive to periodic drought, and both pollen and charcoal reveal decadal-scale variations (Grimm 2001; Clark et al. 2002; Brown et al. 2005). Rapid rates of sediment deposition and minimal sediment mixing provide records with high temporal resolution. In deep NGP lakes that have never dried out, sediment thicknesses may exceed 20 m for complete late-glacial/Holocene sequences, which span the past 12,000–13,000 yr.

Although sediments from NGP lakes offer great potential for developing paleoenvironmental records with high temporal resolution, only a few decadal-scale records have been developed, and with 1 exception for only the late Holocene. These records include a diatom proxy for lake salinity for the past 2300 yr from Moon Lake, North Dakota (Laird et al. 1996b, 1998a); a record of lake salinity from ostracode-shell Mg/Ca ratios for the past 2100 yr from Rice Lake, North Dakota (Yu and Ito 1999); and a multiproxy record of moisture variability from geochemistry, pollen, and charcoal for the past 4500 yr from Kettle Lake, North Dakota (Brown et al. 2005). The only high-resolution mid-Holocene record is a diatom proxy for salinity from Oro Lake, Saskatchewan (Laird et al. 2007). Spectral analyses were carried out on the data from the 3 late Holocene sites, but chronological control on the first 2 of these sites was minimal, based on only 3 (Rice Lake) or 4 (Moon Lake) radiocarbon ages. Development of high-resolution records is hindered by the great time investment required to process hundreds or thousands of samples and by the expense for large numbers of ^{14}C ages necessary for high-resolution age models. Nevertheless, these studies have shown a great potential for extracting a high-resolution climate record for the entire Holocene in the NGP. Given the investment of time and money necessary to develop such a record, a lake was sought with the potential for as many climate proxies as possible. Existing studies have suggested that such a site would be a relatively small lake with a closed basin and simple morphometry without extensive shallow areas because of non-linear bathymetric effects on sedimentation and lake chemistry. The ideal lake should also have thick, laminated sediments, thereby making possible the development of a high-resolution record.

Kettle Lake, North Dakota, USA, met the criteria for a high-resolution multiproxy study of climate change. Coring indicated over 20 m of laminated postglacial sediment. A preliminary study of a ~600-yr sequence centered on ~8000 cal BP (Clark et al. 2002) indicated high sensitivity of geochemistry, pollen, and charcoal proxies to moisture variations. In addition to this paper, 2 other studies of these cores have been published. Donovan and Grimm (2007) reported the episodic appearance of the unusual guano mineral struvite in the middle Holocene section, which they hypothesize resulted from repeated visitations of large numbers of waterfowl when most other lakes in the region were dry. Brown et al. (2005) carried out spectral analysis on pollen, charcoal, and carbonate (as measured by loss-on-ignition) on the late-Holocene section (past 4500 yr), and they found a dominant 160-yr periodicity with a lower-frequency dampening of the signal. Analyses of mineralogy, charcoal, and pollen have now been completed for the entire core, spanning the past 13,000 yr. Mineralogy and charcoal analyses were conducted on contiguous 1-cm sections of core, for an average temporal resolution of ~6 yr; and pollen analyses were carried out at 2–4 cm intervals, for ~20-yr resolution. High-resolution diatom studies have also been completed. Detailed analyses of these data will be reported elsewhere as will a detailed description of the sedimentology. This paper focuses on the development of an accurate age model to determine the timing of events and to facilitate spectral analyses.

Kettle Lake (48°36′25″N, 103°37′27″W, 605 m asl, 2.2 ha) is located in Williams County in northwestern North Dakota (Figure 1). As its name implies, the lake is a glacial kettle, lying in sandy to gravelly outwash. The lake has a simple morphometry and is ~10 m deep. It lies in a deep depression, and the modern lake level is ~10 m below the surrounding land surface. Additional site details are in Donovan and Grimm (2007).

METHODS

Two overlapping cores were collected from the center of Kettle Lake in July 1996 with a Wright square-rod piston corer, 5 cm in diameter (Wright et al. 1984). The cores were taken from a raft fixed in position by a rope stretched across the lake and by 2 large anchors set at right angles to the rope. The cores labeled A and B were spaced ~1 m apart. Individual core drives were generally 1-m long, and the 2 cores were offset vertically by 50 cm. All depths reported are below the water surface. The mud-water interface was at 10.20 m depth, and the maximum core depth was 32.07 m. Thus, the total core length was 21.87 m. Most of the sediment is finely laminated aragonitic gyttja. The laminations may be annual (varves) in sections, but counts of laminations in the upper part of the core by 3 different people resulted in widely different numbers, and none corresponded with the age span estimated from ^{14}C dating. Both cores were split lengthwise to enable stratigraphic description. The splits were photographed in 15-cm increments, and the photographs were then scanned at 600 dpi and stitched together into single images for each core drive at a 1:1 scale. The laminations facilitated accurate stratigraphic correlation of the 2 cores, and a single composite core spanning the entire sedimentary sequence was constructed. The composite core consists of sections from both cores A and B.

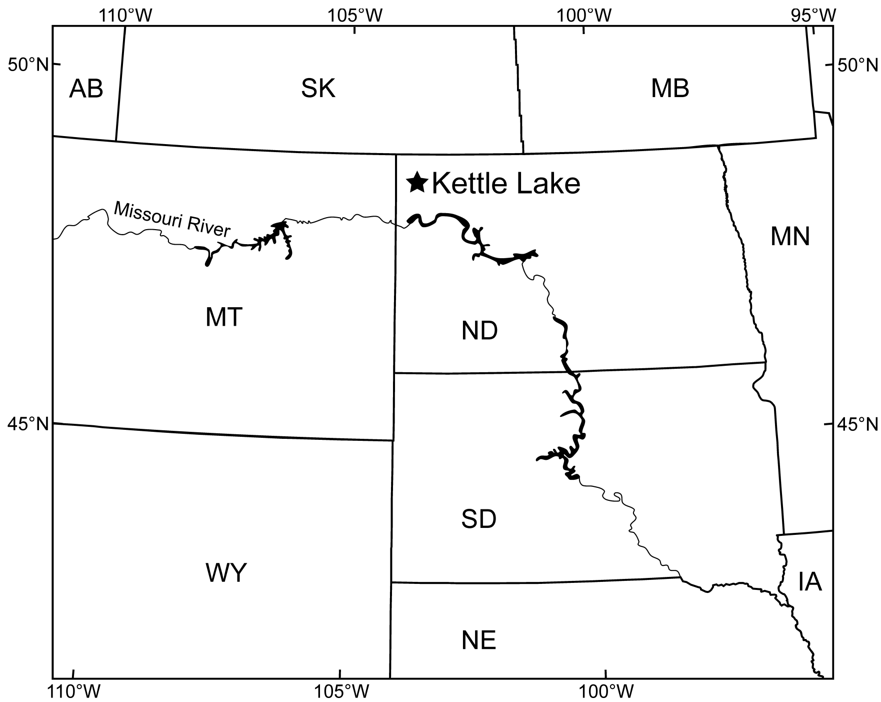

Figure 1 Location of Kettle Lake

The entire composite core was sliced into nominal 1-cm sections, which were stored in vials. The individual 1-cm slices were taken from either core A or B, but not both. The overlapping, unsliced core was retained as an archive. The thicknesses of the slices are "nominal" because an effort was made to maintain the actual thickness of the sediment. Overlapping cores showed complete recovery but with some compression, and thicknesses of sample slices were adjusted accordingly. For example, if a 1-m drive resulted in 90 cm of sediment with complete recovery indicated by the overlapping core, then the sample slices were 0.9 cm in thickness. To keep a record of the stratigraphic locations of core slices, the nominal 1-cm slices were drawn on a hardcopy image of the core as the core was sliced. The digital images of the composite core were then sliced into nominal 4-cm sections, which were stretched to exactly 4 cm with imaging software. These stretched images were re-stitched into 1-m sections and printed at a 1:1 scale. Thus, measurements read off these images with a meter ruler correspond with the nominal sample depths.

Samples for all proxies—pollen, charcoal, diatoms, mineralogy—were taken from the labeled sample vials, thereby ensuring accurate stratigraphic correlation of the various proxies. Larger volumes of sediment to be sieved for materials for accelerator mass spectrometry (AMS) ^{14}C dating were sampled from the unsliced archive core. Stratigraphic correlation was made by visual comparison of the unsliced core with the images of the sliced core. Unique lamination sequences facilitated visual stratigraphic correlation.

For ^{14}C samples, 1-cm slices from 1 split of the archive core were sieved for macrofossils and charcoal. If suitable materials but in an insufficient quantity were found in a sample, additional 1-cm slices were added until an adequate quantity of material was recovered. Non-charcoalized terrestrial plant macrofossils were scarce throughout much of the core, and most of the samples for ^{14}C dating were charcoal. Initially, core sections targeted for dating were sieved until sufficient charcoal was obtained for an age determination. The 1-cm precision charcoal profile developed by Kendrick Brown (Brown et al. 2005) during this study proved invaluable for identifying charcoal peaks, which invariably produced large quantities of charcoal from the matching archive cores; as a consequence, ages obtained from charcoal peaks identified by Brown are from thinner core sections. Samples were first treated with 10% HCl, which disaggregated the carbonate-rich sediment and removed carbonate adhering to charcoal and macrofossils. Sediment was then gently screened through a stack of 0.42-, 0.2-, and 0.15-mm sieves. Charcoal and macrofossils were picked with forceps under a stereomicroscope. Picked samples were repicked at least twice to remove all sediment residues from the charcoal and macrofossil samples. Because the sediment contains lignite—although Kettle Lake had relatively little lignite compared to other northern Great Plains lakes—care was taken to distinguish charcoal from lignite. Under the stereomicroscope, charcoal is typically shiny black and shows cellular structure; whereas lignite, which appears black to the naked eye, is very dark brown and completely amorphous. If any doubt existed, the particle was discarded. Charcoal samples typically consisted of 10 to >100 fragments. Charcoal fragments were typically thin, linear-shaped, and <2 mm in length, characteristic of burned grassland vegetation. Charcoal and macrofossil samples were stored in distilled water with a few drops of 10% HCl to acidify and prevent fungal growth. The wet samples were submitted to the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory. Because the fine herbaceous charcoal fragments tend to turn to dust if dried, it was easier for the ^{14}C laboratory to handle them wet. The disadvantage is that the samples could not be weighed, so determination of sufficient quantity (~1 mg) had to be made by eye.

^{14}C ages were calibrated to calendar years with the BCal calibration program (Buck et al. 1999; http://bcal.sheffield.ac.uk), using the IntCal09 calibration curve (Reimer et al. 2009). BCal uses Bayesian statistics with an option for an *a priori* assumption that ages higher in the core are younger than ages lower in the core. When ages with overlapping calibrated probability distributions occur, BCal produces posterior probability distributions with non-overlapping modes, essentially wiggle-matching the ages to the calibration curve. Outlier analysis is an option within BCal. The calibrated ages from BCal were compared with calibrations from CALIB 6.0 (Stuiver and Reimer 1993) using the IntCal09 calibration curve, which makes no *a priori* assumptions constraining the calibration. CALIB was also used to calibrate ages that were not used for the age model. Although some of the rejected ^{14}C ages may be statistical outliers, most of these ages are probably analytically accurate but are on redeposited materials.

Outlier ^{14}C ages may be either too young or too old. Causes for ages being too young include laboratory contamination or material being dragged down alongside the core barrel. For ages that are too old, the most likely cause is redeposition of older material. Ages that BCal identified as outliers with >95% probability would probably have been rejected as outliers by visual examination. The Bayesian assumption is that ages higher in the sequence should be younger. However, in contrast to tree rings, where outer rings must be younger than inner rings, plant macrofossils have potential taphonomic complications. The age of the macrofossil is not necessarily the age of deposition. Delicate or short-lived materials, such as herbaceous charcoal, seeds, and needles, are less likely to have an inbuilt age as, for example, wood or wood charcoal from long-lived trees may (Gavin 2001) and are less likely to have persisted long on the landscape before deposition in lake sediment. However, within-lake redepositional processes may move even delicate or short-lived materials. Large-scale redeposition events may be evident stratigraphically. However, small-scale redeposition events may not be so clearly visible or evident, especially for events that redeposit materials perhaps only a few decades or centuries old. Consequently, criteria more stringent than BCal were applied to the identification of outliers and stratigraphically reversed ^{14}C ages: reversed ages were not accepted if their 2-σ ranges as determined by CALIB did not overlap with stratigraphically adjacent ages.

RESULTS

A large slump deposit 156 cm in thickness with sharply defined borders occurs from 2358 to 2514 cm (hereafter called the "big slump"). The slumped material does not have the fine laminations of sediment above and below, but rather consists of nearly massive, banded sediment. The bands are essentially horizontal and could be traced between the 2 cores, but were more variable than the fine laminations of the primary sediment. The nature of the slumped material and the abundance of littoral plant macrofossils (especially *Schoenoplectus* and *Chenopodium* seeds) suggest that this sediment was originally deposited in shallower water before slumping into the deeper portion of the basin. In addition to this slump, several strata originating from rapidly deposited debris flows or small landslides are evident. These strata consist of either poorly sorted layers of sand, which may have originated from the beach area or from the steep sides of the basin, or from sediments originally deposited in shallower water, which are characterized by laminations that are either contorted or lie at steep angles. The depths of these strata are 2560–2571 cm, 2657–2669 cm, 2686–2700 cm, 2717–2780 cm, 2981–3010 cm, 3058–3081 cm, 3090–3106 cm, and 3109–3125 cm (shown as gray bars in Figure 5). The sediment at the base of the core (3157–3207 cm) is sandy and was probably deposited very rapidly immediately after the lake formed. The bottom 4 layers listed above are sandy and may represent debris flows or landslides associated with repeated collapse of the basin margins as the underlying ice melted out.

A total of 53 ^{14}C ages were obtained from Kettle Lake (Table 1). Many of the AMS-dated samples are charcoal. Charcoal is necessarily of terrestrial origin, and most of the charcoal from Kettle Lake consists of fragile fragments derived from herbaceous prairie vegetation, which are unlikely to have resided long in the soils before being transported to the lake. Lake-sediment charcoal from herbaceous prairie plants has proven to provide reliable ages (Grimm et al. 2009). For instance, 2 ages from the same depth at Moon Lake, North Dakota, one on charcoal (5420 ± 60 BP, CAMS-6823) and the other on an *Ambrosia* seed (5410 ± 70 BP, CAMS-6824), differ by only 10 yr (Laird et al. 1996a). Two ages from overlapping levels in the Kettle Lake core also demonstrate the reliability of charcoal ages. An age on *Chenopodium* seeds (5950 ± 35 BP, CAMS-105840) from a 1-cm section (2258.5–2259.5 cm) overlaps an age on charcoal (5900 ± 35 BP, CAMS-105839) from a 3-cm section (2256.5–2259.5 cm). As determined by CALIB 6.0, the ages overlap at the 1-σ level. As determined by BCal, the 68% highest posterior density (HPD) ranges overlap slightly, and the 95% HPD ranges overlap substantially (Table 1). The slightly older age on seeds is consistent with their slightly greater depth.

Although all dated charcoal and macrofossil samples used for the Kettle Lake age model are of terrestrial origin, which eliminates the problem of hardwater error, a sample of unidentified organic detritus, presumably from aquatic macrophytes (CAMS-38086, 2680 ± 100 BP), and a charcoal sample (CAMS-38087, 2080 ± 50 BP) from the same level were dated to assess the magnitude of hardwater error. Not unexpectedly, the detritus is 600 ^{14}C yr older than the charcoal sample (Table 1). This magnitude of hardwater error at ~2000 cal BP is typical of Great Plains lakes (Grimm et al. 2009), and the detritus sample was rejected *a priori* for the age model. Two other ages from near the bottom of the sedimentary sequence were also rejected *a priori*, CAMS-113586 (13,080 ± 45 BP) and CAMS-113587 (29,230 ± 230 BP). These ages were on wood-charcoal samples from the sand layer at 2981–3010 cm, and they clearly represent redeposited materials.

Five ages were obtained from the big slump. These ages, although out of sequence, are all in stratigraphic order within the slump, indicating that the slumped material is essentially an intact slab. The slump and these 5 ages were removed from the age model. The remaining 45 ^{14}C ages were cali-

Table 1 AMS radiocarbon dates from Kettle Lake.

CAMS-nr[a]	Depth (cm)	^{14}C age	Median age	cal BP 95% range[b]	Material
41153	1096–1098	570 ± 40	598[c]	651–521	2 *Schoenoplectus* seeds
105787	1119.5–1120.5	125 ± 40	128[c]	277– –3	Charcoal
38080	1138–1144	1380 ± 90	1295[c]	1512–1073	Charcoal
41154	1158–1164	680 ± 50	603	681–550	Charcoal, *Schoenoplectus* seed
38081	1208–1212	720 ± 60	680	744–570	Charcoal
38082	1243–1249	870 ± 60	776	895–692	Charcoal
41155	1289–1295	1250 ± 50	1188[c]	1282–1066	Charcoal, *Schoenoplectus* seed
32010	1316–1317	960 ± 50	879	965–784	Charcoal
38083	1356–1360	1240 ± 70	1166	1292–1001	Charcoal
38084	1393.7–1395.7	1480 ± 70	1380	1525–1288	Charcoal, *Typha* seed
38085	1457–1458	1770 ± 50	1685	1818–1563	*Rosa* seed
32009	1507–1512	1960 ± 70	1906	2038–1742	Charcoal, *Schoenoplectus* seed, *Chenopodium* seed
38086	1540–1542	2680 ± 100	2802[c]	3065–2487	Organic detritus
38087	1540–1544	2080 ± 50	2059	2295–1930	Charcoal
105837	1589.5–1590.5	2320 ± 40	2340	2464–2160	Charcoal, *Schoenoplectus* seed
57143	1688–1690	2580 ± 40	2565	2744–2463	Charcoal
57144	1724–1727	2510 ± 50	2671	2751–2535	Charcoal
57145	1766–1770	2880 ± 50	3015	3205–2870	Charcoal
105838	1870.5–1871.5	3195 ± 35	3416	3479–3351	Charcoal
113569	1907.5–1908.5	3425 ± 35	3666	3807–3575	Charcoal
113570	1931.5–1932.5	3480 ± 35	3769	3848–3684	Charcoal
113571	2007.5–2008.5	3820 ± 35	4213	4406–4092	Charcoal
105788	2058.5–2059.5	4200 ± 45	4728	4851–4582	Charcoal
113572	2125.5–2126.5	4765 ± 35	5513	5588–5332	Charcoal
113573	2151.5–2152.5	4860 ± 35	5605	5660–5487	Charcoal
113574	2179.5–2180.5	5305 ± 35	6085	6189–5950	Charcoal and *Schoenoplectus* seeds
105839	2256.5–2259.5	5900 ± 35	6709	6786–6653	Charcoal
105840	2258.5–2259.5	5950 ± 35	6786	6887–6713	*Chenopodium* seeds
113575	2273.5–2275.5	5005 ± 35	5736[c]	5891–5651	Charcoal
113576	2321.5–2322.5	6275 ± 40	7207	7274–7027	Charcoal
116252	2349.5–2352.5	6365 ± 40	7304	7419–7248	Charcoal
113577	2377.5–2378.5	7490 ± 35	8323[c]	8383–8201	15 *Schoenoplectus* seeds
116253	2417.5–2419.5	7765 ± 35	8547[c]	8601–8449	Charcoal
105789	2424.5–2425.5	7880 ± 40	8683[c]	8974–8585	Charcoal
113581	2458.5–2459.5	8160 ± 35	9092[c]	9252–9011	Charcoal
113582	2488.5–2489.5	8785 ± 35	9801[c]	10,115–9632	10.5 *Schoenoplectus* seeds
116254	2514.5–2515.5	6720 ± 35	7587	7662–7512	2 *Cenchrus longispinus* seeds
116255	2538.5–2539.5	6900 ± 35	7727	7822–7666	Charcoal
105841	2558.5–2559.5	7035 ± 40	7870	7946–7789	Charcoal
57140	2581.8–2585.4	7120 ± 40	7955	8016–7868	Charcoal
57141	2609.7–2613.5	7410 ± 50	8251	8368–8058	Charcoal, Poaceae seed, Cyperaceae seed
57142	2633.8–2638.0	7770 ± 50	8546	8637–8422	Charcoal
105790	2715.5–2716.5	8280 ± 40	9252	9391–9128	Charcoal
105791	2795.5–2796.5	8305 ± 40	9361	9457–9249	Charcoal
113583	2830.5–2833.5	8805 ± 40	9837	10,136–9679	Charcoal
113584	2915.5–2916.5	9295 ± 35	10,498	10,586–10,301	Charcoal
113585	2934.5–2935.5	9530 ± 35	10,844	11,076–10,699	Charcoal
105792	2961.5–2962.5	9685 ± 40	11,138	11,217–10,870	Wood
113586	2990.5–2991.5	13,080 ± 45	15,820[c]	16,413–15,215	Charcoal
113587	3005.5–3007.5	29,230 ± 230	33,910[c]	34,566–33,267	Charcoal
25277	3052.75–3053.25	11,080 ± 80	12,966[c]	13,142–12,710	Wood

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Table 1 AMS radiocarbon dates from Kettle Lake. *(Continued)*

CAMS-nr[a]	Depth (cm)	^{14}C age	Median age	cal BP 95% range[b]	Material
105793	3053.5–3054.5	10,720 ± 45	12,630	12,725–12,556	Wood
113588	3172.5–3176.5	11,030 ± 40	12,874	13,071–12,705	*Picea* needles

[a]All dates from the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory.

[b]The ranges are 95% highest posterior density regions for dates calibrated by BCal or the 2-σ ranges for dates calibrated with CALIB 6.0 (see text for references). Dates are calibrated with BCal unless otherwise indicated by note c.

[c]Date calibrated with CALIB 6.0.

brated with BCal. A uniform probability of 80–60 cal BP was set for the top of the sequence. This age is just before the first appearance of *Salsola* pollen. *Salsola* is an introduced genus that reached North Dakota around AD 1890 (Dewey 1894).

Because ages with overlapping probability distribution functions influence each other in the calibration, BCal must then be rerun with the outliers removed. Run 1 identified 2 ages with a 100% outlier probability, which were eliminated (Table 2). Two samples immediately above CAMS-113575 (which had 100% outlier probability) had 99% outlier probabilities in Run 1. After the removal of CAMS-113575 in Run 2, the calibrated ages on these 2 samples had only 4% outlier probabilities. The third age from the top, CAMS-38080, had 100% outlier probability in Run 1, and the 2 ages above this one had outlier probabilities of 99% and 52%. Removal of CAMS-38080 did not improve the outlier status of these 2 ages, which still had outlier probabilities of 99% and 53%. One of these ages was eliminated in Run 3 and the other in Run 4. Removal of either one reduces the outlier probability of the other to 3–4%. However, retention of either of these ages in the age model produces a sharp kink in the age-depth relationship, whereas the sediment shows no evidence of irregular sedimentation. Elimination of the top 3 problematic ^{14}C ages in Run 5 produces a regular curve that extends from the *Salsola* rise to the fourth age determination and then through a long series of calibrated ages (Figures 3 and 5).

Three reversals occur in the uncalibrated ^{14}C chronology for which BCal does not identify an outlier at the 95% level (Figure 2). The ^{14}C age 1250 ± 50 (CAMS-41155) is older than the 2 ages below it; BCal determined a 35% outlier probability for this age and a 61% outlier probability for the age immediately below. However, the 2-σ CALIB ranges of these 2 ages do not overlap. BCal forms prominent peaks in the calibrated probability density functions (pdfs) within small CALIB peaks that are outside the 2-σ ranges (Figure 2). Thus, CAMS-41155 was rejected as an outlier. The age 11,080 ± 60 (CAMS-25277) is older than the 2 ages below it; BCal determined only a 19% outlier probability for this age and a 15% probability for the age below it. However, because the 2-σ range of this age does not overlap the age below it and because it occurs within a section of the core with several stratigraphically identified redeposition events, it was rejected. The ages 2580 ± 40 (CAMS-57143) and 2510 ± 50 (CAMS-57144) are stratigraphically reversed, but their 2-σ CALIB ranges overlap and are multimodal. BCal amplifies or reduces the probabilities within the overlapping CALIB modes such that the resultant pdf medians are no longer reversed (Figure 2).

If the probability distributions of 2 ages calibrated with no prior assumptions with CALIB do not overlap, then the HPD regions from BCal are essentially identical. However, when the probability distributions do overlap, the ages can constrain each other, and the BCal HPD regions differ from CALIB (Figures 3 and 4). Good examples are the following pairs of ages: 2580 ± 40 and 2510 ± 50 BP described above and 8280 ± 40 and 8305 ± 40 BP (Figures 3 and 4). The first of these pairs is reversed stratigraphically; however, BCal constrains the HPD regions to modes or portions of

Table 2 BCal runs.

CAMS-nr	Depth (cm)	^{14}C age (BP)	Prior outlier prob	Run 1 post outlier prob	Run 2 post outlier prob	Run 3 post outlier prob	Run 4 post outlier prob	Run 5 post outlier prob
41153	1096–1098	570 ± 40	5%	99%	99%	—	4%	—
105787	1119.5–1120.5	125 ± 40	5%	52%	53%	3%	—	—
38080	1138–1144	1380 ± 90	5%	100%	—	—	—	—
41154	1158–1164	680 ± 50	5%	5%	4%	4%	4%	4%
38081	1208–1212	720 ± 60	5%	5%	4%	4%	4%	4%
38082	1243–1249	870 ± 60	5%	3%	3%	3%	3%	3%
41155	1289–1295	1250 ± 50	5%	35%	—	—	—	—
32010	1316–1317	960 ± 50	5%	61%	4%	4%	4%	4%
38083	1356–1360	1240 ± 70	5%	3%	3%	3%	3%	3%
38084	1393.7–1395.7	1480 ± 70	5%	4%	4%	4%	4%	4%
38085	1457–1458	1770 ± 50	5%	4%	4%	4%	4%	4%
32009	1507–1512	1960 ± 70	5%	0%	0%	0%	—	0%
38087	1540–1544	2080 ± 50	5%	4%	4%	4%	4%	4%
105837	1589.5–1590.5	2320 ± 40	5%	11%	11%	11%	11%	11%
57143	1688–1690	2580 ± 40	5%	14%	14%	14%	14%	14%
57144	1724–1727	2510 ± 50	5%	4%	4%	3%	3%	3%
57145	1766–1770	2880 ± 50	5%	4%	4%	4%	4%	4%
105838	1870.5–1871.5	3195 ± 35	5%	5%	5%	5%	5%	5%
113569	1907.5–1908.5	3425 ± 35	5%	4%	4%	4%	4%	4%
113570	1931.5–1932.5	3480 ± 35	5%	3%	3%	3%	3%	3%
113571	2007.5–2008.5	3820 ± 35	5%	4%	4%	4%	4%	4%
105788	2058.5–2059.5	4200 ± 45	5%	5%	5%	5%	5%	4%
113572	2125.5–2126.5	4765 ± 35	5%	4%	4%	4%	4%	4%
113573	2151.5–2152.5	4860 ± 35	5%	7%	7%	7%	7%	7%
113574	2179.5–2180.5	5305 ± 35	5%	3%	3%	3%	3%	3%
105839	2256.5–2259.5	5900 ± 35	5%	99%	4%	4%	4%	4%
105840	2258.5–2259.5	5950 ± 35	5%	99%	4%	4%	4%	4%
113575	2273.5–2275.5	5005 ± 35	5%	100%	—	—	—	—
113576	2321.5–2322.5	6275 ± 40	5%	5%	5%	5%	5%	5%
116252	2349.5–2352.5	6365 ± 40	5%	4%	4%	4%	4%	4%
116254	2514.5–2515.5	6720 ± 35	5%	6%	6%	6%	6%	6%
116255	2538.5–2539.5	6900 ± 35	5%	4%	4%	4%	4%	4%
105841	2558.5–2559.5	7035 ± 40	5%	3%	3%	3%	3%	3%
57140	2581.8–2585.4	7120 ± 40	5%	5%	5%	5%	5%	5%
57141	2609.7–2613.5	7410 ± 50	5%	4%	4%	4%	4%	4%
57142	2633.8–2638.0	7770 ± 50	5%	5%	5%	5%	5%	5%
105790	2715.5–2716.5	8280 ± 40	5%	4%	4%	4%	4%	4%
105791	2795.5–2796.5	8305 ± 40	5%	3%	3%	3%	3%	3%
113583	2830.5–2833.5	8805 ± 40	5%	4%	4%	4%	4%	4%
113584	2915.5–2916.5	9295 ± 35	5%	5%	5%	5%	5%	5%
113585	2934.5–2935.5	9530 ± 35	5%	4%	4%	4%	4%	4%
105792	2961.5–2962.5	9685 ± 40	5%	4%	5%	5%	5%	5%
25277	3052.75–3053.25	11,080 ± 80	5%	19%	—	—	—	—
105793	3053.5–3054.5	10,720 ± 45	5%	15%	5%	5%	5%	5%
113588	3172.5–3176.5	11,030 ± 40	5%	4%	4%	4%	4%	4%

modes that do not overlap, and thereby produces a monotonically consistent sequence of calibrated ages. The second pair of ages is not reversed, but because their unconstrained pdfs overlap, BCal constrains the HPD regions to narrower ranges, and thereby improves the accuracy of the age model.

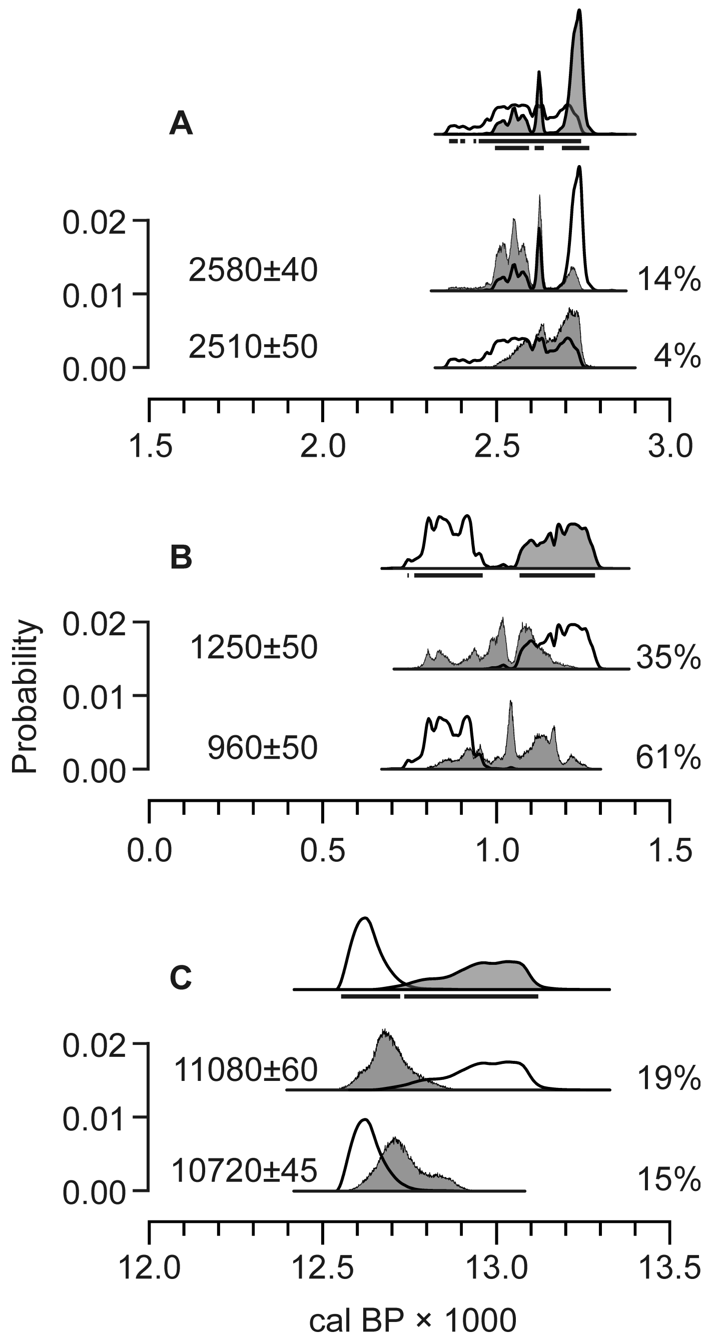

Figure 2 Stratigraphically reversed ^{14}C ages not identified as outliers with BCal at the 95% level. For each pair, the probability density functions (pdfs) of the 2-σ calibrated ages determined with CALIB 6.0 are shown to the right of the letters (A, B, C). The 2-σ age ranges are indicated by the horizontal bars. In A, the 2-σ ranges substantially overlap, whereas in B and C they do not. Below the CALIB pdfs are shown the BCal pdf of each age (shaded) with the CALIB pdf (solid line). To the right of the BCal pdfs are the percent outlier probability as determined by BCal.

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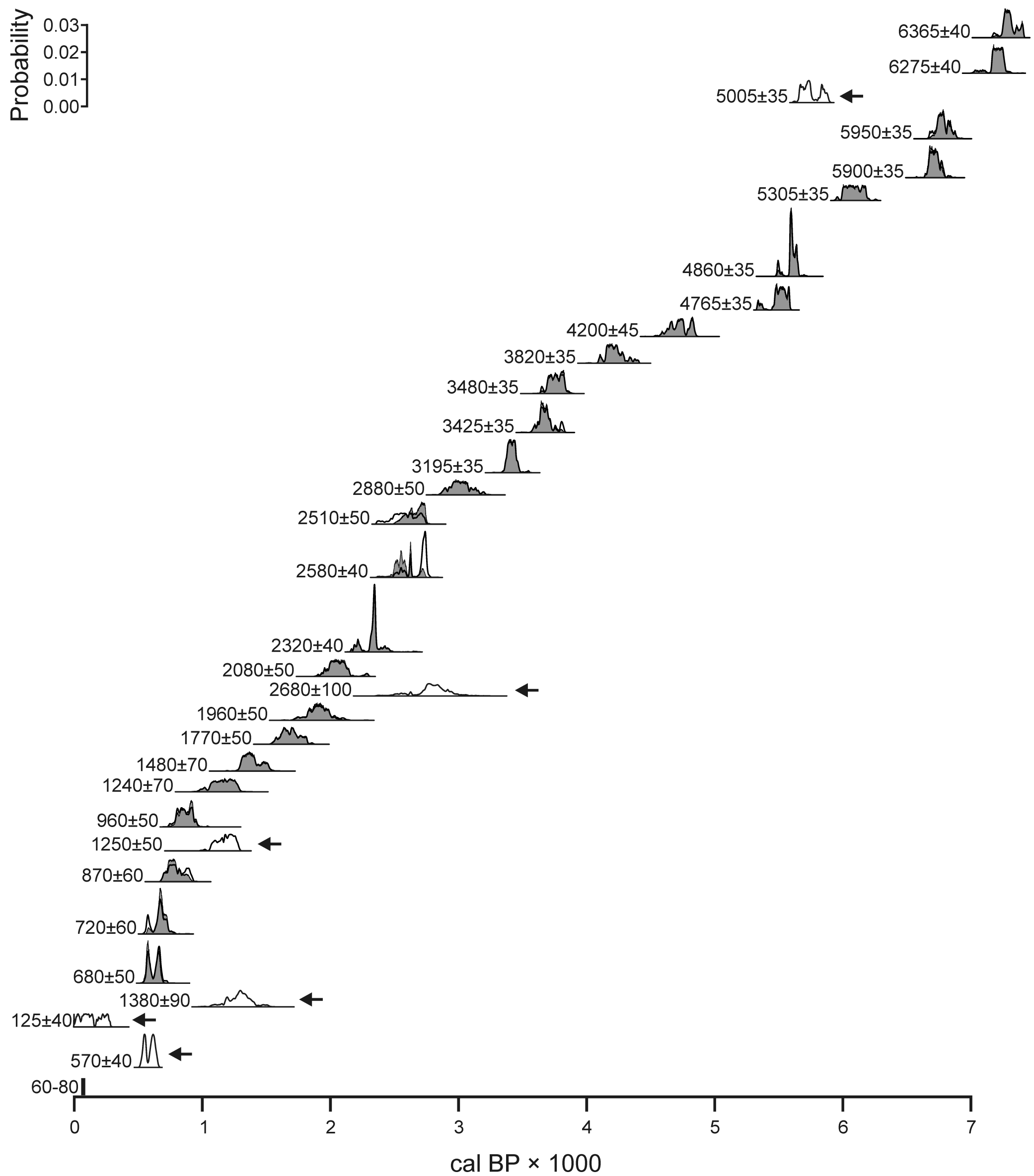

Figure 3 Probability density functions (pdfs) for the calibrated ^{14}C ages from Kettle Lake above the big slump. CALIB pdfs are shown as black lines; BCal pdfs are shaded. If the 2 pdfs are not congruent, BCal has adjusted the pdf based on the *a priori* assumption that ages higher in the sequence must be younger. If the CALIB pdfs for 2 adjacent ^{14}C ages do not overlap, the BCal pdfs are essentially identical. However, when the CALIB pdfs do overlap, the ages can constrain each other, and the BCal pdfs differ from CALIB. ^{14}C determinations shown with only a CALIB pdf (indicated by arrows) were rejected as outliers (see text).

BCal Run 5 on the final set of 39 accepted ^{14}C ages produced a series of calibrations with monotonically increasing median probabilities with depth (Table 1). An age model was developed from this series of calibrated ages by linear interpolation between the calibrated medians (Figure 5). With so

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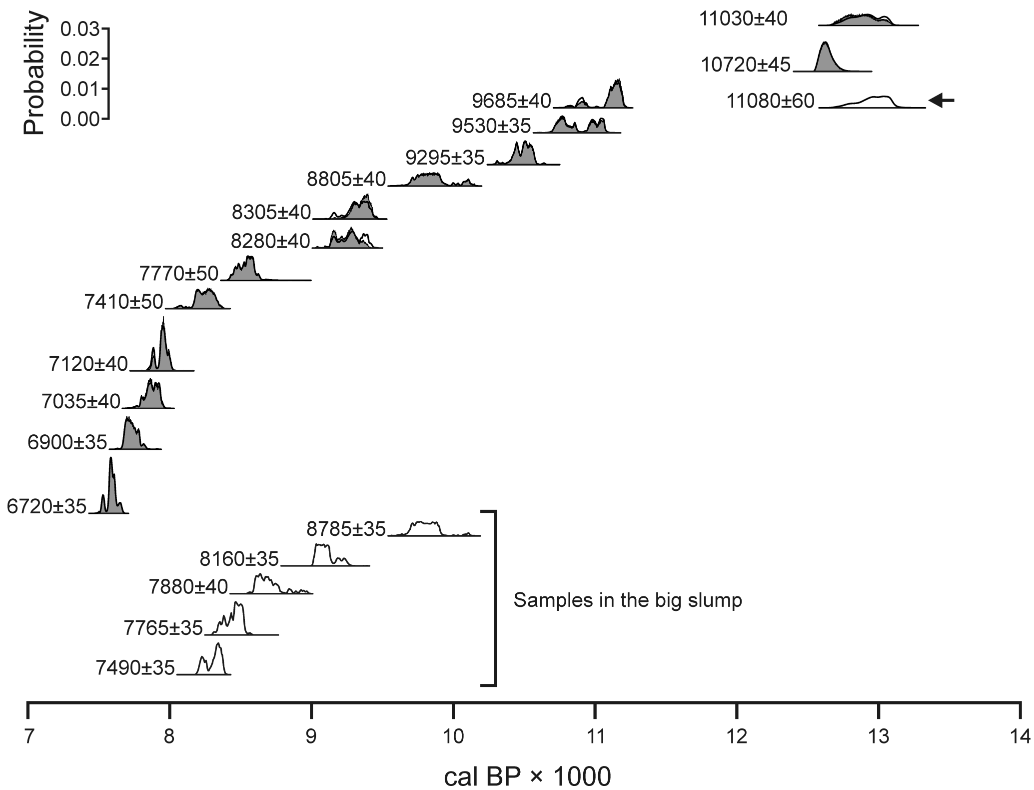

Figure 4 Probability density functions for the calibrated ^{14}C ages from Kettle Lake within and below the big slump. Because stratigraphic superposition could not be assumed *a priori* for samples in the slump, they were calibrated with CALIB only. For ^{14}C determinations below the slump, see the caption for Figure 3.

many age determinations, fitting a smoothed curve, such a spline, results in very little difference from the linear model in the interpolated ages. The slump sections were removed, and contiguous depths were assigned before developing the age model. ^{14}C ages within the big slump were calibrated with CALIB 6.0. Because these ages formed a consistent monotonic sequence, an age model was also developed for the slump section (Figure 5).

^{14}C ages closely bracket the big slump, and these ages are stratigraphically consistent with ages above and below. The age model indicates a gap of 263 yr: 7587–7324 cal BP (Figure 5). The lower bracketing age of 7662–7512 cal BP (95% HPD) at 2514.5–2515.5 cm is immediately below the slump. The upper bracketing age of 7419–7248 cal BP (95% HPD) at 2349.5–2352.5 cm is 7 cm above the slump. According to the age model, the time interval between the upper bracketing age and the top of the slump is 20 yr, and the time interval between the 2 bracketing ages is 283 yr (Figure 6). Thus, the estimate for the missing section of sediment is ~260 yr. The sudden slumping of 1.5 m of sediment would have disturbed the watery, unconsolidated surficial sediments, and the appearance of a hiatus in the record is therefore not surprising. Based on the deposition time of sediment below the slump, the gap in the sedimentary sequence is estimated to be ~43 cm. The smaller debris flows lower in the core, several of which are well constrained by ^{14}C ages, including the largest of these at 2717–2780 cm, do not appear to be associated with significant hiatuses in the record.

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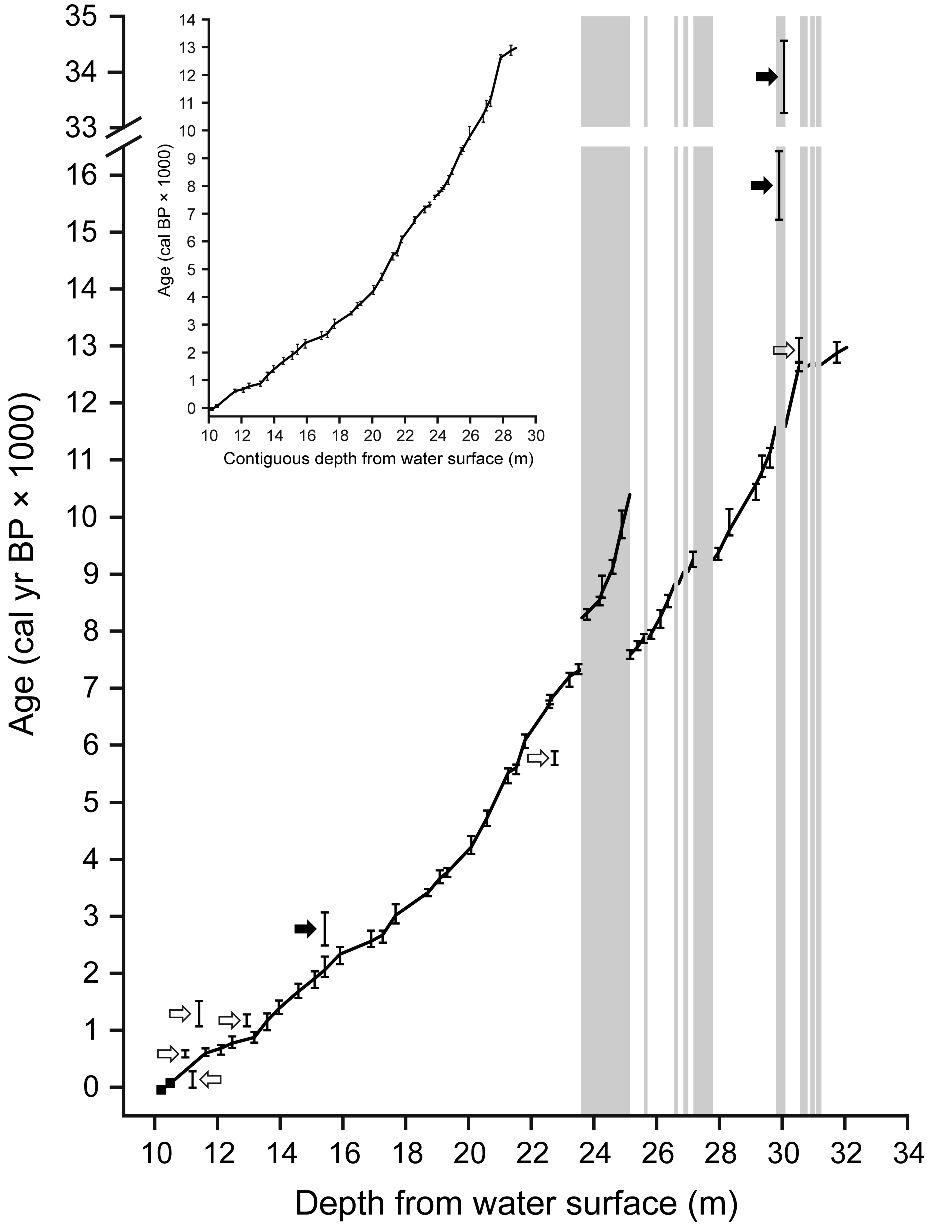

Figure 5 Age model for Kettle Lake. Calibrated ^{14}C ages are shown with 95% posterior probability densities (BCal) or 2-σ ranges (CALIB 6.0). The age model is the black line connecting the median probabilities of the calibrated ages. Ages above and below the big slump were calibrated with BCal. Ages within the slump were calibrated with CALIB. Black arrows indicate ^{14}C determinations rejected *a priori* as outliers. Hollow arrows indicate ages rejected by the BCal outlier analysis or by non-overlapping 95% probability ranges as determined by CALIB. The ^{14}C ages rejected for the age model were calibrated with CALIB. In the inset, the slump, debris flow, or landslide deposits were removed before developing the age model. Estimated ages were not assigned to sediments within these smaller slumps. The black squares in the lower left corner are the fixed ages for the top of the core and the rise in *Salsola* pollen.

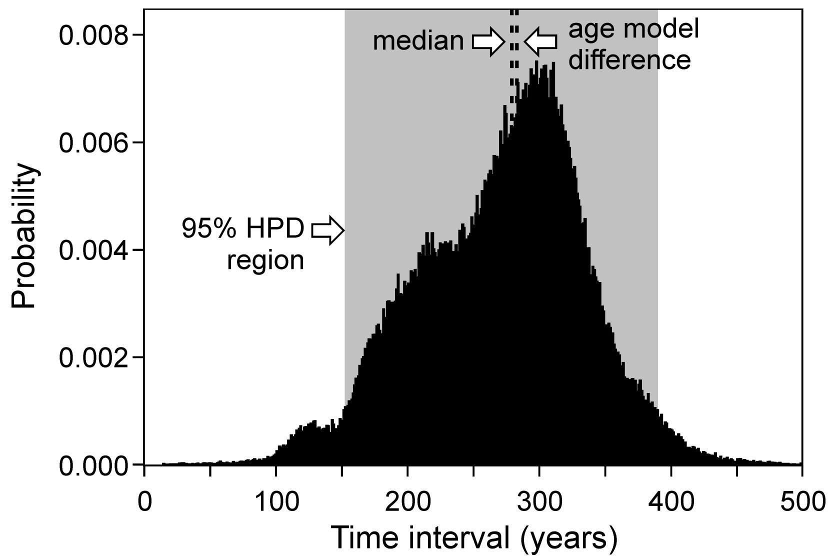

Figure 6 Posterior probability density function generated by BCal for the time elapsed between the 2 ^{14}C ages bracketing the big slump. The median probability is 279 yr. The age-model estimate for the difference between the 2 levels is 283 yr, which is the difference between the medians of the 2 calibrated ages.

DISCUSSION

The large number of calibrated ^{14}C ages from Kettle Lake forms the basis of a well-constrained age model. The observed deposition time (yr/cm), changes gradually with small variations, but is quite constant on a millennial timescale. An inflection point occurs at about 4500 cal BP, when deposition time decreases, either because of increased sedimentation or decreased compaction or both. Removal of slump deposits produces a complete, contiguous Holocene sequence, except for ~43 cm and ~260 yr at the big slump.

The laminated sediments of Kettle Lake along with the large number of ^{14}C ages greatly aid in the identification of slump, debris flow, or landslide deposits. A single age from the initial series of samples submitted to the AMS ^{14}C laboratory appeared to be a classic "reversed" date. Close inspection of the sediment, along with 4 additional ^{14}C ages, indicated that the reversed age was in a slump facies. These ages are analytically accurate but are on materials stratigraphically out of sequence.

The 2 ages in the sand layer at 2981–3010 cm are also reversed, but they are probably on redeposited materials and are also not statistical outliers. The older of these 2 ages (29,230 ± 230 BP, CAMS-113587) is clearly too old based on regional glacial geology (Clayton and Moran 1982); however, the younger of these ages (13,080 ± 45 BP, CAMS-113586) is not implausibly old, and might have been accepted if not for other younger bracketing ages. In contrast to the delicate fragments of herbaceous charcoal dated from most of the core, these 2 ages were on chunky, woody charcoal. They reinforce conclusions from other studies that ages on wood charcoal are frequently too old (Barnekow et al. 1998; Gavin 2001; Oswald et al. 2005). Wood may be from a long-lived tree, and wood charcoal can persist for long periods on the landscape before ultimately being deposited in lake sediments.

A common practice is to simply reject reversed or "too old" ages when developing age models for lacustrine sediments. However, these ages may not simply be statistical anomalies but instead may be an indication and warning of sedimentary discontinuities, which require further investigation. In the case of laminated sediments such as those from Kettle Lake, identification of slump facies is fairly straightforward. However, with massive nondescript sediments identification of slumps may be difficult, and additional ^{14}C ages may be necessary to resolve apparently anomalous out-of-sequence ages. Plant macrofossils and charcoal suitable for AMS ^{14}C dating may be redeposited. If redeposited, the critical question is whether only the dated specimens or the entire sediment package was redeposited. In the case of Kettle Lake, entire sedimentary units were redeposited, and therefore these have been removed to produce a continuous sequence.

Although most of the reported ^{14}C ages have comparatively narrow standard deviations (most are ±35–70 yr), the 95% probability ranges of individual calibrated ages are on the order of 200–400 yr or greater. However, these confidence limits pertain to the absolute estimated age of any particular event. Given the evidence for regular sedimentation—after redeposited facies have been removed—the estimates of deposition time should be fairly accurate, permitting decadal-scale interpretations of cyclical or periodic phenomena, albeit not as accurately fixed in time.

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