

A Disappearing Lake Reveals the Little Ice Age History of Climate and Glacier Response in the Icefields of Wrangell-St. Elias National Park and Preserve

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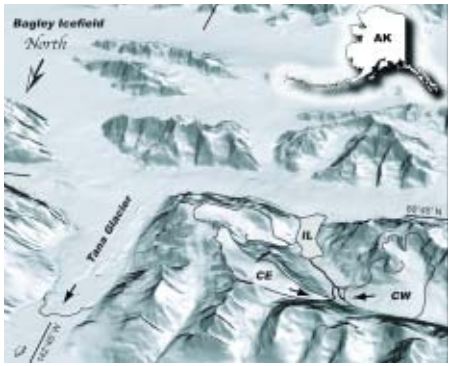


Figure 1. Location and context of Iceberg Lake (IL). Two small glaciers, Chisma East (CE) and Chisma West (CW), provide most meltwater and sediment to Iceberg Lake. Small arrows indicate glacier termini and general flow directions. Scale varies; Chisma Glaciers terminate <3.5 km from the 4-km-long lake. Note figure orientation as shown by north arrow.

(Left) Field assistant Mike Booth works on an outcrop of lake sediments, with stranded icebergs above and a stream traversing the drained lakebed in the background.

Photograph by Michael Loso

A Disappearing Lake

In the late summer of 1999, artist Hamish Fulton took a long walk through the icefields of Wrangell-St. Elias National Park and Preserve. He had spent months planning the trip, and one highlight of his journey would be a traverse of the remote valley where glacier-dammed Iceberg Lake sits alongside a broad tributary of the Bagley Icefield *(Figure 1)*. The lake is scenic enough, in a land of scenic excess, to grace the cover of a recent hiking guide for the park *(Kost 2000),* and Fulton was determined to see the lake in person. On the bright sunny morning of August 27, Fulton already had a week of rough hiking behind him as he crested a low pass and paused for his first look at the lake. In the foreground of his view, a creek emerged from the melting terminus of a small alpine glacier. Instead of flowing into a tranquil, iceberg-dotted lake, however, Fulton was surprised to see the creek running wildly across a naked, muddy lakebed, disappearing in the far distance amidst a pile of heavy, dripping icebergs. The lake was gone.

To be fair, the sudden drainage of a glacier-dammed lake is not all that unusual. There are hundreds of such lakes scattered throughout Alaska *(Post and Mayo 1971),* and many drain on a semi-regular basis. As a lake fills with meltwater from the surrounding mountains, a leak can develop at the base of the ice dam. Impounded water melts and widens the icy hole, turning a trickle into a torrent, and the contents of the lake escape through a subglacial drainage network to emerge from the glacier terminus as a jökulhlaup, or glacier outburst flood. Hidden Creek Lake, one well-studied example of such behavior, has drained—under the Kennicott Glacier and past the town of McCarthy—every summer for at least the last century *(Rickman and Rosenkrans 1997).*

Still, the drainage of Iceberg Lake was a surprise. Old shorelines, visible on the mountainside above Iceberg Lake, attest to the lake's historic tendency to vary in size *(Figure 2)*. But over the years, local pilots, climbers, scientists, and NPS staff had never seen it drain; there was no record, before 1999, of any catastrophic drainage events. Fulton had witnessed something unprecedented in the history of the park. Intrigued by his photographs of a smooth, fine-grained lakebed *(Fulton 1999),* we visited Iceberg Lake the following summer to examine its sedimentary record. The lake had only partially refilled, and we found the exposed lakebed dissected by hundreds of small gullies, each draining towards the new 20-60 ft (6-18 m) deep canyon of Chisma Creek, Iceberg Lake's primary inlet stream.

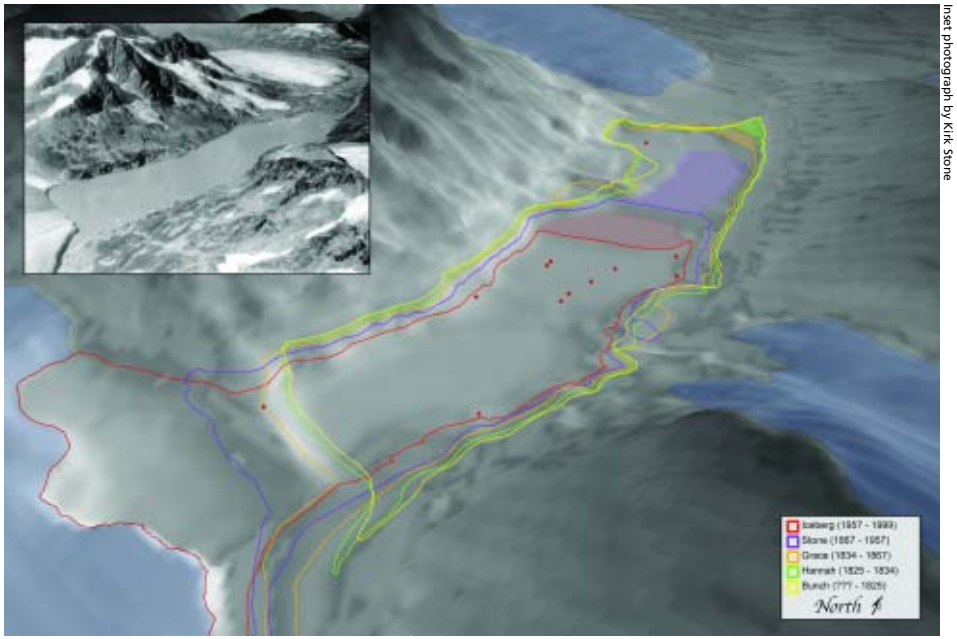
Using Mud to Study Climate

The incipient drainage network was exposing steep-walled, cohesive outcrops of laminated lacustrine sediment. These laminations, known to geologists as varves,

represent the annual cycle of sediment deposition into glacial lakes. Coarse sands and silts, brought to the lake by the high flows of summer rivers, contrast with thinner, finer-grained clay deposits that slowly settle out during the tranquil winter. Like tree rings, these alternating bands *(Figure 3)* keep time and record the climate. Each summer/winter couplet represents one year of deposition, and thicker varves typically correlate with warmer summer temperatures.

Only a stable lake can deposit and preserve such delicate sedimentary features, so the repeated jökulhlaups that characterize most glacier-dammed lakes preclude development of a coherent record. Our preliminary examination revealed over 1,000 laminations, confirming Iceberg Lake's unique stability. The features promised a high-resolution record of summer temperatures over a complete climatic cycle, including both the Little Ice Age (A.D. 1600-1850) and the Medieval Warm Period (A.D. 1000-1250) that preceded it. But, before the summer of 2000 was over, Iceberg Lake drained again *(Table 1)*, reminding us that the rapidly eroding gullies that exposed these varves also threatened to destroy them. We found ourselves in a race to decipher the climatic record before erosion removed the rest of the story.

The Little Ice Age (LIA) makes a compelling target for climate reconstructions because it provides the clearest picture of how glaciers have responded, in the past, to climate changes similar to those of the present. Geological evidence of glacier advances during the height of the LIA (around A.D. 1850) is widespread in southern Alaska, including prominent moraine loops around most land-terminating glaciers, and buried forests exposed by contemporary ice-front retreat *(Figure 4)*. Temperatures responsible for these glacier advances have been confidently reconstructed on the basis of tree-ring records *(Wiles et al. 1998)*. A globally recognized period of warm temperatures that preceded the LIA, the Medieval Warm Period (MWP), is less clearly represented in the geologic record. Most evidence of MWP glacier retreat was destroyed by subsequent LIA advances, and the tree-ring record from this region is too short to reconstruct MWP temperatures. As a consequence, we still have little basis for comparing the intensity of contemporary (or predicted) warming and glacial retreat in southern Alaska with that of our most recent pre-industrial warm period.



Inset photograph by Kirk Stone

Figure 2. Historic shorelines, lakebed topography, and sample locations at Iceberg Lake. Shorelines (colored lines) and accompanying deltas (shaded) are color-coded, with informal names and intervals of occupation (in calendar year A.D.) in legend. Red dots indicate sites where detailed varve chronologies were collected. Scale varies; long axis of smallest, most recent shoreline is ~4 km. Inset: Aerial photograph of Iceberg Lake, showing Stone shoreline, named in honor of the photographer *(Stone 1963)*.

Table 1. Chronology of recent jökulhlaups from post-stable Iceberg Lake, Alaska

Jokulhlaup #	Year	Date†
1	1999	August 27, 1999
2	2000	August 15, 2000
3	2002	August 15, 2002
4	2003	August 3, 2003
5	2004	August 26, 2004
6	2005	August ??, 2005
7	2006	September 6, 2006

† Date of jökulhlaup commencement, ±1 day.

Fieldwork

The record at Iceberg Lake has changed that. In fieldwork conducted between 2001 and 2003, we documented the climate record archived by sediments in the exposed lakebed, and we reconstructed the history of glacial fluctuations around the lake. Taking advantage of the broad outcrops exposed by lakebed incision, we eschewed traditional coring techniques: most description and measurement of the varve record was painstakingly done in situ on cleaned, tagged outcrops. From these outcrops we collected samples for laboratory analyses that included measurements of radiogenic carbon-14 and cesium-137, bulk density, loss on ignition, and sediment grain size. We performed differential GPS surveys to accurately characterize the topography of the lakebed and the surrounding landscape, and also to document the contemporary thickness and extent of glaciers adjacent to the lake. To document the historic extent of those same glaciers, we dated abandoned terminal moraines with lichenometry, a technique that uses the known rates of colonization, growth, and mortality for slow-growing lichen species to date rock surfaces on which those lichens grow *(Loso 2004, Loso and Doak 2005)*. The results of this work tell a coherent story of climate-mediated landscape change beside Alaska's largest icefield.

Measurement, cross-dating, and counting of varves from seven sites in the former lakebed of Iceberg Lake documented continuous sediment accumulation from A.D. 442 to A.D. 1998. Radiocarbon dating, cesium-137 concentrations (from atmospheric nuclear testing), and additional stratigraphic data confirm this chronology, and show that Iceberg Lake has been stably

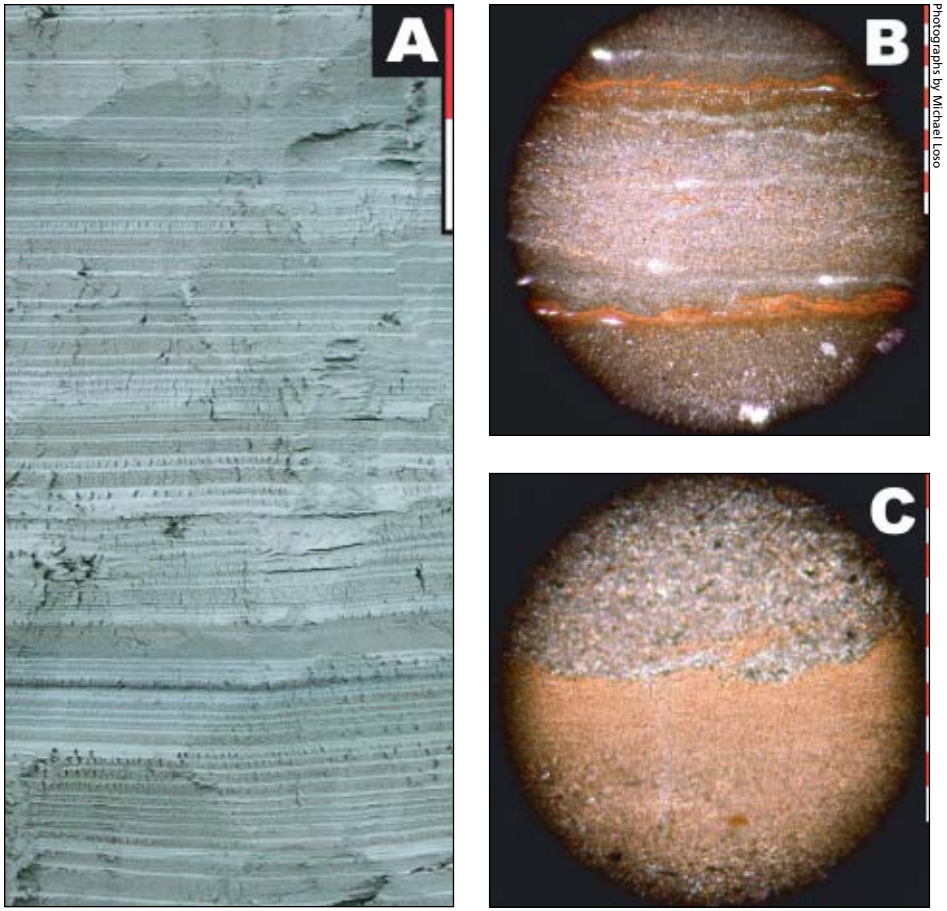


Figure 3. Photographs of varved lacustrine sediments from Iceberg Lake. (A) Varve section photographed *in situ* from a cleaned outcrop. Light gray bands are winter clays. Scale bar is 10 cm. (B and C) Microscope photographs, in plain light, of resin-impregnated, thin-sectioned sediments. Vertical bar in each photo is 1 mm. (B) Typical thin varves showing two reddish winter clays, oxidized subsequent to sample collection. (C) Note winter clay comformably draping underlying summer layer.

impounded by the glacier dam for at least 1,500 years (for details, see *Loso et al. 2006*). Because unstable saturated muds prevented us from examining the oldest (lowest) portion of any of the outcrops, this is a minimum age for the lake, and we are currently planning a more conventional piston coring campaign to document the earliest history of the lake. The resulting chronology of varve thickness measurements *(Figure 5)* nonetheless extends to well before the MWP, and provides an opportunity to compare temperatures from that time period with the subsequent LIA, and of course with the present.

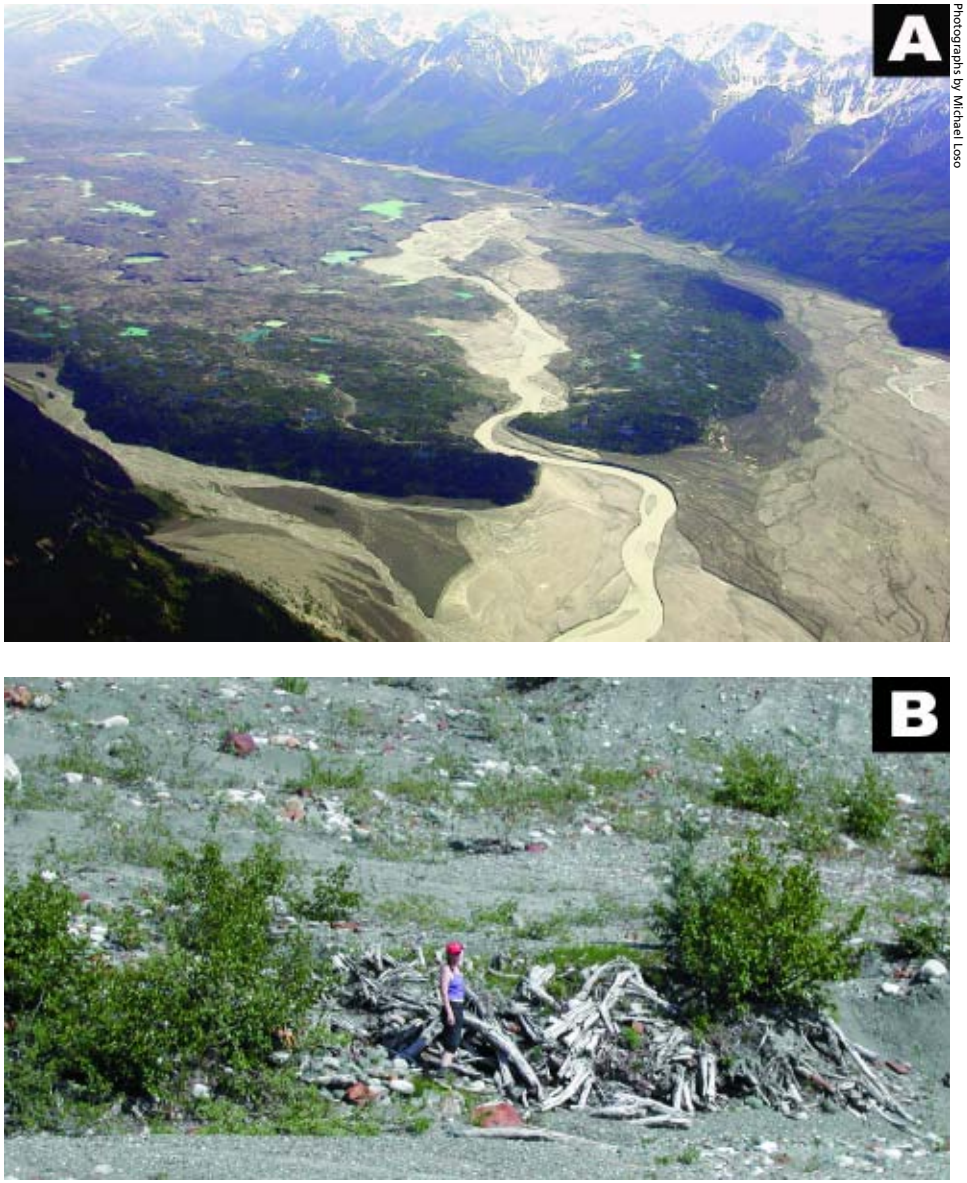


Figure 4. Examples of evidence used for reconstruction of former glacier extents. (A) Terminal moraine loop of the Chitina Glacier, which has retreated several kilometers further up valley at upper left. The Chitina River now cuts through this well-vegetated landform, which remains as evidence of the glacier's maximum advance during the Little Ice Age. (B) Fossil trees in glacial till near the modern terminus of Guyot Glacier, Icy Bay. These trees were overrun by the advancing glacier during a period of climatic cooling, and were subsequently exposed by glacier retreat. Cross-dating of fossil trees like these constrains timing of glacial advances.

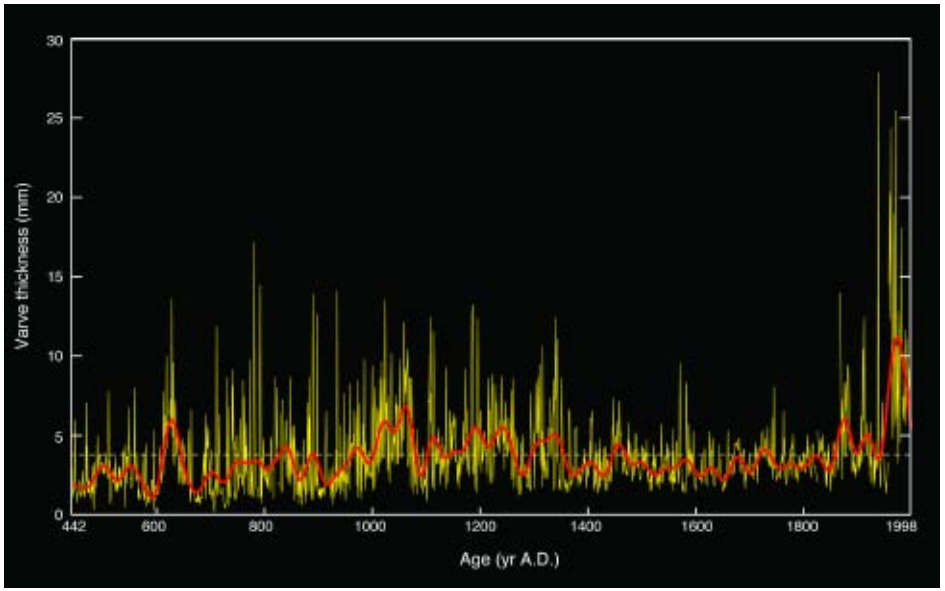


Figure 5. Master chronology of varve thickness measurements compiled from multiple outcrops of lacustrine sediment in Iceberg Lake. Yellow line shows annual measurements. For clarity and to show general trends, red line shows data smoothed with a 40-year low pass filter. Note slightly thicker varves during Medieval Warm Period as compared to those during the Little Ice Age.

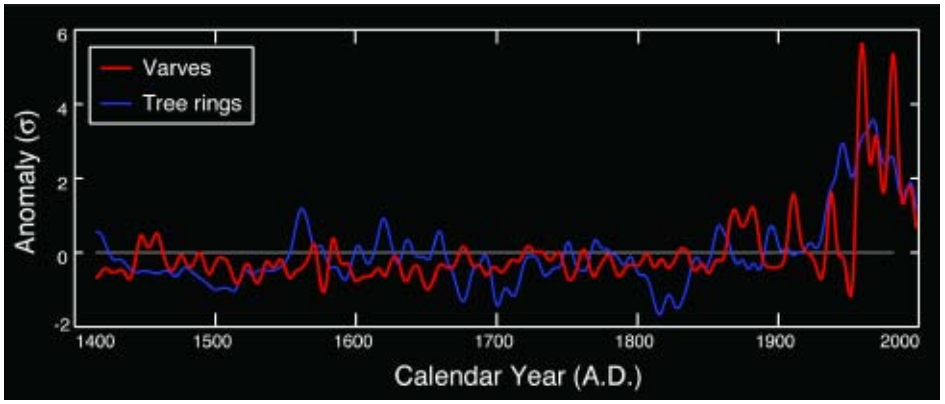


Figure 6. Comparison of the recent portion of the Iceberg Lake varve chronology (red line) with tree ring-width anomalies (blue line) from the adjacent Wrangell Mountains *(Davi et al. 2003),* showing strong correlation between the two records (correlation = 0.62, p<<0.001). Smoothed versions of both records are shown, but correlation was calculated with raw (annual) data.

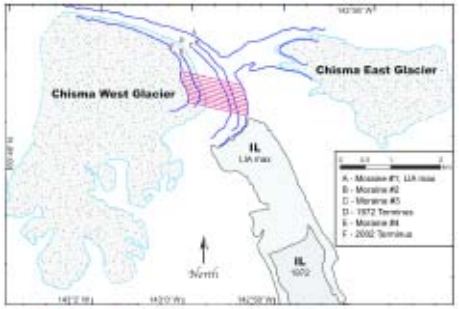


Figure 7. Terminus positions of the Chisma Glaciers. The oldest and most extensive glacier advance, shown by terminus position A (moraine #1), demonstrates that the Chisma West and Chisma East Glaciers were connected at the height of the Little Ice Age, and terminated near a strandline that marks the LIA-maximum highstand of Iceberg Lake (IL). Subsequent glacier retreat history is marked by terminus positions B-F. The mapped outlines of Chisma West and Chisma East glaciers and of the smaller shoreline of Iceberg Lake are derived from 1972 aerial photos. The larger, LIA maximum shoreline is from Loso et al. *(2004).* Glacier terminus positions were measured along ten transects shown by parallel dashed red lines.

Climate and Glacier Response

As mentioned earlier, theory suggests that warm temperatures are correlated with thicker varves, specifically because warm summer temperatures heighten the melt of both seasonal snow cover and alpine glaciers, increasing the discharge and sediment transport capacity of rivers that feed the lake *(Leonard 1985)*. To test this theory at Iceberg Lake, we compared our varve thickness record with the longest annual resolution regional climate reconstruction available: an almost 600 year-long record of growing season temperatures based on tree rings from the nearby Wrangell Mountains *(Davi et al. 2003)*. The two records are strongly and significantly correlated with each other between A.D. 1415 and 1998 *(Figure 6)*, suggesting that the entire varve chronology can be interpreted as reflective of summer temperatures.

The data tells us that Iceberg Lake was glacier-dammed, stable, and accumulating the thinnest varves of its known history when the measured varve record begins in the early fifth century A.D. *(Figure 5)*. The lakebed does not record the onset of this cold period, but is consistent with evidence for glacial advances around this same time in the mountains north and south of Iceberg Lake, based on cross-dating of buried trees *(Wiles et al. 2002, Calkin et al. 2001)*. Warming is marked by an increase in varve thickness and inferred temperatures that are sustained between A.D. 1000 and 1250, peaking around A.D. 1050 in a clear manifestation of the MWP. The LIA is recorded in the varve record as a period of thin varves between A.D. 1500 and 1850, followed by a dramatic increase in varve thickness that culminates in unprecedented values during the mid to late-1900s.

These results are consistent with known regional and global climatic trends, including widespread instrumental evidence for rapid twentieth century warming, and they provide the first detailed evidence that contemporary southern Alaska temperatures are significantly higher than temperatures during the MWP. Evidence of glacial activity in the Iceberg Lake basin reinforces this conclusion. Lichenometric dates on terminal moraines downstream of Chisma Glacier, the small alpine glacier that pro-

vides meltwater and sediment for Iceberg Lake's primary inlet stream *(Figure 7)*, show that the glacier terminus retreated rapidly in the late twentieth century in response to rapid warming *(Figure 8)*.

We have no record of that glacier's behavior during the MWP, but the lake itself provides another form of evidence for how nearby glaciers responded to MWP warming. We examined dozens of outcrops throughout the muddy bottom of Iceberg Lake, and the varve record was in all cases uninterrupted by signs of large-scale erosional unconformities. This continuity of sedimentary layers in Iceberg Lake precludes the possibility that catastrophic lake drainage events—which would have resulted in widespread lakebed erosion comparable to that seen since 1999—occurred at any time during the last 1,500+ years. Contemporary jökulhlaups reflect climatically induced thinning of the large glacier that impounds Iceberg Lake; the absence of evidence for similar events in the varve record strongly argues that the MWP was not warm enough to prompt similarly extensive glacier thinning and retreat, suggesting that contemporary glacier retreat is unprecedented over the last 1,500 years.

Conclusions

Wrangell-St. Elias National Park and Preserve is the park system's primary showcase for glacial landscapes, and the landscape-scale consequences of a warming climate will be central to the resource management and interpretive missions of the National Park Service for the foreseeable future. Iceberg Lake's record of late Holocene climate and glacier response provides researchers, NPS staff, and the general public with important context for understanding and interpreting one increasingly obvious sign of contemporary warming: glacial retreat. Climate and glacier dynamics vary tremendously across southern Alaska, and further research will be needed to judge the broader applicability of our conclusions in other regions. But on the northern margin of the Bagley Icefield, it appears that twentieth century warming is more intense, and accompanied by more extensive glacier retreat, than the Medieval Warm Period or any other time in the last 1,500 years.

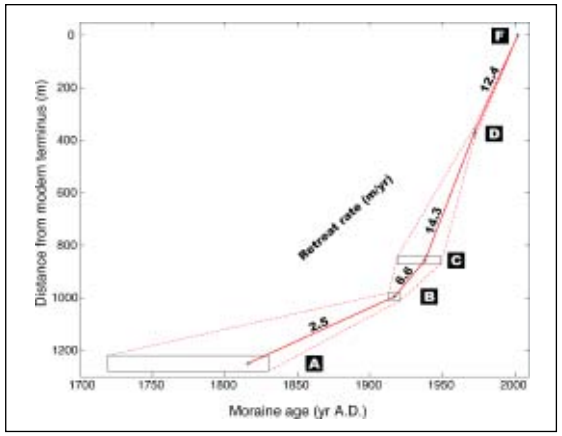


Figure 8. Post-Little Ice Age retreat history for the terminus of the Chisma Glacier, showing acceleration of retreat in the early twentieth century. The ages of moraines A, B, and C (letters correspond to Figure 7) are estimated using a new lichenometric technique; moraines D and F are from aerial photography and GPS surveys. Moraine E was not dated. Distances include 95% confidence intervals based on standard deviation of measurements from 10 transects. The dotted red lines thus enclose overall confidence limits for the retreat history. Mean retreat rate for each interval is shown in bold print.

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