EVALUATION OF ROTO-SONIC CORES AND A LITHOLOGIC CROSS SECTION IN THE EAST FLATHEAD VALLEY

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MBMG
Montana Bureau of Mines and Geology

Front photo: Photo by Larry Smith, showing the fine lacustrine sediments encountered in the Quigley core.

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PREFACE

The Ground Water Investigation Program (GWIP) at the Montana Bureau of Mines and Geology (MBMG) investigates areas prioritized by the Ground Water Assessment Steering Committee (2-15-1523 MCA) based on current and anticipated growth of industry, housing and commercial activity, or changing irrigation practices. Additional program information and project-ranking details are available on the MBMG website (http://www.mbmg.mtech.edu/) under the Ground Water Investigation Program.

Products of the East Flathead Groundwater Investigation include:

- This report, presenting data collected using roto-sonic drilling at two sites, and incorporating that data into a cross section to provide regional context.
- An Interpretive Report that presents interpretations of the data and summarizes the project results (Bobst and others, in prep.). The interpretive report focuses on the study purpose: to evaluate the effects of groundwater pumping from the valley-fill aquifers on surface-water and groundwater availability.
- A Groundwater Modeling Report (Berglund and others, 2024), which combines water budget information with observed groundwater and surface-water behavior to develop calibrated steady-state and transient MODFLOW-based numerical groundwater flow models for the East Flathead Valley study area. These models provide insight into the groundwater system, and were used to test various scenarios to understand the types of hydrologic effects that might be expected from future stresses.
- An Aquifer Test Report (Myse and others, 2023), summarizing the results of three aquifer tests conducted in the East Flathead study area.

ABSTRACT

Two roto-sonic coring locations were selected to better understand the grain sizes and depositional environments of sediments between the shallow and deep aquifers near Jessup Mill Pond and near the center of the Flathead Valley, Montana. A cross section was developed using lithologic data from water wells between two cored sites. The core near Jessup Mill Pond was generally sandy and gravelly compared to the core closer to the basin center. The shallow and deep aquifers appear to be hydrologically connected in the area near Jessup Mill Pond.

INTRODUCTION

Ongoing residential and commercial/industrial development in the east Flathead Valley of northwestern Montana has raised concerns that increased groundwater use may affect surface-water and groundwater availability. The East Flathead study provides a greater understanding of the interconnection between the area's aquifers and surface water.

Sediment cores were collected using roto-sonic methods at two locations near the southern boundary of the East Flathead study area (fig. 1) to better understand the distribution of lithologies and the depositional environments associated with the different hydrogeologic units. Each core was collected from private land, with landowners' permission. Wells were also completed in the shallow, intermediate, and deep aquifers at these sites, which were used for aquifer tests (Myse and others, 2023). Roto-sonic core provides high-resolution, relatively undisturbed sediment samples, with depositional structure largely intact (Barrow, 1994). We were particularly interested in obtaining a better understanding of the heterogeneity of the interval between the shallow and the deep aquifers, which has generally been considered to be a confining unit (LaFave and others, 2004; Rose, 2018; Rose and others, 2022).

Lithologic descriptions from water-well logs along a cross section between the two cored sites were used to interpret and correlate units from the surface to the top of the deep aquifer. Previous studies in the area provided background for this work (Konizeski and others, 1968; LaFave and others, 2004; Smith, 2004a–f; Rose, 2018; Rose and others, 2022).

Geologic Framework

The Flathead Valley is the southernmost expression of the Rocky Mountain Trench, which extends over 1,000 mi north into the Yukon Territory, Canada (Garland and others, 1961; Harrison and others, 1992). The Rocky Mountain Trench formed by extension where the bedrock beneath the valleys dropped relative to the surrounding terrane along normal faults, such as along the west flank of the Swan Range (fig. 1).

Bedrock in this area is composed of the Piegan and Ravalli Groups of the Belt Supergroup, which are primarily siltite, metacarbonates, quartzite, and mafic sills (Smith, 2004b; Lonn and others, 2020). Belt bedrock is exposed in the Swan Range on the east side of the study area (fig. 1).

A thick layer of unconsolidated basin-fill sediments overlies the down-dropped Belt bedrock west of the Swan Range front. These Tertiary to Quaternary sediments are up to 3,000 ft thick (Smith, 2004c). Based on a well drilled in the southern Flathead Valley (Bobst and others, 2022), and similar sediments encountered in other intermountain basins in western Montana, the Tertiary sediments are interpreted to function as a basal aquitard in the Flathead Valley.

The Quaternary deep aquifer overlies the Tertiary sediments (LaFave and others, 2004; Rose, 2018) and is interpreted to be glacial outwash mostly composed of sand, gravel, and cobble clasts. These clasts are dominantly composed of siltite, consistent with a Belt bedrock source. This aquifer is a primary water source in the Flathead Valley, and it is used for municipal water supplies, irrigation wells, and domestic wells. Wells in the deep aquifer may produce over 1,000 gpm.

The deep aquifer is generally overlain by glacial till and lake sediments. These lower permeability sediments comprise the confining layer, which is the focus of this report. Smith (2004e) developed an isopach map of the confining units. Intermediate aquifers, composed of lenticular sand and gravel deposits, occur within the confining layers in some areas. Smith (2004e) mapped areas where the deep and intermediate aquifers are interfingered. At the surface there are areas of sandy glacial lake sediments, interpreted to be near-shore deltaic deposits (Smith, 2004b). Similar near-shore facies would have been deposited throughout the time that a lake filled the valley. These sediments may provide a hydraulic connection between the deep aquifer and shallow aquifers in portions of the study area.

A variety of sediments from the modern depositional environment typically cover the confining layer, and form the shallow aquifers. These shallow aquifers are in direct communication with surface waters (Konizeski and others, 1968; Noble and Stanford, 1986; Smith, 2004b; LaFave and others, 2004).

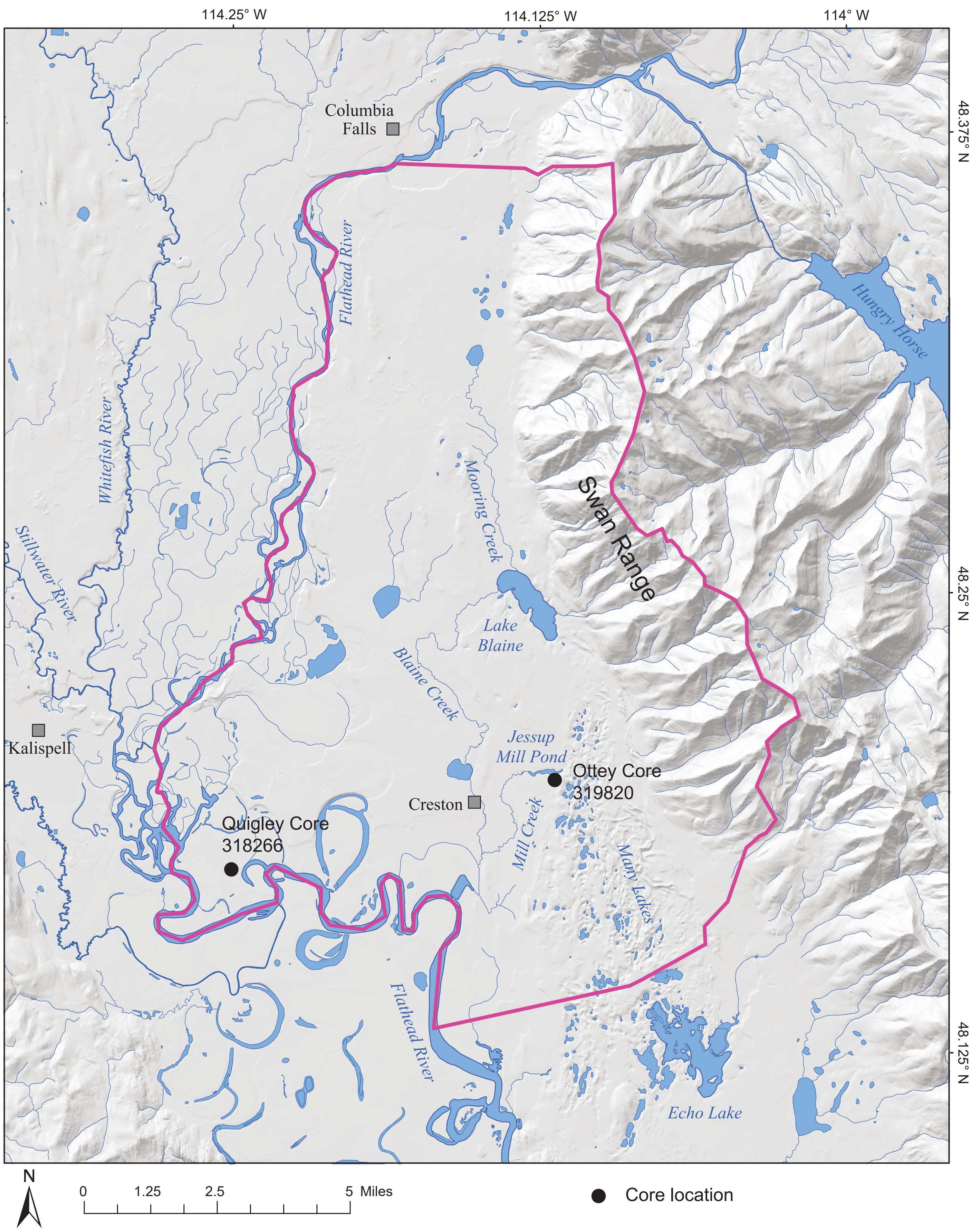


Figure 1. Cores were collected in the southeast and southwest of the East Flathead study area (pink polygon). The southeast site (Ottey) is relatively close to the mountain front, while the southwest site (Quigley) is near the valley center.

METHODS

Roto-sonic coring was conducted in August 2021. Core was initially cut and collected at 5-ft intervals, which was later increased to 10-ft intervals. The retrieved material was extruded from the core barrels into continuous plastic sleeves, which were then cut into 5-ft lengths, tied off at their ends, and laid into core boxes. The plastic sleeves were cut open so that preliminary field descriptions could be made. More detailed core descriptions and photographs were obtained later in a laboratory by scraping the split surfaces clean to expose sedimentary boundaries.

As the sediment was unconsolidated and mostly water-saturated during coring, some of the sediment was disturbed, either folded or mixed, which obscured some of the stratigraphy. Common issues affecting the core, which were accounted for in the descriptions, included:

i. Silty and clayey "skin" around the outside of the core commonly developed, reaching up to 0.5 in. in thickness. This skin is attributed to both clay smearing by the push of the drill string and water pressure and sonic shaking, which apparently led to the movement of fines from the center of the core towards the outside core boundaries.

ii. Non-cohesive sandy and gravel-rich sediment was significantly mixed during coring so that most sedimentary structures were not evident. However, small clumps of intact sediment commonly preserved the original sedimentary texture in these intervals. Some of the water-saturated silty and clayey sand intervals were folded to the extent that layers could not be recognized and described as such.

iii. After a core length is cut and the drill string is pulled up, sediment from the sides of the drill hole tends to be pulled into the open space and fall to the bottom of the hole, only to be on top of the next length of core. On-site geologists attempted to remove much of this "heave" material and to not include it in core descriptions, although some was retained as it was similar to neighboring lithologies.

iv. As cored intervals are extruded from the core barrel into a continuous plastic bag, it was common for the core to stretch in length and narrow in diameter, especially in silty and clayey zones with thin sands. Sandy intervals apparently stretched more as these cored intervals also narrowed in diameter. This led to "expanded" sections of core. Expansion in lengths typically were 1 to 4 ft in a 10-ft section. During descriptions, geologists attempted to describe intervals where lengthening occurred, and core descriptions were corrected for this deformation.

Sediment Descriptions

Sediment description entailed (1) estimation of grain sizes by textural estimations of silt and clay and visual comparisons of sand to grain-size charts, (2) thickness measurements of units >0.1 ft, and (3) counting of couplets of coarser grained and finer grained laminations (varves). Varves, thought to be annual sedimentary cycles in lacustrine deposits, were recognized where silt- or sand-dominated rhythmically bedded laminations were overlain by clay- or silt-rich laminations (Ashley, 1975). The fine-grained sediments in millimeter-scale laminations in varves were typically darker in color and represent wintertime sedimentation; the coarser grain sizes suggest higher energy springtime flows in the annual layers. As most sediment along lake bottoms was deposited by sediment underflows, not all fining-upward sedimentary couplets are necessarily varves. Counting was straightforward in much of the Quigley core, but where very fine laminations were present, varve counting was restricted to more dominant couplets. In intervals where counting was difficult due to disturbance during coring or where many fine laminations may or may not be varves, we estimated the minimum and maximum number of varves. This was done so that a range in ages for deposition of lacustrine intervals could be produced.

Grain-Size Analysis

A few representative samples from each core were selected for grain-size analysis (table 1). About 250 g of sample was collected from parts of the core recognized as thicker and thinner sands and laminated sediment (sandy silt and clay). Following Janitzky (1986), the >2-mm fraction (gravel) was separated. The finer fraction was wet-sieved to separate sand from silt and clay. Silt and clay percentages were measured by the pipette method (Janitzky, 1986).

Age Dating

Wood and plant materials were collected from the cores and analyzed by Beta Analytic (Miami, FL), following their sampling procedures (https://www.radiocarbon.com/sending-carbon-dating-samples.htm). These samples were analyzed for radiocarbon (^{14}C) to estimate the age of the wood or plant materials (tables 2, 3).

Stratigraphic Correlation

A straight-line cross section was drawn from northeast to southwest near the two cored locations (fig. 2). Water-well logs near this cross section were interpreted following the hydrogeologic framework of LaFave and others (2004). Selected well logs include those used for the groundwater flow model (Berglund and others, 2024), wells used by LaFave and others (2004), and any relatively deep and detailed logs from MBMG's Groundwater Information Center (GWIC)

Table 1. Particle-size data for selected samples of the Ottey and Quigley cores.

Core	Sample Depth (ft)	%Gravel	Fine Fraction		
			%Sand	%Silt	%Clay
Ottey	58.5	0	79	18	4
Ottey	134.0	0	92	4	4
Ottey	143.0	0	87	11	3
Ottey	159.0	0	75	20	4
Ottey	162.0	1	67	27	6
Ottey	180.5	0	83	14	4
Ottey	180.7	1	78	18	4
Quigley	101.5	0	70	28	3
Quigley	124.5	0	26	69	5
Quigley	126.8	0	11	82	7
Quigley	129.7	0	34	63	3
Quigley	131.3	0	23	74	3
Quigley	197.0	0	4	64	32
Quigley	247.8	0	16	83	1
Quigley	257.5	2	18	75	6
Quigley	282.5	0	9	89	2

Table 2. Radiocarbon ages showing range of ages from each sample.

Lab no.	Core	Core Depth (ft)	Dated Material	Uncalibrated Age (^{14}C yr BP)	Calibrated Age (Cal yr BP)	Percent	Sum Percent
608402	Ottey	179.4	Organic sediment	>43,500			
608403	Quigley	100.8–101.0	Wood	10,300 ± 40	12,195–11,926	69.5	95.4
608403					12,459–12,350	15.1	
608403					12,269–12,227	4.1	
608403					12,329–12,301	3.4	
608403					11,915–11,880	2.8	
608403					11,847–11,837	0.5	
608404	Quigley	106.7	Plant material	9,740 ± 30	11,237–11,113	95.4	95.4
608405	Quigley	122.5	Plant material	9,970 ± 30	11,412–11,265	59.8	95.4
608405					11,505–11,421	19.5	
608405					11,613–11,526	16.1	
612642	Quigley	257.6	Plant material	13,090 ± 30	15,821–15,566	95.4	95.4

Note. Calibrated dates are calculated using BetaCal4.20 and INTCAL20. Pretreatments: acid/alkali/acid. Reference for probability method: Bronk, 2009. Reference for Database INTCAL20: Reimer and others, 2020.

Table 3. Summary of radiocarbon ages for samples from the Quigley core.

Depth (ft)	Lab no.	Dominant Age (cal yr BP)	Comment
100.85–101.0	Beta 608403	12,195–11,926	and older ages
106.7	Beta 608404	11,237–11,113	
122.5	Beta 608405	11,505–11,421	and older ages
257.6	Beta 612642	15,821–15,566	

Note. cal yr BP: Calendar years before present (present = 1950 AD).

database (http://mbmggwic.mtech.edu/). Water-well log locations were projected along isopach contours of fine-grained sediments onto the cross section.

OTTEY CORE

Overview

A detailed lithologic log of this core is presented in appendix A, and photographs of the entire core are in appendix B. The Ottey core was collected between 50 and 210 ft below ground surface. The coarse-grained nature of this core shows that the sediments were deposited by energetic processes, either flowing water or glacial ice (figs. 3, 4). These relatively coarse-grained sediments are more permeable than the more fine-grained deposits found in other areas, allowing for hydrologic communication between the deep and shallow aquifers. The close association of laminated lacustrine deposits with till suggests that the lacustrine deposits are glaciolacustrine, and therefore are referred to as such.

It is possible that disturbance during drilling, especially washing with water and sonic shaking, has affected the original character of the deposit. Many of the sandy intervals developed a significant thickness of "skin" along the edges of the core. This suggests the deposit has sufficient permeability to allow the transport of the fine material; in comparison, skin did not form in dense, compact material, like lodgment till.

Depositional Environments

An understanding of the past depositional environments at the location of this core provides important context for these sediment types, and allows for a more complete conceptual model of their distribution. For instance, the relatively coarse-grained deltaic deposits at this site suggest that similar sediments should be expected in other near-shore lacustrine deposits that are near stream inputs (e.g., along the Swan Range front).

Till

Till (sediment directly deposited by glacial ice) is interpreted where the core shows that compact silty and/or clayey matrix suspends gravel clasts, forming a diamict. However, as many of the cored intervals contain silt and clay, all are likely not till, and the sediment could be reworked from till.

Granule, pebble, or cobble-dominated sediment with dense clayey and silty sand sediment between, and supporting, gravel clasts is interpreted as till. Some of the beds were rich in gravel clasts, while others are sand dominant (figs. 5, 6). The dense and compact muddy sediments are characteristic of subglacially deposited lodgment till, sediment deposited below flowing glacial ice. Melt-out till, deposited as debris-laden ice melts, may also be represented in some intervals. Unique interpretation of these environments from a core is difficult because this requires knowledge of the environments of subjacent and superjacent sediment. Many subglacial tills can have complex histories including lodgment, deformation, and melt-out (Benn and Evans, 1998).

Sediment deposited by ice can commonly be reworked in near-ice and subglacial environments by flowing water or as mass movements. Where substantially reworked by water, the till is transformed into outwash. However, where subjected only to minor water flow, the sediment may become clast-supported but still contain a high proportion of finer grain sizes, making classification difficult. Therefore, beds interpreted as till can be expected to border, or encase, clast-supported and sorted gravel (fig. 6).

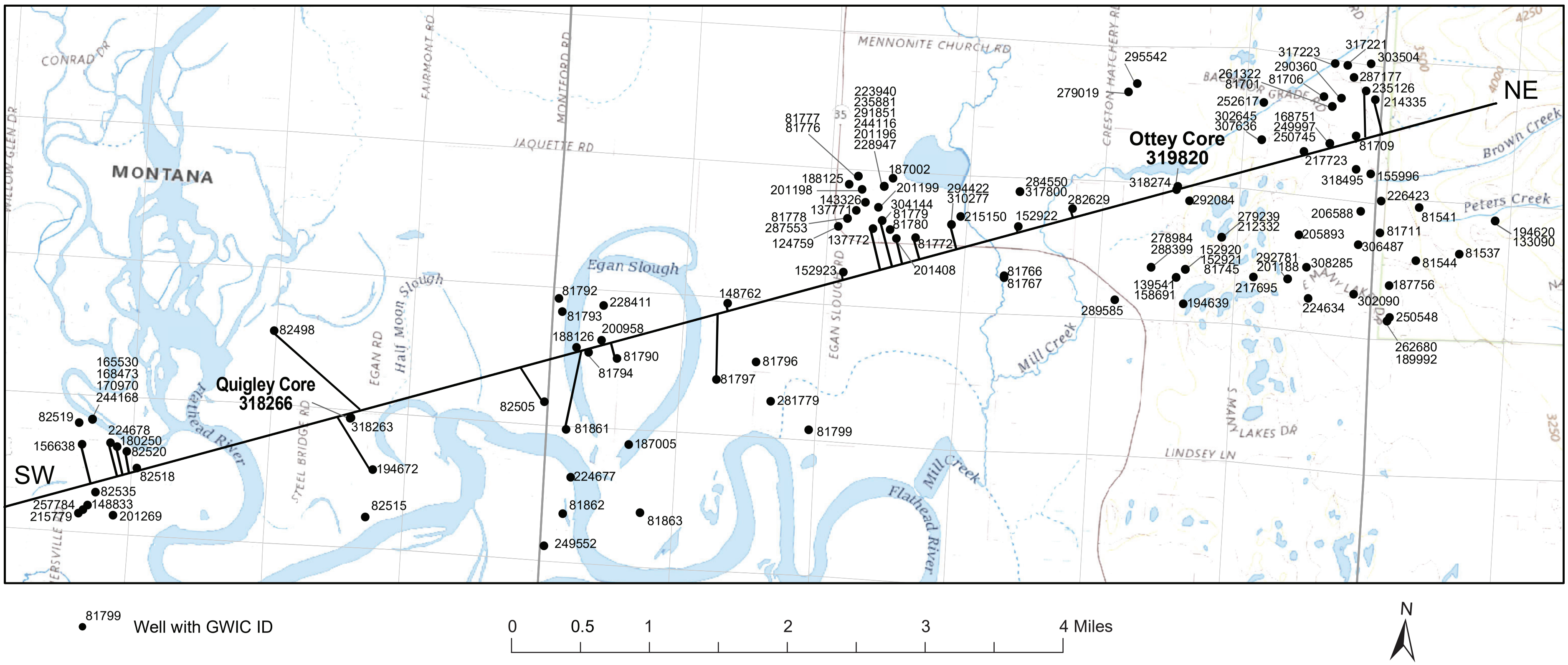


Figure 2. GWIC ID numbers of water-well lithologic logs used to correlate the stratigraphy along the southern boundary of the study area. The northeast–southwest line of the cross section (fig. 19) is shown with the projection of well data onto that line. Note that some wells plot on top of each other due to using the relatively rough Township–Range–Section location method.

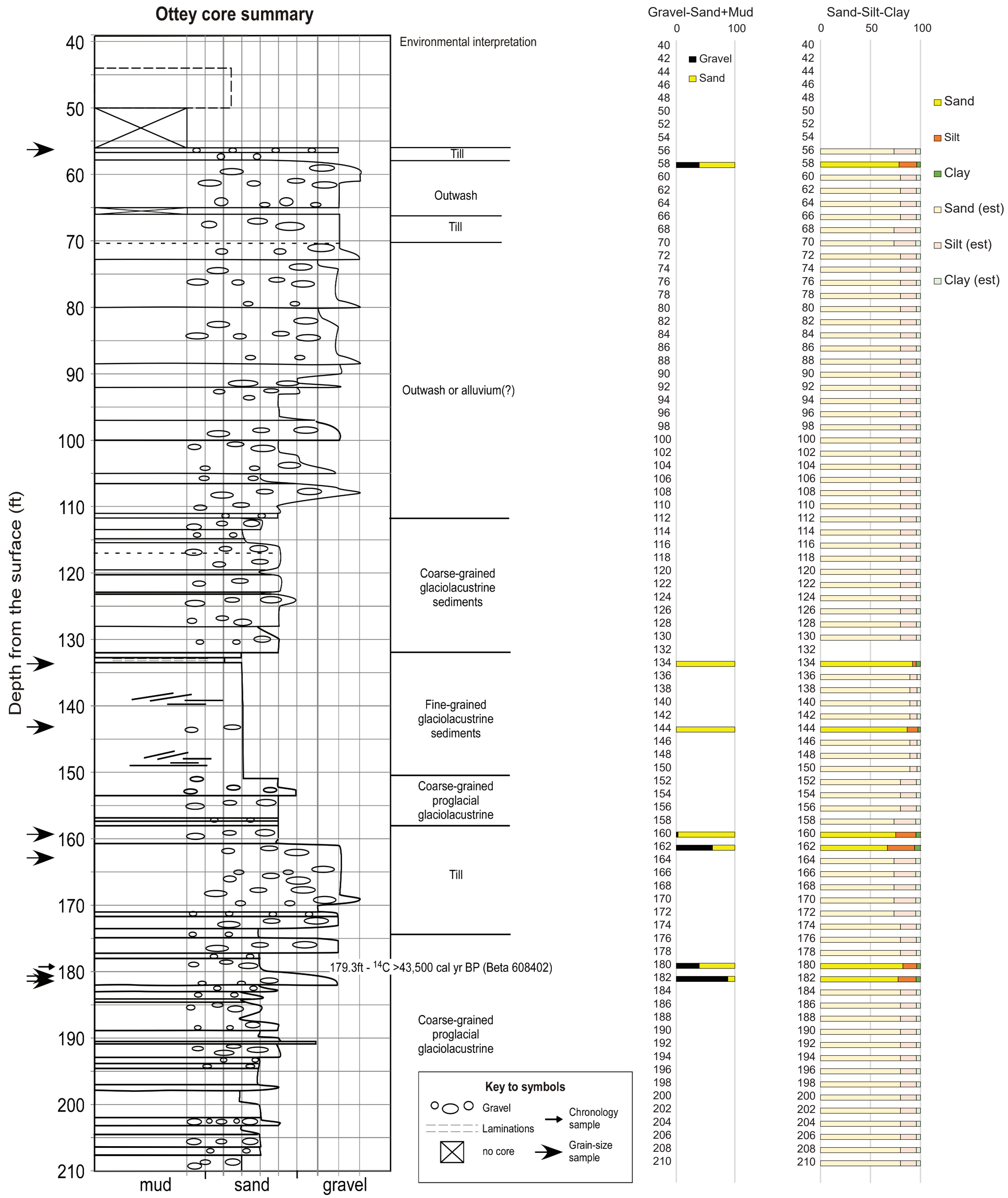


Figure 3. Summary of Ottey core descriptions, depositional environment interpretations, and grain sizes. Arrows and bold colored bars show the depths of samples for grain-size measurements. The grain-size measurements were averaged for the different depositional environments, which were then plotted as light colored bars. Small arrow shows a horizon with recovered organic material. See table 1 for particle-size data. Note that a more detailed log is included in appendix A.

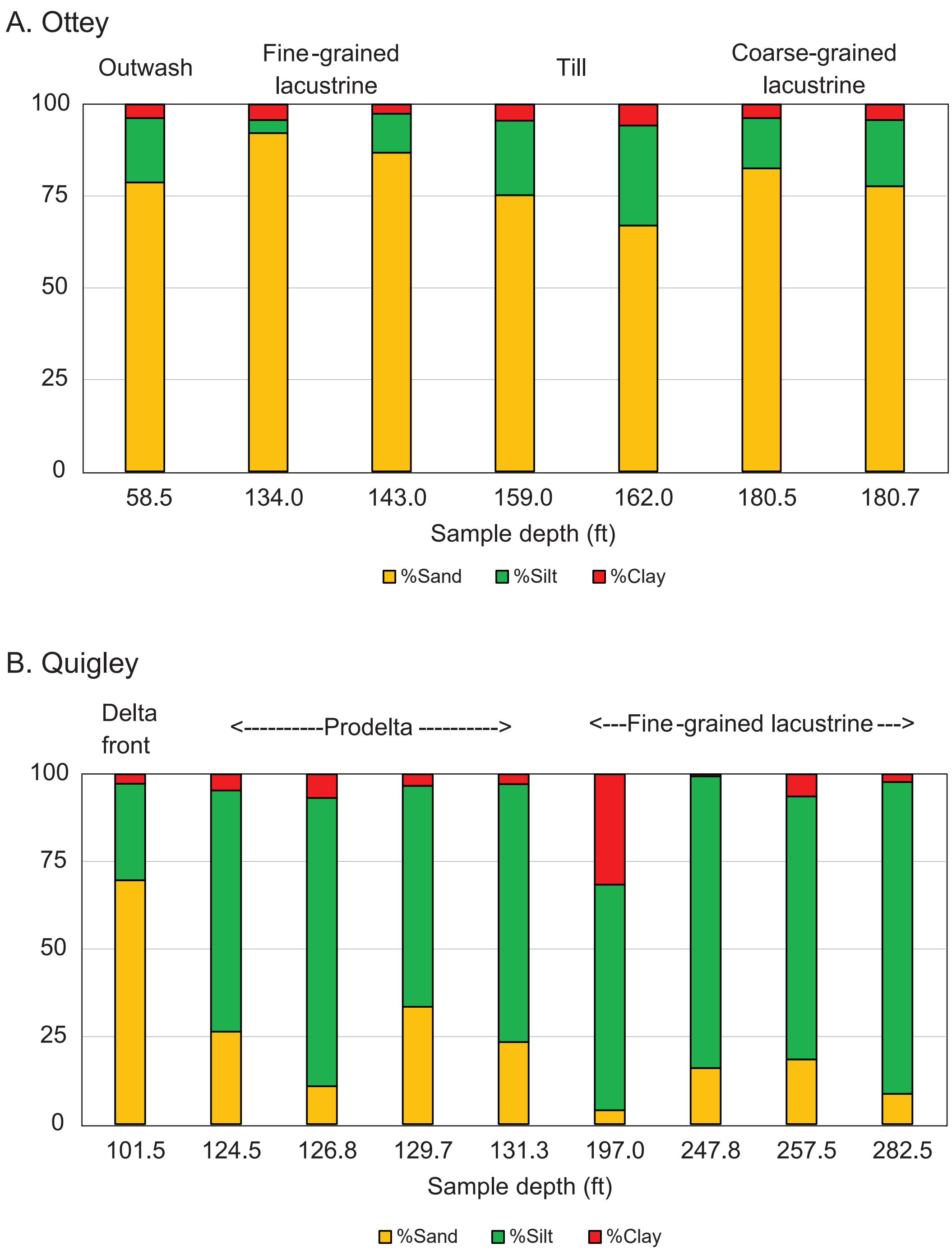


Figure 4. Grain sizes of the fine fraction (<2 mm) in select samples from (A) the Ottey core and (B) the Quigley core. Interpreted depositional environments are shown above the box plots. Note that the Ottey core has considerably more sand than the Quigley core. Also, the comparison of fine vs. coarse-grained lacustrine is between facies within each core, and is not intended for comparison between cores (i.e. the fine-grained lacustrine in the Ottey core is not the same as the fine-grained lacustrine in the Quigley core).

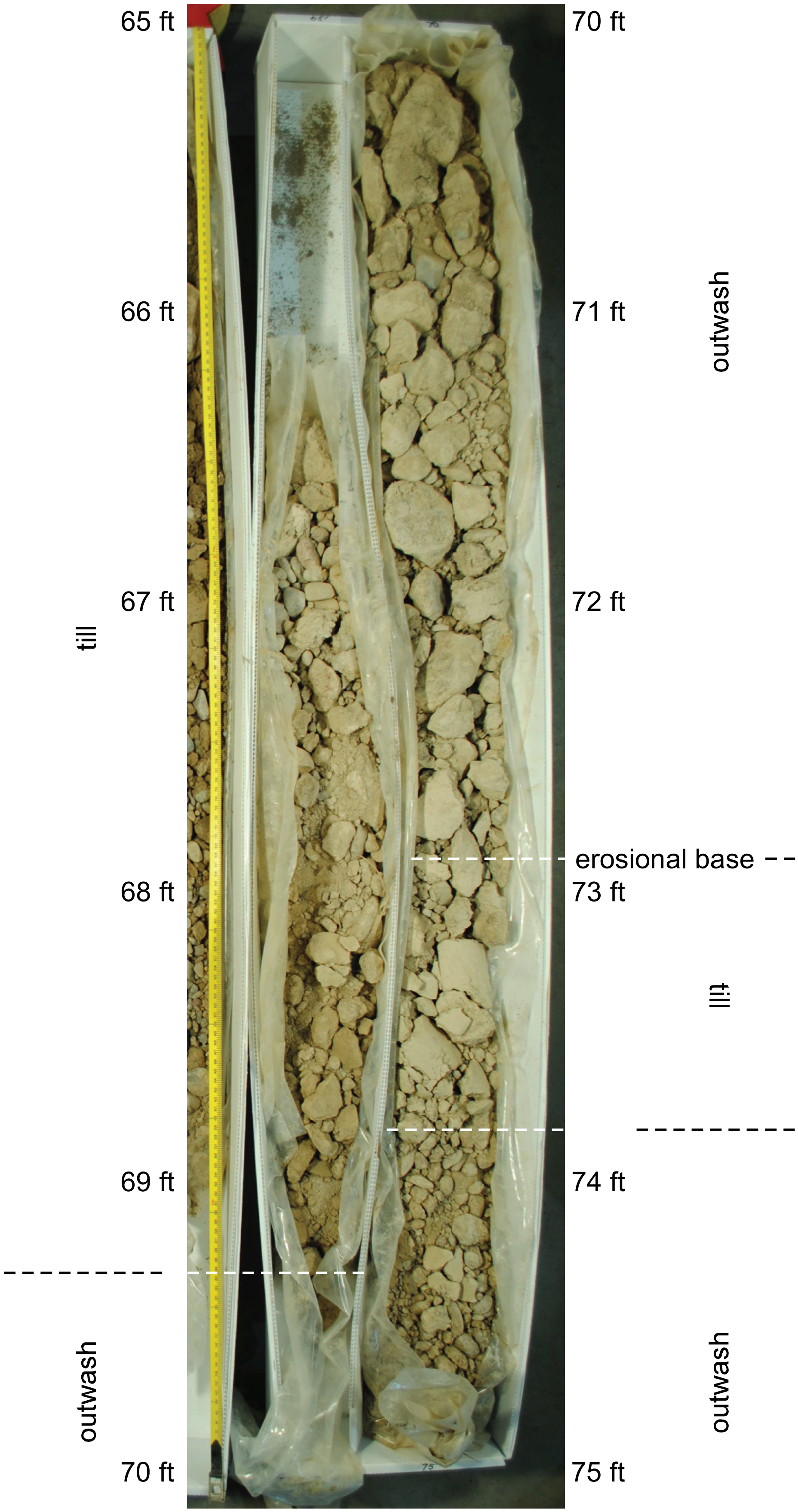


Figure 5. The uppermost portion of the Ottey core recovered till interbedded with sediment interpreted as outwash, or possibly water-reworked till. The till is compact, suggesting deposition as lodgment till. Thus, this interval may represent a glacial advance over outwash.

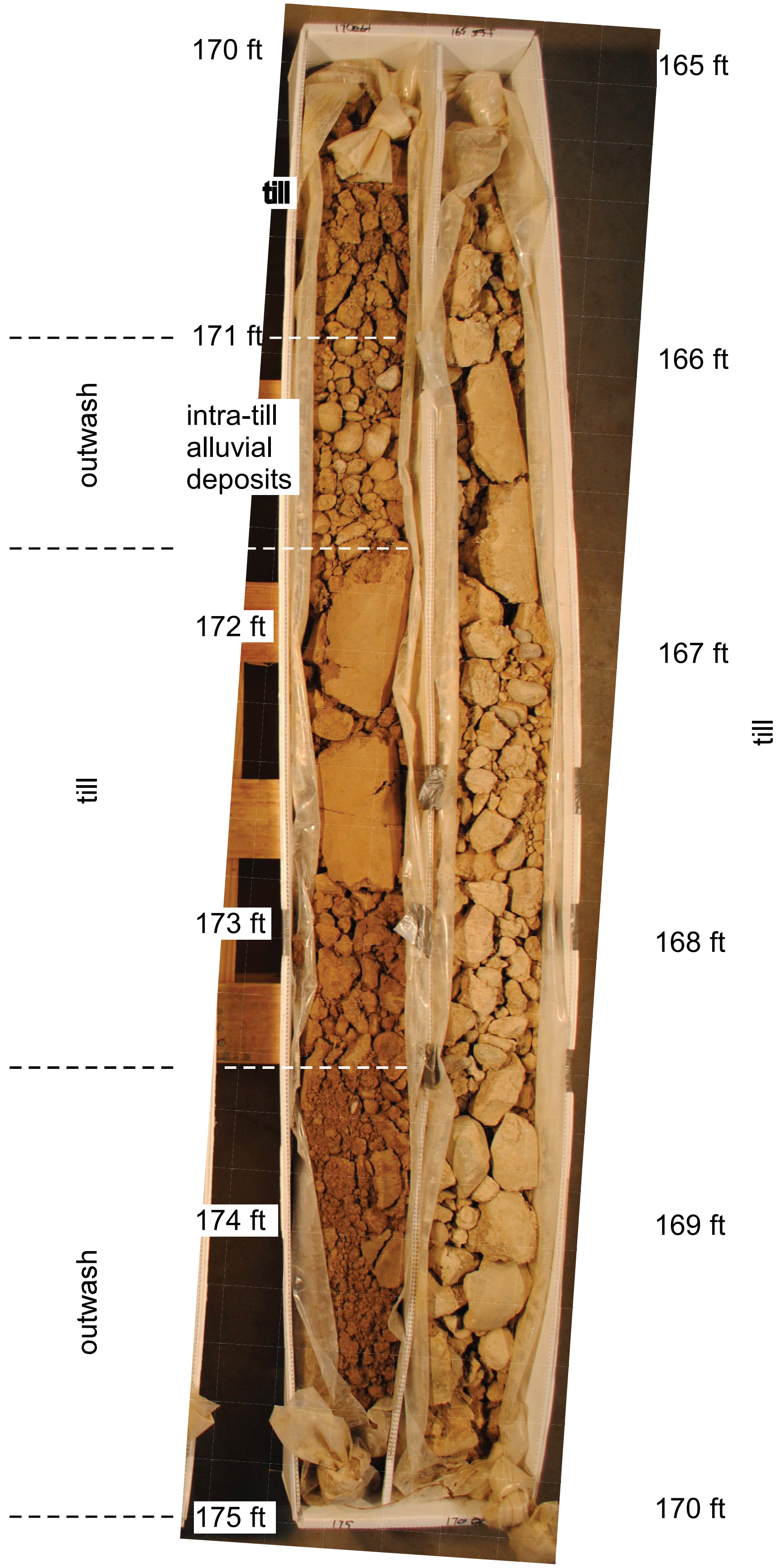


Figure 6. From the Ottey core, till is composed of clay and silt that is locally firm and supports gravel. A bed of loose clast-supported gravel at 171–171.75 ft shows evidence that it is water-washed alluvium. The interval from 165 to 172 ft is interpreted as clast-poor till with a bed of intra-till alluvial deposits (outwash). The till overlies clast-supported gravel interpreted as outwash.

Near ice margins, subaerially deposited ablation till is commonly associated with topographic highs and lows due to differential melting of glacial ice blocks, erosion, and sediment transport into topographic lows (Benn and Evans, 1998). Till from higher areas can thus be redeposited as debris flows, slumps, or slides into lower areas. Such deposits can be difficult to distinguish from melt-out till. Where glacial ice enters a proglacial lake, cohesive debris flow deposits can be indistinguishable from subaerial till deposits if distinct, laminated glaciolacustrine structures are absent.

<u>Outwash</u>

Lithologies include cobble, pebble, and granule gravel with sand between clasts. Gravels are typically rounded, subrounded, and subangular. The sand is typically coarse- or very coarse-grained and is only rarely silty (figs. 5–7). A characteristic feature of sequences is that they are gravelly near an erosional base and then fine upward (e.g., 88.25–85 ft in fig. 7).

In a broad scope, outwash interpreted here only occurs in about the upper half of the core, where it is not clearly associated with glaciolacustrine deposits, except where it does overlie glaciolacustrine sediments at 111.7 ft. However, differentiating subaerial outwash from coarse-grained subaqueous deposits near a toe of a glacier where it enters a proglacial lake is difficult. Therefore, it is possible that some, or all, of the fining-upward, gravelly sequences were not deposited on land, and built-up grounding-line fans (c.f. Benn and Evans, 1998, p. 299–301).

<u>Coarse-grained sandy glaciolacustrine sediments</u>

Coarse-grained sandy glaciolacustrine deposits are predominantly sandy or gravelly but include moderately to well-sorted fine-grained sand and beds of silt. Sand is mostly moderately to moderately well-sorted and loose. Interbedded fine-grained deposits are typically slightly sticky with clay and some silt. Beds of sand commonly fine upwards near their tops and range in average grain size from very coarse and coarse at shallower depths to medium-grained below about 177 ft; however, thin beds of fine-grained sand and granules and pebbles exist throughout all depths (figs. 8–10).

The lower 36-ft interval of the core (from about 174 to 210 ft; fig. 10) is interpreted to be coarse-grained sandy glaciolacustrine deposits but contains more gravel than glaciolacustrine deposits higher in the core. Whereas there is a possibility that some of this section may be alluvial, it is interpreted as proglacial glaciolacustrine sediments, suggesting the section was deposited as the Flathead Lobe advanced into a proglacial lake.

Quartz sand grains are commonly rounded, whereas rock fragments are more commonly subrounded to angular. Without the context of interbedded fine-grained sandy lake deposits, this unit would be interpreted as alluvium. The moderately to well-sorted fine-grained sand and silt layers suggest sedimentation in a water body.

<u>Fine-grained sandy glaciolacustrine sediments</u>

Only one interval of this unit was recognized from 132 to 151 ft (fig. 8). Drilling through most of the unit was more rapid than the rest of the cored interval. The unit is almost entirely made up of loose, moderately and well-sorted fine-grained sand that displays common laminations. The sand is slightly silty. The fine-grained sand bed is capped by a bed of horizontally laminated, very fine-grained sand. In two intervals (at 133 and 137 ft), horizontal and cross bedding is highlighted by manganese-oxide staining.

The consistent grain size and lack of gravels in the interval suggests medial (to distal?) traction-current deposition, possibly in a subaqueous fan downgradient of an outlet of a subglacial stream.

Chronology

Organic sediment and organic fragments were collected from only one interval in the Ottey core, at 179.4 ft (fig. 10). The organic material was beyond the maximum radiocarbon age of analysis (>43,500 yr BP; tables 2 and 3; Beta 608402). This material is interpreted to be organic fragments that were reworked from an older deposit, possibly Tertiary-aged Kishenehn Formation lignite in the drainage basin.

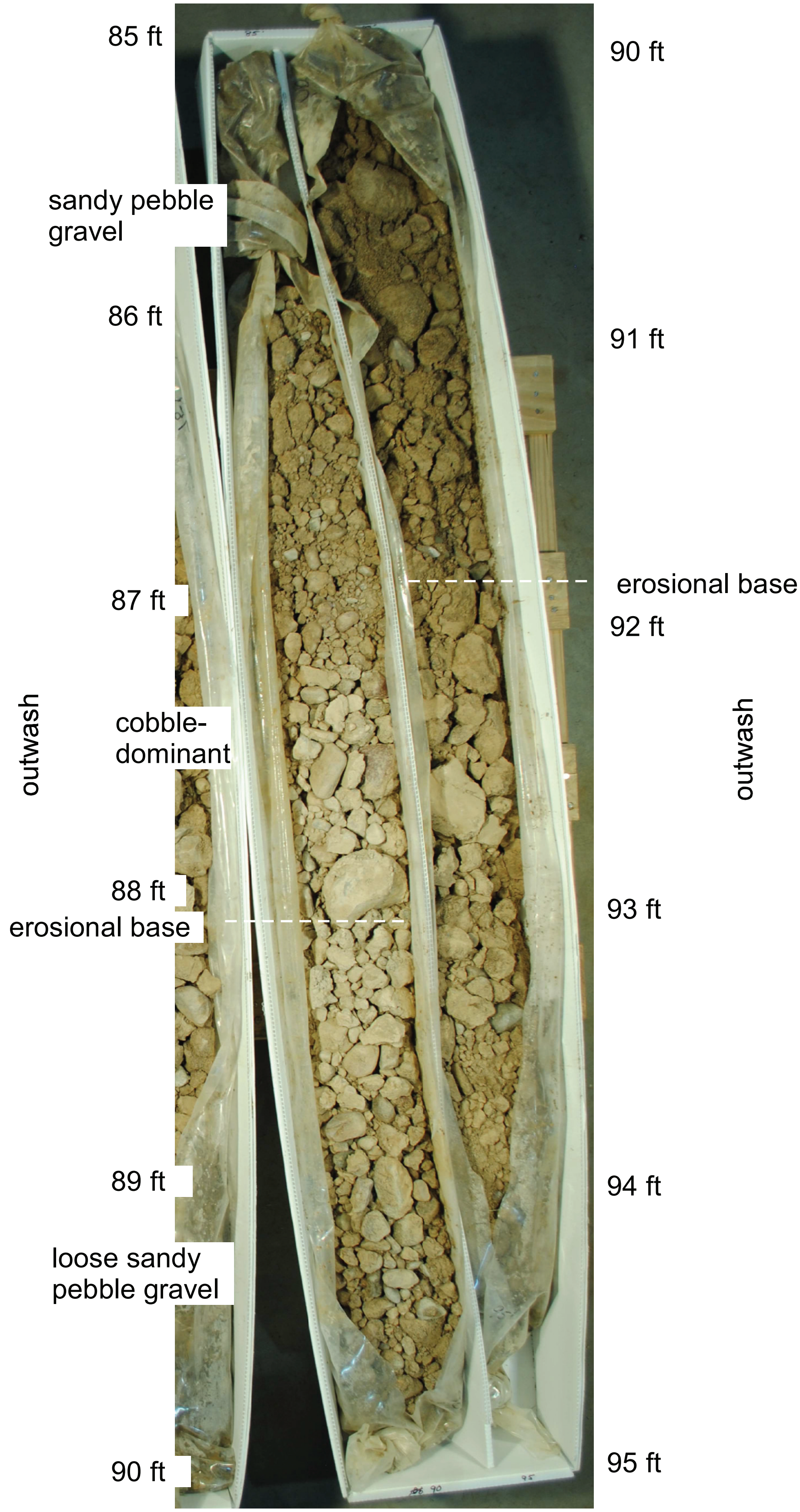


Figure 7. From the Ottey core, sandy pebble and cobble gravel in fining-upward sequences is typical of alluvial deposition. These sequences are interpreted to be outwash downslope from the Flathead Lobe glacier.

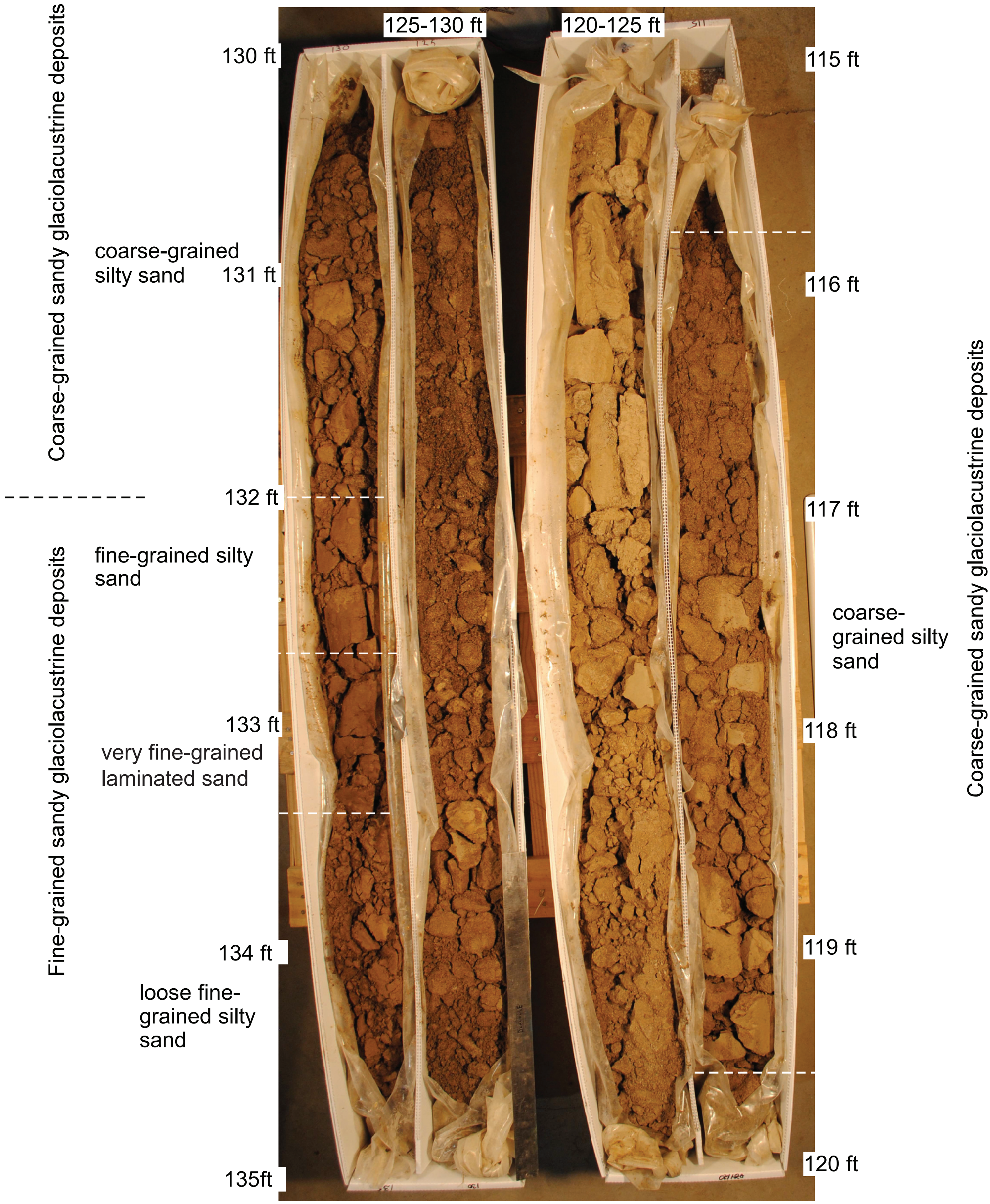


Figure 8. Fine-grained sandy glaciolacustrine deposits, below 132 ft, are overlain by coarse-grained sandy glaciolacustrine deposits. The silty sand with granule- and pebble-gravel interval from 120 to 130 ft is shown but not labeled in this photo.

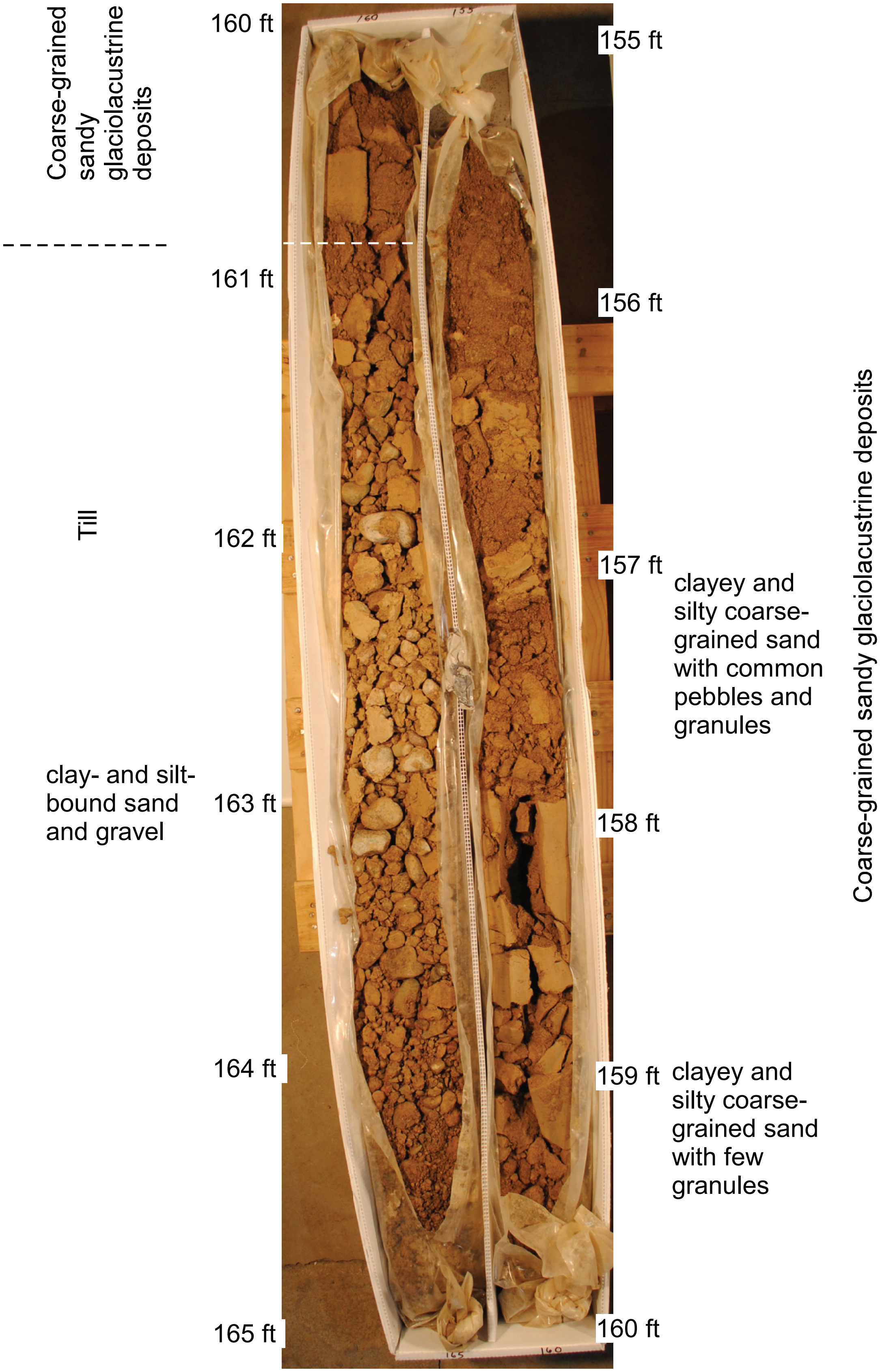


Figure 9. Till below about 160.8 ft is overlain by clayey and silty coarse-grained sand with some granules and pebbles, interpreted as coarse-grained sandy glaciolacustrine deposits.

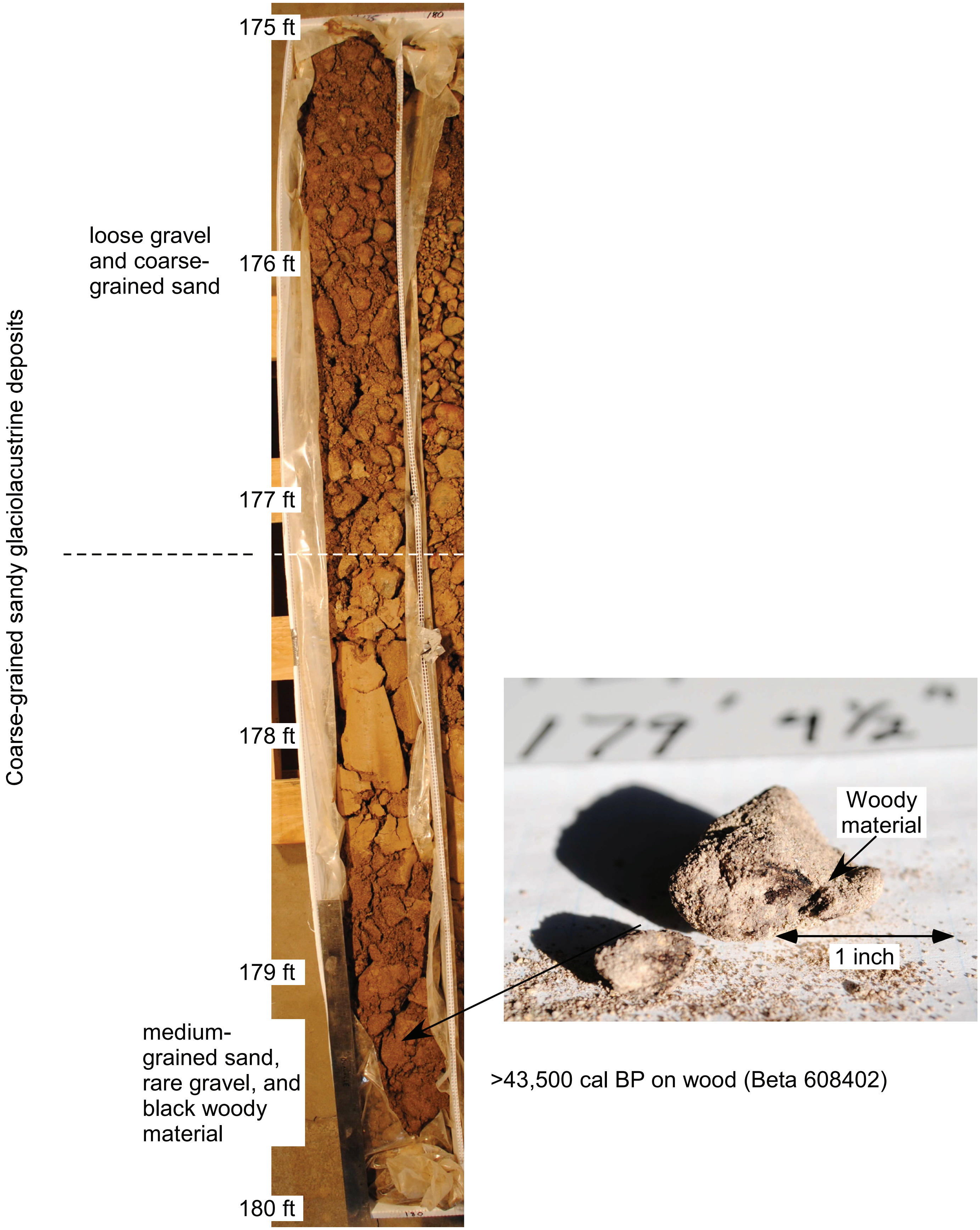


Figure 10. Sandy and gravelly coarse-grained sandy glaciolacustrine deposits contain one interval with woody material. The wood was apparently reworked from an older deposit as its age was beyond the limits of radiocarbon measurement, or >43,500 cal BP (Beta 608402; tables 2 and 3).

QUIGLEY CORE

Overview

A detailed lithologic log of this core is presented in appendix C, and photographs of the entire core are in appendix D. The Quigley core was collected between 100 and 294 ft below ground surface. The dominance of laminated silt and clay in the core attests to its origin as mostly lacustrine or glaciolacustrine (fig. 11). Gravel-sized clasts were only rarely found in the core. The sandy glaciolacustrine deposits encountered in this core are similar to but finer grained than those in the Ottey core. Coarsening-upward sequences of mud to fine- and very fine-grained sand suggest progradation of deltas into a standing body of water, possibly Glacial Lake Missoula, Glacial Lake Kalispell, and ancestral Flathead Lake. As many of the depositional environments are transitional, their boundaries as picked in the core are approximate.

Radiocarbon chronologic data, presented below, suggest that lacustrine sediments in the lower portion of the core were likely deposited as the Flathead Lobe of the Cordilleran ice sheet was retreating from the valley. The upper portion of the core was deposited after the glaciers receded. Therefore, it is difficult to determine whether the lacustrine sediments are glaciolacustrine or not, and they are simply referred to as lacustrine here.

Depositional Environments

Delta front deposits

Characteristics of this unit include thick (>1 ft) laminated fine-grained sand, abundant organic fragments, and minor interbedded sandy mud (fig. 12). Organic material is known to be preserved in deltaic deposits, where it is delivered to the water body because of the rapid sediment accumulation and burial (Boggs, 1987). These deposits [depths of 100–102.2 ft (fig. 12) and ~120–123.4 ft] may represent very shallow water depths because of the preserved fine rootlets and the fining-upward sequence observed in one sand body. The delta front deposits overlie prodelta deposits.

The delta front deposit intervals cap coarsening-upward sequences from laminated silt to beds of fine-grained sand. The sands are silty and clayey and contain common organic fragments from which one sample (figs. 12B, 12C) was dated. Indistinct laminations in the sand bodies and thin interbedded clay and silt beds are evident. The uppermost sand in the sequence, from 122 to 120.7 ft, fines upward, suggesting deposition in a channel, likely at a shallow-water depth.

Prodelta deposits

Interbedded very fine-grained sand, laminated mud, and common organic deposits characterize this unit (fig. 13). Sand beds range in thickness from 0.2 to 0.7 ft and make up about 30 percent of the unit. Each of the two recognized sequences [102.2–~120 ft (fig. 13) and 123.4–131.5 ft] are directly below sands interpreted to be deposited on delta fronts. The prodelta deposits overlie sandy lacustrine deposits.

Laminated and varved mud makes up over half of the deposit thicknesses. Many of the coarser grained layers in varves are fine- or very-fine grained sandy mud. Clay or silt layers in the varves have transitional to abrupt contacts with underlying sandy mud. Most varves in the prodelta deposits are 0.1 in thick or somewhat thicker, with a few intervals that have substantially thinner varve couplets. The fine- and very fine-grained beds of sand appear massive and range up to 0.4 ft thick. Most sand beds are 0.1–0.3 ft thick. Bands of green colors are common, suggesting that intermittent reduction of iron caused the coloration. Organic fragments are commonly preserved, again suggesting mostly reducing environments, but concentrations of plant matter are lower than in the delta front sands.

Very fine-grained sandy lacustrine deposits

These units are defined by having laminated silty and clayey varves with common interbeds of very fine-grained sand and rare beds of fine-grained sand (fig. 14). The sand beds make up less than 25 percent of the unit and are mostly 0.1–0.3 ft thick. The unit underlies prodelta deposits and represents part of a coarsening-upward sequence, although grain-size trends within the sequences are not obvious. Sandy beds within this proximal-to-source unit may be turbidites downslope from channels transporting sediment to the delta front and/or hemipelagic mud derived from sediment plumes entering the lake at a range of lateral positions along a prograding delta (c.f. Gustavson and others, 1975). Although laminated varves of silt and clay dominate the sequence, the sand beds roughly thicken upward from about 0.05 ft to up to 0.2 ft in thickness from 140 to 130 ft, below the prodelta

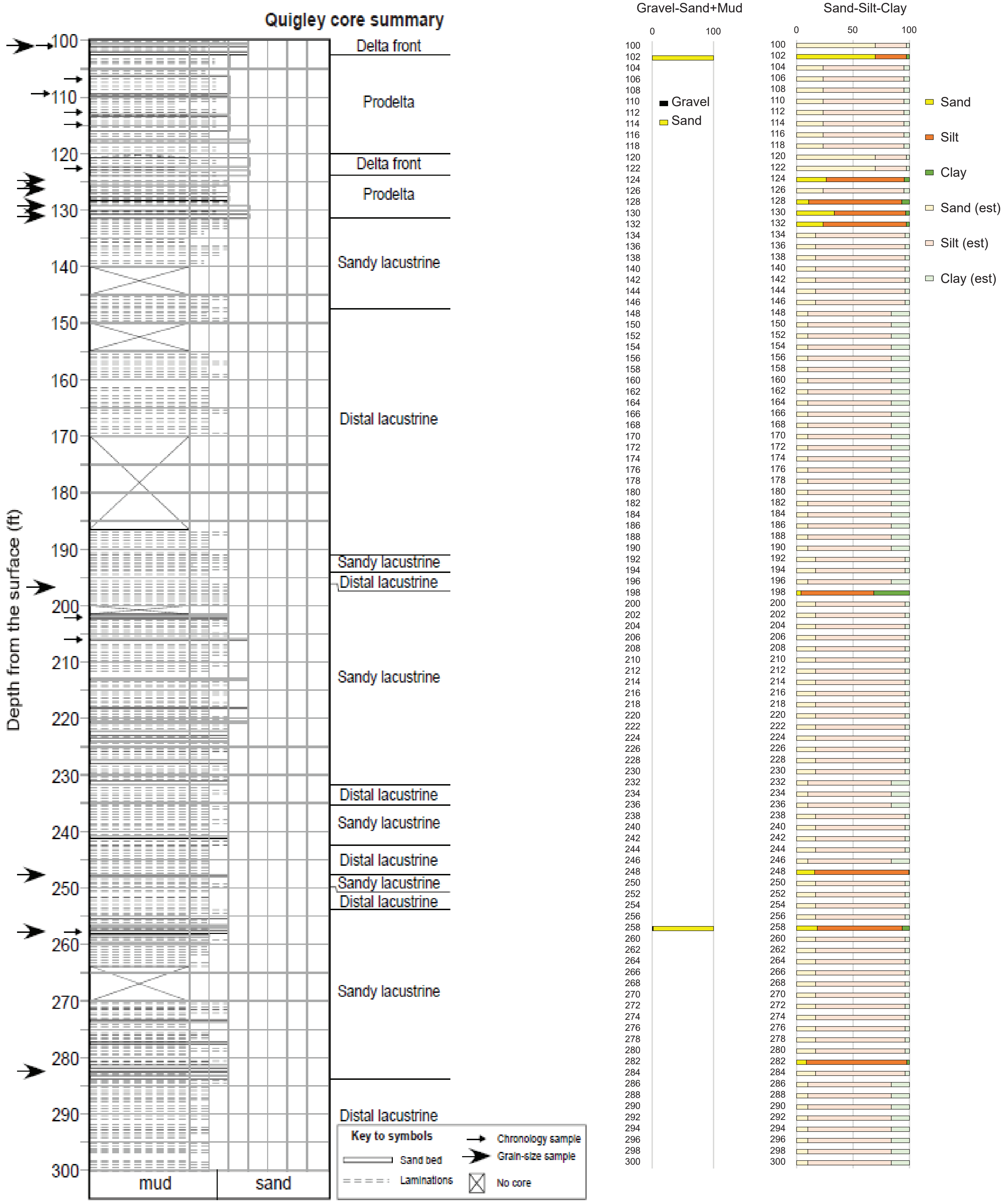


Figure 11. Summary of Quigley core descriptions, depositional environment interpretations, and grain sizes. Arrows and bold colored bars show the depths of samples for grain-size measurements. The grain-size measurements were averaged for the different depositional environments, which were then plotted as light colored bars. Small arrows show horizons with recovered organic material. See table 1 for particle-size data. Note that a more detailed log is included as appendix C.

A

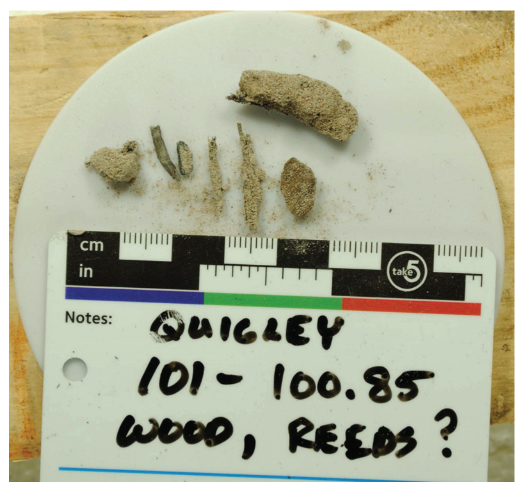
Sandy clayey silt

Delta front deposits

B

clay-rich sand with organic-rich laminae

C



12,195–1,926 cal BP on wood (Beta 608403)

Figure 12. Sandy clayey silt (A) and clayey sand (B) in the Quigley Core with common organic-rich laminae characterize delta front deposits. Wood fragments extracted from the laminae (C) were dated to 12,195–11,926 cal yr BP (Beta 608403).

Figure 13. Laminated very fine-grained silty sand and sandy silt and clay, varves, and thin, very fine-grained sands in the Quigley Core are interpreted as prodelta deposits. One sand at 106.7 ft contained many plant-material fragments that were dated at 11,237–11,113 cal BP (Beta 608404).

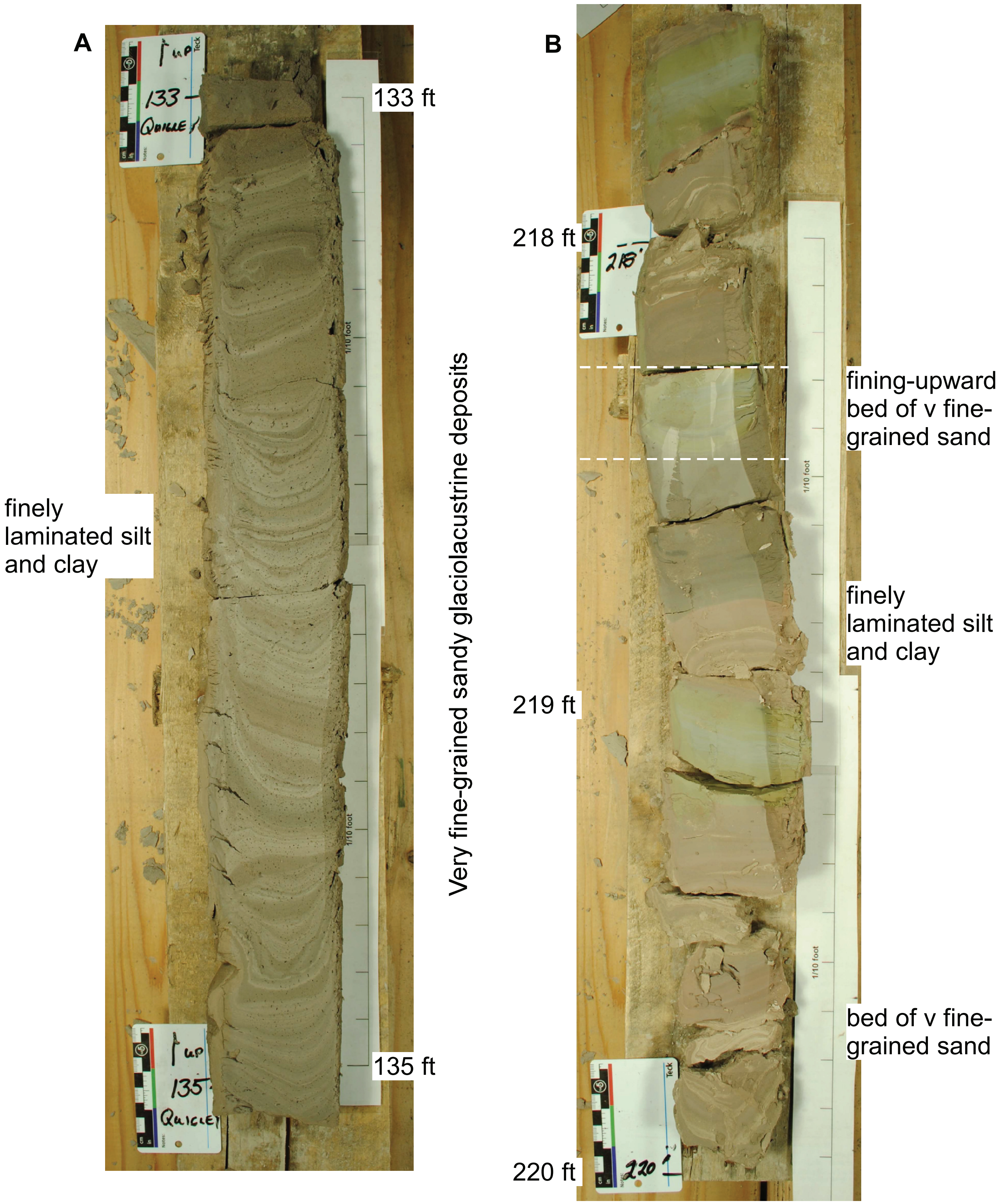


Figure 14. Very fine-grained sand and laminated silt and clay sequences in the Quigley Core are interpreted as very fine-grained sandy lacustrine deposits. (A) Note the folding of sedimentary layers due to coring and extraction of the core from the core barrel. (B) The lacustrine deposits commonly contain distinct beds of very fine-grained sand.

deposits (fig. 11). Within the laminated silt and clay dominant unit, very fine-grained sand in laminae and sandy beds commonly have greenish hues, suggesting coloration by reduced iron.

A distinct sand bed at 205.8–206.1 ft is a well-sorted fine-grained sand with abundant quartz, feldspar, and mafic minerals (fig. 15). X-ray diffraction and handheld X-ray fluorescence and spectrometer (ASD TerraSpec Halo) analysis of the sand suggest dominance of quartz, plagioclase, hornblende, biotite, clinoptilolite, and montmorillonite. Examination showed that the sand resembles sediment that would have been derived from a Hog Heaven tuff clast, and not an air-fall tephra. We hypothesize that the clast(s) originated from land and was entrapped in shore ice. The ice then detached from the shore and floated into the lake before melting and dropping the sediment.

Near the bottom of the core (235.3–242.4 ft, 247.7–249.5 ft, and 253.5–284 ft; fig. 16), varved mud accounts for about 80 percent of the interval thicknesses. Coloration in the muddy layers includes black and green along with a few bluish and brownish beds. The remaining lithology is fine- or very fine-grained sand that ranges in thickness from about 0.05 ft to 0.6 ft. No discernible trends in grain sizes can be seen from the sequences. About half of the sand beds 0.2 ft thick or greater fine upwards from fine- or very fine-grained sand at their bases.

<u>*Distal lacustrine deposits*</u>

The distal lacustrine deposits are almost entirely of varved laminated silt and clay (fig. 17). Some varve bases are very fine-grained sandy silt or silty sand. These sediments appear to have been deposited farther away from sediment sources as compared to other sediments in either the Quigley or Ottey cores. The unit is overlain or underlain everywhere by very fine-grained sandy lacustrine deposits.

Chronology

Organic matter was obtained from nine horizons in the Quigley core. Four of the samples were sent to Beta Analytic for radiocarbon analysis (fig. 11). Sampled material included wood and plant matter. The plant matter appeared to be woody fragments, rootlets, and reed-like material.

The four radiocarbon ages of the Quigley core showed that the sediments are older near the base and younger near the top, as expected, except for the uppermost sample (tables 2, 3). Two of the samples (Beta 608403 and 608405) produced multiple ages, as multiple peaks on a spectrum of results (table 3). The younger and more significant ages are shown in table 3. The uppermost sample (100.85–101 ft) was composed of wood fragments, whereas the deeper samples were all of plant material (table 2).

The out of sequence old age of the uppermost Quigley sample is likely due to the mixing of older and younger woody debris that was redeposited in the glacial lake. Each of the reported dates for the uppermost sample are older than the samples from 106.7 ft and 122.5 ft, suggesting that the uppermost sample is composed of organic material that died hundreds to a thousand years before being deposited. Although the plant material sampled at 122.5 ft also produced a range of ages, suggesting a mix of older and younger material, each of those ages is still in stratigraphic order. The sample from 257.6 ft shows that some of the lacustrine deposits are Late Pleistocene in age. Thus, the lacustrine deposits in the Quigley core suggest deposition from >15 ka to about 10–11 ka, from Late Pleistocene to Holocene time.

Varve Record in the Quigley Core

A total of 1,167 varves were physically counted in the Quigley core. Estimates of varves not recognized due to core deformation ranged from a low of 357 to a high of 976. By adding the low and high estimates of uncounted varves to those that were physically counted, the best estimates of varve sedimentation ranges from 1,524 to 2,143 years. Having radiocarbon ages at multiple core intervals allows comparison of the estimated core ages to radiocarbon ages. The comparison shown in figure 18 hinges on the age at 106.7 ft being the best age to use, in that material at 100.85 ft and 122.5 ft contained ages of older fragments. This scaling suggests that, even assuming the upper value of uncounted varves, the cumulative varve counts represent an underestimation of deposit age at depth (fig. 18). The differences in radiocarbon versus estimated ages based on varve counting reach a value of about 2,950 yr at 257.5 ft, suggesting that the varve counting accounts for less than half of the true age. The disparity between the radiocarbon and estimated ages is likely due to undercounting of varves and unrecognized hiatuses (or erosion surfaces), especially in sandy portions of the stratigraphy.

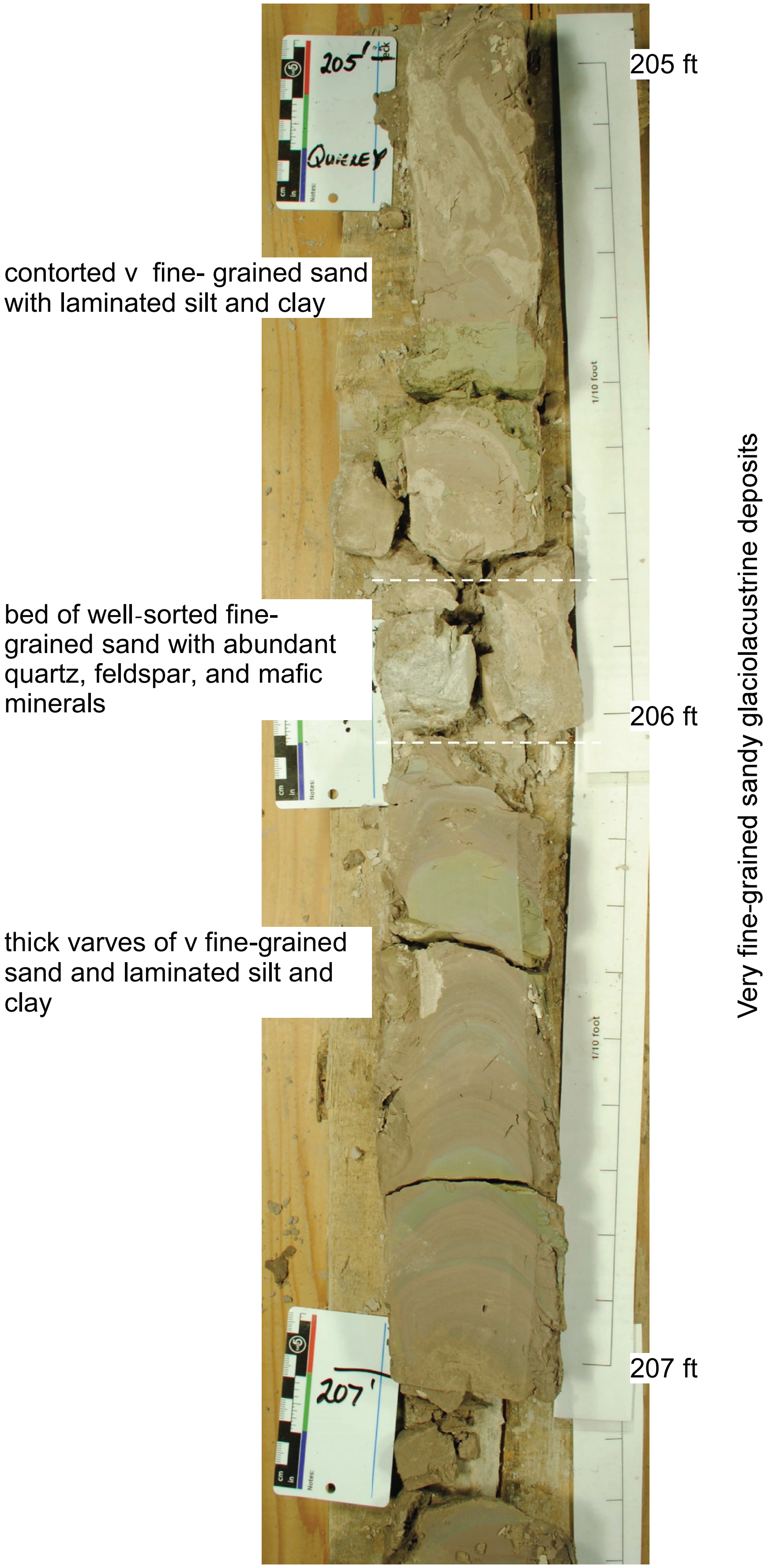


Figure 15. In the very fine-grained lacustrine deposits of the Quigley core, one distinct bed of light gray, well-sorted, fine-grained sand with abundant angular quartz, feldspar, and mafic mineral grains was cored at about 206 ft.

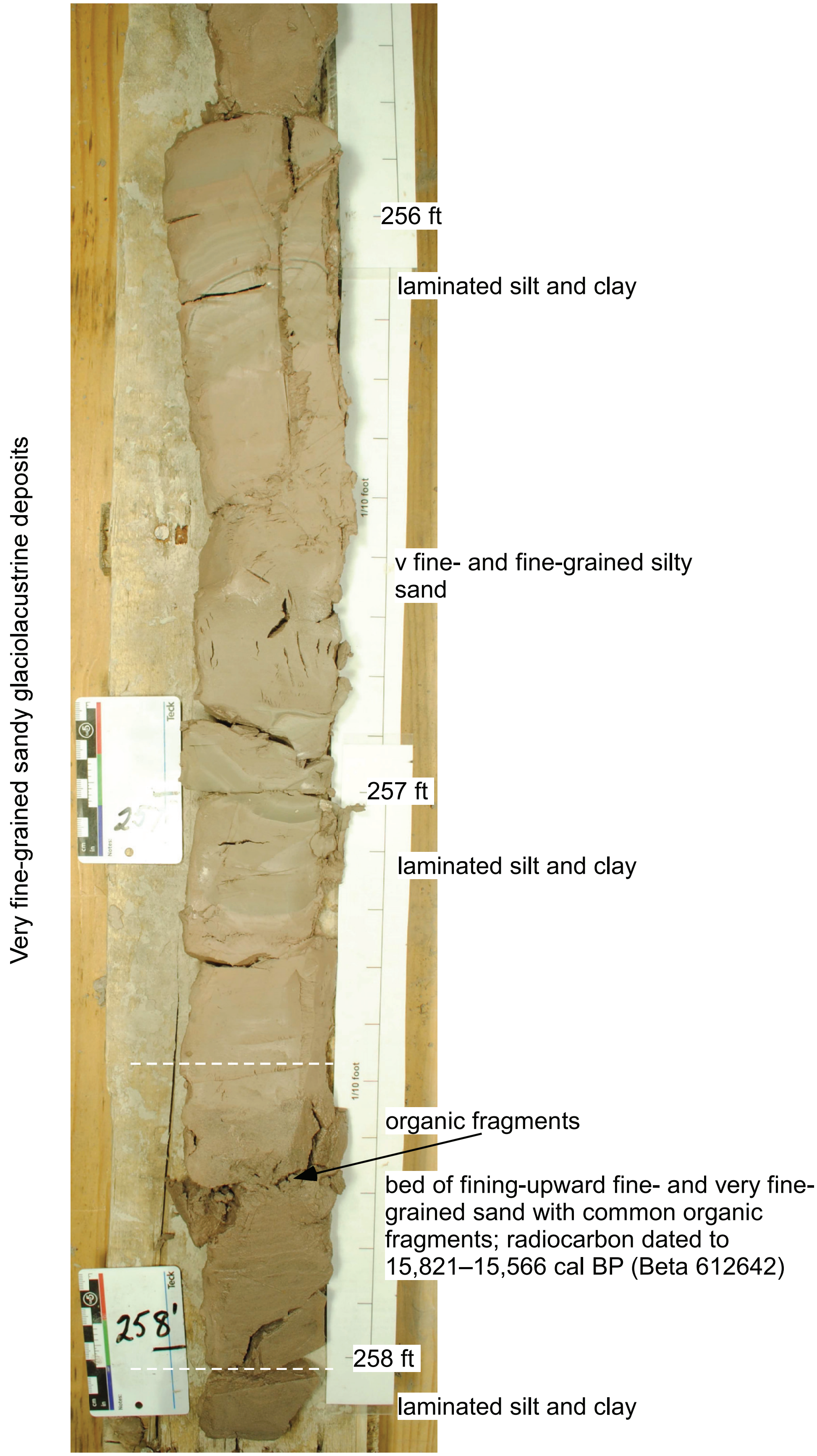


Figure 16. From about 255 to 278 ft in the Quigley core, very fine-grained sand beds are common in the laminated silt and clay dominant, very fine-grained lacustrine deposits. A sand layer at 257.4–258.05 ft contained common organic fragments that were radiocarbon dated at 15,821–15,566 cal BP (Beta 612642).

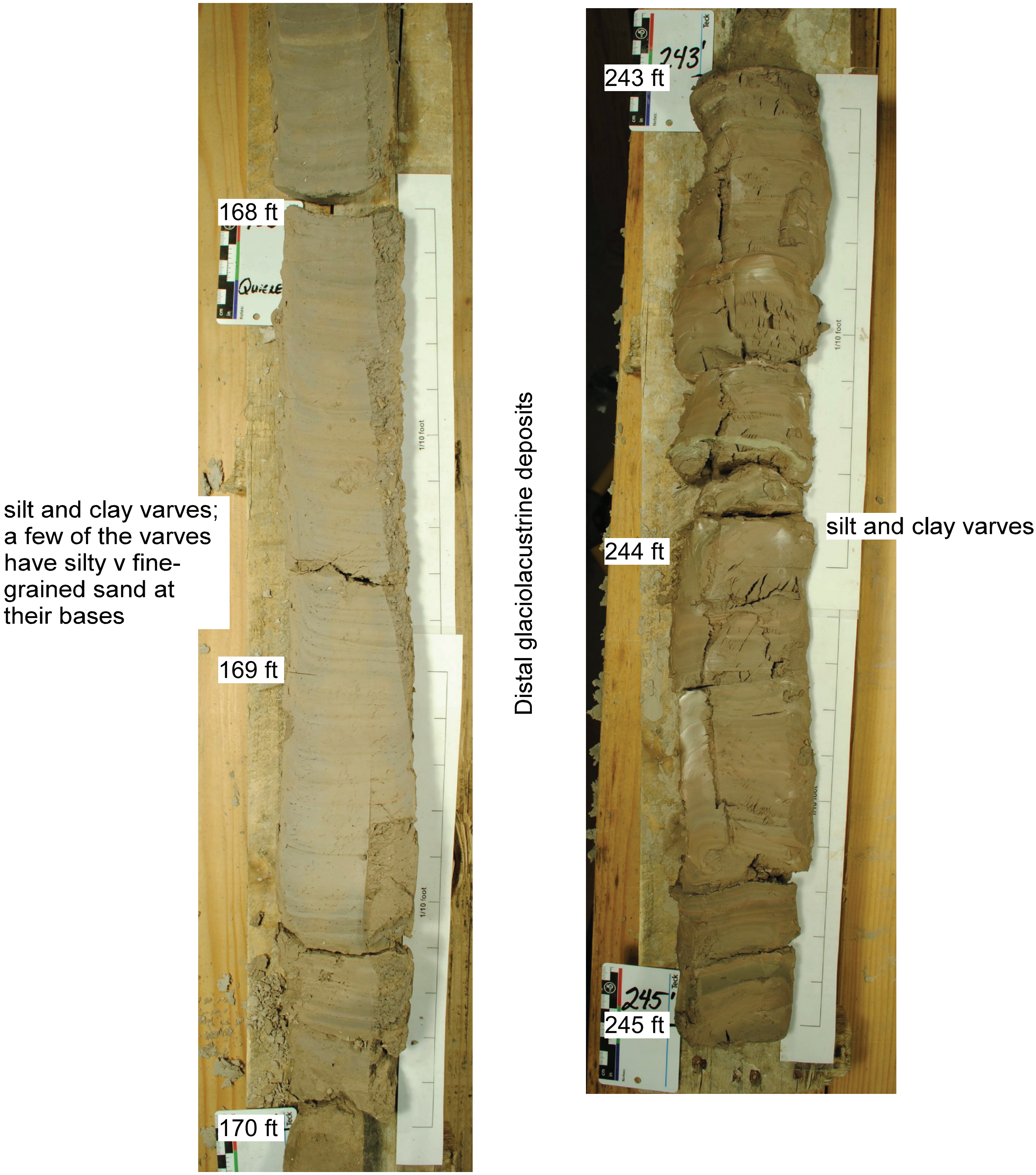


Figure 17. Intervals of locally sandy silt and clay varves in the Quigley core are interpreted as distal lacustrine deposits. The unit apparently coarsens upward overall.

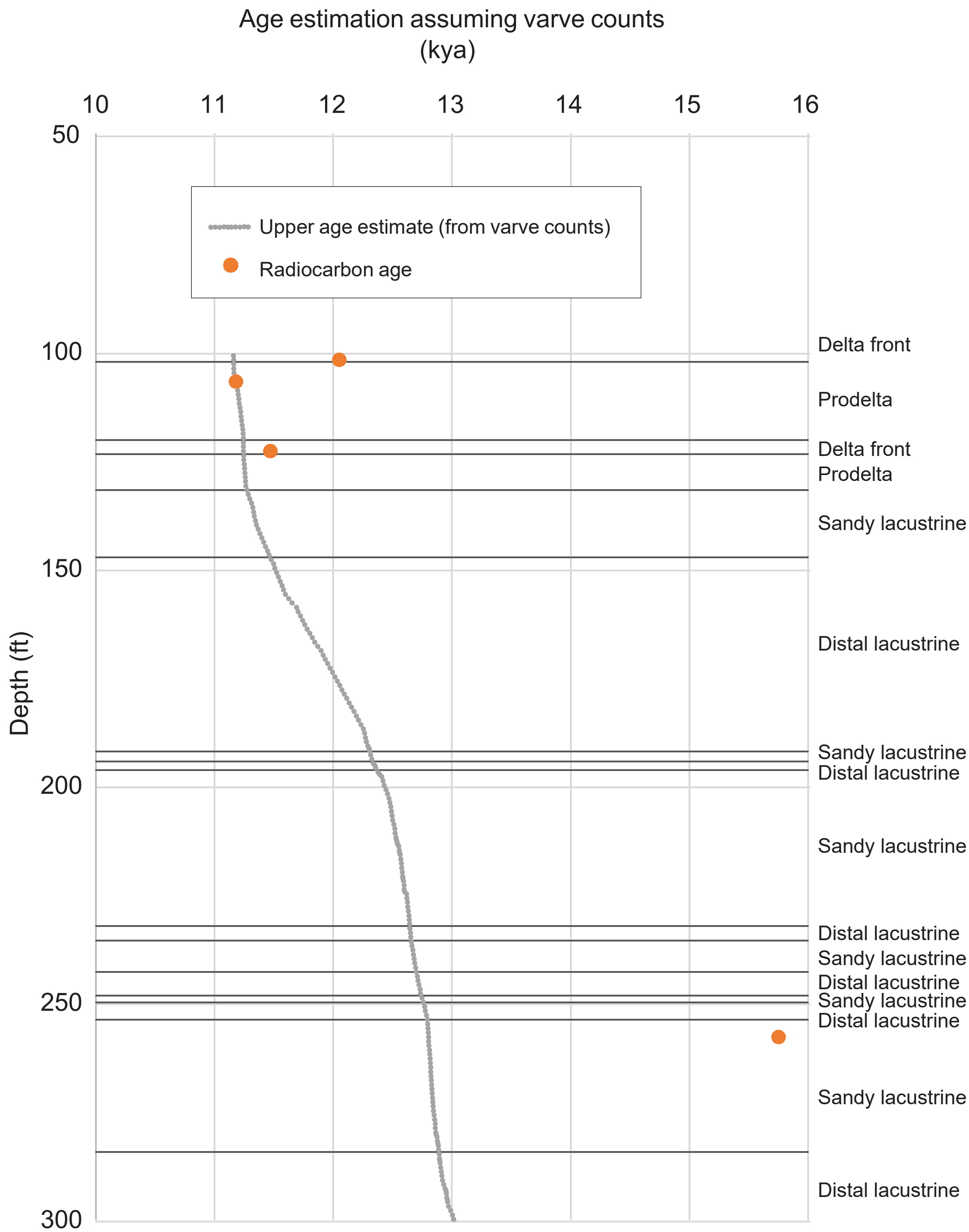


Figure 18. Plotting deposit ages in the Quigley core vs. depth enables comparison of estimated ages from varve counting with radiocarbon ages at four depths. The estimated varve ages are tied to the radiocarbon age at 106.7 ft, which contained only plant material and produced one age. Whereas the upper two radiocarbon ages at 100.85 ft and 122.5 ft contained a range of somewhat older ages, the age of the 257.6 ft sample did not. The older values for the 122.5 ft and 257.6 ft suggest that the varve counts incompletely count the age of the strata.

DISTRIBUTION OF GEOLOGIC UNITS ALONG THE SOUTHERN BOUNDARY OF THE STUDY AREA

The lithologies of units in the Ottey and Quigley cores were correlated with the stratigraphy from 146 drillers' logs and wells drilled for this study across the southern boundary of the study area (fig. 2). A cross section through the study area shows a continuity of units along with a general fining of grain sizes where deposits thicken near to the southwest (Quigley core; fig. 19). The stratigraphy generally consists of sandy and gravelly units near the land surface (shallow alluvium and Creston sand deposits; fig. 19) that overlie fine lake deposits to the southwest and coarse lake deposits and ablation till on the east, near the Swan Range. Till was logged at depth near the southwestern and northeastern ends of the cross section. The lake deposits and till make up the confining unit that separates the shallow and deep aquifers (LaFave and others, 2004). Deep alluvium was penetrated near the bottom of most wells (fig. 19).

The silty and clayey lacustrine deposits and till (here referred to as fine-grained deposits) in the study area represent the low-permeability lithologies of the confining unit. The thicknesses of till and fine-grained and coarse-grained lacustrine sediment in each well log were interpreted to generate maps showing the thickness and character of the confining unit (figs. 20, 21). Strata within this section that produced any water were interpreted to be coarse-grained lacustrine sediments. The thickness of the confining unit is greatest (>600 ft) near the Flathead River (fig. 20). The percent fine-grained lacustrine sediments within fine- and coarse-grained lacustrine deposits in each well was also calculated and plotted (fig. 21). The lacustrine sediments are coarser in the eastern part of the cross section, denoted as having <50 percent fine-grained sediment.

CONCLUSIONS

Ottey Core

The coarse-grained nature of the Ottey core shows that the sediments were deposited by highly energetic processes, either flowing water or glacial ice. Till is interpreted where the core shows evidence of compact silty and/or clayey diamict. As many of the cored intervals contain silt and clay, all may not strictly be till but could be reworked from till. Glacial deposits can commonly be reworked and redeposited, such as where till can be transformed into debris flow deposits or subaqueous fan deposits. So, poorly sorted diamicts can represent multiple sedimentary environments that may be represented in this core.

Sandy deposits in the core, especially where moderately or well sorted, suggest deposition in water bodies, likely a proglacial lake. The generally coarse-grained nature of the sediments suggests that the glaciolacustrine deposits were proximal to the sediment source area. Till above and within the glaciolacustrine sequence supports the interpretation that the proglacial lake was in contact with the glacier (Benn and Evans, 1998, p. 272).

Quigley Core

The sediments of the core are interpreted to be either glaciolacustrine or lacustrine. Glaciers were likely still retreating in the Flathead and Stillwater drainage basins during deposition of at least the lower portion of the section (Smith, 2004a), and therefore the lower portion is likely glaciolacustrine. There is little evidence for dropstones or layers of till in the core, suggesting that sediment-laden glaciers may not have been in close contact with the lake surface during deposition. Therefore, the glaciolacustrine deposits are interpreted as forming in a non-glacier contact proglacial lake (Benn and Evans, 1998, p. 272). However, this interpretation contrasts with that of the Ottey core, suggesting that icebergs calving from the front of the retreating Flathead lobe either contained little sediment or that the Quigley core simply did not encounter iceberg-dropped sediment.

The one instance that may be related to melting ice is the sand bed at 205.8–206.1 ft, where a well-sorted fine-grained sand with abundant quartz, feldspar, and mafic minerals were identified. This sand resembles sediment that would have been derived from clasts of the Hog Heaven tuff. Because glaciers did not exist near the Hog Heaven Volcanics, they cannot be called on to transport clasts into the lake. It is hypothesized that clasts of these volcanic rocks were carried into the lake, possibly from shore ice forming near outcrops of the tuff.

The Quigley core shows shifts between somewhat coarser and somewhat finer grained textures throughout. Overall trends show coarsening-upward sequences were capped by delta front sands at ~124–120 ft

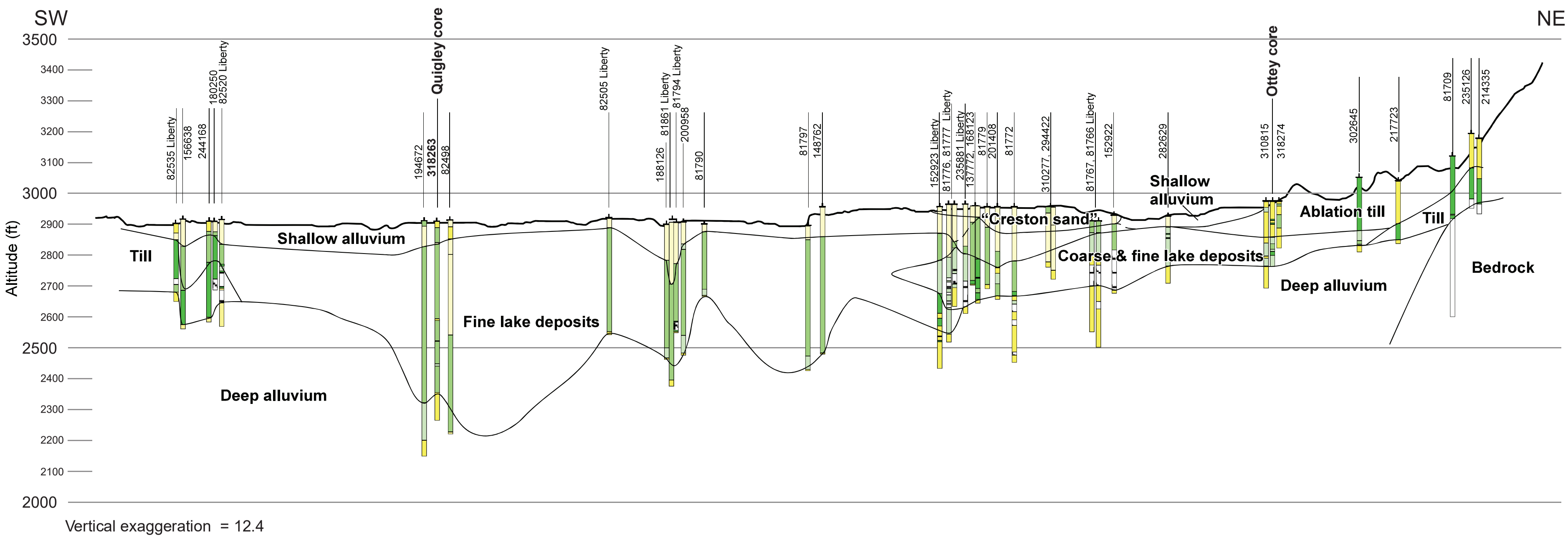


Figure 19. Cross section through the Quigley and Ottey well core locations showing the stratigraphy interpreted from well log data. Not all boundaries of the geologic units match the well data due to projection of the well data onto the cross-section profile. The "fine lake deposits" include all the sandy and distal lacustrine sediments in the Quigley core. The "Ablation till" summarizes much of the outwash, coarse-grained lacustrine, and till in the upper portion of the Ottey core. The GWIC ID numbers of well logs are shown.

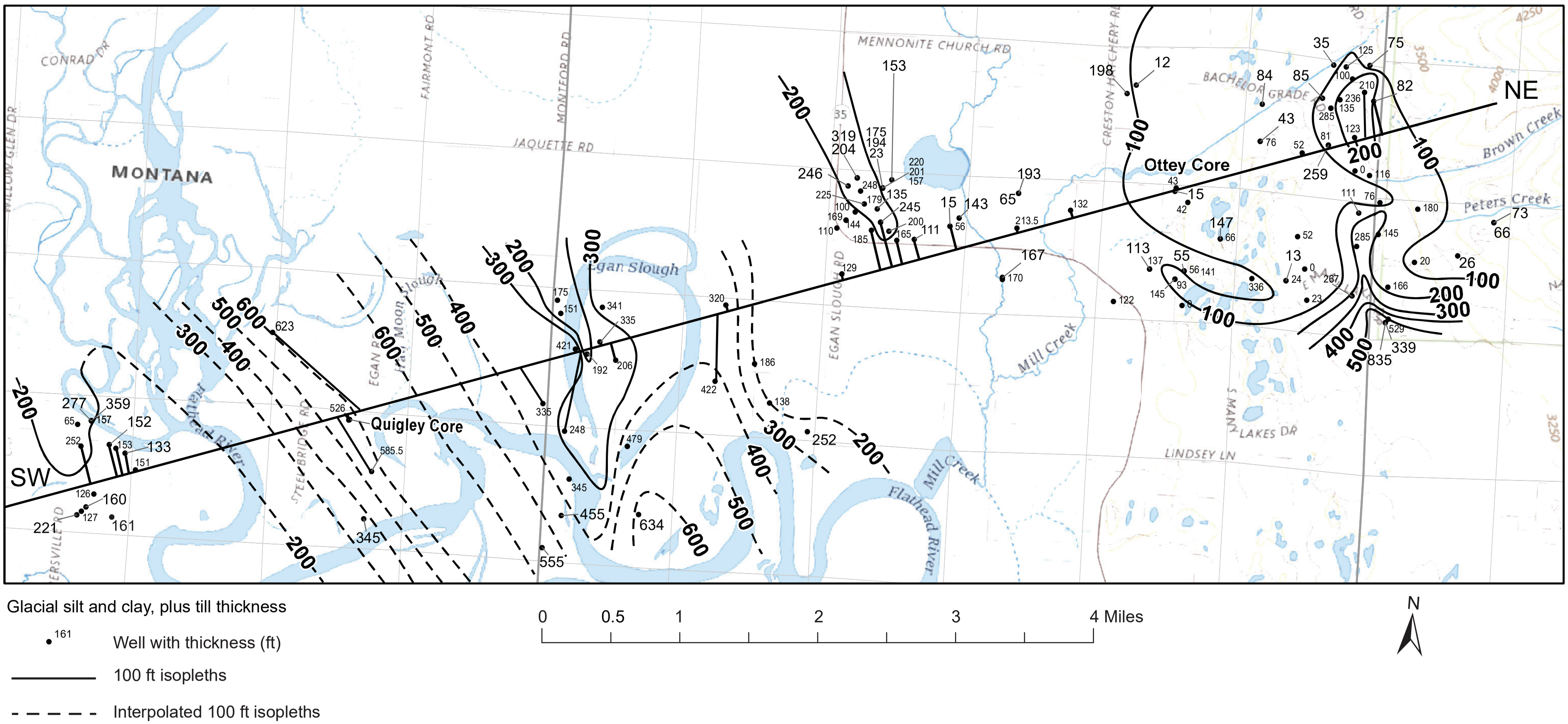


Figure 20. Thickness of till and fine-grained lacustrine sediments in the study area. The thickening near the present course of the Flathead River is evident in two locations, but isopach contours are mostly poorly constrained. To the northeast, the thickness of this unit ranges widely because of the deposition of till, causing increases in thicknesses, and deposition of coarse-grained instead of fine-grained lacustrine deposits, causing decreases in thickness (see fig. 21).

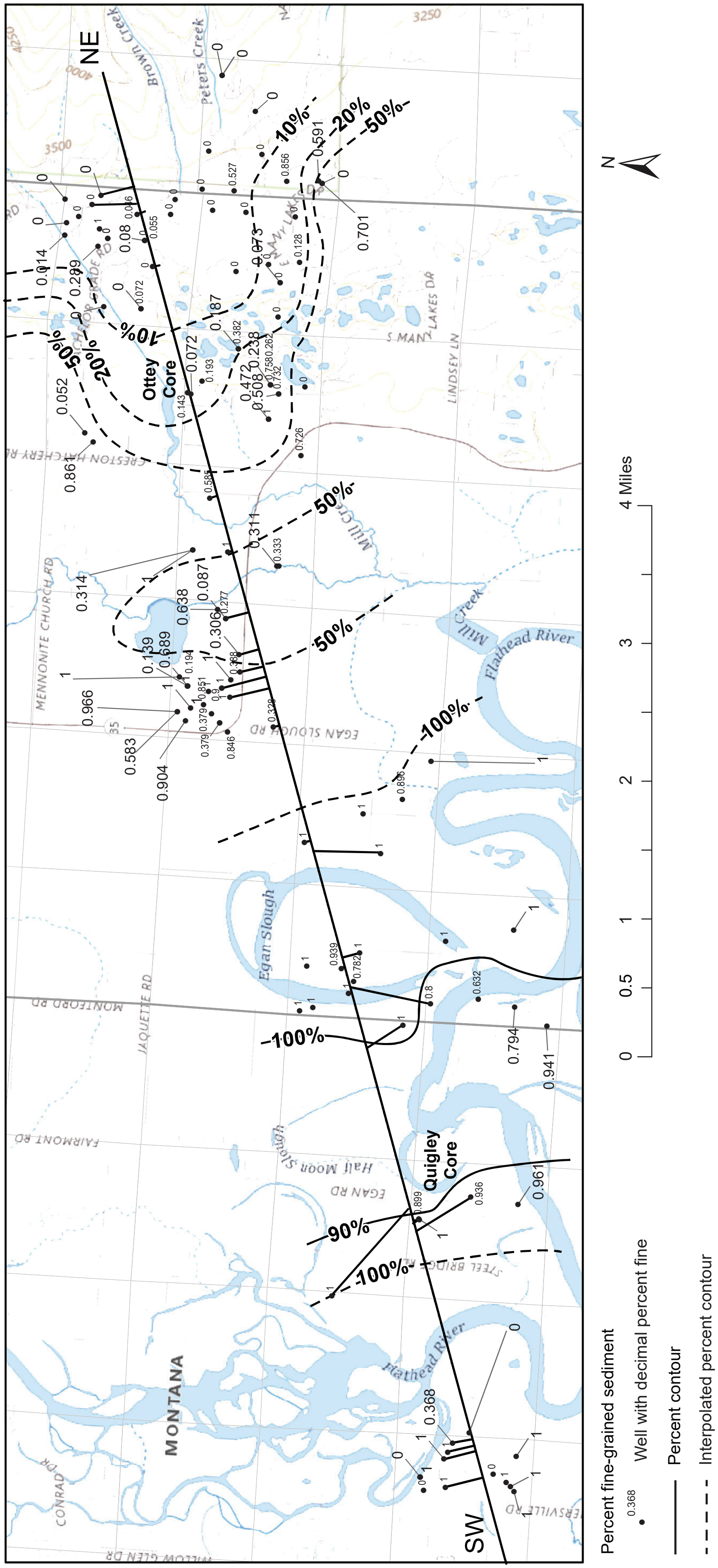


Figure 21. Percent fine-grained lacustrine within lacustrine deposits. Contours are irregular and not well constrained. The coarser nature of the lacustrine sediments in the eastern half of the study area is shown by the values less than 50%. The two areas of thickened lacustrine plus till deposits in the southwestern portion (fig. 20) contain the highest percentage of fine-grained lacustrine deposits.

and ~102–100 ft. The repetition of two major coarsening-upward sequences from distal glaciolacustrine to very fine sandy glaciolacustrine deposits (capped by prodelta and delta front sands in the upper 30 ft of core) suggests lake deepening events at about the 120 ft and 190–200 ft core depths. Each of these coarsening-upward sequences (except for at the top of the core) was followed by deposition of finer sediments. These sequences suggest that the lake underwent shallowing events, which were followed by lake deepening. However, some of the coarsening- and fining-upward cycles could also be explained by lateral shifts in the locus of sediment input towards and away from the core location.

The radiocarbon chronology of the Quigley core shows that it represents more than 4,000 yr of lacustrine sedimentation, to as recently as about 11 ka (tables 2, 3). Comparison of the chronology based on varve counts suggests that erosion surfaces or hiatuses in the sedimentary record may account for up to a few thousand years of missing section (fig. 18). As recently as 14.5 ka, Glacial Lake Missoula still dammed the Clark Fork River near the present Idaho–Montana border (Breckenridge and Phillips, 2010; Balbas and others, 2017). Therefore, glaciolacustrine sediments in the lower portion of the Quigley core were likely deposited in Glacial Lake Missoula. At some point after ~14.5 ka, Glacial Lake Missoula finally drained and the Flathead Valley was flooded by Glacial Lake Kalispell, which was dammed along the Polson Moraine (Konizeski and others, 1968; LaFave and others, 2004; Smith, 2004). However, by 13.7–13.4 cal ka B.P., when the Glacier Peak tephra was deposited in eolian sand in the Flathead Valley east and north of Kalispell, both the glaciers and the glacial lakes had retreated from much of the Flathead Valley (Konizeski and others, 1968; LaFave and others, 2004; Smith, 2004a). Because the upper part of the Quigley core is ~2,000 yr younger than the Glacier Peak tephra, these lacustrine deposits were apparently deposited in the ancestral Flathead Lake without nearby glacial influence.

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REFERENCES

Ashley, G.M., 1975, Rhythmic sedimentation in glacial Lake Hitchcock, Massachusetts-Connecticut, *in* Jopling, A.V. and McDonald, B.C., eds., Glaciofluvial and Glaciolacustrine Sedimentation, SEPM (Society for Sedimentary Geology), p. 304–320, https://doi.org/10.2110/pec.75.23.0304

Balbas, A.M., Barth, A.M., Clark, P.U., Clark, J., Caffee, M., O'Connor, J., Baker, V.R., Konrad, K., and Bjornstad, B., 2017, ^{10}Be dating of late Pleistocene megafloods and Cordilleran Ice Sheet retreat in the northwestern United States: Geology, v. 45, p. 583–586, https://doi.org/10.1130/G38956.1

Barrow, J.C., 1994, The resonant sonic drilling method—An innovative technology for environmental restoration programs: Ground Water Monitoring and Remediation, v. 14, no. 2, p. 153–160, https://doi.org/10.1111/j.1745-6592.1994.tb00110.x

Benn, D.I., and Evans, D.J.A., 1998, Glaciers and glaciation: London, Edward Arnold, 734 p., https://doi.org/10.4324/9780203785010

Bobst, A., Rose, J., and Berglund, J., 2022, An evaluation of the unconsolidated hydrogeologic units in the south-central Flathead Valley, Montana: Montana Bureau of Mines and Geology Open-File Report 752, 16 p., https://doi.org/10.59691/SRLK8303

Bobst, A., Berglund, J., Smith, L., and Gebril, A., in prep, Hydrogeologic investigation of the East Flathead Valley, Flathead County, Montana: Montana Bureau of Mines and Geology Report of Investigation.

Boggs Jr., S., 1987, Principles of stratigraphy and basin analysis: Upper Saddle River, Prentice Hall, 519–526 p.

Breckenridge, R.M., and Phillips, W.M., 2010, New cosmogenic ^{10}Be surface exposure ages for the Purcell Trench Lobe of the Cordilleran ice sheet in Idaho, *in* Geological Society of America

Abstracts with Programs, Geological Society of America, v. 42.5, p. 309, available at https://gsa.confex.com/gsa/2010AM/webprogram/Paper178203.html [Accessed February 2025].

Bronk, Ramsey, C., 2009, Bayesian analysis of radiocarbon dates: Radiocarbon, v. 51, no. 1, p. 337–360, https://doi.org/10.1017/S0033822200033865

Garland, G.D., Kanasewich, E.R., and Thompson, T.L., 1961, Gravity measurements over the southern Rocky Mountain Trench area of British Columbia: Journal of Geophysical Research, v. 66, no. 8, p. 2495–2505, available at https://pubs.usgs.gov/bul/1197/report.pdf [Accessed February 2025].

Gustavson, T.C., Ashley, G.M., and Boothroyd, J.C., 1975, Depositional sequences in glaciolacustrine deltas: Glaciofluvial and glaciolacustrine sedimentation, p. 264–280, https://doi.org/10.2110/PEC.75.23.0264

Harrison, J.E., Cressman, E.R., and Whipple, J.W., 1992, Geologic and structure maps of Kalispell 1 x 2-degree quadrangle, Montana and Alberta, British Columbia: United States Geological Survey Miscellaneous Geologic Investigation 2267, 2 sheets, scale 1:250,000, available at https://pubs.usgs.gov/imap/i2267/ [Accessed February 2025].

Janitzky, P., 1986, Particle size analysis, *in* Singer, M.J., and Janitzky, P., Field and laboratory procedures used in a chronosequence study: USGS Bulletin 1648, p. 11–16, https://doi.org/10.3133/b1648

Konizeski, R.L., Brietkrietz, A., and McMurtrey, R.G., 1968, Geology and ground water resources of the Kalispell Valley, northwestern Montana: Montana Bureau of Mines and Geology Bulletin 68, 42 p., available at https://mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10069 [Accessed February 2017].

LaFave, J.I., Smith, L.N., and Patton, T.W., 2004, Ground-water resources of the Flathead Lake area: Flathead, Lake, and parts of Missoula and Sanders Counties. Part A—Descriptive overview: Montana Bureau of Mines and Geology Montana Ground-Water Assessment Atlas 2-A, 144 p., available at https://mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10310 [Accessed February 2025].

Lonn, J.D., Burmester, R.F., Lewis, R.S., and McFaddan, M.D., 2020, The Mesoproterozoic Belt Supergroup, *in* Metesh, J.J., and Vuke, S.M., eds., Geology of Montana—Geologic History: Montana Bureau of Mines and Geology Special Publication 122, v. 1, 38 p., available at https://mbmg.mtech.edu/pdf/geologyvolume/Lonn_BeltFinal.pdf [Accessed February 2025].

Noble, R.A., and Stanford, J.A., 1986, Ground-water resources and water quality of unconfined aquifers in the Kalispell valley, Montana: Montana Bureau of Mines and Geology Open-File Report 177, 112 p.

Reimer, P.J., Austin, W.E.N., Bard, E., and others, 2020, The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP): Radiocarbon, v. 62, no. 4, p. 725–757, https://doi.org/10.1017/RDC.2020.41

Rose, J., 2018, Three-dimensional hydrostratigraphic model of the subsurface geology, Flathead Valley, Kalispell, Montana: Montana Bureau of Mines and Geology Open-File Report 703, 44 p., 1 sheet, available at https://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=32017 [Accessed February 2025].

Rose, J., Bobst, A., and Gebril, A., 2022, Hydrogeologic investigation of the deep alluvial aquifer, Flathead Valley, Montana: Montana Bureau of Mines and Geology Report of Investigation 32, 44 p., available at https://mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=32476 [Accessed February 2025].

Smith, L.N., 2004a, Late Pleistocene stratigraphy and implications for deglaciation and subglacial processes of the Flathead Lobe of the Cordilleran Ice Sheet, Flathead Valley, Montana, USA: Sedimentary Geology, v. 165, p. 295–332, https://doi.org/10.1016/j.sedgeo.2003.11.013

Smith, L.N., 2004b, Surficial geologic map of the upper Flathead River valley (Kalispell valley) area, Flathead County, northwestern Montana: Montana Bureau of Mines and Geology Montana Ground-Water Assessment Atlas 2-B-06, 1 sheet, scale 1:70,000, available at https://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10317 [Accessed February 2025].

Smith, L.N., 2004c, Altitude of and depth to the bedrock surface: Flathead Lake Area, Flathead and Lake Counties, Montana: Montana Bureau of Mines and Geology Montana Ground-Water Assessment Atlas 2-B-07, 1 sheet, scale 1:150,000, available at https://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10318 [Accessed February 2025].

Smith, L.N., 2004d, Depth to deep alluvium of the deep aquifer in the Kalispell valley: Flathead County, Montana: Montana Bureau of Mines and Geology Montana Ground-Water Assessment Atlas 2-B-08, 1 sheet, scale 1:63,360, available at https://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10319 [Accessed February 2025].

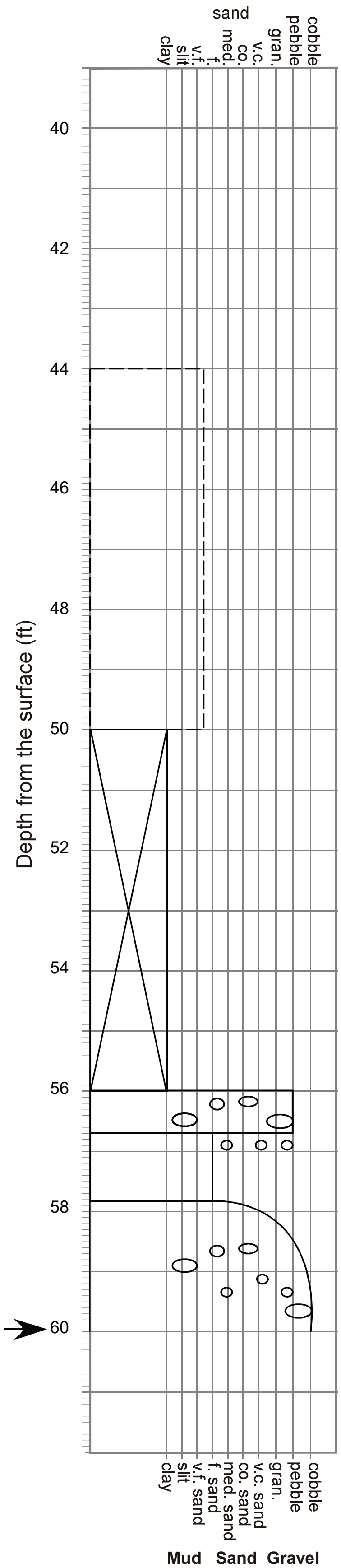
Smith, L.N., 2004e, Thickness of the confining unit in the Kalispell valley, Flathead County, Montana: Montana Bureau of Mines and Geology Montana Ground-Water Assessment Atlas 2-B-09, 1 sheet, scale 1:100,000, available at https://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10320 [Accessed February 2025].

Smith, L.N., 2004f, Thickness of shallow alluvium, Flathead Lake area, Flathead, Lake, Missoula, and Sanders Counties, Montana: Montana Bureau of Mines and Geology Montana Ground-Water Assessment Atlas 2-B-11, 1 sheet, scale 1:100,000, available at https://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10322 [Accessed February 2025].

APPENDIX A

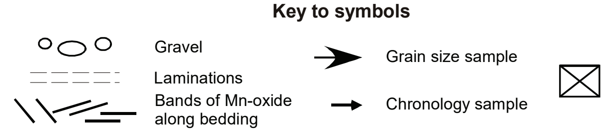
OTTEY CORE DETAILED LOG

Location: Ottey core **Date described:** 9/5/2021 **Name: Larry Smith**



Description	Environment interpretation
Quickly drilled from 0-44 ft; upper ~40 ft were upper sand and gravel aquifer; hit hard drilling every 5 ft or so, probably gravel.	
~44-56 ft - drill pipe quickly “fell” through sediment; assumed to be soft sand or silt. Possilbe 7 ft “plug” at about 40-50 ft in pipe - clay?	
We decided to start coring with 5 ft intervals at 50 ft, instead of 70 ft as predicted.	
Granule-pebbly clay-bound sand and gravel; sticky diamict	Till
Silty and clayey sand; few pebbles near top	
Gravel with coarse sand; rounded and subrounded granules, pebbles, and cobbles	Outwash

Key to symbols



Gravel

Laminations

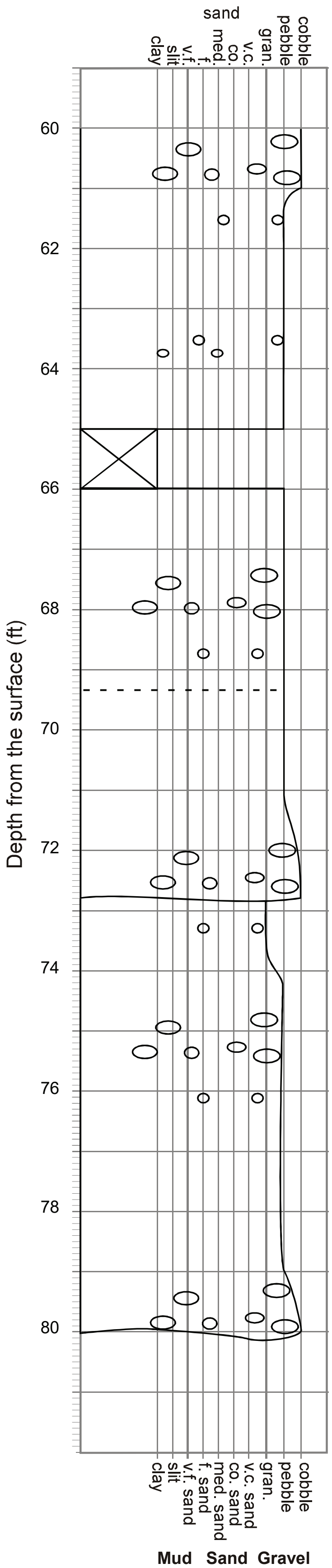
Bands of Mn-oxide along bedding

Grain size sample

Chronology sample

no core

Location: Ottey core **Date described:** 9/5/2021 **Name: Larry Smith**

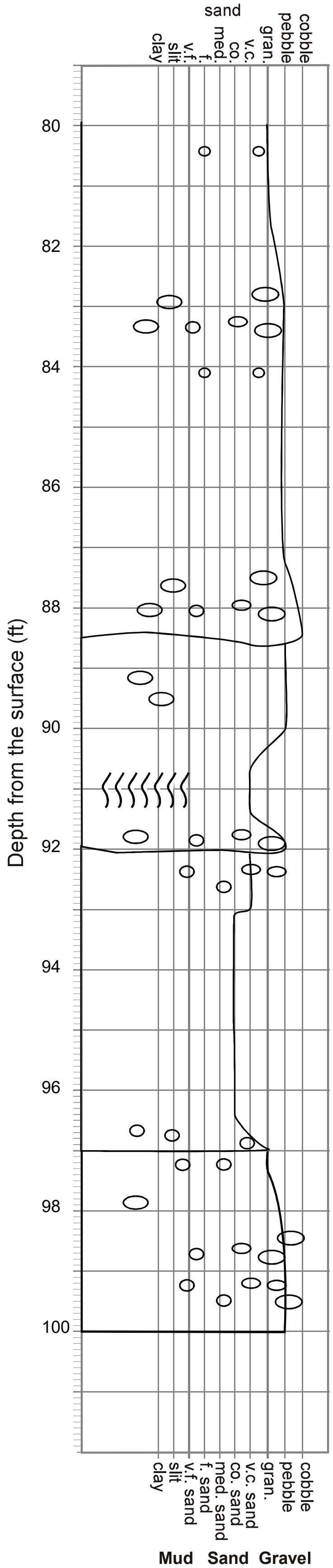


Depth (ft)	Description	Environment interpretation
60–65	Gravel with coarse sand; rounded and subrounded granules, pebbles, and cobbles	Outwash
66–69.4	Silty and clayey gravel, locally dense and compact; diamict with sticky matrix; subangular pebbles and few cobbles; subrounded small pebbles and granules	Till
69.4–72.9	Cobble-dominant at base of fining-upward sequence	Outwash within or under(?) till
72.9–73.9	Granules, pebbles, and sand bound by silt and clay	Till or reworked till(?)
73.9–80	Cobble-dominant at base of fining-upward sequence	Outwash within or under(?) till

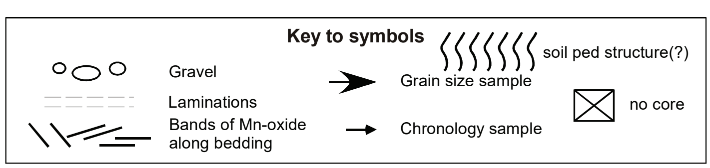
Key to symbols

- Gravel
- Laminations
- Bands of Mn-oxide along bedding
- Grain size sample
- Chronology sample
- no core

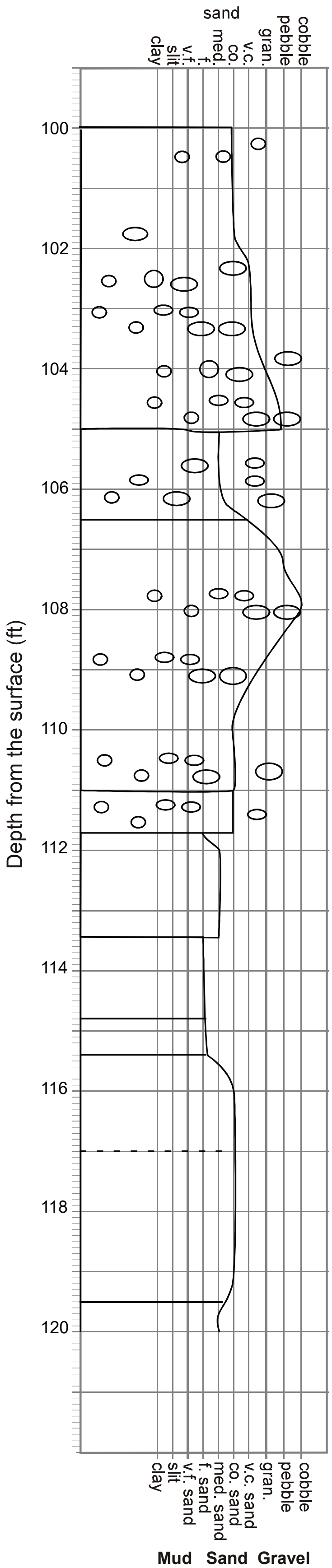
Location: Ottey core **Date described:** 9/5/2021 **Name: Larry Smith**



Description	Environment interpretation
Loose gravel	
silty and clayey clast-supported gravel	
Mostly rounded and subrounded pebbles and cobbles, few subangular clasts	
Sandy pebble gravel with subangular and subrounded pebbles	
Cobble-dominant loose gravel at base of fining-upward sequence	
Loose sandy pebble gravel with poorly sorted sandy matrix	
Possible weak soil?	Outwash
Cohesive very coarse sand with common subangular and subrounded pebbles and granules;	
Coarse-grained sand with few granules and pebbles	
Loose coarse-grained sand with few granules and pebbles	
Poorly sorted coarse sand and silt; few granules	
Pebble gravel with few cobbles with slightly silty, poorly sorted coarse sand matrix; sand subrounded and subangular	



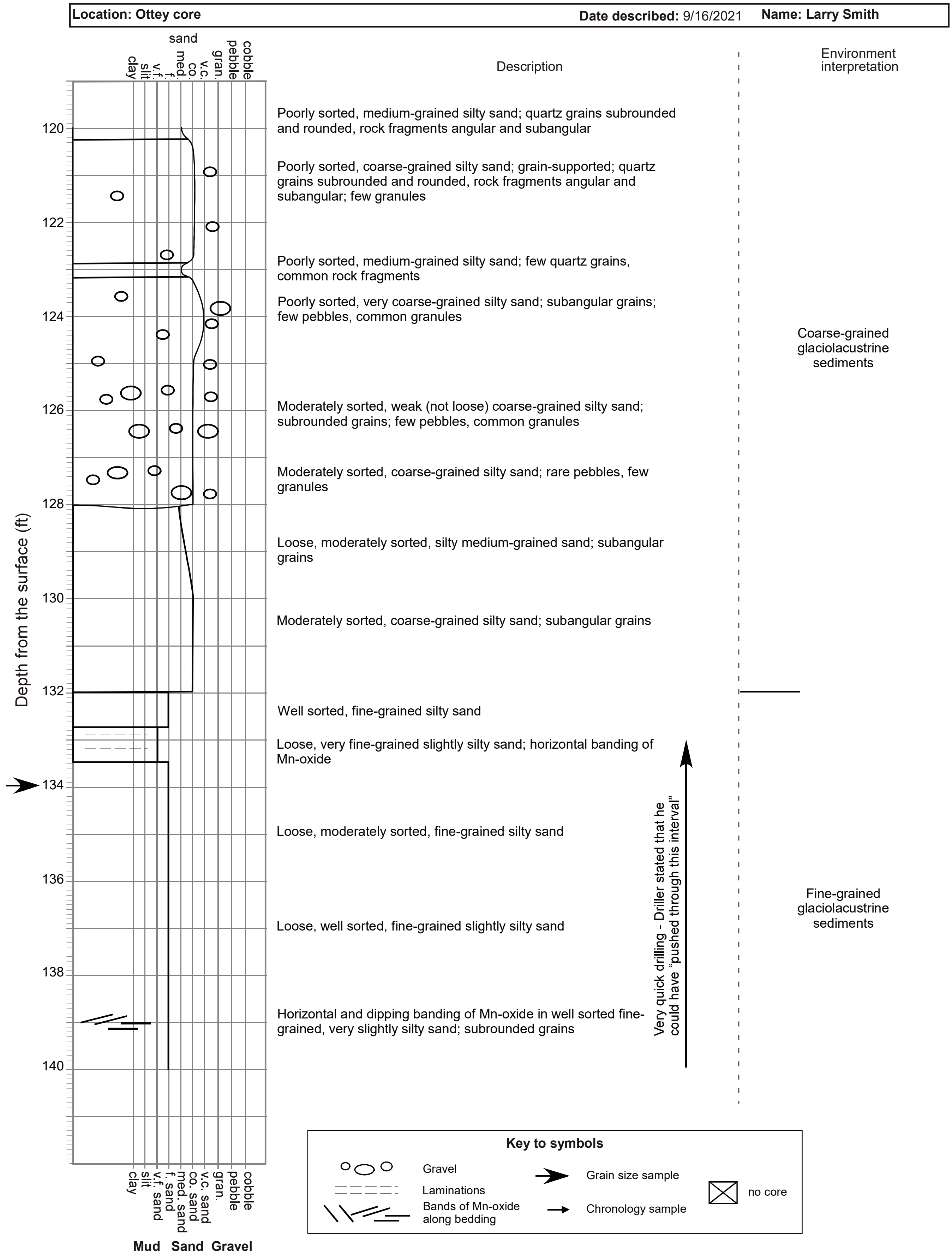
Location: Ottey core **Date described:** 9/20/2021 **Name: Larry Smith**

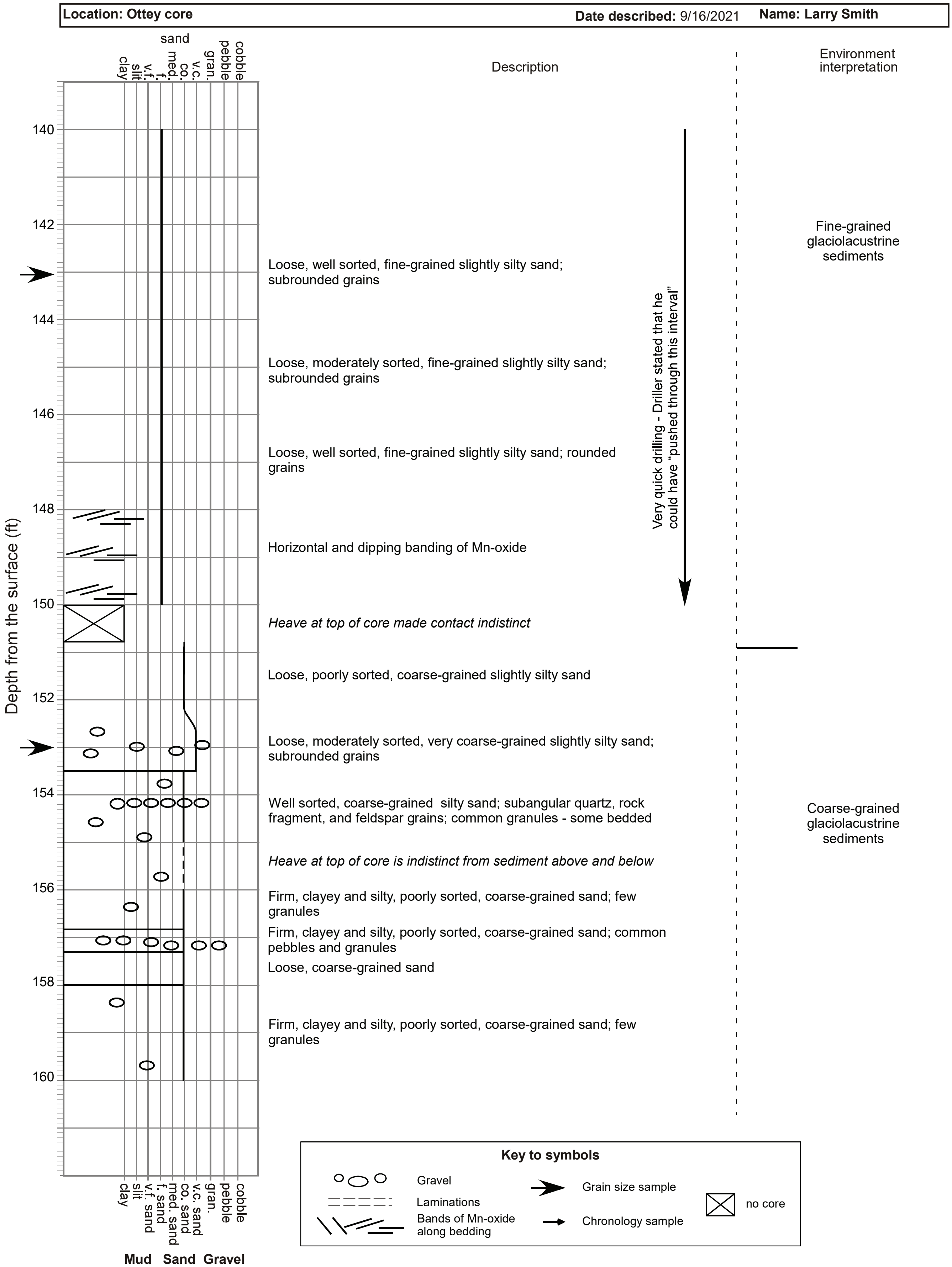


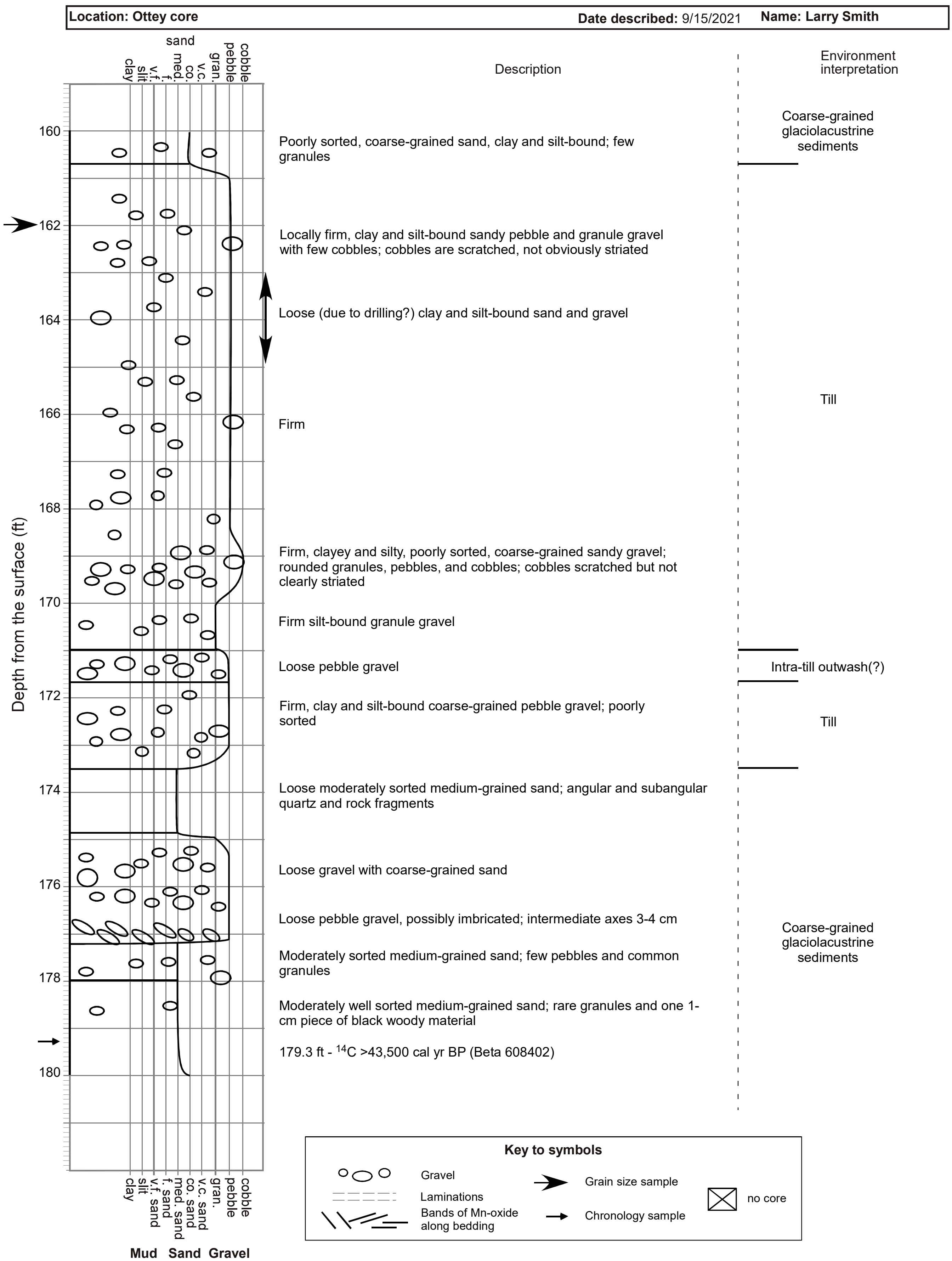
Description	Environment interpretation
Poorly sorted silty coarse sand with few granules; sand subrounded and subangular	Outwash
Pebble gravel with few cobbles with poorly sorted coarse sand matrix; sand subrounded and subangular	
Poorly sorted slightly silty medium-grained sand with few subrounded granules and rare pebbles	
Fining-upward clast-supported cobble gravel with poorly sorted coarse sand matrix	
Coarsening-upward granule-to-pebble gravel in poorly sorted coarse sand matrix	
Coarse-grained sand with granules and rare pebbles	
Pebbly, poorly sorted coarse-grained sand	
Loose, poorly sorted coarse-grained sand with few granules	
Fining-upward medium-to-fine-grained silty sand; moderately sorted	Coarse-grained glaciolacustrine sediments
Moderately sorted, loose, fine-grained sand; rounded quartz grains and subrounded rock fragments	
Loose, well sorted fine-grained sand	
Moderately sorted, loose, silty coarse-grained sand	
transitional contact	
Moderately sorted, firm, silty coarse-grained sand	
Poorly sorted, medium-grained silty sand; quartz grains subrounded and rounded, rock fragments angular and subangular	

Key to symbols

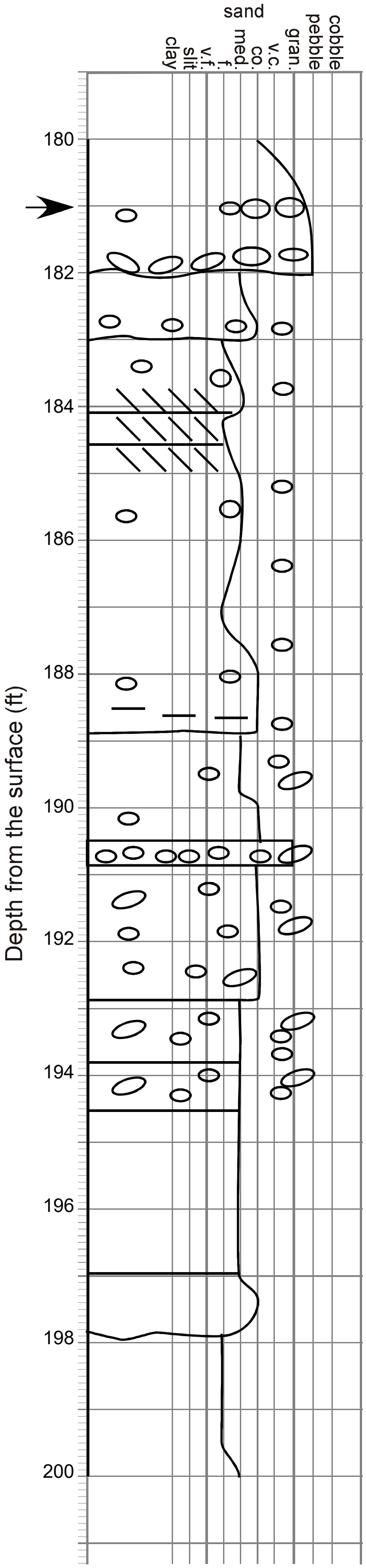
- Gravel
- Laminations
- Bands of Mn-oxide along bedding
- Grain size sample
- Chronology sample
- no core


Location: Ottey core
Date described: 9/16/2021
Name: Larry Smith
sand
clay
silt
v.f.
f.
med.
co.
v.c.
gran.
pebble
cobble
Description
Environment interpretation
Depth from the surface (ft)
120
122
124
126
128
130
132
134
136
138
140
Poorly sorted, medium-grained silty sand; quartz grains subrounded and rounded, rock fragments angular and subangular
Poorly sorted, coarse-grained silty sand; grain-supported; quartz grains subrounded and rounded, rock fragments angular and subangular; few granules
Poorly sorted, medium-grained silty sand; few quartz grains, common rock fragments
Poorly sorted, very coarse-grained silty sand; subangular grains; few pebbles, common granules
Moderately sorted, weak (not loose) coarse-grained silty sand; subrounded grains; few pebbles, common granules
Moderately sorted, coarse-grained silty sand; rare pebbles, few granules
Loose, moderately sorted, silty medium-grained sand; subangular grains
Moderately sorted, coarse-grained silty sand; subangular grains
Well sorted, fine-grained silty sand
Loose, very fine-grained slightly silty sand; horizontal banding of Mn-oxide
Loose, moderately sorted, fine-grained silty sand
Loose, well sorted, fine-grained slightly silty sand
Horizontal and dipping banding of Mn-oxide in well sorted fine-grained, very slightly silty sand; subrounded grains
Very quick drilling - Driller stated that he could have "pushed through this interval"
Coarse-grained glaciolacustrine sediments
Fine-grained glaciolacustrine sediments
clay
silt
v.f. sand
f. sand
med. sand
co. sand
v.c. sand
gran.
pebble
cobble
Mud
Sand
Gravel
Key to symbols
Gravel
Laminations
Bands of Mn-oxide along bedding
Grain size sample
Chronology sample
no core


Location: Ottey core
Date described: 9/16/2021
Name: Larry Smith
clay
silt
v.f.
f.
med.
co.
v.c.
sand
gran.
pebble
cobble
Description
Environment interpretation
Depth from the surface (ft)
140
142
144
146
148
150
152
154
156
158
160
Loose, well sorted, fine-grained slightly silty sand; subrounded grains
Loose, moderately sorted, fine-grained slightly silty sand; subrounded grains
Loose, well sorted, fine-grained slightly silty sand; rounded grains
Horizontal and dipping banding of Mn-oxide
Heave at top of core made contact indistinct
Loose, poorly sorted, coarse-grained slightly silty sand
Loose, moderately sorted, very coarse-grained slightly silty sand; subrounded grains
Well sorted, coarse-grained silty sand; subangular quartz, rock fragment, and feldspar grains; common granules - some bedded
Heave at top of core is indistinct from sediment above and below
Firm, clayey and silty, poorly sorted, coarse-grained sand; few granules
Firm, clayey and silty, poorly sorted, coarse-grained sand; common pebbles and granules
Loose, coarse-grained sand
Firm, clayey and silty, poorly sorted, coarse-grained sand; few granules
Very quick drilling - Driller stated that he could have “pushed through this interval”
Fine-grained glaciolacustrine sediments
Coarse-grained glaciolacustrine sediments
clay
silt
v.f. sand
f. sand
med. sand
co. sand
v.c. sand
gran.
pebble
cobble
Mud
Sand
Gravel
Key to symbols
Gravel
Laminations
Bands of Mn-oxide along bedding
Grain size sample
Chronology sample
no core


Location: Ottey core
Date described: 9/15/2021
Name: Larry Smith
sand
clay
silt
v.f.
f.
med.
co.
v.c.
gran.
pebble
cobble
Description
Environment interpretation
Depth from the surface (ft)
160
162
164
166
168
170
172
174
176
178
180
Poorly sorted, coarse-grained sand, clay and silt-bound; few granules
Locally firm, clay and silt-bound sandy pebble and granule gravel with few cobbles; cobbles are scratched, not obviously striated
Loose (due to drilling?) clay and silt-bound sand and gravel
Firm
Firm, clayey and silty, poorly sorted, coarse-grained sandy gravel; rounded granules, pebbles, and cobbles; cobbles scratched but not clearly striated
Firm silt-bound granule gravel
Loose pebble gravel
Firm, clay and silt-bound coarse-grained pebble gravel; poorly sorted
Loose moderately sorted medium-grained sand; angular and subangular quartz and rock fragments
Loose gravel with coarse-grained sand
Loose pebble gravel, possibly imbricated; intermediate axes 3-4 cm
Moderately sorted medium-grained sand; few pebbles and common granules
Moderately well sorted medium-grained sand; rare granules and one 1-cm piece of black woody material
179.3 ft - ^{14}C >43,500 cal yr BP (Beta 608402)
Coarse-grained glaciolacustrine sediments
Till
Intra-till outwash(?)
Till
Coarse-grained glaciolacustrine sediments
clay
silt
v.f. sand
f. sand
med. sand
co. sand
v.c. sand
gran.
pebble
cobble
Mud
Sand
Gravel
Key to symbols
Gravel
Laminations
Bands of Mn-oxide along bedding
Grain size sample
Chronology sample
no core

Location: Ottey core **Date described:** 9/14/2021 **Name: Larry Smit**



Description

Moderately sorted coarse-grained sand; rare granules

Sandy pebble gravel sorted coarse-grained sand; rare granules

Pebble gravel; 5-6 cm long-, 4-5 cm intermediate-axes

Moderately sorted medium-grained sand; few granules; inclined Mn-oxide bands along cross beds

Well sorted fine-grained sand; inclined Mn-oxide bands along cross beds

Moderately well sorted medium-grained sand; inclined Mn-oxide bands along cross beds

Moderately well sorted fine-grained sand

Moderately sorted medium-grained sand; few granules

Loose, moderately sorted coarse-grained sand; few granules; horizontal Mn-oxide bands

Moderately sorted medium-grained sand; few granules, rare pebbles

Moderately sorted coarse-grained sand; few granules

Granule gravel, few pebbles

Loose, moderately sorted coarse-grained sand; subangular grains; common granules and pebbles

Poorly sorted, silty coarse-grained sand; common granules, few pebbles

Moderately well sorted, silty medium-grained sand; common granules, few pebbles

Well sorted medium-grained sand; rounded and subrounded quartz grains and subangular rock fragments

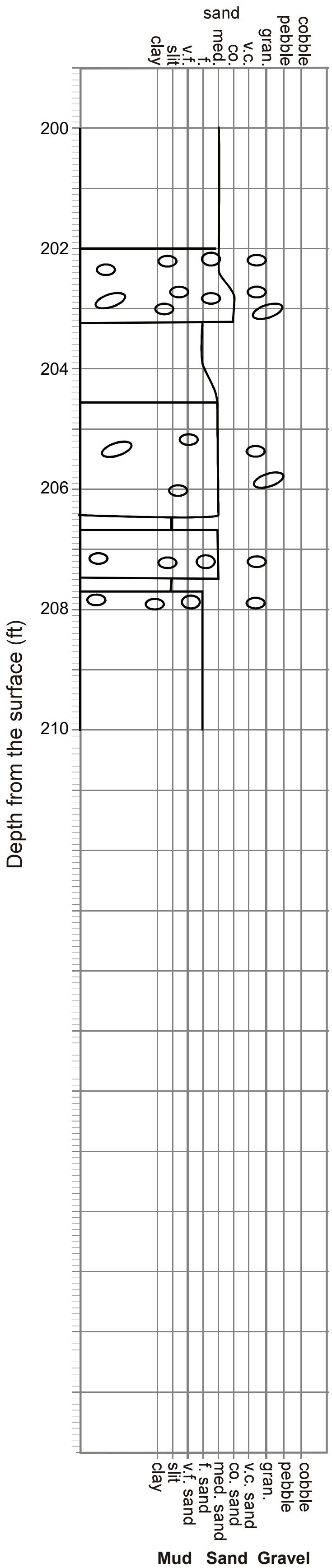
Moderately sorted, silty coarse-grained sand

Well sorted, silty fine-grained sand; common rounded quartz, feldspar, and rock fragments

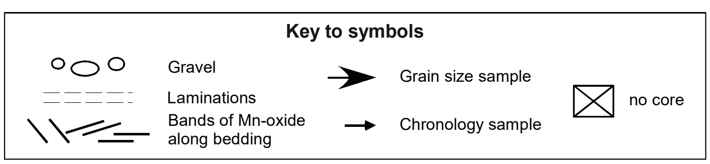
Environr
interpret

Coarse-grai
glaciolacust
sediment

Location: Ottey core | **Date described:** 9/14/2021 | **Name: Larry Smith**

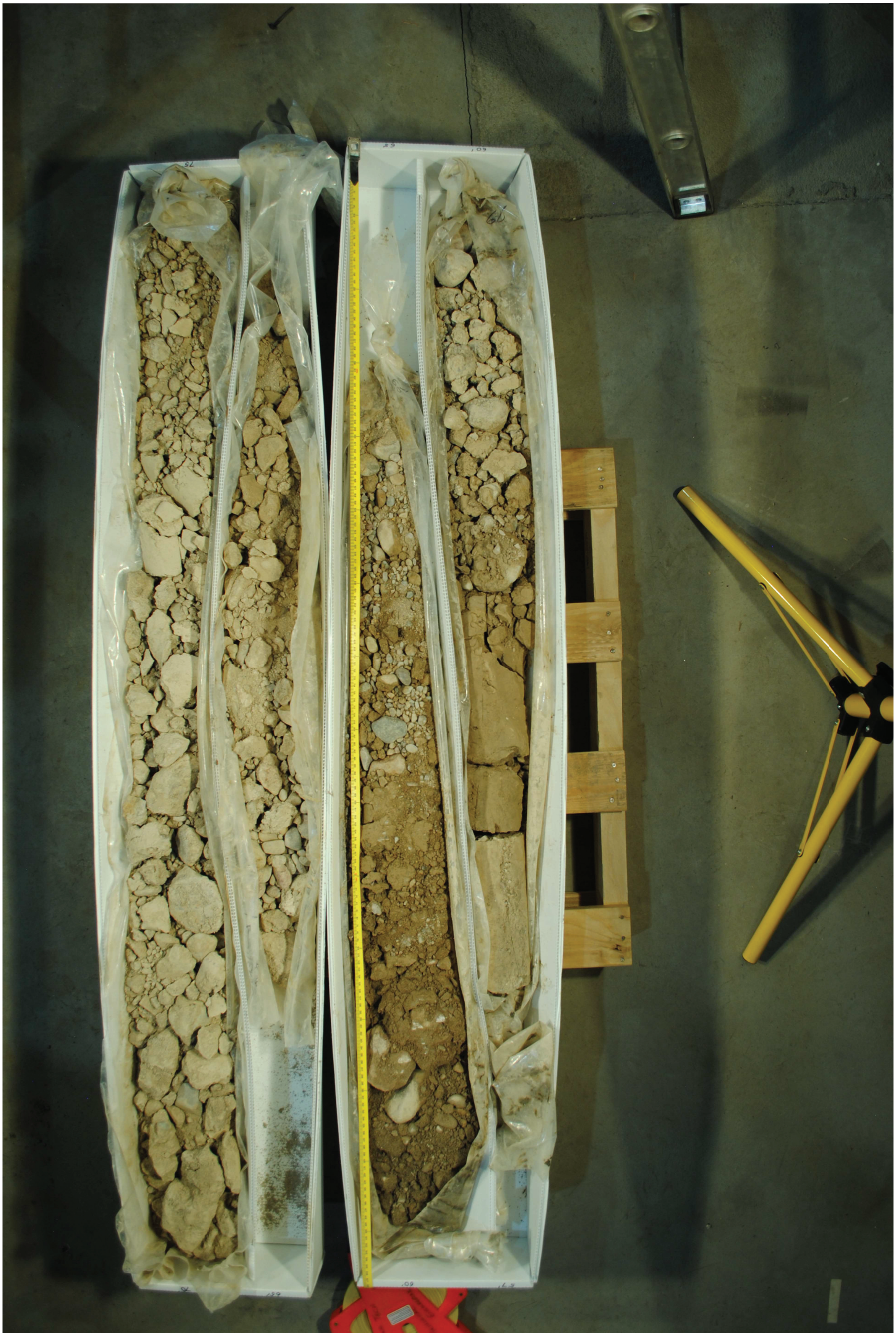


Description	Environment interpretation
Loose well sorted, silty medium-grained sand	
Moderately sorted, coarse-grained sand; few granules, rare pebbles	
Moderately well sorted, fine-grained silty and clayey sand	Coarse-grained glaciolacustrine sediments
Moderately well sorted, medium-grained clayey sand; few granules and pebbles	
Silt bed	
Moderately sorted, medium-grained silty sand; few granules	
Sandy silt bed	
Well sorted, silty fine-grained sand; few granules near top	
Base of core	

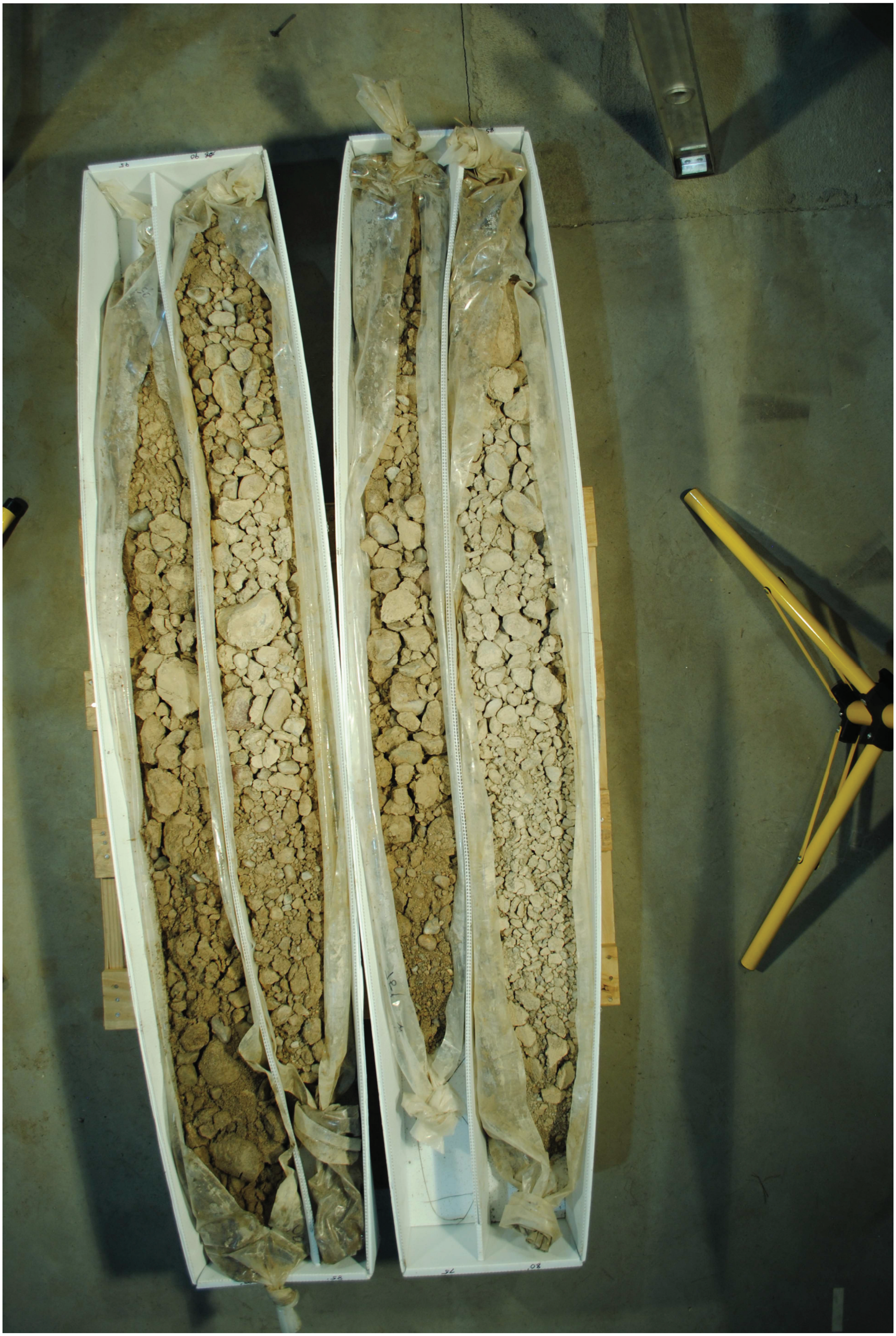


APPENDIX B

OTTEY CORE PHOTOS



Ottey 57–75 ft



Ottey 75–95 ft

Ottey 95–115 ft

Ottey 115–135 ft

Ottey 135–155 ft

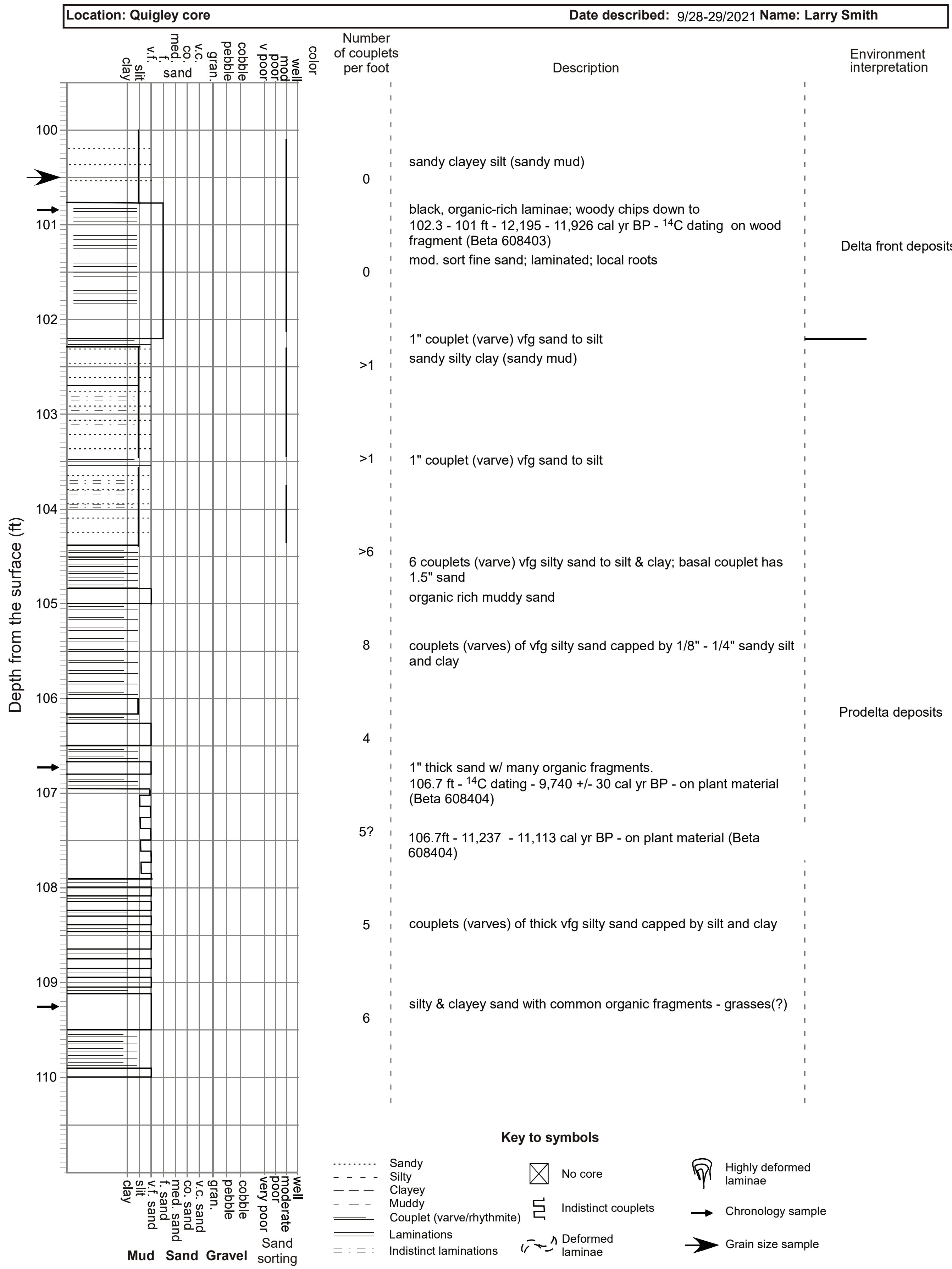
Ottey 155–175 ft

Ottey 175–195 ft

Ottey 195–210 ft

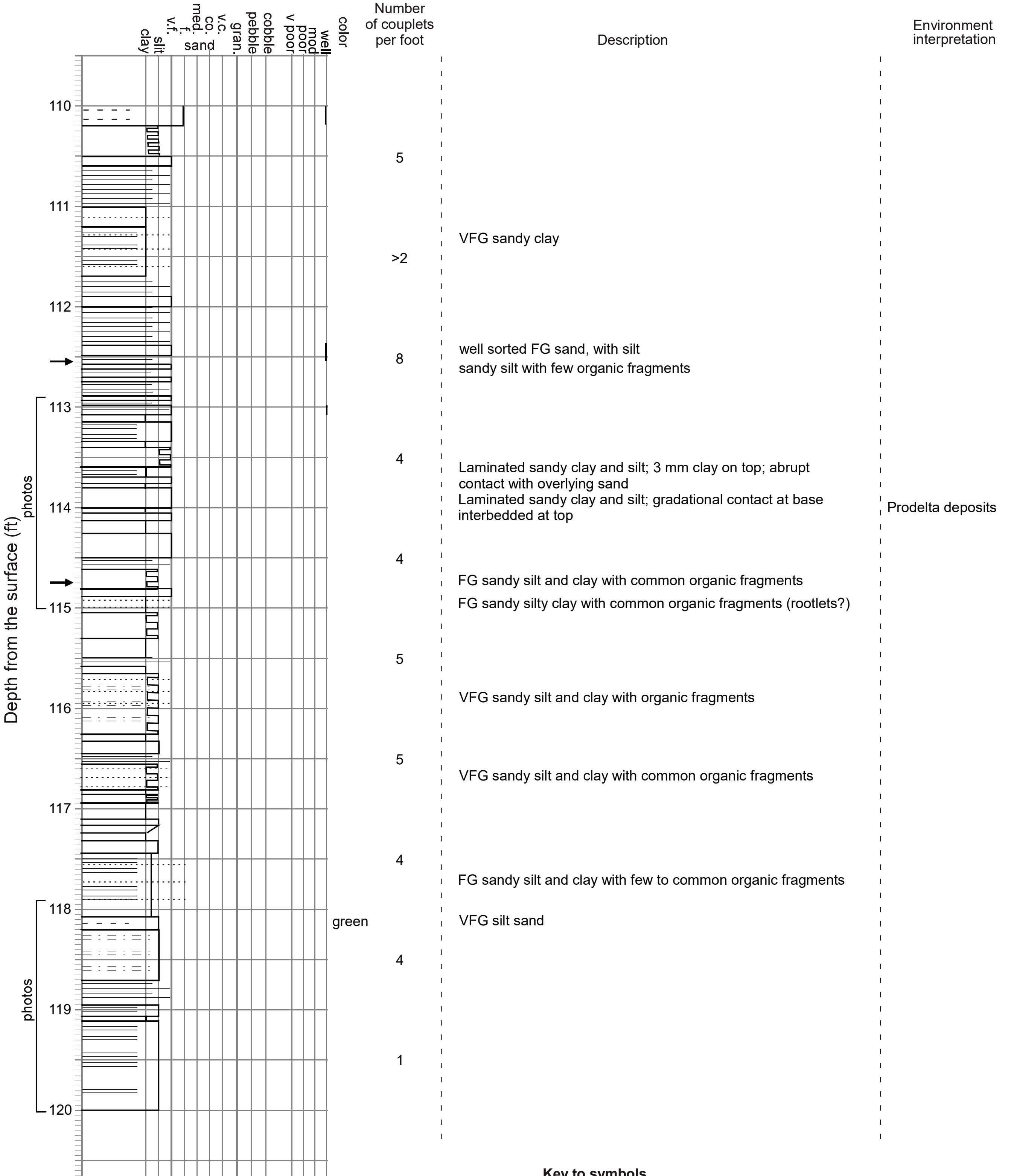
APPENDIX C

QUIGLEY CORE DETAILED LOG

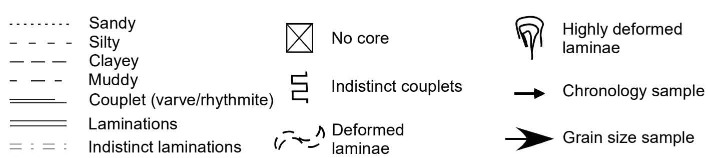


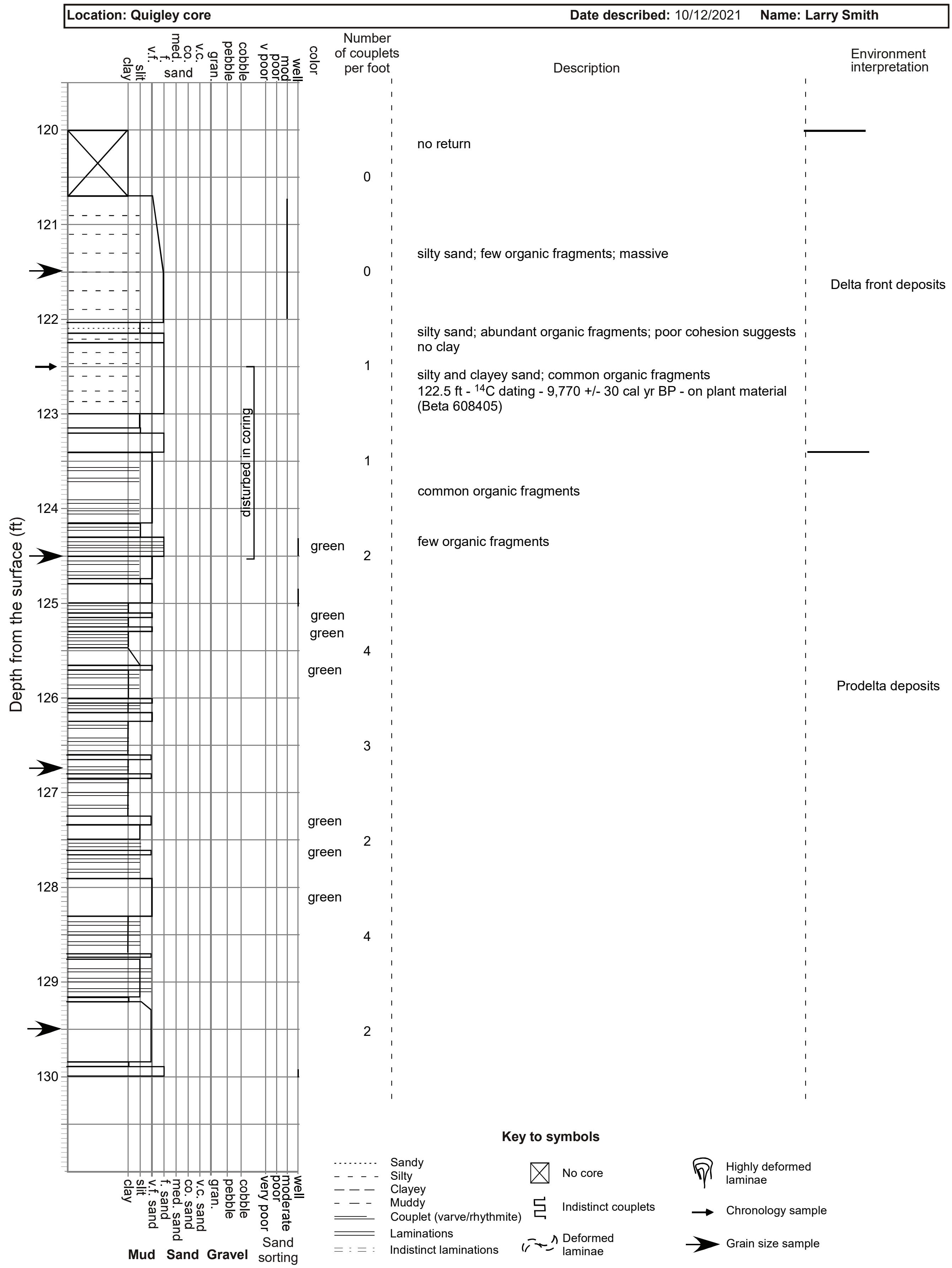
Location: Quigley core
Date described: 9/28-29/2021 Name: Larry Smith
clay
silt
v.f.
f.
med.
co.
v.c.
sand
gran.
pebble
cobble
v poor
poor
mod
well
color
Number of couplets per foot
Description
Environment interpretation
Depth from the surface (ft)
100
101
102
103
104
105
106
107
108
109
110
0
sandy clayey silt (sandy mud)
black, organic-rich laminae; woody chips down to 102.3 - 101 ft - 12,195 - 11,926 cal yr BP - ¹⁴C dating on wood fragment (Beta 608403)
mod. sort fine sand; laminated; local roots
0
Delta front deposits
1" couplet (varve) vfg sand to silt
sandy silty clay (sandy mud)
>1
>1
1" couplet (varve) vfg sand to silt
>6
6 couplets (varve) vfg silty sand to silt & clay; basal couplet has 1.5" sand
organic rich muddy sand
8
couplets (varves) of vfg silty sand capped by 1/8" - 1/4" sandy silt and clay
Prodelta deposits
4
1" thick sand w/ many organic fragments.
106.7 ft - ¹⁴C dating - 9,740 +/- 30 cal yr BP - on plant material (Beta 608404)
5?
106.7ft - 11,237 - 11,113 cal yr BP - on plant material (Beta 608404)
5
couplets (varves) of thick vfg silty sand capped by silt and clay
silty & clayey sand with common organic fragments - grasses(?)
6
clay
silt
v.f. sand
f. sand
med. sand
co. sand
v.c. sand
gran.
pebble
cobble
very poor
poor
moderate
well
Mud
Sand
Gravel
Sand sorting
Key to symbols
Sandy
Silty
Clayey
Muddy
Couplet (varve/rhythmite)
Laminations
Indistinct laminations
No core
Indistinct couplets
Deformed laminae
Highly deformed laminae
Chronology sample
Grain size sample

Location: Quigley core **Date described:** 10/11/2021 **Name: Larry Smith**

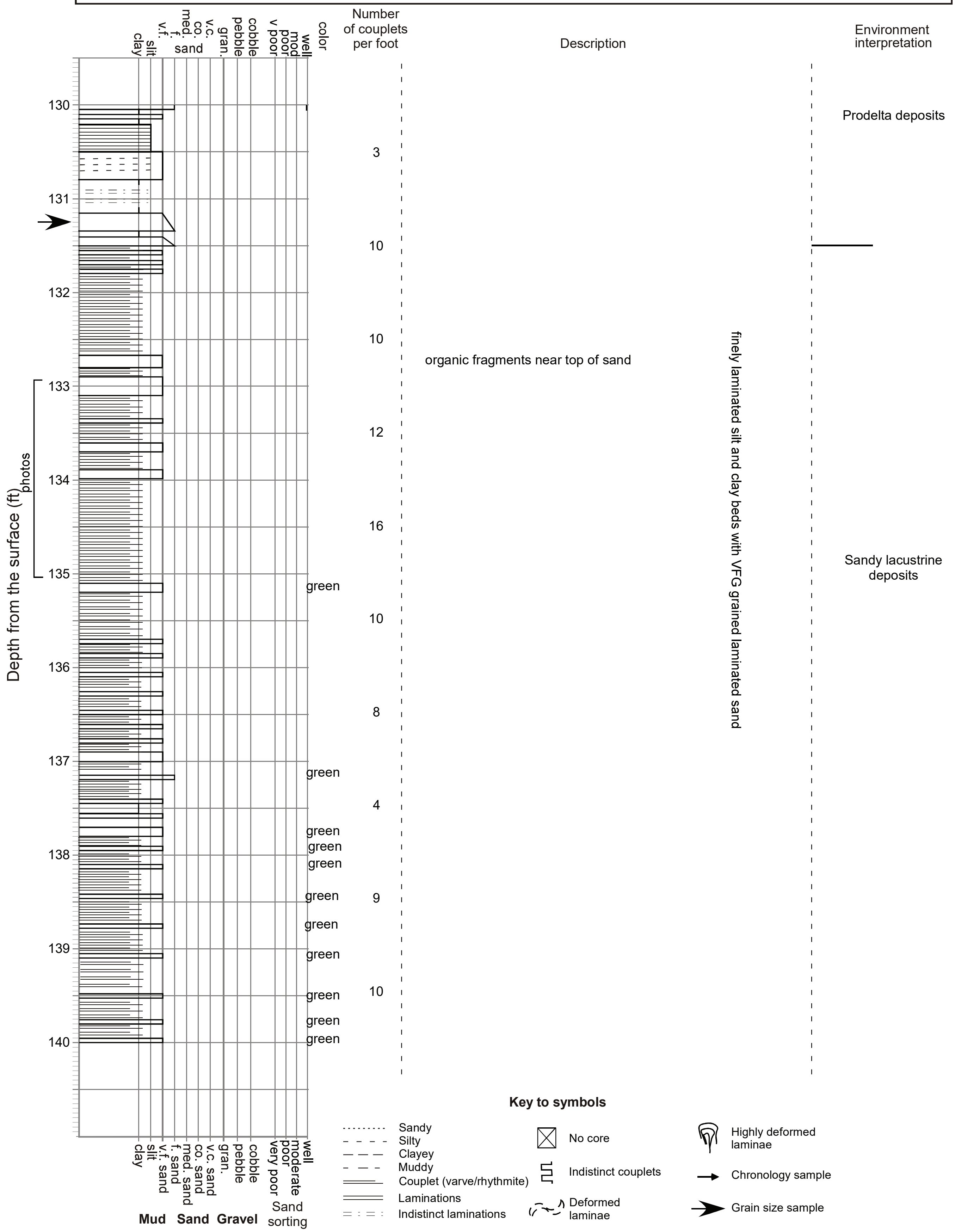


Key to symbols

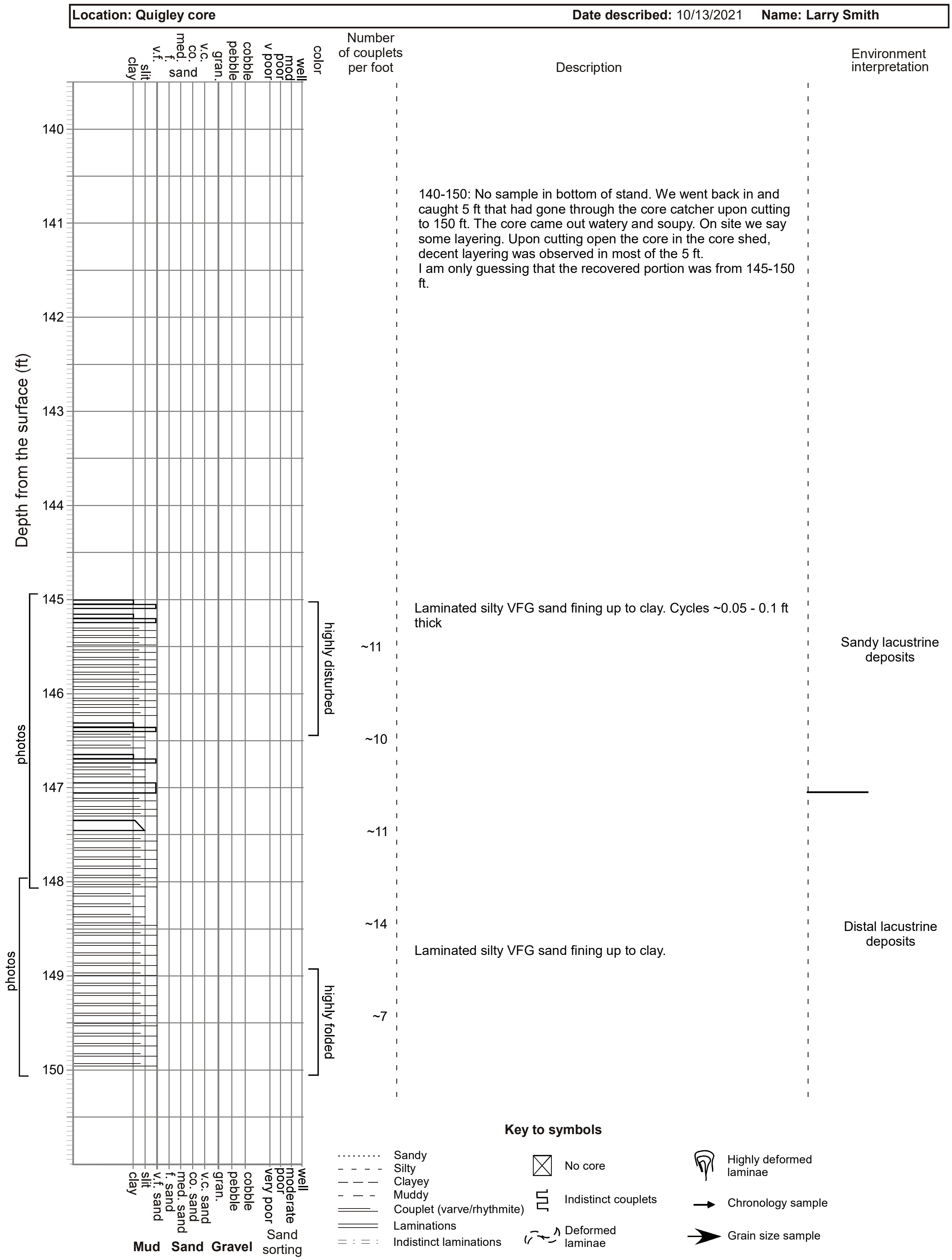


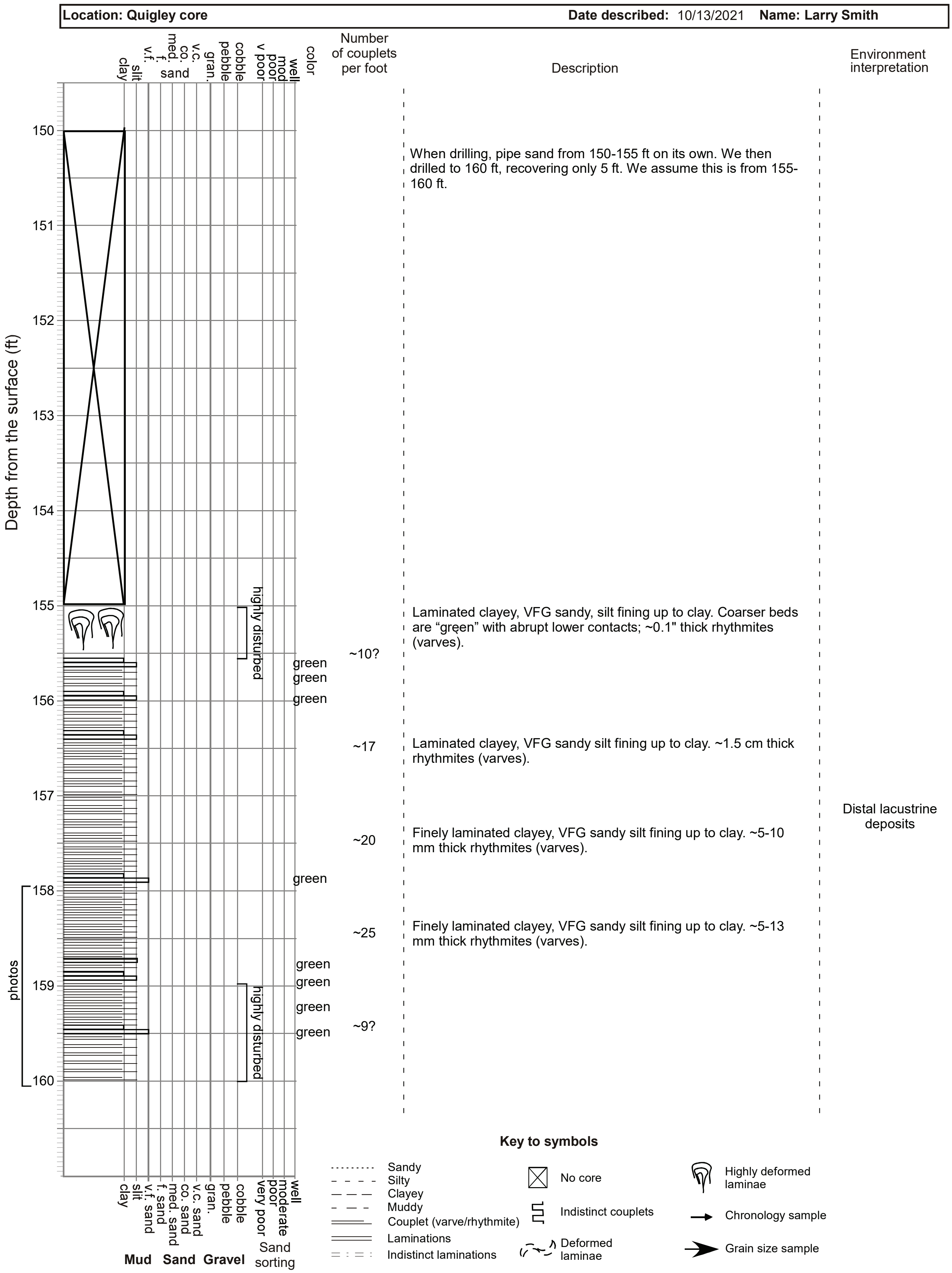

Location: Quigley core
Date described: 10/12/2021
Name: Larry Smith
clay
silt
v.f.
f.
med.
co.
v.c.
sand
gran.
pebble
cobble
v poor
poor
mod
well
color
Number of couplets per foot
Description
Environment interpretation
Depth from the surface (ft)
120
121
122
123
124
125
126
127
128
129
130
no return
silty sand; few organic fragments; massive
silty sand; abundant organic fragments; poor cohesion suggests no clay
silty and clayey sand; common organic fragments
122.5 ft - ^{14}C dating - 9,770 +/- 30 cal yr BP - on plant material (Beta 608405)
common organic fragments
few organic fragments
disturbed in coring
green
green
green
green
green
green
green
0
0
1
1
2
4
3
2
4
2
Delta front deposits
Prodelta deposits
clay
silt
v.f. sand
f. sand
med. sand
co. sand
v.c. sand
gran.
pebble
cobble
very poor
poor
moderate
well
Mud
Sand
Gravel
Sand sorting
Key to symbols
Sandy
Silty
Clayey
Muddy
Couplet (varve/rhythmite)
Laminations
Indistinct laminations
No core
Indistinct couplets
Deformed laminae
Highly deformed laminae
Chronology sample
Grain size sample

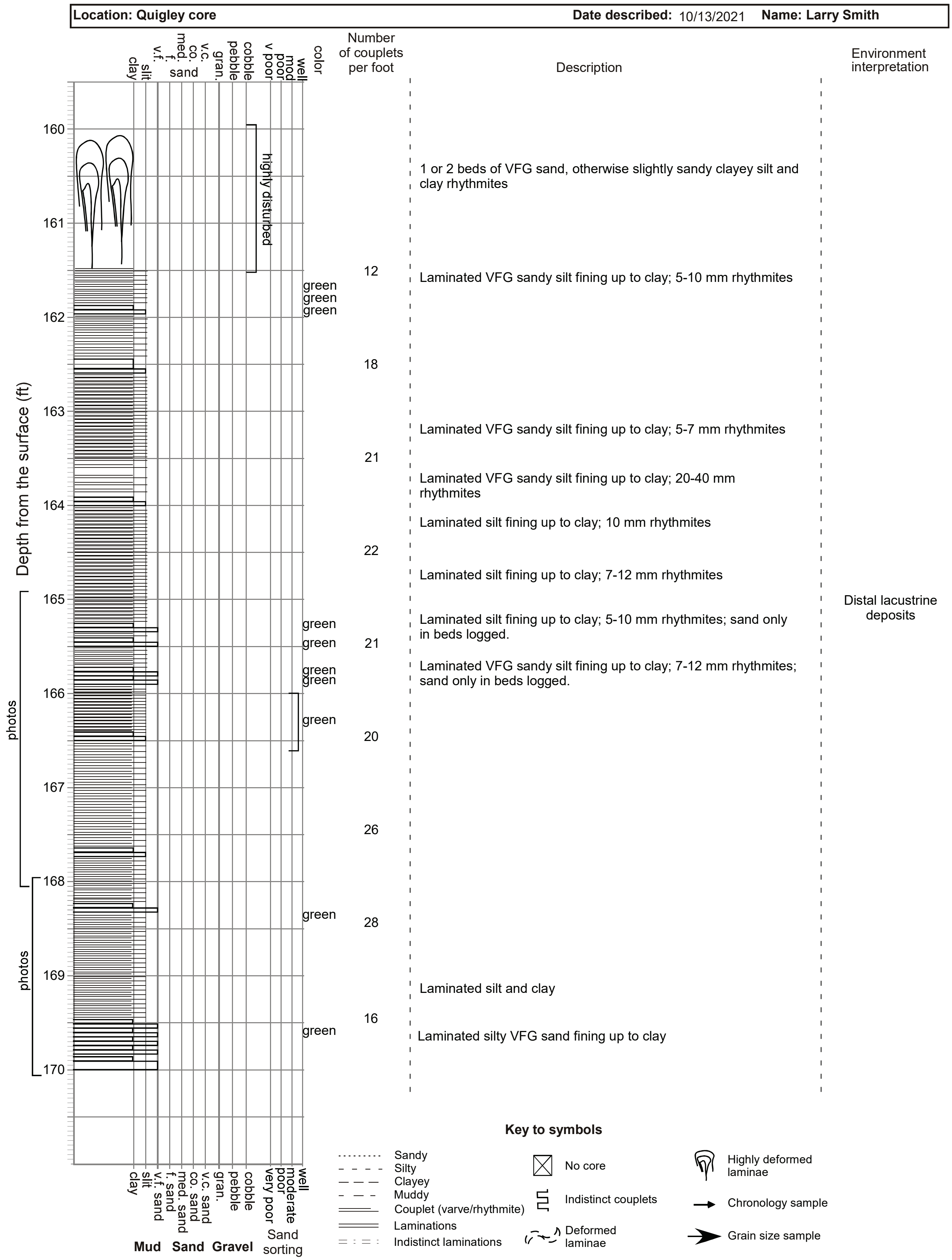
Location: Quigley core **Date described:** 10/12/21 **Name: Larry Smith**



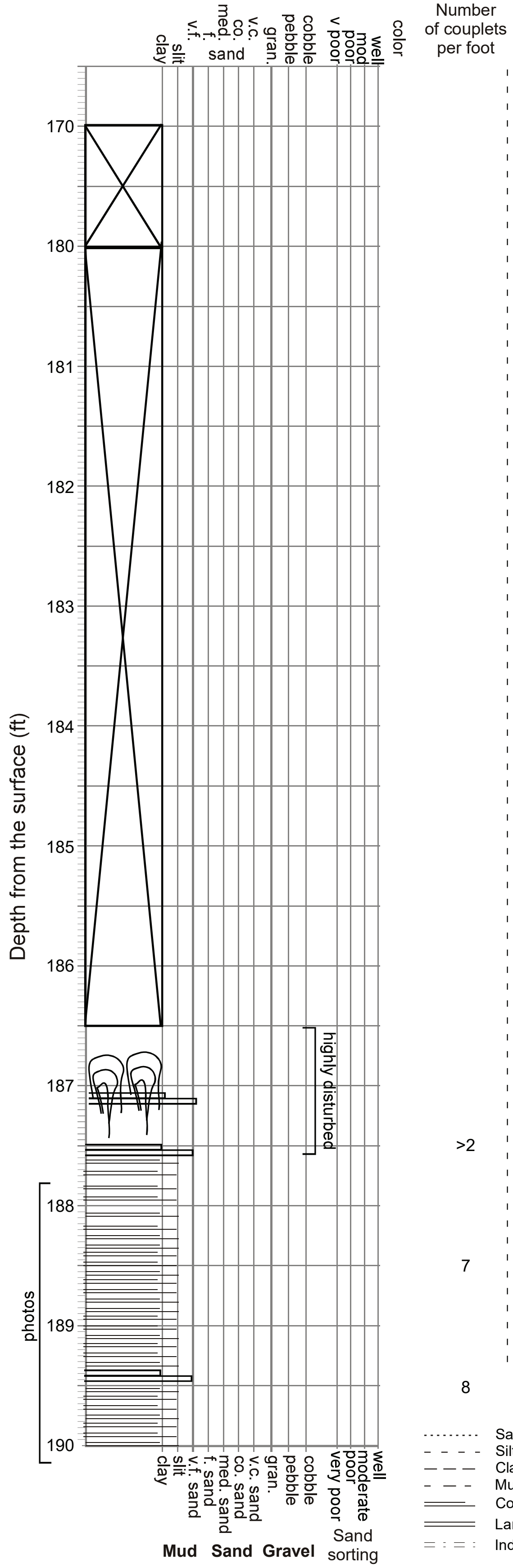
Key to symbols


Location: Quigley core
Date described: 10/13/2021
Name: Larry Smith
clay
slit
v.f.
f.
med.
co.
v.c.
sand
gran.
pebble
cobble
v poor
poor
mod
well
color
Number of couplets per foot
Description
Environment interpretation
Depth from the surface (ft)
140
141
142
143
144
145
146
147
148
149
150
140-150: No sample in bottom of stand. We went back in and caught 5 ft that had gone through the core catcher upon cutting to 150 ft. The core came out watery and soupy. On site we say some layering. Upon cutting open the core in the core shed, decent layering was observed in most of the 5 ft.
I am only guessing that the recovered portion was from 145-150 ft.
photos
photos
highly disturbed
~11
~10
~11
~14
~7
highly folded
Laminated silty VFG sand fining up to clay. Cycles ~0.05 - 0.1 ft thick
Sandy lacustrine deposits
Laminated silty VFG sand fining up to clay.
Distal lacustrine deposits
clay
slit
v.f. sand
f. sand
med. sand
co. sand
v.c. sand
gran.
pebble
cobble
very poor
poor
moderate
well
Mud
Sand
Gravel
Sand sorting
Key to symbols
Sandy
Silty
Clayey
Muddy
Couplet (varve/rhythmite)
Laminations
Indistinct laminations
No core
Indistinct couplets
Deformed laminae
Highly deformed laminae
Chronology sample
Grain size sample


Location: Quigley core
Date described: 10/13/2021
Name: Larry Smith
clay
slit
v.f.
f.
med.
co.
v.c.
sand
gran.
pebble
cobble
v poor
poor
mod
well
color
Number of couplets per foot
Description
Environment interpretation
Depth from the surface (ft)
150
151
152
153
154
155
156
157
158
159
160
photos
When drilling, pipe sand from 150-155 ft on its own. We then drilled to 160 ft, recovering only 5 ft. We assume this is from 155-160 ft.
highly disturbed
~10?
green
green
green
Laminated clayey, VFG sandy, silt fining up to clay. Coarser beds are “green” with abrupt lower contacts; ~0.1" thick rhythmites (varves).
~17
Laminated clayey, VFG sandy silt fining up to clay. ~1.5 cm thick rhythmites (varves).
~20
Finely laminated clayey, VFG sandy silt fining up to clay. ~5-10 mm thick rhythmites (varves).
Distal lacustrine deposits
green
~25
Finely laminated clayey, VFG sandy silt fining up to clay. ~5-13 mm thick rhythmites (varves).
green
green
green
green
~9?
highly disturbed
clay
slit
v.f. sand
f. sand
med. sand
co. sand
v.c. sand
gran.
pebble
cobble
very poor
poor
moderate
well
Mud
Sand
Gravel
Sand sorting
Key to symbols
Sandy
Silty
Clayey
Muddy
Couplet (varve/rhythmite)
Laminations
Indistinct laminations
No core
Indistinct couplets
Deformed laminae
Highly deformed laminae
Chronology sample
Grain size sample

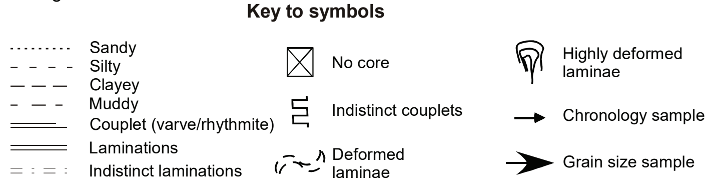

Location: Quigley core
Date described: 10/13/2021
Name: Larry Smith
clay
silt
v.f.
f.
med.
co.
v.c.
sand
gran.
pebble
cobble
v poor
poor
mod
well
color
Number of couplets per foot
Description
Environment interpretation
Depth from the surface (ft)
160
161
162
163
164
165
166
167
168
169
170
highly disturbed
1 or 2 beds of VFG sand, otherwise slightly sandy clayey silt and clay rhythmites
12
green
green
green
Laminated VFG sandy silt fining up to clay; 5-10 mm rhythmites
18
Laminated VFG sandy silt fining up to clay; 5-7 mm rhythmites
21
Laminated VFG sandy silt fining up to clay; 20-40 mm rhythmites
Laminated silt fining up to clay; 10 mm rhythmites
22
Laminated silt fining up to clay; 7-12 mm rhythmites
Distal lacustrine deposits
green
green
21
Laminated silt fining up to clay; 5-10 mm rhythmites; sand only in beds logged.
green
green
Laminated VFG sandy silt fining up to clay; 7-12 mm rhythmites; sand only in beds logged.
green
20
26
green
28
Laminated silt and clay
16
green
Laminated silty VFG sand fining up to clay
photos
photos
clay
silt
v.f. sand
f. sand
med. sand
co. sand
v.c. sand
gran.
pebble
cobble
very poor
poor
moderate
well
Mud
Sand
Gravel
Sand sorting
Key to symbols
Sandy
Silty
Clayey
Muddy
Couplet (varve/rhythmite)
Laminations
Indistinct laminations
No core
Indistinct couplets
Deformed laminae
Highly deformed laminae
Chronology sample
Grain size sample

Location: Quigley core **Date described:** 10/14/2021 **Name: Larry Smith**

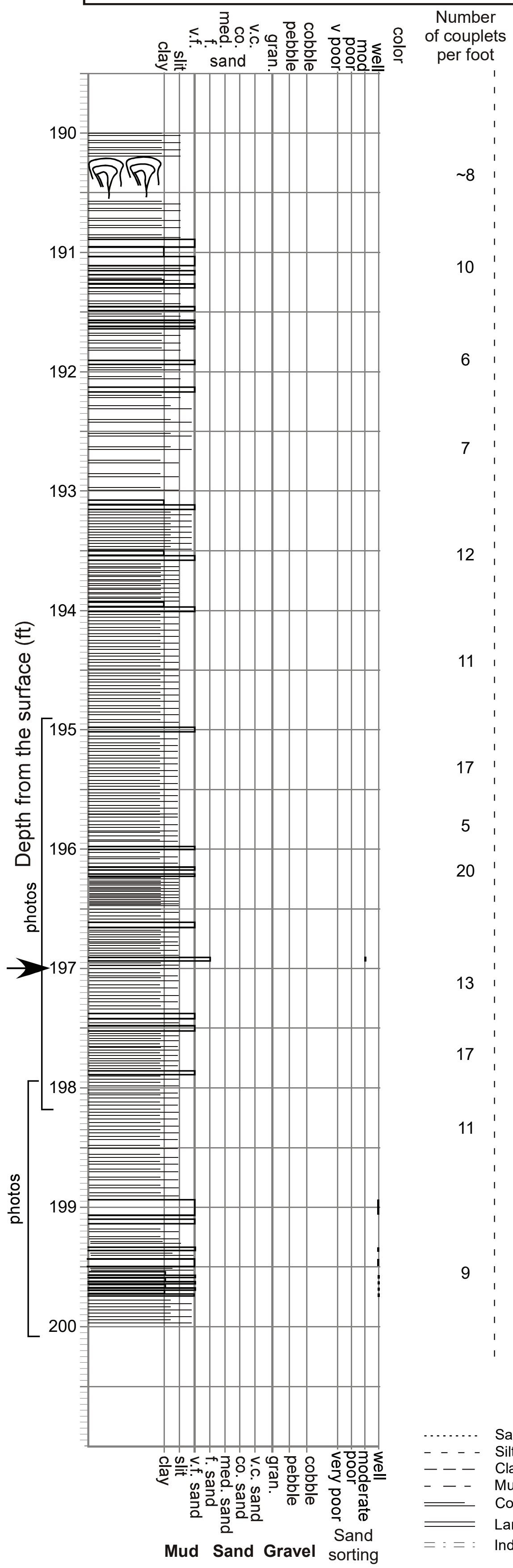


Description	Environment interpretation
170-180: Washed out of catcher and lost when using water to get 6" pipe around 4".	
180-190: Washed out also, even without using water on 6". Then, drilled 20 ft ahead, quickly without using sonic, to 200 ft. Recovered ~3.5 ft from 180-190, likely the lower 3.5 ft to 190 ft.	
Mostly laminated mud; bases of most rhythmites is VFG sandy mud	Distal lacustrine deposits

Key to symbols



Location: Quigley core | **Date described:** 10/14/2021 | **Name: Larry Smith**

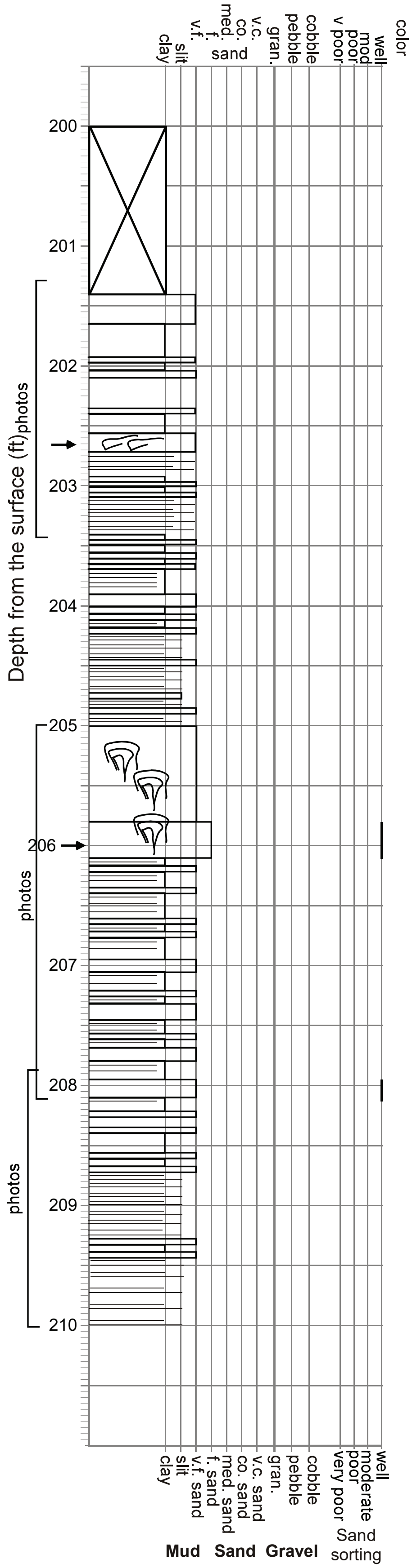


Description	Environment interpretation
Core stretched to 12.85 ft, logged as in boxes, then squeezed back in drafting; those intervals where core was thinner (due to elongation) were squeezed back preferentially.	Distal lacustrine deposits
VFG sand beds 0.005-0.01 ft thick beds logged; other rhythmites have thinner silty sand at bases	Sandy lacustrine deposits
VFG sand and laminated silty clay (mud) - interlaminated with sand at the bases of fine units	
	Distal lacustrine deposits
	Sandy lacustrine deposits

Key to symbols

- Sandy
- Silty
- Clayey
- Muddy
- Couplet (varve/rhythmite)
- Laminations
- Indistinct laminations
- No core
- Indistinct couplets
- Deformed laminae
- Highly deformed laminae
- Chronology sample
- Grain size sample

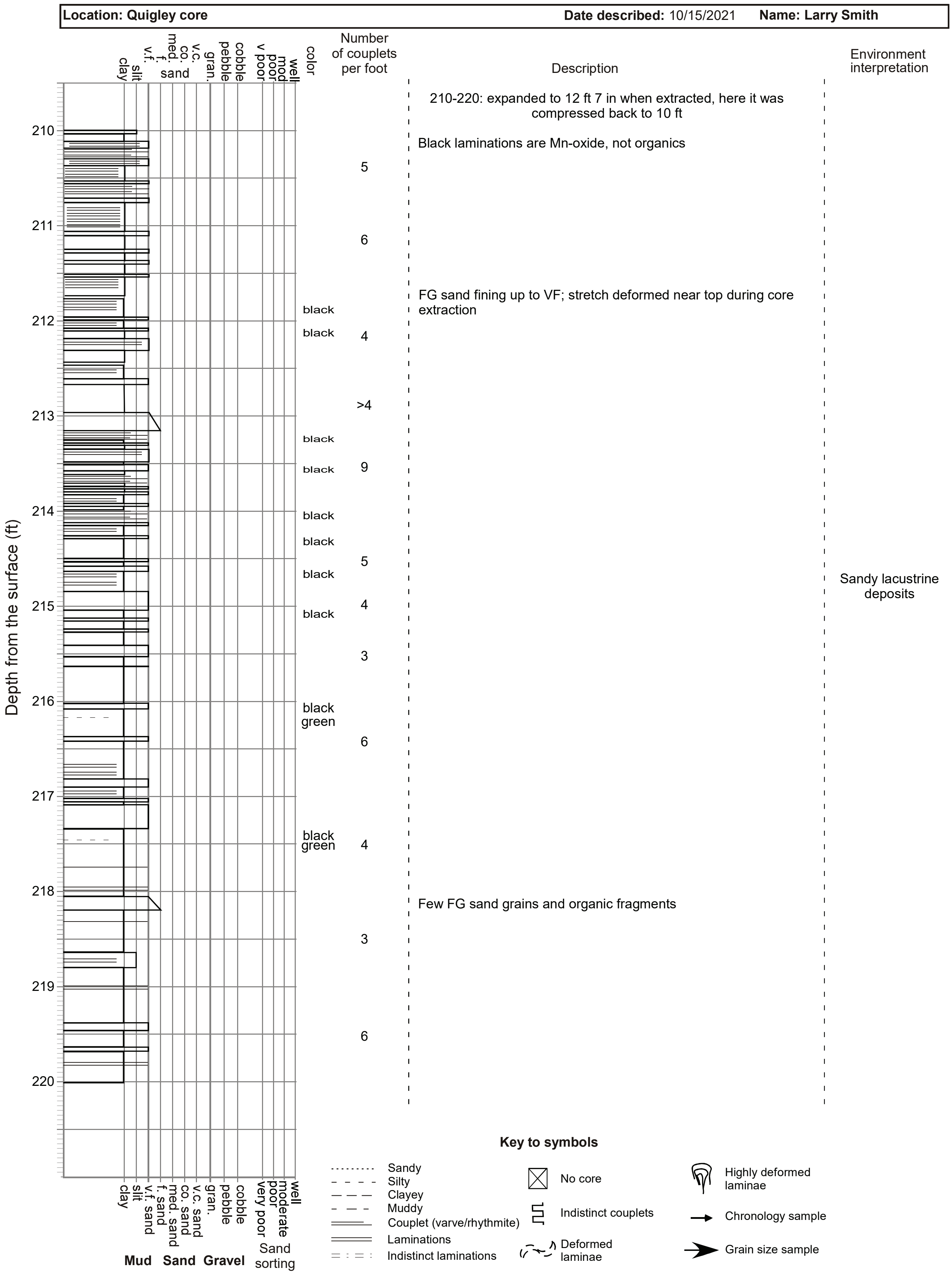
Location: Quigley core **Date described:** 10/14/2021 **Name: Larry Smith**



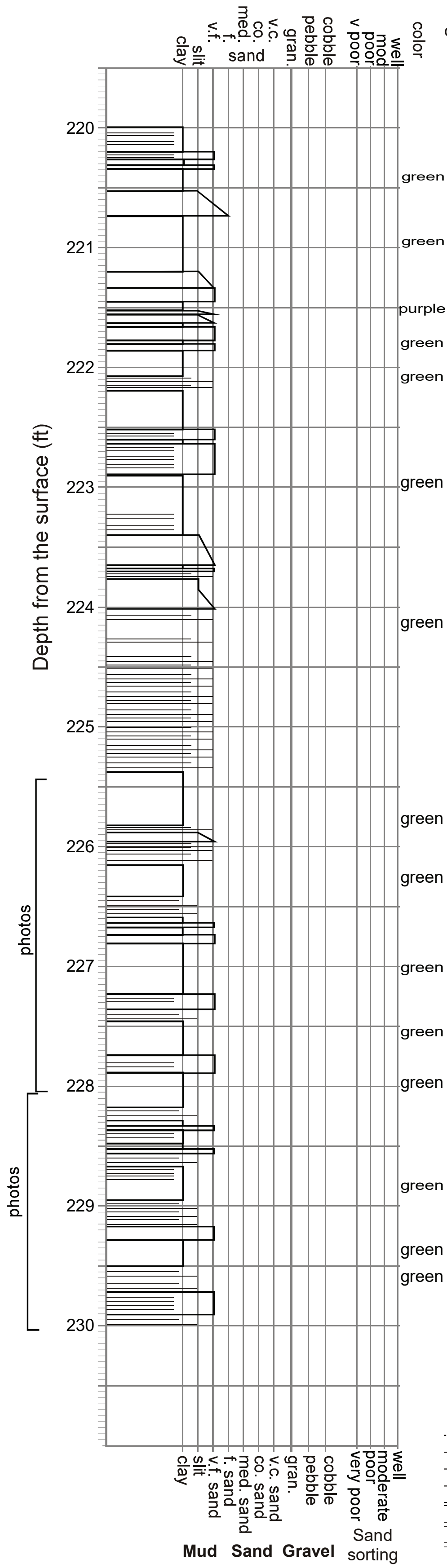
Number of couplets per foot	Description	Environment interpretation
	200-210: Recaptured from inside of 6" pipe; either lost 2 ft at top or was compressed. Assume top section was lost, so moved down to 205 ft.	
>8	The 3.6 ft was shifted down to 205 ft.	
>9	Contorted VFG sand with common organic fragments. Sampled as “201.3 ft” sand based on original depth descriptions.	
9		
~5		Sandy lacustrine deposits
>3	Contorted VFG sand with beds of silt and clay (mud)	
	Well sorted FG sand; quartz and mafic minerals; possible volcanic tephra; poorly cored - flowed during coring, possibly only 0.1-0.2 ft originally thick - Sampled as “206.0"	
5	Thick varves of VFG sand with beds of laminated silt and clay (mud); thicker sands were individually logged.	
5		
	0.15 ft-thick well sorted VFG sand, very little silt	
10		
7	VFG sandy silt fining up to clay varves; 0.1-0.15 ft thick rhythmites	

Key to symbols

- Sandy
- Silty
- Clayey
- Muddy
- Couplet (varve/rhythmite)
- Laminations
- Indistinct laminations
- No core
- Indistinct couplets
- Deformed laminae
- Highly deformed laminae
- Chronology sample
- Grain size sample


Location: Quigley core
Date described: 10/15/2021
Name: Larry Smith
clay
slit
v.f.
f.
med.
co.
v.c.
sand
gran.
pebble
cobble
v poor
poor
mod
well
color
Number of couplets per foot
Description
Environment interpretation
Depth from the surface (ft)
210
211
212
213
214
215
216
217
218
219
220
210-220: expanded to 12 ft 7 in when extracted, here it was compressed back to 10 ft
Black laminations are Mn-oxide, not organics
5
6
FG sand fining up to VF; stretch deformed near top during core extraction
black
black
4
>4
black
black
9
black
black
5
black
4
black
3
black
green
6
black
green
4
Few FG sand grains and organic fragments
3
6
Sandy lacustrine deposits
clay
slit
v.f. sand
f. sand
med. sand
co. sand
v.c. sand
gran.
pebble
cobble
very poor
poor
moderate
well
Mud
Sand
Gravel
Sand sorting
Key to symbols
Sandy
Silty
Clayey
Muddy
Couplet (varve/rhythmite)
Laminations
Indistinct laminations
No core
Indistinct couplets
Deformed laminae
Highly deformed laminae
Chronology sample
Grain size sample

Location: Quigley core | **Date described:** 10/18/2021 | **Name: Larry Smith**

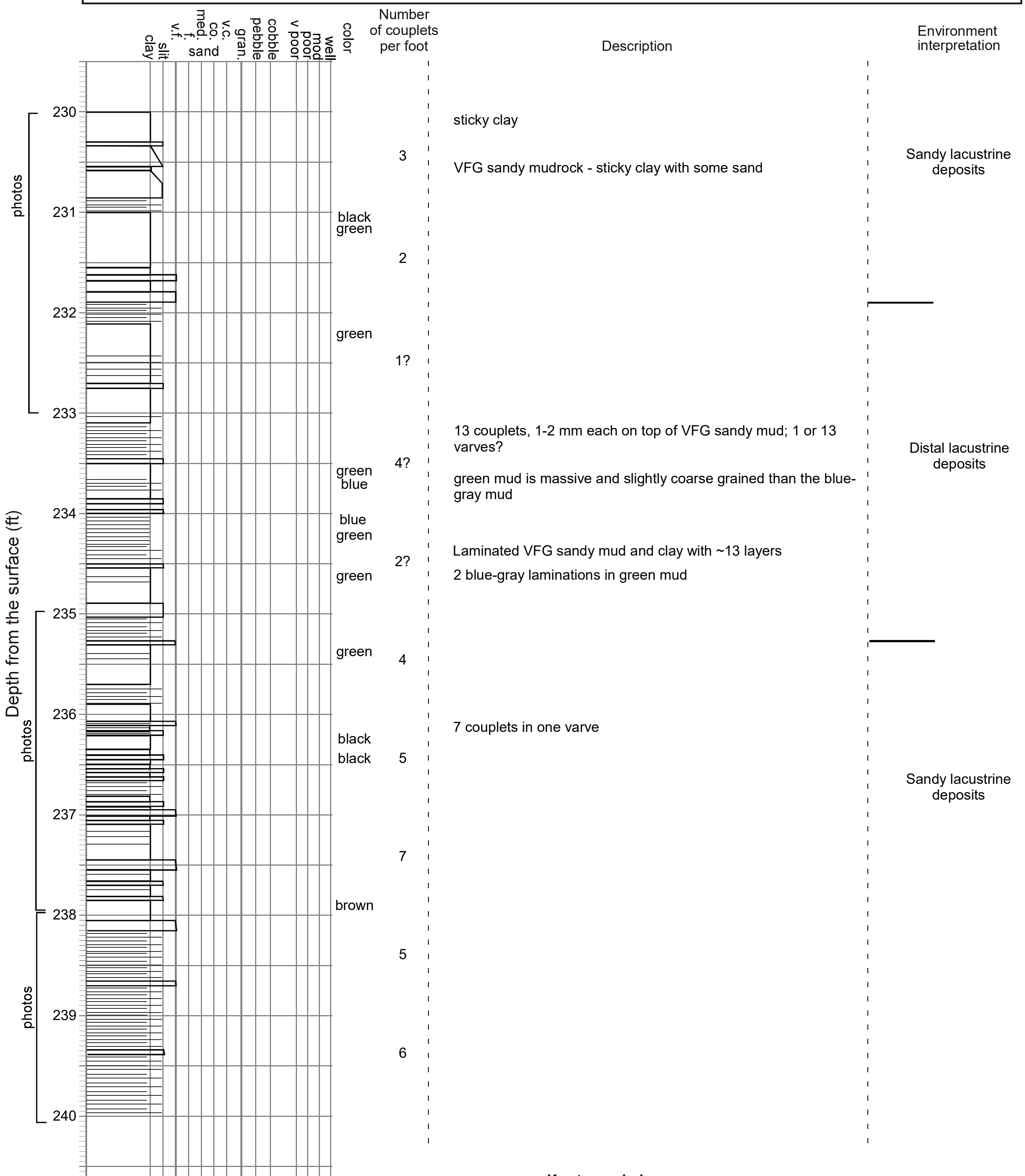


Number of couplets per foot	Description	Environment interpretation
	220-230: Expanded to ~12 ft on core extraction	
	Laminated clay	
	Laminated VFG sand with few laminae of clay	
3		
1	Laminated with 22 partings (not varves: green with lamination of blue-gray;	
	silty VFG sand with clay beds	
5		
6		
1	very silty VFG sand with clay	
4		
10?		
		Sandy lacustrine deposits
4		
	2 blue laminations in green	
4		
3		
6		
	3 blue laminations in green	
4		

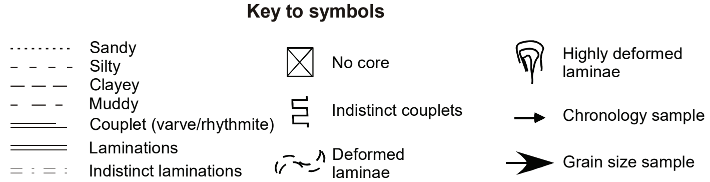
Key to symbols

Sandy
Silty
Clayey
Muddy
Couplet (varve/rhythmite)
Laminations
Indistinct laminations
No core
Indistinct couplets
Deformed laminae
Highly deformed laminae
Chronology sample
Grain size sample

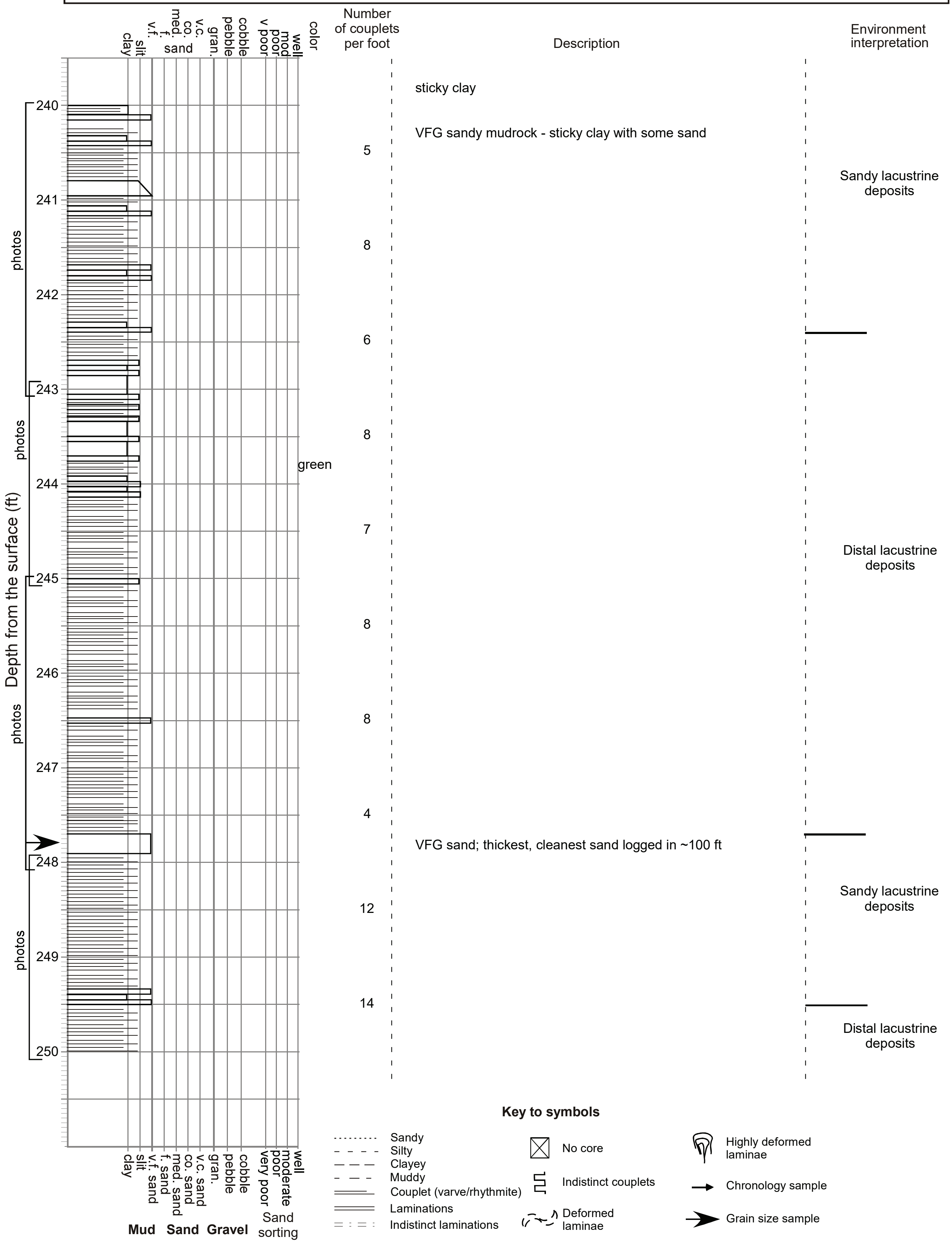
Location: Quigley core **Date described:** 10/19/2021 **Name: Larry Smith**



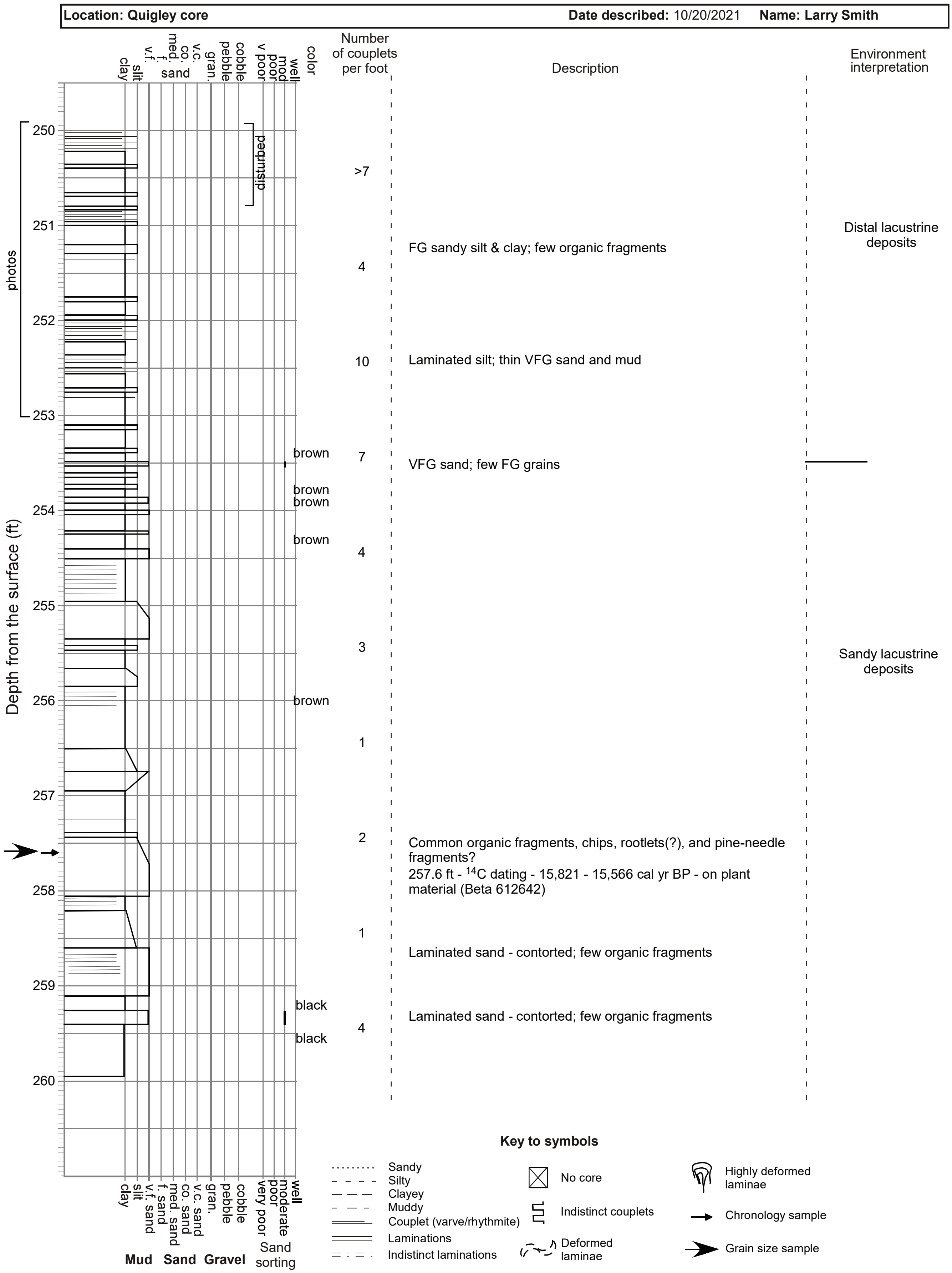
Key to symbols



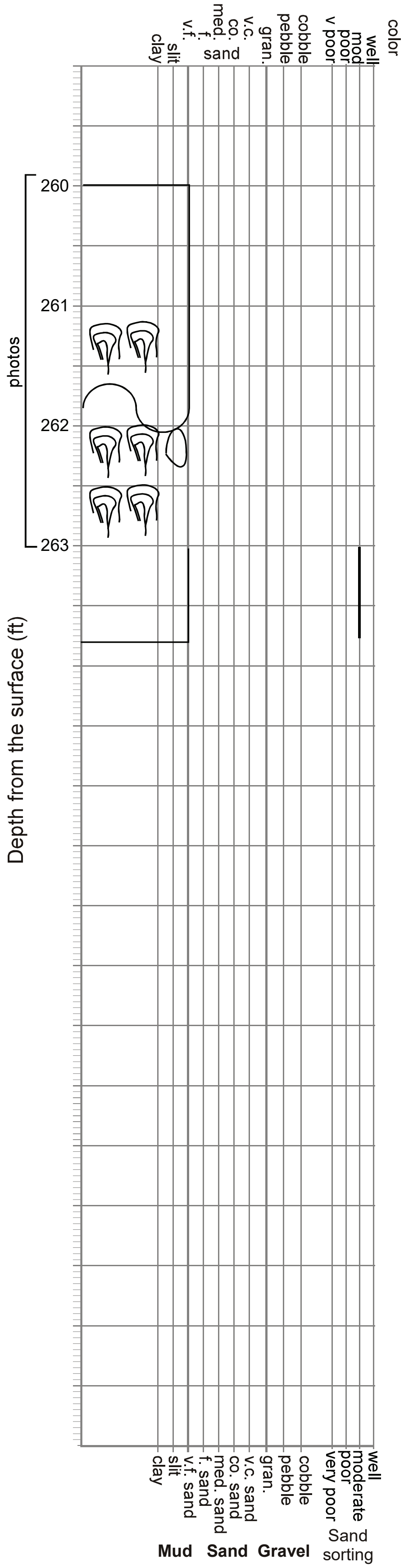
Location: **Quigley core** **Date described:** 10/19/2021 **Name:** **Larry Smith**



Key to symbols


Location: Quigley core
Date described: 10/20/2021
Name: Larry Smith
clay
silt
v.f.
f.
med.
co.
v.c.
sand
gran.
pebble
cobble
v poor
poor
mod
well
color
Number of couplets per foot
Description
Environment interpretation
Depth from the surface (ft)
photos
250
251
252
253
254
255
256
257
258
259
260
disturbed
>7
4
10
7
4
3
1
2
1
4
brown
brown
brown
brown
brown
black
black
FG sandy silt & clay; few organic fragments
Laminated silt; thin VFG sand and mud
VFG sand; few FG grains
Common organic fragments, chips, rootlets(?), and pine-needle fragments?
257.6 ft - 14C dating - 15,821 - 15,566 cal yr BP - on plant material (Beta 612642)
Laminated sand - contorted; few organic fragments
Laminated sand - contorted; few organic fragments
Distal lacustrine deposits
Sandy lacustrine deposits
clay
silt
v.f. sand
f. sand
med. sand
co. sand
v.c. sand
gran.
pebble
cobble
very poor
poor
moderate
well
Mud
Sand
Gravel
Sand sorting
Key to symbols
Sandy
Silty
Clayey
Muddy
Couplet (varve/rhythmite)
Laminations
Indistinct laminations
No core
Indistinct couplets
Deformed laminae
Highly deformed laminae
Chronology sample
Grain size sample

Location: Quigley core | **Date described:** 10/20/2021 | **Name: Larry Smith**

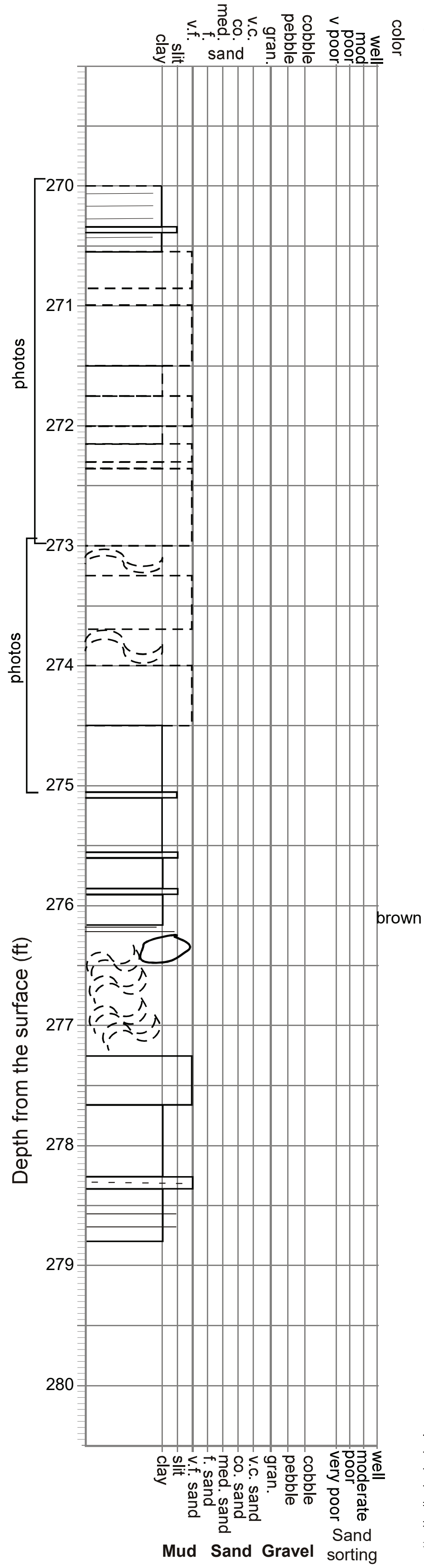


Number of couplets per foot	Description	Environment interpretation
	260-270: 3.8 ft recoved; core barrel got plugged and rest of material was pushed aside. The recovered, disturbed sediment is assumed to be from the top of the interval.	
	Ball of clay with silt	
>2	VFG sand with common organic fragments; clay beds highly deformed	
>2		Sandy lacustrine deposits
	Laminated couplets of sand and clay	
	Ball of sand	
>2	Few black layers	
1?	VFG sand with common FG sand; few organic fragments	

Key to symbols

- Sandy
- Silty
- Clayey
- Muddy
- Couplet (varve/rhythmite)
- Laminations
- Indistinct laminations
- No core
- Indistinct couplets
- Deformed laminae
- Highly deformed laminae
- Chronology sample
- Grain size sample

Location: Quigley core **Date described:** 10/20/2021 **Name: Larry Smith**

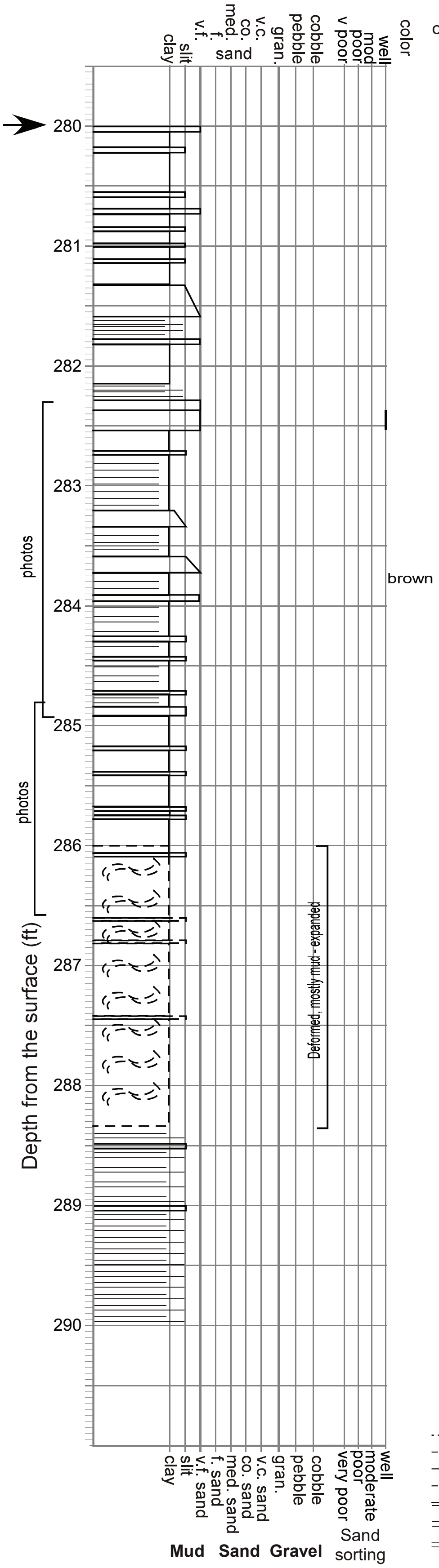


Number of couplets per foot	Description	Environment interpretation
	270-280: Retrieved from pipe above 280-290 core because of being lost down hole, through core catcher, after drilling. Recovered 8 ft; assumed that we lost part of sands.	
	Difficult to reconstruct stratigraphy.	
	Laminated clay with one sandy mud bed	
>2		
>2		
>2	VFG sand with common organic fragments	
	VFG sand and clay beds; mixed	
>2		
>2		
		Sandy lacustrine deposits
3		
>3	Sand clump	
	Laminated mud with some sand beds	
>3	VFG sand, was soupy	
2		
	base of core	

Key to symbols

- Sandy
- Silty
- Clayey
- Muddy
- Couplet (varve/rhythmite)
- Laminations
- Indistinct laminations
- No core
- Indistinct couplets
- Deformed laminae
- Highly deformed laminae
- Chronology sample
- Grain size sample

Location: Quigley core | **Date described:** 10/21/2021 | **Name: Larry Smith**

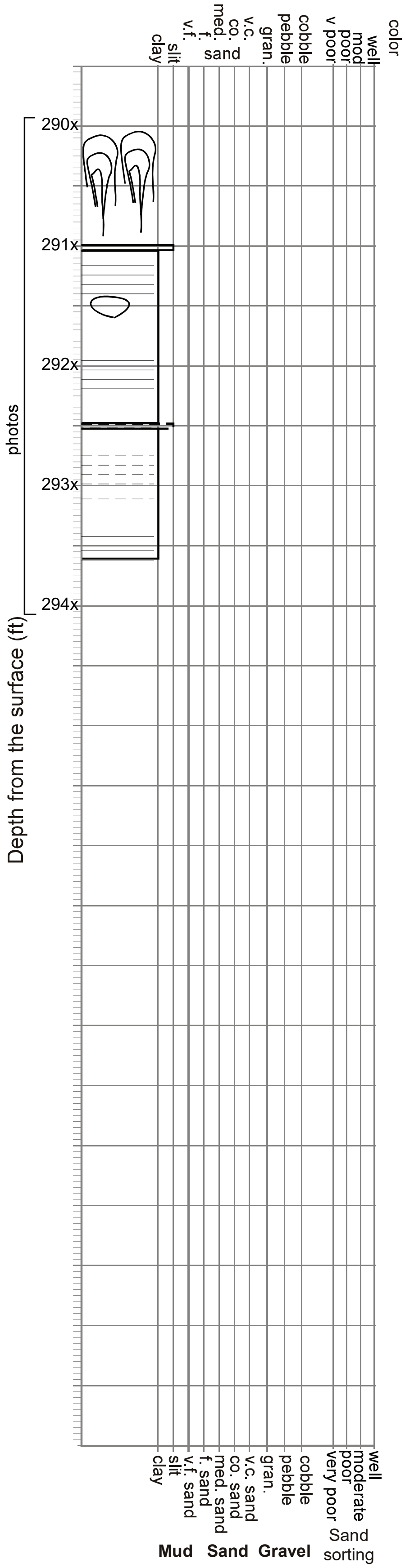


Number of couplets per foot	Description	Environment interpretation
	280-290: Extended to ~13.5 ft	
2		
8	VFG sand with common FG sand; few organic fragments	
2	Thickened ~50%	Sandy lacustrine deposits
6		
	Well sorted VFG sand	
2	Laminated silt & clay	
	VFG sandy mud	
	Laminated silt & clay	
3		
5		
4		
2		
2?		
2?		Distal lacustrine deposits
?		
6		
	Varves unclear as there is very little sand; counted those that had sandy mud bases	
6		

Key to symbols

- Sandy
- Silty
- Clayey
- Muddy
- Couplet (varve/rhythmite)
- Laminations
- Indistinct laminations
- No core
- Indistinct couplets
- Deformed laminae
- Highly deformed laminae
- Chronology sample
- Grain size sample

Location: Quigley core **Date described:** 10/21/2021 **Name: Larry Smith**



Number of couplets per foot	Description	Environment interpretation
	Small amount of sand in clay	
	Ball of sand in clay	
	Laminated silt & clay; breakes into 7-10 mm layers, very faint when scraped	

NOTE - the depths were changed to include these data into the logs. These measurements are needed for comparison to the photos.
- As the photos were taken before unit thickness was adjusted, some interpretation is needed.

Key to symbols

- Sandy
- Silty
- Clayey
- Muddy
- Couplet (varve/rhythmite)
- Laminations
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APPENDIX D
QUIGLEY CORE PHOTOS

Quigley 100–120'

Quigley 120–140'

Quigley 140–160'

Quigley 160–170' and 180–190'

Quigley 190–210'

Quigley 210–212 and 212x–220x'

Quigley 210–230x'

Quigley 230–250'

Quigley 250–260'

Quigley 270–290'

Quigley 280–~283x'

Quigley 290–300'