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Radiocarbon ages and age models for the past 30,000 years in Bear Lake, Utah and Idaho

Steven M. Colman
Large Lakes Observatory and Department of Geological Sciences, University of Minnesota Duluth, Minnesota 55812, USA

Joseph G. Rosenbaum
U.S. Geological Survey, MS 980, Box 25046, Denver Federal Center, Denver, Colorado 80225, USA

Darrell S. Kaufman
Department of Geology, Northern Arizona University, Flagstaff, Arizona 86011, USA

Walter E. Dean
U.S. Geological Survey, MS 980, Box 25046, Denver Federal Center, Denver, Colorado 80225, USA

John P. McGeehin
U.S. Geological Survey, National Center MS 955, Reston, Virginia 20192, USA

ABSTRACT

Radiocarbon analyses of pollen, ostracodes, and total organic carbon (TOC) provide a reliable chronology for the sediments deposited in Bear Lake over the past 30,000 years. The differences in apparent age between TOC, pollen, and carbonate fractions are consistent and in accord with the origins of these fractions. Comparisons among different fractions indicate that pollen sample ages are the most reliable, at least for the past 15,000 years. The post-glacial radiocarbon data also agree with ages independently estimated from aspartic acid racemization in ostracodes. Ages in the red, siliclastic unit, inferred to be of last glacial age, appear to be several thousand years too old, probably because of a high proportion of reworked, refractory organic carbon in the pollen samples.

Age-depth models for five piston cores and the Bear Lake drill core (BL00-1) were constructed by using two methods: quadratic equations and smooth cubic-spline fits. The two types of age models differ only in detail for individual cores, and each approach has its own advantages. Specific lithological horizons were dated in several cores and correlated among them, producing robust average ages for these horizons. The age of the correlated horizons in the red, siliclastic unit can be estimated from the age model for BL00-1, which is controlled by ages above and below the red, siliclastic unit. These ages were then transferred to the correlative horizons in the shorter piston cores, providing control for the sections of the age models in those cores in the red, siliclastic unit.

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These age models are the backbone for reconstructions of past environmental conditions in Bear Lake. In general, sedimentation rates in Bear Lake have been quite uniform, mostly between 0.3 and 0.8 mm yr^{-1} in the Holocene, and close to 0.5 mm yr^{-1} for the longer sedimentary record in the drill core from the deepest part of the lake.

INTRODUCTION

A major goal of our research at Bear Lake was to reconstruct a history of environmental change in the basin. To this end, a wide variety of paleoenvironmental proxies were measured (Rosenbaum and Kaufman, this volume). Changes in these different proxies with time form the basis for the paleoenvironmental reconstruction for Bear Lake. Of course, the other necessary component of any environmental history is an accurate chronology. An accurate chronology depends on many variables, including the sample material, analytical accuracy and precision, and the way in which continuous age models are constructed.

Here we report the results of radiocarbon analyses of sediments in several cores from Bear Lake. In the absence of macrofossils, we analyzed several different fractions of the bulk sediments and compared the resulting ages with each other and with independently estimated ages derived from amino acid analyses in ostracodes. We next rejected certain ages as outliers for several different reasons, and developed depth scales that account for multiple, overlapping cores and loss of surface materials. Finally, we developed continuous age models for each core, using multiple fit methods, to form the chronological framework for other paleoenvironmental studies.

A preliminary version of the present study, confined to the 1996 piston cores, was published as a U.S. Geological Survey Open-File Report (Colman et al., 2005). Some of the radiocarbon ages discussed here were used in the age model for the long (120 m) Bear Lake drill core (Colman et al., 2006), as discussed later in this paper. No other studies of the chronology of Bear Lake cores exist, except for a study of recent sedimentation by ^{210}Pb methods (Smoak and Swarzenski, 2004).

METHODS

Coring

A variety of cores were obtained at several different times in Bear Lake, as described by Rosenbaum and Kaufman (this volume). Detailed radiocarbon dating and age modeling were conducted for five of these core sites: BL96-1, BL96-2, BL96-3, BL02-3, and BL02-4 (Fig. 1). Radiocarbon ages for other cores and materials from Bear Lake are reported in Table 1, but are not discussed further here because these cores were taken in shallow water and many of them contain discontinuities or unconformities. The five cores from relatively deep water were analyzed in

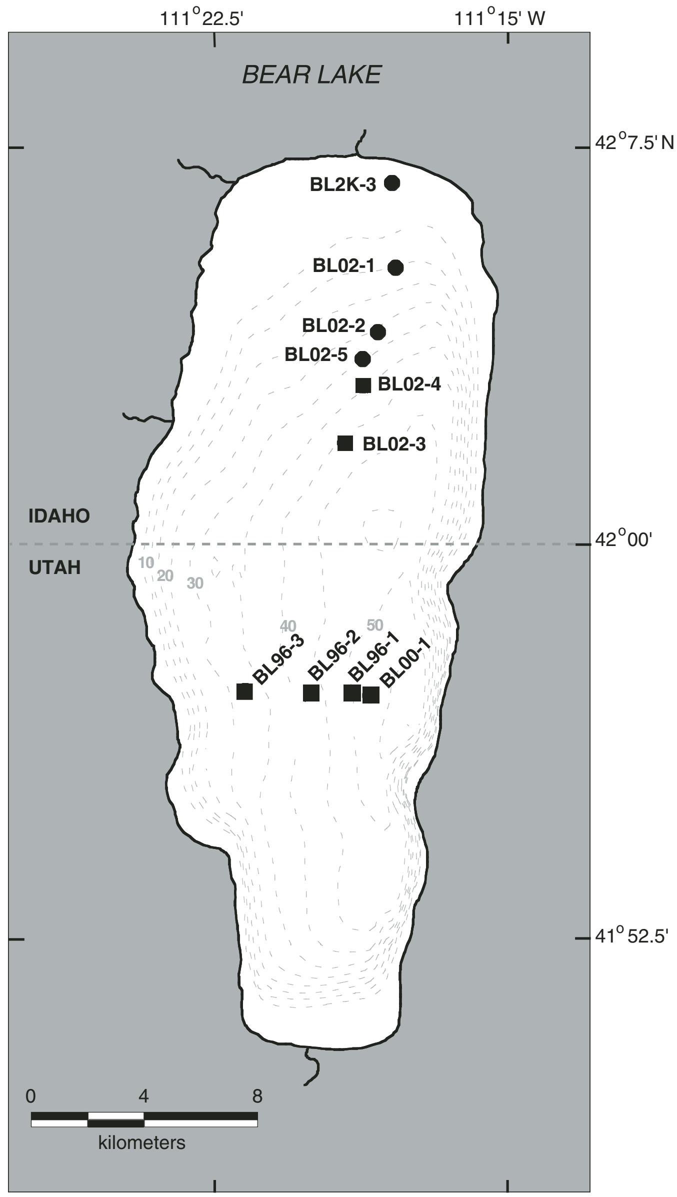

Figure 1. Map of Bear Lake, showing the bathymetry of the lake and location of the cores collected in this study. Cores from sites discussed here in detail are indicated by squares. Core BLR2K-3 is located in a shallow lake (Mud Lake) north of Bear Lake. Bathymetric contour interval 5 m, beginning at 10 m.

TABLE 1. RADIOCARBON MEASUREMENTS MADE IN THIS STUDY

Core (bold) and sample designation	Corrected total depth (cm)[a]	Material	$\delta^{13}C$ (per mil)[b]	Age (^{14}C yr)	Error (1σ yr)	Lab number[c]	Calibrated age (cal yr B.P.)[d]	Calibrated 1σ range (cal yr B.P.)
BL96-1								
1-A 11/12	7	ostracodes	–1.09	905	130	OS-19513	830	700–930
1-A 16/17	12	ostracodes	0	890	130	OS-19507	820	700–920
1-A 27	23	ostracodes	0	900	75	OS-19496	820	740–910
1-A 37/38	33	ostracodes	0	14,500	1700	OS-19509	17,200[e]	15,190–19,330
1-A 52/53	48	ostracodes	–0.31	1450	45	OS-18663	1350	1310–1370
1-A-52/53	48	pollen	–25	1070	40	WW-2774	980	930–1050
1-C-55	252	pollen	–25	3320	40	WW-1754	3550	3480–3610
1-E-39	437	pollen	–25	5260	40	WW-1752	6040	5940–6170
1-E-95	493	TOC	–25	6740	50	WW-1384	7600	7570–7660
BL96-2								
2-A-13	3	pollen	–25	3020	50	WW-1755	3230[e]	3160–3330
2-A-13	3	TOC	–25	1620	50	WW-1758	1510	1420–1560
2-B-9	99	pollen	–25	3435	60	WW-2600	3700	3620–3830
2-B-31	121	ostracodes	0	4620	60	WW-2803	5370	5290–5470
2-B-31	121	pollen	–25	4230	40	WW-2775	4750	4660–4850
2-B-61	151	ostracodes	0	5460	50	WW-2799	6260	6210–6300
2-B-61	151	pollen	–25	5260	40	WW-2776	6040	5940–6170
2-B-73	163	pollen	–25	5810	50	WW-1756	6610	6540–6670
2-B-85	175	pollen	–25	6420	50	WW-1757	7350	7320–7420
2-B-85	175	TOC	–25	6970	50	WW-1759	7800	7730–7920
2-C-10	201	pollen	–25	8265	70	WW-2601	9250	9130–9400
2-C-21	212	ostracodes	0	9070	60	WW-2800	10,230	10,190–10,270
2-C-21	212	pollen	–25	8580	40	WW-2777	9540	9520–9560
2-C-55	246	pollen	–25	10,300	60	WW-1773	12,100	11,980–12,340
2-D-7	299	pollen	–25	12,710	50	WW-1774	15,010	14,900–15,130
2-D-7	299	TOC	–25	13,110	60	WW-1760	15,500	15,320–15,660
2-D-8	300	pollen	–25	12,545	90	WW-2602	14,690	14,470–14,940
2-D-15	307	rotifer	–29.2	12,400	80	OS-18559	14,430	14,190–14,610
2-D-21	313	pollen	–28.14	14,000	100	OS-35973	16,690[f]	16,460–16,920
2-D-41	333	pollen	–27.92	16,200	75	OS-35624	19,370[f]	19,300–19,470
2-D-61	353	pollen	–25.98	18,550	140	OS-35974	22,130[f]	22,000–22,310
2-D-73	365	pollen	–25	8380	40	WW-2783	9420[e]	9320–9470
2-D-81	373	pollen	–25.5	21,000	110	OS-35625	25,290[f]	25,000–25,520
2-D-93	385	pollen	–25.34	21,300	150	OS-36022	25,720[f]	25,560–25,930
2-D-101	393	pollen	–25	22,600	60	WW-2778	26,600[f]	26,540–26,660
BL96-3								
3-A-18	5	pollen	–25.31	4440	40	OS-36023	5050[e]	4970–5270
3-A-33	20	pollen	–25	10,940	75	WW-2607	12,900[e]	12,850–12,940
3-A-46	33	pollen	–25.82	12,800	100	OS-35976	15,110[e]	14,950–15,260
3-A-90	77	pollen	–25	19,980	60	WW-2779	23,940[f]	23,820–24,060
3-B-85	172	pollen	–24.53	21,800	140	OS-36267	25,680[f]	25,540–25,820
3-C-13	201	pollen	–25	21,850	230	WW-2605	25,730[f]	25,500–25,960
3-C-89	277	pollen	–24.54	23,400	130	OS-35626	27,520[f]	27,390–27,650
3-D-89	377	pollen	–25.04	26,700	170	OS-36024	31,280[f]	31,110–31,450
3-E-15	403	pollen	–25	22,150	210	WW-2606	26,080	25,870–26,290
BL98-09								
09-Top	1	pollen	–25	1510	40	WW-2771	1390	1340–1490
09-Top	1	ostracodes	0	600	70	WW-2801	600	540–650
09-30+	30	pollen	–25	980	40	WW-2772	870	800–930
09-30+	30	ostracodes	0	1350	50	WW-2802	1280	1190–1310
BLR2K-3								
R3-1 20-21	20.5	wood	–25	472	92	WW-3885	520	500–540
R3-1 50-51	50.5	wood	–25	1076	86	WW-3886	990	940–1050
R3-1 70-71	70.5	wood	–25	1105	88	WW-3887	1010	970–1060
R3-1 90-91	90.5	wood	–25	950	114	WW-3888	850	800–930
R3-1 140-142	141.0	gastropods	0	7125	80	WW-3859	7960	7880–8000
BL2K-3-1								
3-1 20-21	20.5	wood	–25	3588	116	WW-3883	3890	3780–3980
3-1 40-41	40.5	wood	–25	969	116	WW-3884	870	800–930
3-1 75-76	75.5	wood	–25	100	80	WW-3826	120	0–260
3-1 110-111	110.5	shells	0	3307	140	WW-3982	3540	3460–3620
BL02-1								
1-1 13	13.0	pollen	–25	1295	80	WW-4571	1230	1180–1280
1-1 25	25.0	pollen	–25	1955	80	WW-4572	1910	1870–1970
1-1 31-32	31.5	gastropods	0	6975	90	WW-4655	7810	7740–7920
1-1-44	44.0	pollen	–25	5390	140	WW-4573	6180	6030–6280
1-1-59	59.0	pollen	–25	8040	140	WW-4574	8900	8780–9020
1-1-72	72.0	pollen	–25	7880	260	WW-4575	8740	8560–8980
1-1-82	82.0	pollen	–25	8260	140	WW-4576	9250	9130–9400
1-2 29	29.0	pollen	–25	10,040	80	WW-4577	11,540	11,400–11,690
1-2 37-38	37.5	gastropods	0	10,290	120	WW-4656	12,080	11,840–12,340
1-2 41	41.0	pollen	–25	11,375	90	WW-4578	13,240	13,200–13,290
1-2 86	86.0	pollen	–25	11,880	90	WW-4579	13,750	13,700–13,800
1-2 89	89.0	pollen	–25	12,100	80	WW-4580	13,950	13,890–14,010
BL02-2								
2-1 13	12.0	pollen	–25	1930	80	WW-4581	1880	1830–1920
2-1 21-22	21.5	gastropods	0	7530	80	WW-4657	8360	8330–8390
2-1 35	35.0	pollen	–25	21,550	190	WW-4582	25,390	25,200–25,580

(*Continued*)

TABLE 1. RADIOCARBON MEASUREMENTS MADE IN THIS STUDY (*Continued*)

Core (bold) and sample designation	Corrected total depth (cm)[a]	Material	$\delta^{13}C$ (per mil)[b]	Age (^{14}C yr)	Error (1σ yr)	Lab number[c]	Calibrated age (cal yr B.P.)[d]	Calibrated 1σ range (cal yr B.P.)
BL02-3								
3-1 7	21.0	pollen	–25	2700	70	WW-4596	2800	2760–2840
3-1 58	72.0	pollen	–25	4850	70	WW-4595	5600	5490–5640
3-1-110	124.0	pollen	–25	5975	90	WW-4593	6810	6750–6880
3-1-152	166.0	pollen	–25	7075	70	WW-4594	7900	7860–7950
3-2 60-61	186.5	pollen	–25	6865	80	WW-4262	7700	7660–7740
3-2 90-91	216.5	pollen	–25	8290	80	WW-4263	9310	9150–9400
3-2 102-103	228.5	pollen	–25	8445	60	WW-4264	9480	9450–9500
3-2 123-124	249.5	pollen	–25	8760	80	WW-4265	9760	9680–9890
3-2 127-128	253.5	pollen	–25	9040	80	WW-4266	10,220	10,200–10,230
3-3 10	disturbed	pollen	–25	2750	70	WW-4597	2840	2790–2870
3-3 35	disturbed	pollen	–25	4770	240	WW-4614	5490	5320–5600
3-3 60	disturbed	pollen	–25	7040	70	WW-4598	7880	7850–7930
3-3 65-66	disturbed	pollen	–25	7635	100	WW-4267	8430	8380–8510
3-3 70-71	disturbed	pollen	–25	7950	60	WW-4268	8830	8670–8980
3-3 75-76	disturbed	pollen	–25	8600	80	WW-4269	9550	9530–9600
BL02-4								
4M 8-9	9.0	pollen	–25	1575	80	WW-4914	1470[e]	1420–1520
4M 10-11	11.0	pollen	–25	1040	70	WW-4910	950[e]	930–970
4M 20-21	21.0	pollen	–25	920	140	WW-4911	840	780–920
4M 30-31	31.0	pollen	–25	930	80	WW-4912	850	800–910
4M 38-39.5	38.8	pollen	–25	1270	80	WW-4913	1210	1180–1270
4-3 12	12.0	pollen	–25	680	160	WW-4615	640[e]	560–690
4-3 50	50.0	pollen	–25	1390	70	WW-4600	1310	1290–1330
4-3 79-80	79.5	pollen	–25	2670	80	WW-4270	2780	2750–2840
4-3 83-84	83.5	gastropods	0	2760	90	WW-4658	2860[e]	2790–2920
4-3 83-84	83.5	gastropods	0	3295	60	WW-4659	3520[e]	3480–3560
4-3 86-87	86.5	pollen	–25	4935	80	WW-4271	5660	5610–5710
4-3-131	131.0	pollen	–25	5800	70	WW-4599	6600	6560–6660
4-3 150-151	150.5	pollen	–25	6865	60	WW-4272	7690	7670–7720
4-3 154-155	155.0	pollen	–25	6910	110	WW-5048	7750	7680–7790
4-3 160-161	161.0	pollen	–25	7289	88	WW-5049	8100	8050–8160
4-3 166-167	167.0	pollen	–25	7490	90	WW-5050	8310	8210–8380
4-3 172-173	173.0	pollen	–25	7792	88	WW-5051	8570	8490–8630
4-3 177-178	177.5	pollen	–25	8230	80	WW-4273	9200	9130–9270
4-3 180-181	180.5	gastropods	0	8865	100	WW-4660	10,000[e]	9900–10160
4-3 182-183	182.5	pollen	–25	8820	80	WW-4274	9870	9740–10120
BL02-5								
5-1 6-8	7.0	gastropods	0	6115	80	WW-4661	7000	6910–7150
5-1 11	11.0	pollen	–25	19,460	440	WW-4601	23,170	22,760–23,500
5-1 25	25.0	pollen	–25	22,030	290	WW-4602	25,940	25,650–26,230
BL00-1								
D 6H2 109-110	1800	pollen	–25	24,280	110	WW-6452	28,530	28,420–28,640
D 7H1 19-20	1859	pollen	–25	23,340	100	WW-6453	27,450	27,350–27,550
04EJ-105 Sealy Spring (surface)	–	spring carbonate	–25	8785	70	WW-4915	9800	9710–9890

[a]Top of 1-cm interval. From Rosenbaum et al. (this volume).
[b]Whole values indicated as "0" and "–25" were assumed for ostracodes and organic carbon, respectively; other values were measured.
[c]See text (Methods) for explanation.
[d]Calibrations from program CALIB 5.01 (Stuiver et al., 1998), using 1σ errors and the median probability age. Ages older than 21,381 ^{14}C yr B.P. were calibrated with the relation given in Bard et al. (1998), and their 1σ ^{14}C errors were retained (see text).
[e]Rejected for various reasons (see text for explanation) and not used in age models.
[f]Ages from red, siliclastic zone (Rosenbaum and Heil, this volume): not initially rejected, but eventually eliminated from age models (see text).

detail for paleolimnological proxy analyses, so these cores are the focus here. With one exception (BL02-4) these cores contain no major unconformities, although they may contain minor hiatuses (Smoot, this volume). In light of the results presented here, the age model for the upper part of the 2000 Bear Lake drill core, BL00-1 (Colman et al., 2006), was re-examined.

The three 1996 cores were collected with the University of Minnesota Kullenberg-type piston coring system (Kelts et al., 1986). As is commonly the case for this type of core, the uppermost sediments were not recovered. The two 2002 cores consist of multiple overlapping segments obtained with an Austrian UWITEC piston coring system. A small gravity core designed to sample the sediment-water interface was also used at all 2002 sites. Composite depth scales for the surface core and multiple sections of the piston cores were constructed by using key marker horizons (Dean, this volume; Rosenbaum et al., this volume).

Radiocarbon Dating

Ideally, radiocarbon chronologies for temperate lakes are based on dating of small terrestrial macrofossils, but, as is the case in many large lakes, macrofossils in Bear Lake are rare. We were unable to find any macrofossils suitable for dating in our cores, except for mollusks and detrital wood in some shallow-water cores. Consequently, for the deep-water cores that contain a nearly continuous sedimentary record, we focused on three types of material that were separated from the sediments and analyzed by accelerator-mass spectrometer (AMS) methods:

(1) total organic carbon (TOC), (2) biogenic carbonate (ostracodes and mollusks) hand-picked from the sediments, and (3) material remaining after minerogenic sediment was removed by standard pollen-preparation procedures (Faegri and Iverson, 1975), here called "pollen+."

For TOC, samples of bulk sediment were acidified with organic-free HCl and filtered through a nominal 1 μm diameter, precleaned quartz-fiber filter. Pollen+ samples were prepared using standard palynological methods (Faegri and Iverson, 1975). The processed material contains charcoal and other refractory organic material in addition to pollen, but visual inspection indicated that non-pollen materials were minor components of most of the samples. Ostracodes were separated from the sediment by hand picking, following the procedures described in Colman et al. (1990).

The samples were then converted to CO_2 by combustion (TOC and pollen+) or dissolution in phosphoric acid using standard methods (Jones et al., 1989; Slota et al., 1987). Carbon dioxide from the samples was reduced to elemental graphite over hot iron in the presence of hydrogen (Vogel et al., 1984). The graphite targets were prepared and analyzed at the NOSAMS facility in Woods Hole (OS- numbers in Table 1) or they were prepared at the U.S. Geological Survey (WW- numbers in Table 1) and run at the Lawrence Livermore's Center for Accelerator Mass Spectrometry (CAMS). Ages were calculated according to the methods of Stuiver and Pollach (1977), using either measured $\delta^{13}C$ values or, in some cases, assumed $\delta^{13}C$ values (–25 for pollen or TOC, 0 for biogenic carbonate; Table 1).

Calibrated ages were calculated with the CALIB 5.01 program (Stuiver et al., 1998), using the terrestrial calibration data set. 1σ errors were used in the calibration procedure, and the median probability was used as the age estimate. Ages greater than 21,381 ^{14}C yr B.P. were converted to calibrated years using the relationship developed by Bard et al. (1998). The equation used is:

$$A = -3.0126*10^{-6}*C^2 + 1.2896*C - 1005,$$

where A is calibrated age and C is the age in radiocarbon years. Their 1σ ^{14}C errors were retained. Although other calibration schemes are available for ages older than the CALIB 5.01 data set, the Bard et al. (1998) equation was used for consistency with previous analyses of Bear Lake data (Colman et al., 2005, 2006).

Reservoir corrections for TOC and carbonate samples were used in the calibration exercise, as described in the next section.

Age-Depth Modeling

In order to produce continuous records of various paleoenvironmental proxies, age models are required for each core. We generated age models for the five cores discussed in detail, as well as for the upper part of the Bear Lake drill core (BL00-1) using two methods: (1) polynomial regression, and (2) a generalized additive model (GAM) regression using smooth cubic splines (Heegaard et al., 2005). Core BL02-4 was divided into three sections, separated by two unconformities, for the age models.

Polynomials of various orders were fit to the data by regression. In the case of each of the five cores, a second-order polynomial (quadratic) produced the best fit, as judged from R^2 values. These quadratic equations were all calculated with a zero-order coefficient; i.e., the core-top age was not specified. As shown later, they all have quite high R^2 values and do not have serious problems at the ends of the depth range that are common with polynomial fits. Ages at any depth are easily calculated from the equations. A disadvantage of this method is that the uncertainties associated with the curve fit are difficult to define.

Our second method of constructing age models uses newly developed statistical methods, which weigh data by their uncertainty and include both the uncertainty in the measurements and the uncertainty introduced by the regression procedure (Heegaard et al., 2005). These methods use weighted, nonparametric regression within generalized additive models (GAM). Functions are fitted to the data using multiple smooth cubic splines; the degree of smoothing is determined by the number of spline functions (k). The methods (here called "spline fits") also produce confidence limits for the age model, based on uncertainties in both the control points and the regression procedure. We found that using a value for k equal to about half the number of control points yielded a good balance between smoothness and precision of fit. This balance follows the recommendation to use "the simplest parsimonious model," i.e., the "simplest statistically significant solution that uses the fewest terms in the model and the fewest degrees of freedom in the fitted smoother" (Birks and Heegaard, 2003). Because the sediment-water interface was recovered in the BL02-4 short core, an age of −52 yr B.P. (1950–2002) was used as a control point at zero depth. The long drill core (BL00-1) also appeared to recover nearly the entire sedimentary section, so, considering the scale of the ~250,000 yr record in the drill core, a simple (0,0) control point was used in the age-depth model. For all other cores, no control point was used for the core top.

One disadvantage of the spline-fit procedure is that it does not produce a single age equation with an associated R^2 value, and depths must be converted to ages by using tabulated data produced by the method. On the other hand, an advantage of this procedure is that it generates confidence intervals that can be used to infer the reliability of the age model with depth.

RESULTS

Different fractions of the same samples allow comparisons among TOC, pollen+, and biogenic carbonate (ostracodes). On general principles, the pollen+ samples are thought to be the most reliable, even though they may contain fragments of refractory organic matter, which may be significantly older than the enclosing sediment, in addition to pollen. In the glacial part of the section, however, this may not be true, as discussed in the next section. TOC samples contain all grain sizes and molecular forms of carbon and are likely to include detrital organic carbon that has been washed into the lake. Both biogenic and authigenic carbonate samples are subject to reservoir effects, the size of which were not known a priori.

Biogenic and authigenic carbonate samples share this limitation equally; authigenic carbonate was not analyzed because of the additional potential problem of contamination with detrital carbonate.

The ^{14}C ages are subject to various sources of error, including contamination and mixed ^{14}C sources. TOC and biogenic carbonate are subject to inputs of carbon from two different reservoirs that may be depleted in ^{14}C compared to the atmosphere. First, reworked terrestrial organic matter and diagenetic activity (e.g., carbon bound to clay minerals) may contribute to TOC. Second, ^{14}C-depleted water may be used by aquatic organisms that produce both biogenic carbonate and organic carbon, thus affecting radiocarbon ages of both materials. Depletion of ^{14}C in lake water is a complex function of local bedrock, groundwater flow rates, mixing, and other aspects of the lake's hydrological budget.

Two pairs of pollen+ and TOC samples (Table 2) indicate a consistent difference between the two kinds of samples: pollen+ samples average 480 ± 105 yr younger than corresponding TOC samples. This result is consistent with the assumption that TOC samples contain more detrital organic carbon than the pollen+ samples. Although it unlikely that the difference between TOC and the pollen+ samples was constant through time, we corrected the relatively few TOC analyses by 480 ± 105 yr, treating it as a "reservoir effect" in the calibration process.

Five pairs of pollen+ and ostracode samples (Table 2) show a remarkably consistent relationship: pollen+ samples average 370 ± 105 yr younger than the ostracode samples. The consistency of this result suggests that difference is due to the radiocarbon content of the water being slightly out of equilibrium with that of the atmosphere; i.e., there is a reservoir effect of ~370 yr. Although the magnitude of the reservoir effect likely varies with time, no consistent trend with time was seen in our data set, and this reservoir correction was used in the calibration procedure for carbonate samples.

A number of samples produced anomalous results and were treated as outliers for various reasons ("Rejected" in Fig. 2). Most commonly, these were anomalously old ages near the tops of several cores (one in BL96-1, one in BL96-2, three in BL96-3, and three in BL02-4). In the case of BL02-4, the uppermost three ages (on pollen+), already mentioned, are at or above the geochemically defined horizon that marks the diversion of the Bear River into Bear Lake ca. 1912 (Dean, this volume). These samples apparently contain older materials transported during that diversion and were thus rejected as a group. Diversion-related reworking may explain anomalously old ages near the tops of other cores, although, of the cores examined here, the diversion horizon has been identified only in BL02-3 and BL02-4. Core BL02-4 also contains two shallow-water, graded shell layers (Smoot, this volume) that are clearly unconformities. We therefore rejected three ages on gastropod shells that were probably reworked within these layers. In some cases (e.g., BL96-3), the Holocene section of the core is thin and clearly reworked (Colman, 2006), so ages in these reworked sediments were rejected (Fig. 2). Thin, reworked Holocene sediments tend to occur in most cores taken in present water depths of less than ~30 m.

In addition to the radiocarbon ages in Figure 2, a few other age constraints were used in the age models. The multiple cores taken at the sites of BL02-3 and BL02-4 ensured that the uppermost sediments and the sediment-water interface were recovered (see Methods). For these cores, various geochemical data are available that reveal the core depth at which the diversion of the Bear River into Bear Lake is recorded (Dean, this volume). We used the depth and approximate age (1912 common era; 38 cal yr B.P.) of this event ("Diversion" in Fig. 2). The depth of the diversion horizon in BL02-3 is only slightly above a much older radiocarbon age, suggesting some erosion between the two, but in BL02-4, the diversion horizon is compatible with the core top and the ages below. In addition, the sediments in the lower part of BL02-4 contain distinctive profiles of magnetic properties that allow close correlations with similar profiles in core BL96-2 (Rosenbaum et al., this volume). Three horizons from BL96-2, with interpolated ages from that core, were correlated to BL02-4 in this way, assuming the horizons were not time transgressive. These correlations were used as control points ("Mag correlation" in Fig. 2) in the lower part of core BL02-4.

Numerous ages were obtained from the red, siliclastic zone that is interpreted as containing rock flour deposited near the time of the last glacial maximum (LGM; Rosenbaum et al., 2002, this volume; Rosenbaum and Heil, this volume), especially in cores BL96-2 and BL96-3. These ages (indicated in Table 1) are generally in stratigraphic order (Fig. 2) and there was no a priori reason to suspect them. However, as discussed in the next section, we concluded that these ages are significantly too old and we developed an alternative strategy for age models in the red, siliclastic zone.

TABLE 2. AGES FOR POLLEN+ SAMPLES COMPARED TO THOSE FOR TOTAL ORGANIC CARBON AND OSTRACODE SAMPLES

Pollen+	TOC	Ostracodes	TOC-Pollen	Ostracodes-Pollen
1070		1450		380
4230		4620		390
5260		5460		200
8580		9070		490
980		1350		370
6420	6970		550	
12,710	13,110		400	
		Mean[a]	480	370
		St. Dev.[a]	105	105

Note: Data from Table 1; all values in ^{14}C yr BP. TOC—Total Organic Carbon.
[a]Rounded to nearest 10 years (Mean) or 5 years (Standard Deviation).

EVALUATION OF RADIOCARBON AGES

Although some ages were rejected for the reasons discussed in the previous section, we made several other attempts to evaluate the overall accuracy of the remaining ages before developing age models for the cores. The radiocarbon ages that are less than 15 cal ka compare well with age estimates based on amino acid racemization. We used an independently derived equation for racemization of aspartic acid in ostracodes (Kaufman, 2000), with an effective temperature of 4.6 °C for the bottom of Bear Lake, to derive amino acid age estimates (Fig. 3). The two types of age estimates are entirely consistent (Fig. 3), lending strong support for the validity of ages that are <15 cal ka.

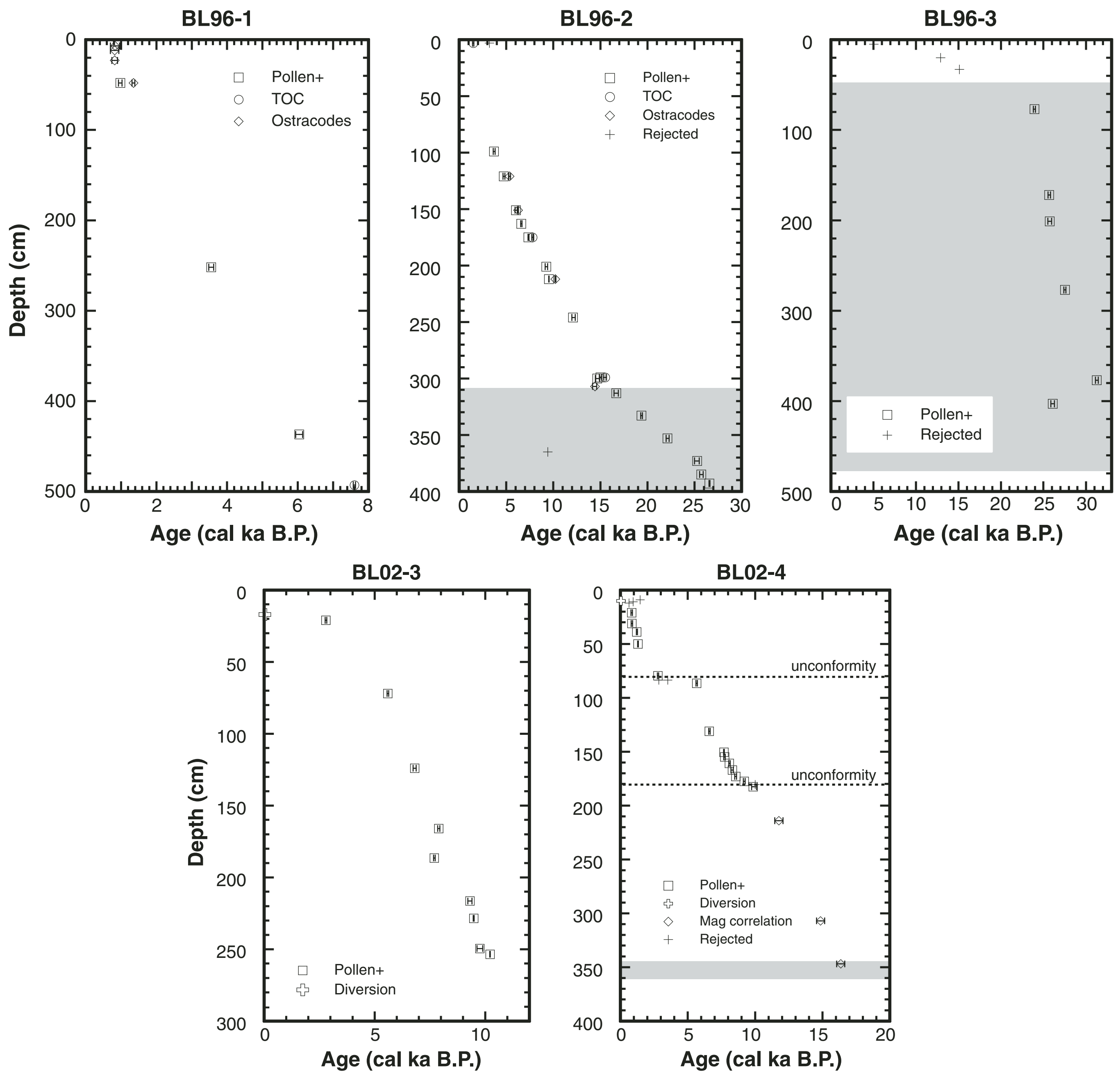

Figure 2. Radiocarbon ages for five Bear Lake cores plotted against depth in the sediment sequence. Depth is the independent variable in these plots. Data from Table 1. Ostracode and total organic carbon (TOC) ages were corrected for reservoir effects (see text and Table 2). One rejected age for core BL96-1 is off scale of plot. 1σ errors are shown. See text for discussion of rejected, diversion, and "Mag correlation" ages. Shaded areas indicate the red, siliclastic unit of Rosenbaum et al. (this volume).

A second method of evaluating the radiocarbon ages involves comparisons of ages for several distinct horizons that occur in two or more cores and that can be confidently correlated on the basis of detailed analytical data. Age estimates for each of these horizons can be estimated from the age models for each core. Where the horizon is dated in multiple cores, a more robust age for each horizon can then be generated by calculating a mean of the ages derived from each core. These horizons and their depths in various cores are given in Table 3. In our initial attempts (not shown) at age modeling to produce age estimates for the horizons, two results emerged. First, ages for these horizons in sediments from different cores above the red, siliclastic unit were remarkably consistent, in most cases essentially identical within the errors. Second, model ages for horizons within the red, siliclastic unit were commonly incompatible between cores BL96-2 and BL96-3. This discrepancy was our first indication that a problem existed with the ages from the red, siliclastic unit.

Another problem with the ages in the red, siliclastic zone involves the age of the local LGM. Taken at face value, the ages in the red, siliclastic zone (BL96-2 and BL96-3, Fig. 2), combined with geochemical and magnetic indicators of rock flour (Rosenbaum and Heil, this volume; Rosenbaum et al., 2002), suggest that the local LGM occurred as much as 25 k.y. ago. In contrast, cosmogenic radionuclide exposure ages for terminal moraines in the headwaters of the Bear River (Uinta Mountains) are much younger. Cosmogenic-exposure analyses from two LGM moraines in the Uinta Mountains yield age estimates of 17.1 ± 0.7 ka (n = 5) and 18.5 ± 0.7 ka (n = 6) (Laabs et al., 2007). On the basis of cosmogenic-exposure dating throughout the western United States, Licciardi et al. (2004) suggested that there were two pulses at the LGM, at 17 and at 21 cal ka, although Pierce (2004) points out that the cosmogenic-exposure ages are consistently younger than radiocarbon ages for comparable events. In any case, the radiocarbon ages from the red, siliclastic zone yield an apparent age of the LGM at Bear Lake that appears to be significantly too old compared to nearby estimates for the age of the LGM.

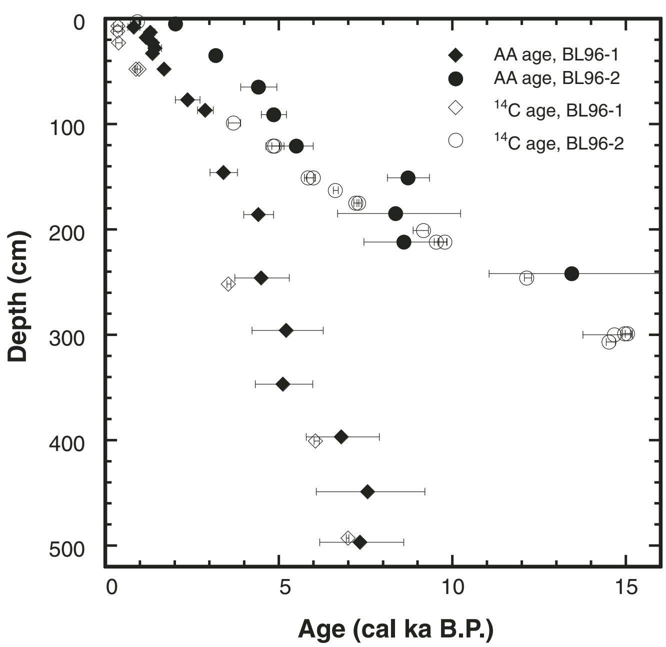

Figure 3. Comparison between ages estimated from radiocarbon (^{14}C) and amino acid racemization (AA) methods for two Bear Lake cores. See text for explanation.

Even though the ages for the red, siliclastic unit in BL96-2 and BL96-3 progressively increase in age with depth, the organic carbon content in these samples is very low. Furthermore, the pollen+ samples from this interval that have been examined under the microscope contain little pollen, and that pollen is badly degraded (R. Thompson, 2004, personal commun.). This suggests that the material is mainly refractory organic matter, and as such, may be significantly older than the sediment in which it was deposited. For this and the other reasons discussed above (the ages appear to be too old compared with other LGM records), we decided to reject the ages from the red, siliclastic unit in the age models for the cores.

AGE MODELS AND DISCUSSION

Colman et al. (2006) developed an age model for the entire 120 m of Bear Lake drill core BL00-1. This model used the radiocarbon ages from the red, siliclastic unit in BL96-2 and BL96-3, correlated to BL00-1 on the basis of magnetic susceptibility profiles. These ages produced a kink in the age model indicating relatively slow rates of sedimentation for the glacial times represented by the red, siliclastic unit. Because we now believe that the radiocarbon ages from the red, siliclastic unit are several thousand years too old, we have recalculated the spline-fit age model for the upper 20 m of the drill core, excluding those ages (Fig. 4). In addition to providing a more accurate age model for the upper part of the drill core, the lithologic horizons (Table 3, Fig. 4) are well correlated among the cores. Thus we can use their ages—derived from the age model for the upper part of BL00-1—for age control in the red, siliclastic unit. These ages are given in Table 3.

Above the red, siliclastic unit, control for the age model of the upper 20 m of the drill core comes from radiocarbon ages from BL96-1 and BL96-2, correlated to BL00-1 on the basis of magnetic susceptibility profiles (Rosenbaum et al., this volume). The lowest radiocarbon age in BL96-3 is below the red, siliclastic unit, and since the Colman et al. (2006) study, we have obtained two new pollen+ radiocarbon ages from below the red, siliclastic unit in BL00-1 (Table 1). Microscopic examination of the three associated samples showed that they contain much more well-preserved pollen than samples from the red, siliclastic unit, and significantly, all three resulting ages are notably younger than ages in the red, siliclastic unit (Fig. 4). These ages are used to constrain the age model through the red, siliclastic unit to 20 m depth in the drill core.

For the five piston cores in Bear Lake, age models were constructed as described in the Methods section. Two types of control points were used for these age models (Fig. 5). Above the red, siliclastic zone, the ages shown in Figure 2 were used

TABLE 3. AGES OF PROMINENT STRATIGRAPHIC HORIZONS PRESENT IN MORE THAN ONE CORE, DERIVED FROM SPLINE-FIT AGE MODELS

Horizon	Data type	Comment	Depth (m) in BL96-3	Depth (m) in BL02-4	Depth (m) in BL96-2	Depth (m) in BL96-1	Depth (m) in BL00-1	Age or mean age[a]	Error[a]
AA1	AA-14C	AA-^{14}C match			0.10	0.55		1.43	0.16
D1	Diatoms	*N. oblongata* spike			0.25	0.97		1.86	0.06
D2	Diatoms	Top, zone 3b			0.63	1.67		2.75	0.20
Mag1	Mag. susc.					2.42	3.24	3.41	
Mag2	Mag. susc.					3.46	4.48	4.59	
Mag3	Mag. susc.					3.97	5.22	5.38	
D3	Diatoms	Bottom, zone 3b			1.50	4.27		6.09	0.17
AA2	AA-14C	AA-^{14}C match			1.40	4.50		6.11	0.53
Mag4	Mag. susc.					4.45	5.79	6.37	
Min1	Mineralogy	Midpoint, calcite decrease	<0.4	1.55	1.80		6.75	7.81	0.03
R1	Seismic	Base of upper marl	<0.4		1.90		7.30	8.42	
Min2	Mineralogy	Midpoint, calcite increase	<0.4	1.70	1.95		7.60	8.63	0.13
Mag5	Mag. susc.			2.14	2.35		8.65	11.12	0.11
Min3	Mineralogy	Begin decrease in calcite	<0.4	2.14	2.37		8.39–9.89	11.18	0.20
Mag6	Mag. susc.			3.07	2.92		9.82	14.60	0.26
R2	Seismic	Top of red unit	<0.40		3.10		10.40	16.31	0.39
Min4	Mineralogy	Begin calcite, qtz decline	<0.40	3.47	3.47		10.03–10.24	15.60	0.38
Mag7	Mag. susc.		<0.40	3.47	3.47		10.42	16.36	0.39
Mag8	HIRM		0.76		3.62		11.02	17.74	0.42
Mag9	HIRM		0.86		3.70		11.24	18.22	0.43
Mag10	HIRM		1.05		3.88		11.38	18.52	0.44
Mag11	Mag. susc.		1.47				12.10	19.98	0.47
Mag12	Mag. susc.		1.65				12.46	20.67	0.49
Mag13	Mag. susc.		1.85				12.85	21.37	0.50
Mag14	Mag. susc.		2.01				13.11	21.81	0.52
Mag15	Mag. susc.		2.78				14.44	23.86	0.58
Mag16	Mag. susc.		3.55				15.78	25.54	0.64
Mag17	HIRM		4.01				16.68	26.47	0.68

Note: Gray shading indicates horizons in or bounding the red, siliclastic unit. HIRM—hard isothermal remanent magnetization; Mag. susc.—magnetic susceptibility.

[a]Age and error are estimated differently for horizons above and below the top of the red, siliclastic unit. For those above, the age is the average of ages derived from spline-fit age-depth model (Fig. 5) for the different cores in which the depth is given (blank error column indicates age from only one core). For horizons below the top of the red, siliclastic unit, the age and error are derived from the age model for BL00-1 (Fig. 4).

directly as control points (BL96-1 and BL02-3 do not penetrate to the unit). Within the red, siliclastic unit and in the lowest section of BL02-4, ages of the lithological horizons derived from the drill core (Fig. 4) were transferred to other cores according to the depth correlations in Table 3.

The two different types of age models (quadratic and spline fit) for each core are very similar (Fig. 5), and in many cases (e.g., BL96-3 and BL02-4) are nearly identical. No regression is shown for BL00-1 (see Fig. 4). The spline-fit model is better able to handle multiple or irregular changes in apparent sedimentation rate, although such changes are minor in the deep-water Bear Lake cores. The spline-fit method has the advantage of providing confidence intervals for the age model, although the confidence intervals are relatively large because they account for uncertainties in both the control points and the regression procedure. The average 95% confidence interval for 8000 cal yr B.P. (five cores, not BL96-3), is about ± 280 yr (Fig. 5). This age has relatively high data density; sparser data lead to larger confidence intervals.

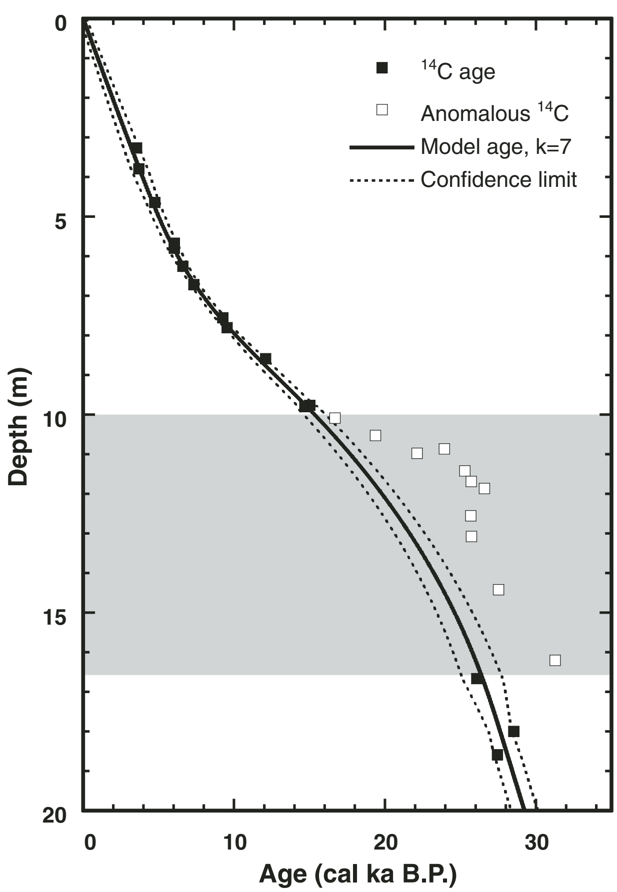

Figure 4. Age model for the upper part of core BL00-1. Shaded area indicates the red, siliclastic unit of Rosenbaum et al. (this volume). Depth is the independent variable in this plot. Control for the age model comes from radiocarbon ages above and below the red, siliclastic unit, as described in the text. Radiocarbon ages from within the red, siliclastic unit from cores BL96-2 and BL96-3, correlated by depth on the basis of magnetic susceptibility profiles, are labeled as "Anomalous ^{14}C." No polynomial regression is shown for the upper part of BL00-1 because no quadratic equation (as used for the other cores) or other low-order polynomial produced a satisfactory fit to the data.

Because the primary purpose of this study is to provide chronologies for paleoenvironmental proxies, mass accumulation rates (e.g., g cm^{-2} yr^{-1}) are not calculated here. Density data are available (Rosenbaum et al., this volume), and these data have been used to calculate carbon and carbonate mass accumulation rates (Dean et al., 2006). However, sedimentation rates (in mm yr^{-1}) are still of interest. Sedimentation rates in the cores generally decrease with depth, for most cores creating a convex-upward shape in the age-depth plots (Fig. 3). Presumably, this is due at least in part to progressive compaction and diagenesis of the sediments. In the uppermost, least compacted sediments, ^{210}Pb data indicate sedimentation rates in two cores of 0.76 and 0.91 mm yr^{-1} (Smoak and Swarzenski, 2004). For the Holocene section in the deep part of the lake, sedimentation rates are as high as 0.64 mm yr^{-1} (BL96-1) to 0.80 mm yr^{-1} (BL00-1). At shallower sites, Holocene sedimentation rates are 0.30 mm yr^{-1} (BL96-2) to 0.37 mm yr^{-1} (BL02-4). Slow apparent sedimentation rates occur in the upper part of relatively shallow water cores (BL96-3 and BL02-3) because of reworking and (or) erosion of the surface sediments. From the drill core (BL00-1), sedimentation rates for the past 220,000 years or so average ~0.5 ± 0.03 mm yr^{-1} (Colman et al., 2006; Kaufman et al., this volume) and show remarkably little variation with time.

CONCLUSIONS

Radiocarbon analyses of total organic carbon, pollen, and ostracodes provide a reliable chronology of post-glacial sediments deposited in Bear Lake. The differences in apparent age between TOC, pollen, and carbonate fractions are consistent and in accord with the origins of these fractions. The data are also in accord with ages independently estimated from aspartic acid racemization in ostracodes. Ages in the red, siliclastic unit, inferred to be of last glacial age, are several thousand years too old, seemingly because of a high proportion of refractory organic carbon in the pollen samples.

Age-depth models for five piston cores and the Bear Lake drill core (BL00-1) were constructed using two methods: quadratic equations and smooth cubic-spline fits. The two types of age models, each of which has its own advantages, are compatible for the Bear Lake cores, differing only in detail. Specific horizons defined by paleontologic, mineralogic, or magnetic properties were dated in several cores and correlated among them. The average of the interpolated ages for these horizons provides more robust age estimates. The age of the correlated horizons in the red, siliclastic unit can be estimated from the age model for BL00-1, which is controlled by ages above and below the red, siliclastic unit. These ages can then be transferred to the correlative horizons in the shorter piston cores, providing control for the sections of the age models in those cores in the red, siliclastic unit. These age models are the backbone for reconstructions of past environmental conditions in Bear Lake. In general, sedimentation rates in the deeper parts of Bear Lake have been quite

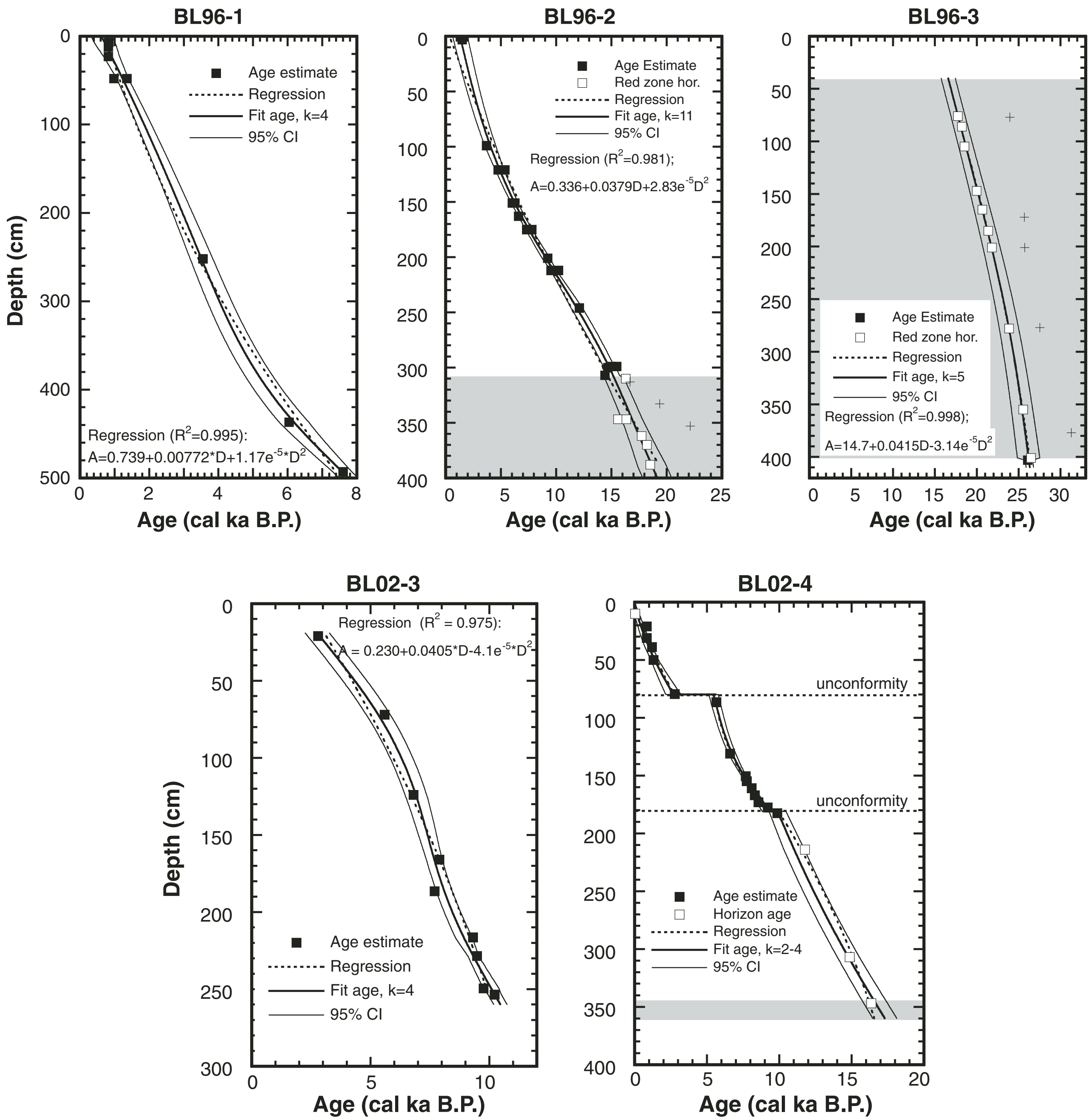

Figure 5. Age models for five Bear Lake cores. Shaded area indicates the red, siliclastic unit of Rosenbaum et al. (this volume). Depth is the independent variable in these plots. Data points outside the red, siliclastic unit are from Figure 2, excluding rejected ages. Data points within the red, siliclastic unit ("Red zone hor.") and in the lowest section of BL02-4 ("Horizon age") are ages of the lithological horizons derived from BL00-1 (Fig. 4), which were transferred to other cores according to the depth correlations in Table 3. Thick dashed line is a quadratic regression through the data; thick solid line is a spline fit (see text). Thin solid lines are the 95% confidence limits for the spline fit. Also shown (pluses) are the anomalously old radiocarbon ages in the red, siliclastic unit in cores BL96-2 and BL96-3 (cf. Fig. 2). The model for BL02-4 was done in three sections for the parts of the core separated by two unconformities at 80 and 181 cm. From the top, these regressions are:

$A = -0.0523 + 0.0263 * D + 1.09e^{-4} * D^2$ ($R^2 = 0.967$)

$A = 7.01 - 0.0415 * D + 2.99e^{-4} * D^2$ ($R^2 = 0.988$)

$A = 8.13 - 0.00561 * D + 8.78e^{-5} * D^2$ ($R^2 = 0.996$).

uniform, mostly between 0.3 and 0.8 mm yr^{-1} in the Holocene, and close to 0.5 mm yr^{-1} for the longer term.

Deriving age models from radiocarbon ages of lake sediments commonly is a difficult process, and Bear Lake proved not to be an exception. Different types of samples each have potential problems, ranging from reservoir effects to terrestrial residence times, all of which can lead to radiocarbon ages that are different than the age of the sediment from which the sample was taken. We experienced most of these problems with samples from Bear Lake, including erroneous ages that were in an attractive stratigraphic progression. However, by analyzing multiple sediment fractions, performing stratigraphic and correlation comparisons, and using multiple consistency checks, we believe that we have generated valid and useful age models for the past 30,000 years of sedimentation in Bear Lake.

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ARCHIVED DATA

Archived data for this chapter can be obtained from the NOAA World Data Center for Paleoclimatology at http://www.ncdc.noaa.gov/paleo/pubs/gsa2009bearlake/.

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