



Reconnaissance luminescence dating of Laurentide Ice Sheet deposits in western New York, USA

Caleb K. Walcott-George^{a,b,*}, Jason P. Briner^b, Nathan D. Brown^c

^a University of Kentucky, Department of Earth and Environmental Science, 101 Slone Research Building, Lexington, KY 40506, USA

^b University at Buffalo, Department of Earth Science, 126 Cooke Hall, Buffalo, NY 14260, USA

^c University of Texas at Arlington, Department of Earth and Environmental Science, 500 Yates St., Arlington, TX 76019, USA

ARTICLE INFO

Communicated by Harvey Thorleifson

Keywords:

Glacier history
Laurentide Ice Sheet
Luminescence dating

ABSTRACT

We present luminescence ages from glaciofluvial and glaciolacustrine sediments in western New York, USA, that build on prior constraints on the timing of ice sheet retreat during the last deglaciation. Fourteen luminescence ages from six sites indicate that 1) glaciofluvial outwash just inboard of the maximum Olean ice limit in western New York was deposited before 19.0 ± 1.8 to 16.7 ± 1.2 ka (age $\pm 1\sigma$), providing a minimum constraint on ice retreat from this position and suggesting that the Olean Moraine is local Last Glacial Maximum in age, 2) the Laurentide Ice Sheet deposited the Lake Escarpment Moraine at between 20.1 ± 4.2 ka and 18.7 ± 1.7 ka, and before 15.3 ± 2.4 to 14.0 ± 2.1 ka, 3) Lake Warren I existed between 11.2 ± 2.9 ka and 12.0 ± 2.8 ka, and 4) large deltas formed in a proglacial lake in the Genesee Valley between 16.3 ± 2.2 ka and 15.6 ± 2.1 ka. Despite uncertainties, luminescence dating in western New York can be of use in future studies aiming to constrain the age of glacial deposits where organic material for radiocarbon dating is sparse, or where deposits are beyond the age range of radiocarbon dating.

1. Introduction

The Laurentide Ice Sheet was the largest Northern Hemisphere ice sheet during the Last Glacial Maximum (LGM; 26–19 ka; Clark et al., 2009), stretching longitudinally from the Rocky Mountains to the Atlantic Ocean and latitudinally from the Arctic Ocean to the northern United States of America (USA; Fig. 1). Widely traceable moraine systems across much of the northern USA record retreat from the ice sheet's terminal position. During ice-sheet retreat, large proglacial lakes formed across the Great Lakes basins. These lakes periodically shifted drainage routes as ice sheets waxed and waned, leading to significant meltwater re-routing events that are hypothesized to have greatly impacted North Atlantic climate and led to marked cold periods as recorded in Greenland ice core records (Barber et al., 1999; Broecker et al., 1989; Calkin and Feenstra, 1985; Donnelly et al., 2005; Fairchild, 1907; Leydet et al., 2018; Porreca et al., 2018; Rayburn et al., 2007; Yu et al., 2010). Thus, characterizing shifting ice front positions and associated meltwater routing throughout the last deglaciation is of much interest.

The chronology of Laurentide Ice Sheet recession across the northern USA has been investigated using radiocarbon dating of stratigraphic

sections and basal sediments in kettle bogs and lakes, varve chronologies, and cosmogenic nuclide dating (e.g., Balco et al., 2002; Balter-Kennedy et al., 2024; Corbett et al., 2017; Curry and Petras, 2011; Glover et al., 2011; Heath et al., 2018; Ridge, 2003, 2004; Ridge et al., 2012; Ullman et al., 2015). However, there is a dearth of chronological data across much of New York state between the Hudson Valley, where deglaciation is constrained with cosmogenic nuclide dating and also tied to the New England Varve Chronology, and Lake Erie at the western end of the state (Balter-Kennedy et al., 2024; Ridge, 2003; Ridge et al., 2012). This paucity of constraints across New York is largely due to a dearth of organic matter suitable for radiocarbon dating found within key stratigraphic sections (Muller and Calkin, 1993). Additionally, basal radiocarbon ages from kettle basins have been shown to date permafrost melt that took place thousands of years following moraine deposition, compromising their use for dating deglaciation (Prince et al., 2024). Finally, there are few published cosmogenic nuclide exposure ages due to the lack of suitable boulders. While the overall framework of deglaciation is in place, details on the exact timing are still lacking across New York State (Dalton et al., 2023).

Luminescence dating can fill in chronological gaps in areas where

* Corresponding author at: University of Kentucky, Department of Earth and Environmental Science, 101 Slone Research Building, University of Kentucky, Lexington, KY 40506, USA.

E-mail address: c.wg@uky.edu (C.K. Walcott-George).

<https://doi.org/10.1016/j.jglr.2026.102868>

Received 16 February 2026; Accepted 1 June 2026

Available online 9 June 2026

0380-1330/© 2026 International Association for Great Lakes Research. Published by Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

radiocarbon dating and/or cosmogenic nuclide dating is challenging. This technique provides a sediment burial age, which in turn constrains the age of sedimentary deposits associated with moraine formation (e.g., kame deltas and outwash deposits) and proglacial lake levels (e.g., shorelines and deltas). Luminescence dating of glacial deposits thus provides a direct constraint on ice positions rather than minimum- or maximum-limiting ages often derived using radiocarbon dating (e.g., Fisher et al., 2008; Fisher et al., 2020; Lowell et al., 1990; Szabo et al., 2003). However, luminescence dating of glacial sediments can be challenging due to a variety of factors, including poor luminescence properties of glaciogenic quartz and the high likelihood of incomplete bleaching of sediment grains in glacial, glaciofluvial, and glaciolacustrine deposits (Fuchs and Owen, 2008; Rhodes and Pownall, 1994; Rhodes, 2000; Thrasher et al., 2009). The advent of single-grain luminescence techniques has led to substantial advances in dating glaciofluvial and glaciolacustrine sediments. With this technique, luminescence signals from single sand grains—rather than aliquots of hundreds of grains—can be measured. By looking at the luminescence signal from individual grains, fully bleached sediment grains that more accurately record the timing of deposition can be identified using various age models, offering more precise burial ages (e.g., Duller, 2006; Ou et al., 2015; Rittenour et al., 2015).

We measured infrared stimulated luminescence (IRSL) signals from individual potassium feldspar grains and optically stimulated luminescence (OSL) signals from aliquots of quartz grains to date the deposition of glacial outwash deposits, lake shorelines, and deltas to probe the potential of luminescence dating for refining the Laurentide Ice Sheet chronology in western New York. We chose a variety of glacial and associated landforms that span a several thousand-year time frame (~20–13 ka) to assess whether luminescence dating could help refine the local glacial chronology. We find our moraine and glacial lake chronologies are consistent with the few published local investigations and with inferred ages correlated to regional studies in adjacent regions.

Although this first suite of luminescence ages from across western New York is somewhat limited by precision, we suggest that luminescence dating in western New York holds promise as a tool for dating deposits in areas lacking organic material for radiocarbon dating, for deposits that are beyond the range of radiocarbon dating, or in areas where there are no suitable boulders for cosmogenic nuclide dating.

2. Background

Previous investigations have described the Laurentide glacial and lake-level history of western New York in detail (Fig. 2; Calkin, 1970; Calkin and Brett, 1978; Fairchild, 1907, 1932; Muller and Calkin, 1993; Prince et al., 2024). The landscape today hosts striking glacial features including broad moraine belts, outwash terraces, proglacial lake shorelines, and meltwater flood deposits (Fairchild, 1932; Muller, 1977). In western New York, early mapping suggested that the different units of glacial drift marking the maximum Laurentide Ice Sheet extent were uniform in age, dating to the late Wisconsinan (LGM; Lewis, 1884). Later researchers suggested that tills bordering the Salamanca Reentrant (the ice-free area in western New York; Fig. 2) were of different ages based on weathering profiles and lithology, assigning the Kent Moraine to the late Wisconsinan and the Olean Moraine to the Altonian (pre-LGM; MacClintock and Apfel, 1944; Muller, 1977). However, subsequent studies shifted back to the original 19th century interpretation, reclassifying the Olean Moraine as LGM in age, coeval with the Kent Moraine, though absolute chronology remains greatly lacking (Braun and Brennan, 1988; Cotter et al., 1986; Muller and Calkin, 1993).

The LGM terminal moraine in western New York is correlated with the Kent Moraine in northeastern Ohio, the Olean Moraine in Pennsylvania, the Harbor Hill Moraine in New Jersey and Long Island, New York, and the Martha's Vineyard Moraine in Massachusetts. Two OSL ages of 19.8 ± 2.6 and 20.6 ± 2.9 ka from an ice contact delta associated with the Kent Moraine in western New York (Prince et al., 2024) are

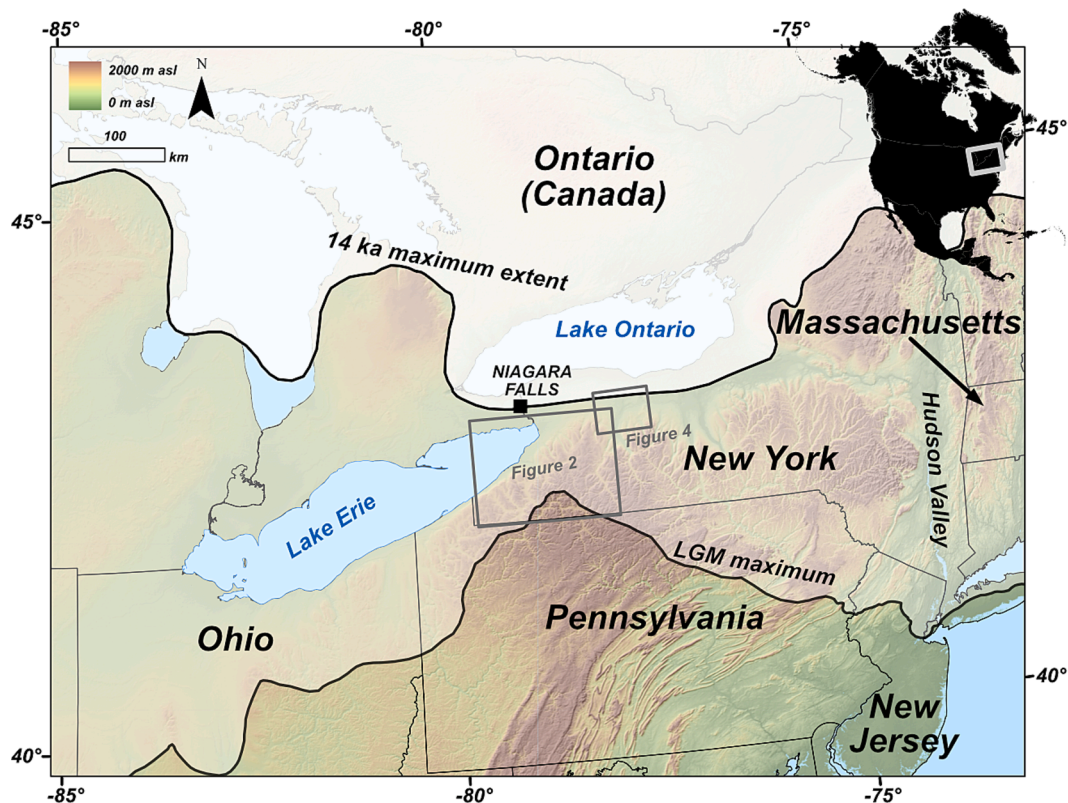


Fig. 1. Northeastern United States and southeastern Canada showing Laurentide Ice Sheet Last Glacial Maximum ice limit and 14 ka ice limit from Dalton et al. (2023).

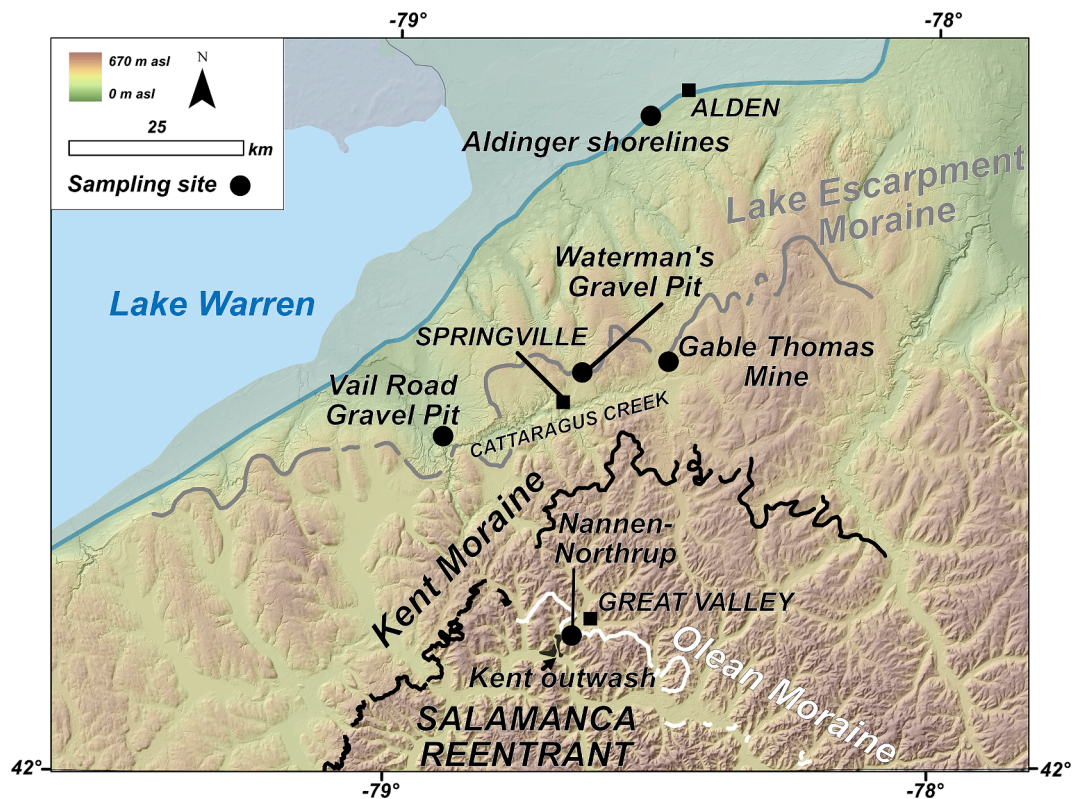


Fig. 2. Western New York showing sample sites. Lake Warren extent shown in transparent light blue; modern Lake Erie in solid blue. Mapped ice limits and lake extents after Muller (1977). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

coeval with estimates of deglaciation in Ohio at ~ 22 ka based on basal radiocarbon ages from across the state summarized by Glover et al. (2011). These ages postdate the onset of retreat in New Jersey at 25.2 ± 2.1 ka (cosmogenic nuclide ages of moraine boulders; Corbett et al., 2017) and ~ 24 cal ka (basal radiocarbon ages; Stanford et al., 2021), and 25.5 ± 0.4 ka in Massachusetts (cosmogenic nuclide ages of moraine boulders; Balco et al., 2002, Balco et al., 2009). A recent synthesis of cosmogenic nuclide ages from southern New York and New England found that the Laurentide Ice Sheet reached its maximum extent ~ 26 – 25 ka and stayed near this position until ~ 22 ka, after which there was slow recession over the following few millennia (Balter-Kennedy et al., 2024). Prince et al. (2024) produced basal radiocarbon ages in kettle basins on top of the Kent Moraine of ~ 15.4 – 15.0 cal ka in western New York. This post-dates local constraints on moraine deposition and may instead reflect the presence of persistent permafrost conditions until the melt out of ice-cored moraines after ~ 15 ka (Prince et al., 2024).

The southernmost widely traceable post-LGM recessional moraine in western New York is the Lake Escarpment Moraine, which has been correlated with the Ashtabula Moraine in Ohio and northwestern Pennsylvania, and the Valley Heads Moraine in central New York (Fig. 2; Muller and Calkin, 1993). The Lake Escarpment Moraine formed following the Erie Interstade, constrained with radiocarbon dating to between 19.3 and ~ 17.7 cal ka (Mörner and Dreimanis, 1973; Ridge, 1997). A recent study posits that maximum ice recession during the Erie Interstade occurred at 17.7 ± 0.1 cal ka, with the deposition of the Valley Heads Moraine sometime after (Karig, 2023). Previously published luminescence ages in interstadial sediments broadly support this timing, though the reported age range of 20.1–14.5 ka does not offer more precise temporal estimates for the Erie Interstade (Young et al., 2020). Ties to the New England Varve Chronology place the outer and inner Valley Heads moraines at 17.2 cal ka and 16.2 cal ka, respectively (Ridge et al., 2012). This varve-chronology age assignment predates

moraine deposition recorded by basal radiocarbon ages in basins on the outer Valley Heads moraine of ~ 14.9 – 14.2 cal ka (Kozłowski et al., 2018; Ridge, 2003). While Kozłowski et al. (2018) suggested that these data reflected reoccupation of the outer Valley Heads moraines, widespread permafrost across New York until the Bølling may instead be responsible for these younger basal radiocarbon ages (Prince et al., 2024).

In western New York, ages constraining Lake Escarpment Moraine deposition are sparse. Calkin and McAndrews (1980) dated wood stratigraphically above Lake Escarpment outwash sands at the Nichols Brook Site to ~ 15.3 – 13.7 cal ka, which Muller and Calkin (1993) used to extrapolate a Lake Escarpment Moraine age of ~ 17.6 cal ka. Prince et al. (2024) produced basal radiocarbon ages in basins on top of the Lake Escarpment Moraine of ~ 15 – 14 cal ka, suggesting moraine deposition prior to this time. The ice front positioned at the Lake Escarpment Moraine created Lake Maumee in the Lake Erie Basin, which drained westward (Bleuer and Moore, 1971). This lake level has been dated to 16.8 ± 1.0 ka with OSL dating of shorelines in Ohio (Fisher et al., 2015). There are no direct ages on Lake Escarpment Moraine deposition in western New York.

The timing of further Laurentide Ice Sheet retreat in western New York is not well-constrained (Fig. 3). Instead, existing knowledge relies on age correlations with scarcely dated ice-dammed lake levels in the Lake Erie basin that fluctuated with shifting ice positions (Muller and Calkin, 1993). After deposition of the Lake Escarpment Moraine, many moraines were deposited in western New York during northward retreat including: the Gowanda, Hamburg, Marilla, Alden, Buffalo, Niagara Falls, Batavia, Barre, and Albion moraines. There are ice sheet-dammed lake levels marked by distinct shorelines coeval with these various moraine positions in the Lake Erie Basin (from highest to lowest elevation): Whittlesey, Arkona, Warren I–III, Wayne (hypothesized to be a low stand between Warren II and III), Grassmere, Lundy, and a hypothesized short-lived post-Lundy glacial lake (Calkin, 1970; Fisher et al., 2015;

Stratigraphic order of moraines and lake levels

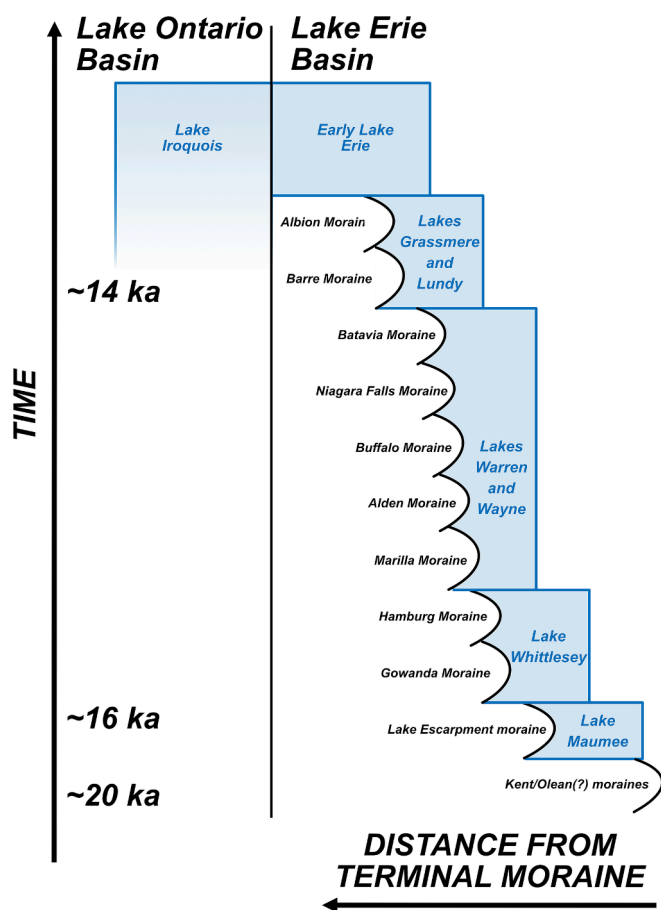


Fig. 3. Summary time-distance diagram of moraines and associated proglacial lake levels in western New York demonstrating spatial and cross-cutting relationships. Existing age constraints are presented in more detail in Fig. 7.

Howard, 2010).

Essentially, rapidly shifting ice margins across western New York and the growth and decay of proglacial lakes in the Erie and Ontario basins led to complex interactions between numerous moraine deposits and rapidly fluctuating lake levels in a short period of time between ~16 and ~14 ka. This is further complicated by large uncertainties in calibrated radiocarbon ages in western New York, leading to imprecise age control. Because of a lack of ages from the Lake Erie basin, much of the glacier margin and proglacial lake chronology here is pinned on relationships to the inception and demise of Lake Iroquois in the Ontario basin (Calkin and Feenstra, 1985; Muller and Prest, 1985). A brief overview follows.

Stratigraphic correlation and cross-cutting relationships of lake shorelines and moraines in western New York indicates that the Gowanda and Hamburg moraines were formed coevally with Lake Whittlesey, constrained to between 16.6 and 14.2 cal ka with radiocarbon (Calkin and Feenstra, 1985; Goldthwait, 1958) and OSL dating of shoreline deposits (Fisher et al., 2015). The Marilla, Alden, Buffalo, Niagara Falls, and Batavia moraines are correlated with lakes Warren and Wayne, though their exact relationships remain unclear (Calkin, 1970; Calkin and Feenstra, 1985; Calkin and McAndrews, 1980; Muller and Calkin, 1993). Maximum-limiting radiocarbon ages on the Lake Warren I level from New York and Ohio date to between 16.4 and 14.2 cal ka (Calkin and McAndrews, 1980; Totten, 1985) and are supported by an OSL age from an undifferentiated Warren shoreline in Ohio of 14.2 ± 1.3 ka (Higley et al., 2014). Local constraints of these proglacial lake

sequences and associated moraines are sparse due to the lack of direct dating of Warren and Wayne shorelines in western New York. However, peat now submerged in Lake Erie with a radiocarbon age of 15.6–14.2 cal ka constrains the cessation of the proglacial lake sequence in the Erie basin and provides a distant minimum age for lakes Warren and Wayne (Calkin and Brett, 1978; Lewis, 1969). However, Calkin and Feenstra (1985) and Coakley and Lewis (1985) note that this may have occurred shortly after the reported 15.6–14.2 cal ka age. In sum, available data bracket the timing of lakes Warren and Wayne to sometime between 16.4 and shortly after 14.2 cal ka.

Following ice retreat from the Batavia Moraine, lake levels dropped in the Erie basin, forming lakes Grassmere and Lundy at the same time as the Barre and Albion moraines (Calkin and Feenstra, 1985; Muller and Prest, 1985). Lake Grassmere likely formed—Lake Lundy existed contemporaneously—with early Lake Iroquois in the eastern Ontario basin, before the formation of early (non-glacial) Lake Erie. The genesis of Lake Iroquois in the eastern Ontario basin is dated to as early as 14.7 cal ka with bulk radiocarbon ages from gyttja sediment samples, though these can be anomalously old due to carbon recycling (Calkin and Brett, 1978; Clark and Karrow, 1984; Karrow, 1981; Lewis and Anderson, 2019; Muller and Prest, 1985; Terasmae, 1980). In western New York, wood from an Iroquois shoreline feature near Lewiston, New York, dates to between 16.1 and 13.8 cal ka, which was later rerun and dated to 15.1–13.4 cal ka (Muller and Prest, 1985). These are supported by a minimum-limiting age from twigs embedded in silt overlying Lake Iroquois beach gravel dated to between 14.3 and 13.8 cal ka (Muller and Calkin, 1985, 1993). Meanwhile, recent evidence suggests that Lake Iroquois terminated by ~13.0 cal ka, serving as an absolute minimum-limiting age on the glacial lake sequence in the Erie basin (Lewis and Anderson, 2019).

Early (non-glacial) Lake Erie formed following glacial lakes Grassmere and Lundy and existed concurrently with Lake Iroquois (Muller and Prest, 1985). Dates for early Lake Erie formation are sparse, but it may have occurred as early as between 15.6 and 14.2 cal ka (Lewis, 1969), though Calkin and Feenstra (1985) estimated this as between approximately 14.1–13.7 cal ka. In any case, early Lake Erie could have formed no earlier than 14.7 ka, as this is the earliest inception date of Lake Iroquois. The relationships between Lake Iroquois and early Lake Erie tentatively date glacial lakes Grassmere and Lundy to between 14.7 and 13.7 cal ka.

Additional information on ice sheet and proglacial lake history can be found in the Genesee River Valley near Avon, New York (Fig. 4). Here, proglacial Lake Avon formed in the valley following ice-sheet retreat from the Batavia Moraine. Three primary channels and associated deltas indicating the eastward flow of Erie basin proglacial lake water into Lake Avon are apparent: the Taylor, Dugan, and White Creek channels (Fig. 4). The Taylor Channel delta is ~210 m asl, while the Dugan and White Creek channels are ~180 m asl, representing two distinct periods of deposition into two different levels of Lake Avon (Muller et al., 1988). All three deltas were deposited after ice retreat from the Batavia Moraine (Calkin and Feenstra, 1985). While Taylor Channel and its delta were formed during a Lake Lundy drainage event, the Dugan and White Creek channels and the associated deltas are hypothesized to have been created when water from the Erie Basin entered Lake Avon during 1) normal outflow of a short-lived post-Lundy glacial lake, 2) jökullhups as ice receded and opened up eastern flow out of Lake Grassmere or Lake Lundy, or 3) normal drainage from Lake Warren I (Calkin and Feenstra, 1985; Fairchild, 1932; Kehew et al., 2009; Muller and Calkin, 1988; Muller and Prest, 1985; Paardekooper et al., 2008). Peat deposited on top of delta deposits in the Dugan Channels dated to between 13.2 and 12.7 cal ka serves as a distant minimum estimate of channel abandonment and deposition of these deltas (Muller et al., 1988).

Clearly, existing additional geochronological data has the potential to lead to better understanding of the glacial history in western New York.

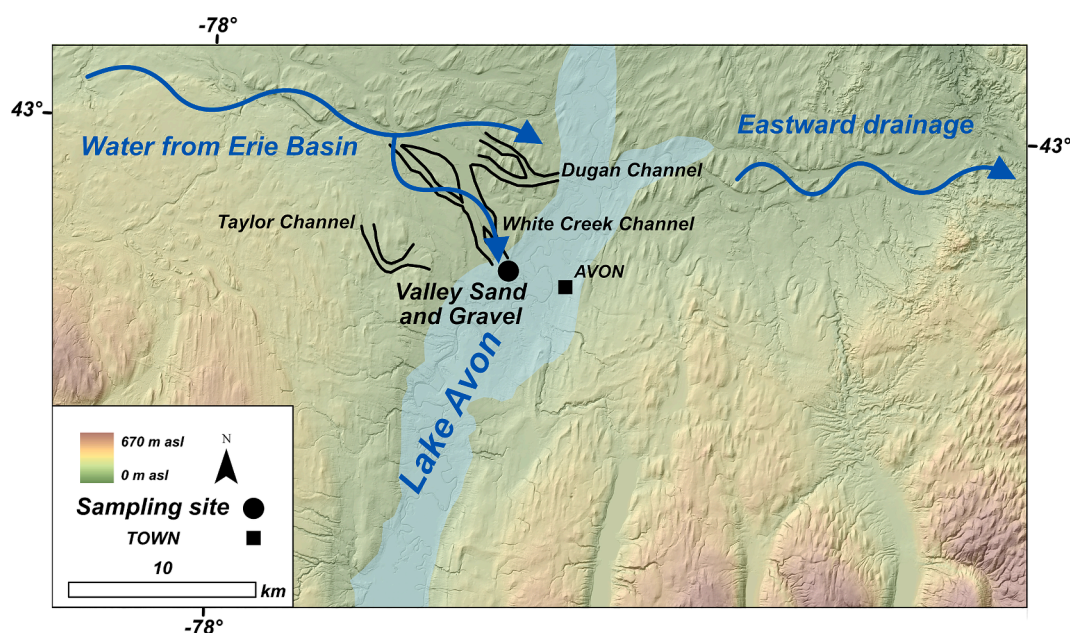


Fig. 4. Genesee Valley showing Lake Avon extent, eastward meltwater routes, and channels with deltas deposited in Lake Avon (Muller et al., 1988).

3. Sampling techniques and locations

To build on the local chronological framework of the glacial history of western New York, we explored the utility of luminescence dating of various sediments related to the Laurentide Ice Sheet. We targeted sediment deposits associated with the various moraines and proglacial lake-levels for luminescence dating. We identified sampling targets such as outwash terraces, shorelines, and deltas using previously published surficial maps assisted with LiDAR-based hillshade maps (Muller, 1977). We targeted fine sand/silt layers in these deposits for sampling. At most sites, we collected samples from exposed quarry faces in 2.5-cm-diameter, 25-cm-long steel tubes following standard sampling protocols for luminescence dating including exposing fresh surfaces, minimizing light exposure, and collecting water and dose rate samples in water-tight bags. At all quarry sites, quarry operators indicated that some amount of material was removed from the land surface before quarrying began.

At our Lake Warren I shoreline site, we collected our samples in ~4-cm-diameter, 20-cm-long aluminum tubes using a handheld auger modified to eliminate light exposure and below 1 m depth to minimize cosmogenic contributions to the geologic dose rate (Hanson et al., 2015; Nelson et al., 2019).

3.1. Glaciofluvial outwash inboard of Olean Moraine – Nannen Northrup Quarry

We collected two samples (Electronic Supplementary Material (ESM) Figs. S1 and S3) from the Nannen Northrup Quarry (42.20°, -78.64°) near Great Valley, New York, where we identified a deposit of glaciofluvial outwash via LiDAR mapping (Fig. 2, Fig. 5). The age of the glaciofluvial outwash was not assigned in previous mapping, likely as a result of the map resolution, but it is inboard of the terminal Olean Moraine and beyond the limit of the Kent Moraine (Fig. 1, Fig. 5; Muller, 1977). It is also adjacent to a deposit of mapped Olean outwash (Fig. 5). Thus, it may relate to an ice-sheet position during ice retreat from the Olean Moraine, and its age could serve as a minimum age constraint on the deposition of this moraine. This could confirm whether the Olean Moraine is LGM or pre-LGM in age, settling a longstanding debate in western New York glacial history (Braun and Brennan, 1988; Cotter et al., 1986; Lewis, 1884; MacClintock and Apfel, 1944; Muller, 1977; Muller and Calkin, 1993). However, glaciofluvial outwash associated

with the Kent Moraine is mapped farther down valley beyond the Nannen Northrup Quarry, opening the possibility that our target deposit may instead relate to the Kent Moraine (Fig. 1).

On one quarry face, we noted ~6.7 m of imbricated cobbles overlying 20 cm of gravel and a ~10 cm lens of fine sand (21NN-01; collected ~7 m below top of quarry wall). Another quarry face was capped with 2.5 m of fine, massive silt (21NN-02; collected ~2.4 m below surface) that overlies the main deposit of rounded gravels and sands.

3.2. Lake Escarpment glaciofluvial outwash – Waterman's Gravel Pit

Waterman's Gravel Pit (42.54°, -78.64°) is quarried into an outwash deposit ~200 m down valley of the Lake Escarpment Moraine. We sampled from an actively quarried face dominated by cobbles that contained minor sand lenses (ESM Fig. S6). The top of the sample face consisted of ~0.6 m of imbricated, rounded cobbles. Below this was a ~1.8-m thick coarse sand layer with sub-rounded gravels, which in turn overlaid another ~0.6-m layer of imbricated, rounded cobbles. Next, was an 18-cm-thick layer of interbedded medium and fine sands, from which we collected sample 21WAT-01 (~3.1 m below surface). Matrix-supported coarse sands and gravels extended from here to the quarry floor.

3.3. Lake Escarpment glaciofluvial outwash – Gable Thomas Mine

The Gable Thomas Mine (42.56°, -78.48°) is in another outwash plain deposited during Lake Escarpment Moraine formation and lies ~13 km east of Waterman's Gravel Pit. Here, we noted 1.8 m of rounded, imbricated gravels with interspersed 5 cm layers of coarse sands. Below this was ~15 cm of coarse sand and a < 4.5-cm fine sand lens, from which we collected 21GT-01 (~3 m below original surface; ESM Fig. S8). Below this sampled layer was coarse sand that became covered by slumped material from quarry activity. We sampled a second sand layer ~30 m away. At this second site were ~2.5 m of coarse sands, rounded gravels, layers of interspersed sands and gravels, and cross-bedded coarse sands overlying a <12-cm fine-medium sand lens, where we collected our second sample (21GT-02; ~3.5 m below original surface; ESM Fig. S11).

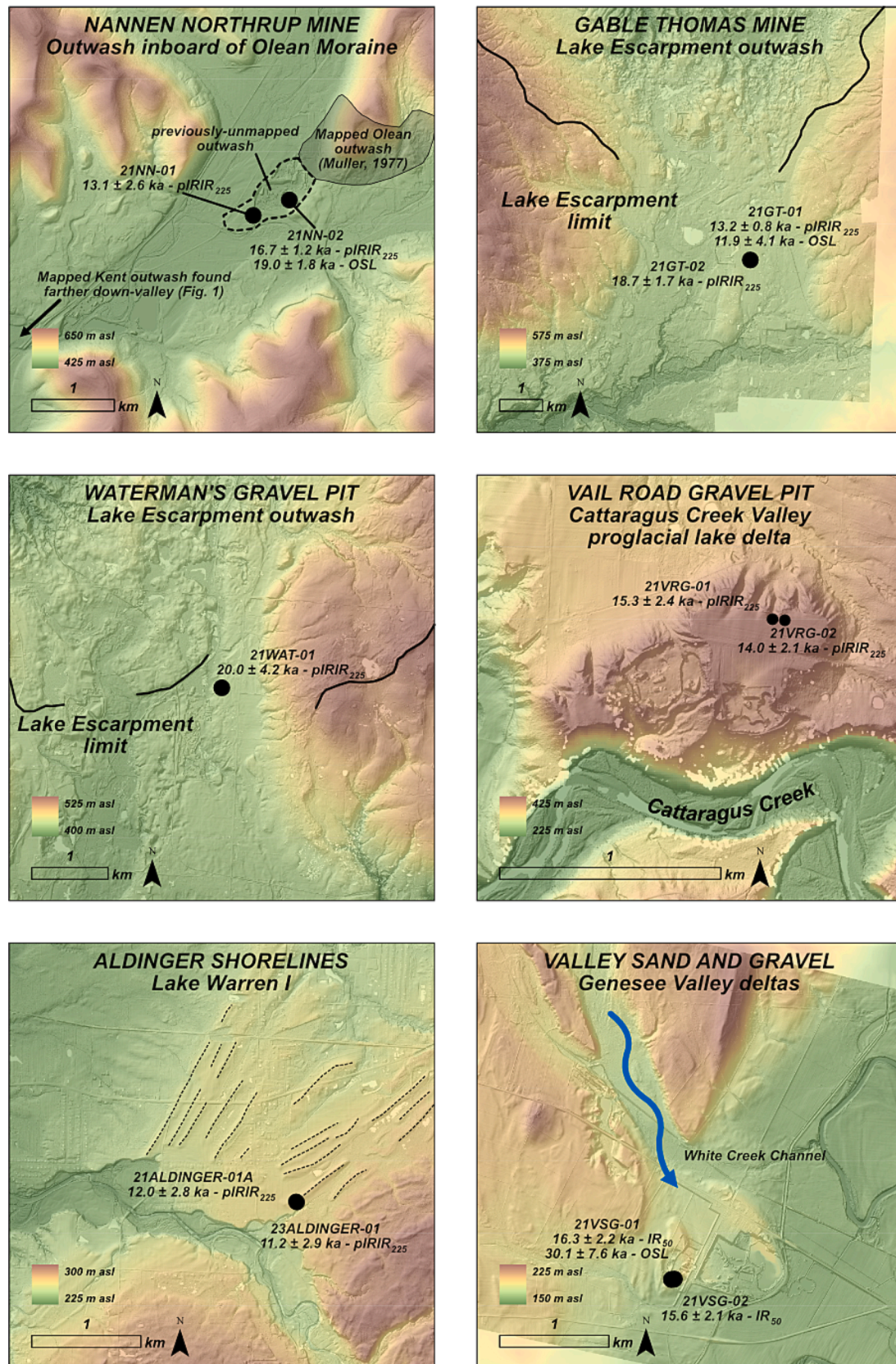


Fig. 5. Maps of field sites and luminescence ages. Base DEMs are from 1-m New York LiDAR survey (<https://gis.ny.gov/lidar>; last accessed 8 December 2025).

3.4. Cattaraugus Creek Valley proglacial lake delta – Vail Road Gravel Pit

Soon after the Laurentide Ice Sheet retreated from the Lake Escarpment Moraine position, a small ice-dammed lake formed in the lower Cattaraugus Creek Valley with a present-day elevation of 348 m asl. This is higher than the Lake Whittlesey shoreline in this vicinity (247 m asl), so we interpret this lake as being localized and not part of the Lake Erie basin lake sequence. Instead, this lake was likely dammed by ice as it stabilized at the Gowanda Moraine position (Muller, 1977). Sediments deposited in this lake formed a Gilbert-type delta at the Vail Road Gravel Pit (42.45°, –78.90°). There are >7-m high sediment sections exposed with sub-horizontal topset beds atop foreset beds. We collected two samples from sub-horizontal fine-sand lenses within these foreset beds near the quarry floor 6.5 m (21VRG-01; ESM Fig. S13) and 5.5 m (21VRG-02; ESM Fig. S15) below the modern surface.

3.5. Lake Warren ages– Warren I shorelines

Lake Warren I shorelines are clearly expressed near Alden, New York (42.89°, –78.52°; Calkin, 1970). Here, we collected two samples from a Warren I shoreline using a handheld soil auger and a lightproof sampling tube (ESM Fig. S17). We found rounded gravels, sands, and clays down to at least 1.5 m and collected samples from 1.05–1.25 m (23ALDINGER-01) and 1.12–1.39 m (23ALDINGER-01A).

3.6. Genesee Valley deltas – Valley Sand and Gravel

Water from proglacial lakes in the Lake Erie basin drained into proglacial Lake Avon in the Genesee Valley, forming large deltaic deposits at the distal end of the Taylor, Dugan, and White Creek channels (Fig. 4, Fig. 5). We sampled two outcrops at the Valley Sand and Gravel quarry (42.92°, –77.79°) built into the White Creek Channel delta. Both samples are from fine sediments overlain by ~10 m of bedded coarse sands and gravels. We collected 21VSG-01 (~10.5 m below surface; ESM Fig. S20) from dipping silt and fine-medium sand layers, which continued down 4 m to the quarry floor. We sampled 21VSG-02 (~11 m below surface; ESM Fig. S24) from dipping silt, and fine sand layers ~0.25 m below the bedded sands and gravels.

4. Luminescence dating

We applied luminescence dating methods to our samples to constrain their depositional age. We used both IRSL measurements from potassium feldspar and OSL measurements from quartz to derive our burial ages.

We processed and analyzed all samples at the University of Texas at Arlington Luminescence Laboratory under amber-light conditions. We prepared potassium feldspar and quartz separates from each sample through wet sieving to isolate the 150–200- μm size fraction, hydrochloric acid digestion for 24 h, heavy liquid separation (target density <2.565 g cm⁻³ for potassium feldspar and 2.62–2.68 g cm⁻³ for quartz), and concentrated hydrofluoric acid treatments for 1 h (for quartz). To estimate the burial dose of our samples, we measured the equivalent dose (D_e) on single grains of potassium feldspar and small aliquots (~2-mm diameter monolayer grain mask) of quartz on a Risø DA-20 luminescence reader. For all feldspar samples, we used the post-infrared IRSL protocol (Buylaert et al., 2009) modified for single grain stimulation. Following a preheat to 250 °C for 10 s, grains were stimulated at 50 °C and then 225 °C for 3 s per grain to measure the infrared 50 (IR₅₀) and post-infrared infrared 225 (pIRIR₂₂₅) signals, respectively. We incorporated a hot bleach with infrared diodes at 290 °C for 60 s at the end of each cycle. We conducted fading tests of individual grains for several samples on timescales of hours to several days. The pIRIR₂₂₅ signal did not fade on observed timescales and the IR₅₀ signal yielded a g-value of $3.56 \pm 0.39\%$ loss per decade ($t_c = 1325$ s; ESM Fig. S27; Huntley and Lamothe, 2001). We performed fading corrections with the R-

Luminescence package (Kreutzer et al., 2012).

For quartz OSL measurements (21GT-01, 21VSG-01, and 22NN-02), we used a standard single aliquot regenerative (SAR) protocol (Murray and Wintle, 2003) with a preheat of 220 °C and a cutheat of 200 °C for 10 s each. Following the preheat, aliquots were stimulated with infrared diodes at 60 °C for 60 s (Duller, 2003) and then with blue diodes at 125 °C for 60 s. We added a hot bleach of 220 °C with blue diodes for 60 s at the end of each SAR cycle.

We summarize our D_e measurements using standard age models (Galbraith et al., 1999). Most of our samples exhibited single-grain potassium feldspar overdispersion (OD) values larger than are typical for a single dose population ($OD > 20 \pm 9\%$; Arnold and Roberts, 2009). This is expected in glaciofluvial environments where incomplete bleaching is likely. In these cases, we applied a minimum age model (MAM), solving for three parameters and imposing an OD value of 24% (based on observed overdispersion of samples 21GT-01 and 21NN-02; Fuchs and Owen, 2008; Galbraith et al., 1999; Thrasher et al., 2009). Post-infrared IRSL₂₂₅ measurements on 21GT-01 and 21NN-02 had overdispersion values of 24.5 and 24.0%, respectively, and we used a central age model (CAM) to model their D_e values. For our quartz measurements, we applied a CAM to 21NN-02 ($OD = 10.2\%$) and 21GT-01 ($OD = 0\%$; only three aliquots accepted). For quartz measurements from 21VSG-01 ($OD = 40.4\%$), we applied a MAM, solving for three parameters and imposing an OD value of 15%.

To determine environmental dose rates, we sent 10 g of bulk sediment to SGS Canada for elemental composition determination via inductively-coupled plasma mass spectrometry and inductively-coupled plasma optical emissions spectrometry. We determined water content by drying portions of sediment for 48 h in a 50 °C oven and subtracting the dry mass from the wet mass. We calculated environmental dose rates using the DRAC luminescence age calculator (ESM Table S1), applying standard attenuation factors (Brennan et al., 1991; Guérin et al., 2011; Liritzis et al., 2013), an internal potassium content of 12.5 ± 0.5 wt% (Huntley and Baril, 1997), and standard error propagation (Durcan et al., 2015).

5. Results

Here, we report the results of samples collected at each of our six sites described above. We group the results into four phases of the glacial history of western New York: 1) the Olean terminal limit, 2) the Lake Escarpment (Valley Heads) stadial, 3) Lake Warren I development, and 4) the formation of the White Creek Channel and delta complex in the Genesee Valley (Fig. 4, Fig. 5, Fig. 6; Table 1).

5.1. Glaciofluvial outwash inboard of Olean Moraine

Sample 21NN-01 from the terminal moraine glaciofluvial outwash yielded D_e estimates (ESM Fig. S2) with a clear leading edge; in turn, this provided an age of 13.1 ± 2.6 ka (pIRIR₂₂₅; all ages reported $\pm 1\sigma$). We interpret the massive silt unit capping the outwash gravels as loess, given its fine, uniform grain-size (silt) and lack of larger clasts, lack of lateral variability in facies, and lack of sedimentary structures. Equivalent dose estimates from our sample (21NN-02) within this silt unit suggest a well-bleached sediment (ESM Figs. S4 and S5). Luminescence ages of 16.7 ± 1.2 ka (pIRIR₂₂₅) and 19.0 ± 1.8 ka (OSL) from this loess provide a minimum age constraint for the underlying glaciofluvial outwash.

5.2. Lake Escarpment stadial

Equivalent dose measurements using the pIRIR₂₂₅ signal from Lake Escarpment outwash sediments at Waterman's Gravel Pit have a clear leading edge and yield an age of 20.0 ± 4.2 ka (21WAT-01; ESM Fig. S7). Post-infrared infrared 225 estimates of D_e from our lower sample at the Gable Thomas Mine also display a clear leading edge with

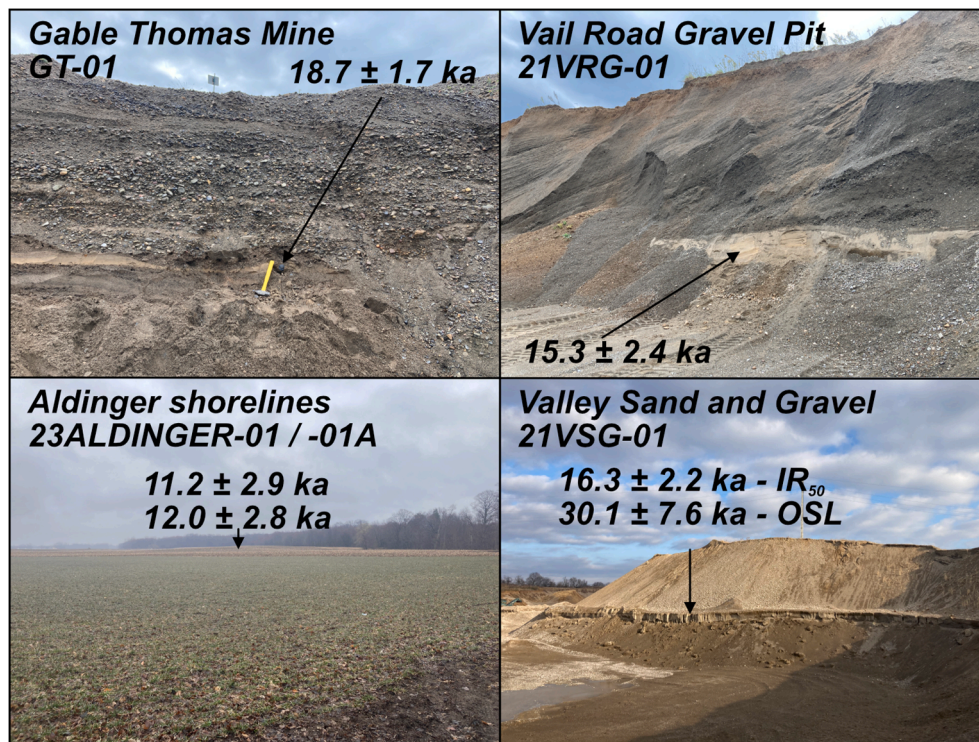


Fig. 6. Representative photos from field sites and luminescence ages. Unless noted, all ages are pIRIR₂₂₅ ages.

an age of 18.7 ± 1.7 ka (21GT-02; pIRIR₂₂₅). In our sample stratigraphically above this (21GT-01), pIRIR₂₂₅ equivalent dose measurements show a more normal distribution (ESM Fig. S9). 21GT-01 has ages of 13.2 ± 0.8 ka (21GT-01; pIRIR₂₂₅) and 11.9 ± 4.1 ka (21GT-01; OSL). Our two samples from Gowanda delta deposits (formed after the Lake Escarpment ice position) at the Vail Road Gravel Pit both yielded D_e distributions with clear leading edges, and date to 15.3 ± 2.4 ka (21VRG-01; pIRIR₂₂₅; ESM Fig. S14) and 14.0 ± 2.1 ka (21VRG-02; pIRIR₂₂₅; ESM Fig. S16).

5.3. Lake Warren I

Equivalent dose measurements (pIRIR₂₂₅) from our two samples within the Warren I shoreline show clear leading edges (ESM Figs. S18 and S19) and provide ages of 11.2 ± 2.9 ka (23ALDINGER-01) and 12.0 ± 2.8 ka (23ALDINGER-01A).

5.4. Genesee Valley channel formation and delta deposition

Post-infrared infrared 225 D_e estimates from the Valley Sand and Gravel quarry built into the White Creek Channel delta show a leading edge typical of a well-bleached sub-population of grains, but have anomalously high D_e values of 99.03 Gy and 48.19 Gy for 21VSG-01 and 02, respectively (ESM Figs. S21 and S25). These correspond to ages of 29.4 ± 3.6 ka and 20.0 ± 2.1 ka; at this time, the area was covered by the Laurentide Ice Sheet, thus suggesting the likelihood of incomplete bleaching (Table 1; ESM Figs. S20 and S24). IR₅₀ measurements of D_e also show a clear leading edge, with corresponding ages of 16.3 ± 2.2 ka (21VSG-01) and 15.6 ± 2.1 ka (VSG-02). These are compatible with existing ice-sheet chronologies and suggest that a population of grains were fully bleached before deposition; this may be expected given the increased bleachability of the IR₅₀ signal relative to the pIRIR₂₂₅ signal (ESM Figs. S22 and S26; Buyllaert et al., 2009). We also obtained an OSL age of 30.1 ± 7.6 for 21VSG-01, but we consider this unreliable as D_e measurements exhibited poor OSL characteristics including relatively low signal-to-noise, irregular growth with dose, an elevated early

background, and did not show a clear leading edge (ESM Figs. S23 and S28).

6. Discussion

6.1. Age of glaciofluvial outwash inboard of Olean Moraine

The loess (21NN-02) overlying the outwash has ages of 16.7 ± 1.2 ka (pIRIR₂₂₅) and 19.0 ± 1.8 ka (OSL). The underlying glaciofluvial outwash (21NN-01) has an age of 13.1 ± 2.6 ka (pIRIR₂₂₅) and statistically overlaps with 21NN-02 at the 2 σ level. However, given the individual sample precision and local context, we favor the ages of the capping loess samples of 16.7 ± 1.2 and 19.0 ± 1.8 ka as a stronger constraint post-dating the retreat of ice from the Olean position (Fig. 7). We suggest that the pIRIR₂₂₅ age of 16.7 ± 1.2 ka may be slightly preferable compared to the OSL age of 19.0 ± 1.8 ka because of a higher number of accepted measurements (30 vs. 12) and greater precision. This is also consistent with OSL ages reported by Prince et al. (2024) from an ice-contact delta at the maximum Kent Moraine position of 19.8 ± 2.6 and 20.6 ± 2.9 ka.

Our luminescence chronology from glaciofluvial outwash inboard of the terminal Olean position opens the possibility of an LGM age for this ice limit (Fig. 7). However, because Kent outwash is found farther down-valley from this site, we cannot rule out the possibility that our sampled deposit instead relates to the Kent position (Muller, 1977). Additional constraints from mapped Olean deposits along the Salamanca Reentrant are required to confirm an LGM age for the Olean Moraine.

6.2. Age of the Lake Escarpment stadial

Our luminescence ages on Lake Escarpment glaciofluvial outwash sediments of 20.0 ± 4.2 ka (21WAT-01) and 18.7 ± 1.7 ka (21GT-02) provide the first direct constraints on the deposition of this moraine in western New York (Fig. 7). We attempted to replicate our youngest pIRIR₂₂₅ date of 13.2 ± 0.8 ka (21GT-01) using OSL on quartz separates, but this was hampered by poor quartz response (as often seen in glacial

Table 1

Pertinent luminescence age after Mahan et al. (2022), calculated using DRAC (Durcan et al., 2015). All additional information is included in ESM Table S1. Age models are either Minimum Age Model with three parameters (MAM-3) or Central Age Model (CAM). The total dose rate includes internal dose rate from assumed internal K-feldspar K content of 12.5 ± 0.5 wt% (Huntley and Baril, 1997). IR₅₀ ages are corrected for fading.

Sample ID	Quartz or K-feldspar?	Measured signal	Aliquots (quartz)/Grains (K-feldspar) accepted [measured]	Age model	D _e (Gy) $\pm 1\sigma$	Depth (m)	H ₂ O (wt %) $\pm 1\sigma$	K (%) $\pm 1\sigma$	Th (ppm) $\pm 1\sigma$	U (ppm) $\pm 1\sigma$	Rb (ppm) $\pm 1\sigma$	Cosmic dose rate (Gy/kyr) $\pm 1\sigma$	Total dose rate (Gy/kyr) $\pm 1\sigma$	Age (ka) $\pm 1\sigma^c$
21NN-01	K-feldspar	pIRIR ₂₂₅	16 [300]	MAM-3	39.9 $\pm$ 7.7	7	22.9 $\pm$ 5	1.4 $\pm$ 0.1	9.8 $\pm$ 0.5	2.7 $\pm$ 0.1	71.4 $\pm$ 3.6	0.10 $\pm$ 0.01	3.0 $\pm$ 0.1	13.1 $\pm$ 2.6
21NN-02	K-feldspar	pIRIR ₂₂₅	30 [300]	CAM	64.4 $\pm$ 3.3	2.4	3.2 $\pm$ 5	1.5 $\pm$ 0.1	10.0 $\pm$ 0.5	3.1 $\pm$ 0.2	77.3 $\pm$ 3.9	0.17 $\pm$ 0.02	3.9 $\pm$ 0.2	16.7 $\pm$ 1.2
21NN-02	Quartz	OSL	12 [12]	MAM-3	58.7 $\pm$ 4.9	2.4	3.2 $\pm$ 5	1.5 $\pm$ 0.1	10.0 $\pm$ 0.5	3.1 $\pm$ 0.2	77.3 $\pm$ 3.9	0.17 $\pm$ 0.02	3.1 $\pm$ 0.2	19.0 $\pm$ 1.8
21WAT-01	K-feldspar	pIRIR ₂₂₅	8 [300]	MAM-3	64.7 $\pm$ 13.2	3.1	11.4 $\pm$ 5	1.6 $\pm$ 0.1	6.6 $\pm$ 0.3	2.3 $\pm$ 0.1	63.3 $\pm$ 3.2	0.15 $\pm$ 0.02	3.2 $\pm$ 0.2	20.0 $\pm$ 4.2
21GT-01	K-feldspar	pIRIR ₂₂₅	71 [300]	CAM	39.8 $\pm$ 1.4	3	11.2 $\pm$ 5	1.5 $\pm$ 0.1	5.3 $\pm$ 0.3	2.1 $\pm$ 0.1	65.6 $\pm$ 3.3	0.16 $\pm$ 0.02	3.0 $\pm$ 0.1	13.2 $\pm$ 0.8
21GT-01	Quartz	OSL	3 [12]	CAM	27.4 $\pm$ 9.4	3	11.2 $\pm$ 5	1.5 $\pm$ 0.1	5.3 $\pm$ 0.3	2.1 $\pm$ 0.1	65.6 $\pm$ 3.3	0.16 $\pm$ 0.02	2.3 $\pm$ 0.1	11.9 $\pm$ 4.1
21GT-02	K-feldspar	pIRIR ₂₂₅	102 [300]	MAM-3	46.2 $\pm$ 3.4	3.5	16.3 $\pm$ 5	1.3 $\pm$ 0.1	3.9 $\pm$ 0.2	1.5 $\pm$ 0.1	45.3 $\pm$ 2.3	0.15 $\pm$ 0.01	2.5 $\pm$ 0.1	18.7 $\pm$ 1.7
21VRG-01	K-feldspar	pIRIR ₂₂₅	61 [300]	MAM-3	40.8 $\pm$ 6.1	6.5	14.2 $\pm$ 5	1.4 $\pm$ 0.1	4.5 $\pm$ 0.2	1.8 $\pm$ 0.1	55.8 $\pm$ 2.8	0.10 $\pm$ 0.01	2.7 $\pm$ 0.1	15.3 $\pm$ 2.4
21VRG-02	K-feldspar	pIRIR ₂₂₅	60 [300]	MAM-3	40.3 $\pm$ 5.6	5.5	5.9 $\pm$ 5	1.4 $\pm$ 0.1	4.6 $\pm$ 0.2	1.8 $\pm$ 0.1	52.6 $\pm$ 2.6	0.12 $\pm$ 0.01	2.9 $\pm$ 0.1	14.0 $\pm$ 2.1
23ALDINGER-01	K-feldspar	pIRIR ₂₂₅	15 [300]	MAM-3	44.9 $\pm$ 11.4	1.2	12.1 $\pm$ 5	2.0 $\pm$ 0.1	7.5 $\pm$ 0.4	3.7 $\pm$ 0.2	83.9 $\pm$ 4.2	0.19 $\pm$ 0.02	4.0 $\pm$ 0.2	11.2 $\pm$ 2.9
23ALDINGER-01A	K-feldspar	pIRIR ₂₂₅	13 [300]	MAM-3	51.6 $\pm$ 11.8	1.2	13.5 $\pm$ 5	2.1 $\pm$ 0.1	8.8 $\pm$ 0.4	4.5 $\pm$ 0.2	94.7 $\pm$ 4.7	0.19 $\pm$ 0.02	4.3 $\pm$ 0.2	12.0 $\pm$ 2.8
21VSG-01	K-feldspar	IR ₅₀	27 [500]	MAM-3	38.6 $\pm$ 4.3	10.5	1.7 $\pm$ 5	1.8 $\pm$ 0.1	4.8 $\pm$ 0.2	1.9 $\pm$ 0.1	60.4 $\pm$ 3.0	0.07 $\pm$ 0.01	3.4 $\pm$ 0.2	16.3 $\pm$ 2.2
21VSG-01	K-feldspar	pIRIR ₂₂₅	27 [500]	MAM-3	99.0 $\pm$ 10.9	10.5	1.7 $\pm$ 5	1.8 $\pm$ 0.1	4.8 $\pm$ 0.2	1.9 $\pm$ 0.1	60.4 $\pm$ 3.0	0.07 $\pm$ 0.01	3.4 $\pm$ 0.2	29.4 $\pm$ 3.6
21VSG-01	Quartz	OSL	12 [12]	MAM-3	79.9 $\pm$ 19.7	10.5	1.7 $\pm$ 5	1.8 $\pm$ 0.1	4.8 $\pm$ 0.2	1.9 $\pm$ 0.1	60.4 $\pm$ 3.0	0.07 $\pm$ 0.01	2.7 $\pm$ 0.1	30.1 $\pm$ 7.6
21VSG-02	K-feldspar	IR ₅₀	87 [900]	MAM-3	26.5 $\pm$ 3.0	11	6.7 $\pm$ 5	1.2 $\pm$ 0.1	3.4 $\pm$ 0.2	1.3 $\pm$ 0.1	39.0 $\pm$ 2.0	0.07 $\pm$ 0.01	2.4 $\pm$ 0.1	15.6 $\pm$ 2.1
21VSG-02	K-feldspar	pIRIR ₂₂₅	87 [900]	MAM-3	48.2 $\pm$ 4.2	11	6.7 $\pm$ 5	1.2 $\pm$ 0.1	3.4 $\pm$ 0.2	1.3 $\pm$ 0.1	39.0 $\pm$ 2.0	0.07 $\pm$ 0.01	2.4 $\pm$ 0.1	20.1 $\pm$ 2.1

environments; Fuchs and Owen, 2008; Thrasher et al., 2009). Quartz from 21GT-01 responded poorly during measurement, with only three of 12 measured aliquots giving acceptable signals (ESM Fig. S10), with all measured aliquots having a low signal-to-noise ratio. Thus, we have greater confidence in the pIRIR₂₂₅ ages at this site (ESM Figs. S9 and S12). However, because existing chronology constrains Lake Escarpment Moraine deposition locally to ~18–16 ka (Muller and Calkin, 1993; Prince et al., 2024; Ridge, 2003), we posit that this sample is a young outlier. Additionally, its normal distribution of D_e measurements (ESM Fig. S9; D_e populations from other glaciofluvial outwash samples yielded a distinct leading edge) may indicate a different depositional setting, perhaps in a fluvial system following ice retreat from this position. Therefore, we suggest that the ages of 20.0 ± 4.2 ka (21WAT-01) and 18.7 ± 1.7 ka (21GT-02) represent our best constraint for the deposition of the Lake Escarpment outwash and associated moraine

(Fig. 7).

The ice-dammed lake delta in the lower Cattaraugus Creek Valley formed soon after ice retreat from the Lake Escarpment Moraine as water was dammed by ice at the Gowanda position. The pIRIR₂₂₅ ages of 15.3 ± 2.4 (21VRG-01) and 14.0 ± 2.1 ka (21VRG-02) provide an estimate of Gowanda Moraine deposition, and a minimum age on Lake Escarpment Moraine deposition (Fig. 7).

Our Lake Escarpment glaciofluvial outwash pIRIR₂₂₅ ages of 20.0 ± 4.2 ka and 18.7 ± 1.7 ka are supported by estimates of Kent Moraine deposition at ~20 ka (Prince et al., 2024) and the Erie Interstade between 19.3 and 17.7 ka (Ridge, 1997), both of which preceded Lake Escarpment Moraine deposition. This is further bolstered by Muller and Calkin's (1993) extrapolation of wood ages found above Lake Escarpment outwash (Fritz et al., 1987) dating this ice position to ~17.6 cal ka (Fig. 7). Additionally, our new ages are compatible (overlap at 1σ) with

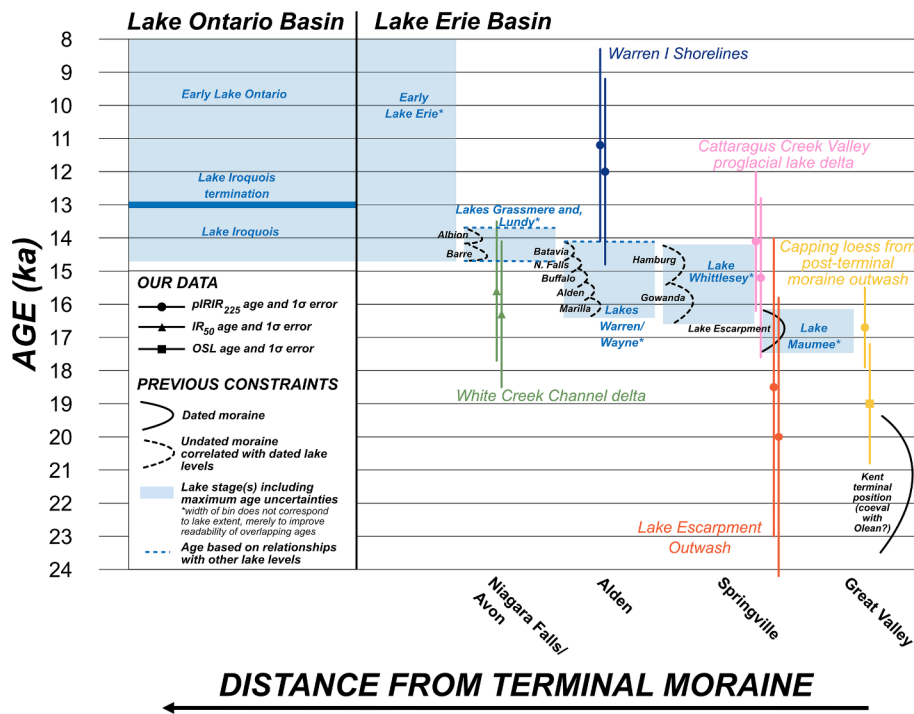


Fig. 7. Summary ice-sheet time-distance diagram showing moraines, lake levels, and drainage events in western New York. Neither lakes stages nor moraines overlapped with each other; the height of these merely represents the full range of possible ages for these based on existing chronology.

existing chronologies from the Valley Heads Moraine in central New York dated to between ~ 17.2 and ~ 16.2 cal ka (Ridge, 2003) and an OSL age of 16.8 ± 1.0 ka from a Lake Maumee shoreline in the Ohio (Fisher et al., 2015), both thought to be equivalent in age to the Lake Escarpment Moraine. Our ages from the Cattaraugus Creek Valley proglacial lake delta associated with the Gowanda Moraine postdating the Lake Escarpment stadial corroborate these existing chronologies.

6.3. Age of Lake Warren I shorelines in western New York

Our luminescence ages from Warren I shorelines of 11.2 ± 2.9 ka (23ALDINGER-01) and 12.0 ± 2.8 ka (23ALDINGER-01A) statistically overlap with maximum-limiting ages on Lake Warren I shoreline inception dating between 16.4 and 14.2 cal ka (Fig. 7; Calkin and McAndrews, 1980; Totten, 1985). Our IRSL ages also overlap with an OSL age of 14.2 ± 1.3 ka from an undifferentiated Lake Warren shoreline in Ohio (Higley et al., 2014). Furthermore, our new ages from the Lake Warren I shoreline are within error of a minimum-limiting radiocarbon age from peat formed on top of Lake Warren shorelines dated to 15.7–14.1 cal ka (Lewis, 1969). Unfortunately, the large errors on our IRSL ages from a Warren I shoreline make it difficult to more precisely date this lake level and its associated ice positions.

6.4. Timing of Genesee Valley channel formation

Infrared stimulated luminescence ages of 16.3 ± 2.2 ka (21VSG-01) and 15.6 ± 2.1 ka (VSG-02) provide the first direct constraints on the formation of the White Creek Channel complex. This new age of channel formation between 16.3 ± 2.2 ka and 15.6 ± 2.1 ka for this outburst flood is compatible with extreme minimum-limiting ages from peat deposited in the Dugan Channel (formed at the same time as the White Creek Channel Complex) dating to between 13.2 and 12.7 cal ka (Muller et al., 1988). However, based on these ages, we cannot confirm any of the hypothesized mechanisms that formed these channels and the associated deltas, whether normal outflow of a short-lived post-Lundy glacial lake, jökullhaups as ice receded and opened eastern flow out of

Lake Grassmere or Lake Lundy, or normal drainage from Lake Warren I.

6.5. Luminescence dating in western New York

Our luminescence ages bolster the limited chronology of glacial fluctuations in western New York and broadly agree with existing age constraints. Luminescence dating is often challenging in proglacial settings (Fuchs and Owen, 2008; Thrasher et al., 2009), but nevertheless our single grain potassium feldspar luminescence measurements provide useful ages for proglacial depositional features in western New York. Given the poor luminescence characteristics of quartz grains we measured in Lake Escarpment outwash deposits and deltaic sediments in the Genesee Valley, we caution using solely OSL approaches in western New York. Optically stimulated luminescence ages from the Kent Moraine seem robust (Prince et al., 2024) but, given the variability of quartz luminescence characteristics depending on source lithology, transport history, and weathering history (e.g., Jeong and Choi, 2012), we suggest that future OSL work in western New York should be paired with IRSL measurements on potassium feldspars.

We note that all our luminescence ages apart from a single young outlier (21GT-01 pIRIR₂₂₅ age of 13.2 ± 0.8 ka) overlap with each other at the 2σ level. While these ages are compatible with the limited existing radiocarbon-based chronology in western New York, at present they do not add additional precision (Fig. 7). Because of large uncertainties on the luminescence ages, we propose that luminescence dating in western New York should focus on 1) dating sediments beyond the usable range of radiocarbon dating (>45 ka, $<\sim 200$ ka; typical limit of luminescence dating), and 2) assigning ages to deposits whose age is unknown by 5 kyr or more. Thus, luminescence dating has great promise for dating – and confirming the age of – mapped pre-LGM deposits that are not currently dated, like those at previously described sections at the Otto and Gowanda Hospital sites (Muller and Calkin, 1993).

7. Conclusions

- A loess capping glaciofluvial outwash within the Olean ice limit dates to 17.9 ± 2.2 ka consistent with an LGM age. This age overlaps with OSL ages from Prince et al. (2024) on a nearby kame delta sequence associated with the Kent Moraine of 19.8 ± 2.6 and 20.6 ± 2.9 ka. This suggests that the Olean Moraine is LGM in age and defines the LGM limit along the Salamanca Reentrant with the Kent Moraine. However, Kent outwash is also found further down-valley from this site meaning that the dated deposit could instead be related to the Kent Moraine. Additional dates from mapped Olean deposits are required to confirm this.
- Depositional ages of outwash terraces date the formation of the Lake Escarpment Moraine to 20.0 ± 4.2 ka to 18.7 ± 1.7 ka. The Cattaraugus Valley proglacial lake delta associated with Gowanda Moraine deposition dates to 15.3 ± 2.4 to 14.0 ± 2.1 ka. These are minimum ages for Lake Escarpment Moraine formation. Our ages are compatible with the existing chronology of the Lake Escarpment Moraine and Lake Maumee.
- We provide first constraints on proglacial lake stages in the Lake Erie basin from western New York and associated deltas within the Genesee Valley. These ages overlap (at 2σ) with existing chronology and additional work may improve their precision.
- Given the poor OSL characteristics of many of our quartz samples, we suggest that future efforts to date sediments in western New York should consider making IRSL measurements on potassium feldspar in addition to, or in lieu of, OSL dating of quartz.
- Further luminescence work in western New York should focus on constraining the age of pre-LGM deposits whose age is beyond the usable range of radiocarbon dating (>45 ka). Potential targets include deposits at the Otto and Gowanda Hospital sites.

CRedit authorship contribution statement

Caleb K. Walcott-George: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jason P. Briner:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Nathan D. Brown:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge that western New York is territory traditionally belonging to the Seneca Nation, a member of the Haudenosaunee/Six Nations Confederacy. This work was supported by NSF/GSA Graduate Student Geoscience Grant [#13538-22, which is funded by NSF Award # 1949901] and the Mark Diamond Research Fund of the Graduate Student Association of the State University of New York at Buffalo. We thank Gernatt Gravel (especially Rich Pecnick and Brian Schmitt), Valley Sand and Gravel (especially Thomas Murphy), and the Aldinger family for access to sampling sites. Thank you to Karlee Prince, Brandon Graham, Joe Tulenko, Hayley Martinez, Maya Lasker, and August Briner for assistance with sample collection, and Cindy Lou Skipper for help with sample preparation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jglr.2026.102868>.

References

- Arnold, L.J., Roberts, R.G., 2009. Stochastic modelling of multi-grain equivalent dose (De) distributions: implications for OSL dating of sediment mixtures. *Quat. Geochronol.* 4, 204–230.
- Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., Schaefer, J.M., 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quat. Geochronol.* 4, 93–107.
- Balco, G., Stone, J.O.H., Porter, S.C., Caffee, M.W., 2002. Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts. *USA. Quat. Sci. Rev.* 21, 2127–2135.
- Balter-Kennedy, A., Schaefer, J.M., Balco, G., Kelly, M.A., Kaplan, M.R., Schwartz, R., Oakley, B., Young, N.E., Hanley, J., Varuolo-Clarke, A.M., 2024. The Laurentide Ice Sheet in southern New England and New York during and at the end of the Last Glacial Maximum: a cosmogenic-nuclide chronology. *Clim. Past* 20, 2167–2190.
- Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., McNeely, R., Southon, J., Morehead, M.D., 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature* 400, 344–348.
- Bleuer, N.K., Moore, M.C., 1971. Glacial stratigraphy of the Fort Wayne area and the draining of glacial Lake Maumee. *Proceedings of the Indiana Academy of Science* 81, 195–209.
- Braun, D.D., Brennan, W.J., 1988. Wisconsin deglacial history of the Genesee Valley from the Terminal moraine to the Valley Heads moraine, Friends of the Pleistocene, State University of New York, College at Geneseo, pp. 29–39.
- Brennan, B.J., Lyons, R.G., Phillips, S.W., 1991. Attenuation of alpha particle track dose for spherical grains. *Int. J. Radiat. Appl. Instrum. Part D. Nucl. Tracks Radiat. Meas.* 18, 249–253.
- Broecker, W.S., Kennett, J.P., Flower, B.P., Teller, J.T., Trumbore, S., Bonani, G., Wolfli, W., 1989. Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode. *Nature* 341, 318–321.
- Buylaert, J.P., Murray, A.S., Thomsen, K.J., Jain, M., 2009. Testing the potential of an elevated temperature IRSL signal from K-feldspar. *Radiat. Meas.* 44, 560–565.
- Calkin, P.E., 1970. Strand lines and chronology of the glacial Great Lakes in northwestern New York. *Ohio J. Sci.* 70, 78–96.
- Calkin, P.E., Brett, C.E., 1978. Ancestral Niagara River drainage: Stratigraphic and paleontologic setting. *Geol. Soc. Am. Bull.* 89, 1140–1154.
- Calkin, P.E., Feenstra, B.H., 1985. Evolution of the Erie-Basin Great Lakes. In: Karrow, P.F., Calkin, P.E. (Eds.), *Quaternary Evolution of the Great Lakes*. Geological Society of Canada, St. John's, pp. 149–170.
- Calkin, P.E., McAndrews, J.H., 1980. Geology and paleontology of two late Wisconsin sites in western New York State. *Geol. Soc. Am. Bull.* 91, 295–306.
- Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J. X., Hostetler, S.W., McCabe, A.M., 2009. The Last Glacial Maximum. *Science* 325, 710–714.
- Clark, P., Karrow, P.F., 1984. Late Pleistocene water bodies in the St. Lawrence Lowland, New York, and regional correlations. *Geol. Soc. Am. Bull.* 95, 805–813.
- Coakley, J., Lewis, C., 1985. Postglacial lake levels in the Erie basin. In: Karrow, P.F., Calkin, P.E. (Eds.), *Quaternary Evolution of the Great Lakes*. Geological Society of Canada, St. John's, pp. 195–212.
- Corbett, L.B., Bierman, P.R., Stone, B.D., Caffee, M.W., Larsen, P.L., 2017. Cosmogenic nuclide age estimate for Laurentide Ice Sheet recession from the terminal moraine, New Jersey, USA, and constraints on latest Pleistocene ice sheet history. *Quat. Res.* 87, 482–498.
- Cotter, J.F., Ridge, J.C., Evenson, E.B., Sevon, W.D., Sirkin, L., Stuckenrath, R., 1986. The Wisconsin history of the Great Valley, Pennsylvania and New Jersey, and the age of the "Terminal Moraine", The Wisconsin Stage of the First Geological District, Eastern New York. University of the State of New York, State Education Department, pp. 22–49.
- Curry, B., Petras, J., 2011. Chronological framework for the deglaciation of the Lake Michigan lobe of the Laurentide Ice Sheet from ice-walled lake deposits. *J. Quat. Sci.* 26, 402–410.
- Dalton, A.S., Duffer, H.E., Margold, M., Heyman, J., Clague, J.J., Froese, D.G., Gauthier, M.S., Hughes, A.L.C., Jennings, C.E., Norris, S.L., Stoker, B.J., 2023. Deglaciation of the north American ice sheet complex in calendar years based on a comprehensive database of chronological data: NADI-1. *Quat. Sci. Rev.* 321, 108345.
- Donnelly, J.P., Driscoll, N.W., Uchupi, E., Keigwin, L.D., Schwab, W.C., Thiel, E.R., Swift, S.A., 2005. Catastrophic meltwater discharge down the Hudson Valley: a potential trigger for the Intra-Allerød cold period. *Geology* 33, 89–92.
- Duller, G.A.T., 2003. Distinguishing quartz and feldspar in single grain luminescence measurements. *Radiat. Meas.* 37, 161–165.
- Duller, G.A.T., 2006. Single grain optical dating of glacial deposits. *Quat. Geochronol.* 1, 296–304.
- Durcan, J.A., King, G.E., Duller, G.A.T., 2015. DRAC: Dose Rate and Age Calculator for trapped charge dating. *Quat. Geochronol.* 28, 54–61.
- Fairchild, H.L., 1932. Closing stage of New York glacial history. *Bull. Geol. Soc. Am.* 43, 603–626.
- Fairchild, H.L.R., 1907. Glacial waters in the Lake Erie basin. New York State Education Department.
- Fisher, T.G., Blockland, J.D., Anderson, B., Krantz, D.E., Stierman, D.J., Goble, R., 2015. Evidence of sequence and age of Ancestral Lake Erie lake-levels, northwest Ohio. *Ohio J. Sci.* 115, 62.

- Fisher, T.G., Dzikian, M.R., McDonald, J., Lepper, K., Loope, H.M., McCarthy, F.M.G., Curry, B.B., 2020. Minimum limiting deglacial ages for the out-of-phase Saginaw Lobe of the Laurentide Ice Sheet using optically stimulated luminescence (OSL) and radiocarbon methods. *Quat. Res.* 97, 71–87.
- Fisher, T.G., Yansa, C.H., Lowell, T.V., Lepper, K., Hajdas, I., Ashworth, A., 2008. The chronology, climate, and confusion of the Moorhead Phase of glacial Lake Agassiz: new results from the Ojata Beach, North Dakota, USA. *Quat. Sci. Rev.* 27, 1124–1135.
- Fritz, P., Morgan, A.V., Eicher, U., McAndrews, J.H., 1987. Stable isotope, fossil Coleoptera and pollen stratigraphy in late quaternary sediments from Ontario and New York state. *Palaeogeogr. Palaeoclim. Palaeoecol.* 58, 183–202.
- Fuchs, M., Owen, L.A., 2008. Luminescence dating of glacial and associated sediments: review, recommendations and future directions. *Boreas* 37, 636–659.
- Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., Olley, J.M., 1999. Optical dating of single and multiple grains of quartz from Jinnium rock shelter, northern Australia: Part I, experimental design and statistical models. *Archaeometry* 41, 339–364.
- Glover, K.C., Lowell, T.V., Wiles, G.C., Pair, D., Applegate, P., Hajdas, I., 2011. Deglaciation, basin formation and post-glacial climate change from a regional network of sediment core sites in Ohio and eastern Indiana. *Quat. Res.* 76, 401–410.
- Goldthwait, R.P., 1958. Wisconsin age forests in western Ohio. I, Age and glacial events. *Ohio J. Sci.* 58, 10.
- Guérin, G., Mercier, N., Adamiec, G., 2011. Dose-rate conversion factors: update. *Ancient TL* 29, 5–8.
- Hanson, P.R., Mason, J.A., Jacobs, P.M., Young, A.R., 2015. Evidence for bioturbation of luminescence signals in eolian sand on upland ridgetops, southeastern Minnesota, USA. *Quat. Int.* 362, 108–115.
- Heath, S.L., Loope, H.M., Curry, B.B., Lowell, T.V., 2018. Pattern of southern Laurentide Ice Sheet margin position changes during Heinrich Stadials 2 and 1. *Quat. Sci. Rev.* 201, 362–379.
- Higley, M.C., Fisher, T.G., Jol, H.M., Lepper, K., Martin-Hayden, J.M., 2014. Stratigraphic and chronologic analysis of the Warren Beach, northwest Ohio, USA. *Can. J. Earth Sci.* 51, 737–749.
- Howard, J.L., 2010. Late Pleistocene glaciolacustrine sedimentation and paleogeography of southeastern Michigan, USA. *Sediment. Geol.* 223, 126–142.
- Huntley, D.J., Baril, M.R., 1997. The K content of the K-feldspars being measured in optical dating or in thermoluminescence dating. *Ancient TL* 15, 11–13.
- Huntley, D.J., Lamothe, M., 2001. Ubiquity of anomalous fading in K-feldspars and the measurement and correction for it in optical dating. *Can. J. Earth Sci.* 38, 1093–1106.
- Jeong, G.Y., Choi, J.-H., 2012. Variations in quartz OSL components with lithology, weathering and transportation. *Quat. Geochronol.* 10, 320–326.
- Karig, D.E., 2023. A reassessment of the Erie Interstade from field work in the Cayuga basin, central New York. *Can. J. Earth Sci.* 60, 1223–1243.
- Karrow, P.F., 1981. Late-glacial regional ice-flow patterns in eastern Ontario: discussion. *Can. J. Earth Sci.* 18, 1386–1390.
- Kehew, A.E., Lord, M.L., Kozłowski, A.L., Fisher, T.G., 2009. *Proglacial megaflooding along the margins of the Laurentide Ice Sheet, Megaflooding on Earth and Mars*. Cambridge University Press.
- Kozłowski, A.L., Bird, B.C., Lowell, T.V., Smith, C.A., Feranec, R.S., Graham, B.L., 2018. Minimum age of the Mapleton, Tully, and Labrador Hollow moraines indicates correlation with the Port Huron Phase in central New York State. In: Kehew, A.E., Curry, B.B. (Eds.), *Quaternary Glaciation of the Great Lakes Region: Process, Landforms, Sediments and Chronology*. Geological Society of America, pp. 191–216.
- Kreutzer, S., Schmidt, C., Fuchs, M.C., Dietze, M., Fischer, M., Fuchs, M., 2012. Introducing an R package for luminescence dating analysis. *Ancient TL* 30, 1–8.
- Lewis, C.F.M., 1969. *Late Quaternary history of lake levels in the Huron and Erie basins*. Proceedings of the 12th Conference on Great Lakes Research, University of Michigan, Ann Arbor, MI, pp. 250–270.
- Lewis, C.F.M., Anderson, T.W., 2019. A younger glacial Lake Iroquois in the Lake Ontario basin, Ontario and New York: re-examination of pollen stratigraphy and radiocarbon dating. *Can. J. Earth Sci.* 57, 453–463.
- Lewis, H.C., 1884. *Report on the Terminal Moraine in Pennsylvania and Western New York*. Board of Commissioners for the Second Geological Survey, Pennsylvania.
- Leydet, D.J., Carlson, A.E., Teller, J.T., Breckenridge, A., Barth, A.M., Ullman, D.J., Sinclair, G., Milne, G.A., Cuzzone, J.K., Caffee, M.W., 2018. Opening of glacial Lake Agassiz's eastern outlets by the start of the Younger Dryas cold period. *Geology* 46, 155–158.
- Lowell, T.V., Savage, K.M., Scott Brockman, C., Stuckenrath, R., 1990. Radiocarbon analyses from Cincinnati, Ohio, and their implications for glacial stratigraphic interpretations. *Quat. Res.* 34, 1–11.
- Liritzis, I., Singhvi, A.K., Feathers, J.K., Wagner, G.A., Kadereit, A., Zacharias, N., Li, S.-H., 2013. *Dose Rate. Luminescence Dating in Archaeology, Anthropology, and Geoarchaeology: An Overview*. Springer, pp. 21–24.
- MacClintock, P., Apfel, E.T., 1944. Correlation of the drifts of the Salamanca re-entrant, New York. *Geol. Soc. Am. Bull.* 55, 1143–1164.
- Mörner, N.-A., Dreimanis, A., 1973. The Erie Interstade. In: Black, R.F., Goldthwait, R.P., Willman, H.B. (Eds.), *The Wisconsin Stage*. Geological Society of America, pp. 107–134.
- Muller, E.H., 1977. *Quaternary Geology of New York, Niagara Sheet, Map and Chart Series No. 28*, New York State Geological Survey.
- Muller, E.H., Braun, D.D., Young, R.A., Wilson, M.P., 1988. Morphogenesis of the Genesee Valley. *Northeast. Geol.* 10, 112–133.
- Muller, E.H., Calkin, P.E., 1988. Late Pleistocene and Holocene geology of the eastern Great Lakes region: geologic setting of the Hiscok paleontological site, western New York. *Bull. Buffalo Soc. Nat. Sci.* 33, 53–63.
- Muller, E.H., Calkin, P.E., 1993. Timing of Pleistocene glacial events in New York state. *Can. J. Earth Sci.* 30, 1829–1845.
- Muller, E.H., Prest, V.K., 1985. Glacial lakes in the Ontario basin. In: Karrow, P.F., Calkin, P.E. (Eds.), *Quaternary Evolution of the Great Lakes*. Geological Society of Canada, St. John's, pp. 213–229.
- Murray, A.S., Wintle, A.G., 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. *Radiat. Meas.* 37, 377–381.
- Nelson, M., Rittenour, T., Cornachione, H., 2019. Sampling methods for luminescence dating of subsurface deposits from cores. *Methods Protoc.* 2, 88.
- Ou, X., Duller, G.A.T., Roberts, H.M., Zhou, S., Lai, Z., Chen, R., Chen, R., Zeng, L., 2015. Single grain optically stimulated luminescence dating of glacial sediments from the Baiyu Valley, southeastern Tibet. *Quat. Geochronol.* 30, 314–319.
- Paardekooper, S.M., Sprangers, M., Autin, W.J., van der Perk, M., 2008. *Geomorphology of the Caledonia Channels, New York (M.Sc. thesis)*. Utrecht University, Netherlands.
- Porreca, C., Briner, J.P., Kozłowski, A., 2018. Laurentide ice sheet meltwater routing along the Iro-Mohawk River, eastern New York, USA. *Geomorphology* 303, 155–161.
- Prince, K.K., Briner, J.P., Walcott, C.K., Chase, B.M., Kozłowski, A.L., Rittenour, T.M., Yang, E.P., 2024. New age constraints reveal moraine stabilization thousands of years after deposition during the last deglaciation of western New York, USA. *Geochronology* 6, 409–427.
- Rayburn, J.A., Franz, D.A., Knuepfer, P.L.K., 2007. Evidence from the Lake Champlain Valley for a later onset of the Champlain Sea and implications for late glacial meltwater routing to the North Atlantic. *Palaeogeogr. Palaeoclim. Palaeoecol.* 246, 62–74.
- Rhodes, E.J., 2000. Observations of thermal transfer OSL signals in glacial quartz. *Radiat. Meas.* 32, 595–602.
- Rhodes, E.J., Pownall, L., 1994. Zeroing of the OSL signal in quartz from young glaciofluvial sediments. *Radiat. Meas.* 23, 581–585.
- Ridge, J.C., 1997. Shed Brook discontinuity and Little Falls gravel: evidence for the Erie interstade in central New York. *Geol. Soc. Am. Bull.* 109, 652–665.
- Ridge, J.C., 2003. The last deglaciation of the northeastern United States: a combined varve, paleomagnetic, and calibrated 14C chronology. In: Hart, J.P., Creameans, D.L. (Eds.), *Geochronology of Landscapes in the Glaciated Northeast*. New York State Museum Bulletin, pp. 15–45.
- Ridge, J.C., 2004. The Quaternary glaciation of western New England with correlations to surrounding areas. In: Ehlers, J., Gibbard, P.L. (Eds.), *Developments in Quaternary Sciences*. Elsevier, pp. 169–199.
- Ridge, J.C., Balco, G., Bayless, R.L., Beck, C.C., Carter, L.B., Dean, J.L., Voytek, E.B., Wei, J.H., 2012. The new North American Varve Chronology: a precise record of southeastern Laurentide Ice Sheet deglaciation and climate, 18.2–12.5 kyr BP, and correlations with Greenland ice core records. *Am. J. Sci.* 312, 685–722.
- Rittenour, T.M., Cotter, J.F.P., Arends, H.E., 2015. Application of single-grain OSL dating to ice-proximal deposits, glacial Lake Benson, west-central Minnesota, USA. *Quat. Geochronol.* 30, 306–313.
- Stanford, S.D., Stone, B.D., Ridge, J.C., Witte, R.W., Pardi, R.R., Reimer, G.E., 2021. Chronology of Laurentide glaciation in New Jersey and the New York City area, United States. *Quat. Res.* 99, 142–167.
- Szabo, J.P., Bradley, K., Tevesz, M.J.S., 2003. Foundations from the past: clues to understanding Late Quaternary stratigraphy beneath Cleveland, Ohio. *J. Great Lakes Res.* 29, 566–580.
- Thrasher, I.M., Mauz, B., Chiverrell, R.C., Lang, A., 2009. Luminescence dating of glaciofluvial deposits: a review. *Earth Sci. Rev.* 97, 133–146.
- Totten, S.M., 1985. Chronology and nature of the Pleistocene beaches and wave-cut cliffs and terraces, northeastern Ohio. In: Karrow, P.F., Calkin, P.E. (Eds.), *Quaternary Evolution of the Great Lakes*. Geological Society of Canada, St. John's, pp. 170–184.
- Ullman, D.J., Carlson, A.E., LeGrande, A.N., Anslow, F.S., Moore, A.K., Caffee, M., Syverson, K.M., Licciardi, J.M., 2015. Southern Laurentide ice-sheet retreat synchronous with rising boreal summer insolation. *Geology* 43, 23–26.
- Young, R.A., Gordon, L.M., Owen, L.A., Huot, S., Zerfas, T.D., 2020. Evidence for a late glacial advance near the beginning of the Younger Dryas in western New York State: an event postdating the record for local Laurentide ice sheet recession. *Geosphere* 17, 271–305.
- Yu, S.-Y., Colman, S.M., Lowell, T.V., Milne, G.A., Fisher, T.G., Breckenridge, A., Boyd, M., Teller, J.T., 2010. Freshwater outburst from Lake Superior as a trigger for the cold event 9300 years ago. *Science* 328, 1262–1266.

Electronic Supplemental Material figures S1 – S28

***Reconnaissance luminescence dating of Laurentide Ice Sheet deposits in western New York,
USA***

Caleb K. Walcott-George, Jason P. Briner, Nathan D. Brown

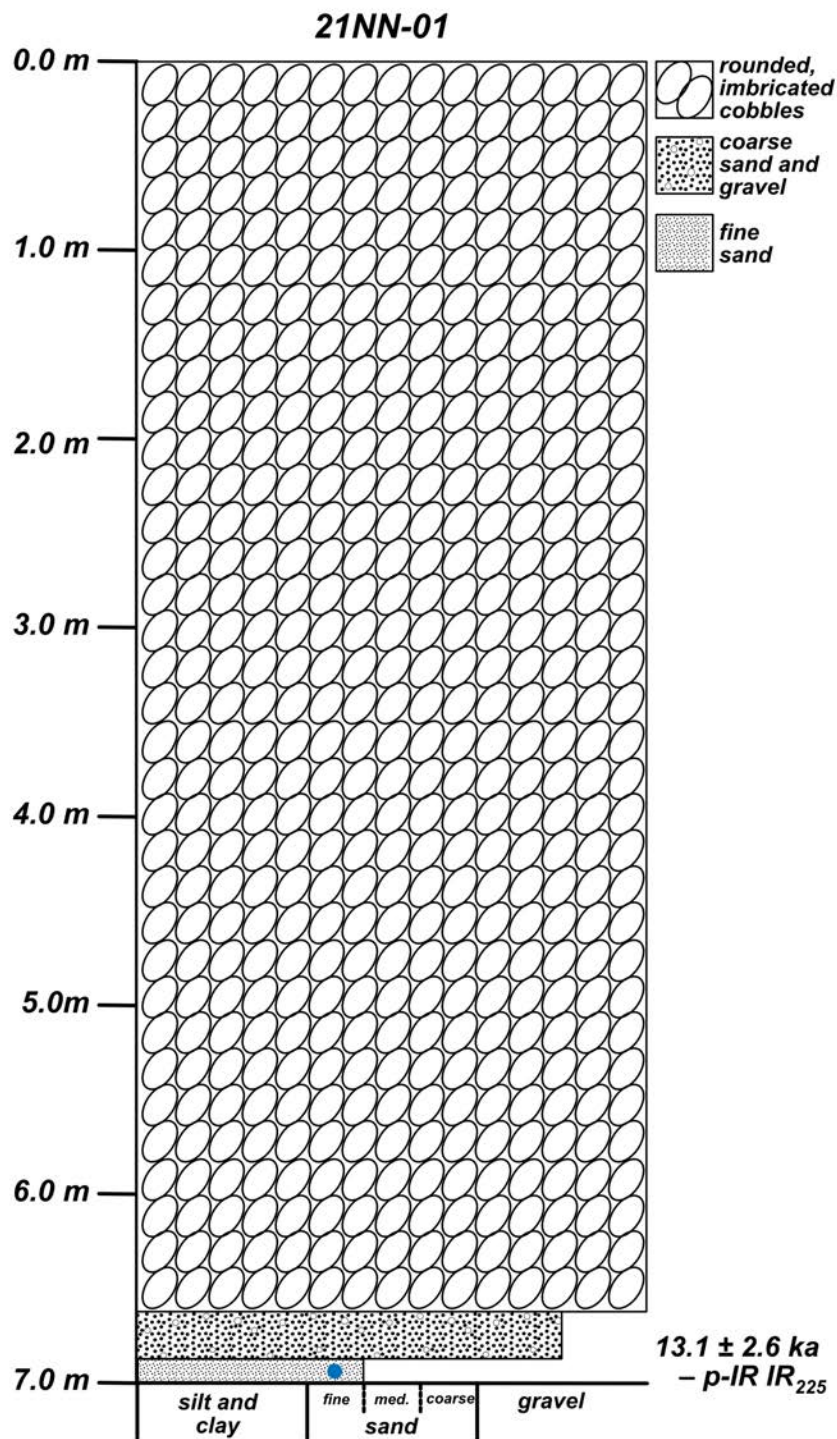


Figure S1: stratigraphic column from Kent Moraine outwash (21NN-01) at Nannen-Northrup Quarry

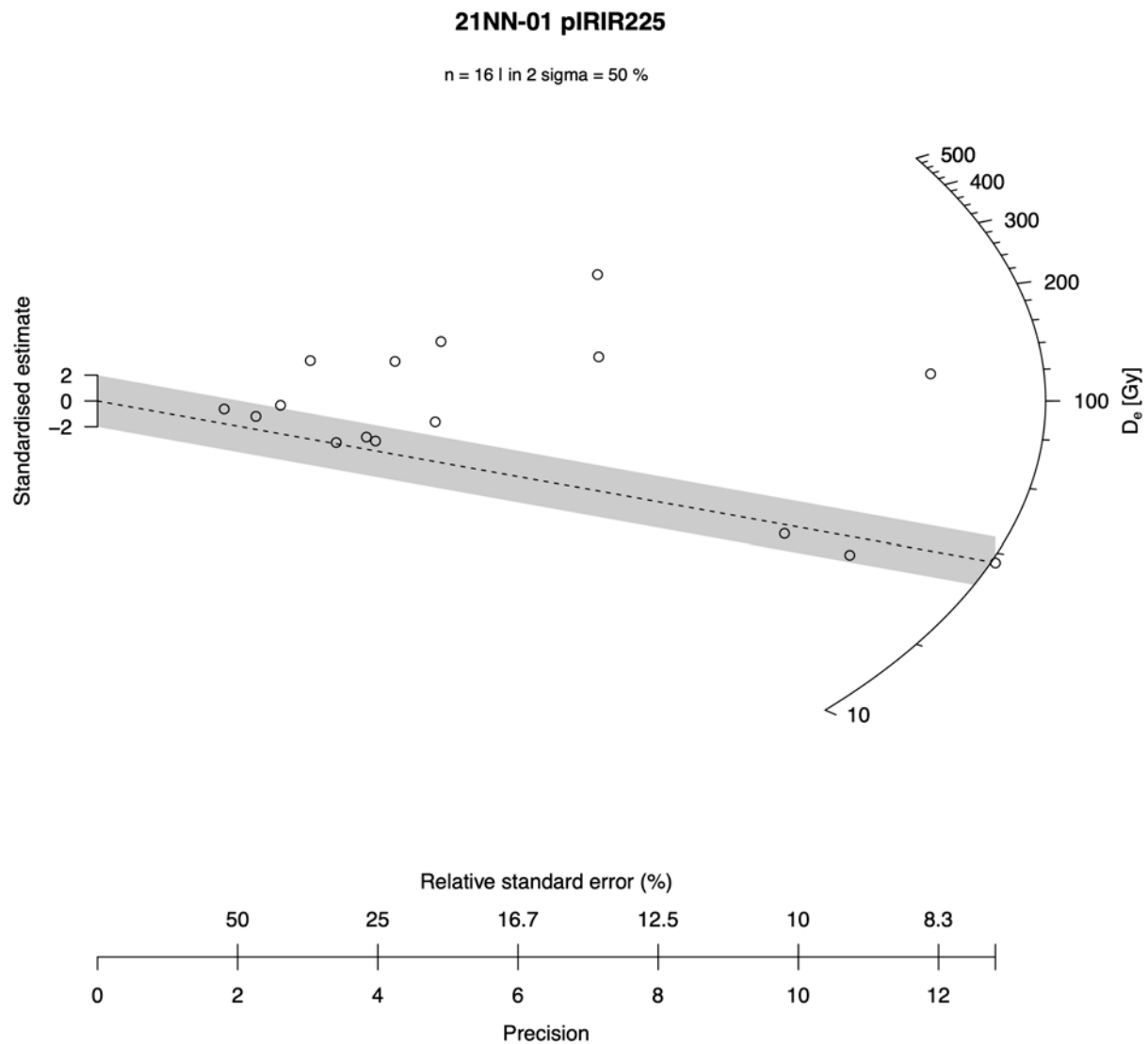


Figure S2: Radial plot from 21NN-01 – pIR IRSL₂₂₅

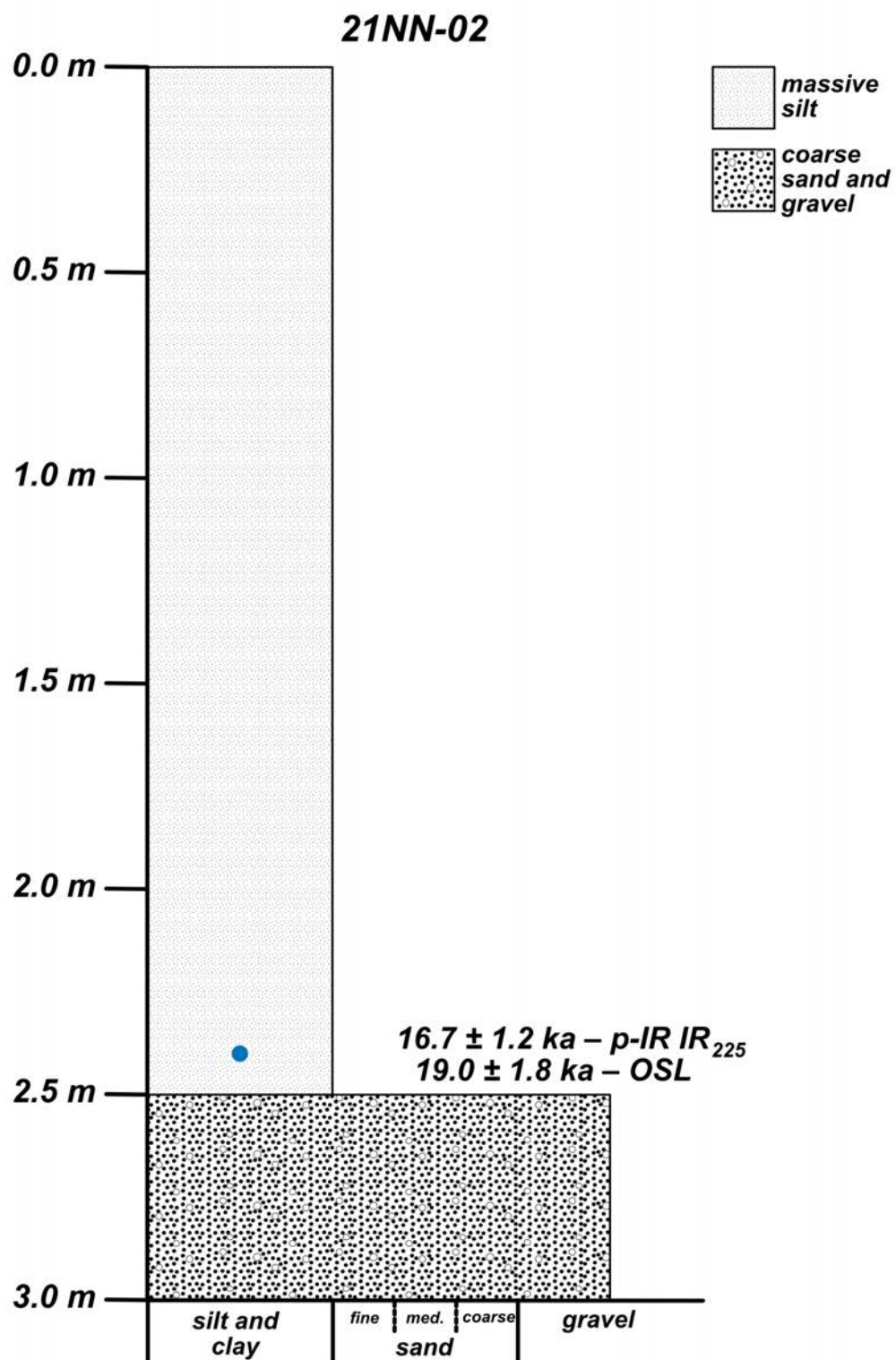


Figure S3: stratigraphic column from Kent Moraine outwash and capping loess (21NN-02) at Nannen-Northrup Quarry

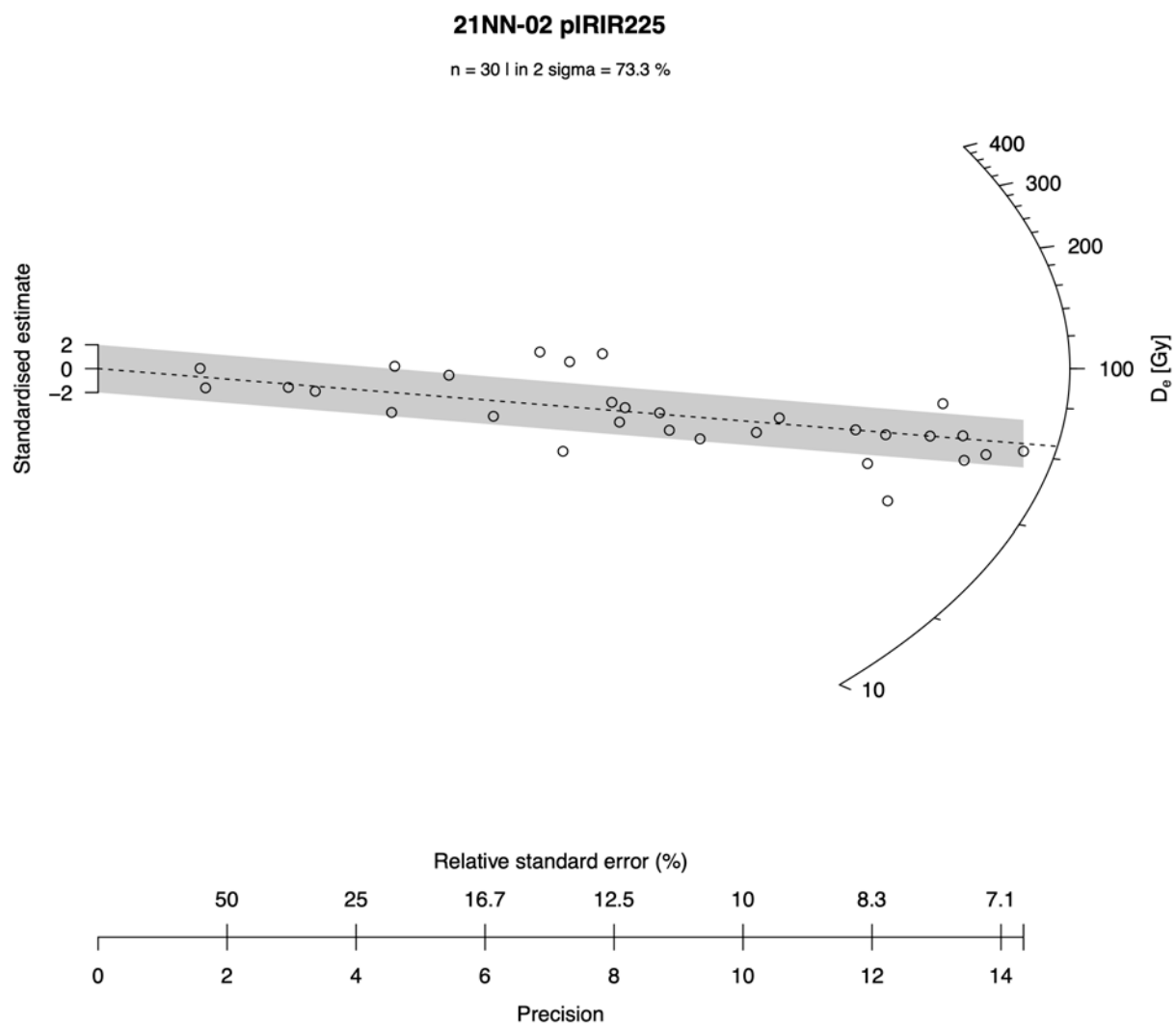


Figure S4: Radial plot from 21NN-02 – pIR IRSL₂₂₅

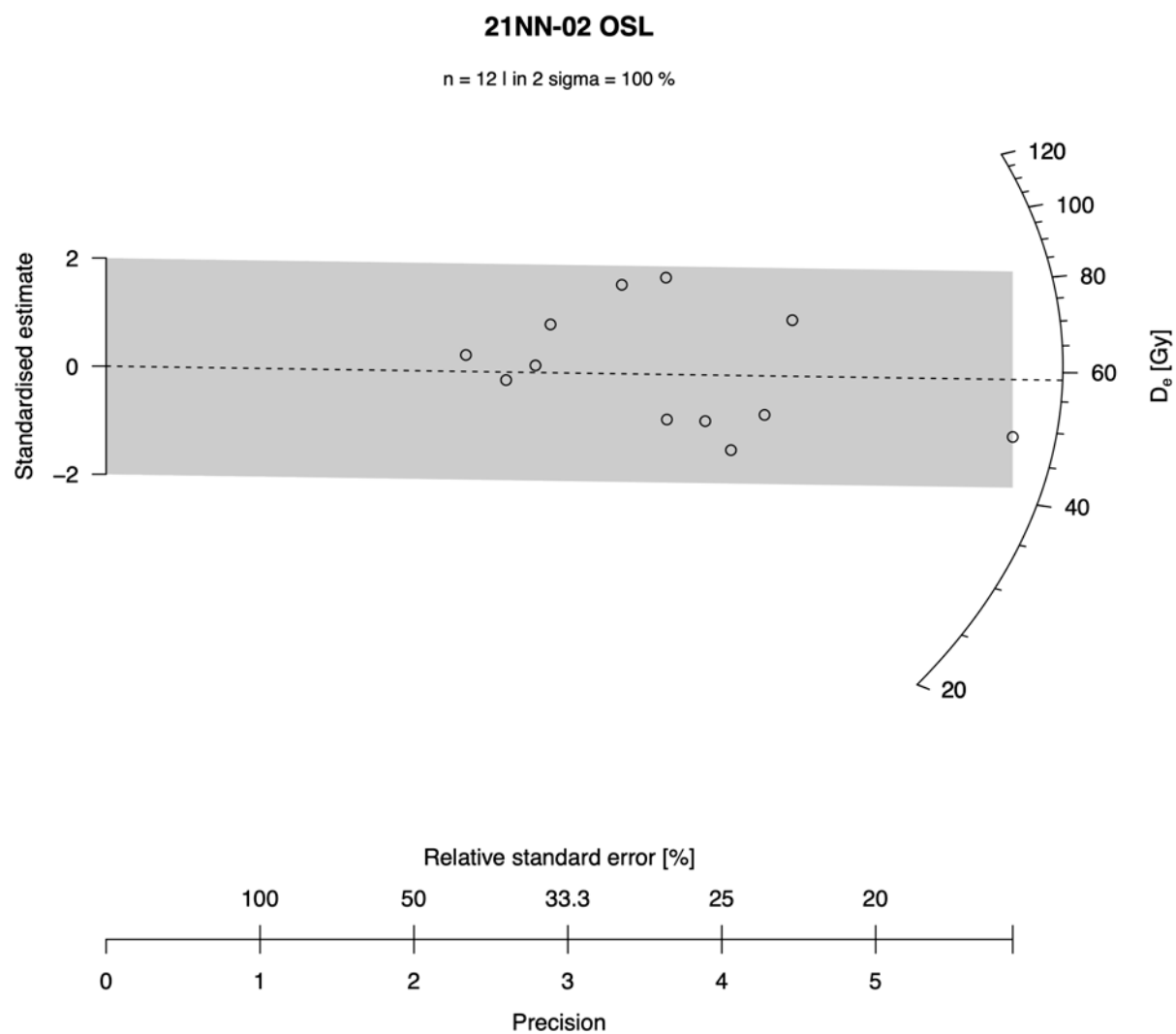


Figure S5: Radial plot from 21NN-02 – OSL

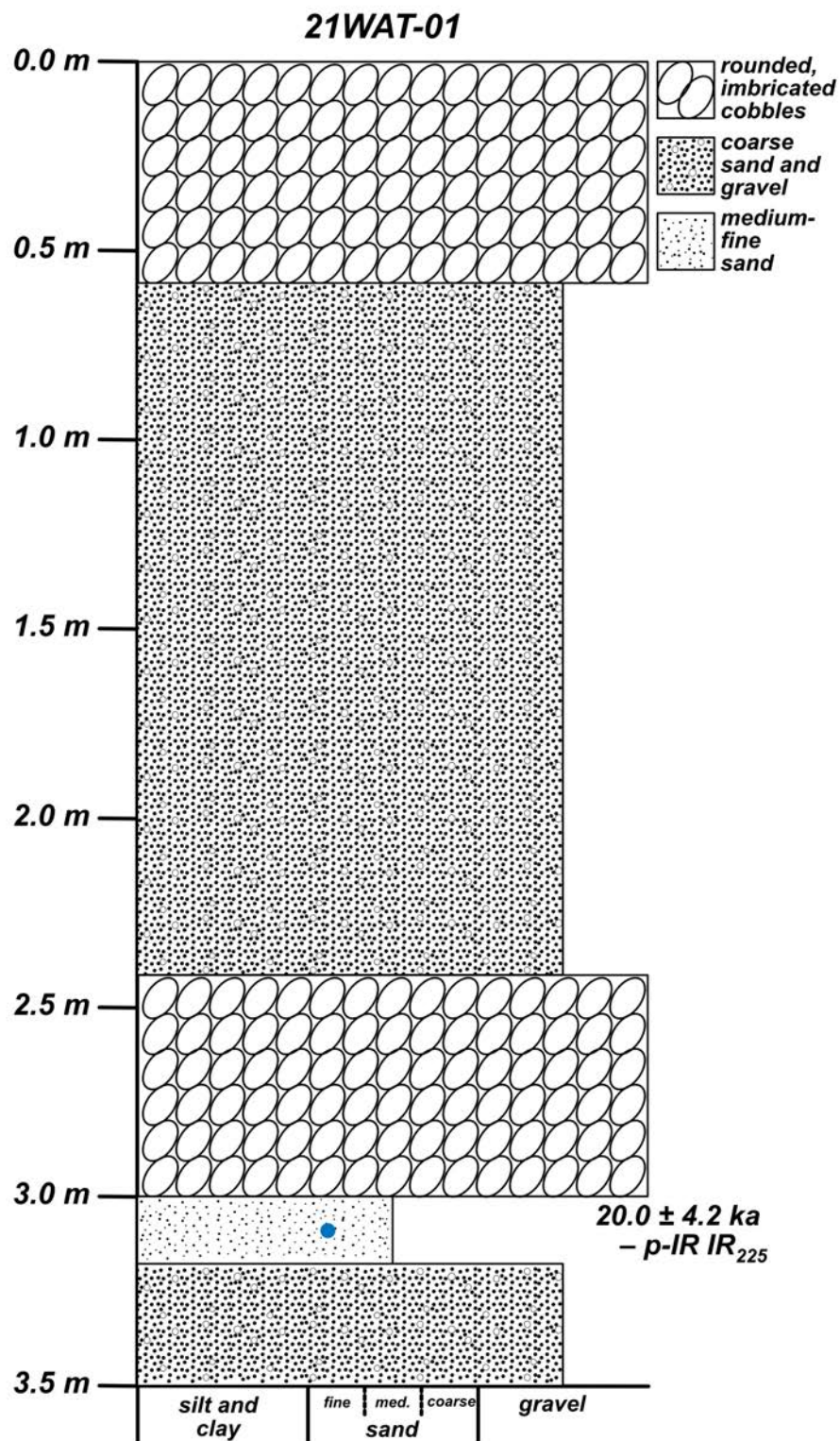


Figure S6: stratigraphic column from Lake Escarpment Moraine outwash (21WAT-01) at Waterman's Gravel Pit

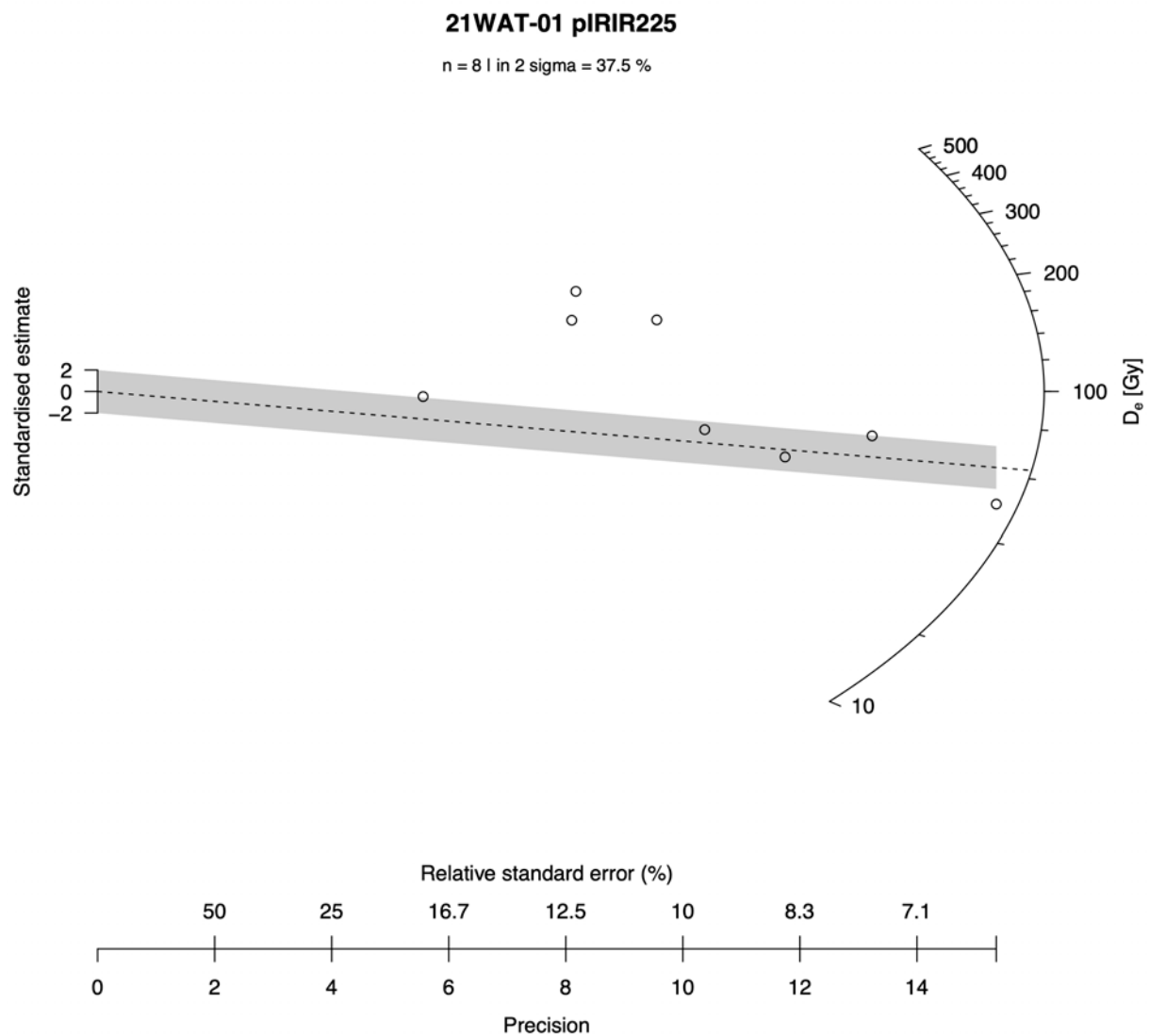


Figure S7: Radial plot from 21WAT-01 – pIR IRSL₂₂₅

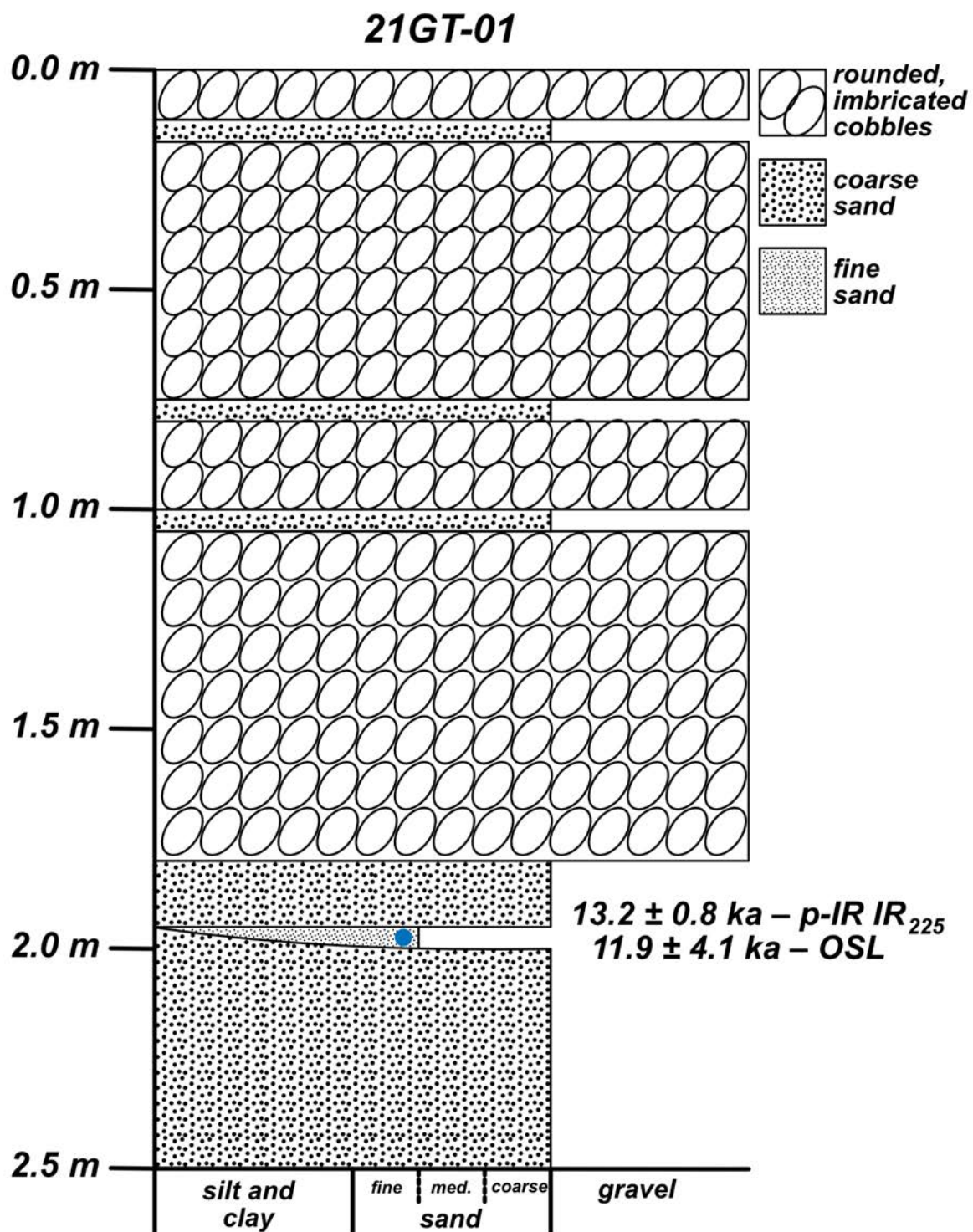


Figure S8: stratigraphic column from Lake Escarpment Moraine outwash (21GT-01) at Gable Thomas Mine

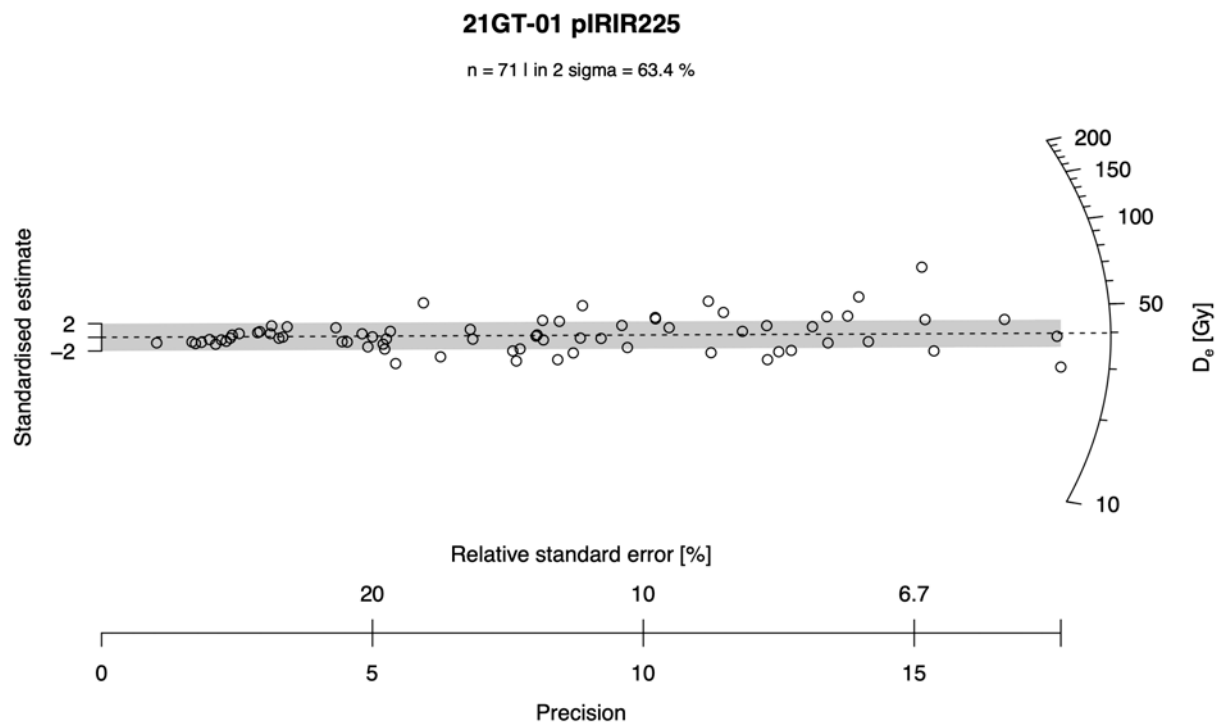


Figure S9: Radial plot from 21GT-01 – pIR IRSL₂₂₅

21GT-01 OSL

n = 3 | in 2 sigma = 100 %

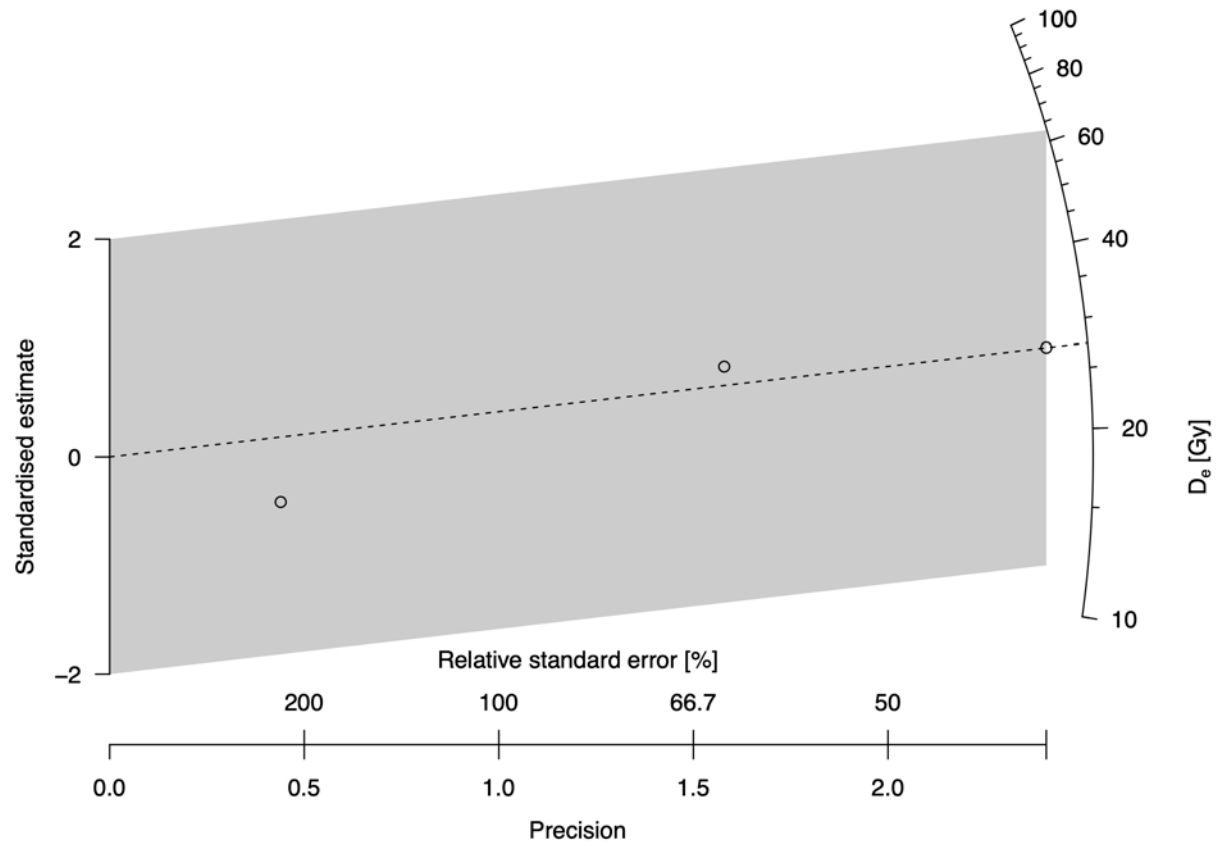


Figure S10: Radial plot from 21GT-01 – OSL

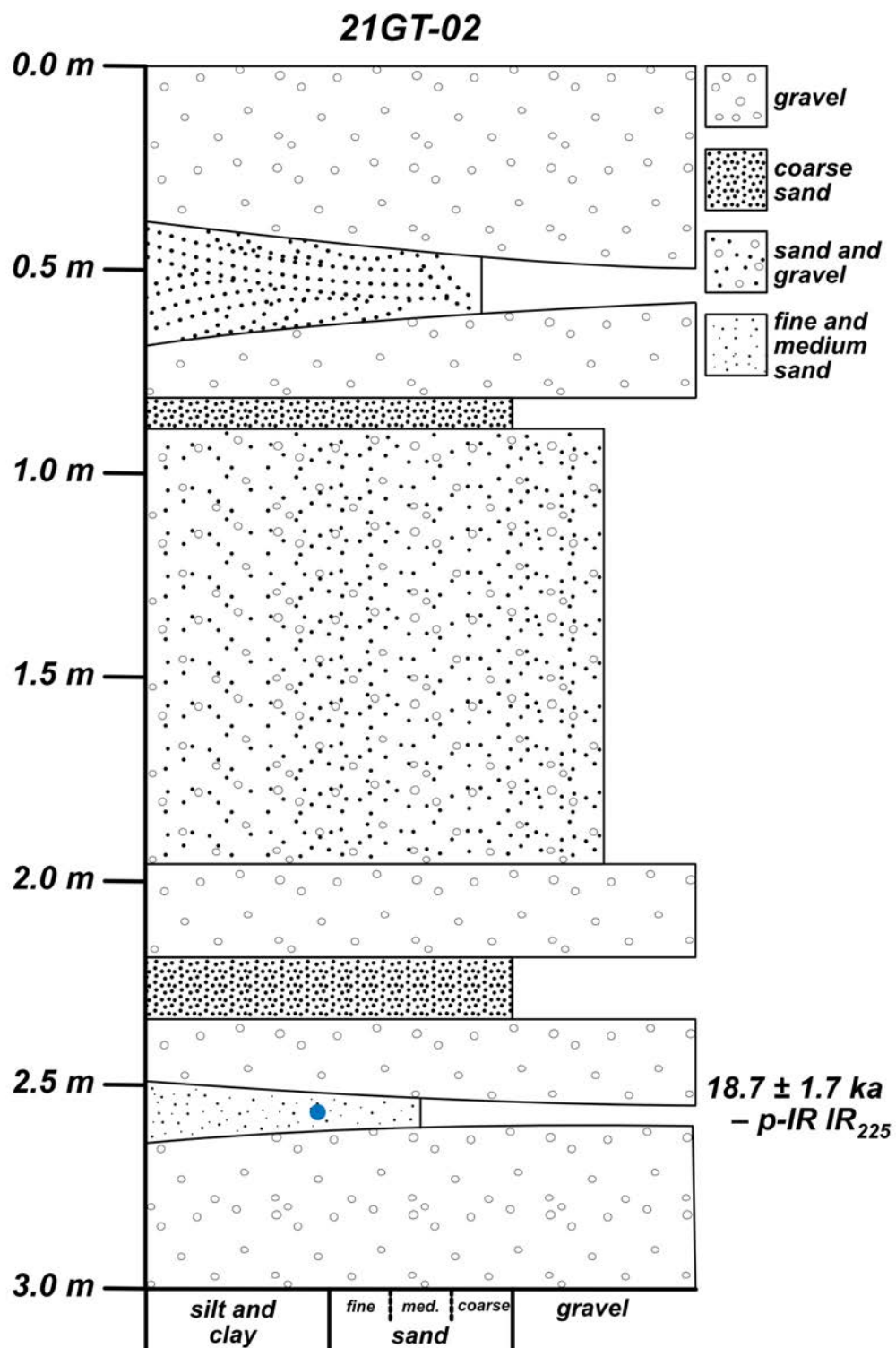


Figure S11: stratigraphic column from Lake Escarpment Moraine outwash (21GT-02) at Gable Thomas Mine

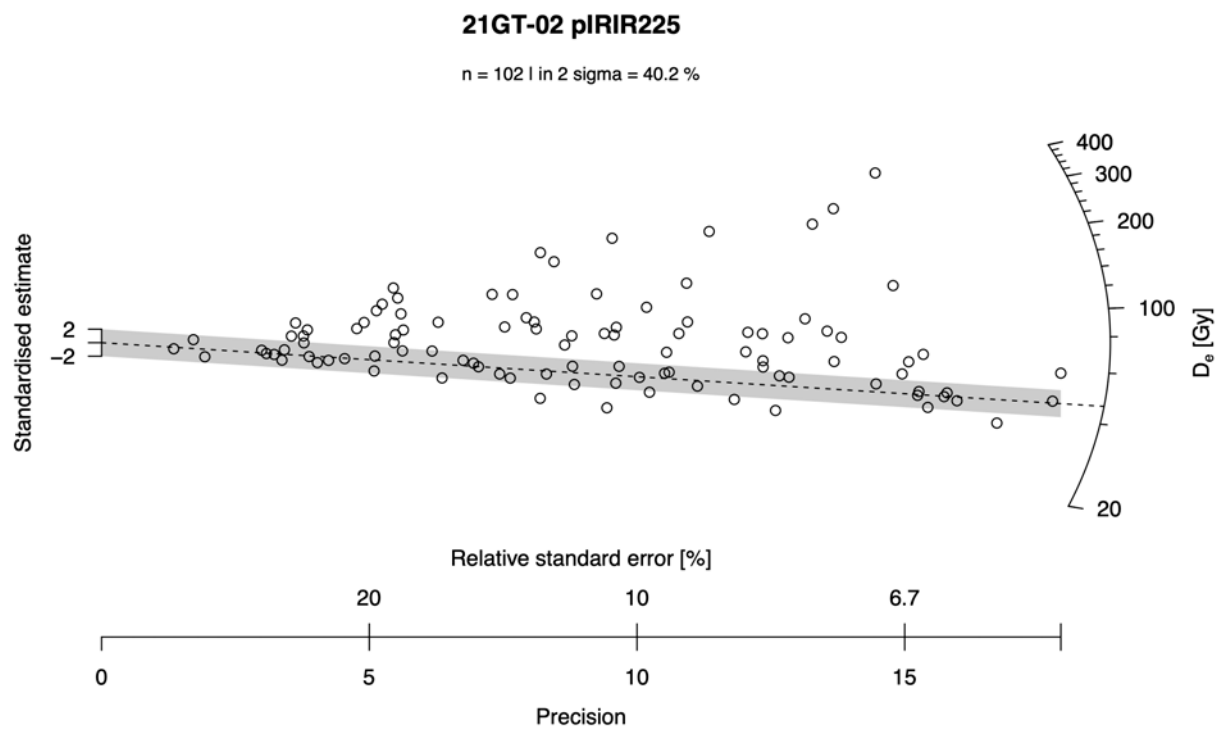


Figure S12: Radial plot from 21GT-02 – pIR IRSL₂₂₅

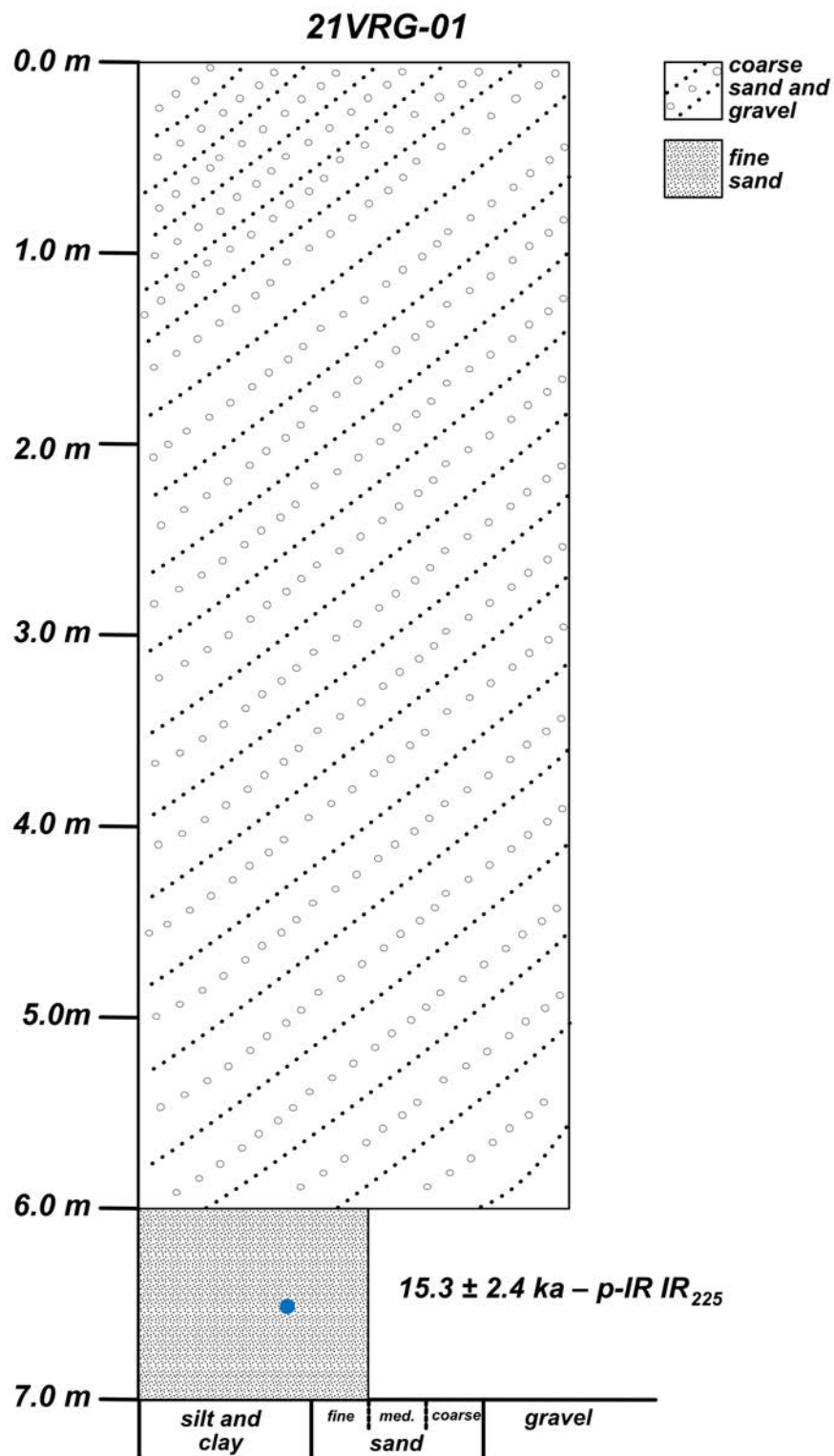


Figure S13: stratigraphic column from Cattaraugus Creek ice-dammed lake delta at Vail Road Gravel (21VRG-01) formed following retreat from the Lake Escarpment Moraine.

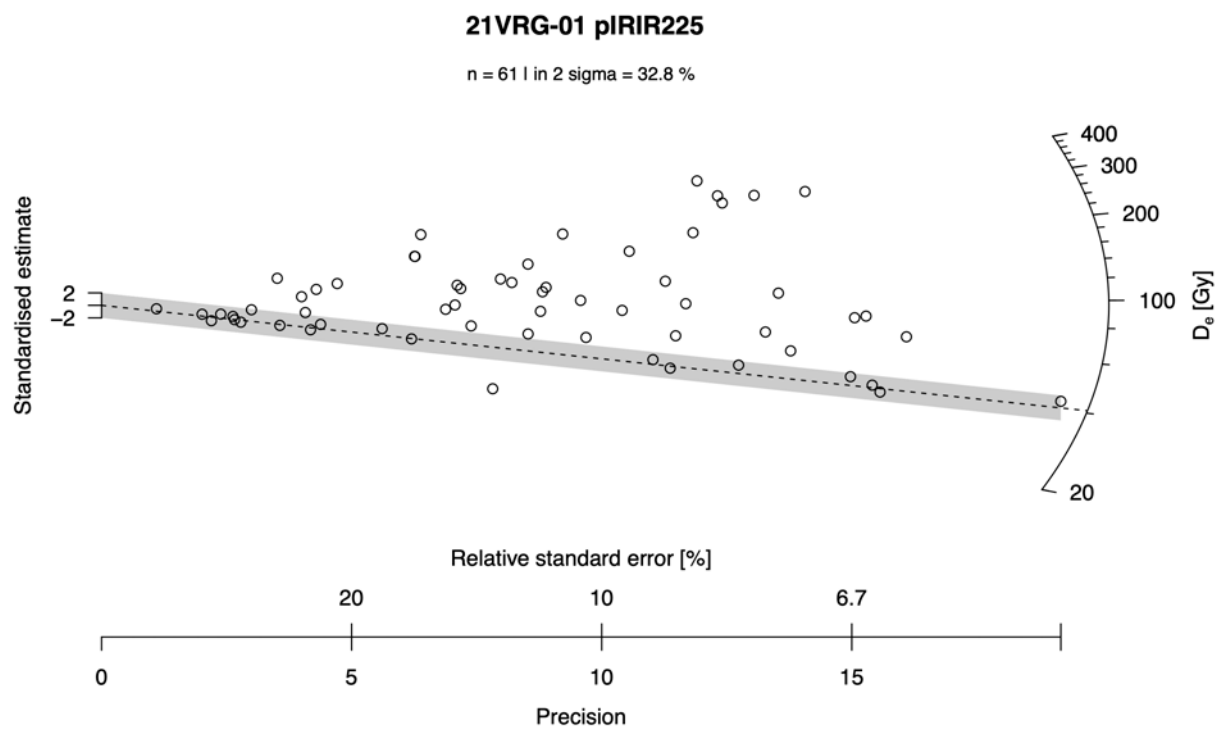


Figure S14: Radial plot from 21VRG-01 – pIR IRSL₂₂₅

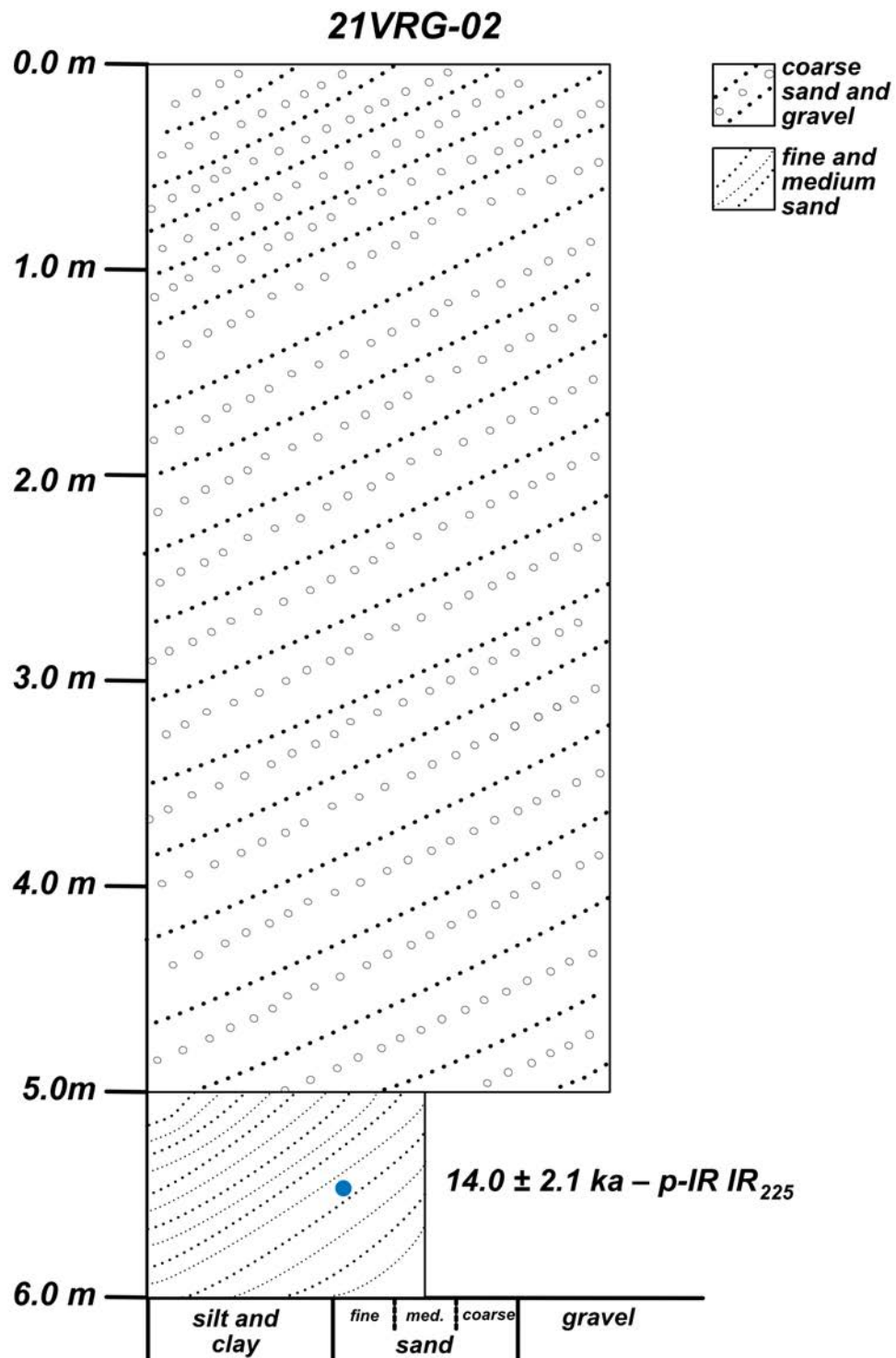


Figure S15: stratigraphic column from Cattaraugus Creek ice-dammed lake delta at Vail Road Gravel (21VRG-02) formed following retreat from the Lake Escarpment Moraine.

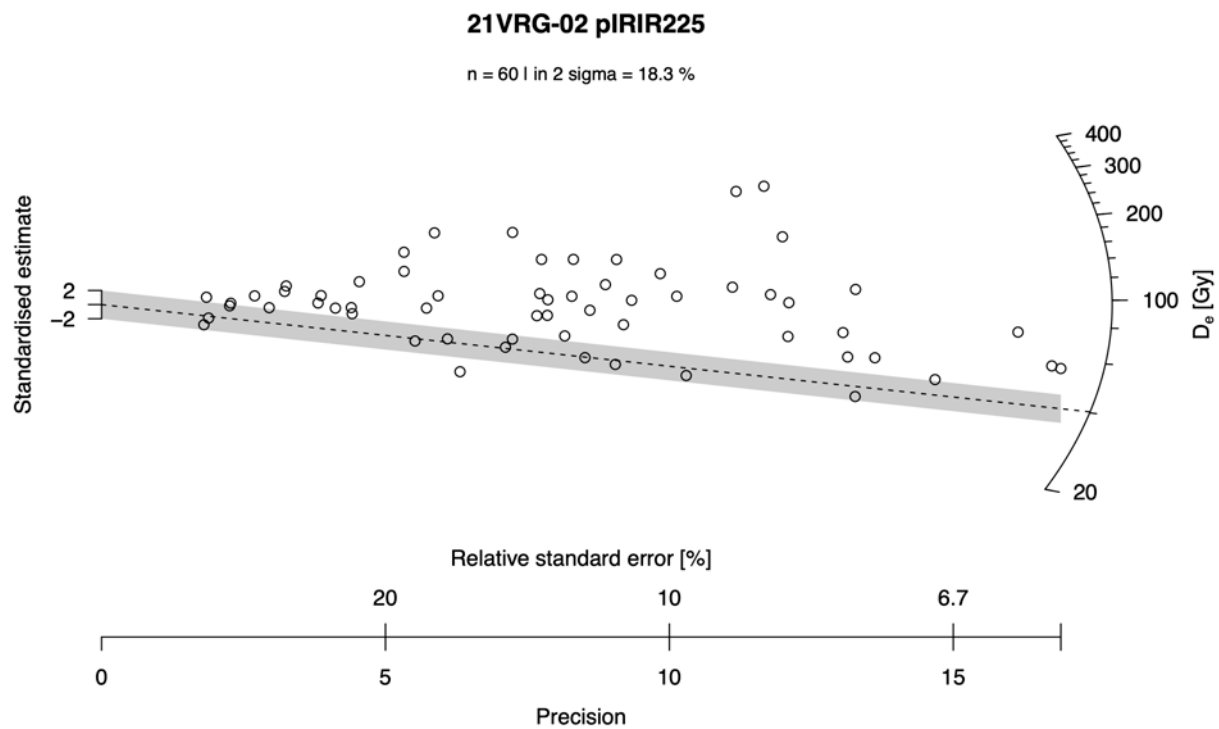


Figure S16: Radial plot from 21VRG-02 – pIR IRSL₂₂₅

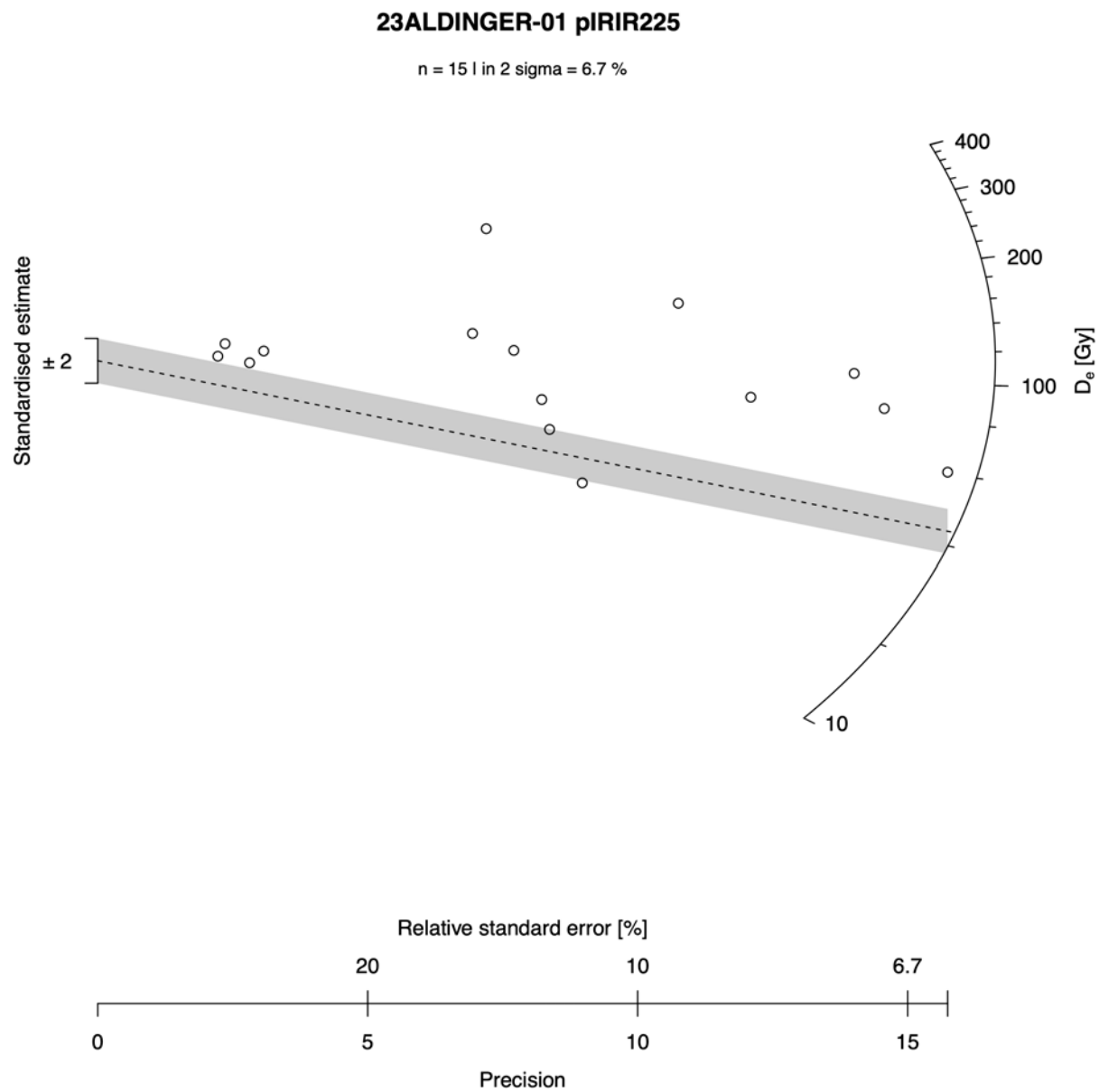


Figure S18: Radial plot from 23ALDINGER-01 – pIR IRSL₂₂₅

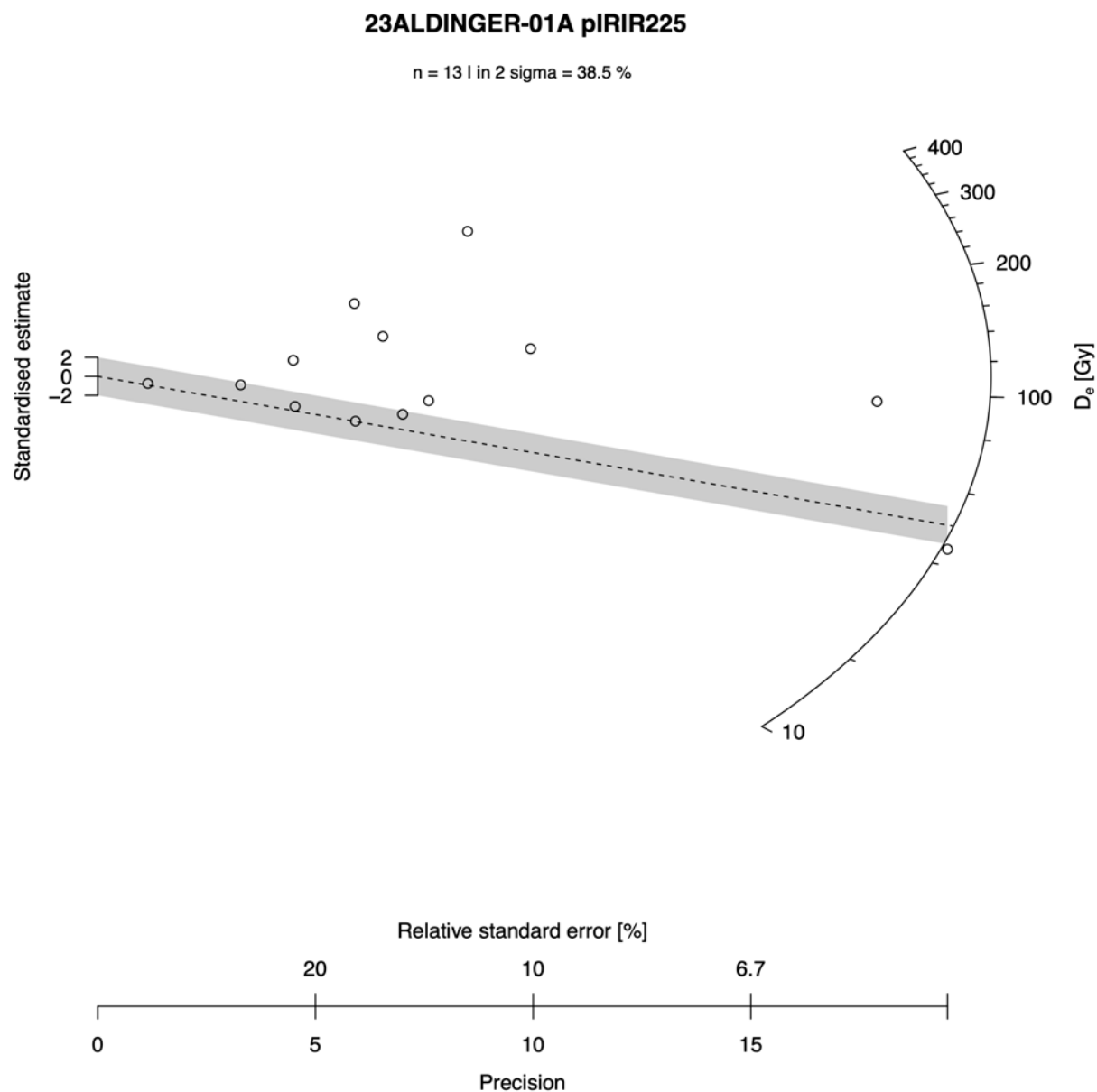


Figure S19: Radial plot from 23ALDINGER-01A – pIR IRSL₂₂₅

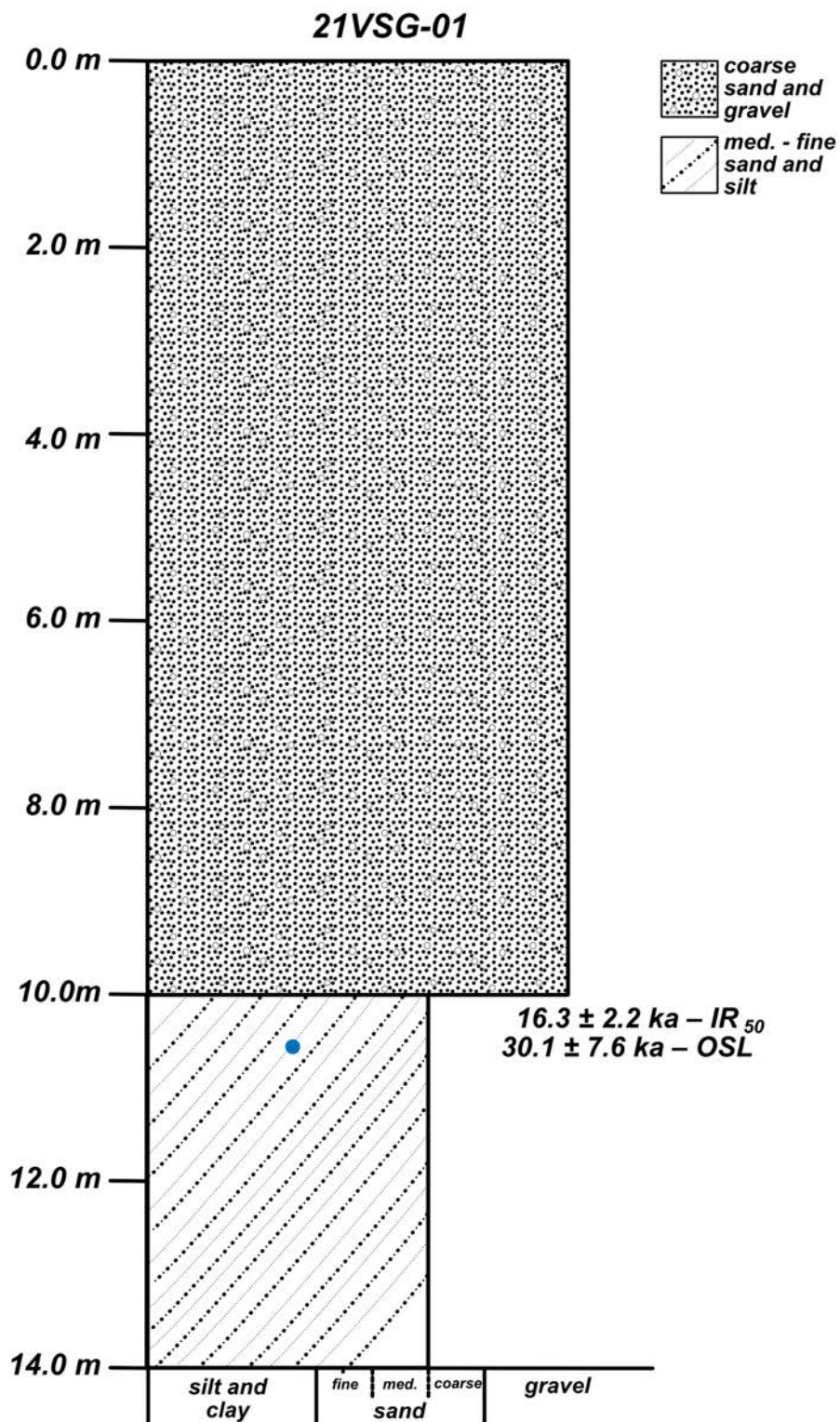


Figure S20: stratigraphic column from the White Creek Channel delta in the Genesee Valley formed in Lake Avon at Valley Sand and Gravel (21VSG-01).

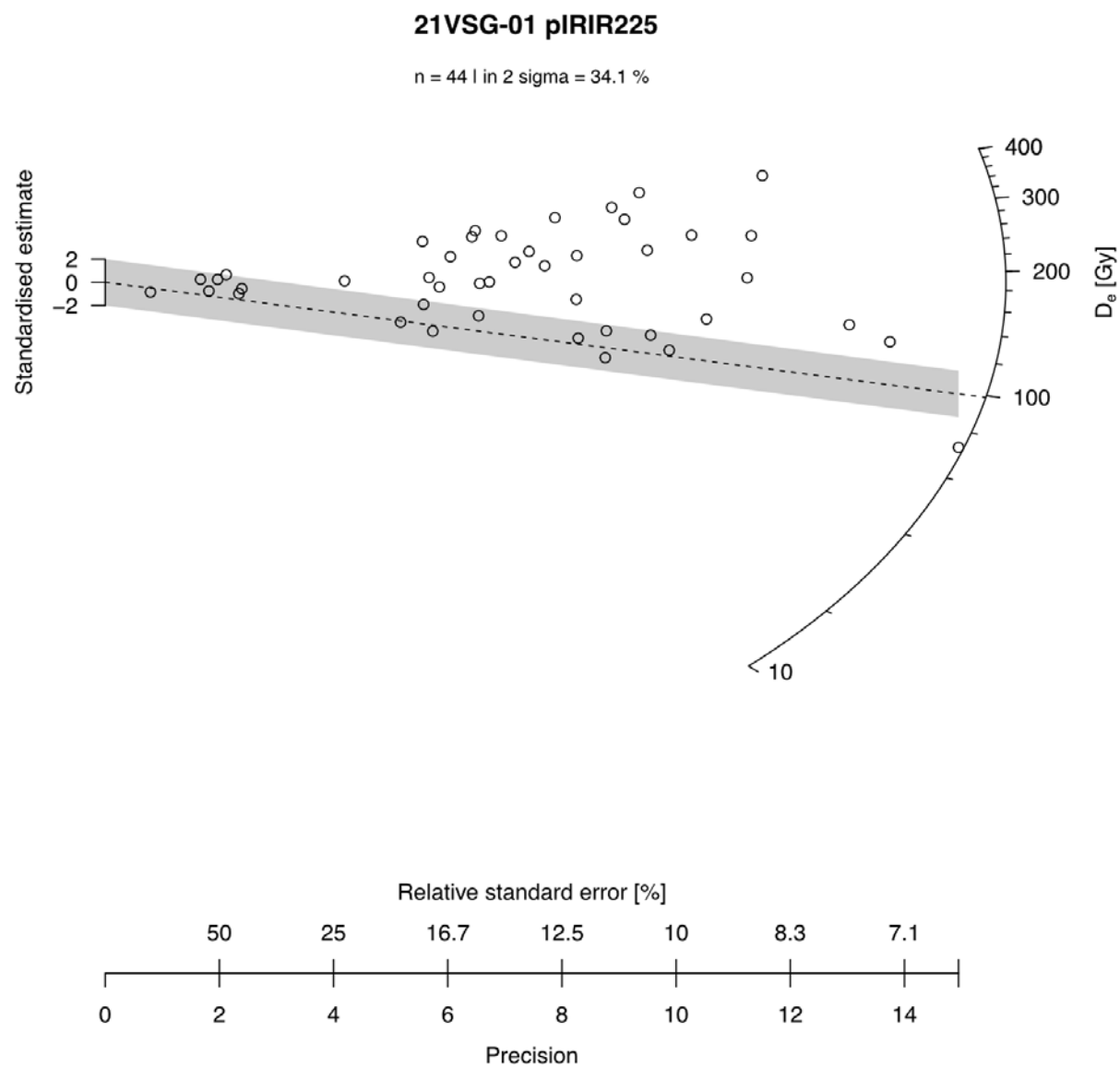


Figure S21: Radial plot from 21VSG-01 – pIR IRSL₂₂₅

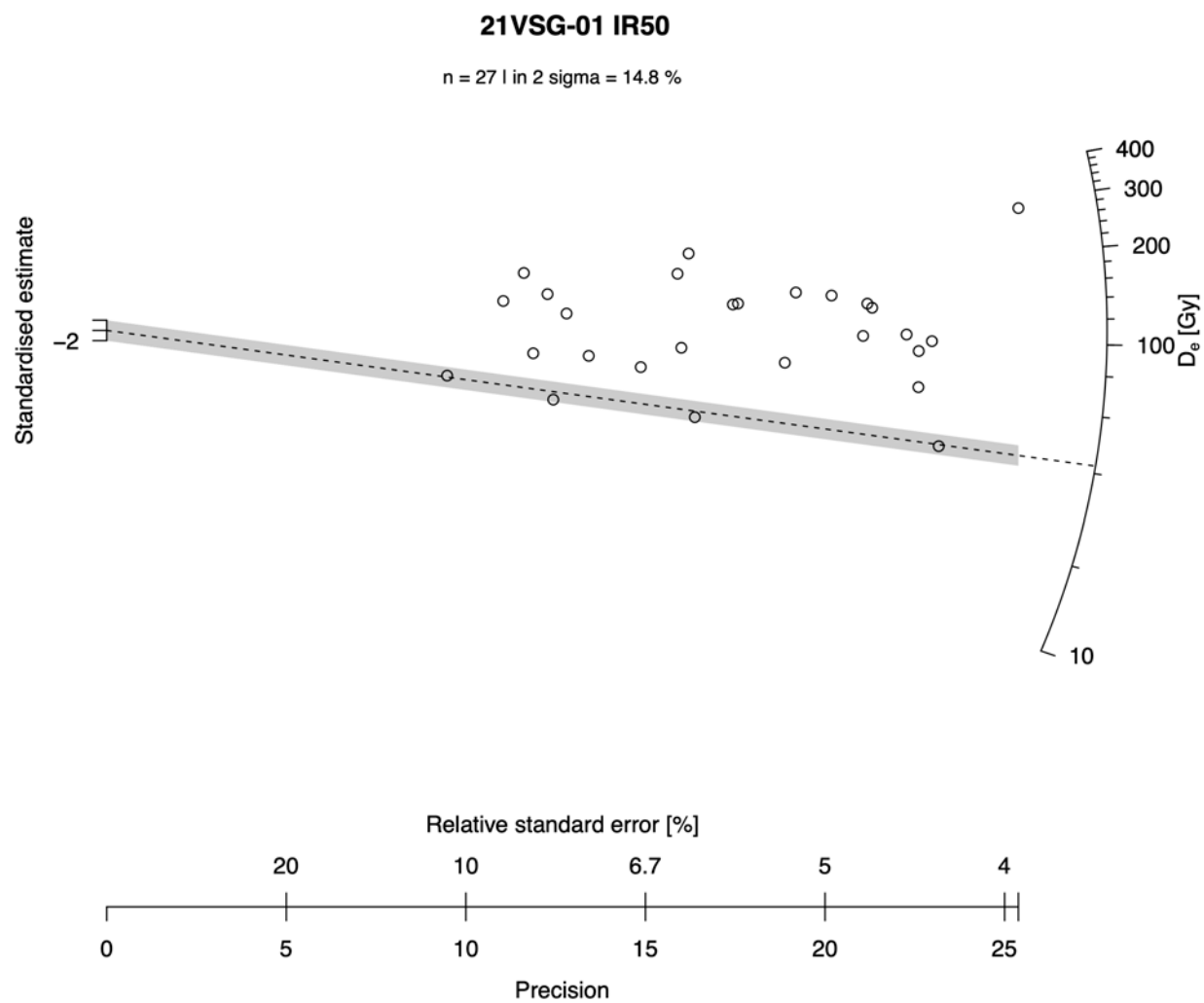


Figure S22: Radial plot from 21VSG-01 – IR₅₀

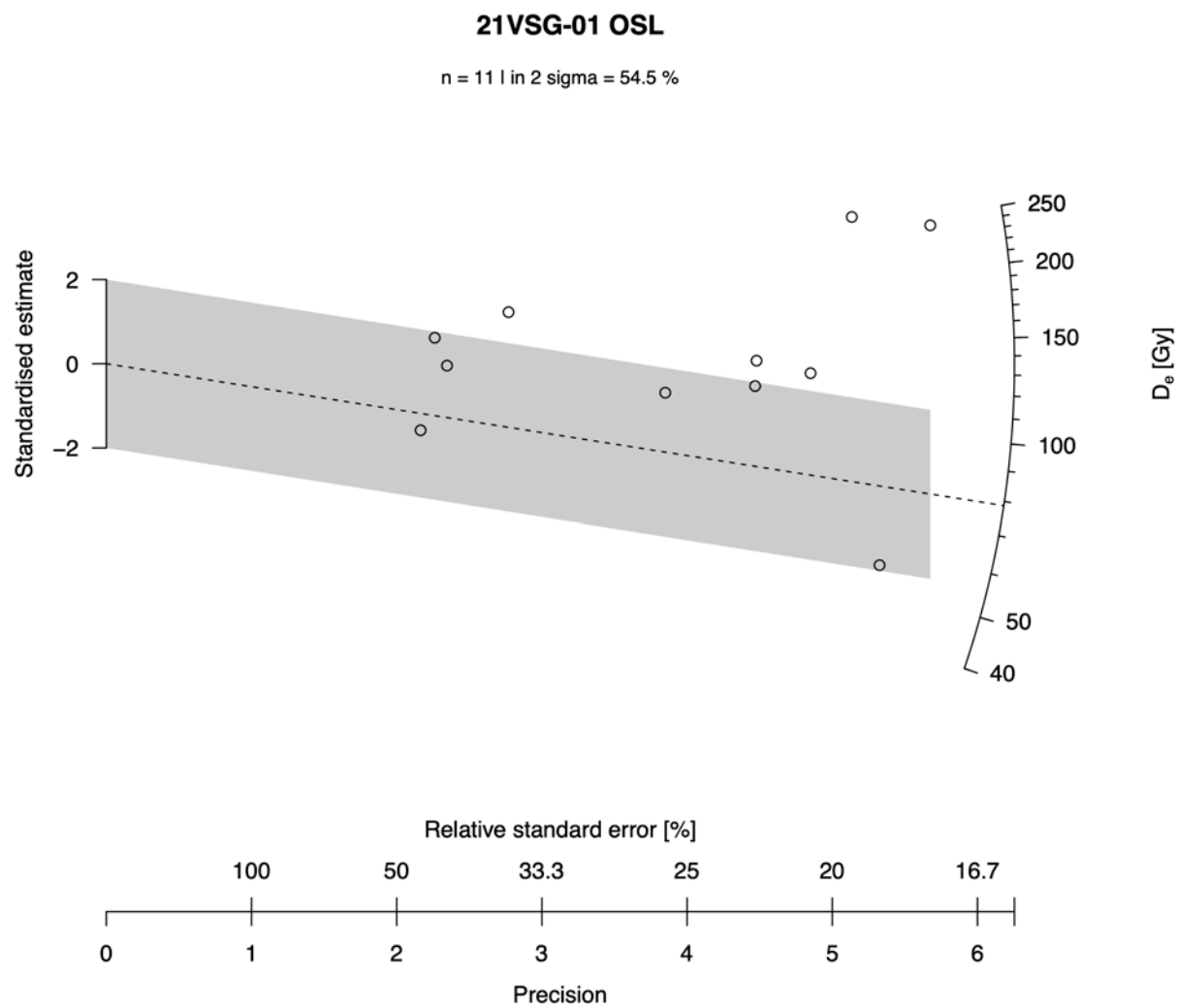


Figure S23: Radial plot from 21VSG-01 – OSL

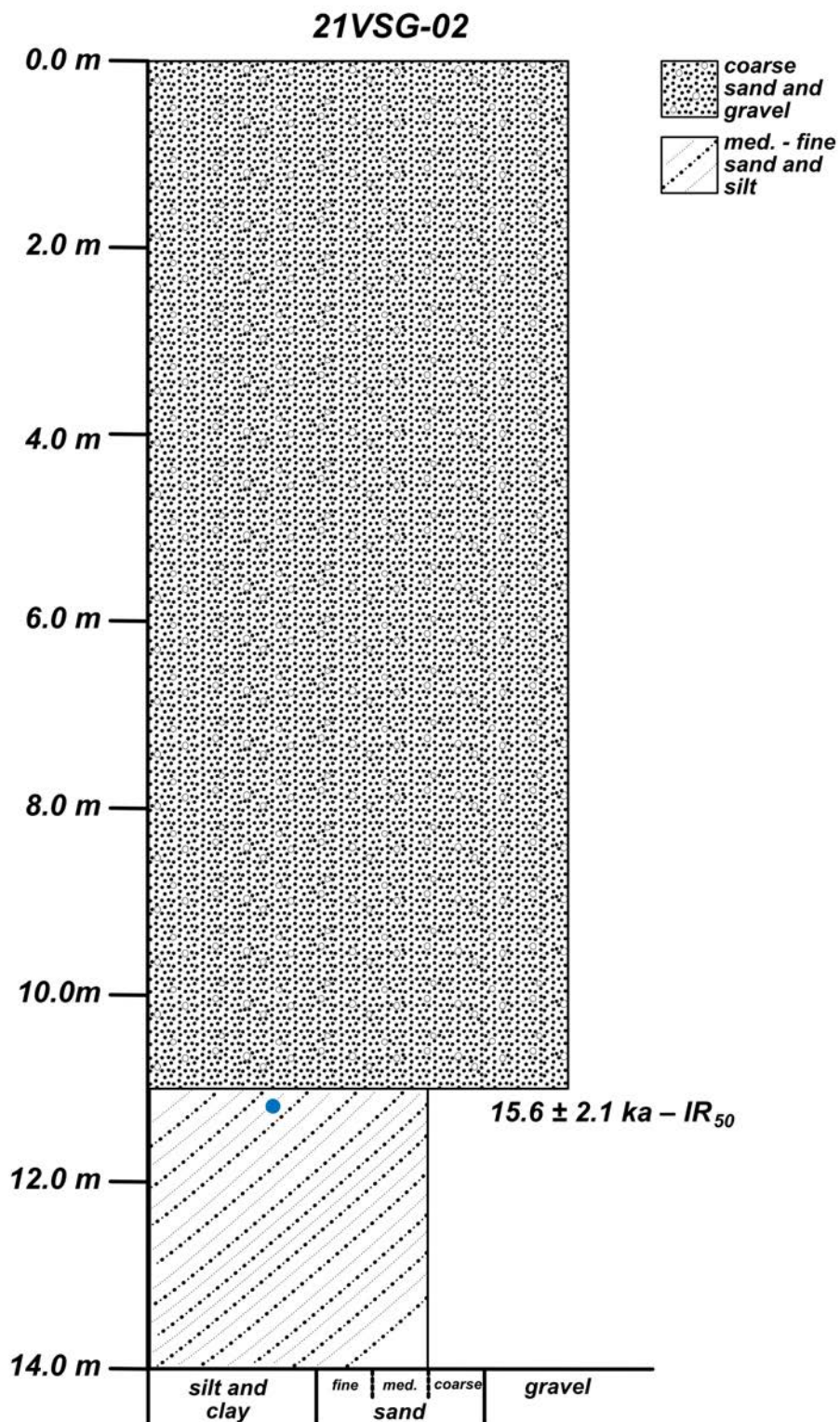


Figure S24: stratigraphic column from the White Creek Channel delta in the Genesee Valley formed in Lake Avon at Valley Sand and Gravel (21VSG-02).

21VSG-02 pIRIR225

n = 106 | in 2 sigma = 7.5 %

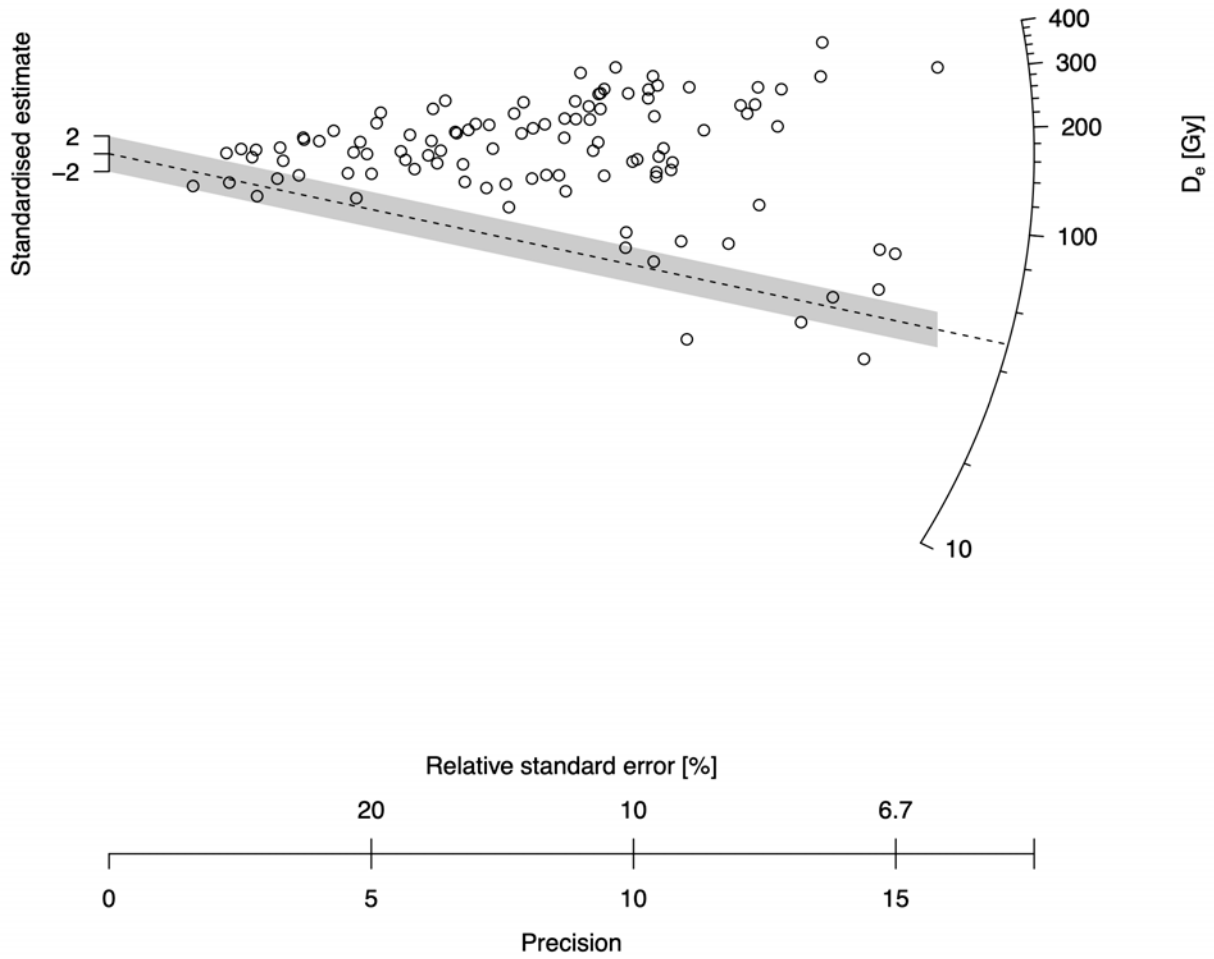


Figure S25: Radial plot from 21VSG-02 – pIR IRSL₂₂₅

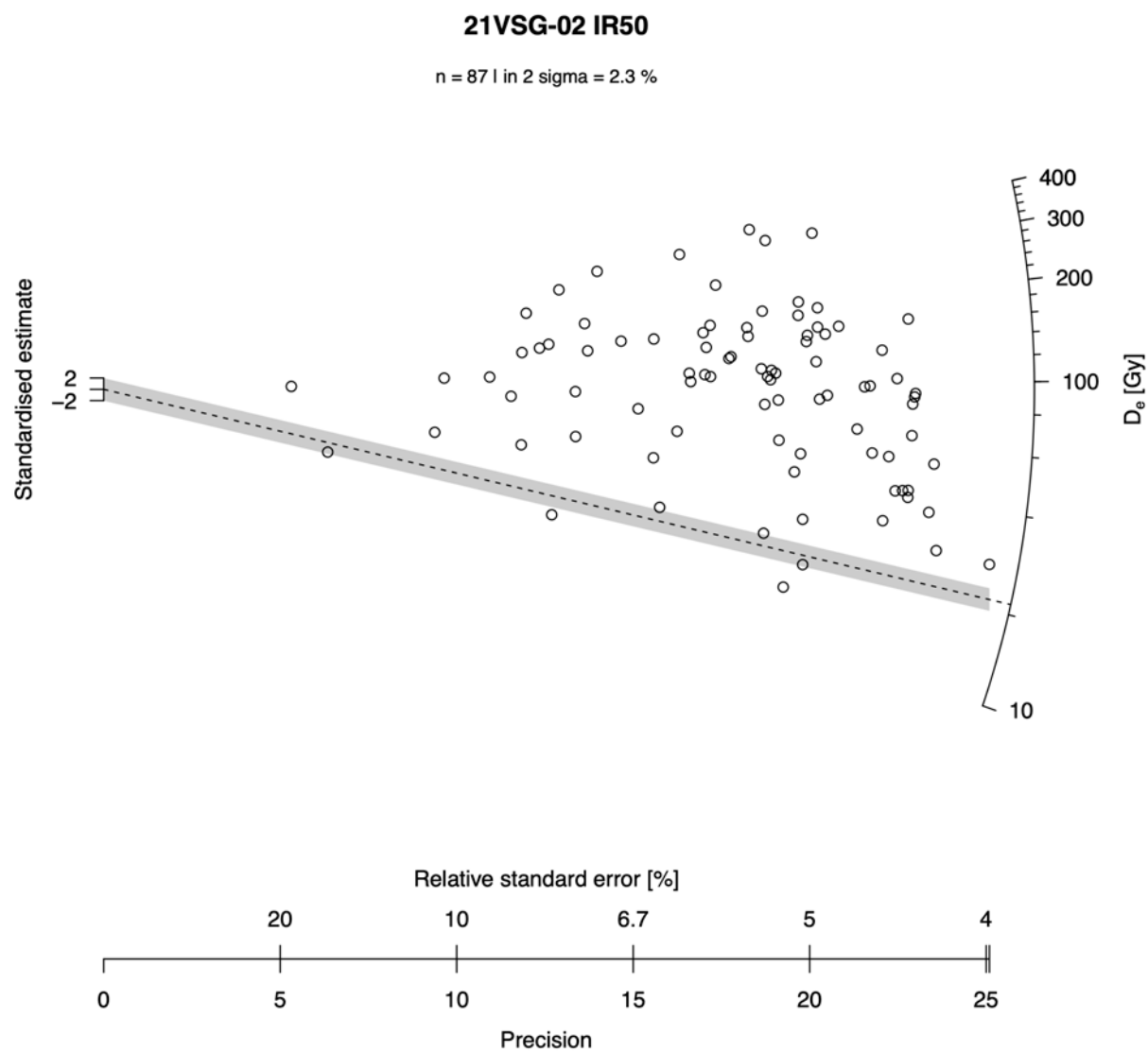


Figure S26: Radial plot from 21VSG-02 – IR₅₀

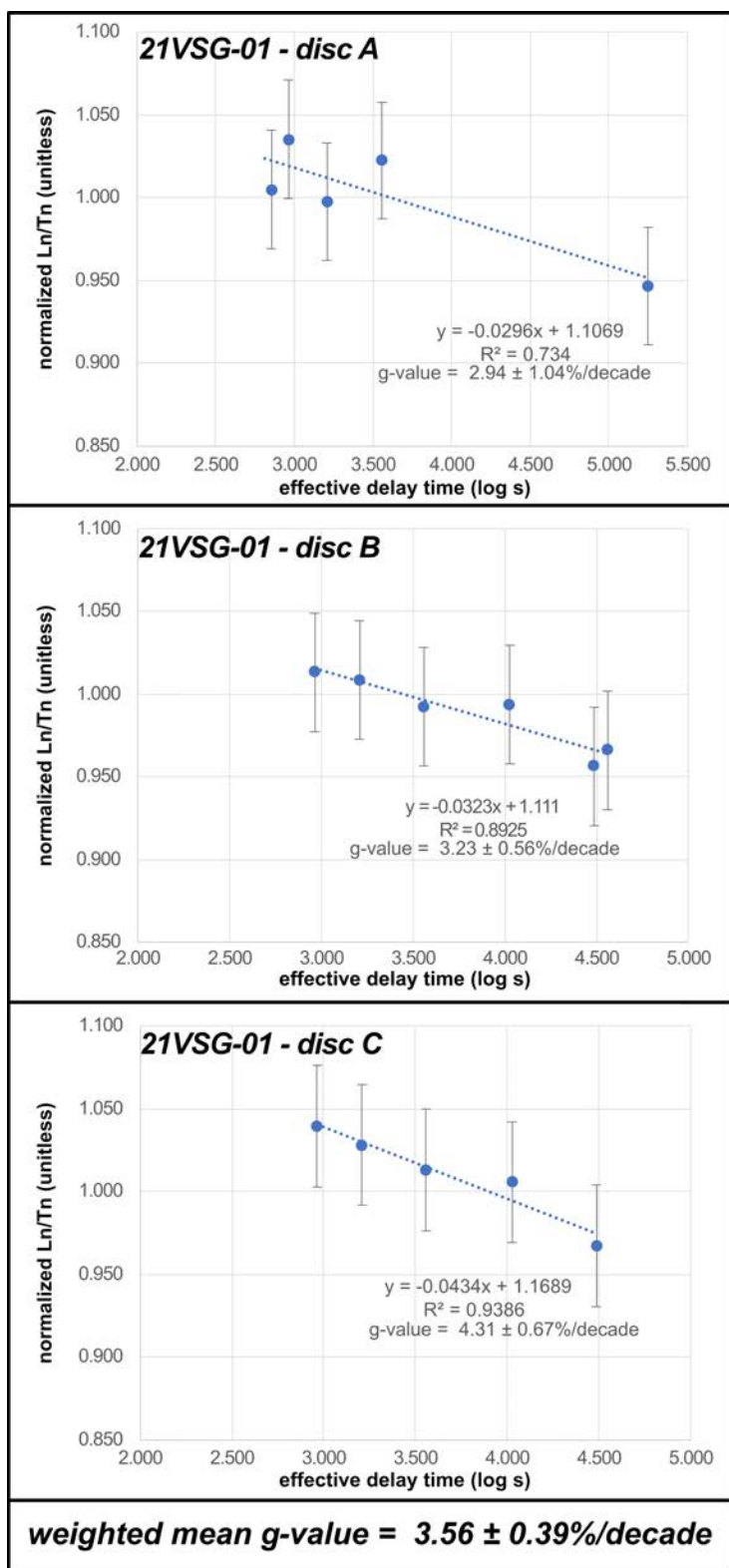


Figure S27: IR_{50} fading test results from 21VSG-01

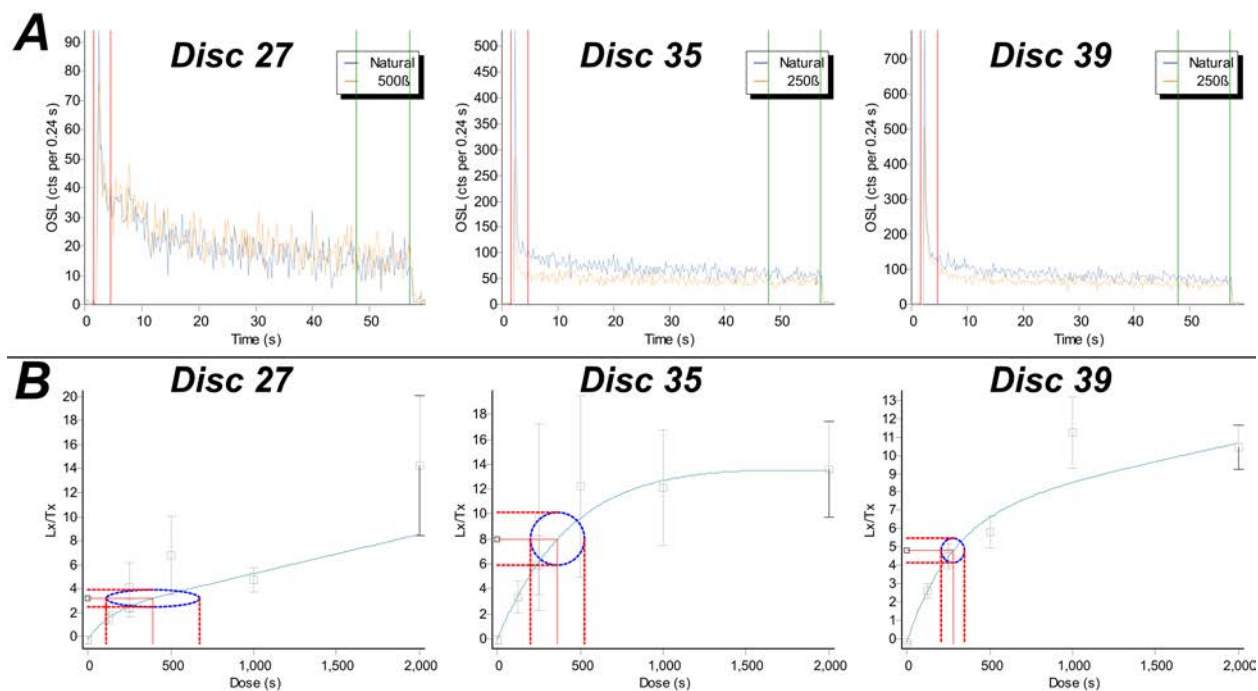


Figure S28: plots of representative quartz characteristics from 21 VSG-01. A) OSL shinedown curves. B) Dose response curves.