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Quaternary Research 67 (2007) 193–203

QUATERNARY RESEARCH

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Century-scale variability in late-summer rainfall events recorded over seven centuries in subannually laminated lacustrine sediments, White Pass, British Columbia

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Received 14 February 2005
Available online 17 January 2007

Abstract

Formation of annually laminated sediments in Summit Lake, White Pass, British Columbia is controlled by runoff generated by snowpack and glacier melt and major rainfall events. The 700-yr varve record is divided into two subannual series (early and late) based on sedimentological criteria and sedimentary structures within each varve. A comparison of recent subannual laminae with nearby meteorological records supports the interpretation they are formed by river discharge events generated by major snow and glacier melt events and large late-summer rainfall events. A significant correlation exists between the late subannual thickness series and the size of the largest rainfall events in late summer. The long record indicates there was an abrupt increase in the thickness and frequency of major rainfall-induced sedimentary events at the end of the seventeenth century. In addition, the frequency of laminae generated by early runoff events also increased. However, early subannual varve thickness component remains statistically the same as the thickness prior to the end of the seventeenth century. This suggests the change in varve thickness at this time is due to increases in major late-summer rainfall frequency rather than increased sediment availability caused by regional Little Ice Age glacier advances.

Keywords: Varves; Climate change; Precipitation; Subannual sedimentary units; Little Ice Age; British Columbia

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Introduction

The processes that drive long-term hydrologic variability are difficult to assess, given the typically short hydrometric records that are available. One means of investigating past climate beyond the time scale of instrumental records is through the use of annually laminated (varved) lake sediments. Varved lake deposits formed by seasonal variation in sediment delivery to the lake can be used to reconstruct the conditions that control sediment delivery (e.g., hydrological and meteorological factors). Using varved sediments, researchers have been able to reconstruct temperature (e.g., Leemann and Niessen, 1994; Hardy et al., 1996; Hughen et al., 2000; Francus et al., 2002; Lamoureux and Gilbert, 2004), rainfall (Østrem and Olsen, 1987; Lamoureux, 2000), and river discharge (Sander et al., 2002) records that extend substantially beyond available instrument data. Like other quantitative proxy approaches, these reconstructions use instrumental records to calibrate the sedimentary signal in order to estimate the meteorological or hydrological conditions that control varve formation.

Most paleoclimate reconstructions based on varve chronologies rely on linkages with a single hydroclimatic process (e.g., varve thickness and temperature; Hardy et al., 1996). Typically, these varves have simple couplet structures that reflect the dominant relationship between sediment delivery and one hydroclimatic control. Some studies have identified more complicated relationships between weather and sediment delivery, especially in cases where the varves contain subannual laminae that represent discrete, short-lived episodes of deposition. Desloges and Gilbert (1994) noted that some subannual laminae represented extreme hydroclimatological events (e.g., late autumn storms) or events caused by geomorphic events (e.g., subaqueous slumps). Similarly, Lamoureux (2000) identified subannual laminae produced by major rainfall-runoff events, which can be systematically removed to identify a

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doi:10.1016/j.yqres.2006.10.003

residual thermal signal. This work and other studies suggest that the subdivision of varves into subannual components potentially increases the utility and understanding of the derived hydroclimate signal. For instance, Leemann and Niessen (1994) recognized that there were two different meteorological signals in the varves from Oeschinensee Lake, Switzerland. The dominant temperature signal was muted when rainfall was above average because the two hydroclimatic signals within the record were not considered independently, resulting in weaker climate relationships. Therefore, measuring subannual portions of the varve record potentially allows for the isolation of a more dominant signal (e.g., snow melt; Hambley and Lamoureux, 2006) from a signal that may be more intermittent (e.g., rainfall; Lamoureux, 2000).

This paper presents a 700-yr subannual record of hydroclimatic change at Summit Lake, White Pass, British Columbia. This study focuses on systematically differentiating the sedimentary deposits produced by different discharge mechanisms and investigates the long-term hydroclimatic variability. The subannual record is of particular interest given the recent attention to climate variability in the northeast Pacific Ocean (Mantua et al., 1997) and the emergence of several new ice core records from the nearby Wrangell–St. Elias Mountains (e.g., Moore et al., 2002; Thompson et al., 2004; Yalcin et al., 2006).

Study site

White Pass was selected for this study due to the dynamic hydrological environment (nival and glacial melt and rainfall). The pass is located in the northern Coast Mountains and is influenced by the strong precipitation gradients resulting from the proximity to the Pacific Ocean and the interplay of maritime and continental weather systems. Summit Lake is located in the pass near the British Columbia–Alaska boundary (59°00′N, 135°08′W, elevation 875 m; Fig. 1). The lake is long and narrow with numerous sills and basins, some of which are

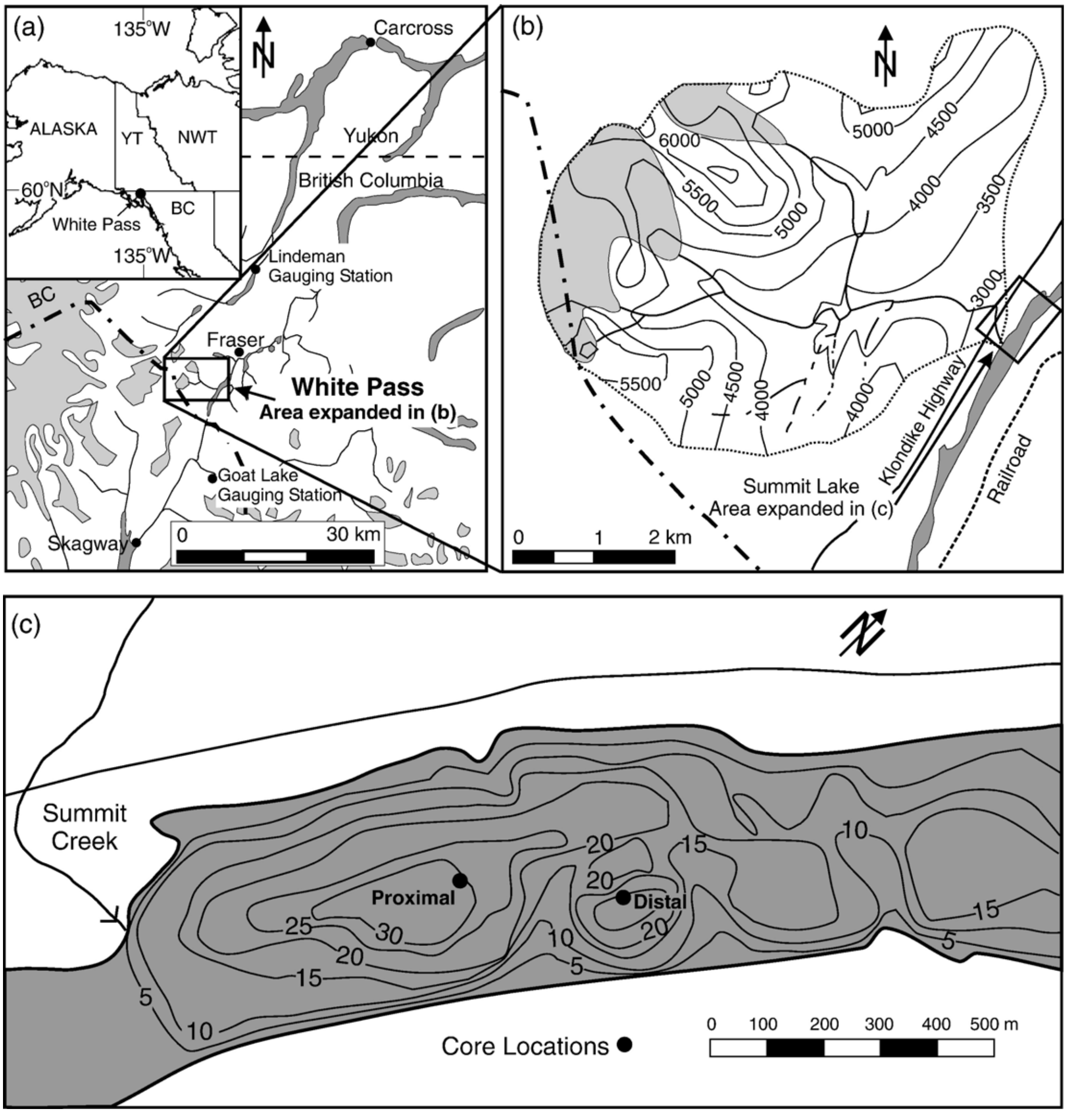

Figure 1. (a) A map of the White Pass and Summit Lake region. The inset map indicates the location of the study site with respect to the Pacific Coast of northwest North America. (b) The Summit Lake watershed and drainage pattern (contour interval 500 feet, approximately 150 m). (c) Bathymetry and coring sites in the proximal basin of Summit Lake. The isobath interval is 5 m. The darkest shading represents bodies of water in all panels, lighter shading in panels a and b represent glaciers.

relatively deep (maximum depth 34 m in the proximal zone). The surrounding mountains rise to 1900 m and are underlain with resistant granodiorite and mantled with patchy Quaternary glacial sediments (Clague, 1989). Inflow from the 28-km^2 watershed (17% glacierized) originates from heavy winter snowpack, summer melt from cirque glaciers in the headwaters, and runoff particularly during late-summer rainfall (Fig. 2).

Temperature and precipitation records from this region of British Columbia, Alaska, and Yukon Territory vary in length and frequently contain extended gaps. The record from Fraser, British Columbia (Environment Canada, 1998, Station ID 120036, 8 km from Summit Lake), spans 18 yr (1980–1998) but is missing 4 yr (1983–1986) (Fig. 2). Mean monthly temperatures at Fraser range between −15°C and +11°C (Fig. 2). An average of 8 m of snow falls between October and March each winter. Rainfall occurs through the spring and summer months but intensifies in August and September, until temperatures decrease and snow becomes the dominant form of precipitation (Fig. 2). Several stream gauging stations operate in catchments in Alaska and British Columbia and have comparable annual trends to the expected runoff regime from the Summit Lake watershed. A 5-yr discharge record from the outlet of Goat Lake, Alaska (USGS National Water Information System, 2002, Station ID 15056095, watershed area 7.5 km^2), is potentially the most similar to the expected stream behaviour in White Pass because the two watersheds are approximately the same distance from the coast and both have glaciers in their headwaters (Fig. 2). A second, 44-yr discharge record from Lindeman River, British Columbia (USGS National Water Information System, 2002, Station ID 15304800, watershed 240 km^2), has a similar hydrograph shape and offers information on hydrological conditions farther inland (Fig. 2).

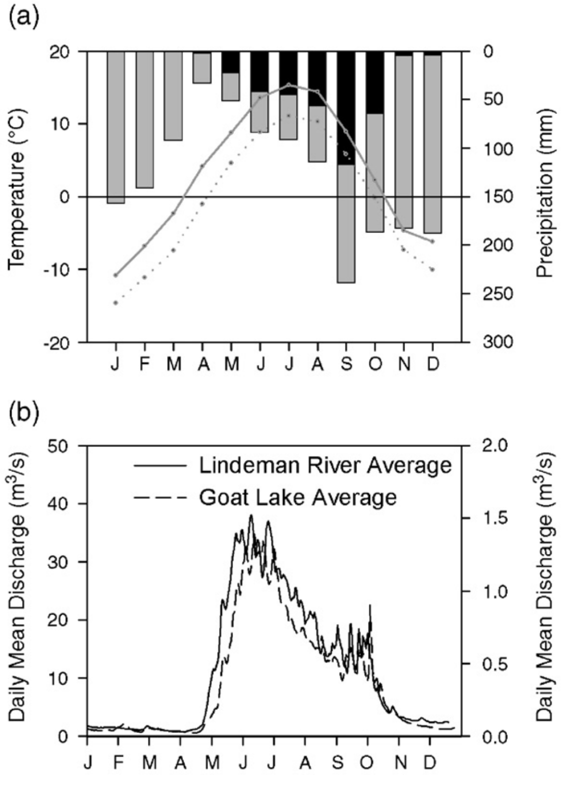

Figure 2. (a) Annual climate at White Pass from the Fraser, British Columbia (1987–1997, $n=10$; Environment Canada). The mean monthly daily maximum temperature (solid gray line) and daily mean temperature (dashed gray line) are shown, along with total (gray bars) and liquid (black bars) precipitation (mm equivalent). (b) Mean discharge hydrographs for Lindeman River (left axis) and Goat Lake (right axis) outlet. The mean discharge for Lindeman River was calculated with 40 yr of daily discharge data (1955–1994) and for Goat Lake 6 yr of daily discharge data was available (1992–1997). All hydrological data was compiled by the USGS National Water Information Systems.

Methods

Sediment coring and processing

Two long vibracores (Smith, 1998) and matching surface cores (Boyle, 1995) were collected in April 2000 and 2001 from Summit Lake (Fig. 1). The long cores were cut into sections and transported unfrozen to the laboratory for analysis. Water was siphoned off the surface cores and molten paraffin wax was used to seal the top and minimize disturbance of the sediments during transport. The surface cores were transported standing vertically and unfrozen. The long core and corresponding surface core used to construct the chronology were retrieved from the distal part of the subbasin fed by Summit Creek and are the focus of this research (Fig. 1).

In the laboratory, cores were split lengthwise and the exposed surfaces cleaned, logged, and photographed. Overlapping sediment monoliths (7 × 1.5 × 1 cm) were sampled from the cores by pressing aluminum trays into the core face and removing them. The undisturbed samples were separated from the trays, wrapped in paper towel (to prevent collapse of sandy structures when dry), freeze-dried, and then embedded with Spurr's low viscosity epoxy resin under low vacuum (Lamoureux, 2001). Large-format thin sections were produced from the cured slabs using standard methods. Samples were also removing them from the cores for bulk density and radioisotope determinations at 1-cm intervals.

Transmitted light images of the thin sections were obtained using a flatbed scanner at 600 dpi (dots per inch). The images were compiled in a graphics program (CorelDraw 10) and the overlapping images were arranged to produce a composite. Sedimentary structures were identified and measured (0.001-mm precision) in the graphics program. This process was repeated eight separate times over a period of ten weeks in order to be sure of consistent sedimentary structure identification.

Analyses for ^{137}Cs were obtained on freeze-dried samples counted in an EG&G ORTEC high-purity germanium coaxial-well photon detector. Each sample was measured for at least 80,000 s. Initially, samples were measured at approximately 5-cm intervals to isolate the presence of ^{137}Cs, independent of the varve chronology. Additional samples were subsequently measured to further constrain the 1963/4 bomb peak. ^{210}Pb determinations obtained with the same instrument indicated unsupported lead levels in all samples were not significantly above instrumental background levels and precluded the use of ^{210}Pb for dating purposes.

Results

Sedimentology

The basal sediments from the long distal core contain angular gravel. This is overlain by silty-clay laminae from 656 to 289 cm that includes a white ash layer at 372-cm depth. In thin section, the uppermost silty-clay sediments (289 cm to surface) are composed of well-laminated silt and clay laminae. Laminae vary from 0.18 to 15 mm in thickness and grain size ranged from clay to sand. Multiple silty rhythmites were frequently constrained by prominent thin clay layers. In the upper laminated unit (above 289 cm), the consistent recurrence of clay layers and grading in each lamina suggests that these rhythmites may be annual units similar to those found in other glacial lakes (e.g., Gilbert, 1975; Leemann and Niessen, 1994). Independent dating of the laminae with ^{137}Cs supported the hypothesis that the rhythmites in the upper unit of the sediment core (upper 289 cm) are likely varves (Fig. 3). Wavelet analysis of the varve series did not yield notable or significant results.

The varve chronology continues from the top of the core (AD 1999) down to 289 cm (AD 1299, Fig. 3). In the field, the distal long core was cut for transport and during this process an estimated 5 cm of sediment was lost. Using distinct marker beds from the distal core that bracket the gap and the proximal long core, 11 yr were identified as lost from the 1800s in the core chronology. The varve and subannual event thicknesses from the proximal core spanning this gap were not included with the record from the distal core because the proximal core was from a location with increased sedimentation rates. Using these values could bias this section of the results. Furthermore, this core was punctuated with turbidites and thus unusable for the Summit Lake chronology.

The ash layer identified at 372-cm depth in the distal long core was also present in the proximal long core at 740-cm depth. Geochemical composition of the ash from the proximal long core indicated the source as the White River eruption (Westgate, J. personal communication, 2001), with an age estimated by radiocarbon dates as AD 803 (Clague et al., 1995). Proportional sedimentation rates support the likelihood that the ash in the distal long core is the same as the White River Ash identified in the proximal long core. Although there are two known White River Ash tephras (the north lobe at AD ~ 500 and the east lobe at AD 803; (Clague et al., 1995), only the younger of the two tephras have been identified in the White Pass area (Cwynar, 1993). The stratigraphic position of the tephra does not allow for absolute age verification with the varve chronology, because it occurs below the laminated unit. However, the tephra's age, which is greater than the estimated onset of the laminated unit, is consistent with the varve age model. In particular, it supports the interpretation of multiple subannual laminae in the varves. If the laminae were consistently misinterpreted and represented annual structures, the resultant chronology would be substantially older than the tephra.

Subannual sedimentary analysis

Based on the annual limits defined by the varves, it is possible to further partition and characterize the subannual events with sedimentological criteria (Table 1; Fig. 4). Varves without subannual structures (simple) also occur in the record and are distinguished from varves with multiple rhythmites by the presence of a single graded couplet. The presence of discrete laminae within a given varve represents a transition from relatively low- to high-energy transport conditions. Each varve is defined by an initial coarse layer that conformably overlies the clay cap from the year before. The coarse layer grades into finer silt that is usually interrupted by one or more coarse graded silt layers grading into a distinctly fine clay laminae (which has a dark colour and uniform texture). In

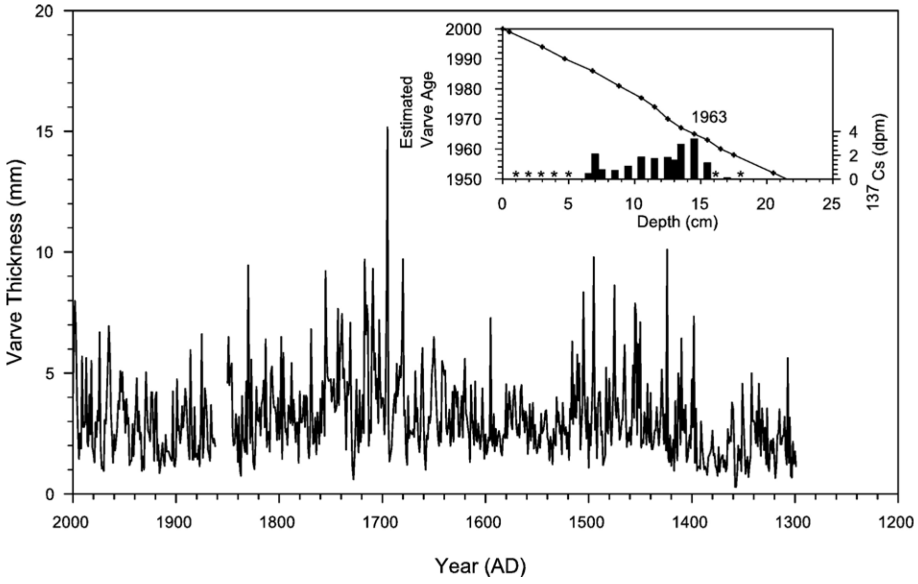

Figure 3. The total varve thickness series from Summit Lake. The gap between 1855 and 1866 is due to a core break. Inset indicates ^{137}Cs profile from the surface core taken from the distal location. Measured samples that were below detection limits are indicated by * symbols.

Table 1
Sedimentary criteria used to identify and classify laminae in Summit Lake

Class	Stratigraphic position (within varve)	Macro-organic content (qualitative)	Grain size range (qualitative)	Other features
Early	Beginning	Typically rare detrital material, first laminae	Clay-rich	Clay content increases from the lowermost laminae
Late	End	Detrital material relatively frequent	Relatively coarse, minimal clay	Grading absent
Simple	Single couplet	Variable	Full range, clay–sand	Normally graded
Turbidites	Anywhere	Coarse fragments of moss or grass	Full range, coarse silt/sand grades to fines	Substantially thicker than most subannual events (ranged 10–40 mm)

Early and late classes are subannual sedimentary events and the simple class refers to years without subannual events. The criteria for turbidite identification are also included.

many instances, the final clay cap is interrupted by a massive unit of coarse silt that is abruptly overlain by fine clay. This coarse sedimentary layer differs from earlier units by the lack of grading and narrow range of particle sizes present. Given the stratigraphic position and common occurrence of these coarse laminae, the most likely mechanism for deposition is a discharge event generated late in the hydrological season. Similar deposits have been reported in varves from other montane and arctic lakes and have been commonly attributed to autumn rainstorm deposits (Gilbert, 1975; Desloges and Gilbert, 1994; Leemann and Niessen, 1994; Lamoureux, 2000).

Based on the sedimentological criteria (Table 1), each subannual event was classified as an “early” or “late” event, and two time series were constructed. Early events were not separated into different series due to the absence of clearly distinctive sedimentological characteristics in many instances and the likelihood that deposition was effectively uninterrupted between the nival and glacial phases of hydrological activity. Infrequent turbidites were sedimentologically distinct from the subannual units and simple varves (Table 1). The turbidites were not included in varve thickness measurements because their distinct sedimentology and their irregular occurrence suggest that they are likely related to stochastic processes (e.g., subaqueous slumping).

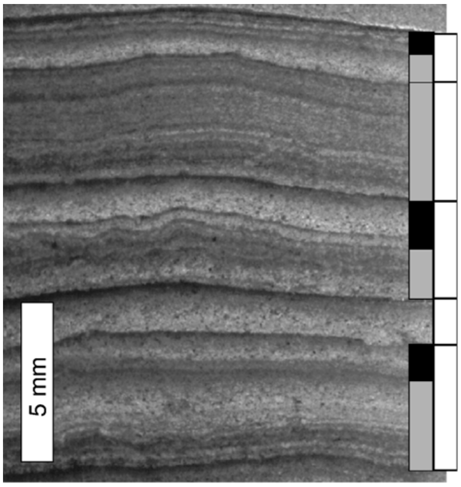

Figure 4. Sedimentary units identified in the Summit Lake varve record. The white boxes represent the extent of each varve (annual unit). Gray boxes are examples of early events and black boxes are late events. Varves without subannual units (shown without black and gray boxes) were classified as simple (Table 1).

Comparison of the recent sedimentary record with meteorological records

The subannual sedimentary record was hypothesized to reflect major river-competence transitions induced by different hydrometeorological processes. Using the available meteorological record from Fraser (8 km distant, Fig. 1), August and September (hereafter referred to as “late summer”) daily rainfall magnitude was compared to the three thickness series. The rainfall data were ranked to isolate the largest daily events. The single largest daily event, as well as sums inclusive of up to the five largest daily events, were compared with total, early, and late thickness sedimentary-unit measurements, for both months separately and combined. The strongest correlation observed was between the sums of the two largest daily rainfalls from the combined late-summer period (Fig. 5). Although the Fraser meteorological record is short (14 yr available), the correlation between the largest two rainfalls and total varve thickness, as well as the late-event series thickness, are highly significant (total varve thickness $r^2=0.695$, $p<0.001$, $n=14$; late varve thickness $r^2=0.615$, $p<0.001$, $n=14$; Table 2). Correlations with more than the two largest rainfalls were also significant, but weaker (Table 2). Comparison with the discharge record at Goat Lake (Fig. 1) is more constrained due to the short discharge record (5 yr). However, where comparison is possible, increased late-summer discharge is associated with major rainfall events and demonstrates the hydrological link between late-summer rainfall and late-season sedimentation (Fig. 6).

There are a number of other meteorological stations within a 100-km radius with longer records of temperature and rainfall. Correlations between the varve record and these stations are insignificant, likely due to the extreme precipitation gradient across the Coast Mountains and spatial variability in precipitation in this mountainous region. For example, at Atlin, British Columbia (~80 km east of Fraser and Summit Lake), the largest late-summer rainfall of the series occurred in 1992, while at Fraser, 1992 was not an exceptional year for late-summer rainfall (Fig. 5) and the corresponding Summit Lake varve does not contain late-season events. Other differences are frequent in other years. Therefore, the meteorological record at Fraser and sedimentary record from Summit Lake appear to record highly localized precipitation conditions and justify only the use of the Fraser record for meteorological comparisons.

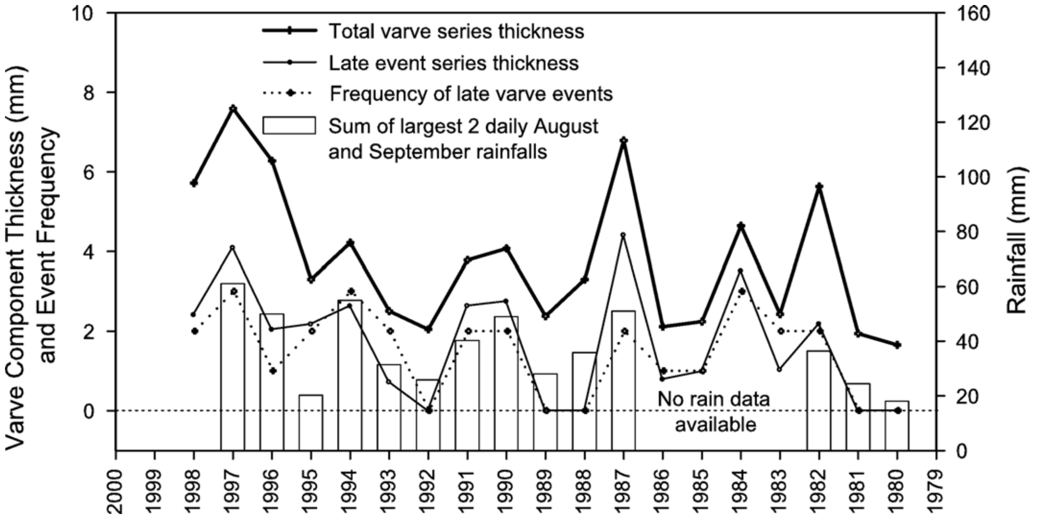

Figure 5. The sum of the largest two daily rainfalls in August and September at Fraser, British Columbia compared to total and late varve series from Summit Lake. The varve thickness axes are offset for clarity.

The correlation between the two largest daily late-summer rainfalls at Fraser and the total and late-component thickness series indicates that the record from Summit Lake is a reliable quantitative proxy for the interannual magnitude of the most intense late-summer rainfalls. However, there is one departure from this interpretation during the 14-yr meteorological record. The sum of the two largest rainfall events in 1995 is the second lowest on record, but the varve thickness (both total and late event) for that year is above average. Examination of the 1995 meteorological record (Fig. 6b) indicates that September mean maximum daily temperatures were the warmest (13.1°C) on record and exceeded the mean conditions (8.9°C, 1977–1997, $n = 14$ due to missing years) by two standard deviations ($\sigma = 1.8$°C). Furthermore, the daily discharge record from Goat Lake on the coastal slope of the mountains illustrates that there was an increase in discharge during this pronounced warm period. Thus, 1995 is the only year that the varve record appears to misinterpret a late-season warming (presumably caused by glacial melt) event as rainfall. This suggests that the certainty of the interpretation, based on misinterpreting 1 yr out of fourteen is approximately 93%.

While it is difficult to assess if the misinterpretation of anomalous late-summer warming events was more frequent in the past, examination of the long varve record suggests that it is unlikely. During periods of known warmer conditions in the early part of the record (e.g., Mann et al., 1999), the sedimentology remains similar and the inferred rainfall thickness and event frequency is substantially reduced (Figs. 7, 8). There is no evidence to suggest that warmer periods have led to systematic misinterpretation of the source for late-season events. Furthermore, based on northern hemisphere temperature reconstructions over the time period considered in this paper, the late 20th century remains the warmest (Mann et al., 1999).

Table 2
Correlations between the Summit Lake varve series and the largest August–September daily rainfalls at Fraser (r^2 values are reported with p-values in italics)

Varve series	L_1	L_2	L_3
Total varve series	0.673, *<0.001*	0.695, *<0.001*	0.642, *0.001*
Early event series	0.209, *0.100*	0.143, *0.182*	0.118, *0.229*
Late event series	0.517, *0.004*	0.615, *0.001*	0.588, *0.001*

The sum of the largest 4 and 5 rainfall days were also calculated but the correlations were not improved by the addition of more rainfall days.
L_X is the sum of the X largest daily rainfalls during August and September.

Discussion

The subannual sedimentary record

Summit Lake is located on a steep precipitation gradient (marine–alpine–continental). River discharge is driven by snow and glacial melt in late May through August and by large late-summer rain storms. Given the sensitivity of the watershed to relatively small hydrometeorological events and the frequency of these events, sediment is delivered to the lake in discrete pulses, producing subannual sedimentary laminae. Thus the total varve thickness does not correlate well to mean climatic conditions (e.g., monthly mean temperature).

Despite the added detail regarding past hydrometeorological activity resolved in the Summit Lake varves, the results are conceptually similar to many published varve records where climatic controls have been identified. For instance, Hardy et al. (1996) recognized that sediment transfer in a high arctic watershed was highest during the short-lived nival peak and substantially reduced thereafter. Hence, the significant correlation between spring temperatures and annual sediment transfer were effectively reflecting the short-lived (5- to 10-day) period of high sediment delivery and deposition conditions for the same period (annual sediment delivery was dominated by processes that took place over a few days) (Hardy et al., 1996). Similarly, sediment deposition in other nival environments has been related to spring temperatures during the short nival discharge peak (e.g., Hughen et al., 2000; Forbes and

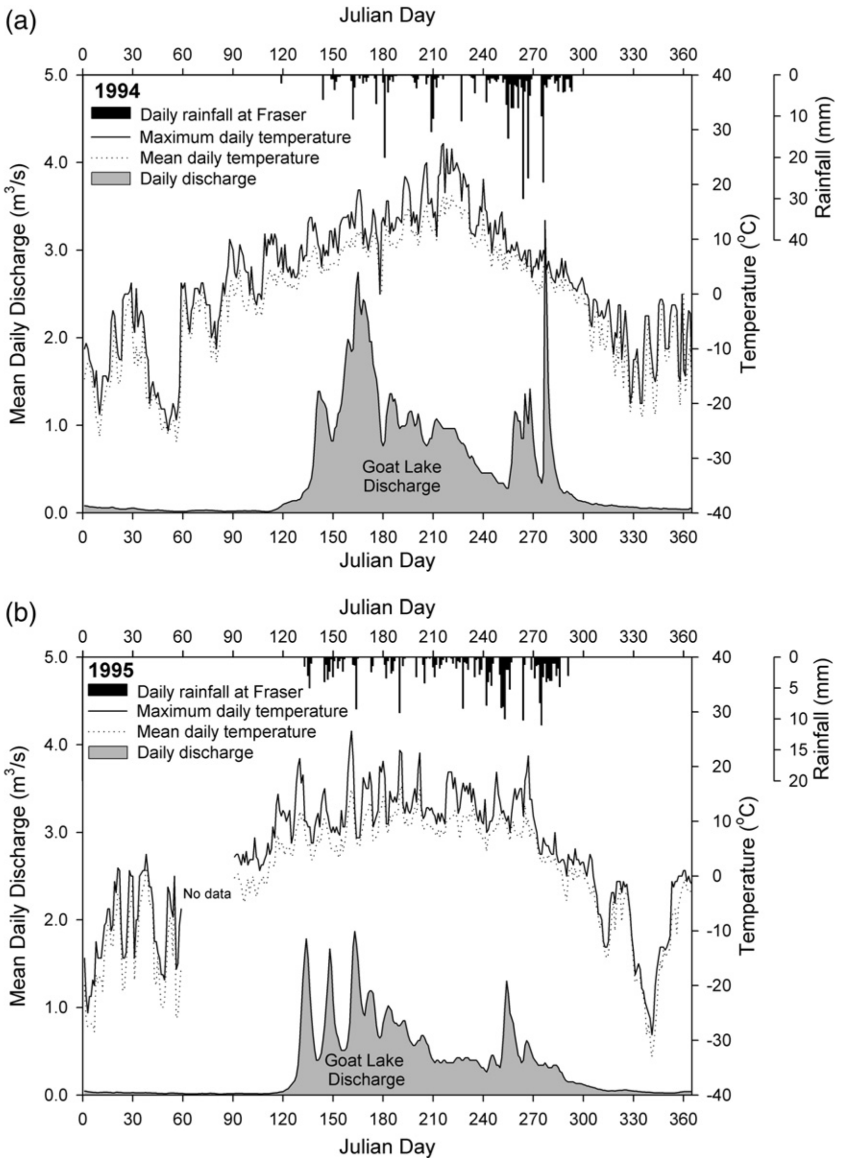

Figure 6. Hydrological responses at Goat Lake outlet, Alaska to meteorological conditions at Fraser, British Columbia in panel a) 1994 and panel b) 1995.

Lamoureux, 2005). In other cases, additional influences by subsequent hydrometeorological activity have been identified directly and indirectly in the sedimentary record. Lamoureux (2000) noted that major summer rainfall events generated prominent sedimentary units, in addition to the annual nival sedimentary unit. Similarly, a delayed onset of the glacial ablation season after nival discharge has been linked to the production of varves with two distinct coarse units (Smith, 1978; Ohlendorf et al., 1997; Tomkins and Lamoureux, 2005). The influence of summer rainfall was also shown to mute the melt signal contained in varves in a Swiss lake, although discrete subannual units were not specifically identified (Leemann and Niessen, 1994).

More generally, the results from Summit Lake and other studies point to the potential for recording both short-lived (hydrometeorological) and seasonal (hydroclimatological) conditions in varved sediments. Key controls over the preservation of hydrologic information in the sedimentary record reflect a number of controls, particularly the hydrological regime, sediment availability and depositional controls in the lake.

For instance, watersheds with relatively simple hydrological regimes dominated by a single hydrological process (e.g., nival) frequently correlate more closely with mean meteorological conditions (e.g., Hardy et al., 1996; Hughen et al., 2000) and produce varves with relatively simple couplet structures (e.g., Hughen et al., 2000), although this may vary between proximal and distal areas of the lake (Smith, 1978; Lamoureux, 1999). As the number of mechanisms that generate discharge (and sediment transport) increases, in cases where the sediment supplies are sufficient for transport throughout the season, varve complexity will also increase due to the deposition of multiple subannual laminae. However, the presence of subannual laminae is intermittent in nature and related to the proximity of the sedimentary record to inflow, catchment hydrological response, sediment availability, and other controls. Total varve-thickness records in these situations do not necessarily

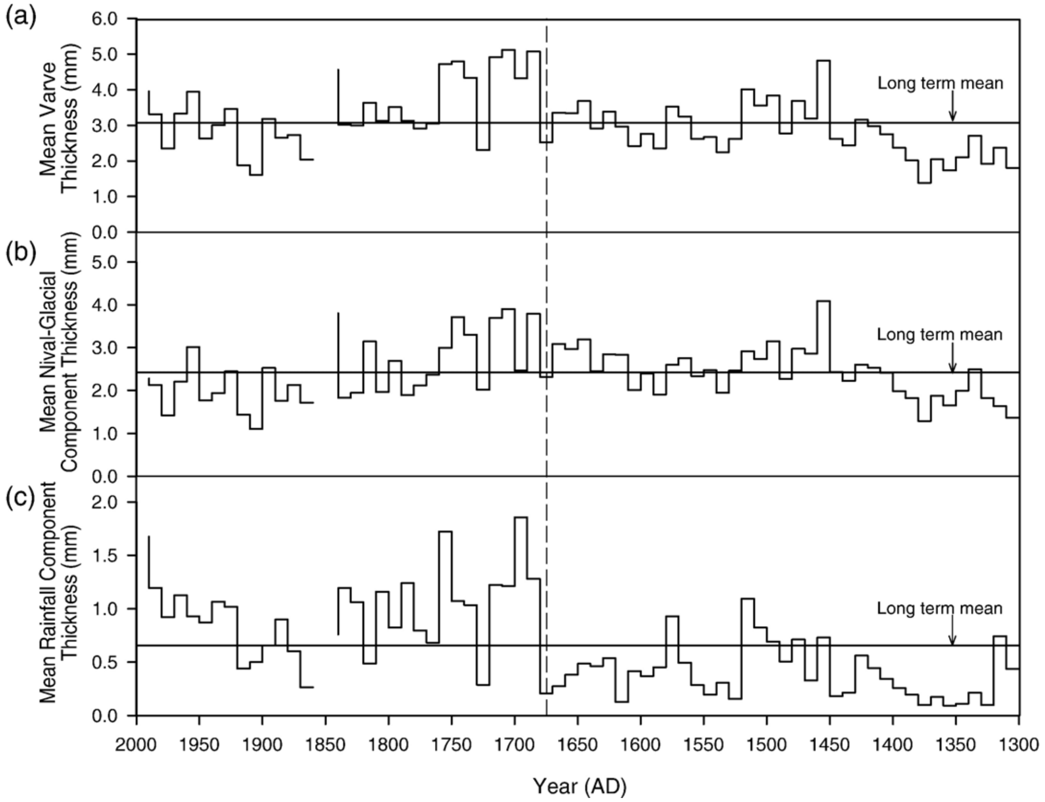

Figure 7. The long Summit Lake varve thickness records summarized by decade: (a) total varve, (b) nival–glacial component, and (c) rainfall component. The vertical dashed line is at AD 1675 and the long-term means for each series is identified. The gap from AD 1850–1870 is due to the core break (see text). The vertical dashed line separates to two main periods discussed.

correspond to mean monthly or seasonal conditions and are often more strongly associated with single hydrometeorological events (e.g., rainfall, Lamoureux, 2000; snowmelt, Hambley and Lamoureux, 2006).

In the case of Summit Lake, the sedimentation interpreted to be the result of major late-summer rainfall events is not correlated to monthly precipitation totals. The largest (and most intense) rainfall events extracted from the late-summer weather record reveal a significant correlation with sedimentary rainfall record. Therefore, the signal contained in the varves is defined in much more specific terms than similar proxy records and will be potentially affected by hydrometeorological and geomorphic complexities to a greater extent. Nonetheless, detailed analyses like those from Summit Lake offer the opportunity to identify additional hydrological information beyond a single parameter. The ability to use the sedimentary record to document major hydrological events is particularly valuable for the purposes of investigating long term dynamics of extreme runoff (Lamoureux, 2000).

Variation in the sediment availability in the watershed further complicates interpretations of the hydrological signal that may be preserved in the sedimentary record. Sediment yield may vary in a complex manner in response to discharge, due to supply and exhaustion of sediment sources over inter- and intraseasonal or possibly longer timescales (e.g., Orwin and Smart, 2004). Moreover, long-term sediment availability may be controlled by geomorphic controls that act over decades to centuries. In glacierized catchments, long-term sediment availability may vary in response to glacier activity, reaching maximums as the glacier expands and retreats (Leonard, 1997), although results from some locations suggest these relationships may be more complicated (Loso et al., 2004).

In the case of Summit Lake, where there is undated evidence for more extensive past ice extent in the surrounding cirques, controls over short-term sediment availability are not clearly apparent. The lake sediments prominently change to laminated silt and clay and higher sedimentation rates in the late Holocene due to the growth of the cirque glaciers (Lamoureux and Cockburn, 2005), indicating the important role of glacier activity in generating material for suspended sediment transport. Where varves are present during the past 700 yr, there is relatively limited evidence for major increases in sediment availability and delivery due to glacial activities. An increase in varve thickness at AD 1675 is inferred to be from late-season rainfall events rather than associated with glacier advance in the region (Wiles et al., 2004). Perhaps surprisingly, the retreat of glaciers after the Little Ice Age appears to have had minimal impact on sediment delivery, particularly from nival and glacial runoff. These results are contrary to many proglacial records in the western Cordillera (e.g., Leonard, 1997), but they bear an interesting similarity to the results from a site to the west in the Wrangell Mountains (Loso et al., 2004), although the latter represents a much more extensively glacierized catchment and ice-proximal setting than Summit Lake. Therefore, the absence

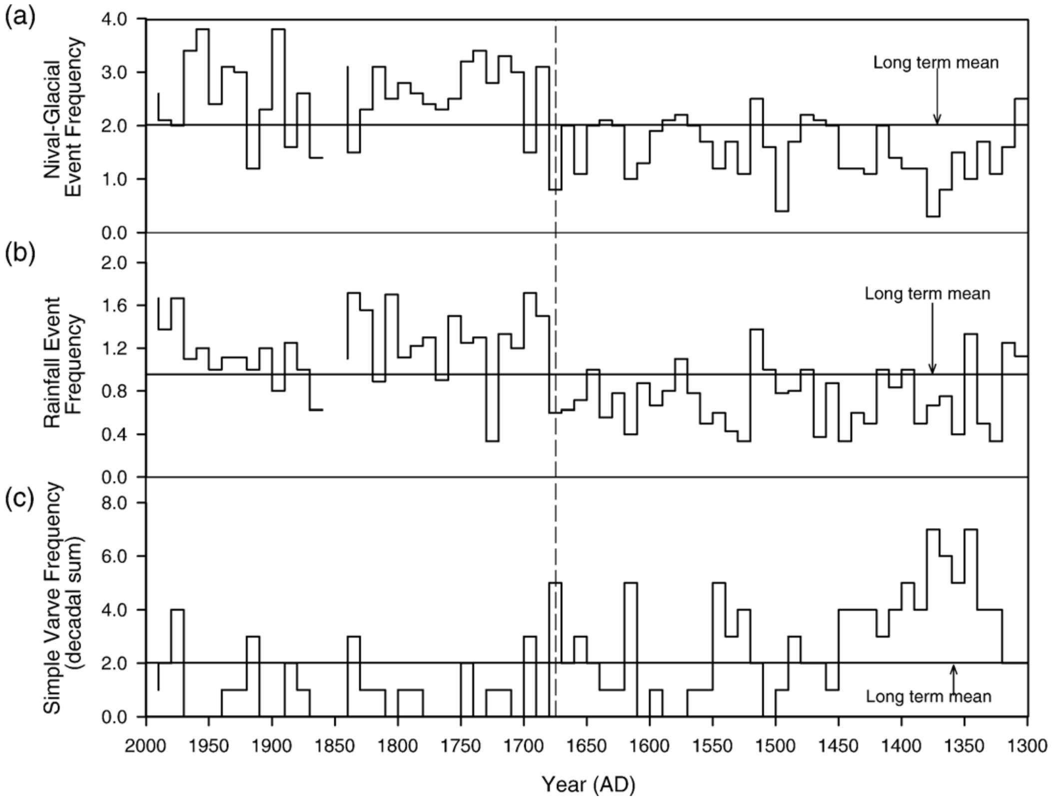

Figure 8. The long Summit Lake varve event frequency records totaled by decade: (a) nival–glacial events, (b) major autumn rainfall events, and (c) simple varves. The vertical dashed line is at 1675 and the long term means for each series is identified. The gap from AD 1850 to 1870 is due to the core break (see text). The vertical dashed line separates to two main periods discussed.

of clear low-frequency changes to sediment availability in the Summit Lake record suggest that changes in the occurrence of sedimentary events identified in this study reflect changes in the hydrological environment.

Long term hydroclimatic variability in White Pass

Comparison of the varve series with the weather record from Fraser, British Columbia, provides the basis to interpret the late season sedimentary events as occurrences of intense late-summer rainfall at White Pass with relative certainty (i.e. 93% of the time). Furthermore, the frequency of these events is also highly correlated with the rainfall depth, further supporting the interpretation that late-season sedimentary events are dominated by rainfall events. Consequently we surmise that late-season sedimentary events are induced by hydrologically significant rainfall events that are generated by low-pressure systems developed in association with the Aleutian Low over the Gulf of Alaska.

Prior to AD 1675, early sedimentary events (nival–glacial melt induced) dominate the varve thickness record and account for more than half of the overall thickness variation (Fig. 7). During this period, simple varves are more frequent as well (Fig. 8). The early subannual laminae do not change in appearance through the record and the frequency of early subannual events in a year do not substantially change (Fig. 8). An ANOVA of the decadally averaged data set demonstrates that the early subannual event series before and after 1675 remains statistically the same ($F=0.021$, $p=0.885$, $n=68$). By contrast, the thickness and frequency of late events (rainfall) change significantly after AD 1675 ($F=53.99$, $p<0.000$ and $F=76.10$, $p<0.000$, respectively, $n=68$).

In the post-1675 varve record, total varve thickness variation is increasingly explained by the thickness of the rainfall event series, particularly after 1980 (Table 3). The increased importance of rainfall contributions to total varve thickness in the last century may in part explain the poor correlations between instrumental temperature records and varve thickness.

The prominent shift in hydrometeorological variability at AD 1675 coincides with the Maunder Minimum, a period of low solar irradiance (Eddy, 1976). Lean et al. (1995) report low solar irradiance during the Maunder Minimum from 1645 to

Table 3
Portion of the total varve thickness series explained by the two major subcomponents (early events or late events) during the past 700 yr

Time period (AD)	n	Early series	Late series
		r^2	r^2
1299–1999	689	0.692	0.395
Pre-1675	376	0.849	0.274
Post-1675	313	0.607	0.456
Post-1900	99	0.502	0.652
Post-1980	19	0.425	0.770

All correlations are significant at 99%.

1715, based on reconstructed solar irradiation records. Wiles et al. (2004) note that this is a period of regional glacier advance in south-central Alaska, one of several advances potentially triggered by periods of reduced solar irradiance. During this period, the precipitation regime in White Pass appears to have shifted to more frequent and intense late-season rainstorm events. Since the nival–glacial record is not significantly different before or after 1675, it is likely that the abrupt change in sedimentation is due to a hydroclimatic shift that resulted in more late-summer precipitation. Furthermore, increased precipitation, particularly if it extended into the winter, combined with lower solar irradiation or cooler conditions, could contribute to positive glacier mass balance, which corresponds with ice advance observations elsewhere in the region (Wiles et al., 2004). Therefore, the Summit Lake record suggests that increased precipitation may have contributed to the prominent 17th century ice advance in the region coincident with lower solar irradiance (leading to decreased melt energy or temperatures).

Paleoclimate studies from this region have identified varying scales of climatic regime variability (D'Arrigo et al., 2001; Gedalof and Smith, 2001; Moore et al., 2002). At White Pass, late autumn rainfall events have increased in intensity and frequency since AD 1675. These changes are likely due to more frequent influence of low-pressure systems developing in the northeast Pacific Ocean over the Gulf of Alaska. Analysis of north Pacific Ocean sea-surface temperatures (SST) indicates that a type of Pacific decadal variability (PDV) has been persistent through, at least, the last century (Mantua et al., 1997; Zhang et al., 1997). One type of PDV, the Pacific Decadal Oscillation (PDO), has been linked to discharge anomalies in coastal watersheds along the Alaskan panhandle (Neal et al., 2002) and to salmon stock variations in Alaskan fisheries (Mantua et al., 1997). Unfortunately, paleoclimate reconstructions of PDV and the PDO exhibit substantial differences prior to approximately AD 1850 (Mantua and Hare, 2002). Thus, it is difficult to attribute changes found in the Summit Lake records to specific features in reconstructed PDO. For instance, Gedalof and Smith (2001) developed a PDO index from tree-ring chronologies collected from sites along the Pacific Coast (Washington State to Alaska), but the only notable similarity with the Summit Lake record is a persistent high positive anomaly in the tree-ring series at AD 1680. A positive trend in reconstructed PDO anomalies abruptly switches at the end of the 17th century (AD 1662), a time with some of the most negative sediment accumulation anomalies in the Summit record (D'Arrigo et al., 2001; Gedalof and Smith, 2001; Mantua and Hare, 2002). However, it is difficult to directly compare these records given the regional climate complexity and differences amongst available records.

Conclusions

Using sedimentological criteria and superposition, the subannual sedimentary events in Summit Lake were classified as either nival–glacial or rainfall-derived. Correlations between monthly mean temperature or total precipitation at nearby weather stations and the varve thickness series (total varve, nival–glacial and rainfall) were weak and insignificant. The rainfall sedimentary component was significantly correlated to the magnitude of the largest late-summer rainfall events, and hence, these units appear to be produced by short-lived responses to intense hydrometeorological events rather than total late-summer rainfall. The record of major late-summer rainfall events is the first of its kind and is informative in describing how these events have changed in this wet region of North America during the past 700 yr. Rainfall event laminae became thicker and more frequent, coincident with Little Ice Age glacial advances in the region (after AD ~ 1675). However, subannual laminae attributed to nival–glacial runoff do not significantly change through this period, suggesting that the rainfall record changed independently of geomorphic changes in the watershed or increased sediment supply due to the Little Ice Age glacier advances. Given the association of increased rainfall at White Pass with changes to the Aleutian low pressure system in the Gulf of Alaska, the rainfall record from Summit Lake provides additional information to investigate the long-term ocean–climate dynamics in this sensitive region.

Acknowledgments

This work was supported by an NSERC grant to S.F.L. and Northern Studies Training Program and Sigma Xi grants to J.M.H.C. We thank B. Beierle, B. LeBarge and M. Nowasad for field assistance. Comments by R. Gilbert on an earlier draft and two anonymous reviewers improved the presentation.

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