Application of Single-grain OSL dating to ice-proximal deposits, glacial Lake Benson, west-central Minnesota, USA

Tammy M. Rittenour - Utah State University, Department of Geology, Logan Utah,
tammy.rittenour@usu.edu

James F.P. Cotter - University of Minnesota-Morris, Division of Math and Science, Morris Minnesota

Heather E. Arends - Minnesota Department of Natural Resources, St. Paul Minnesota

ABSTRACT

Glacial Lake Benson formed in west-central Minnesota as the Des Moines Lobe of the Laurentide ice sheet retreated north of a small moraine in the Minnesota River lowland. Although previous research has constrained the timing of Glacial Lake Agassiz immediately to the north, little age control is available for the formation of glacial Lake Benson and ice-marginal positions to the south. In order to constrain the age of glacial Lake Benson and test the application of single-grain optically stimulated luminescence (OSL) dating to ice-marginal deposits, seven OSL samples were collected from a variety of depositional settings. These included deltaic deposits linked to specific lake levels, pro-glacial fluvial, ice-contact and supra-glacial deposits. Single-grain OSL results indicate evidence for incomplete resetting (partial bleaching) of the luminescence signal, as expected for glacial environments, and therefore ages were calculated using a minimum age model. OSL results constrain the timing of ice-margin retreat and lake formation to 14.4-14.8 ka. Analysis of single-grain equivalent dose distributions indicates that deposits created by glacial-dominated processes typically had higher over-dispersion (>50%) and greater positive skew (>0.9) than deposits originating from fluvial processes. These results suggest that water-lain deposits should be targeted for OSL sampling over those created by glacial processes when dating ice-proximal settings.

26 Key words: single-grain OSL, glacial Lake Benson, partial bleaching, Des Moines lobe

1. Introduction

Glacial volume and related ice positions reflect the climate-driven mass balance between ice accumulation and ablation. Therefore, reconstructed ice-margin positions record ice-sheet response to past climate change; a subject of interest in light of future projected sea-level rise due to melting of the Greenland and west-Antarctic ice sheets (e.g. Overpeck et al. 2006). Moreover, reconstructions of ice-retreat and drainage reorganization are important for understanding linkages between meltwater discharge and cooling events during deglaciation (e.g. Clark et al., 2001). However without good age control, relationships between glacial dynamics, meltwater discharge and climate change cannot be assessed. While ice-retreat chronologies exist for the southern margins of the Laurentide ice sheet (e.g. Dyke and Prest, 1987), the multi-centennial to millennial-scale resolution of these reconstructions are difficult to reconcile with the annual to decadal-scale resolution of available climate records, such as from the Greenland ice sheet (e.g. Steffensen et al., 2008).

Age control for ice-margin positions along the southern Laurentide ice sheet has been largely limited by the scarcity of material for radiocarbon dating in pro-glacial settings. Moreover, most radiocarbon-dated sequences only provide minimum age estimates for ice-retreat due to the delay in vegetative succession in recently deglaciated landscapes (e.g. Cotter et al., 1984). Additional uncertainties arise when radiocarbon ages are calibrated to allow comparison to other records, due to large variations in atmospheric radiocarbon during deglaciation (e.g. Hughen et al., 2000; Reimer et al., 2013). These problems with radiocarbon-dated sequences have been side-stepped in unique cases where calibrated varve chronologies have been developed (e.g. Ridge et al. 2012), locations where ice re-advance has over-run forest beds (e.g. the Two Creeks re-advance in Wisconsin, Black, 1976) and situations where suitable boulders for cosmogenic dating are available (e.g. Balco et al., 2002).

Optically stimulated luminescence (OSL) dating (Huntley et al., 1985) may provide an avenue to better constrain ice-retreat chronologies, as quartz- and feldspar-rich sand for dating is abundant in glacial settings. However, OSL dating requires sufficient exposure of sediment to sunlight prior to deposition in order to reset the luminescence signal, which can be difficult to accomplish in glacial settings where sediments are sourced from sub-glacial settings and high sediment loads are common (e.g. Fuchs and Owen, 2008; Wyshnytzky et al., 2015). Technological advances in methods and instrumentation have allowed for the development of single-aliquot (Murray and Wintle, 2000) and single-grain (Duller et al. 1999) dating techniques that can be used to expand the applications of OSL dating to more challenging environments (e.g. Rittenour 2008; Duller 2008; Rhodes, 2011). The purpose of this paper is to test the application of single-grain OSL dating to ice-marginal deposits in a continental ice sheet setting and to provide the first age control for ice retreat and formation of glacial Lake Benson in west-central Minnesota, USA.

2. Background

Portions of Minnesota and Iowa in north-central United States were glaciated by the Des Moines lobe, an ice stream fed by the Keewatin sector of the Laurentide ice sheet (Clayton and Moran, 1982). In the absence of a well constrained chronology it has been suggested that the late-glacial Des Moines lobe experienced multiple periods of rapid ice advance followed by regional stagnation (e.g. Patterson, 1997, 1998; Clayton and Moran, 1982; Jennings, 2006). These dynamic ice-lobe fluctuations are suggested to have been driven by episodic low basal shear stresses due to high sub-glacial water pressure and till rheology (e.g. Clark 1994; Hooyer and Iverson, 2002).

Following an initial advance at ~20ka, the Des Moines lobe re-advanced to reach its late-glacial maximum position at the Bemis Moraine in central Iowa (Figure 1) at ~14.0 ¹⁴C ka BP (~17.0 cal ka BP, calibration using Intcal13 Reimer et al., 2013 and presented as the median value) (Clayton and Moran,

1982; Halberg and Kemmis, 1986). Subsequent re-advances to the Altamont and Algona moraines in northern Iowa occurred by ~ 13.5 ^{14}C ka BP (~ 16.3 cal ka BP) and ~ 12.6 ^{14}C ka BP (~ 14.8 cal ka BP) respectively (Figure 1, Clayton and Moraine, 1982). Following formation of the Algona Moraine, the Des Moines lobe is suggested to have stagnated leaving dead ice covering most of its former extent in Minnesota (Clayton and Moraine, 1982). However, the presence of several minor moraines in central Minnesota (e.g. Leverett, 1932; Gwyne, 1951) indicates active ice-margin processes during retreat (Figure 1). Glacial Lake Benson formed during this phase of retreat as water ponded between the Echo and outer Big Stone moraines in the upper Minnesota River valley (Figure 1, Rittenour et al., 1998).

After retreat from the position of the outer Big Stone moraine, ice re-advanced to the inner Big Stone moraine and the glacial Pomme de Terre River formed along its eastern margin (Condit et al., 2010). This second phase is characterized by clay-rich diamict suggesting an ice marginal lake was over-ridden (Patterson et al. 1999). Geomorphic relationships indicate that glacial Lake Benson had drained by this time as delta deposits did not form where the glacial Pomme de Terre River enters the Lake Benson basin (Friedrich and Loughry, 2000). Age constraints from radiocarbon dating suggest advance to the inner Big Stone moraine occurred prior to ~ 12.0 ^{14}C ka BP (~ 14.0 cal ka BP) (Figure 1, Clayton and Moran, 1982; Lepper et al., 2007). Glacial Lake Agassiz later formed in the Red River valley as water ponded between the Big Stone Moraine and retreating ice margin.

INSERT FIGURE 1 HERE

Glacial Lake Agassiz is characterized by three lake-level phases. Briefly, these include the Lockhart Phase when the lake drained southward to the Gulf of Mexico via glacial River Warren, a pre-cursor to the Minnesota River (~ 14.1 - 13.5 cal ka, Herman, Norcross, Upham and Tintah strandlines), the Moorhead Phase when lake levels fell and the southern outlet was abandoned (~ 11.0 ^{14}C ka BP, 12.8 cal ka) and the Emerson Phase when lake levels rose and the southern outlet was re-occupied (~ 10.5 cal ka,

Campbell strandline) (Teller et al., 1983; Fisher et al., 2003; 2005; Lepper et al., 2007; 2013). Following the Emerson Phase the southern outlet was abandoned and the lake shifted northward as the ice margin migrated towards Hudson Bay. At 8.2 ka the then combined Lake Agassiz and Lake Ojibway rapidly drained to the Arctic Ocean producing a short-lived cooling event in the Northern Hemisphere (e.g. Teller et al., 2002; Clarke et al., 2004).

No direct age control previously existed for the timing of glacial Lake Benson, however based on geomorphic relationships, it must have formed following retreat of the Des Moines lobe from the Algona moraine by ~ 12.6 ^{14}C ka BP (~ 14.8 cal ka BP, Clayton and Moran, 1982) but prior to initial formation of glacial Lake Agassiz at 14.1 ± 1.2 ka, based on mean OSL ages from the Herman strandline (Lepper et al., 2013). Glacial River Warren, the southern outlet channel for Lake Agassiz, cuts through the glacial Lake Benson basin and geomorphic evidence suggests that Lake Benson was no longer present by the time of initial drainage of Lake Agassiz. Other evidence for the timing of Lake Benson comes from lowest radiocarbon age collected a small kettle lake near the northwestern shore of Lake Benson that suggest that ice had retreated from the Lake Benson basin by 13.7 ± 0.2 cal ka BP ($11,850 \pm 85$ ^{14}C ka ETH-32335, Lepper et al., 2007).

2.1 Glacial Lake Benson

Glacial Lake Benson was first identified during soil surveys based on the presence of clay-rich soils and generally flat topography below 1050 ft asl (320 m) in the upper Minnesota River valley (Diedrick et al., 1973, Diedrick and Rust, 1975). Subsequently glacial Lake Benson appeared on the Quaternary Geologic map of Minnesota (Hobbs and Goebel, 1982) and has been further defined as part of mapping efforts in the region (e.g., Patterson et al., 1999; Harris, 2006).

Rittenour et al. (1998) described the geomorphology and sedimentology of deposits and landforms associated with glacial Lake Benson. Lake sediment composed of 44 ice-proximal to ice-distal varve

couplets were identified and indicate that glacial Lake Benson was short-lived and the ice margin retreated rapidly between the Echo and Big Stone moraines (69 km distance) without evidence for ice re-advance. Rittenour et al. (1998) described shorelines features at ~1070-1080 ft asl (~328 m) and identified Chetamba Creek as the outlet spillway and the Echo moraine as the dam for the lake. Lake levels at 335 m and 328 m were identified based on delta deposits in the northeastern portion of the lake basin (Mauss and Reiss, 2000; Solmonson, 2001). The higher lake level is interpreted to reflect short-lived local damming following initial ice pull back from the Alexandria moraine to the east (Wright et al., 1973; Cotter, 1993). The presence of deltas at 328 m at the mouth of the East Branch Chippewa River and the main Chippewa River to the north indicate that glacial Lake Benson maintained a stable lake level throughout ice retreat within the basin.

3. Study sites

As part of this study, seven OSL samples were collected in order to improve the chronology of ice retreat and provide the first direct age constraints on the formation of glacial Lake Benson. Sample sites were chosen to track the retreat of the ice margin and formation of Lake Benson. Ice-contact and ice-marginal deposits can be very difficult to date with OSL methods due to limited transport distances and potential for incomplete solar resetting of the luminescence signal (Fuchs and Owen, 2008; King et al., 2013). Therefore, care was taken to select the most suitable sediments for sampling based on sedimentary structures and the degree of sorting, while still being cognizant of only sampling deposits that can be linked to known ice margins. As a related goal, we examined equivalent dose distributions to test the ability of single-grain OSL dating to provide age constraint for a variety of challenging deposits and inform the most suitable deposits for OSL dating. Sample sites are described from south to north, following the expected pattern of ice retreat (see Figure 1 and S1).

3.1 Site A: supra-glacial deposit

The southernmost sample collected for this study was from a small kame-like hill in the northeastern portion of the lake basin that contains at least 6-8 m of well-sorted, medium-grained deltaic sands (Figure S1a). Sediments contain numerous closely spaced micro-faults displaying normal and reverse displacement indicating shear. This deltaic deposit is capped in places by diamict and isolated boulders. Given the inverted topography of this isolated hill, lack of geomorphic evidence for a tributary stream, evidence for shear and the presence of capping boulders and diamict, this deposit is interpreted to represent a supra-glacial lake deposit that was let-down during ice wasting.

Sample USU-1256 was collected from the upper portion of the deposit in faulted rippled sands underlying a sandy diamict and a large granitic boulder (see Figure S1c). As this sample was collected from the southern-most location, it is expected that it will record the earliest deposition related to ice retreat in the region. However, given the supra-glacial nature of this deposit, it could have formed at any time prior to deglaciation.

3.2 Sites B and C: pro-glacial delta

The next two OSL samples were collected from pro-glacial delta deposits of the East Branch Chippewa River where it enters into the glacial Lake Benson basin (Figure S1a). The higher delta is positioned at 335 m asl (site C) and is less extensive than the lower and geomorphically younger delta at 328 m asl (site B). Where sampled, the upper delta is composed predominantly of sandy deposits while the lower delta is composed of pebble-gravel deposits with occasional sand lenses (Figure S1d,e).

Sample USU-1253 was collected from the upper delta at site C and sample USU-1255 was collected from the lower-level delta at site B. These samples can be used to test the timing of the two lake-level phases of glacial Lake Benson. It is expected that the higher lake level was established during early ice retreat in the basin and that the lower, stable lake level was established after the ice margin migrated to the position of the outer (recessional) Big Stone moraine.

3.3 Site D: ice-proximal deposit

Site D is located upstream of sites B and C along the margin of the East Branch Chippewa River valley. Deposits are characterized by cross-bedded sand and gravel and contain ice-collapse features and diamict facies with evidence of post-depositional fluidized flow (Mauss and Reiss, 2000). Sedimentary and geomorphic evidence suggests an ice-proximal setting for the deposits at this site.

Sample USU-1254 was collected from rippled sands overlying a package of diamict conformably overlying a package of cross-bedded sand and gravel (Figure S1f). The juxtaposition of facies suggests a dynamic ice-marginal location. The rippled sands at the site were chosen over the higher-energy cross-bedded sand and gravel below the diamict to improve chances of solar resetting in this ice-proximal setting. Given the setting of site D, sample USU-1254 is expected to provide an age for early fluvial deposition following ice retreat in the northeastern portion of the lake basin.

3.4 Site E: sub-glacial deposit

Site E is located within a series of linear, discontinuous ridges composed of sand and gravel (Figure S1a). These ridges, known as the Blue Mounds, have been interpreted to represent various depositional environments such as eskers (Hobbs and Goeble, 1982), crevasse-fill deposits (Komai et al., 2000) and inter-lobe features deposited between the Des Moines lobe in the Minnesota River valley and ice on the Alexandria moraine (Reid, 1974).

Sample USU-1254 was collected from a sand bed within the predominantly gravel sequence at site E (Figure S1g). While sediment sourced from an entirely sub-glacial setting is not expected to have been optically reset prior to deposition, it is possible that the sediments could have been derived from supra-glacial and ice-marginal streams. Populations of reset grains can help to test hypotheses about the

origin of these ridges. However, it has also been suggested that shearing in sub-glacial settings may also reset OSL signals (Bateman et al., 2012), possibly confounding interpretations.

3.5 Site F: glacial fluvial deposit

The next two OSL samples (USU-1250 and USU-1251) were collected from trough-crossbedded sands and gravel in a glacial-fluvial terrace along the Pomme de Terre River at site F (Figure S1a,h). Given the lack of a delta at the mouth of the Pomme de Terre River it is expected that the OSL ages from these samples will post-date the drainage of glacial Lake Benson. These samples may also constrain the timing of ice re-advance to the inner Big Stone moraine position as the glacial Pomme de Terre River has been interpreted as an ice-marginal stream (Condit et al., 2010).

4. Methods

Samples for OSL dating were collected by pounding metal pipes into the sediment exposures and collection of the surrounding sediment for dose-rate analysis. Quartz sand was purified using hydrochloric (HCl) acid to remove carbonates, density separation (2.7 g/cm³ sodium polytungstate) to remove heavy minerals and 47% hydrofluoric acid to remove feldspars and etch the quartz, followed by 37% HCl to remove fluorites.

OSL samples were analyzed using the single-aliquot regenerative-dose (SAR) technique (Murray and Wintle, 2000) on a Risø OSL/TL DA-20 luminescence reader with a single-grain attachment (Bøtter-Jensen et al., 2000) using a green laser (532 nm) at 90% power (135 mW/cm²) and detection through a 7.5-mm UV filter (U-340). Luminescence signals were measured over 1 second and calculated by subtracting the average of the last 0.2s from the initial 0.05s of the luminescence signal. Preheat temperatures following administered and natural doses were 240°C for 10s and cutheat temperatures following test doses (10 Gy) were 160°C for 10s, as indicated by preheat plateau test results from small aliquots and dose recovery tests on single-grain analyses (see Figures S2 and S3 and captions for details).

Single-grain equivalent dose (D_E) estimates were calculated using the minimum age model (MAM, Galbraith et al., 1999) on at least 70 grains that passed rejection criteria. Grains were rejected if they had evidence of feldspar contamination (IR depletion ratios >2), low luminescence signals (signal to background ratios <3 for administered doses), poor recycling ratios ($>30\%$ difference in corrected response between repeated doses), high recuperation ($>20\%$ of the natural signal generated during the zero-dose step), D_E greater than the highest regenerative dose, and/or high error due to a poor dose-response growth-curve fit (Table S1). MAM D_E estimates were calculated using 15% over-dispersion (OD) based on single-grain dose-recovery test results (11.5% OD, see Figure S3 and caption) and assumptions of additional OD due to microdosimetry effects on single-grain data.

Samples for water content and dose-rate determination were collected from a ~ 30 cm diameter area surrounding each OSL sample tube. Radioisotope concentrations were determined using ICP-MS/ICP-AES analysis and uncertainty in elemental concentrations was calculated following Rittenour et al. (2005). Elemental concentrations were converted to dose rate using the conversion factors of Guérin et al. (2011) and beta attenuation coefficients of Brennan (2003) (Table S2). Total dose rates were calculated based on water content, cosmic contribution (Prescott and Hutton, 1994) and radioisotope concentration.

Single-grain OSL ages were calculated by dividing the D_E value (in Grays, $1 \text{ Gy} = 1 \text{ J/kg}$) by the dose-rate (Gy/ka). OSL ages are reported at 1-sigma standard error (Table 1) and include errors related to instrument calibration and dose rate and equivalent dose calculations.

5. Results

OSL ages are presented in Table 1 and single-grain D_E distributions are presented in Figure S4. At the onset of this project it was expected that OSL dating would be difficult in the ice-proximal settings targeted for dating the timing of ice retreat and formation of glacial Lake Benson. Precautions were

taken in the field to sample ice-proximal deposits that were most likely to have been reset prior to deposition and single-grain OSL dating was employed to allow the greatest resolution possible in identifying reset populations of grains.

INSERT TABLE 1 HERE

Single-grain D_E results showed considerable scatter and evidence for partial bleaching. As displayed in the radial plots (Figure S4) and reported in Table 1, D_E distributions from all samples had significant positive skew and over-dispersion values ranging from ~40-60%, both indicators of partial bleaching (e.g. Olley et al., 1999). Moreover, luminescence signal intensities were weak and ~90% of grains were rejected due to lack of signal (Table S1). After rejection of grains that did not meet data quality checks, acceptance rates were ~4-6%.

Single-grain OSL results show promise for dating ice-marginal deposits within glacial Lake Benson. Samples from the East Branch Chippewa River valley (sites B-D) produced a series of tightly grouped ages between 14.4-14.8 ka (Table 1). These samples were from upper and lower Lake Benson deltas and ice-proximal deposits feeding these deltas. As expected the upper delta produced an older age (14.8 ± 1.8 ka) than the lower delta (14.4 ± 1.8 ka), which was developed into the regionally stable lake level (328 m asl). Rippled sands overlying diamict at site D produced an intermediate age of 14.6 ± 1.9 ka (Figure S1).

Samples collected from near the top and center a glacial stream terrace along the Pomme de Terre River (site F) produced ages of 14.5 ± 1.8 ka from basal cross-bedded gravels and 13.7 ± 1.8 ka from upper capping sands (Table 1). These results fit well with expected geomorphic relationships. Based on the lack of a delta deposit at the mouth of the Pomme de Terre River it was expected that this terrace would be younger than the delta deposits at the mouth of the East Branch Chippewa River valley (14.4-14.8 ka).

The samples described above from the East Branch Chippewa and Pomme de Terre River valleys date to 13.7-14.8 ka and provide age control for deglaciation of the Lake Benson basin that is consistent with the regional ice-retreat chronology. In contrast, samples collected from supra-glacial and sub-glacial settings produced older age results. These are discussed in greater detail below.

Sample USU-1256 was collected from a deposit interpreted to be a supra-glacial lake deposit that was let-down onto the landscape during ice decay. Given the interpreted supra-glacial setting, it was expected that it would be well bleached and ideal for OSL dating. However, OSL results reveal similar skew and over-dispersion as with the other samples (Figure 2, Table 1). The resultant age of 15.7 ± 2.0 ka is older than expected for the timing of deglaciation in the region. However, this result may reflect supra-glacial lake formation during initial stagnation and retreat of the Des Moines lobe from the Algona moraine (prior to 14.8 ka, Halberg and Kemmis, 1986).

Sample USU-1252 was collected from a sand lens in a gravel-cored ridge in the Blue Mounds northeast of the Lake Benson basin (site E, Figure S1a, g). The formation of these ridges is enigmatic and may reflect esker, crevasse-fill or an inter-lobe setting. The positive relief of the Blue Mounds ridges suggests an ice-contact or sub-glacial setting. D_E distributions from sample USU-1252 show high over-dispersion and skew (Table 1), suggesting partial bleaching. This sample has a much greater range in D_E values than other samples. For example, D_E values ranged from 20 - 260 Gy (Figure S4) and ~8% of grains were rejected due to D_E values >300 Gy that were not bracketed by the dose-response curve during measurement ($n = 145$ grains, Table S1). Use of the MAM produced a good fit with a population of lower D_E grains and an apparent age of 18.7 ± 2.1 ka. Given that we cannot be certain if the sediments were exposed to light prior to deposition, we are hesitant to interpret this age result as the timing of the formation of the Blue Mounds. Instead it is possible that this apparent age reflects sub-glacial transport of older deposits without solar resetting or a period of resetting due to glacial shear

(e.g. Bateman et al., 2012). The apparent age of 18.7 ka is intriguing as it may reflect sub-glacial re-deposition of sediments associated with ice-free conditions in the region following an advance at ~20 ka but prior to re-advance to the position of the Bemis moraine at ~17 ka (Halberg and Kemmis, 1986).

6. Discussion

Samples for OSL dating were collected from five ice-proximal settings in order to test the suitability of single-grain OSL dating in glacial settings and to provide age constraint for the timing of ice retreat and formation of glacial Lake Benson in west-central Minnesota.

6.1 Relationship between D_E distribution and depositional setting

As part of the first goal of this project, the level of solar resetting in each depositional environment was assessed by analyzing single-grain D_E distribution characteristics. As described above, D_E distributions from all samples show signs of incomplete solar resetting as evidenced by high over-dispersion and significant positive skew. Figure 2 plots these metrics along with the percent of grains within 2σ error of the MAM D_E value. Results suggest that processes in glacial- and fluvial-dominated environments produce different ranges for skew and over-dispersion in single-grain D_E distributions.

INSERT FIGURE 2 HERE

In summary, depositional environments identified in the field as dominated by glacial processes, such as sub-glacial (site E, USU-1252) and supra-glacial settings (site A, USU-1256), were found to have over-dispersion values greater than 50% and values of skew greater than 0.9 (Figure 2, Table 1). Moreover, less than 25% of the accepted grains were within error of the MAM D_E values for these samples (Figure 2, S4). In contrast, deposits identified in the field as dominated by fluvial processes, such as deltaic deposits at the mouth of the East Branch Chippewa River (site C and B, USU-1253 and USU-1254) and the glacial fluvial deposits in Pomme de Terre River valley (site F, USU-1250 and USU-

1251), have D_E over-dispersion values less than 50%, values of skew generally less than 0.9 and greater than 25% of the grains lie within 2-sigma error of the MAM D_E value (Figure 2, Table 1). These observations from D_E distributions probably reflect the greater bleaching potential within glacial-fluvial systems in comparison to glacial-dominated environments. This is likely due to longer sediment transport distances in the fluvial settings, although all samples were collected from ice-proximal settings (less than 5 km from the ice margin).

Sample USU-1254 was collected from ice-proximal deposits associated with re-deposited diamict and ice-collapse features. The interpreted depositional environment for this sample is neither fully glacial nor fully fluvial as evidence for both processes are seen at site D. Moreover, the skew of this sample lies outside values for either end-member category (Figure 2). While D_E over-dispersion was 49.3%, or just below the 50% base-line derived from glacial-process dominated deposits, the skew was the highest value of all samples analyzed (1.49) and this sample has the second highest percent of grains within error of the MAM D_E (Figure 2, Table 1). Interestingly, although this sample suffers from high over-dispersion and skew, the calculated OSL age (14.6 ka) is in line with the regional chronology of ice retreat and consistent with OSL ages from fluvial-dominated delta settings that display greater evidence for solar resetting prior to deposition (Table 1). While these metrics are commonly interpreted to represent evidence for partial bleaching, it has been suggested that high over-dispersion and large skew may instead be an indicator of a higher degree of bleaching in single-grain populations (King et al., 2013).

Conclusions from analysis of samples from this study suggest that samples collected from settings dominated by glacial processes (sub-glacial and supra-glacial deposits) were characterized by high over-dispersion (> 50%), large positive skew in D_E distributions (>0.9) and smaller percentages of grains within error of the MAM D_E value (<25%) than samples collected from fluvial-dominated settings (Figure 2).

Implications of these results are that deposits transported by fluvial processes, in contrast to glacial processes, should be targeted for sampling ice-proximal environments. This is not meant to suggest that only deposits entirely fluvial in nature should be sampled. Instead water-transported pro-glacial deposits should be targeted when multiple facies are present within a deposit. Sample USU-1254 at site D is a good example. While deposits at this site indicate an ice-proximal to ice-contact setting, results from this sample are consistent with delta deposits downstream in the same valley. While OSL ages obtained from deposits originating from glacial-dominated processes may be producing accurate ages for the last resetting event, more work is needed to better test the application of OSL dating to sub-glacial and supra-glacial deposits from this continental glacial setting.

6.2 Revised chronology of ice retreat and formation of glacial Lake Benson

The second goal of this pilot project was to provide age control for the timing of ice retreat and formation of glacial Lake Benson in the upper Minnesota River valley. Samples were collected from deposits that can be linked to ice-margin positions for this purpose. As described above, samples from fluvial-dominated settings provided the best results regarding D_E distributions and are the focus of the discussion.

Single-grain OSL results from the upper delta deposit at the mouth of the East Branch Chippewa River valley constrain deglaciation of the northeastern portion of the lake basin and initial formation of Lake Benson to prior to 14.8 ± 1.8 ka (USU-1253, Table 1). Ice-proximal sands in the delta graded to the stable lower elevation of glacial Lake Benson suggest the lake persisted until 14.4 ± 1.8 ka (USU-1255, Table 1). OSL results from the Pomme de Terre River valley produced ages that are generally younger than the results from the East Branch Chippewa River valley (14.5 ± 1.8 ka and 13.7 ± 1.8 ka Table 1). These ages are expected to bracket drainage of glacial Lake Benson and ice re-advance to the inner Big Stone Moraine. The single-grain OSL ages presented here are consistent with previous radiocarbon age

constraints limiting deglaciation to ~15-14 cal ka BP (Clayton and Moran, 1982) and OSL ages from Lake Agassiz shorelines that limit the formation of glacial Lake Benson to prior to 14.1 ka (Lepper et al., 2013). Moreover, the narrow and overlapping age constraints for the timing of glacial Lake Benson are consistent with geomorphic and sedimentary evidence that suggests rapid ice retreat in the region and short duration of the lake (e.g. Rittenour et al., 1998).

7. Conclusions

Single-grain OSL results from ice-proximal and deltaic settings provide the first direct age control for the timing of ice retreat and formation of glacial Lake Benson in the upper Minnesota River valley. Analysis of metrics related to D_E distributions indicate that while all samples displayed evidence for partial bleaching, settings dominated by glacial processes have higher over-dispersion (> 50%) and greater positive skew (>0.9) in single-grain D_E distributions than samples from fluvial-dominated settings. Results suggest deglaciation of the northeastern portion of the lake basin by 14.8 ka and development of the stable lake level by 14.4 ka. Future work will target samples that can be linked to additional ice-margin and lake-level positions to help improve the resolution of the largely radiocarbon-based chronology of ice retreat in the region. Sample selection will be guided by results suggesting that ice-proximal deposits dominated by fluvial processes are better suited for OSL dating than deposits originating from glacial-dominated processes.

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508

509 **Table and Figure Captions**

510 **Table 1.** OSL age Information.

511 **Figure 1.** Location of glacial Lake Benson in west-central Minnesota and samples collected for OSL
512 dating. Also shown are general age constraints for ice marginal positions following Clayton and
513 Moran (1982) and other features and age constraints discussed in the text.

514 **Figure 2.** Equivalent dose-distribution metrics plotted versus sample number and depositional
515 environment. Note that samples from glacial-dominated depositional settings have higher over-
516 dispersion, greater skew, lower percentages of grains within error of the minimum age model
517 (MAM) calculated equivalent dose and older age estimates than expected for the timing of
518 deglaciation of the region than fluvial-dominated environments. All samples have significant skew.

Table 1. OSL Age Information

Site (Fig.1)	USU lab number	Deposit setting	OD ^a (%)	Skew ^b	Number of grains ^c	Dose rate ^d (Gy/ka)	Equivalent dose ^e ± 2σ (Gy)	OSL age ^f ± 1σ (ka)
A	USU-1256	supra-glacial	50.1	0.95*	83 (2400)	1.46 ± 0.08	22.85 ± 3.19	15.68 ± 2.00
B	USU-1255	delta (lower)	41.7	0.53*	83 (2200)	1.50 ± 0.08	21.57 ± 2.69	14.40 ± 1.83
C	USU-1253	delta (upper)	47.9	0.79*	93 (1900)	1.61 ± 0.08	23.92 ± 3.11	14.83 ± 1.78
D	USU-1254	ice-proximal	49.3	1.49*	81 (2200)	1.50 ± 0.08	21.96 ± 3.22	14.61 ± 1.85
E	USU-1252	sub-glacial	57.1	0.92*	105 (1900)	1.63 ± 0.09	30.38 ± 3.87	18.67 ± 2.05
F	USU-1251	glacial fluvial	37.5	0.45*	72 (2000)	1.57 ± 0.08	21.63 ± 3.05	13.74 ± 1.75
F	USU-1250	glacial fluvial	47.8	0.94*	98 (1900)	1.60 ± 0.08	23.11 ± 3.02	14.45 ± 1.78

^a Overdispersion (OD) is calculated as part of central age model Galbraith et al. (1999) and represents scatter in Equivalent dose (D_E) beyond calculated uncertainties in data.

^b Significant skew indicated with asterisk (*) as defined by a calculated value >1 when skew is divided by the square root of $6/n$ where n = number of accepted grains.

^c Number of grains used in age calculation and total number of grains analyzed in parentheses.

^d See Table S2 for information on dose-rate calculation.

^e Equivalent doses (D_E) and ages calculated using the minimum age model of Galbraith et al. (1999) using excel macros written by S. Huot (UQAM) and 15% OD as determined by dose-recovery tests.

^f Datum for OSL ages is 2010 AD.

Figure 1

Figure 2