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Cosmogenic ^{36}Cl and ^{10}Be ages of Quaternary glacial and fluvial deposits of the Wind River Range, Wyoming

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ABSTRACT

We measured cosmogenic ^{36}Cl in 56 samples from boulders on moraines and fluvial terraces in the vicinity of the Wind River Range, Wyoming. We also measured ^{10}Be in 10 of the same samples. Most of the ^{10}Be ages were in good agreement with the ^{36}Cl ages, indicating that rock-surface erosion rates were very low. The oldest moraine investigated, the type Sacagewea Ridge site, yielded only a limiting minimum age of >232 ka. The oldest moraines in the type Bull Lake complex also could be constrained only to >130 ka. The main sequence of type Bull Lake moraines yielded age distributions indicating deposition within the intervals 130 to 100 ka and 120 to 100 ka; the best estimates are closer to the upper limits of these ranges, and associated uncertainties are in the range of 10% to 15%. These uncertainties could permit deposition in either marine isotope stage 6 or stage 5d. We found no evidence of glacial deposits dating to marine isotope stage 4. Both Bull Lake–age moraines from Fremont Lake, on the opposite side of the Wind River Range, and boulders on a fluvial terrace above the Wind River, gave age distributions very similar to that of the second oldest Bull Lake advance (ca. 130 to 100 ka). The distribution of boulder ages for Pinedale moraines at Bull Lake indicated deposition between 23 and 16 ka, nearly identical to the distribution of ^{10}Be ages previously reported for the type Pinedale moraines at Fremont Lake.

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INTRODUCTION

The glacial deposits of the Wind River Range, Wyoming, have long held a strong interest for Quaternary geoscientists. This interest is in large part due to their selection by Blackwelder (1915) as type sites for Quaternary glaciation of the Rocky Mountains. Numerous subsequent studies have investigated in detail the glacial stratigraphy and that of the associated fluvial terraces (e.g., Fall et al., 1995; Hall and Shroba, 1995; Love, 1979; Morris et al., 1951; Richmond, 1962, 1964; Richmond and Murphy, 1965). As Blackwelder (1915) intended, the names of the type localities, such as Pinedale and Bull Lake, have been used as a basis for chronostratigraphic correlation throughout the Rocky Mountain region. Unfortunately, the actual chronology of glacial deposition at the type sites has, until recently, been scarcely investigated. The poor chronological control at the type sites has largely been a result of the difficulties of directly dating glacial deposits. Geochronological studies of glaciation in the Rocky Mountains have therefore tended to focus on sites such as the Yellowstone area, where more readily datable materials, such as tephras and travertines, can be used to indirectly establish the chronology of the glacial deposits (e.g., Richmond, 1986; Pierce, 1979; Sturchio et al., 1994).

The difficulties of directly dating surficial deposits have recently been addressed through the development of methods using the accumulation of cosmogenic nuclides in minerals to determine surface-exposure ages (Cerling and Craig, 1994). As part of a large-scale effort to date and correlate the response of North American montane glaciers to Quaternary climate change (Zreda and Phillips, 1995) we have applied cosmogenic ^{36}Cl dating to the type Wind River moraines. This is the first application of this method to glacial deposits in the Rocky Mountains. Because the type Pinedale moraines at Fremont Lake on the west side of the range were investigated using cosmogenic ^{10}Be and ^{26}Al (Gosse et al., 1995a, 1995b), we focused the use of ^{36}Cl on the type Bull Lake moraines on the east side of the range. However, for purposes of comparison of methods we sampled a limited number of Bull Lake–age boulders at Fremont Lake for ^{36}Cl analysis, and some of the ^{36}Cl samples from Bull Lake were processed for ^{10}Be. These comparisons are reported here. This paper describes the surface exposure dating methods and results. The stratigraphic and paleoclimatic implications of these results are discussed in Chadwick et al. (1997).

METHODS

Sampling

Samples were collected with hammer and chisel from close to the center of boulders on, or nearly on, moraine crests. The boulders were

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predominantly banded gneiss; a few samples were granite and diorite. We generally selected the largest boulders available because moraines, being composed of loose sediment, tend to degrade fairly rapidly (Bursik, 1991; Hallet and Putkonen, 1994), and tall boulders are more likely to have stood above the original level of the moraine crest than short ones. This hypothesis has been supported by random-sampling data (Zreda et al., 1994). In general, the boulders sampled were taller than 1.5 m, ranging to as high as 4 m, but both the youngest (Pinedale) and the oldest (Bull Lake moraines BLIV–BLII and Sacagewea Ridge moraines) deposits had significantly fewer large boulders than the main Bull Lake–age moraines and in some cases only boulders shorter than 1 m were available. Both the geomorphic setting and the surficial characteristics (e.g., ventifaction, striations, evidence of spalling or grussification) were carefully considered in selecting boulders to be sampled. Sample locations are shown in Figure 1.

Sample Preparation and Analysis

The whole-rock samples were ground to a size smaller than the average grain size of the rock and leached in deionized water. An aliquot was removed for elemental analysis. Major elements were determined by X-ray fluorescence and Cl by specific ion electrode in a Teflon diffusion cell (Aruscavage and Campbell, 1983). Uncertainty in the specific ion electrode Cl analyses ranged from 3% (for high Cl samples) to 6% (for low Cl samples). Boron and Gd were measured in selected samples by prompt gamma emission spectrometry. Boron and Gd are significant because they compete with Cl for thermal neutrons; they were therefore measured in samples with Cl greater than approximately 100 ppm (and hence in which thermal neutron absorption was an important reaction) and were estimated for low Cl samples on the basis of correlation with major element composition.

Extraction of Cl for ^{36}Cl analysis was accomplished by dissolving 20 to 100 g of powdered rock (depending on Cl concentration) in a mixture of hot HF and HNO_3 within a Teflon bottle. $AgNO_3$ was added to the reaction vessel to precipitate the Cl released as AgCl. The AgCl was extracted from the dissolution residue by solution in NH_4OH. The AgCl was reprecipitated and purified of sulfur using standard methods (Bentley et al., 1986). Full details of the extraction and purification procedure were given in Zreda (1994). The ^{36}Cl/Cl ratio of the purified AgCl precipitate was measured by accelerator mass spectrometry (Elmore et al., 1979) at the PRIME Lab, Purdue University. Results are listed in Table 1.

We measured ^{10}Be on quartz separates extracted from the same whole-rock samples used for ^{36}Cl dating. The quartz was chemically purified of meteoric ^{10}Be as described by Kohl and Nishiizumi (1992), and the ^{10}Be concentration was measured by accelerator mass spectrometry at the University of Pennsylvania. Results are given in Table 2.

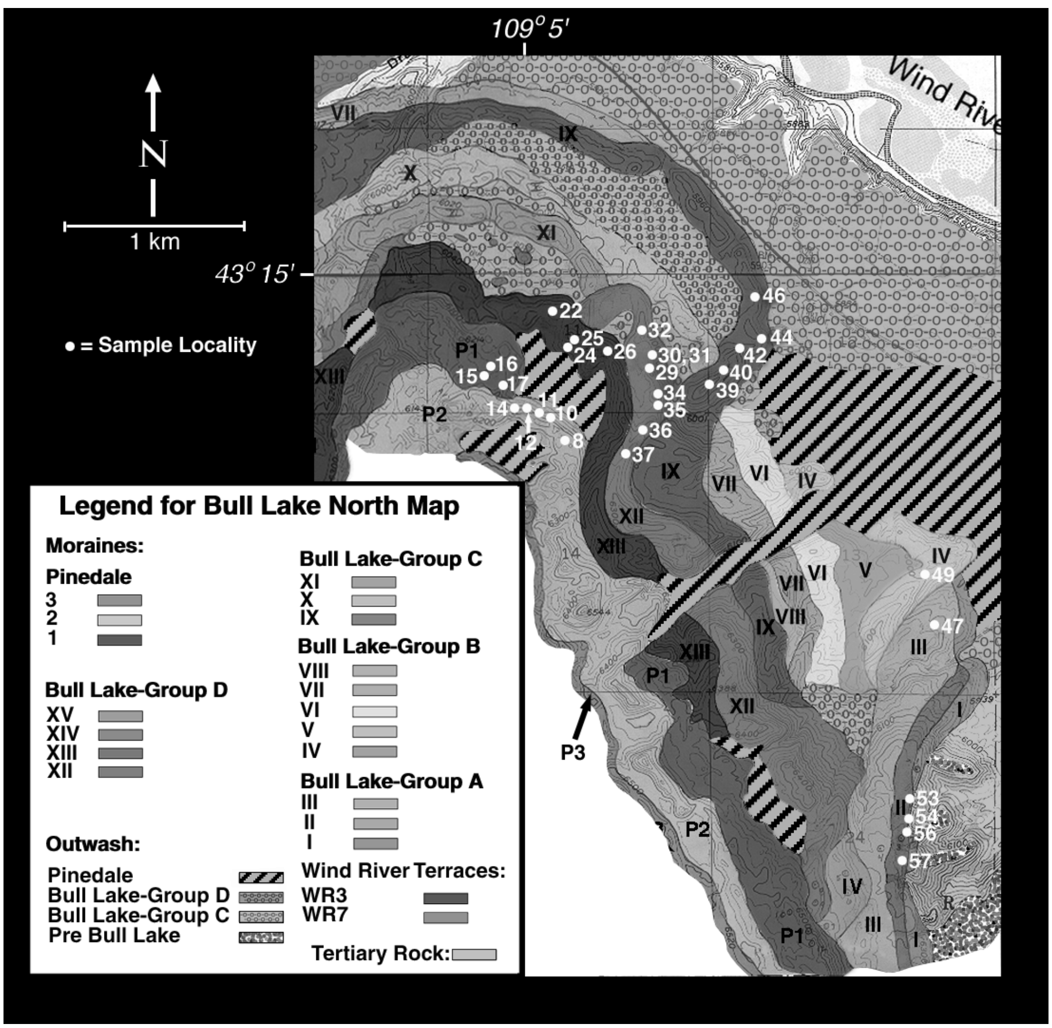

Figure 1. Locations of samples collected in the vicinity of Bull Lake.

TABLE 1. LOCATIONS, GEOCHEMISTRY AND ^{36}CL AGES OF SAMPLES FROM THE WIND RIVER RANGE, WYOMING

Sample	^{36}Cl ages (ka)* Zero erosion	0.6 mm/k.y.	Min.	Max. erosion	Lat. (°N)	Long. (°W)	Elev. (m)	^{36}Cl ratio[†] (^{36}Cl/10^{15}Cl)	SiO_2 (wt. %)	TiO_2 (wt. %)	Al_2O_3 (wt. %)	Fe_2O_3 (wt. %)	MgO (wt. %)	CaO (wt. %)	MnO (wt. %)	Na_2O (wt. %)	K_2O (wt. %)	P_2O_5 (wt. %)	Cl (ppm)	B (ppm)	Gd (ppm)
Pinedale 3 (P3)																					
BL92-2-PN3	17.2 ± 1.8	16.9 ± 1.7	15.5 ± 1.5	15.5 ± 1.5	43.236	109.083	1925	474 ± 44	67.3	0.56	19.2	0.93	0.32	5.20	0.04	6.15	0.35	0.03	53	5.0[§]	4.9[§]
BL92-5-PN3	10.0 ± 1.2	9.8 ± 1.2	8.9 ± 1.0	8.9 ± 1.1	43.234	109.083	1930	211 ± 20	62.1	0.51	18.2	4.69	1.94	6.01	0.09	5.06	0.93	0.02	154	5.0	4.9
BL92-6-PN3	18.1 ± 1.2	17.8 ± 1.2	16.7 ± 1.1	16.7 ± 1.1	43.235	109.085	1925	586 ± 37	77.7	0.11	12.3	0.50	0.20	1.80	0.02	2.77	4.27	0.02	78	5.6[§]	2.7[§]
BL92-7-PN3	21.0 ± 0.8	20.6 ± 0.8	18.8 ± 0.7	18.8 ± 0.7	43.236	109.086	1940	553 ± 19	77.3	0.05	13.0	0.25	0.16	1.08	0.01	4.28	3.87	0.04	93	5.0[§]	5.0[§]
Pinedale 2 (P2)																					
BL92-8-PN2	6.2 ± 0.8	6.1 ± 0.8	5.5 ± 0.7	5.5 ± 0.7	43.242	109.081	1895	70 ± 7	49.1	1.53	12.7	16.10	6.97	11.2	0.23	1.72	0.25	0.03	862	5.6	2.7
BL92-10-PN2	17.3 ± 1.7	16.8 ± 1.7	15.0 ± 1.4	15.0 ± 1.4	43.243	109.083	1900	256 ± 23	63.4	0.77	16.5	5.48	1.58	4.97	0.08	4.51	1.73	0.03	203	11.4	7.4
BL92-11-PN2	27.0 ± 6.1	25.9 ± 5.5	22.1 ± 4.4	22.1 ± 4.4	43.243	109.083	1900	428 ± 113	61.3	0.47	17.3	4.71	2.23	4.82	0.08	4.24	1.50	0.02	183	12.0	2.0
BL92-12-PN2	22.8 ± 1.6	"22.2 ± 1.5"	19.9 ± 1.3	19.9 ± 1.3	43.243	109.084	1905	640 ± 40	73.8	0.07	14.9	0.96	0.18	3.88	0.02	5.04	0.74	0.05	48	9.5[§]	0.5[§]
BL92-14-PN2	19.1 ± 1.5	18.7 ± 1.4	16.6 ± 1.2	16.6 ± 1.2	43.243	109.084	1905	468 ± 32	69.6	0.35	15.7	1.66	0.51	4.73	0.04	4.28	0.69	0.02	71	9.5[§]	0.5[§]
Pinedale 1 (P1)																					
BL92-15-PN1	16.6 ± 1.5	16.2 ± 1.4	14.2 ± 1.2	14.2 ± 1.2	43.245	109.085	1870	275 ± 22	65.7	0.80	12.3	6.82	3.84	5.61	0.12	2.76	0.31	0.03	124	7.0	4.0
BL92-16-PN1	14.6 ± 1.4	14.2 ± 1.4	12.6 ± 1.1	12.6 ± 1.1	43.245	109.085	1870	311 ± 26	74.4	0.20	14.2	0.85	0.25	1.94	0.02	5.58	1.46	0.04	85	9.5[§]	0.5[§]
BL92-17-PN1	18.0 ± 1.8	17.5 ± 1.8	15.6 ± 1.5	15.6 ± 1.5	43.244	109.085	1870	438 ± 40	70.2	0.20	15.5	1.91	0.46	4.14	0.03	4.82	0.56	0.03	60	9.5[§]	0.5[§]
Bull Lake XIII																					
BL92-22-BLVI	119 ± 14	104 ± 11	94 ± 11	104 ± 18	43.248	109.081	1875	2159 ± 218	71.8	0.18	14.7	1.66	0.24	2.67	0.02	4.86	2.01	0.02	97	9.5[§]	0.5[§]
BL92-24-BLVI	88.7 ± 6.3	79.8 ± 5.1	69.7 ± 4.8	71.1 ± 5.7	43.247	109.080	1890	1778 ± 110	69.8	0.17	16.2	0.91	0.33	3.11	0.02	6.13	0.89	0.03	65	9.5[§]	0.5[§]
BL92-25-BLVI	92.4 ± 6.1	87.6 ± 5.5	85.3 ± 5.7	112 ± 11	43.247	109.080	1890	2235 ± 130	50.4	0.52	6.6	13.70	15.5	10.30	0.20	0.32	0.15	0.02	78	5.6[§]	2.7[§]
BL92-26-BLVI	112 ± 4.0	102 ± 3.5	96.4 ± 3.5	112 ± 5.3	43.246	109.079	1885	2776 ± 86	71.2	0.22	15.0	1.61	0.47	3.72	0.03	4.65	1.42	0.02	55	9.5[§]	0.5[§]
Bull Lake XII																					
BL92-29-BLV	105 ± 5.1	87.5 ± 3.7	70.4 ± 3.3	71.0 ± 3.7	43.246	109.074	1865	1384 ± 58	73.5	0.19	15.1	1.57	0.37	3.55	0.02	5.02	0.82	0.02	170	9.5[§]	0.5[§]
BL92-30-BLV	91 ± 16	87 ± 15	86 ± 15	109 ± 36	43.246	109.074	1865	1822 ± 281	46.9	1.33	10.8	20.70	7.36	11.50	0.30	0.97	0.23	0.02	102	7.0[§]	3.5[§]
BL92-31-BLV	69.2 ± 3.6	64.6 ± 3.2	58.8 ± 3.1	59.9 ± 3.5	43.246	109.074	1865	1488 ± 70	72.9	0.10	14.4	0.59	0.21	1.55	0.02	4.89	3.39	0.02	98	9.0[§]	2.0[§]
BL92-32-BLV	74.6 ± 3.5	68.2 ± 2.9	59.6 ± 2.8	60.2 ± 3.0	43.248	109.075	1865	1477 ± 62	74.4	0.11	14.5	0.87	0.40	2.97	0.03	4.74	1.26	0.02	73	9.0[§]	2.0[§]
BL92-34-BLV	99.5 ± 6.5	81.2 ± 4.5	62.8 ± 3.9	62.9 ± 4.1	43.244	109.074	1880	1010 ± 56	71.2	0.26	15.4	1.66	0.39	1.79	0.03	6.78	1.85	0.02	537	9.5	0.5
BL92-35-BLV	126 ± 5.1	102 ± 3.5	84.9 ± 3.3	88.8 ± 4.3	43.244	109.074	1880	1392 ± 47	71.0	0.29	14.1	2.44	0.78	2.36	0.04	4.82	1.52	0.02	260	9.0	3.0
BL92-36-BLV	93.0 ± 6.3	84.2 ± 5.2	76.2 ± 5.1	80.6 ± 6.8	43.242	109.075	1895	1736 ± 102	64.1	0.46	18.1	3.74	1.28	5.68	0.06	5.16	0.99	0.03	101	8.0	1.5
BL92-37-BLV	88.9 ± 7.0	77.5 ± 5.4	64.9 ± 5.0	65.6 ± 5.6	43.241	109.076	1905	1260 ± 86	67.9	0.28	16.5	3.06	1.00	3.55	0.06	5.87	0.99	0.03	143	12.0	0.5
Bull Lake IX																					
BL92-39-BLIV	56.3 ± 2.6	53.3 ± 2.4	48.3 ± 2.2	48.5 ± 2.3	43.244	109.070	1865	2046 ± 224	74.7	0.16	12.5	1.12	0.36	1.86	0.02	3.20	3.51	0.04	89	7.0[§]	0.5[§]
BL92-40-BLIV	76.7 ± 4.4	72.4 ± 4.0	68.8 ± 3.9	73.6 ± 5.3	43.245	109.070	1860	1644 ± 84	56.7	0.52	21.5	4.79	2.27	5.91	0.08	5.03	1.92	0.02	96	12.0[§]	2.0[§]
BL92-42-BLIV	122 ± 7.8	107 ± 6.1	95.4 ± 5.7	105 ± 9.3	43.245	109.069	1850	2184 ± 117	71.2	0.26	15.3	1.76	0.40	4.15	0.03	4.79	0.96	0.02	84	9.5[§]	0.5[§]
BL92-44-BLIV	119 ± 7.6	99.2 ± 5.5	84.4 ± 5.1	88.8 ± 5.7	43.247	109.067	1830	1403 ± 75	65.8	0.35	17.2	2.71	0.89	4.24	0.04	5.54	1.11	0.04	220	6.0	4.0
BL92-46-BLIV	124 ± 11	103 ± 7.5	85.8 ± 7	89.3 ± 9.2	43.249	109.067	1825	1723 ± 122	74.0	0.16	14.0	1.62	0.29	2.40	0.02	4.99	1.46	0.17	139	6.5	0.5
Bull Lake IV																					
BL92-49-BLIVB	126 ± 11	111 ± 8.5	103 ± 8.5	123 ± 18	43.235	109.055	1825	1976 ± 141	70.7	0.32	15.2	2.39	0.65	1.39	0.03	3.34	5.66	0.03	209	7.0[§]	0.5[§]
Bull Lake III																					
BL92-47-III	146 ± 12	117 ± 8	105 ± 8.2	127 ± 18	43.232	109.054	1835	1091 ± 71	48.7	1.46	11.0	15.60	8.19	11.70	0.23	1.47	0.28	0.05	831	6.0[§]	3.0[§]
Bull Lake II																					
BL92-53-BLII	83.1 ± 4.8	76.3 ± 4.1	69.1 ± 3.9	71.6 ± 4.8	43.224	109.056	1900	1739 ± 88	71.6	0.20	15.0	1.54	0.54	2.08	0.03	4.71	3.00	0.02	101	7.5	1.0
BL92-54-BLII	152 ± 6.8	130 ± 5.2	123 ± 5.3	179 ± 20	43.224	109.057	1900	1977 ± 73	51.4	0.79	13.7	12.10	6.88	11.30	0.20	1.86	0.28	0.03	223	5.0	3.0
BL92-56-BLII	67.0 ± 9.5	63.2 ± 8.3	58.9 ± 8.3	61.0 ± 10	43.223	109.057	1905	1385 ± 179	49.2	0.47	15.4	9.36	9.47	12.30	0.16	1.50	0.33	0.02	133	6.0	3.0
BL92-57-BLII	74.6 ± 11	68.0 ± 9.2	60.2 ± 8.1	60.4 ± 9.8	43.222	109.057	1905	1358 ± 240	75.0	0.12	13.8	1.11	0.23	1.29	0.03	4.85	3.33	0.03	128	9.0[§]	1.0[§]
Sacagawea Ridge (SR)																					
BL92-60-SR	259 ± 11	219 ± 8.1	215 ± 8.8	inf	43.388	109.328	2090	5462 ± 163	73.5	0.21	14.0	1.54	0.39	1.93	0.03	4.47	2.92	0.06	84	9.0[§]	1.0[§]
BL92-62-SR	149 ± 11	138 ± 10	136 ± 10	326 ± inf	43.388	109.328	2095	3670 ± 221	50.4	0.41	14.6	9.66	8.90	12.30	0.17	1.46	0.52	0.02	108	9.0	4.0
BL92-63-SR	126 ± 6.0	119 ± 5.5	118 ± 5.6	191 ± 28	43.386	109.328	2110	3479 ± 141	50.8	0.44	13.1	10.70	9.23	13.00	0.19	1.16	0.12	0.03	94	9.0[§]	4.0[§]
BL92-64-SR	261 ± 16	232 ± 12	232 ± 12	inf	43.387	109.329	2110	6609 ± 264	74.7	0.16	12.8	1.17	0.22	0.52	0.02	3.61	4.60	0.03	82	9.0[§]	1.0[§]
BL92-67-SR	151 ± 3.5	137 ± 3.0	132 ± 3.0	213 ± 16	43.382	109.332	2150	4277 ± 133	73.9	0.13	13.3	0.93	0.24	1.34	0.02	4.37	3.32	0.04	71	9.0[§]	1.0[§]
BL92-68-SR	99.9 ± 8.9	95.4 ± 8.1	93.6 ± 8.2	115 ± 18	43.381	109.332	2155	3746 ± 292	74.8	0.12	13.1	1.05	0.24	0.64	0.02	3.61	4.76	0.04	65	9.0[§]	1.0[§]
Bull Lake Terrace (BLT)																					
BL92-70-BLT	125 ± 6.5	110 ± 5.2	102 ± 5.2	123 ± 11	43.463	109.484	2035	2133 ± 95	74.4	0.27	13.5	1.99	0.52	1.44	0.02	3.26	4.29	0.20	180	7.0[§]	5.0[§]
BL92-71-BLT	116 ± 3.2	102 ± 2.5	93.6 ± 2.5	107 ± 4.2	43.463	109.474	2035	1908 ± 45	74.0	0.24	13.6	2.01	0.36	1.37	0.03	3.79	4.18	0.09	191	7.0	5.0
BL92-72-BLT	115 ± 4.2	99.8 ± 3.2	89.6 ± 3.1	98.6 ± 4.9	43.464	109.474	2035	1832 ± 58	73.4	0.17	13.9	1.27	0.39	1.67	0.02	3.73	3.66	0.05	197	5.0	5.0
BL92-73-BLT	331 ± 16	256 ± 11	255 ± 12	inf	43.466	109.474	2035	4265 ± 134	73.3	0.24	13.6	1.84	0.54	1.36	0.02	3.13	4.59	0.08	216	7.0[§]	5.0[§]
Pinedale Terrace (PNT)																					
BL92-75—PNT	18.8 ± 0.9	17.7 ± 0.9	16.4 ± 0.8	16.4 ± 0.8	43.729	109.556	2055	496 ± 24	72.0	0.22	14.3	1.33	0.39	1.81	0.02	4.23	3.51	0.03	91	7.0[§]	5.0[§]
BL92-76-PNT	21.3 ± 1.1	20.7 ± 1.0	18.4 ± 0.9	18.4 ± 0.9	43.730	109.555	2055	504 ± 25	74.9	0.24	13.4	1.56	0.40	1.39	0.03	3.80	3.77	0.03	126	7.0	0.5
BL92-78-PNT	27.1 ± 4.1	26.6 ± 3.9	24.6 ± 3.6	24.6 ± 3.6	43.731	109.556	2055	874 ± 127	74.5	0.18	12.9	1.02	0.28	0.93	0.02	3.31	5.05	0.04	92	7.0[§]	0.5[§]
BL92-79-PNT	15.2 ± 1.6	15.0 ± 1.5	13.8 ± 1.3	13.8 ± 1.3	43.730	109.554	2055	444 ± 44	75.7	0.10	12.5	0.60	0.24	1.16	0.01	3.27	4.05	0.02	96	7.0[§]	0.5[§]
Bull Lake V moraine at Fremont Lake																					
FL92-1	106 ± 7.8	93.5 ± 6.3	85.4 ± 6.2	94.8 ± 9.9	42.896	109.800	2315	1960 ± 90	65.0	0.76	16.6	5.27	1.10	3.84	0.05	4.31	3.11	0.04	218	1.5	6.4
FL92-2	79.6 ± 4.0	71.9 ± 3.3	63.1 ± 3.1	64.2 ± 3.6	42.893	109.802	2290	1740 ± 80	71.5	0.44	14.8	2.38	0.39	3.20	0.03	4.93	1.54	0.03	109	3.0	4.8
FL92-3	124 ± 4.9	112 ± 4.2	106 ± 4.1	133 ± 9.5	42.890	109.803	2270	3210 ± 110	77.4	0.16	11.9	1.15	0.23	1.62	0.02	2.77	4.31	0.03	120	3[§]	4.8[§]
FL92-4	104 ± 4.7	92.9 ± 3.8	85.6 ± 3.8	96.4 ± 6.1	42.909	109.849	2285	1760 ± 67	64.5	0.76	16.1	5.59	1.28	4.18	0.08	4.85	2.19	0.04	189	8[§]	8[§]
FL92-5	123 ± 5.5	114 ± 4.8	111 ± 4.8	158 ± 16	42.913	109.845	2310	3150 ± 120	67.1	0.53	16.2	3.42	0.59	3.63	0.04	4.57	3.18	0.04	109	8[§]	8[§]
FL92-6	97.5 ± 5.2	85.2 ± 4.0	74.0 ± 3.9	76.6 ± 4.8	42.964	109.846	2325	1900 ± 90	70.5	0.41	15.0	2.80	0.57	3.27	0.03	4.11	2.94	0.06	213	0.5	3.7
FL92-7	101 ± 9.1	93.5 ± 7.9	89.7 ± 8.0	108 ± 16	42.914	109.848	2300	2150 ± 170	64.8	0.97	15.5	6.24	0.79	3.83	0.05	4.29	3.09	0.04	144	8.4	8.5

*^{36}Cl age categories are illustrated in Figure 2. Reported age uncertainties reflect only ^{36}Cl/Cl analytical uncertainties. Reported uncertainties are plus or minus one standard deviation.

†^{36}Cl/Cl ratios are reported after all analytical corrections.

§Indicates estimated value.

TABLE 2. ^{10}BE AND ^{10}BE/^{36}CL AGES AND EROSION RATES

^{36}Cl sample no.	^{10}Be sample no.	Unit	^{10}Be (10^6 atoms/g)	^{10}Be Zero Erosion Age (ka)	^{36}Cl Zero Erosion Age (ka)	Combined age* (ka)	Erosion rate* (mm/ka)
BL92-7	BRL 872	PN3	0.448 ± 0.026	19.2 ± 1.1	21.0 ± 0.8	20.5 ± 1.0	2.4 ± 2.0
BL92-12	BRL 873	PN2	0.342 ± 0.020	15.0 ± 0.9	22.8 ± 1.6	18.5 ± 1.5	12 ± 6
BL92-26	BRL 874	BL XIII	2.43 ± 0.07	111 ± 3.3	112 ± 4.0	110 ± 4	<0.2
BL92-35	WY-93-320	BL XII	2.56 ± 0.08	118 ± 4	126 ± 5.1	121 ± 5	0.15 ± 0.15
BL92-42	BRL 875	BL IX	2.72 ± 0.08	126 ± 4	122 ± 7.8	126 ± 6	<0.2
BL92-44	BRL 876	BL IX	2.77 ± 0.14	131 ± 7	119 ± 7.6	129 ± 9	<0.1
BL92-60	WY-92-144	SR	7.74 ± 0.23	331 ± 11	259 ± 11	†	†
BL92-64	BRL 877	SR	7.01 ± 0.27	283 ± 15	261 ± 16	274 ± 22	<0.2
BL92-67	WY-92-145	SR	3.98 ± 0.12	154 ± 5	151 ± 3.5	153 ± 6	<0.1
FL92-7	WY-91-007	BLt2	3.32 ± 0.10	114 ± 4	101 ± 9.1	113	

*Combined age and erosion rate are calculated from both ^{36}Cl and ^{10}Be data, using model illustrated in Figure 7.
†No solution in combined ^{36}Cl/^{10}Be model.

Calculation of Surface-Exposure Ages

The principles of ^{36}Cl buildup dating, and of cosmogenic nuclide dating of surface exposures in general, were described by Phillips et al. (1986), Cerling and Craig (1994), and Lal (1991). The calculated rate of cosmogenic nuclide production depends on the elevation and latitude of the sample, the extent of shielding of the sample by surrounding topography from exposure to cosmic rays, and the concentrations of the target elements and assumed elemental production rates. The elevation and latitude dependence of the ^{36}Cl production was calculated using the coefficients given in Table 2 of Lal (1991). The piedmont settings of the moraines we sampled are flat, and no topographic shielding corrections were necessary. For the ^{36}Cl production parameters we used the values (scaled to high latitude and sea level) determined by Phillips et al. (1996a): 73.3 ± 4.9 atoms ^{36}Cl (g Ca)$^{-1}$ yr^{-1}, 154 ± 10 atoms ^{36}Cl (g K)$^{-1}$ yr^{-1}, and 586 ± 40 fast neutrons (g air)$^{-1}$ yr^{-1}.

Thermal neutron absorption by ^{35}Cl was calculated as a function of depth according to the formulation of Liu et al. (1994) and production by epithermal neutron absorption was calculated in an analogous fashion, as implemented in the computer program CHLOE (Chlorine-36 exposure) (Phillips and Plummer, 1996). Background production of ^{36}Cl by thermal neutrons resulting from U and Th decay-series nuclear reactions was calculated according to the method given by Fabryka-Martin (1988). Uranium and Th concentrations of 2.8 and 11 ppm, respectively, were assumed, as was a 3 cm sample thickness. A volumetric water content of 0.5% was assumed for all samples. For the calculation of ^{10}Be ages the elevation and latitude coefficients in Table 1 of Lal (1991) were applied. A ^{10}Be production rate (scaled to high latitude and sea level) of 5.60 atoms ^{10}Be (g quartz)$^{-1}$ yr^{-1} was used.

Typical analytical uncertainties for the ^{36}Cl/Cl measurements are in the range of 3% to 8%, except for low ^{36}Cl samples. Uncertainty in the other geochemical parameters typically adds another 3% to 5% uncertainty. Systematic uncertainty, however, is also important. For both ^{36}Cl and ^{10}Be (as for other cosmogenic nuclides) the largest systematic source of uncertainty in surface exposure ages is the production rate estimate. The ^{36}Cl production coefficients determined by Phillips et al. (1996a) for spallation reactions on Ca and K are within 15% of those theoretically calculated by Masarik and Reedy (1995) and are about 30% higher and 15% lower, respectively, than those obtained by Stone et al. (1996) and Evans et al. (1996). In contrast, the coefficients determined by Swanson (1996) are about 20% higher for spallation of Ca and 30% higher for spallation of K. The reasons for these discrepancies are not clear, but may relate to the nature of the sample suites used for calibration in the various studies. Stone et al. (1996) and Evans et al. (1996) used essentially single sample sites for calibration of production. Swanson (1996) used a large number of samples of varying lithology, but all were from a single locality (Whidby and Fidalgo Islands, Washington). In contrast, Phillips et al. (1996a) used 33 samples of widely varying ages from 15 separate localities. The approach employed in the first two studies may result in biased estimates if locality-specific factors introduce significant error, and the last approach may result in imprecision or compensating errors from the averaging of scaling factors and geochronological controls over wide geographical and temporal ranges. However, the internal statistics of the large number of samples measured by Phillips et al. (1996a) provide some means of testing this calibration. The average of the absolute deviations of the ^{36}Cl ages from the independent ages for all 33 samples was 10.7%, and that for the means of groups of replicate samples (2 to 5 replicates at 9 sites) was 4.6%. These statistics provide an empirical basis for estimating that the error in ^{36}Cl exposure ages due to both random (mainly analytical uncertainties in both the ^{36}Cl/Cl ratios and the elemental analyses) and systematic (mainly production coefficients, latitude and elevation scaling, and secular variation in production rates) sources probably does not exceed 15% for studies in which multiple samples are analyzed. Phillips et al. (1996a) did not find that incorporation of corrections for secular variation of production rates due to changes in geomagnetic field intensity improved the fit of the ^{36}Cl exposure ages to the independent ages. This result does not necessarily imply that such temporal variations are not significant, but it also does not provide any justification for corrections based on them, within the context of this set of production parameters, and we have therefore not corrected the ages in this study for varying production.

Estimates of ^{10}Be production yield about the same degree of variation. On the basis of measured ^{10}Be accumulation in glacially polished Sierra Nevada samples (Nishiizumi et al., 1989), the production rate in quartz (normalized to high latitude and sea level) was estimated to be 6.0 atoms ^{10}Be (g quartz)$^{-1}$ yr^{-1}. On the basis of a revised chronology for Sierra Nevada glaciation, as well as additional data from other areas, Clark et al. (1995) proposed a production rate in the range 4.75 to 5.10 atoms (g quartz)$^{-1}$ yr^{-1}. Brown et al. (1991) obtained a production rate of 6.4 atoms (g quartz)$^{-1}$ yr^{-1} for samples from Antarctica. For this study, the production rate was estimated using the modern production rate of 5.32 atoms (g quartz)$^{-1}$ yr^{-1} experimentally measured by Nishiizumi et al. (1996) as a starting point. This production rate was corrected for modulation by fluctuations in the dipole geomagnetic field intensity using the intensity reconstructions of McElhinny and Senanayake (1982), Meynadier et al. (1992) and Valet and Meynadier (1993). Following the approach of Nishiizumi et al. (1989), the production rate at the latitude and altitude of the Wind River Range was integrated through the magnetic field variations of the past 300 k.y. For the period from 300 to 25 ka, the effective integrated production rate varied from 5.50 to 5.67 atoms (g quartz)$^{-1}$ yr^{-1}. The value of 5.60 atoms (g quartz)$^{-1}$ yr^{-1} was selected because most of the samples analyzed for ^{10}Be were toward the older end of the age range. In order to be consistent with the ^{36}Cl calculations a constant production rate was employed.

Internal consistency between the ^{36}Cl and ^{10}Be production rates is probably more important for the purposes of this study than is the absolute accuracy of either one. This consistency can be checked using data from a granite boulder in the Sierra Nevada that was cored and analyzed for both nuclides by Dep (1995). The ^{36}Cl content of the boulder gives an exposure age of 97 ka when the exposure-age calculation methodology described herein is applied to Dep's (1995) data. This age is comparable to that of the Bull Lake–age boulders we investigated. Analysis of the ^{36}Cl profile, which is very sensitive to erosion, showed that the rate of rock erosion was negligible (Dep, 1995). The relative ^{36}Cl and ^{10}Be concentrations should therefore reflect only the ratio of the production rates. Using the nuclide concentration data reported by Dep (1995) and the ^{36}Cl production rates of Phillips et al. (1996a), the ^{36}Cl-consistent ^{10}Be production rate is back calculated to be 5.4 ± 0.3 atoms ^{10}Be (g quartz)$^{-1}$ yr^{-1}. This rate agrees, within analytical uncertainty, with the value of 5.60 adopted in this study.

Several issues related to the systematics of cosmogenic nuclide production remain unresolved. These include the refinement of production-rate parameters, the quantification of nuclide production by muons, the role of muon production in elevation and latitude scaling, and the correction of production rates for fluctuations in geomagnetic field intensity. After these issues have been resolved, cosmogenic ages calculated on the basis of our present understanding will need to be revised. On the basis of the empirical evidence discussed previously, we do not anticipate that the magnitude of these corrections will exceed 15%.

INTERPRETATION OF ^{36}Cl AGES

Stated in the most general way, the accumulation of a cosmogenic nuclide in an eroding landform such as a moraine is a function of the time of exposure and the erosion rate (here we use *erosion* simply to denote the progressive removal of mass from the surface with time; no mechanism is implied). In reality, the process of erosion can lead to complex results. Erosion rates cannot be expected to be uniform, either temporally or spatially. Furthermore, the response to erosion can be complex. For a purely spallogenic nuclide (such as ^{10}Be), the buildup is only a function of the erosion rate and not of the rock composition, because production follows a simple exponential dependence on depth. However, the depth profile of ^{36}Cl production depends both on the proportion of production by spallation versus that by thermal and epithermal neutron absorption (which in turn depends on the concentrations of

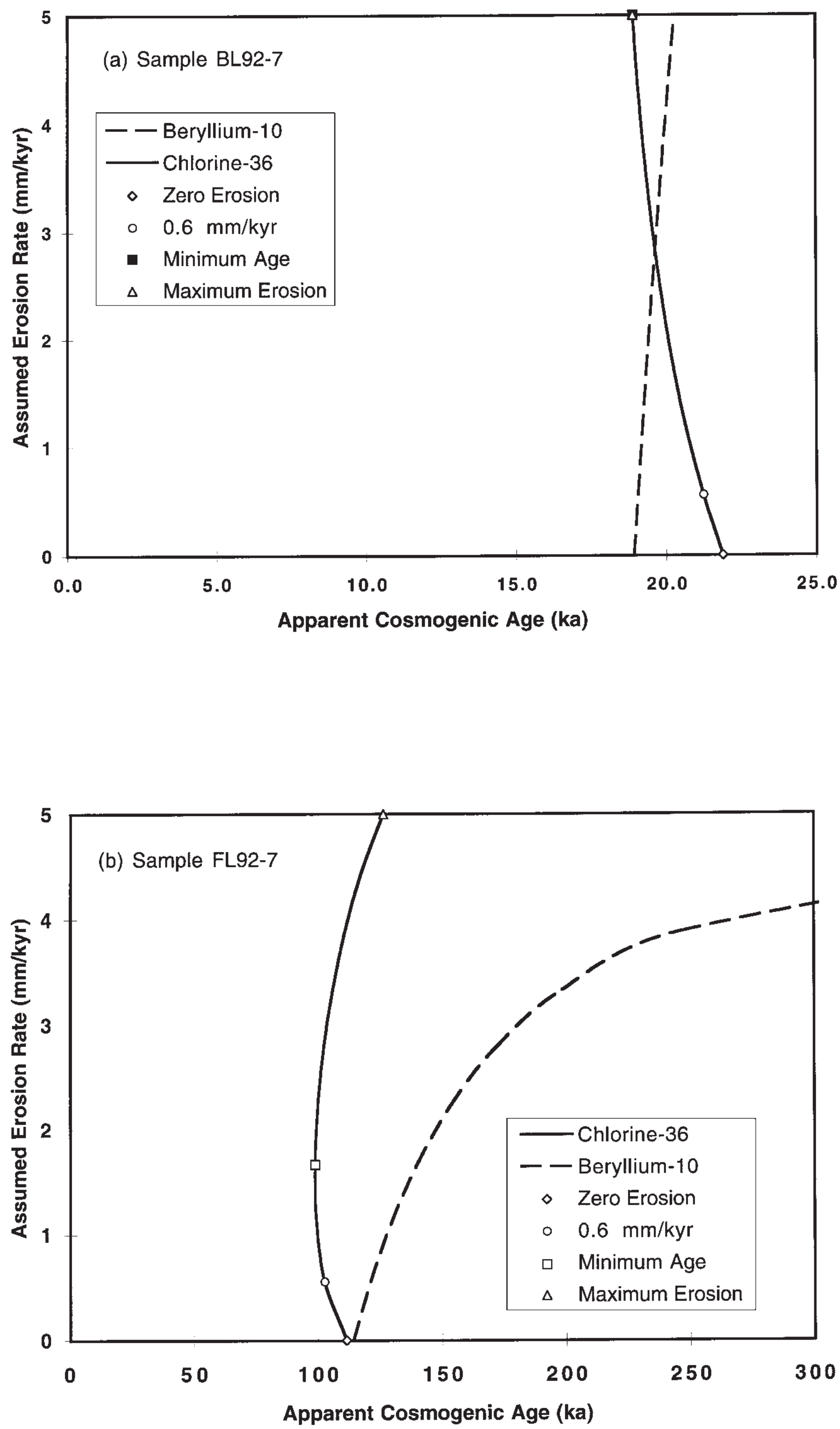

Figure 2. (A) Sample BL92-7. (B) Sample FL92-7. Illustrations of combined ^{36}Cl and ^{10}Be apparent ages as functions of assumed erosion rates. The combination of age and erosion rate that is consistent with the concentrations of both nuclides is that at the intersections of the two curves. The zero erosion, 0.6 mm/k.y., minimum age, and Maximum Erosion designations used in Figures 3 and 4 are indicated on the ^{36}Cl curve.

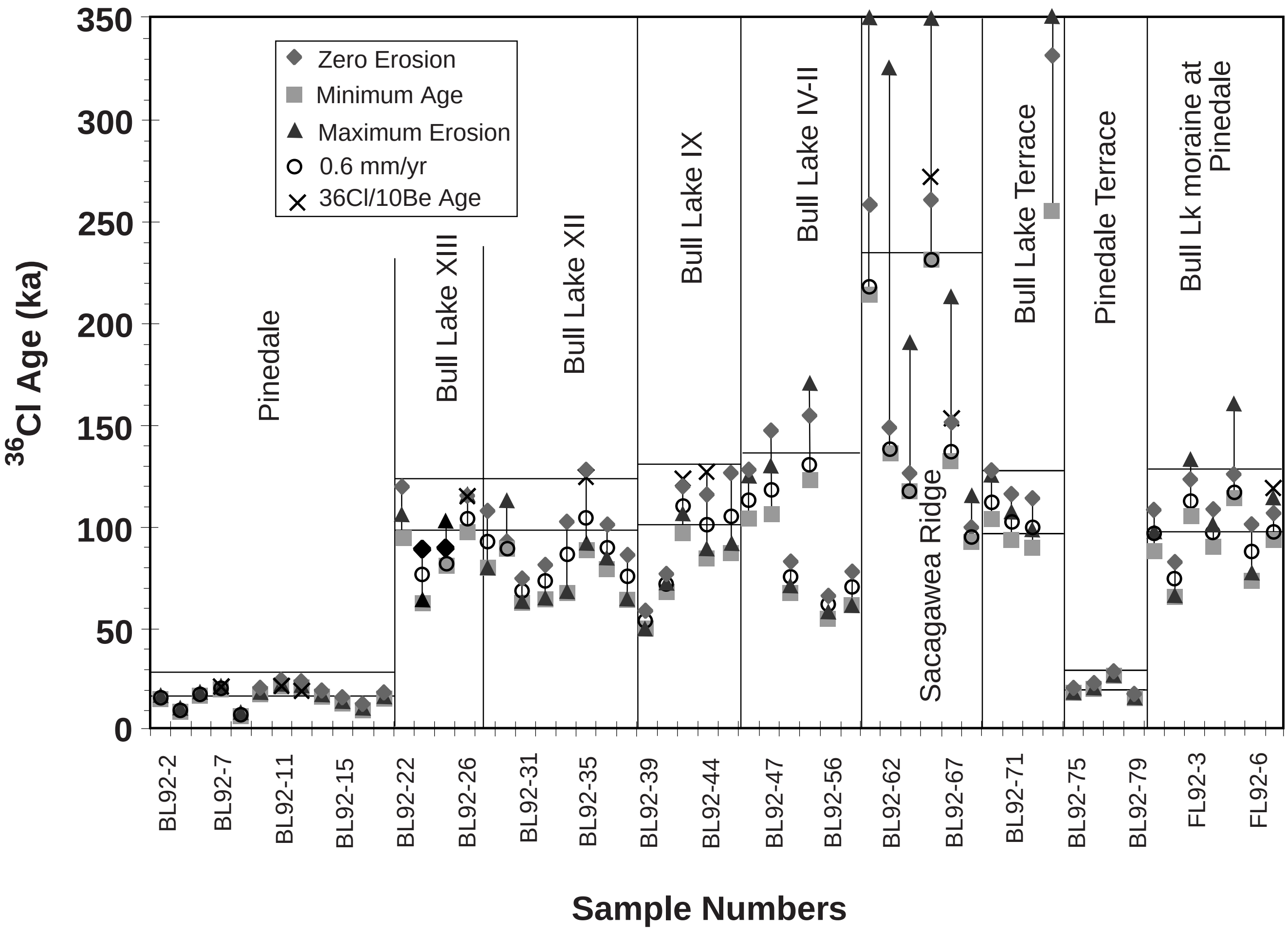

Figure 3. Summary of ^{36}Cl apparent ages and ^{36}Cl/^{10}Be ages for Wind River Range samples. The significance of the categories of ages is illustrated in Figure 2. Symbols at the top of the graph (350 ka) indicate infinite apparent ages.

Ca, K, and Cl) and on the bulk composition of the rock (which governs the depth distribution of the thermal neutron flux). The apparent age can be calculated as a function of assumed erosion rate for any sample, but this relationship will vary widely for samples of differing composition (Fig. 2). In Table 1 and Figures 3 and 4 we have calculated apparent exposure ages for four different assumed erosion rates: zero erosion (i.e., a stable surface); 0.6 mm/k.y. (which our data, discussed below, indicate to be a typical erosion rate); the minimum apparent age calculated over the entire range of 0 to 5 mm/k.y. (designated minimum age in Table 1); and the apparent age calculated assuming an erosion rate of 5 mm/k.y. (designated maximum erosion because it represents an upper limit to the erosion rate).

In spite of this complexity of response, a simple solution for the exposure age can be obtained if some assumptions can be justified. If all samples have eroded at a temporally uniform rate, and if the erosion rates can be bounded, when the range of possible age solutions is plotted as in Figure 3, the actual age of the surface should correspond to the time interval for which all of the sample ages overlap. Unfortunately, this simple approach is not directly applicable to boulders on moraines. The rate of erosion of the till matrix is high (typically ≥ 1 cm/k.y.), whereas that of boulder surfaces is low (about 1 mm/k.y.). As a result, many boulders that are sampled on older moraines are likely to have undergone rapid erosion of overlying till while they were buried within the moraine, then slow erosion of the rock surface subsequent to exhumation. This type of erosion history was modeled and experimentally investigated by Zreda et al. (1994). They showed that soil erosion produces a distribution of apparent ages between the actual moraine age and some younger age limit, the width of the distribution being proportional to the moraine age and the actual age being close to the maximum of the distribution. We have used these results as a guide in interpreting the age distributions observed on the Bull Lake moraines.

We estimate age ranges for individual moraines, rather than specify single values, due to the range in age that is produced by considering the effects of erosion. The estimated age ranges are based on inspection of the boulder age distributions plotted in Figure 3. We define the upper limit of the range on the basis of closely grouped maximum ages, inasmuch as the modeling results of Zreda et al. (1994) showed a clustering of apparent ages close to maximum limit provided by the actual moraine age. The lower limit is less easily defined, but is usually selected to include at least the maximum ages of some of the younger boulders, as well as the apparent age calculated for the older boulders using a rock-erosion rate of 0.6 mm/k.y. This value was chosen on the basis of a conservative interpretation of the results of the combined ^{36}Cl/^{10}Be analyses, described in the following. In some cases, such as Bull Lake moraines BLIV–BLII and Sacagewea Ridge moraines, there was no well-defined upper limit and we assigned only a minimum age, using

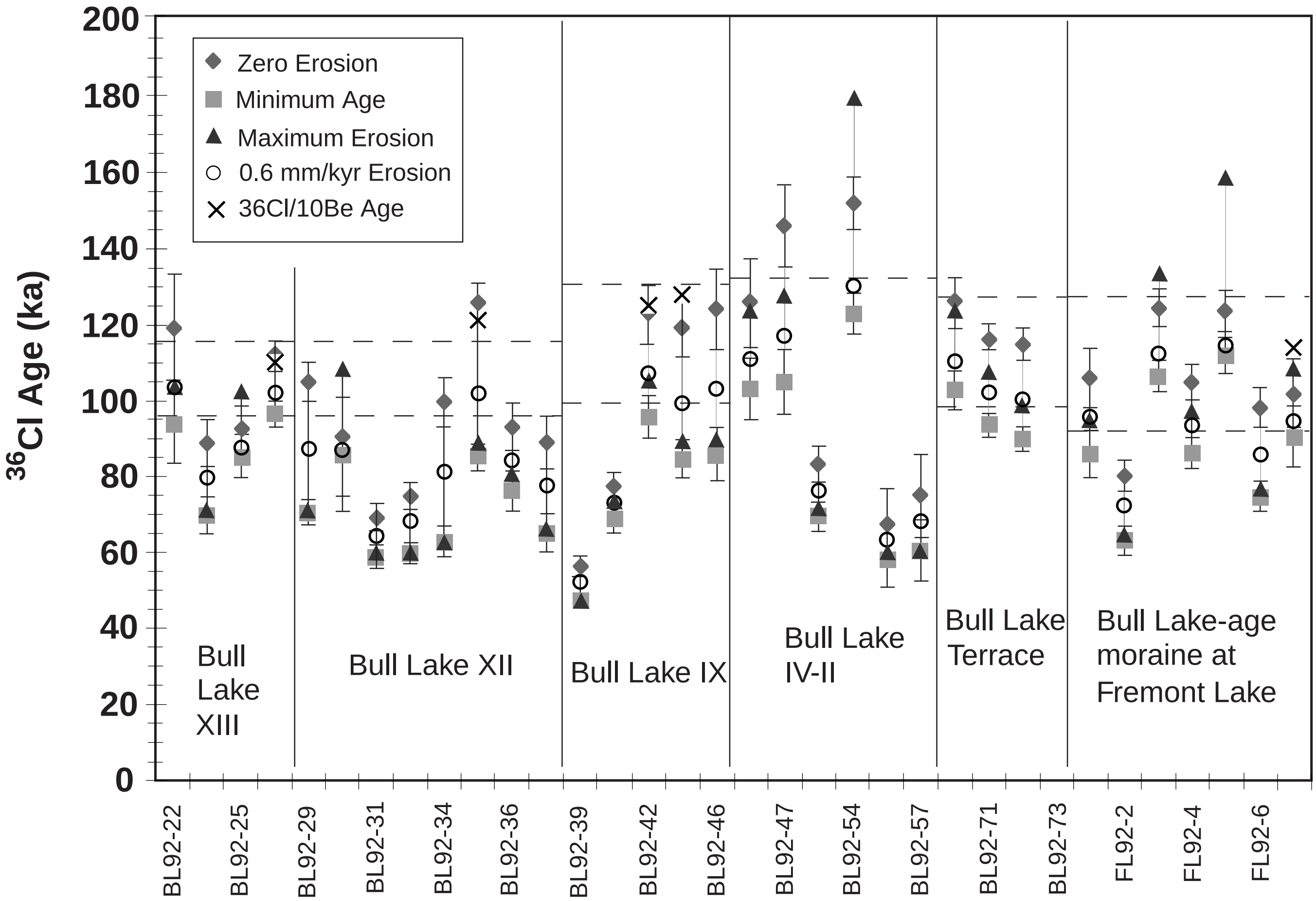

Figure 4. Summary of ^{36}Cl apparent ages and $^{36}Cl/^{10}Be$ ages for the Bull Lake–age moraines at Bull Lake and Fremont Lake and the "Bull Lake terrace" (WR3). Error bars illustrating age uncertainties arising from analytical uncertainty in the $^{36}Cl/Cl$ ratios are shown for the zero erosion and minimum age points.

the minimum erosion-dependent apparent age from the boulder giving the oldest minimum age. The age ranges selected for each moraine are indicated by the dotted horizontal lines in Figures 3, 4, and 5. The age range estimates do not include analytical and systematic uncertainties, which total in the range of 10% to 15%.

In addition to the effects of erosion, the possibility that a sample was exposed to cosmic radiation prior to deposition on a moraine (or other landform) must also be considered. Although in a few cases such inheritance is obvious (e.g., sample BL92-73), it does not appear to be a common problem for glacial deposits, as evidenced by the numerous tightly grouped ages of the type Pinedale moraines obtained by Gosse et al. (1995b).

Sacagewea Ridge Moraine

The Sacagewea Ridge moraine (Richmond and Murphy, 1989) at Dinwoody Lakes is preserved as a broad, low ridge, clearly a much-degraded remnant of the original morainal topography. Few large boulders remain on the surface; only seven boulders higher than 1 m could be located on the entire moraine, and only one was higher than 2 m. The boulders are rounded, and most are extensively weathered. The maximum age limit is undefined. For erosion rates greater than 3 to 4 mm/k.y., samples BL92-60, BL-62, and BL-64 gave infinite ages. The minimum age for the oldest sample (BL92-64) was selected as defining a limiting minimum age of 232 ka for the moraine.

On the basis of correlation of the outwash terrace below the moraine with a fluvial terrace on the opposite (west) side of Dinwoody Lake that contains the Lava Creek B tephra, the Sacagewea Ridge glaciation has been dated as 660 ± 20 ka (Chadwick et al., 1997). Our ^{36}Cl ages are consistent with this assignment, although they could also be consistent with an age assignment as young as about 250 ka.

Bull Lake Moraines

The ^{36}Cl age distribution for the Bull Lake–age moraines is illustrated in Figures 3 and 4. In general, the Bull Lake moraines BLXII through BLIX have similar boulder frequencies and amounts of apparent rock weathering. Morainal forms are distinct. Numerous boulders from 1.5 to 2.5 m high are available for sampling. On the basis of surface texture and angularity, we believe that many of the surfaces of boulders sampled underwent negligible rock erosion after deposition. In contrast, boulders are uncommon on the surfaces of the Bull Lake moraines BLIV through BLI. Morainal topography is subdued. The largest boulders observed were ~1.5 m high and some boulders less than 1.0 m high were sampled due to the lack of anything larger. Boulder surfaces were generally much more rounded than on moraines BLXII through BLIX, and many showed clear indications of granular disintegration or spalling.

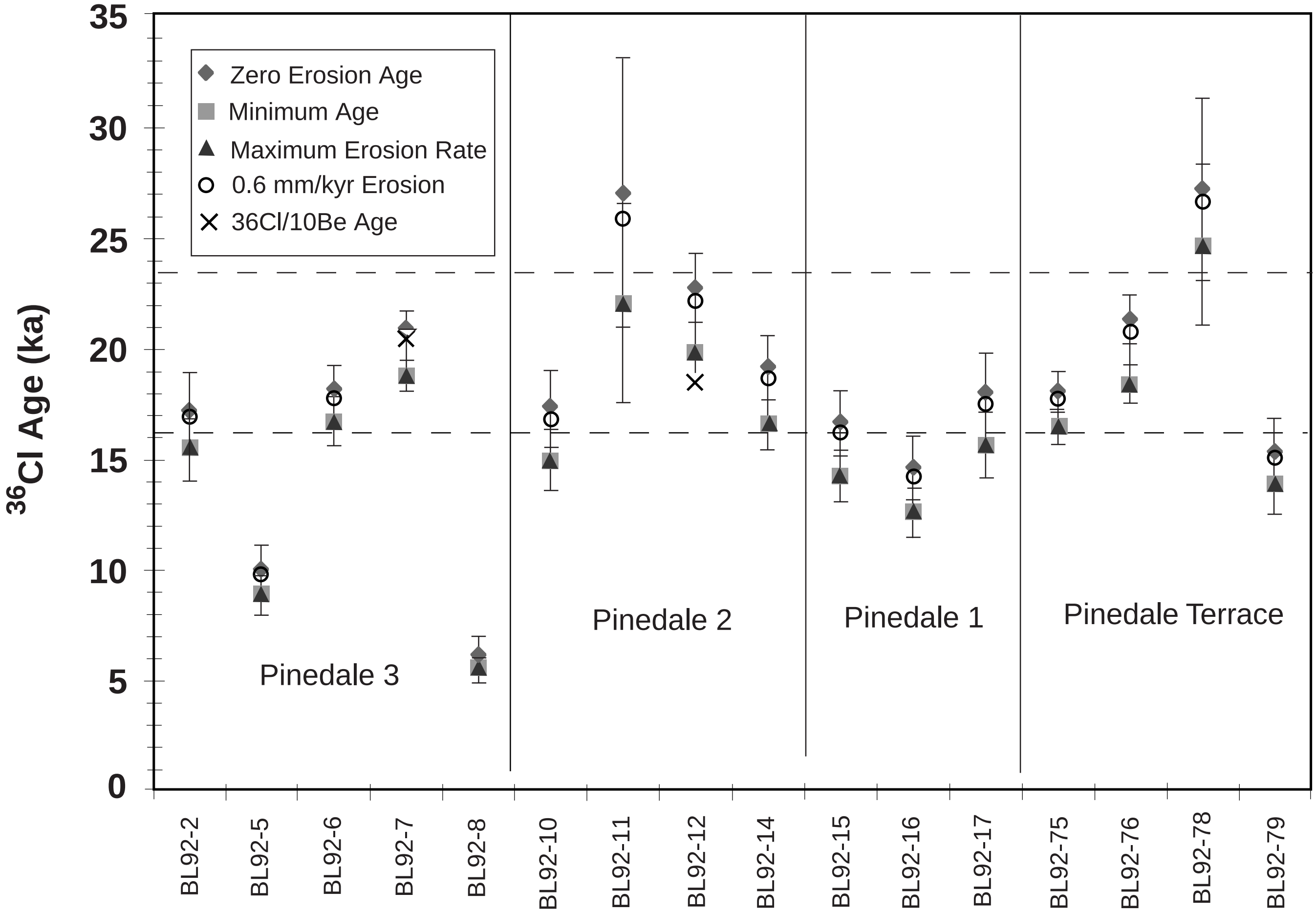

Figure 5. Summary of ^{36}Cl apparent ages and ^{36}Cl/^{10}Be ages for Pinedale-age moraines at Bull Lake and the "Pinedale terrace" (WR1). Error bars illustrating 1σ age uncertainties arising from analytical uncertainty in the ^{36}Cl/Cl ratios are shown for the zero erosion and minimum age points.

Bull Lake moraines BLXIII and BLXII exhibit such similar distributions of ^{36}Cl ages that they cannot be easily distinguished. Maximum ages in both distributions have a poorly defined upper limit close to 115 ka; there is one slightly older outlier (BL92-35, 126 ka). Bull Lake moraine BLIX has an upper limit close to 125 ka, as defined by three out of five samples. The Bull Lake BLIV through BLII moraine group shows a much wider scatter than the younger moraines, and there is no clearly defined maximum. Given this distribution and the field observations regarding the absence of well-preserved large boulders, the data are best interpreted as providing only a limiting minimum age of about 130 ka. Minimum limits were estimated as previously described (Table 2).

The ^{36}Cl age distribution for the Pinedale-age moraines is detailed in Figure 5. All but two of the samples are within the range 23.0 to 15.8 ka. The numbers of samples are not sufficient to estimate age ranges individually for the three Pinedale crests. The ages for the Pinedale 2 crest appear to be slightly older than those for Pinedale 3, in conformity with the relative age sequence, but there is a minor reversal in the Pinedale 1 ages, which stratigraphically should be the oldest of the three. We believe that this reversal is due to the Pinedale 1 sampling position. The other Pinedale samples were collected from moraine crest positions, but along our west-to-east sampling transect, the Pinedale 1 moraine formed a low bench in front of the younger Pinedale moraines. Although this bench is 2–3 m above a nearby drainage channel, we suspect that it was dissected by meltwater during the early stages of deglaciation and that the ages at this position reflect that dissection event rather than the timing of moraine deposition.

Wind River Terraces

We sampled large boulders on two terraces above the Wind River. The upper terrace was called the Bull Lake terrace (WR 3 of Chadwick et al., 1997). It was sampled on the high surface between the east and main forks of the Wind River, 2 km north of the confluence. At this point the terrace surface is 60 m above the present level of the Wind River. This terrace is correlative with the Circle terrace of Blackwelder (1915) and can be traced directly to Bull Lake age outwash and moraines at Whiskey basin. The boulders sampled ranged from 2 to 3 m in height. The boulders apparently were deposited in their present position by an outburst flood that resulted from a glacial lobe pushing across the Wind River at Whiskey basin (Chadwick et al., 1997). One of the boulders (BL92-73) has clearly undergone prior exposure (Fig. 4), but the upper age limit of the other boulders from this terrace (ca. 125 ka) is similar to that for Bull Lake moraine BLIX and strongly suggests that the boulders were deposited on the WR 3 surface during this phase of the Bull Lake glaciation.

The lower terrace, called the Pinedale terrace (WR 1 of Chadwick et al., 1997) was sampled between Jakeys Fork and Torrey Creek, on the southwest side of the Wind River. The terrace is about 3 m above the present level of the Wind River. The boulders sampled ranged from 2 to 4 m in height and were probably deposited due to a later outburst flood from an ice lobe in the same position as the lobe that which produced the Bull Lake terrace boulders. The zero erosion ages vary between 27 and 15 ka (Fig. 5), very similar to the distribution of ages for the Pinedale moraines at Bull Lake.

Bull Lake–Age Moraine at Fremont Lake

For purposes of comparison with the ^{10}Be and ^{26}Al dating being conducted at Fremont Lake (Gosse et al., 1995b), and to test for possible early Wisconsin (isotope stage 4) glaciation, we collected seven samples from the innermost Bull Lake–age moraine (BL V of Richmond, 1987) near the southwestern end of Fremont Lake. (Note that the numbering schemes of Richmond at Fremont Lake and that of Chadwick et al. [1997] at Bull Lake are not intended to be correlative.) The boulders were 2 to 4 m in height. The distribution of ^{36}Cl ages, shown in Figure 4, was quite similar to that for the Bull Lake moraine BLIX at Bull Lake, giving limits of 120 to 100 ka.

Correlation of the Bull Lake V moraine at Fremont Lake with the Bull Lake moraine BLIX at Bull Lake, as suggested by the ^{36}Cl age distributions, appears to be anomalous, inasmuch as the BLIX moraine is nearly the outermost Bull Lake moraine loop at Bull Lake and the V moraine is the innermost Bull Lake moraine at Fremont Lake. However, relative positions may be misleading, given the geomorphic settings at the two localities. At Fremont Lake the Bull Lake moraines form a relatively compact band (typically 0.8 to 1.0 km wide) of contiguous ridges that in most places lie immediately outward from the Pinedale moraine band (Richmond, 1987). In contrast, the glacier at Bull Lake had two lobes that had different characteristics. The northern lobe was formed by ice that overflowed the main trough and advanced over a relatively flat topography sloping gently toward Bull Lake. The type Bull Lake–age moraines at this site form a broad band (typically 1.5 to 2.0 km wide); many of the individual ridges are often separated by outwash-filled depressions. It was probably this distinctness and separation of the moraines that caused Blackwelder (1915) to designate it as the type locality. In contrast, the eastern lobe was formed by ice flowing down the deep trough that is now partially filled by Bull Lake. There are no Bull Lake–age moraines preserved for this lobe; the Pinedale glacier advanced completely over whatever Bull Lake moraines were originally present. This anomalous relationship (relative to the more typical situation at Fremont Lake) is possibly explained by progressive downcutting of the Bull Lake trough in response to the gradual lowering of the Wind River base level (Chadwick et al., 1997). This downcutting would increase both the cross-sectional area and the gradient of the main (eastern) glacial lobe with time, causing an increase in the ice discharge of this lobe that would result in younger advances overriding the deposits of earlier glaciations. This diversion of some of the ice discharge to the eastern lobe would progressively starve the northern lobe, causing successive advances to be less extensive. As a result of this long-term instability it is possible that in the Bull Lake north lobe certain moraines of less extensive advances were preserved, whereas at most valleys they were later covered by Pinedale deposits. In summary, the innermost Bull Lake–age moraines at Fremont Lake may not necessarily correlate with the innermost Bull Lake–age moraines at Bull Lake, but rather with some other moraine toward the outside of the complex.

^{10}Be DATA AND INTERPRETATION

The results from the 10 samples also analyzed for ^{10}Be are given in Table 2. In general, the comparison of the ^{10}Be zero-erosion ages with those calculated from the ^{36}Cl data is favorable. For six of the samples the ages are indistinguishable, within 1 σ error limits (Fig. 6). Two sample ages (BL92-7 and BL92-35) are discordant to a degree only slightly greater than the analytical uncertainties, and are in a direction consistent with the effects of erosion. Of the remaining two, one (BL92-60) was from the Sacagewea Ridge moraine, which is erosionally modified to an extent that renders plausible complex exposure histories. The hypothesis of complex history (i.e., more than one episode of erosional exposure and reburial) is supported by the measured ^{26}Al concentration of 2.402×10^7 atoms/g, which is not consistent with the ^{10}Be concentration for a simple exposure history. For sample BL92-12, the zero-erosion ^{10}Be age (15.0 ± 0.9 ka) is much younger than the ^{36}Cl age (22.8 ± 1.6 ka). Although the direction of the discrepancy could be explained by erosion, the magnitude is anomalously large. The zero-erosion ^{10}Be age is not only much younger than the ^{36}Cl age, it is also younger than the ^{10}Be ages of 20 out of 21 boulders sampled on the Pinedale recessional moraine

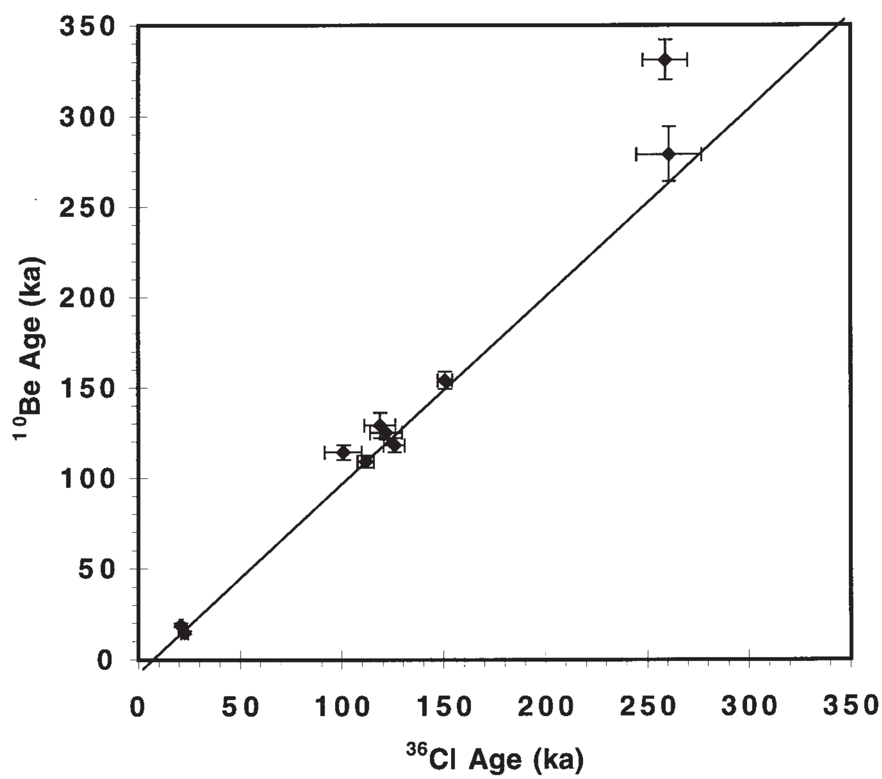

Figure 6. Comparison of ^{36}Cl and ^{10}Be zero-erosion ages. The diagonal line indicates complete concordance of the ages.

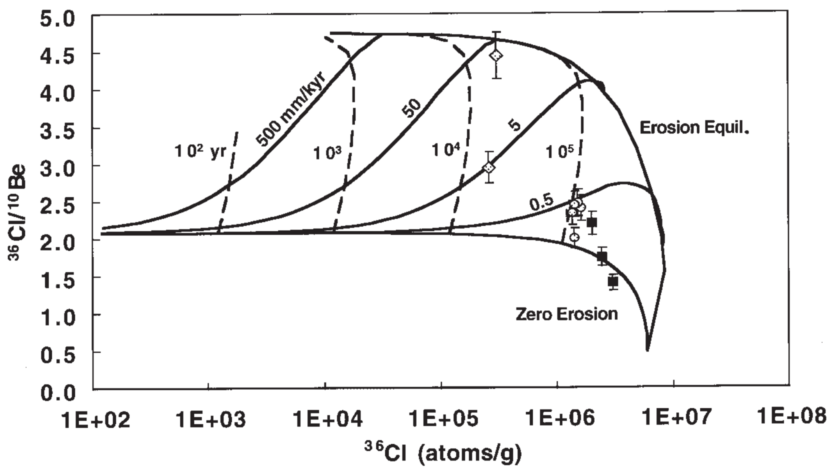

Figure 7. Plot of $^{36}Cl/^{10}Be$ ratio versus ^{36}Cl concentration. The bottom solid line represents the range of compositions to which a sample would evolve after a finite time (given by the solid contours) with no erosion. The top solid line represents the range of compositions a sample would evolve to after infinite time at the erosion rate indicated by the dashed contours. The composition of sample BL92-44 was used to compute the plot. The positions of the Pinedale-age samples are given by stippled diamonds, the Bull Lake–age samples by stippled circles, and the Sacagewea Ridge samples by solid squares.

at Fremont Lake by Gosse et al. (1995b). Field notes did not give any indication of spalling or unusually rapid rock erosion on this boulder. We therefore suspect that this discrepancy may be an analytical artifact, although there is no direct evidence to indicate an analytical problem.

Liu et al. (1994) pointed out that, due to the difference in the profile of production with depth for ^{36}Cl produced by thermal neutron absorption versus the spallogenic production profile, the measurement of ^{36}Cl together with a spallogenic nuclide such as ^{10}Be is advantageous for simultaneous determination of both exposure age and erosion rate. In Figure 7 we illustrate the position of these 10 samples on a $^{36}Cl/^{10}Be$ versus ^{36}Cl diagram. (Each sample has a slightly differently shaped area on the diagram due to the composition-dependent nature of the ^{36}Cl production profile; we have therefore transferred the position of each sample in erosion-age coordinates to the diagram for one of the samples.) All of the samples except BL92-7, BL92-12, and BL92-60 plot close to the zero-erosion line on the graph. Calculated erosion rates are listed in Table 2. With the exceptions noted, these are all less than 0.2 mm/k.y. The low rock-erosion rates obtained by the $^{36}Cl/^{10}Be$ approach strongly support the arguments made by Gosse et al. (1995b) for small rates of rock erosion.

CONCLUSIONS

The cosmogenic nuclide geochronological data are summarized in Table 3. The oldest of the deposits investigated was the Sacagewea Ridge moraine. The calculation of infinite ages for higher assumed rock-erosion rates and the lack of any well-defined grouping of maximum ages permit the assignment of only a limiting minimum age of greater than 232 ka. This minimum age is not in conflict with a tephrochronological age of 660 ka, although it could also be consistent with ages as young as about 250 ka.

At Bull Lake, the oldest deposits sampled, according to the relative age sequence of Chadwick et al. (1997), were Bull Lake moraines BLIV, BLIII, and BLII. Due to the limited number of samples and the deeply eroded form of the moraines, we assign only a limiting minimum age of greater than 130 ka. It seems likely that at least the oldest of these moraines could be much older than 130 ka.

TABLE 3. SUMMARY OF AGE ESTIMATES FOR GLACIAL DEPOSITS

Unit	^{36}Cl age range* (ka)	$^{36}Cl/^{10}Be$ ages† (ka)	Combined age range (ka)
Pinedale	23–16	20.5 and 18.5	23–16
Bull Lake XIII	115–95	110	120–95
Bull Lake XII	115–95	121	120–95
Bull Lake IX	125–95	126 and 129	130–100
Bull Lake IV–II	>130		>130
Sacagawea Ridge	>236	153 and 274	>272

*See Figures 3, 4 and 5.
†From Table 2.

In contrast to the dissected older moraines, the younger of the Bull Lake moraines (BL XIII through BLIX) do not appear to be as deeply eroded, and they yield relatively consistent groupings of ages near the upper limits of their age distributions. On the basis of both the ^{36}Cl and the $^{36}Cl/^{10}Be$ ages, the best maximum age estimates are as follows: BLIX, 130 ka; BLXII, 120 ka; and BLXIII, 120 ka. The results of the $^{36}Cl/^{10}Be$ analyses indicate that it is unlikely that high rock-erosion rates have had a significant effect on the apparent ages. This, in turn, shows that the actual ages of the moraines are probably close to the maxima of the zero-erosion ^{36}Cl age distributions. Comparison with these ages shows clearly that the Bull Lake moraine V at Fremont Lake and the Bull Lake terrace deposit are correlative with the Bull Lake–age moraines at Bull Lake, probably with the moraine BLIX.

The age range for the type Bull Lake moraines (BLIX to BLXIII), 130 to 120 ka, clearly overlaps the age range of the last interglacial (marine isotope stage 5e), ca. 132 to ca. 117 ka (Gallup et al., 1994; Szabo et al., 1994; Winograd et al., 1992). The Bull Lake glaciation has usually been correlated with the Illinoian glaciation (isotope stage 6, 189 to ca. 132 ka) (Pierce, 1979). However, isotope stage 5d (ca. 117 ka to 103 ka) appears to represent a rapid return to a glacial type of climate (Linsley, 1996); mountain glacial advances have been noted globally (Gillespie and Molnar, 1995), as well as continental ice-sheet expansion (Clark, 1992). Given an approximate ±15% total uncertainty in the cosmogenic nuclide ages in this time range, moraine BLIX could be as old as 150 ka, placing it close to the maximum of isotope stage 6, or as young as 110 ka, at the middle of isotope stage 5d. Thus, at present, the most parsimonious interpretation for the cosmogenic nuclide data is to correlate moraines BLXI through BLIX with the late stages of isotope stage 6, and BLXV through BLXII with isotope stage 5d. However, given the limited degree of calibration and control samples for cosmogenic nuclide dating in this time range (Phillips et al., 1996a), we cannot rule out the possibility that both sets of moraines were deposited during either stage 6 or 5d. The data clearly demonstrate that none of the dated type Bull Lake moraines can be attributed to marine isotope stage 4 (74 to 59 ka). Further discussion of the Bull Lake glaciation chronology in the context of the regional geology can be found in Chadwick et al. (1997).

The cosmogenic nuclide data indicate that the three terminal Pinedale-age moraines at Bull Lake were deposited between 23 and 16 ka. This range agrees well with that of 21.8 to 15.7 ka previously determined using ^{10}Be measurements on the Pinedale moraines at Fremont Lake by Gosse et al. (1995b). Our data, like theirs, appear to support a relatively stable terminal position (see Fig. 1) over that interval, although the morphological evidence for oscillations back and forth from the terminal limit may be somewhat stronger at Bull Lake. These ages also coincide with the range of 23 to 16 ka obtained for the most prominent Tioga glacial advances in the Sierra Nevada using ^{36}Cl (Phillips et al., 1996b), indicating nearly simultaneous climatic forcing over the western United States.

Comparison of ^{36}Cl and ^{10}Be ages shows generally excellent agreement. This agreement indicates low rock-erosion rates. Most of the calculated erosion rates were less than 0.2 mm/k.y. Erosion rates this low have only a minor effect on cosmogenic surface-exposure dating of samples younger than a few hundred thousand years.

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