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Exploring Relationships between Watershed Properties and Holocene Loss-on-Ignition Records in High-Elevation Lakes, Southern Uinta Mountains, Utah, U.S.A.

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Abstract

Sediment cores were retrieved from 12 lakes in the southern Uinta Mountains ranging in elevation from 2960 to 3475 m. Organic content was determined by loss-on-ignition (LOI) at 1-cm intervals (n = 2850), corresponding to 20 to ~100 yrs per sample. This data set was used to explore relationships between watershed variables and LOI records. Average LOI values are strongly correlated with lake elevation, elevation of the watershed, extent of late-lying snow and bare rock in the watershed, and the area of upstream lakes. Average LOI values are not significantly correlated with lake depth, or with lake or watershed area. The 12 LOI records can be visually divided into 3 groups with contrasting patterns: Steady, Trending, and Rising. Steady lakes have the lowest average LOI values, and are located in watersheds with the highest maximum elevations and the largest area of upstream lakes and late-lying snow. The most significant determinant on average LOI and LOI pattern is hydrologic through-flow as revealed by the configuration and number of inlets and outlets. The repetition of Steady, Trending, and Rising LOI patterns in different parts of the range, combined with contrasting LOI patterns in adjacent lakes, suggests that watershed characteristics strongly influence organic sedimentation.

Introduction

Paleoclimate records derived from lake sediment provide valuable context for modern climate studies and are important inputs to models used for generating future climate simulations. Cores can provide continuous records spanning the complete history of a lake, and the presence of terrestrial macrofossils allows robust depth-age models to be constructed through radiocarbon dating. Simultaneous investigation of diverse physical, chemical, and biological proxies can, therefore, generate multiple time-series from a single lacustrine core, allowing complicated paleoclimate records to be disentangled and interpreted (e.g., Fritz, 1996; Cohen, 2003).

One of the most commonly applied techniques in paleolimnological investigations is determination of percent organic material via loss-on-ignition (LOI) (Dean, 1974). LOI can be inexpensively determined for large numbers of samples, offering the ability to rapidly conduct high-resolution investigations through complete sedimentary sequences. As a result, LOI is usually one of the first proxies to be investigated in multi-proxy studies, and is often relied on to identify intervals of a core where rapid environmental changes are recorded, and where more time-consuming methods should be targeted.

Despite the widespread utilization of this technique, fluctuating LOI values in a sediment core can be difficult to interpret unequivocally in the absence of other information, for two reasons. First, the organic content of sediment reflects both autochthonous production within the lake and inwashing of allochthonous (terrestrial) material (Dean, 1974; Cohen, 2003; Shuman, 2003). Because organics derived from these disparate sources are intermixed in the sediment, their relative contributions can be difficult to identify without consideration of other proxies.

Second, aspects of the surrounding watershed can influence aspects of a lake system, including productivity and sedimentation rates. This issue has been investigated by modern limnological studies (e.g., Schindler, 1971; Rasmussen et al., 1989; D'Arcy and Carnigan, 1997; Gergel et al., 1999; Prepas et al., 2001; Xenopoulos et al., 2003; and Håkanson, 2005), but is more difficult to evaluate in paleolimnological investigations (e.g., Rubensdotter and Rosqvist, 2003). Nonetheless, it is important to consider the possibility that a given lake might record a biased view of the regional paleoclimate if aspects of its physical setting amplify or diminish the signal of environmental changes. For instance, a slight regional decrease in effective moisture could lower the water level in a hydrological closed lake, but have little effect on a through-flowing lake. Sediment from the depocenter of the closed lake might record this change as an increase in organic matter as a result of increased proximity to the productive littoral zone (e.g., Shuman, 2003), yet a corresponding change might be absent from the through-flowing lake record. The LOI records from these two lakes could, therefore, suggest divergent paleoclimate interpretations. Investigation of multiple proxies is one technique to address this situation, but the potential for making accurate paleoclimate interpretations would be further improved by consideration of the degree to which a lake is sensitive (or insensitive) to environmental changes given its physical setting.

A recent effort aimed at retrieving cores from high-elevation lakes in the Uinta Mountains provides the opportunity to evaluate how watershed properties impact the LOI record stored in lake sediment. In this paper, a preliminary analysis is made of post-glacial LOI records from 12 lakes. The focus is on LOI because it is routinely applied in paleolimnological investigations and because it can readily be determined for large numbers of

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samples. The Uinta Mountains data set is used because of the number of lakes cored, the quality of the age-control on the sedimentary records, and recent surficial mapping in the area that provides information about the physical setting of the lakes (Munroe and Laabs, unpublished). This exploration of the Uinta lakes data set is divided into two parts: First, the correlation between watershed variables and LOI records is considered. Second, the LOI records are divided into groups with common patterns, and the reasons for the differences between these groups are evaluated.

Study Site

The lakes are located in the Uinta Mountains (hereafter, Uintas), which extend more than 150 km across northeastern Utah. The Uintas contain the highest mountains in the state (summits in excess of 4000 m a.s.l.), and hosted more than 2000 km^2 of glacier ice during the Late Pleistocene Smiths Fork Glaciation, ca. 18 ka BP (Munroe, 2005a; Laabs and Carson, 2005; Munroe et al., 2006). No glaciers remain in the range today.

The landscape of the Uintas is dominated by deep U-shaped valleys leading to broad compound cirques. The floors of the highest cirques reach above modern treeline (~3300 m a.s.l.) and are mantled by alpine tundra. The higher interfluves support a tundra community intermixed with extensive areas of patterned ground (Munroe, 2005b). The upper subalpine forest is composed of *Picea engelmannii* and *Abies bifolia* with an understory of *Vaccinium scoparium*. Elevations between 2700 and 3000 m a.s.l. are dominated by a monoculture of *Pinus contorta*.

The mean annual temperature at 3700 m a.s.l. in the alpine zone is −2.0°C, while summer (J/J/A) air temperatures average 8.2°C, and winter (D/J/F) temperatures average −10.2°C. Temperatures are warmer in the subalpine forest, with mean annual temperatures between −1.0 and 2.0°C. Mean annual precipitation in the subalpine forest ranges from 50 to 100 cm, and western parts of the range receive the majority of their annual precipitation in the winter (Munroe, unpublished analysis of SNOTEL data).

Lakes are abundant in the Uintas, with some studies estimating their number to be greater than 500 (Atwood, 1908). The lakes discussed here were selected for coring on the basis of four criteria: (1) location, because of interest in obtaining sediment records from lakes clustered in different sectors of the range; (2) depth, because the coring equipment operates best in water depths between 4 and 20 m; (3) surface area, because large lakes would be difficult to survey and were expected to contain more complex bathymetry; and (4) accessibility, because coring equipment had to be transported to each lake by pack animals.

Methods

FIELD AND LABORATORY METHODS

Sediment cores were extracted using a percussion corer (Reasoner, 1993) operated from a floating platform. Prior to coring, a bathymetric survey was conducted for each lake using a digital depth sounder linked to a GPS receiver to identify the lake depocenter. After the platform was anchored in place, a continuous core (7.5-cm diameter), was taken from the sediment-water interface to the point of refusal. Loose sediment immediately below the sediment-water interface (10–50 cm) was lost during retrieval, and additional poorly consolidated sediment from the upper part of each core was discarded because it was too soft to survive transport undisturbed. The resulting cores ranged from ~150 to 350 cm long. Cores were cut into ~50-cm lengths, capped, and transported to the trailhead in specially designed panniers. After shipping, the cores were stored at 5°C until opening.

In the laboratory, cores were split lengthwise, measured, photographed, and described. Samples of approximately 3 cm^3 were taken at 1-cm intervals throughout one half of each core for LOI analysis (Dean, 1974). Measurements were made with an automated thermogravimetric analyzer (TGA) that dried, and then heated samples at 550°C until they reached mass constancy. LOI analysis in a TGA eliminates many of the concerns raised by Heiri et al. (2001), including issues of sample position in the furnace (crucibles are constantly cycled around the perimeter of the furnace), length of time each crucible is at high temperature (all crucibles are run through the same steps simultaneously), temperature fluctuations (furnace temperature is tightly regulated and recorded), and differential rates of mass lost (each step continues until all samples reach constant mass).

CHRONOLOGY

The remaining half of each core was wet-sieved to 500 μm at 1-cm intervals to recover organic fragments suitable for AMS radiocarbon dating. Identifiable fragments included *Picea* and *Abies* cones and needles, *Salix* twigs, and pieces of bark. Lower sections of several cores were dominated by *Daphnia ephippia* (eggs, hereafter DE) in concentrations sufficient for AMS dating. To date the inorganic basal sediments, pollen was concentrated, using a methodology adapted from Brown et al. (1989) and Mensing (1999), for AMS analysis. The resulting samples ranged from 1 to 20 mg, and consisted of more than 90% *Pinus* pollen.

AMS results were converted to calendar years with CALIB 5.0 (Stuiver et al., 2005). For developing depth-age relationships, the midpoint of the 2σ age-range with the greatest probability was taken as the calibrated age.

WATERSHED VARIABLES

Variables describing the morphology and characteristics of the lakes and surrounding watersheds were determined through GIS analysis. Watershed boundaries were digitized from published 1:24,000-scale U.S. Geological Survey (USGS) topographic maps with a 40-foot (12-m) contour interval, supplemented by field inspection. Watershed boundaries were used to clip a 30-m digital elevation model (DEM) of the Uintas acquired from the USGS Seamless Data Distribution System. Slope and aspects grids were derived from the clipped DEM, and values for each watershed were calculated.

Lake outlines were downloaded from the State of Utah Automated Geographic Reference Center and used to calculate lake area, perimeter, and complexity (ratio of lake perimeter to that of a circle with the same area). Maximum depths of each lake were noted during the bathymetric surveys preceding coring. The number of inlet and outlet streams was determined from 1:24,000-scale topographic maps, and the order of the inflowing streams was determined (Strahler, 1952). Hydrologic through-flow was scored for each lake as follows using information gained during field surveys: 1—no inlet or outlet; 2—little or no obvious inflow, weak outflow; 3—modest inflow and outflow; 4—robust inflow and outflow.

The extent of different landcover types in each watershed was determined through analysis of multispectral data captured by the

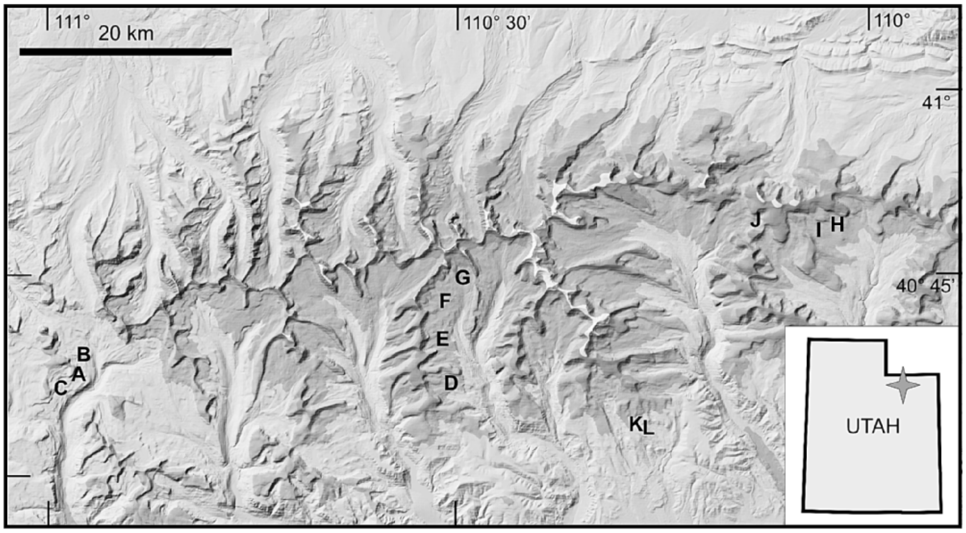

FIGURE 1. Shaded relief map of the Uinta Mountains showing locations of the lakes cored in this study. A—Marshall Lake (core 04-01), B—Hoover Lake (04-02), C—Pyramid Lake (04-03), D—Swasey Lake (04-06), E—Spider Lake (04-07), F—Little Superior Lake (04-08), G—North Star Lake (04-09), H—Elbow Lake (04-04), I—Reader Lake (05-01), J—Taylor Lake (05-10), K—Upper Lily Pad (06-01), and L—Lower Lily Pad (06-02). Inset shows the location of the Uinta Mountains in northeastern Utah.

Landsat 5 Thematic Mapper sensor on 2 July 1989 (scene P037R32_5T890702). Bands 2, 3, and 4 were combined in a false-color image, which was subdivided with an unsupervised classification into 16 fields. Information gained through past ground surveys was used to combine these fields into groups representing ice/snow, rock, water, forest, tundra, and wetland. The percent of each watershed occupied by these landcover types was then calculated for each watershed. The area of bedrock outcrops was considered constant over the period of interest. Similarly, given the strong topographic control on snowbank location and size, the area of these features (as a proportion of the total watershed area) was considered relatively constant. The area of forest, tundra, and wetland were not considered further because of the likelihood that they have changed over the past 10,000 years.

STATISTICS

Mean, median, and modal values were calculated for each LOI record starting at 10,000 cal yr BP; earlier parts of the records (i.e., pre-10 ka BP) were ignored to avoid comparing basal sediments from one lake with organic-rich sediment from another. Standard deviations and the coefficient of variation (as a percent) were also computed. Given the complexity and variability of records from the different lakes, these descriptive statistics were considered most useful for describing the LOI records. The correlation between the watershed variables calculated in the GIS and the LOI statistics was assessed with Spearman's Rank Correlation, and the robustness of the significant correlations was evaluated by iterative recalculation of the correlations with one lake excluded each time. The 12 lakes were then divided by visual inspection into 3 groups with common LOI patterns, and the differences between these groups were evaluated with the Kruskal-Wallis test.

Results

SEDIMENTOLOGY

The locations of the 12 lakes are given in Figure 1, and information about each lake is provided in Table 1. The lakes range from 3.7 to 12.8 m in depth, from 4.0 to 14.6 ha in area, and from 2957 to 3474 m in elevation. Cores 04-08 and 04-09 are from lakes located above treeline. All cores penetrated more than 2 m below the sediment-water interface, and recovery ranged from 62 to 98% (Table 1).

Almost all of the cores contain a similar bipartite stratigraphy of gyttja overlying a lower section with reduced organic content. The gyttja ranges from black (10YR 2/1) to very dark grayish

TABLE 1

Locations and properties of lakes cored in the southern Uinta Mountains.

Fig. 1	Lake ID	Lake name	Coring date*	Latitude N (DD MM.mm)	Longitude W (DD MM.mm)	Elevation (m)	Area (ha)	Depth (m)	Temp (°C)	Drive (m)	Recovery (m)
A	04-01	Marshall	6/25/04	40° 40.538	110° 52.452	3043	8.0	10.7	12.8	2.4	1.90
B	04-02	Hoover	6/26/04	40° 40.824	110° 50.824	3018	7.8	7.9	13.3	2.1	1.56
C	04-03	Pyramid	6/27/04	40° 39.192	110° 54.094	2957	5.8	10.7	13.3	2.2	1.80
D	04-06	Swasey	7/10/04	40° 40.048	110° 28.000	3267	14.6	9.5	12.8	2.7	1.98
E	04-07	Spider	7/11/04	40° 42.019	110° 28.756	3316	8.1	12.8	12.2	4.1	3.24
F	04-08	Little Superior	7/12/04	40° 44.003	110° 28.461	3417	14.6	9.5	12.2	4.1	3.24
G	04-09	North Star	7/13/04	40° 45.195	110° 27.075	3474	5.8	5.8	12.2	3.2	1.98
H	04-04	Elbow	7/2/04	40° 47.619	110° 02.502	3326	10.0	10.7	10.0	2.4	2.17
I	05-01	Reader	7/7/05	40° 47.450	110° 03.620	3341	4.8	4.0	13.3	4.1	2.59
J	05-10	Taylor	9/11/05	40° 47.230	110° 05.510	3421	9.0	10.9	8.3	3.1	3.05
K	06-01	Upper Lily Pad	7/12/06	40° 37.660	110° 15.950	3129	4.0	10.0	12.8	4.3	3.71
L	06-02	Lower Lily Pad	7/12/06	40° 37.580	110° 15.750	3128	2.3	3.7	15.6	3.7	2.40

* Month/day/year.

TABLE 2

Loss-on-Ignition (LOI) values, and lake and watershed variables.

		Steady				*Trending*					*Rising*		
		04-02	04-07	05-10	04-09	04-04	04-08	04-01	04-06	06-01	04-03	05-01	06-02
LOI Records													
Max LOI	%	22.4	29.8	15.0	13.6	40.3	26.0	34.8	25.8	39.2	30.7	31.6	34.8
Mean LOI	%	14.9	16.7	8.8	10.8	21.8	14.7	19.7	16.4	22.4	24.3	18.3	20.9
Median LOI	%	17.5	17.6	10.4	11.6	22.8	13.5	20.6	19.8	30.7	25.2	17.6	24.7
Modal LOI	%	20.8	18.0	10.4	11.6	19.5	13.0	20.6	20.6	4.3	27.7	17.1	—
10 ka Mean LOI	%	18.6	17.6	10.5	11.8	28.8	16.2	21.7	20.8	32.9	25.4	20.3	26.8
10 ka Median LOI	%	19.3	17.8	10.7	11.9	30.0	15.2	21.4	20.9	33.1	26.0	19.8	28.1
10 ka Modal LOI	%	20.8	18.0	10.4	11.6	19.5	13.0	20.6	20.6	31.3	27.7	17.1	—
10 ka C.V.	%	11.5	15.6	17.3	7.6	21.5	23.7	16.3	13.5	8.5	12.6	20.2	18.1
Lake													
Elevation	m	3018	3316	3421	3474	3326	3417	3043	3267	3129	2957	3341	3128
Max. Depth	m	7.9	12.8	11.0	5.8	10.7	9.5	10.7	9.5	9.8	10.7	4.0	3.7
Area (A_L)	ha	7.8	8.1	9.0	5.8	10.0	6.0	8.0	14.6	4.0	5.8	4.8	2.3
Perimeter	m	1168	2412	1337	939	2013	1039	1170	2072	800	988	1179	645
Complexity	—	1.2	2.4	1.3	1.1	1.8	1.2	1.2	1.5	1.1	1.2	1.5	1.2
Inflows	#	2	2	0	1	1	3	0	0	0	0	0	0
Order	#	1	1	0	1	1	2	0	0	0	0	0	0
Outflow	#	1	1	0	1	0	1	0	1	1	0	1	1
Throughflow	—	4	3	3	4	2	3	1	2	2	1	2	2
Upstream Lakes	ha	7.3	22.5	0.0	11.1	0.0	7.5	0.0	0.0	0.0	0.0	0.0	0.0
Upstream Lakes	%	5.3	6.2	0.0	3.9	0.0	2.4	0.0	0.0	0.0	0.0	0.0	0.0
Upstream Lakes	ratio	0.9	2.8	0.0	1.9	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0
Watershed													
Area (A_W)	ha	139	363	319	288	335	311	60	317	305	77	54	318
Perimeter	m	5840	8451	7550	7768	7316	7501	3084	8250	7625	3596	3118	8073
A_L / A_W	ratio	18	45	35	50	34	52	8	22	76	13	11	138
A_W / Max. Depth	ratio	18	28	29	50	31	33	6	34	31	7	14	86
Min. Elevation	m	3015	3312	3421	3475	3330	3418	3041	3268	3133	2956	3305	3132
Max. Elevation	m	3418	3736	3862	3982	3752	3869	3285	3664	3473	3247	3489	3473
Elev. Range	m	403	424	441	507	422	451	244	396	341	291	185	341
Mean Elev.	m	3115	3453	3620	3634	3532	3557	3092	3406	3303	3074	3387	3296
Elev. Stdev	m	94	132	117	120	135	99	66	107	80	90	64	84
Max. Slope	deg	56	52	45	65	54	57	63	53	40	52	43	40
Mean Slope	deg	14	15	11	18	14	13	15	14	10	19	11	10
Slope Stdev	deg	13	13	8	14	10	10	16	11	6	14	10	6
Mean Aspect	deg	106	123	143	181	167	152	122	126	162	123	194	161
Ice/Snow	%	4	23	13	26	6	6	0	6	1	1	0	1
Rock	%	27	33	40	46	36	49	38	31	22	40	29	21

brown (10YR 3/2) to dark reddish gray (2.5YR 3/2) in color, and is usually massive near the top of the recovered core. Some sections contain faint millimeter-scale laminations reflecting oscillations between slightly lighter and darker sediment. In some lakes, particularly 04-03, the gyttja is vesicular.

Organic content was determined for 2850 samples. LOI values range from less than 2% in basal silty sand (04-02) to 40% in gyttja (04-04) (Table 2). Mean organic contents per lake decrease with elevation, with values of 10% or less in cores from the highest lakes (04-09 and 05-10).

CHRONOLOGY

A total of 71 AMS radiocarbon determinations were made (Table 3). The majority of these dates are in stratigraphic order and yield sedimentation rates of 0.5 to 0.1 mm yr^{-1} (50 to 10 cm·10^{-3} yr^{-1}). In core 04-01 bulk sediment and a conifer needle from the same stratigraphic depth (47 cm) returned similar ages, suggesting that there is no hard-water effect in this lake, or that if there is one, the effect is limited to shifts of a century or two. A similar situation is expected in the other lakes given the lack of carbonate bedrock in their watersheds, which supports the validity of dating DE.

The dates returned on pollen concentrates yielded more equivocal results. For instance, in core 05-01, pollen returned an age statistically indistinguishable from a conifer needle at the same depth (218–220 cm). In other cases the pollen dates appear too old, for instance in core 04-06, where the pollen dates (ca. 18 ka BP) is impossible to reconcile with the cosmogenic ^{10}Be surface-exposure age of 18 ka BP determined for the terminal moraine 20 km downvalley (Munroe et al., 2006). In contrast, some pollen dates appear too young relative to other ^{14}C analyses on the same cores (e.g., 04-02, 04-04, 05-01). Because it is not clear how to consistently interpret the pollen dates, and because the majority of them are from near-basal sediments that are not the focus of this report, they were ignored and depth-age models were based on linear sedimentation rates between dated non-pollen samples, with extrapolation to the core top and bottom as necessary. In core 04-01, the age of a pronounced LOI minimum was shifted slightly to match the dated minimum (4.4 ka BP) in core 04-03 given the similarity of these two records, a synchronous LOI minimum in core 04-02, and the close proximity of all three lakes.

TABLE 3

Radiocarbon dates for the southern Uinta Mountains lake cores.

Sample ID	Lake depth	Depth (cm)	Material	$\delta^{13}C$ (‰)	^{14}C age BP (yr)	2-σ max (yr)	2-σ min (yr)	Calib 5.0.2 (yr)	Lab # *
04-01b	5–6	5.5	conifer needle	−28.11	1475 ± 35	1414	1299	1357	AA62135
04-01b	46–47	46.5	conifer needle	−26.11	3464 ± 39	3836	3638	3737	AA62136
04-01b	46–48b	47	bulk sediment	−27.95	3615 ± 42	4007	3831	3919	AA62137
04-01b	59–60	59.5	wood	−26.56	4040 ± 50	4647	4416	4532	52727
04-01b	102–103	102.5	wood	−21.5	5640 ± 50	6511	6305	6408	52728
04-01b	130	130	wood	−24.21	8935 ± 52	10221	9906	10064	AA62138
04-01b	188–190b	189	bulk sediment	−22.86	10,856 ± 63	12923	12793	12858	AA62139
04-02a	2–3	2.5	conifer needle	−25.18	1835 ± 36	1870	1696	1783	AA62140
04-02	50–51	50.5	conifer needles	−23.85	4990 ± 75	5898	5602	5750	52730
04-02a	54–55	54.5	conifer needle	−24.67	5391 ± 44	6289	6172	6231	AA62141
04-02a	111–112	111.5	conifer needle	−26.56	9482 ± 54	10872	10579	10726	AA62142
04-02a	143–144b	143.5	bulk sediment	−23.08	12,410 ± 120	14950	14047	14499	AA62143
04-02	156	156	*Pinus* pollen	−25.13	11,400 ± 65	13386	13140	13263	52731
04-03	13–14	13.5	conifer needle	−23.76	2032 ± 42	2072	1892	1982	AA62264
04-03	57–58	57.5	conifer needles	−23.92	3970 ± 40	4527	4339	4433	52732
04-03	85–86	85.5	wood	−27.4	4831 ± 42	5650	5472	5550	AA62265
04-03	115–116	115.5	organic frag.	−21.31	7190 ± 140	8320	7737	8029	52733
04-03	125–126	125.5	wood	−23.31	7741 ± 48	8639	8432	8536	AA62266
04-03	171–172	171.5	conifer needles	−24.46	9390 ± 120	10883	10265	10574	52734
04-03	177–179	178	bulk sediment	−28.35	9845 ± 64	11406	11155	11281	AA62267
04-04	30–31	30.5	*Daphnia ephippia*	−27.89	3218 ± 40	3489	3364	3427	AA62734
04-04	96–97	96.5	conifer needle	−23.4	5863 ± 44	6786	6560	6673	AA62735
04-04	127–128	127.5	conifer needle	−22.69	8270 ± 55	9432	9089	9261	52735
04-04	142–143	142.5	conifer needle	−26.43	9188 ± 54	10497	10240	10369	AA62736
04-04	153–154	153.5	*Daphnia ephippia*	−27.54	10,050 ± 60	11825	11307	11566	52736
04-04	153–154	153.5	*Pinus* pollen	−26.2	9280 ± 65	10598	10258	10428	52737
04-04	216–217	216.5	*Daphnia ephippia*	−18.38	12,068 ± 72	14082	13771	13927	AA62737
04-06	10–11	10.5	conifer needles	−26.81	2756 ± 39	2947	2773	2860	AA62798
04-06	59–60	59.5	conifer needles	−23.83	4995 ± 41	5771	5642	5707	AA62797
04-06	141–142	141.5	*Daphnia ephippia*	−24.53	9025 ± 59	10278	10116	10197	AA62799
04-06	166–168	167	*Daphnia ephippia*	−23.59	11,632 ± 64	13655	13323	13489	AA62800
04-06	185–190	187.5	*Pinus* pollen	−24.66	14,750 ± 90	18428	17379	17904	55207
04-06	190–195	192.5	*Pinus* pollen	−24.61	15,350 ± 80	18848	18589	18719	52740
04-07	16–17	16.5	conifer needle	−25.12	1288 ± 38	1295	1168	1232	AA63503
04-07	51–52	51.5	conifer needles	−24.33	2220 ± 35	2331	2151	2241	52741
04-07	64–65	64.5	wood/needles	−21.48	2470 ± 45	2623	2426	2525	52742
04-07	172–173	172.5	wood	−22.01	5078 ± 44	5918	5752	5835	AA63504
04-07	249–250	249.5	conifer needles	−24.00	7720 ± 55	8593	8412	8503	52743
04-07	301–302	301.5	wood	−21.67	9277 ± 56	10587	10267	10427	AA63505
04-07	331–334	322.5	*Daphnia ephippia*	−27.4	9827 ± 67	11404	11103	11254	AA63506
04-08	2–3	2.5	organic frag.	−24.53	2010 ± 160	2343	1606	1975	AA64117
04-08	80–81	80.5	wood	−22.65	3381 ± 41	3719	3551	3635	AA64118
04-08	125–126	125.5	wood	−25.45	5130 ± 50	5949	5746	5848	52744
04-08	137–138	137.5	wood	−26.86	5490 ± 55	6400	6193	6297	52745
04-08	229–230	229.5	wood	−25.4	9483 ± 64	10,885	10,571	10728	AA64120
04-08	250–252	251	*Daphnia ephippia*	−25.00	9700 ± 170	11,620	10,565	11093	53888
04-08	252–254	253	*Daphnia ephippia*	−27.34	12,150 ± 160	14,715	13,678	14197	52746
04-08	255–256	255.5	*Daphnia ephippia*	−26.4	13,610 ± 350	17,168	15,161	16165	AA64121
04-09	92–93	92.5	*Carex*	−24.8	5130 ± 130	6186	5606	5896	AA65027
04-09	121–122	121.5	conifer needle	−24.00	6334 ± 58	7342	7163	7253	AA65028
04-09	173–174	173.5	*Daphnia ephippia*	−25.00	9481 ± 58	10,877	10,574	10726	AA65029
04-09	176–177	176.5	*Daphnia ephippia*	−22.6	7527 ± 55	8415	8277	8346	AA65030
04-09	177–179	178	*Daphnia ephippia*	−21.49	9860 ±60	11,406	11,175	11291	52701
05-01b	106–107	106.5	conifer needle	−25.32	4660 ± 55	5485	5297	5391	52707
05-01b	150–151	150.5	conifer needle	−26.11	7860 ± 65	8817	8538	8678	52708
05-01b	218–220	219	*Pinus* pollen	−25.78	9700 ± 70	10,978	10,785	10882	53889
05-01b	220–221	220.5	conifer needle	−23.18	9560 ± 60	11,136	10,701	10919	52709
05-01b	238–240	239	*Daphnia ephippia*	−25.9	10,150 ± 55	12,052	11,601	11827	53890
05-01b	238–240	239	*Pinus* pollen	−25.33	10,400 ± 50	12,403	12,077	12240	53914
05-01b	242–246	244	*Pinus* pollen	−24.73	9460 ± 60	10,871	10,556	10714	52710

TABLE 3

(continued)

Sample ID	Lake depth	Depth (cm)	Material	$\delta^{13}C$ (‰)	^{14}C age BP (yr)	2-σ max (yr)	2-σ min (yr)	Calib 5.0.2 (yr)	Lab # *
05-10b	19–20	19.5	conifer needle	−23.86	1610 ± 35	1556	1412	1484	52711
05-10b	90–91	90.5	wood	−23.81	3890 ± 40	4422	4227	4325	52712
05-10b	140–141	140.5	conifer needles	−25.2	6240 ± 60	7274	6979	7127	52713
05-10b	188	188	conifer needle	−25.00	9270 ± 160	10,900	10,157	10529	53911
05-10b	245–246	245.5	organic frag.	−25.38	10,850 ± 70	12,935	12,775	12855	52714
5-10b	258–266	262	*Daphnia ephippia*	−16.92	10,800 ± 60	12,893	12,734	12814	53912
05-10b	267–270	268.5	*Daphnia ephippia*	−19.41	9800 ± 65	11,361	11,093	11227	53913
05-10b	267–270	268.5	*Pinus* pollen	−24.7	13,850 ± 65	16,891	16,123	16507	52705
06-01	1–2	1.5	conifer needle	−24.23	880 ± 35	911	727	819	56855
06-01	216–217	216.5	wood	−24.45	9390 ± 45	10,727	10,508	10618	56856
06-02	71	71	organic frag.	−32.00	4060 ± 40	4650	4430	4540	B-222170
06-02	258	258	*Daphnia ephippia*	−32.00	9990 ± 60	11,720	11,250	11485	B-222171

* AA- samples run at the NSF-Arizona AMS Facility.
5xxxx samples run at NOSAMS.
B- samples run at Beta Analytic.

WATERSHED VARIABLES, LOI PATTERNS, AND STATISTICAL ANALYSIS

The variables calculated for each watershed are presented in Table 2. Statistical evaluations of correlations between watershed variables and LOI values for the past 10,000 years are given in Table 4. Lake elevation, hydrologic through-flow, watershed elevation, percent ice/snow and bare rock, and the area of upstream lakes in the watershed are strongly correlated with average LOI (mean, median, mode) over the past 10,000 years. Correlations are not significant between LOI and lake dimensions (depth, area, perimeter, complexity), between LOI and watershed/lake ratios (area, depth), or between LOI and watershed slope.

Visual inspection supports division of the 12 LOI records into 3 groups with distinct patterns: Steady, Trending, and Rising (Fig. 2). Steady lakes (cores 04-02, 04-07, 04-09, and 05-10) feature fairly stable LOI values after the initial latest Pleistocene rise. Trending lakes (cores 04-01, 0-04, 04-06, 04-08, 06-01) feature greater LOI variability organized into multi-centennial to millennial-scale increasing and decreasing trends. Rising lakes (cores 04-03, 05-01, 06-02) feature monotonically increasing LOI, interrupted by spikes to higher or lower LOI values. Significant differences exist in average LOI, through-flow, extent of upstream lakes, maximum watershed elevation, and ice/snow cover between the three groups of lakes (Table 5).

Discussion

LOI VALUES

The organic contents determined for these cores are equivalent to those reported by other studies from similar settings. For instance, Zielinski (1989) documented LOI values of 10 to 25% in Miller Lake (3234 m a.s.l.), and Fall et al. (1995) reported Holocene LOI values between 10 and 20% in Rapid Lake (3134 m a.s.l.), both in the Wind River Range (Wyoming), ~250 km north of the Uintas.

CORRELATIONS BETWEEN WATERSHED VARIABLES AND LOI RECORDS

Lake elevation, through-flow, watershed elevation, extent of ice/snow and bare rock, and the area of upstream lakes are strongly correlated with average LOI over the past 10,000 years (Table 4). The statistical strength of these relationships decreases slightly when individual lakes are removed from the data set, but most retain P-values < 0.10. This situation suggests that although some lakes, particularly those at higher elevations, exert a somewhat disproportionate influence on the statistical significance of the correlations, the overall relationships are robust.

All of the variables that are notably correlated with average LOI are interrelated through hydrology. Watersheds at higher elevation hold more late-lying ice and snow, contain more exposed rock, and receive greater amounts of precipitation. As a result, more water runs off these landscapes and through the higher lakes. The positive correlation (Spearman's rho = 0.528, P = 0.078) between elevation and through-flow, which was assessed on the basis of observed inlets and outlets, indicates the extent to which the geomorphology of the higher lake basins has evolved to convey greater volumes of water.

Greater through-flow contributes to lower LOI values because stream water temperatures are low in these watersheds due to their high elevation, long duration of seasonal ice cover, and lingering summer snowmelt. The flux of this cold water into the lakes suppresses aquatic productivity and encourages oligotrophic conditions. Furthermore, given the low nutrient status of soils derived from quartzite-derived glacial deposits in the Uintas (Bockheim et al., 2000), greater water volumes may lead to overall dilution of the already minimal dissolved nutrient load, reducing aquatic productivity and corresponding sediment LOI. In contrast, lakes not fed by lingering snowmelt can be more readily warmed by the sun, and evaporation in closed basins may concentrate nutrients. Both processes would lead to enhanced productivity and higher LOI values.

LOI PATTERNS AND WATERSHED VARIABLES

The repetition of Steady, Trending, and Rising LOI patterns in lakes from different sectors of the range, combined with adjacent lakes having different LOI curve types, suggests that aspects of the surrounding watershed strongly influence organic sedimentation, possibly to an extent sufficient to overprint shifts in the lacustrine environment driven by regional climatic changes. Table 5 presents a comparison of LOI statistics and watershed

TABLE 4

Strength of correlations between LOI over the past 10,000 years and watershed variables.

	10 ka Mean LOI	10 ka Median LOI	10 ka Modal LOI		10 ka Mean LOI	10 ka Median LOI	10 ka Modal LOI
Lake Elevation†	**−0.61****	**−0.61****	**−0.92***	Lake Area/Watershed Area	0.00	0.00	−0.23
	0.04	***0.04***	***0.00***		*1.00*	*1.00*	*0.50*
Max. Depth	−0.06	−0.06	0.05	Watershed Area / Max. Depth	−0.04	−0.04	−0.35
	0.84	*0.84*	*0.89*		*0.91*	*0.91*	*0.30*
Lake Area	−0.26	−0.26	−0.20	Min. Watershed Elev.	**−0.59****	**−0.59****	**−0.89***
	0.41	*0.41*	*0.55*		***0.04***	***0.04***	***0.00***
Lake Perimeter	−0.27	−0.27	−0.26	Max. Watershed Elev.	**−0.60****	**−0.60****	**−0.83***
	0.40	*0.40*	*0.43*		***0.04***	***0.04***	***0.00***
Complexity	−0.05	−0.05	−0.24	Watershed Elev. Range	**−0.64****	**−0.64****	**−0.63****
	0.87	*0.87*	*0.48*		***0.03***	***0.03***	***0.04***
Inflows	−0.42	−0.42	−0.26	Mean Watershed Elev.	**−0.60****	**−0.60****	**−0.85***
	0.17	*0.17*	*0.43*		***0.04***	***0.04***	***0.00***
Order	−0.40	−0.40	−0.33	Stdev Watershed Elev.	−0.36	−0.36	−0.42
	0.20	*0.20*	*0.32*		*0.25*	*0.25*	*0.19*
Outflows	−0.15	−0.15	−0.03	Max. Watershed Slope	−0.40	−0.40	−0.21
	0.63	*0.63*	*0.93*		*0.20*	*0.20*	*0.53*
Throughflow	**−0.73***	**−0.73***	−0.51	Watershed Slope Range	−0.40	−0.40	−0.21
	0.01	***0.01***	*0.11*		*0.20*	*0.20*	*0.53*
Upstream Lake Area	**−0.62****	**−0.62****	−0.36	Mean Watershed Slope	−0.21	−0.21	0.10
	0.03	***0.03***	*0.28*		*0.51*	*0.51*	*0.77*
Upstream Lakes %	**−0.57****	**−0.57****	−0.22	Stdev Watershed Slope	−0.24	−0.24	0.14
	0.05	***0.05***	*0.51*		*0.45*	*0.45*	*0.67*
Upstream Lakes ratio	**−0.62****	**−0.62****	−0.36	Mean Aspect	0.09	0.09	−0.45
	0.03	***0.03***	*0.28*		*0.77*	*0.77*	*0.17*
Watershed Area	−0.07	−0.07	−0.27	% Ice & Snow	**−0.65****	**−0.65****	**−0.57*****
	0.83	*0.83*	*0.42*		***0.02***	***0.02***	***0.07***
Watershed Perimeter	−0.15	−0.15	−0.21	% Exposed Rock	**−0.54*****	**−0.54*****	**−0.55*****
	0.65	*0.65*	*0.53*		***0.07***	***0.07***	***0.08***

† Spearman rho statistic given in first row, *P*-value in italics in second row. Significant correlations shown in boldface.

* Correlation is significant at the 0.01 level (2-tailed).

** Correlation is significant at the 0.05 level (2-tailed).

*** Correlation is nearly significant ($0.10 > P > 0.05$, 2-tailed).

variables from these three groups. Once again the commonality between variables exhibiting significant differences is related to hydrology. Overall, lakes with Steady LOI patterns have lower average LOI values. These lakes are found in watersheds that attain greater elevations, and their inlet/outlet configuration attests to greater volumes of through-flowing water. The watersheds around these lakes also contain significantly more ice/snow cover, and a larger area of upstream lakes; both of which represent temporary storage in the hydrologic cycle. Steady LOI records, therefore, are associated with lakes that are hydrologically active, accommodating large volumes of cold through-flowing water that encourage oligotrophic conditions. Given the constancy of their LOI values over the period of interest, lakes with Steady LOI records have apparently had higher levels of hydrologic activity throughout the Holocene.

Lakes with Rising LOI patterns tend to be found at the lowest elevations within generally smaller watersheds (Table 5). They are also surrounded by significantly less late-lying snow, are not connected to upstream lakes, and have only minimal development of inlets and outlets. Together these characteristics encourage warmer water and greater productivity within these lakes, leading to enhanced accumulation of organic sediment. Furthermore, two of the three lakes in this group are considerably shallower than the rest (~4 m, Table 2). When the length of the cores retrieved from these lakes is compared with their modern depths, it is apparent that theses lakes have lost approximately half their depth since the early Holocene. Thus the increasing LOI values characteristic of these lakes likely reflect their progressive shallowing and eutrophication over time.

Lakes with Trending LOI patterns have watershed and lake properties that are intermediate between the other groups (Table 5). In particular, their average LOI values overlap with those common to the Rising group, but they are found at generally higher elevations and feature at least some evidence for through-flowing water. On the other hand, they have fewer inflows and a considerably smaller area of upstream lakes and late-lying snow than Steady LOI lakes, so they are not dominated by their open hydrology. In the absence of overriding external (i.e., geohydrologic) or internal (shallowing, eutrophication) factors, the shifting LOI trends in these lakes may reflect paleoclimate variability at multi-centennial to millennial scales, especially for trends that are similar in lakes from different areas. For instance, four of the five Trending lakes feature LOI values that peak in the early to middle Holocene. Because these lakes are located all across the southern Uintas (Fig. 1), the shifting trends in their records may reflect a limnologic response to regional climate forcing, perhaps the early Holocene insolation maximum (Berger, 1978; Bartlein et al., 1998). Evidence from other proxies suggests that the distribution of high-altitude vegetation in the Uintas shifted in response to warmer temperatures in the early Holocene. Specifically, the only conifer needle found in the highest lake (core 04-09), which is located ~100 m above modern treeline, dates to 7250 cal yr BP, and palynological evidence for a higher-than-modern treeline in the northern Uintas during the early Holocene was reported by Munroe (2003).

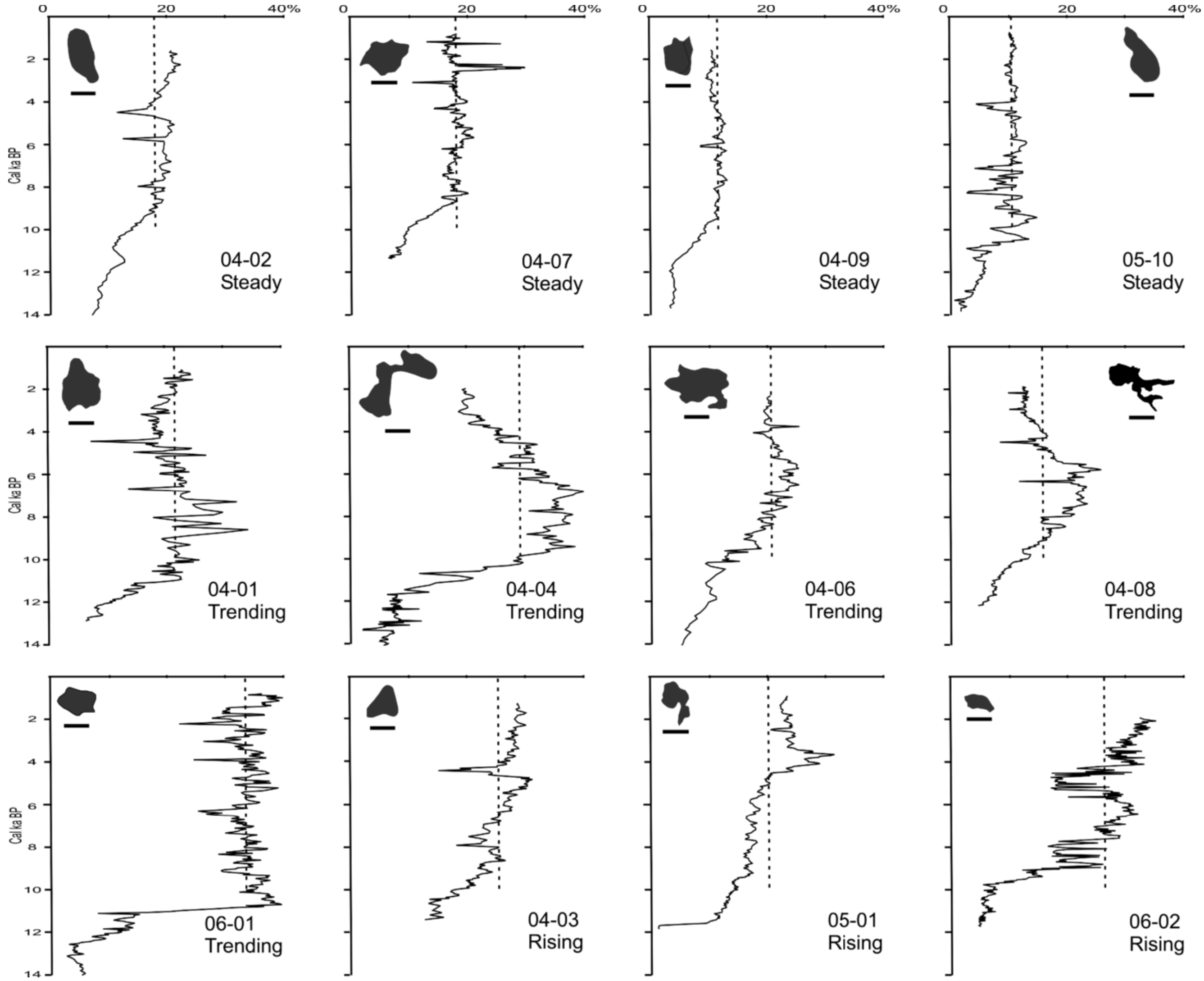

FIGURE 2. Loss-on-ignition records for the 12 lakes in this study. All records are plotted at the same scales (LOI from 0 to 40%, age from 0 to 14,000 cal yr BP). Records are labeled by their patterns (Steady, Trending, Rising), and mean values for the past 10,000 years are shown by dashed lines. All lake outlines are shown with a 200-m scale bar.

IMPLICATIONS FOR PALEOLIMNOLOGY

It is useful to consider which types of mountain lakes would be most valuable from a paleolimnology perspective. The answer, of course, depends on the objectives of a particular study, yet the exploration of the Uinta lakes data set presented here supports a few generalizations. First, lakes in active hydrologic settings will likely have LOI records that are insensitive to minor-to-modest climate changes because the large amounts of through-flowing water buffer them against changes in water level, temperature, and salinity that may affect productivity. Second, records from lakes with minimal through-flow in low-elevation basins may be dominated by continuous eutrophication driven by progressive shallowing. Major climatic shifts may still be recorded in the sediment of these lakes; for instance, the two departures to lower LOI values in core 04-03 at ca. 8000 and ca. 4000 BP (Fig. 2) represent notable disruptions in the overall increasing LOI over the past 10,000 years that are paralleled by similar fluctuations in neighboring lakes with different LOI patterns (cores 04-01 and 04-02). However, the possible role of changing internal factors (i.e., depth, volume, nutrient status) would need to be considered for the development of accurate paleoclimate records from lakes in these settings. Finally, lakes with moderate values in a few key categories (i.e., elevation, through-flow, upstream lake area, ice/snow cover) may offer the best potential for paleolimnological investigations in high mountain environments. LOI records from these lakes are neither Steady nor Rising, suggesting that they are not dominated by through-flow or eutrophication. Instead, variations in LOI trending over multi-centennial to millennial scales imply that lake sediments in these settings are recording environmental responses to paleoclimate variability.

Conclusion

Post-glacial loss-on-ignition (LOI) records were developed for 12 high-elevation lakes in the southern Uinta Mountains, permitting exploration of the watershed controls over sediment organic content. Comparison of these records with one another, and with variables of the watershed surrounding each lake, reveals significant correlations related to hydrology. Lakes at higher elevations have generally lower average LOI values. Low organic contents are also associated with large volumes of through-flowing water, and with extensive areas of exposed bedrock and late-lying

TABLE 5

Significance of differences in mean values between LOI patterns.

		LOI Pattern			
		Steady	Trending	Rising	P-value*
LOI Records					
Max LOI	%	**20.2**	**33.2**	**32.4**	**0.059*** **
Mean LOI	%	**12.8**	**19.0**	**21.2**	**0.067*** **
Median LOI	%	**14.3**	**21.5**	**22.5**	**0.066*** **
Modal LOI	%	15.2	15.6	22.4	0.621
10 ka Mean LOI	%	**14.6**	**24.1**	**24.2**	**0.059*** **
10 ka Median LOI	%	**14.9**	**24.1**	**24.6**	**0.059*** **
10 ka Modal LOI	%	15.2	21.0	22.4	0.415
C.V.	%	0.7	1.4	1.3	0.395
Lake					
Elevation	m	3307	3236	3142	0.395
Max. Depth	m	9.4	10.0	6.1	0.479
Area (A_L)	ha	7.7	8.5	4.3	0.151
Perimeter	m	1464	1419	937	0.125
Complexity	–	1.5	1.4	1.3	0.475
Inflows	#	1.3	0.8	0.0	0.205
Order	#	0.8	0.6	0.0	0.229
Outflow	#	0.8	0.6	0.7	0.902
Throughflow	–	**3.5**	**2.0**	**1.7**	**0.025** **
Upstream Lakes	ha	**10.2**	**1.5**	**0.0**	**0.093*** **
Upstream Lakes	%	**3.8**	**0.5**	**0.0**	**0.062*** **
Upstream Lakes	ratio	**1.4**	**0.3**	**0.0**	**0.093*** **
Watershed					
Area (A_W)	ha	277	266	150	0.450
Perimeter	m	7402	6755	4929	0.450
A_L / A_W	ratio	31.2	26.9	35.6	0.879
A_W / Max. Depth	ratio	3306	3238	3131	0.303
Max. Elevation	m	3749	3609	3403	0.271
Mean Elev.	m	3456	3378	3252	0.214
Elev. Range	m	**444**	**371**	**272**	**0.052** **
Elev. Stdev	m	116	97	79	0.120
Max. Slope	deg	54	53	45	0.211
Mean Slope	deg	15	13	14	0.685
Slope Stdev	deg	12	11	10	0.731
Mean Aspect	deg	138	146	159	0.668
Ice/Snow	%	**17**	**4**	**1**	**0.055** **
Rock	%	36	35	30	0.695

* P-value from Kruskal-Wallis test; significant values shown in boldface.
** Correlation is significant at the 0.05 level (2-tailed).
*** Correlation is nearly significant ($0.10 > P > 0.05$, 2-tailed).

ice and snow in the watershed. In contrast, lakes at lower elevations, or those in closed basins, contain sediment with a generally greater organic content.

The 12 records can be divided into 3 groups with contrasting LOI patterns over the post-glacial period. Steady lakes feature LOI values that exhibit only minor fluctuations around an average value. Trending lakes exhibit LOI values that change progressively to higher and lower values over multi-centennial to millennial timescales. Rising lakes exhibit a persistent shift toward greater LOI values upon which shorter term fluctuations are superposed. Average LOI values are notably different between the three groups, with the lowest values found in the Steady lakes. Throughflow, percent ice/snow cover, and maximum watershed elevation are also significantly different between the groups, with the greatest values associated with Steady lakes, and the lowest values with the lakes featuring constantly rising LOI.

The analysis reported here is based on a relatively small number of lakes, and the relationships identified should be tested by expansion to other lakes in the area. Nonetheless, these preliminary results indicate that geohydrologic setting is a major control on the nature of organic sedimentation in high-elevation lakes. Paleoenvironmental studies with a choice of lakes should consider the possibility that organic records from through-flowing lakes surrounded by exposed rock and sparse vegetation will be less sensitive to climatic shifts than those from lakes featuring less robust through-flow. Lakes with minor to modest through-flow, minimal amounts of late-lying snow in the surrounding watershed, and moderate elevation ranges may be best suited for tracking paleoenvironmental changes through organic records.

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