Evidence for liquefaction and flooding in the past 1,000 years along the Duwamish River, Seattle, Washington

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Abstract

Geology along the Duwamish waterway, south of downtown Seattle, provides preliminary clues to the city's earthquake and tsunami hazards. The banks of the dredged waterway expose the muddy deposits of an estuary that formerly drained Mount Rainier. Different outcrops expose evidence for former events. So far, inferred events include two episodes of liquefaction and two unusual floods from land or sea. All events postdate the large Seattle fault earthquake of 900—930 CE.

Evidence for liquefaction consists of dikes and extrusive lenses of andesitic sand among muddy tidal deposits. This sand was likely vented from lahar runout deposits that underlie the tidal mud. One prominent outcrop on the east side of the waterway displays coalesced sand lenses, which are up to 12cm thick, bulbous, and intersected by parallel, mostly vertical sand dikes. One sand lens drapes *Triglochin maritima* leaf bases in growth position, which dates to 1010—1150 CE. Later liquefaction is evidenced by a dike which approached the stratigraphic level of *T. maritima* leaf bases dated to 1250—1290 CE. Two dikes at a site on Kellogg Island were observed no higher than *Bolboschoenus* sp. corms dated to 1470—1640 CE. Though additional sand dikes have yet to be dated, none of the dikes observed are likely to be as young as the 1700 Cascadia earthquake or any of the historical Puget Sound earthquakes of 1949, 1965, or 2001.

Two persistent, horizontal silt layers observed in one outcrop suggest unusual flooding, either from Puget Sound or from upriver. Radiocarbon ages of *T. maritima* and *Bolboschoenus* sp. limit the times of this flooding to 1030–1180 CE and 1320–1400 CE.

These preliminary findings may yield insights into Seattle's earthquake and tsunami hazards, after further work including comparison with histories of earthquakes and tsunamis elsewhere in the region.

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1. Introduction

Geology along the Duwamish Waterway, just south of downtown Seattle, provides clues to the city's earthquake hazard. This report describes a MESSAGe capstone project which identified and dated evidence along the Waterway for at least two episodes of liquefaction and two anomalous floods within the past 1,000 years.

The city of Seattle and surrounding areas face substantial earthquake hazards from multiple sources (Petersen et al., 2016). The region's dense urban population, critical transit corridors, and current period of rapid development further emphasize the need for accurate and sober-minded earthquake hazard analysis.

Earthquakes in the Puget Sound region come from three generalized sources. The Cascadia subduction zone, off the coast of Washington, Oregon, and northern California has produced giant (M 8-9) but relatively infrequent megathrust earthquakes that affect Washington (Atwater and Hemphill-Haley, 1997). Estimates of recurrence range from a few hundred to >1000 years. Seafloor deformation from such earthquakes may produce tsunamis that enter Puget Sound (Garrison-Laney, 2017). The most recent earthquake and tsunami occurred in 1700 CE (Atwater 1987; Atwater et al., 2005; Yamaguchi et al., 1997).

Crustal faults that cross the Puget Lowland have produced earthquakes (M~7) with variable recurrence (Bucknam et al., 1992; Sherrod, 2001). Rupture style and frequency of individual crustal faults is a subject of active study. In particular, the Seattle fault zone is an east-west trending assemblage of thrust faults that crosses the city of Seattle, though the location of particular strands under the city is unknown (Pratt et al., 2015). An earthquake along the main thrust of this fault in 900 – 930 CE produced a M 7-7.5 earthquake, ~6m of offset, and a Puget Sound tsunami (Atwater and Moore, 1992; Bucknam et al., 1992; Atwater, 1999; Bourgeois and Johnson, 2001; ten Brink et al., 2006; Kelsey et al., 2008).

Earthquakes also occur within the Watabi-Benioff zone of the downgoing Juan de Fuca plate as it subducts below North America (Ludwin et al., 1991). Deformation within the subducting plate produces deep earthquakes that recur decades apart. Six earthquakes over M 6.0 have occurred within the past 100 years, including historical ruptures in 1949, 1964, and 2001 (PNSN).

Estimates of modern earthquake hazard rely on analysis of the magnitude and recurrence intervals of prehistoric earthquakes. Such earthquakes can be identified through traces they leave behind, which can include evidence of liquefaction and fluidization of sediments, abrupt land level change, and tsunamis.

I investigated evidence for earthquakes from along the banks of the Duwamish Waterway, a dredged former river delta just south of downtown Seattle. Such evidence consists of sand blows likely produced via coseismic liquefaction and anomalous silt layers with the potential to have been deposited by tsunamis. No published paleoseismic study has yet investigated this site, which is in close proximity to inferred traces of the Seattle fault thrusts (Fig. 2) (Pratt et al, 2015). Through investigations between 1996 and 2000, Brian Atwater and others (Table 1) uncovered the first evidence for sand venting and anomalous floods in the Waterway (B. Atwater, pers. comm.).

The scope of this project consisted of three objectives:
1. Describe bank stratigraphy at four Duwamish outcrops, including one new site
2. Identify deposits capable of having been produced through liquefaction or tsunamis
3. Use radiocarbon dating to constrain the ages of deposition

This resulted in three major contributions to the existing body of observations:
- Refined dates of at least two episodes of sand venting and two anomalous floods
- Identification of sand venting at one new site
- More detail about the extent of stratigraphic markers at one site

These observations will add to a growing body of information that describe the seismic hazards faced by the city of Seattle and surrounding area.

2. Geologic Setting

2.1 Puget Lowland, Seattle Fault

The field site, city of Seattle, and surrounding urban areas lie within the Puget Lowland, the structurally complex forearc basin of the northern Cascadia subduction zone (Fig. 1). Oblique subduction of the Juan de Fuca oceanic plate, in combination with rotation of crustal blocks in Washington and Oregon, results in north-south compression of the forearc (Wells et al., 1998; Wells and Simpson, 2001; McCaffrey, 2002). This compression is accommodated by several east-west trending thrust fault structures which cross the Puget Lowland.

These faults include the Seattle fault zone, a ~6km wide band of shallow thrust fault strands that stretches about 80km E-W and crosses downtown Seattle (Fig. 2) (Pratt et al., 2015). Despite its proximity to the city, the shallow expression of the fault is poorly-resolved. Figure 2 shows two recent mappings of fault strands. Blakely et al., (2002) used aeromagnetic anomalies to define three strands and a deformation front (gray lines on Fig. 2) of the Seattle fault. Pratt et al., (2015) interpreted legacy marine seismic data to map three south-dipping main thrusts (A,B,C in Fig. 2) and three north-dipping backthrusts (b,c,d,e).

Holocene activity along the fault zone was described in detail by Bucknam et al., (1992), who noted uplift up to 7m in several locations around Puget Sound. This included a wave-cut platform at Restoration Point, 5km west of Seattle. Radiocarbon dating constrained the age of uplift to between 500 and 1700 years B.P. This timing has been tied to numerous landslides and a tsunami in Puget Sound (Atwater and Moore, 1992; Jacoby et al., 1992; Karlin and Abella, 1992; Karlin et al., 2004). Atwater (1999) further constrained the timing of this event to 900—930 CE. Modelling elevation change of shorelines led ten Brink et al., (2006) to estimate the fault geometry, slip direction, and magnitude of this “Restoration Point earthquake” (Mw 7.5).

Nelson et al., (2014) provided a summary of the evidence for and timing of other interpreted fault ruptures within the Seattle fault zone, including earthquakes B (700 BCE—10CE), C (600—700 CE), D (910—1040 CE), interpreted to be an observation of the Restoration Point earthquake, and E, (1010—1570 CE). Also described are earthquakes along east and west strands of the Saddle Mountain deformation zone dated to 790—1640 CE and 750—980 CE, and an earthquake on the Tacoma Fault (900—970 CE).

2.2 Duwamish River

The Duwamish Waterway refers to the ~7km long dredged channel at the mouth of the former Duwamish River. Presently, the Duwamish drainage begins in the Cascade Range as the Green River, and empties through the Port of Seattle into Elliott Bay (Fig. 3B).

The drainage has been drastically altered by humans in the past century. Prior to alteration, the White River, which drains Mount Rainier, and the Black River, which drained Lake Washington and the Cedar River, both fed the Green River (Fig. 3A), which ended in a large tide flat in

Elliott Bay (Lawson, 1875; Palmer, 1997). In 1900, the level of Lake Washington was lowered approximately 9 feet by the dredging of a ship canal on its northern shore (Chrzastowski, 1983), the Black River was blocked, and the Cedar diverted into the lake. In 1907, the White River was diverted south to the Puyallup River. In the late 1800s and early 1900s, Seattle's tide flats were filled with hydraulic dredge spoils during extensive regrading, and dredging of the lower Duwamish Waterway began in 1914 (Palmer, 1997). By 2001, as a result of industrial pollutants, the lower four miles of the Waterway were classified as a Superfund site (EPA, 2014).

The stratigraphy underlying the modern Duwamish Waterway is informed by the geologic history of the Duwamish Valley (Fig. 4). The valley, occupied first by the river and now the Waterway, is a wide trough thought to have been scoured by sub-glacial meltwater under the Puget lobe of the Cordilleran ice sheet during the Vashon stade of the Fraser glaciation (Crandell, 1963; Mullineaux, 1970; Booth, 1994). Deep bedrock is overlain by compact glacial drift deposits (Zehfuss, 2005). During ice retreat, the Puget lobe dammed a freshwater proglacial lake, then opened to allow incursion of marine waters and deposition of tens of meters of bay mud (Bretz, 1913; Thorson, 1989; Zehfuss, 2003). The delta prograded northward with sediment sourced from Mount Rainier lahars (Dragovich et al., 1994; Zehfuss, 2005). Sedimentation probably occurred as episodes of rapid deposition interspersed with latent periods, but averaged a rate of 7m/yr. Lahar runout sands are characterized by dark andesitic sand as visible in geotechnical borings.

The delta likely reached its current position about 850 CE. Zehfuss (2005) inferred that the end of lahar runout preceded the 900—930 CE Restoration Point earthquake, which lifted the delta sediments ~5m, forming a valley-floor terrace higher than the elevation of historic floods (Zehfuss, 2003). The andesitic sands contain burrows of ghost shrimp now located at or above high tide. The Duwamish river would have incised into these sediments. Tidal mud and peat are inset into the andesitic sand.

3. Methods

3.1 Field methods

Outcrops of intertidal mud along the Duwamish Waterway are exposed at low tide between walls of rip-rap and industrialized shoreline. I visited seven channel bank exposures, including three locales on Kellogg Island (Fig. 5; Table 1), where I recorded sediment characteristics and the presence or absence of sand and silt deposits. At a few sites, I explored sediments via small pits or gouge cores.

Site selection was based primarily on the availability of outcrops. With the exception of one locale (Diagonal Park, Table 1), this report only discusses locales that were previously investigated by Atwater and others (B. Atwater, pers. comm.), and that I reoccupied. At the most-studied outcrop (Federal Center), I focused on refining the radiocarbon dates of the formerly-identified sand blows and anomalous silt layers, as well as extending the observed extend of these deposits. At Diagonal Park, I identified and dated new evidence for sand fluidization. At Kellogg C and Kellogg S, I added new radiocarbon dates.

At each site, I established or re-occupied a vertical benchmark, and related the elevations of these benchmarks to the Mean Lower Low Water (MLLW) tidal datum by surveying each day's low tide and comparing low tide measurements with the Seattle tide gauge's 1-min observed tides (NOAA).

I inferred episodes of sand liquefaction (i.e. fluidization as distinguished by Lowe, 1975, and venting onto a ground surface as described by Obermeier, 1996) through the morphology and sedimentology of sand deposits. In order to classify a sand deposit as sand venting that reached the surface, I looked for a thick sand deposit with a domed shape that was met from below by a vertical sand dike. Presence of silty intraclasts within the sand body strengthened the evidence for fluidization.

3.2 Radiocarbon dating

In order to constrain the timing of inferred liquefaction and flood events, I collected plant fossils found within the sediment and submitted them for radiocarbon dating. I identified two species, *Triglochin maritima*, and *Bolboschoenus* sp., for sampling. On a field trip to a modern-day tidal marsh in Discovery Bay, Washington, I encountered both species and observed their growth positions. I noted that leaf bases of *T. maritima* were growing at or just under the marsh surface, while tubers of *Bolboschoenus* sp. were growing up to ~15cm below the mud surface. I used these observations of modern plants to interpret the fossil plant fragments I found along the Duwamish Waterway.

I selected samples carefully from close proximity to inferred event deposits in order to interpret whether or not the plant fossil pre-dated or post-dated the event, and whether it was a close or distant limiting age.

The day of collection, I rinsed all radiocarbon samples with fresh water, then air dried them for 1-2 days, and picked them clean under a dissecting microscope to remove contaminating roots and other material.

Prepared samples were sent to the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility at Woods Hole Oceanographic Institution for Accelerator Mass Spectrometry (AMS) analysis. Sample pretreatment at NOSAMS consisted of a series of heated washes (acid-base-acid) to remove mobile phases of organic carbon and inorganic carbon.

NOSAMS reported radiocarbon ages in 14C yr BP. In order to translate these "radiocarbon years" to calendar years, I calibrated ages using the IntCal13 atmospheric curve (Reimer et al., 2013) and OxCal version 4.3.2 (Bronk Ramsey, 1995; Bronk Ramsey, 2009; Bronk Ramsey, 2017). I also used this program to model ages of events, which is described in detail in later sections.

Age ranges in this report are presented as a 2σ range of calibrated years CE. This 2σ range only accounts for uncertainty reported by NOSAMS, and does not account for any other errors, particularly systematic laboratory error. Other sources of unaccounted error include errors introduced during sampling, preparation, and interpretation.

In order to simplify reporting, I rounded calibrated years CE "out" to the nearest decade. That is, an age range of 986 – 1022 CE became 980 – 1030 CE.

4. Sedimentary Facies and Soils

Medium stiff, silty deposits crop out along the edges of the modern dredged channel. Outcrops, named for the businesses near their banks, are shown in Fig. 5, overlain onto three eras of site maps. In 2017, these sites were accessible by foot or via canoe only during low tides, and were covered by a thin film of mud and algae produced during their periodic submergence.

Zehfuss (2005) described the underlying material as alluvium, glacial drift, and lahar runout sand sourced from Mount Rainier. Lahar runout at this site was described as clay-poor, andesitic sand. This sand is inferred to be the source of the vented sands described in this report.

Depositional environments that produced these outcrops, from earlier to later, probably include an intertidal mudflat, an intertidal salt marsh, and a historical pasture soil created following the diking of the salt marsh in the early 1900s. The 1875 survey map shows the area prior to the dike; the 1901 map includes the dike (Fig. 5).

These depositional environments produced different sedimentary facies that were recorded at different outcrops. I identified intertidal facies based on sediment color and texture, the presence and type of preserved plant fossils in growth position, and sedimentary structure. In addition, I found a deposit that I inferred to represent the pasture soil that developed when the marsh was diked between 1875 and 1901.

4.1 Facies I: intertidal mudflat

Facies I deposits are present in erosional benches underlying outcrops and are visible in gouge cores or by digging into the surface of the bench. Deposits consist of massive, gray mud or interbedded silts and sands with no observed fossil vegetation. This facies grades into facies II above as recognizable by the gradual appearance of fossil plants.

The lack of vegetation compared with overlying facies drives the interpretation of these deposits as intertidal mudflats, where too much saltwater was present to support vegetative growth.

4.2 Facies II: salt marsh

Facies II is characterized by massive gray mud containing fossil plants in growth position. Fossil plants included parts of sedges, *T. maritima*, *Bolboschoenus* sp., and other unidentified organic matter. At three outcrops, including Federal Center, I observed a color change at the upper margin of this facies. Below, mud is darker gray and was observed for at least 50 cm. Above, mud is lighter gray and about 10 cm thick. The contact at this color change consists of about 8 cm of mottling, and I interpreted it as having been produced by bioturbation.

The presence of intertidal vegetation including sedges and bulrush drive the interpretation of this facies as the soil of an intertidal marsh.

4.3 Facies III: laminated salt marsh

Facies III is a brown-orange clayey silt characterized by fine laminations. Laminations formed notches in weathered outcrops, ranged in thickness from 8 mm to 2 cm. Generally, laminations are about 0.5 cm thick and alternate in color from white, dark gray, light gray, to reddish brown. Frequently this unit is about 1m thick and is easily identifiable above Facies II. Fossil vegetation is typically abundant. The vegetation assemblage appeares to evolve through elevation at individual outcrops. Sedges and *Bolboschoenus* sp. generally appear lowest, while *T. maritima* is present higher in the outcrops. Further work could better characterize a vegetation succession, which would be an indicator of environmental change.

The source of the laminations is unknown. White laminae may represent annual varves sourced from the spring glacial melting from Mount Rainier, when glacial rock flour would have been carried through the White River drainage to the Duwamish.

The presence of vegetation supports interpretation of this facies as intertidal marsh deposits.

4.4 Facies IV: sand

Deposits at several outcrops are punctuated by layers, dikes, or lenses of andesitic sand. The sand appears to have a similar composition across all outcrops where present, and consists of medium dense, dark gray, fine sand with rounded to subangular grains of brick-red andesite, gray lithics, quartz, and some green clasts. Sand ranges from well-sorted and clean at some outcrops (dikes at Kellogg N and Diagonal Park) to silty at others (layer at Kellogg S, lenses at Federal Center).

The morphology of sand deposits also varies across outcrops. Subvertical sand dikes cutting through other strata were observed at Federal Center, Diagonal Park, and on Kellogg Island. Horizontal, bulging sand lenses were observed at Federal Center and are described in notes from Kellogg Central in 1997. An 11 cm thick sand layer with some silt partings was observed at the southern end of Kellogg Island.

The sand layers form erosive notches in the otherwise cohesive outcrops.

A major goal of this project was to identify and date vented sand deposits that may have resulted from earthquake shaking. Martin and Bourgeois (2012) summarized the morphology of earthquake-induced vented sediments in the Puget Lowland: Vented sand deposits can consist of dikes and sills injected into the surrounding material, domes or volcanoes ejected onto a free surface, or infilled lateral spreading cracks (Obermeier, 1996; Martin and Bourgeois, 2012). Vented sand deposits typically fine upwards and can contain intraclasts of deeper sedimentary units (Tuttle, 2001), massive or graded bedding, and structures such as laminae, soft-sediment deformation, or fluid escape structures.

Based on this morphology, I classified sands as either sedimentary sand (i.e. no evidence of venting), intruded sand (i.e. sand dikes), or extruded sand (i.e. sand blows). In order to classify a deposit as a sand blow, I looked for evidence that the sand was variable in thickness, met by a feeder dike, and contained silt clasts.

4.5 Facies V: flood silt

Facies V consists of persistent, horizontal, gray silt layers with massive bedding and regular structure that distinguished them from the surrounding mud. The silt layers are up to 2.5 cm thick.

The persistence and massive structure of these deposits suggests rapid deposition like a river flood or tsunami. River flood and tsunami deposits are typically thin (<25cm), sheet-like, massive or fining-upward, and thicken into depressions (Morton et al., 2007). Additionally, tsunami deposits thin and fine landwards, can extend for kilometers inland along rivers, and may range in grain size depending on the available sediment for transport (Bourgeois, 2009).

4.6 Soil

This deposit consists of dark brown or red, undulating, fibrous peat and mud. It is about 1.5 cm thick and observed near the top of outcrops at Federal Center and Kellogg S. There is a clear contact between this unit and Facies 4.

I interpret this soil to be the former soil of the early 20th Century pasture, formed after diking of the salt marsh.

5. Stratigraphy and Chronology

Stratigraphic columns and radiocarbon dates from each outcrop are plotted in Figures 6-11. Figure 11 summarizes stratigraphy and dates across all five outcrops. I split each outcrop into units, described the material present, then assigned the units to the facies described in section 4.

5.1 Federal Center

The Federal Center outcrop is the longest and most continuous outcrop amongst all of all the field locales, and it has also been subject to the most observations (Table 1). This east bank site lies directly below the Federal Center South compound that fronts on E Marginal Way. The outcrop is accessible via canoe or on foot across rip-rap from Diagonal Ave S Public Shoreline.

The outcrop consists of a nearly-continuous, 55 m long mud bank and erosional bench exposed during low tides. The top surface of the bank is vegetated with bulrush and littered with rotting wood and other debris. The bank is punctuated by one wide channel and two jetties of rip-rap that stick out into the Waterway. Over the course of several field trips, I described stratigraphic units and took radiocarbon samples along the length of the outcrop.

Figure 6 shows the Federal Center outcrop, stratigraphic section, and unit descriptions. This characteristic section is based on a sketch of the outcrop. Figure 7 shows radiocarbon sample sites and presents chronology of the section.

Intruded or extruded sand

The 55 m long outcrop at Federal Center exposes several horizontally-aligned and persistent sand lenses that range in thickness from <1cm to >12cm. The sand appears undulating and bulbous, and at one location drapes over a mound of *T. maritima* leaf bases (Figure 12). At multiple locations, silt clasts resembling the surrounding mud were observed within the sand, and several sand dikes terminate in its lower surface.

I observed three sand dikes. Eight sand dikes had been observed previously (B. Atwater, pers. comm*.)*. The strike, lateral, and vertical extents of dikes are listed in Table 4. Dikes are generally sub-parallel, striking within 30 degrees of N-S. Dikes terminate in front of the outcrop face (n=4), at a sand lens (n=3), above the sand (n=1) and even higher in the outcrop, above the lower silt (n=1). Dikes may have been associated with lateral spreading from one of the existing channel banks, which would explain their nearly parallel orientations.

These observations are consistent with at least two episodes of liquefaction and fluidization.

The earlier episode is represented by the horizontally-aligned sand lenses, which were likely vented onto the ground surface. This is evidenced by the draping of the mound of *T. maritima*. Assuming the plants were living up to the point of sand venting, these fossils provide a close maximum age constraint for the timing of this event. I developed an age model in OxCal for this event, using the “Combine” function, which assumes that any variability in age is due to lab error, to model the age of both of these samples and the event. This assumes that the variation in radiocarbon age of the plants in this mound, and the difference between the radiocarbon age and the age of the event, is within 15 years, the error range of the original radiocarbon date. This routine produced a modelled age range (2σ) for sand venting: 1020 – 1150 CE. Table 3 summarizes inferred episodes of sand venting.

The later episode of venting is evidenced by sand dikes which extend above the stratigraphic level of the sand lenses. I have represented this age range as following 1020 – 1150 CE. This may or may not represent the same venting episode as episodes of venting that produced dikes at other outcrops.

Evidence for land level change

The horizontally-aligned sand lenses are at the same elevation of a facies change from orange-gray peaty mud, interpreted as salt marsh deposits (below) and gray mud with only patches of peat interpreted as intercalated salt marsh and mud flat deposits (above). The color change is present along the length of the outcrop, even where sand lenses are not. At the mound of *T. maritima* described above, the leaf bases do not extend up through the thin layer of vented sand (Figure 12). This suggests some sort of environmental change, perhaps relative sea level change, may have accompanied sand venting.

Anomalous silts

Two prominent tabular silt layers, 2-2.5 cm thick, extend horizontally across the outcrop, and were visible via eroded notches before outcrop cleaning. The lower silt is patchier than the upper silt.

The silts were dated via radiocarbon samples of *T. maritima* leaf bases in growth position between the silts and above the upper silt (Figure 7). I did not take radiocarbon samples from between the sand and the lower silt, though the two were separated by about 20 cm of tidal marsh deposits and at least one mound of *T. maritima*, suggesting they did not represent the same event.

I modelled the ages for emplacement of the two silt layers using an OxCal "sequence," which forces radiocarbon ages reported in stratigraphic order to have sequential calibrated ages. This routine resulted in modelled ages of 1320 – 1400 CE for the upper silt, and 1030 – 1180 CE for the lower silt.

5.2 Diagonal Park

This site, the second on the eastern edge of the waterway, is located ~400 m NW of the Federal Center outcrop. The outcrop consists of about 55 m of muddy bank up to 1 m tall. This site is accessible via canoe from the Waterway, or on foot through mud from the Diagonal Avenue South Park Public Shoreline Access.

I established a 55 m long lateral transect and measured sections in the bank at x=1.5 m and x=31.5 m, in addition to logging five gouge cores from up to 3.5 m east and 1.4 m west of the transect line.

Figure 8 shows a generalized stratigraphic column describing the units present at Diagonal Park.

Intruded or extruded sand

Though I observed several sand dikes in the beach at this outcrop, I only thoroughly described one sand dike that extended up into the outcrop. No sand lens was observed here.

The Diagonal Park sand dike is subvertical, 3-3.5 cm thick, narrows upward, and consists of dark brown, fine, sand with brick red clasts. It extends into the outcrop with no evidence of surface breach. I traced the dike vertically to a unit that contained at least three *T. maritima* in growth position. I sampled these leaf bases and submitted one for radiocarbon dating to provide a minimum date for the dike. If the dike cut through that unit but did not reach the surface, those plants must have been growing near or before the time of sand fluidization.

The *T. maritima* sampled here has an age range of 1250 – 1290 CE. I interpret the fluidization to be more recent than this.

Anomalous silts

This outcrop conspicuously lacks prominent silts similar to those observed at the Federal Center outcrop. I observed one layer of patchy, dark gray, silt at the same elevation as the Federal Center lower silt.

A better understanding of this outcrop would be gained by producing a lateral sketch such as that performed at Federal Center.

5.3 Kellogg N

This site consists of the northern tip and northeastern edge of Kellogg Island and is accessible by boat at low tide. The outcrop is a diminutive assortment of mud stacks that stand about 1 m high above the low-angle eroded bench surface. These are interspersed with narrow wooden piers. There is a sandbar at the northern tip of the island. This is composed of dark sand and curves around the northern and eastern sides of the island. Stratigraphy and chronology at Kellogg N are summarized in Figure 9.

Intruded or extruded sand

These outcrops expose a 0.3cm thick, subvertical dike of well-sorted andesitic fine sand that bifurcates moving up in the outcrop. The dike crosses a contact (laminated peaty mud below and massive gray mud above) which may represent a disconformity. Above this, the laminated peaty mud resumes, replete with numerous *Bolboschoenus* sp. fossils.

I sampled two *Bolboschoenus* sp. corms from this level, with calibrated ages of 1410 – 1490 and 1420 – 1460 CE. Combining these ages using OxCal's "combine" function returns an age of 1430—1460 CE (Appendix 1), which I interpret to be the timing of appearance of this species.

However, these dates cannot be meaningfully compared to the timing of dike emplacement. The dike may have occurred prior to the growth of the tubers, or more recently, and may have failed to reach the surface.

Anomalous silts

Two sub-horizontal silts less than a centimeter thick cut across laminated peaty mud below, and presumably before, the growth of the tubers with the calibrated radiocarbon age range of 1430 – 1460 CE. This age range is consistent with the silt layers present at Federal Center. The lower of these silts is cut by that outcrop's bifurcated dike.

5.4 Kellogg C

Kellogg C refers to the central part of the eastern edge of Kellogg Island, which consists of several separate outcrops. I summarized stratigraphy from a 1997 sketch (Appendix 2). This sketch describes several parallel or subparallel dikes that narrow upward. These were traced over 1 m vertically, with the upper ends terminating in sand lenses.

Intruded or extruded sand

Atwater and others (Table 1) took radiocarbon samples of *Bolboschoenus* sp. corms, culms, and rhizomes from 0-10cm above the top of the sand lenses. After adding an error multiplier of 1.6 (Nelson et al., 1995 Table 1), these dates calibrate to 1470 – 1640 CE. Fluidization and venting which emplaced the dikes and lenses likely would have occurred 10-20 years prior, shifting the age range of probable venting to 1450 – 1630 CE and before.

Anomalous silts

At this outcrop, I observed a gray sandy silt layer about 0.5 cm thick across about a half a meter of outcrop. I sampled *T. maritima* from above this layer, but these have yet to be submitted for radiocarbon analysis.

5.5 Kellogg S

The Kellogg S outcrop, on the southern tip of Kellogg Island, consists of a ~1.5 m tall mud face exposed under rip-rap, trees, and meters of fill (Fig. 10A). A large notch cuts back into the outcrop at the surface of the eroded platform. The outcrop extends below the eroded platform, and contains more notches. I made one trip to this outcrop on 6 August, 2017. Nearly all my observations are from the mud face below the rip-rap and above the surface of the eroded platform.

Intruded or extruded sands

I saw no evidence of intrusive dikes or extrusive sand blows at this locale. Though a thick band of andesitic sand was present, I did not observe dikes, rip-up clasts within this body, or any other evidence of liquefaction or fluidization. On the contrary, thin, sub-horizontal silt seams within this sand unit suggest a fluvial deposition. I interpret this sand, and the other subparallel thinner sand beds, as sedimentary sand.

Chronology

I found one *T. maritima* colony in growth position at the lower margin of the thick sand bed described in Figure 10B. Figure 10C shows the leaf bases of this colony. Following this photo, the outcrop was cut back 6 cm. The plants appear to cut up into the sand body before petering out. I interpreted this as the plants having been inundated by the sand, then beginning to grow up through the thick layer. This suggests that the age of these plants would closely post-date the deposition of the bottom of the sand.

One sample from this colony was submitted for analysis, returning a conventional age of 910 +/- 20 yrs (Fig. 10D). Calibrating this age gives two likely 2σ age ranges: 1030 – 1170 CE (94.1% weighting) and 1170 – 1190 CE (1.3%). I combined these for a 2σ age range of 1030 – 1190 CE.

6. Discussion

This study identified at least two, and possibly more than four, episodes of sand venting, as well as at least two anomalous floods that occurred along the Duwamish waterway within the past 1,000 years (Table 3). These results suggest that the lower Duwamish records shaking from at least some local or regional earthquakes and floods from land or sea. Comparison with other regional events can produce more clues to address the following questions: what were the sources and magnitudes of the earthquakes that produced the sand deposits? Were the silt layers tsunamis or river floods? Why are some events recorded in the Duwamish strata, while some are excluded?

6.1 Inferred sources of shaking and flooding

Figure 13 plots the timing of the events described here compared with other inferred earthquakes and tsunami events from in the Puget Sound region. Note that while the radiocarbon dates of the new first liquefaction event and first flood event overlap, these event layers were present in one outcrop, separated by decimeters of sediment, and therefore represent separate events.

Earthquakes

Earthquake sources include crustal fault earthquakes, Cascadia subduction zone earthquakes, and deep Wadati-Benioff zone earthquakes.

The first episode of liquefaction overlaps in time with one earthquake on the Seattle fault zone, earthquake “E” (Nelson et al., 2014), and one Cascadia subduction zone event, earthquake “W”. The later episode or episodes of liquefaction also overlap with earthquake “E”. Is one of these earthquakes more likely than others to have produced the deposits I observed along the Duwamish? This question could be addressed through a literature review to learn what is known about each source earthquake, and by analyzing whether or not ground shaking might have been strong enough to produce sand fluidization in the Duwamish delta.

The Wadati-Benioff zone produced earthquakes in 1949, 1965, and 2001, none of which apparently produced liquefaction that remains visible at these outcrops (PNSN). However, liquefaction was reported along other stretches of the Duwamish valley during the M6.8 2001 event (Nisqually Earthquake Clearinghouse Group, 2001). This suggests that the liquefaction deposits explored during this project do not represent a complete catalog of all earthquakes to have impacted the region.

For example, I found no evidence of liquefaction likely young enough to have been produced by the 1700 Cascadia subduction zone earthquake. This does not necessarily suggest that ground shaking along the Duwamish was insufficient to produce such a deposit.

Unusual Floods

Flood deposits may have been produced by tsunamis from Puget Sound or by river floods. Rigorously evaluating evidence for either of these sources was outside of the scope of this project.

However, as a first pass at addressing this question, I compared the ages of the flood deposits observed at Federal Center with the ages of other inferred Puget Sound tsunami deposits.

The first episode of flooding overlaps with two separate inferred tsunami deposits at Discovery Bay, Bed 3 and Bed 4 (Garrison-Laney 2017). The wide age ranges of all of these events demonstrate the uncertainty of correlating via age alone. The tail end of the date for this flood episode also overlaps with a separate silt layer at Lynch Cove.

Another silt layer at Discovery Bay, interpreted as a tsunami deposit, dates to 1170 – 1230 CE, which closely overlaps with the second episode of flooding (Garrison-Laney 2017).

Even if one or both layers were produced by a tsunami, this does not ensure that an earthquake occurred during this time period. Tsunamis in Puget Sound may also be triggered by landslides.

Notably absent is a strong tsunami signature from the 1700 Cascadia earthquake. This event produced a tsunami that left deposits across Puget Sound, including Discovery Bay (Garrison-Laney, 2017). Numerical simulations by Garrison-Laney indicate that such a tsunami may also have inundated Elliott Bay and the former Duwamish estuary. However, I found no evidence for liquefaction this recent, and little evidence for an unusual flood. (One regular gray layer less than 1cm thick was observed at one part of the Federal Center outcrop, about half a meter above the 1320 – 1400 CE silt deposit and below the ~1900 CE pasture surface. This silt layer was much lighter than the other silt markers, and was not investigated during the course of this project). Future field work should explore this silt marker to determine whether or not it resembles a tsunami deposit, and if so, to date the deposit.

Even if the outcrop records a 1700 CE tsunami, the deposit would be much fainter than the existing silt deposits. Did the 1700 earthquake and tsunami have a lesser impact on the Duwamish than other earthquakes and/or floods? Or were deposits from a strong tsunami ephemeral?

6.2 Implications for hazards

The sand blows and flood deposits described in this report demonstrate the general susceptibility of the Lower Duwamish waterway to natural hazards.

Assessment of earthquake hazard is based upon a combination of magnitude and recurrence interval of former earthquakes. While this project demonstrates a general presence of at least two earthquakes, it does little to address specific magnitude, recurrence, or source of earthquakes. Furthermore, any earthquake catalog compiled from inferred liquefaction events at these outcrops would necessarily be incomplete, as evidenced by missing events in 1700, 1949, 1965, and 2001.

6.3 Future work

There are many opportunities for future work that would shed light on some of the questions introduced above. Future field work in the style of this project, or submission of more radiocarbon samples collected during this project, would probably improve ages of inferred liquefaction events, with the possibility of distinguishing more episodes of liquefaction. An attempt could be made to constrain the magnitudes of earthquakes required to produce these liquefaction deposits, in the style of Maurer et al., (2015), although this method has not yet been demonstrated in this region.

The silt layers present at Federal Center could be systematically analyzed for marine or freshwater microfossils, as described in Garrison-Laney (2017). A lack of marine microfossils in the silts could rule out a tsunami origin.

The upper third of the Federal Center outcrop could be inspected for evidence of deposition during 1700. In order to test whether a 1700 tsunami might have inundated the Duwamish, tsunami models could be updated to use the historical bathymetry of the Duwamish delta.

7. Conclusions

This study contributes new radiocarbon dates to constrain ages of two episodes of sand venting and two silt layers within the past 1000 years along the lower Duwamish Waterway. All of these episodes are likely to be older than 1700. This adds to the growing catalog of paleoearthquake and paleo-flood evidence in the Puget Lowland. Future research can capitalize upon this reconnaissance to better constrain the nature of earthquake hazards to Seattle.

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Figures

1. Regional map of western Washington state showing Seattle, Mount Rainier, the Cascade Range, Puget Sound, Olympic Mountains, and the general locale of the Cascadia Subduction Zone.
2. Local map showing traces of the Seattle fault as mapped by Pratt et al., (2015) and Blakely (2002) and the location of the study site. The background consists of multibeam bathymetry surveys from NOAA (color) and Puget Sound lidar (gray).
3. Map of the Duwamish River drainage showing the former (A) and present (B) configurations. From Palmer, 1997.
4. Stratigraphic cross-section of the Duwamish Valley. Adapted from Zehfuss, 2003.
5. Field sites in the lower Duwamish waterway. Sites are plotted on an 1875 survey map (Lawson, 1875), a 1901 survey (Lawson and Gilbert, 1889), and a 2017 Google Earth image.
6. Stratigraphy: Federal Center
7. Chronology: Federal Center
8. Stratigraphy and Chronology: Diagonal Park
9. Stratigraphy and Chronology: Kellogg N
10. Stratigraphy and Chronology: Kellogg S
11. Stratigraphic summary
12. Photo and tracing of vented sand draping *T. maritima* fossil plants at the Federal Center outcrop.
13. Timeline (cal yr CE) showing inferred events described in this report compared with other regional events. Distributions (2s) for modelled age ranges of inferred liquefaction events are described in green. Distributions for inferred floods (from land or sea) are shown in blue. Gray bars represent age ranges for other events as described by Nelson et al., 2014 (Seattle fault zone and Tacoma fault zone), Garrison-Laney 2017 (tsunami deposits at Discovery Bay and Lynch Cove), and Jacoby et al., 1997, Yamaguchi et al., 1997, Atwater and Griggs, 2012 (Cascadia Subduction Zone).

Tables

1. Summary of outcrops and outcrop investigations. This table presents outcrops along the Duwamish River and the dates and summaries of the field investigations at those outcrops that contributed to this project.
2. Radiocarbon samples submitted for analysis, prior to use in age models
3. Interpreted sand venting events and 2s age ranges.
4. Sand dikes observed at the Federal Center outcrop. X-coordinate reported as distance along the face of the outcrop.

Figure 1. Regional map of western Washington state showing Seattle, Mount Rainier, the Cascade Range, Puget Sound, the Olympic Mountains, and the general locale of the Cascadia Subduction Zone nearest Seattle.

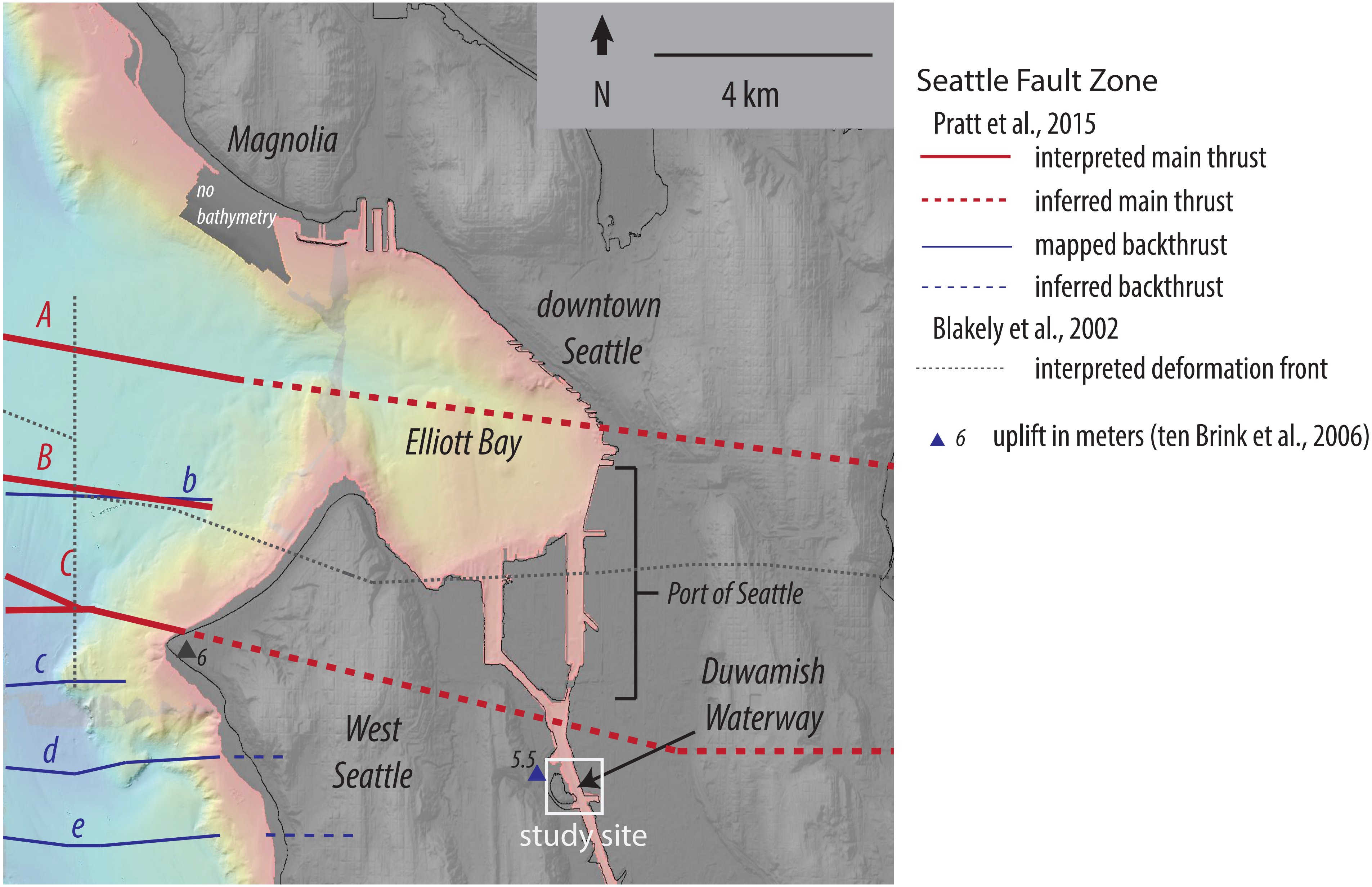


Figure 2. Local map showing traces of the Seattle fault as mapped by Pratt et al., (2015) and Blakely (2002) and the location of the study site. The background consists of multibeam bathymetry surveys from NOAA (color) and Puget Sound lidar (gray).

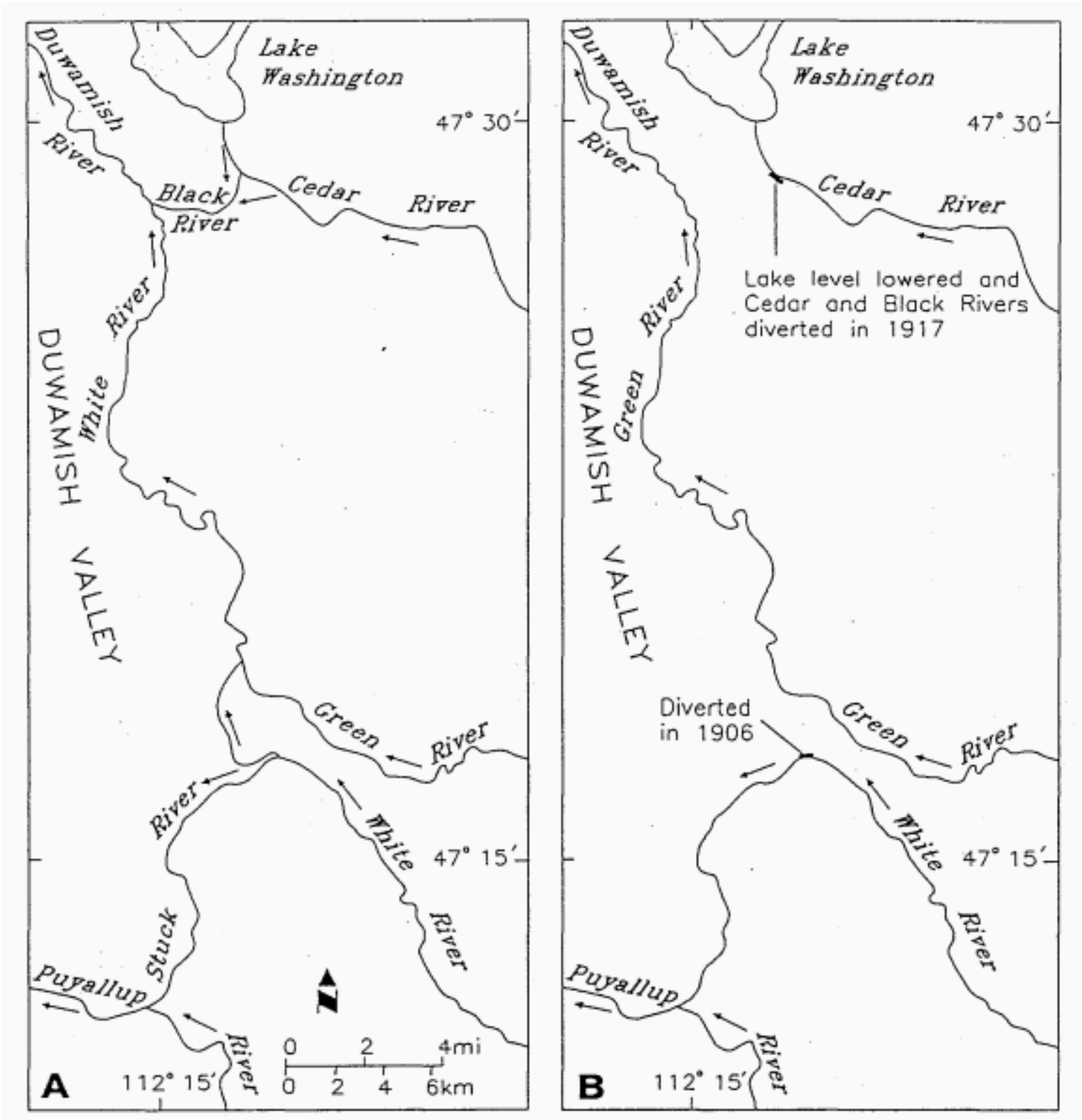


Figure 3. Map of the Duwamish River drainage showing the former (A) and present (B) configurations. From Palmer, 1997.

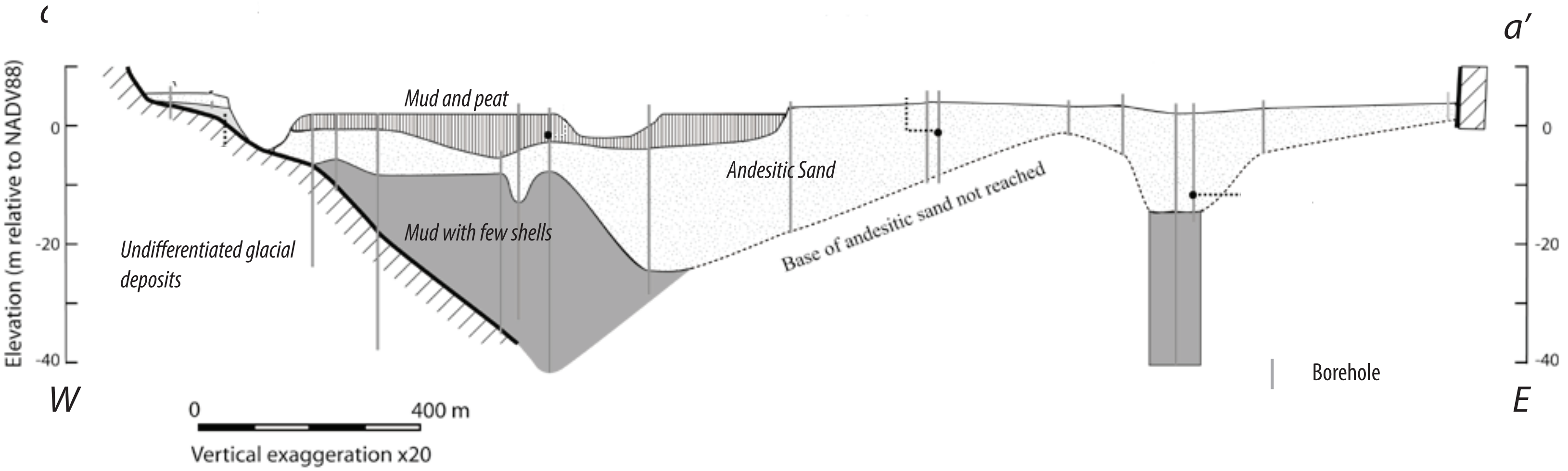


Figure 4. Stratigraphic cross-section of the Duwamish Valley. Adapted from Zehfuss, 2003.

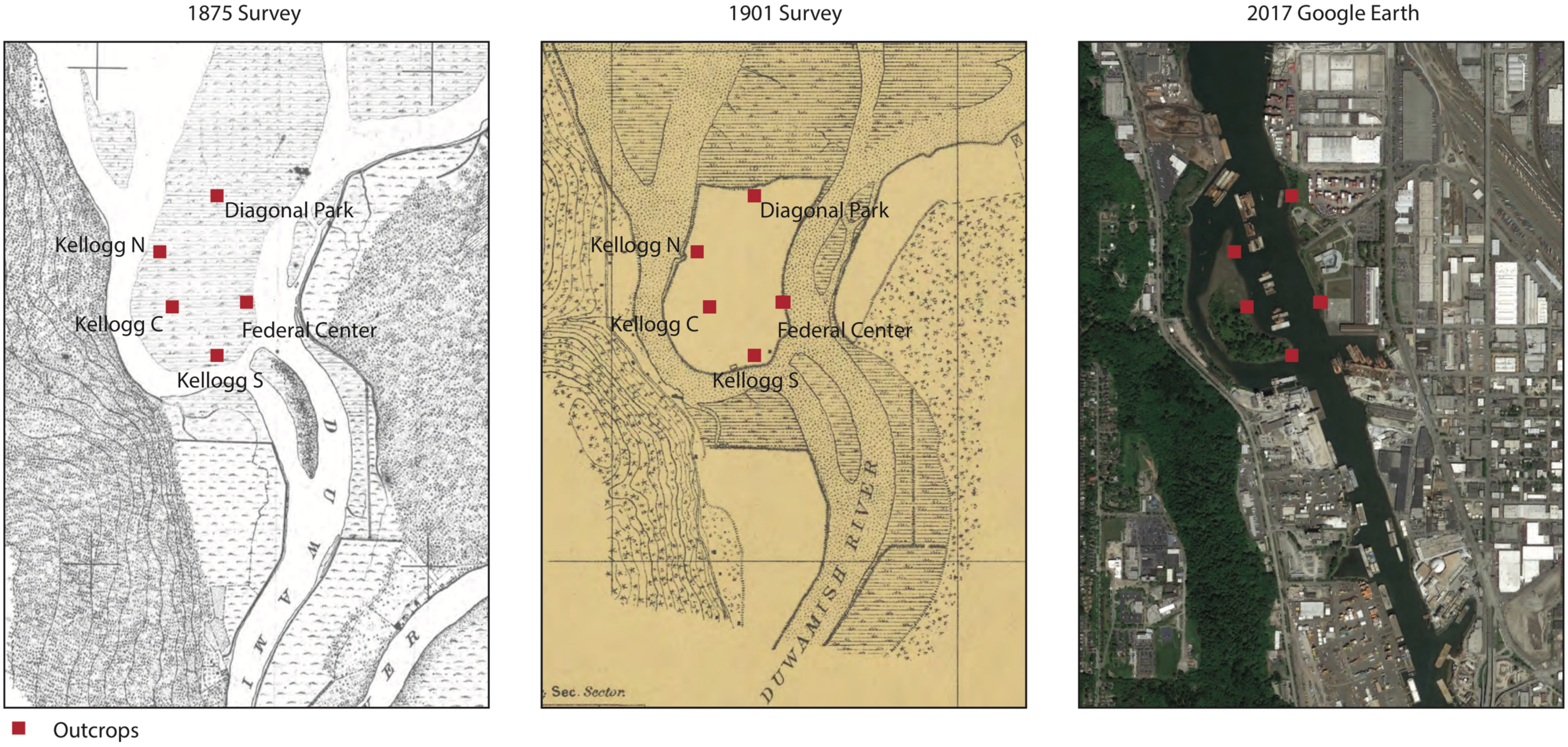
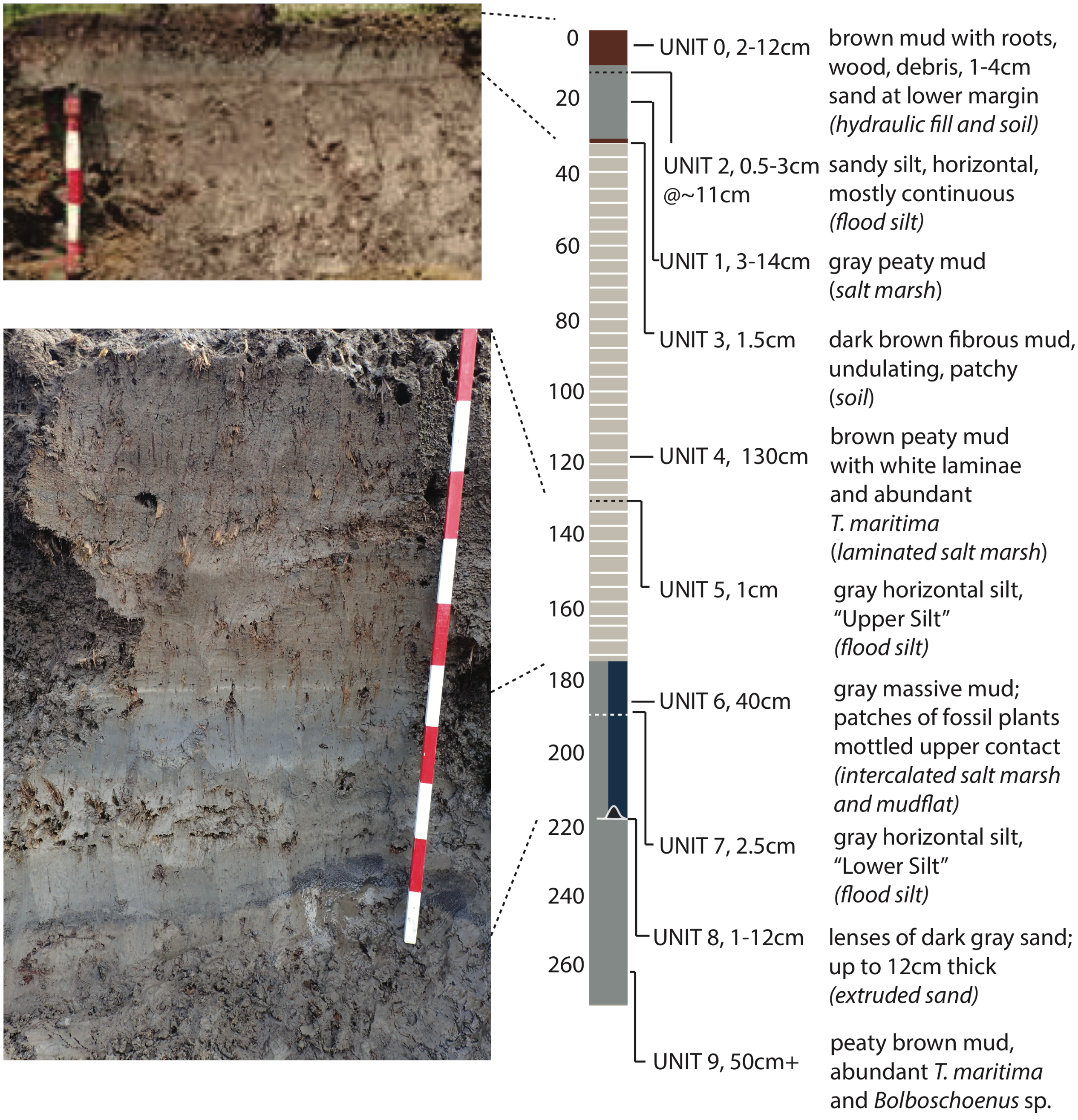
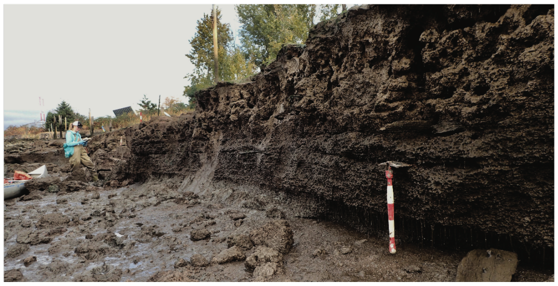


Figure 5. Field sites in the lower Duwamish waterway. Sites are plotted on an 1875 survey map (Lawson, 1875), a 1901 survey (Lawson and Gilbert, 1889), and a 2017 Google Earth image.

Figure 6. Stratigraphy: Federal Center

B.





A. Outcrop, looking north.
Shovel blade in Upper Silt notch.

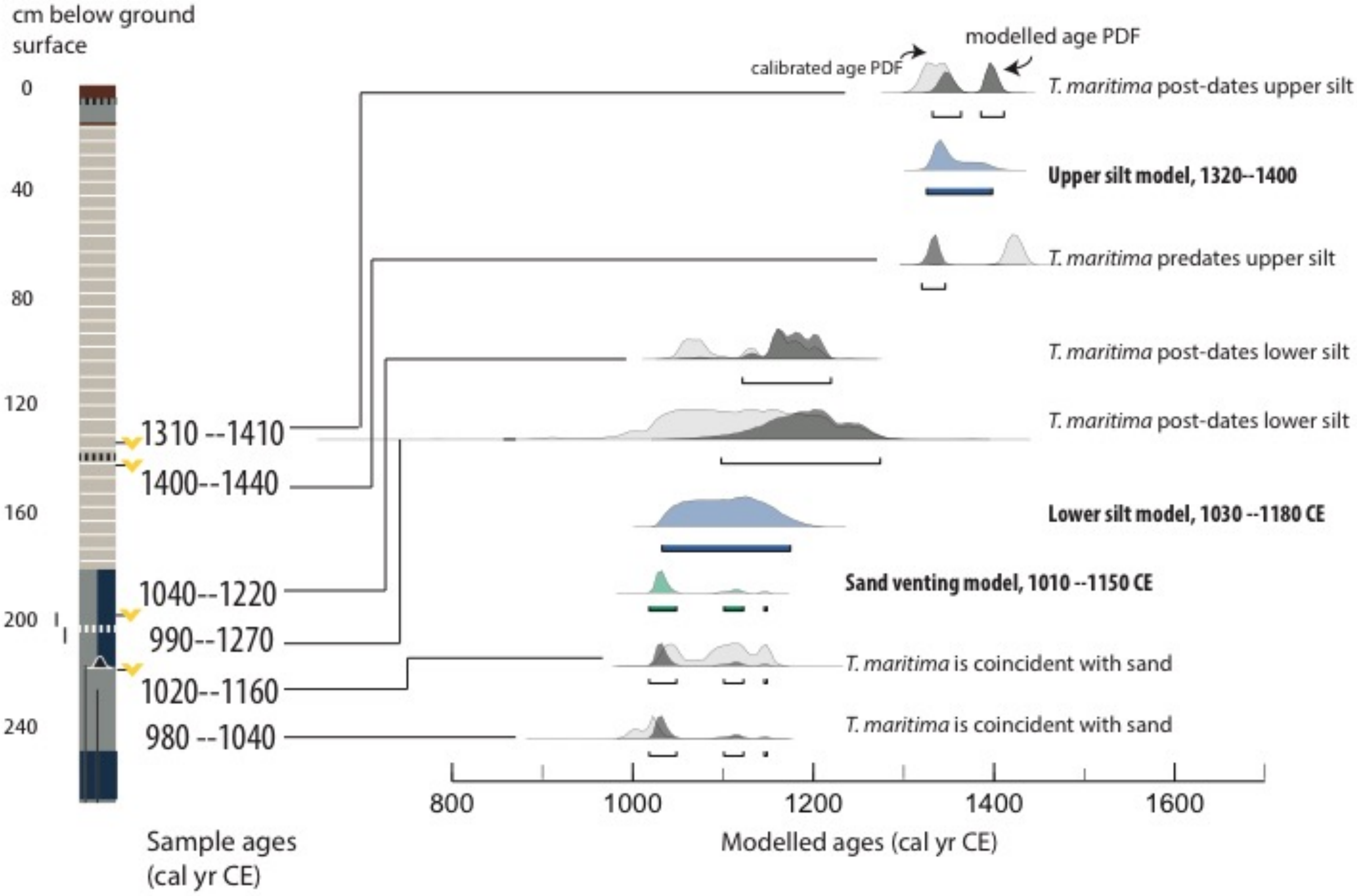


Figure 7. Federal Center Chronology. Stratigraphic column, locations of radiocarbon samples used in age models, and modelled age PDFs of each sample and event. The age of sand venting was modelled using the two lowest samples. The age ranges of the upper and lower silts were modelled using all samples in this sequence.

Figure 8. Stratigraphy and Chronology: Diagonal Park

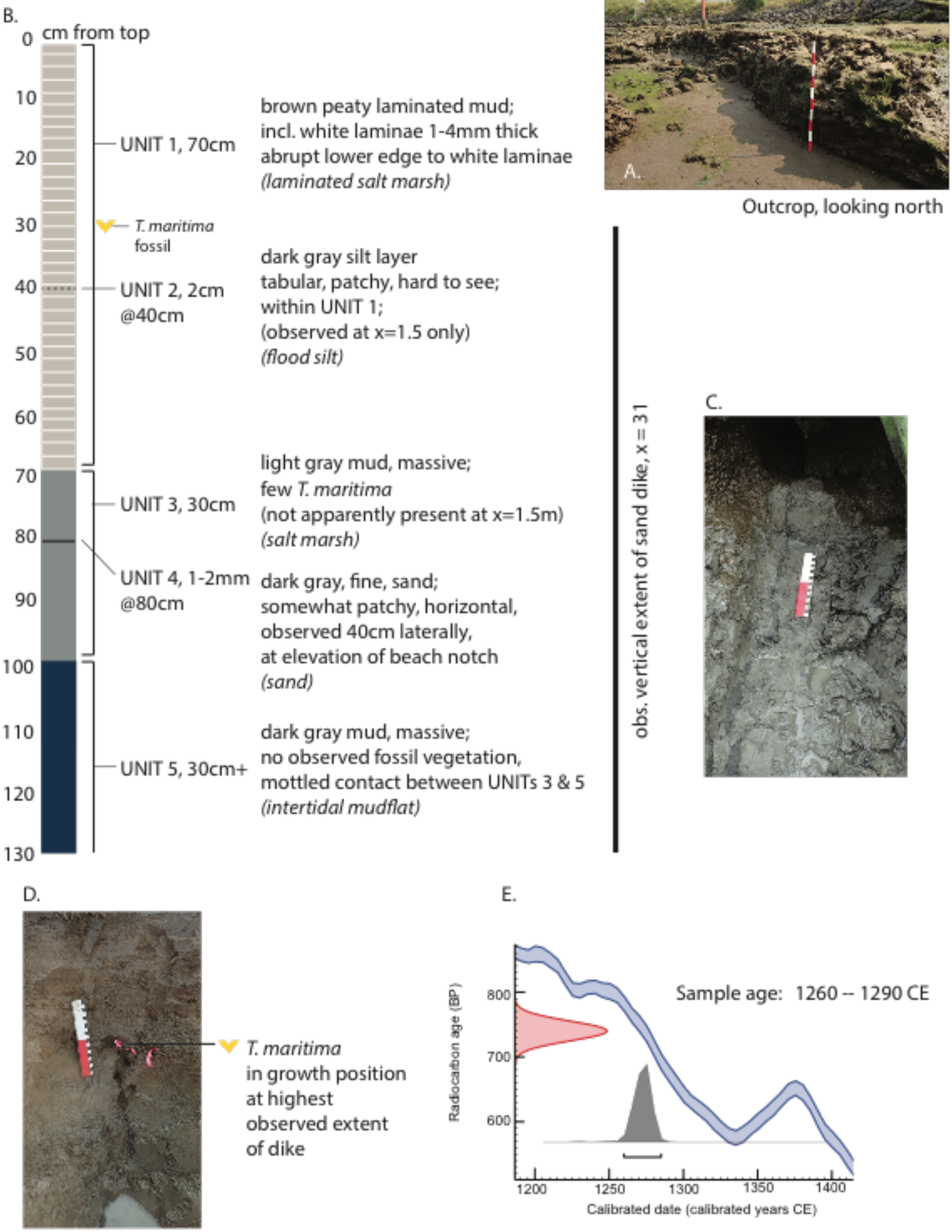
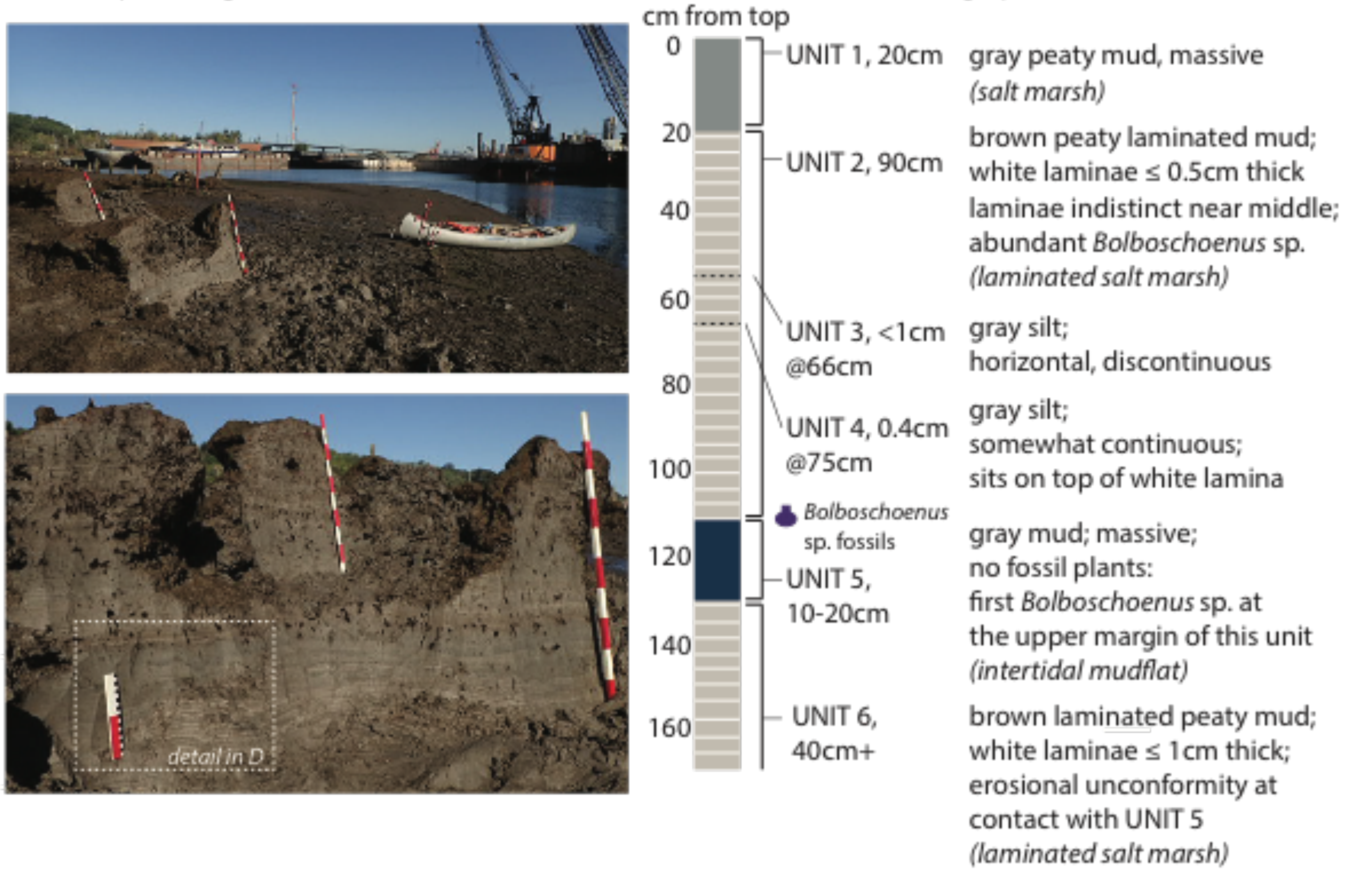


Figure 9. Stratigraphy and Chronology: Kellogg N

A. outcrop, looking N

B. stratigraphic section



D. radiocarbon samples

E. radiocarbon calibration

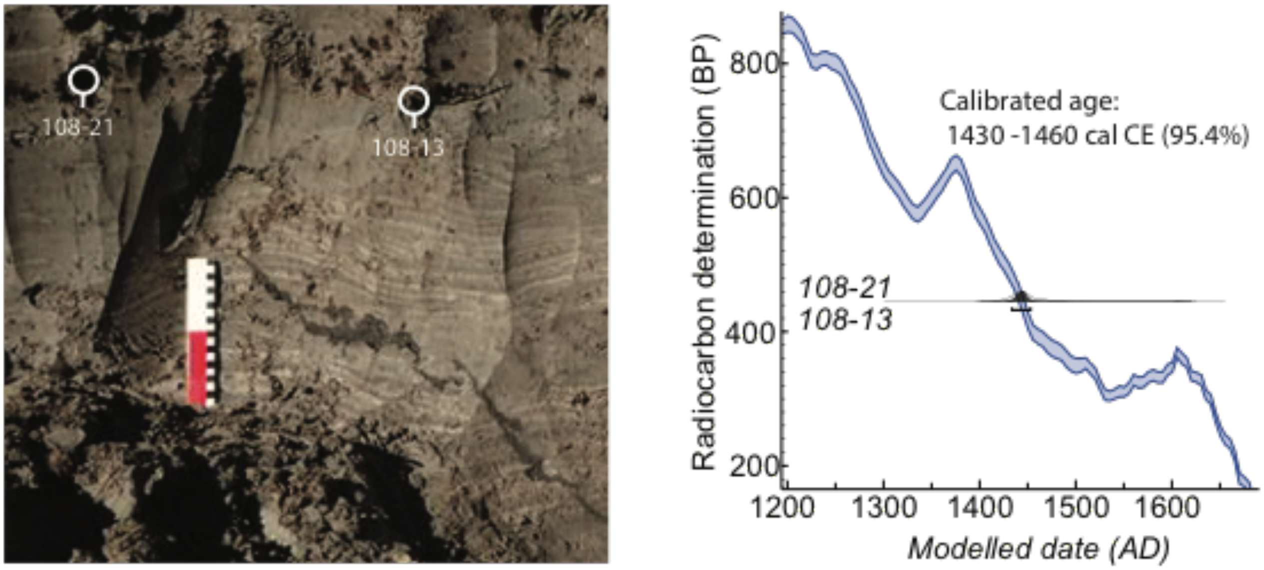
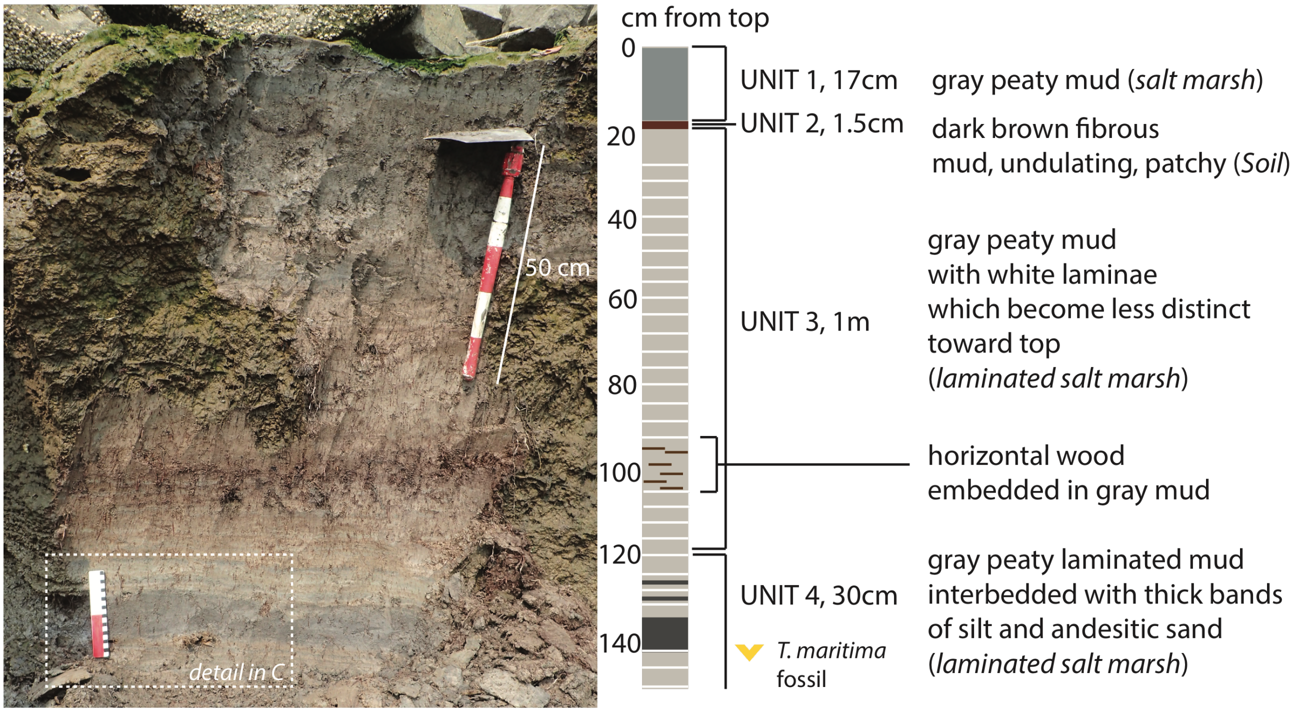
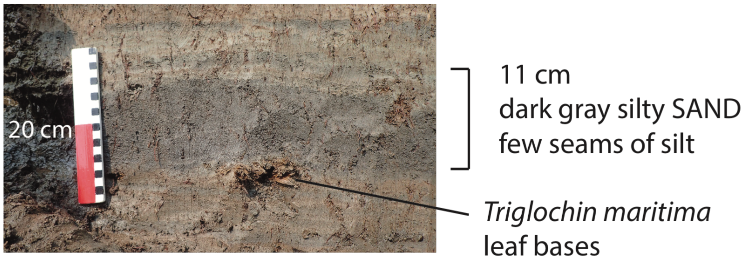


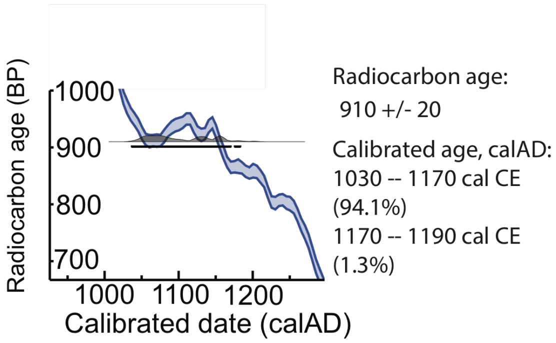
Figure 10. Stratigraphy and Chronology: Kellogg S



B. Outcrop close-up and schematic stratigraphic column



C. Radiocarbon samples



D. Radiocarbon calibration

A. Photo of the outcrop at Kellogg S, looking south.

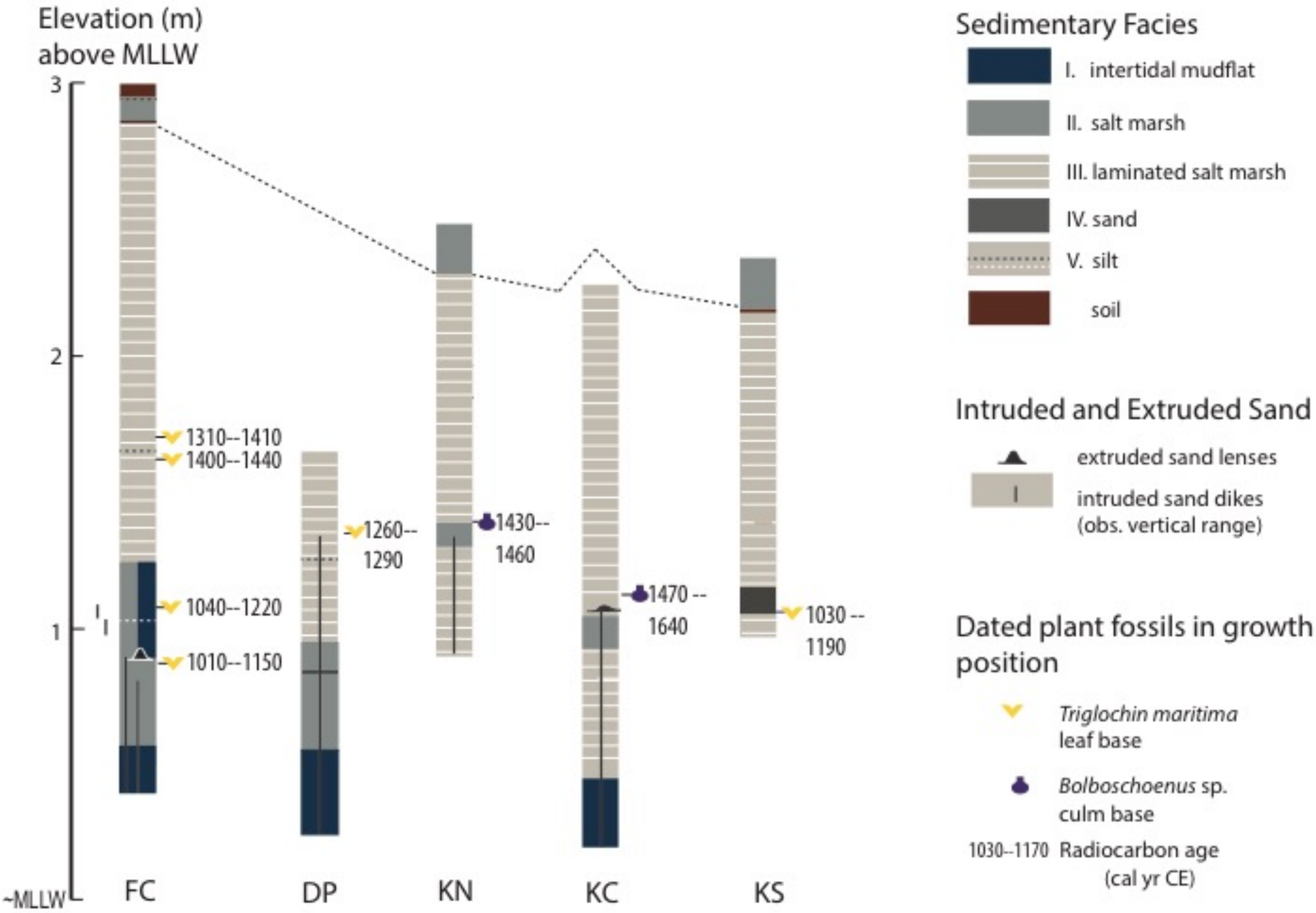


Figure 11. Stratigraphic summary: columns from outcrops (FC-Federal Center; DP-Diagonal Park; KN-Kellogg N; KC-Kellogg C; KS-Kellogg S). Stratigraphy and dates at Kellogg C derived from 1997 sketch (B. Atwater, pers. comm.). All radiocarbon ages are single sample ages, with the exception of the lowest age at Federal Center, which represents the combined model of two ages (see Fig. 7).

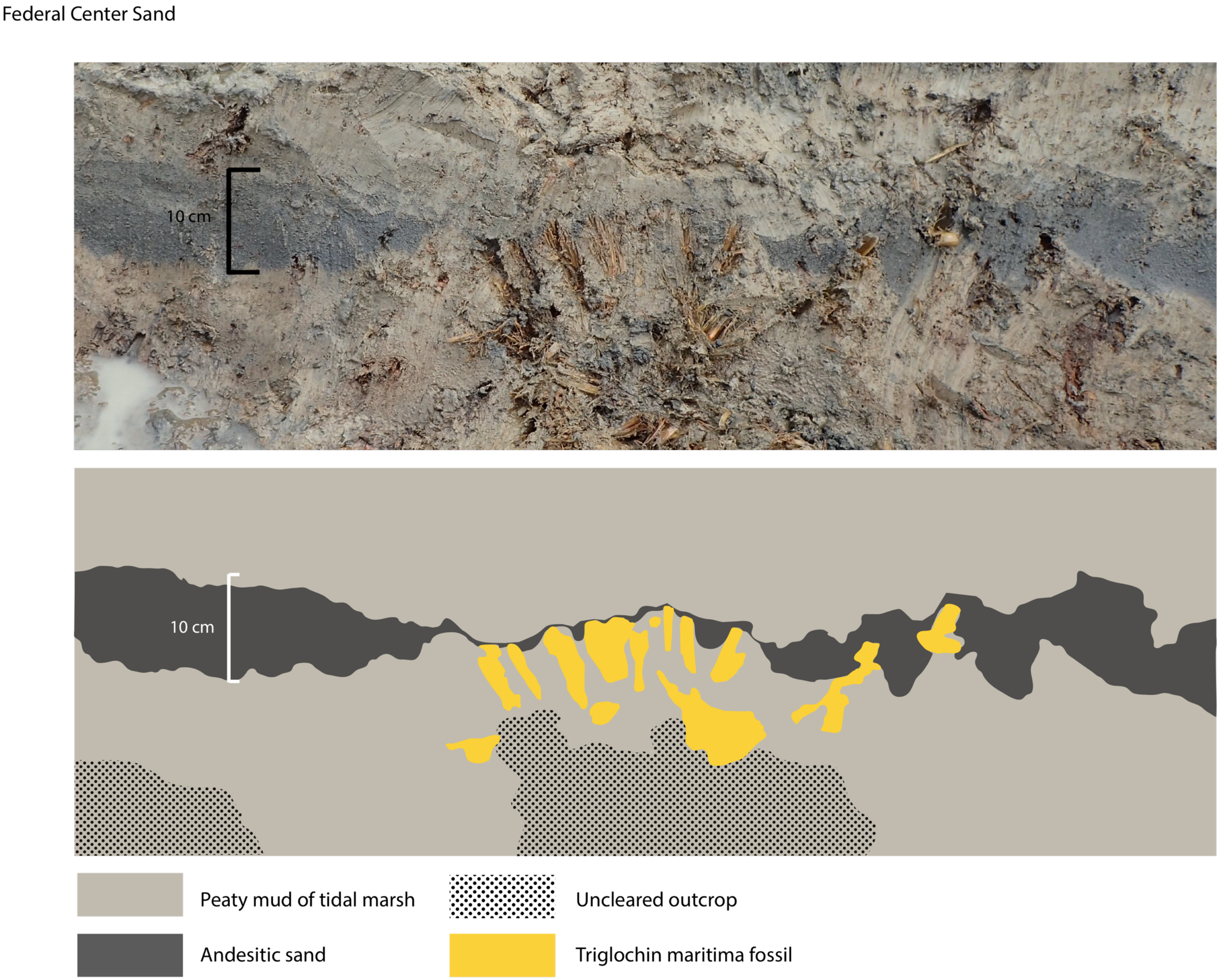


Figure 12. Photo and tracing of vented sand draping *T. maritima* fossils at the Federal Center outcrop. Radiocarbon samples were taken from these fossils.

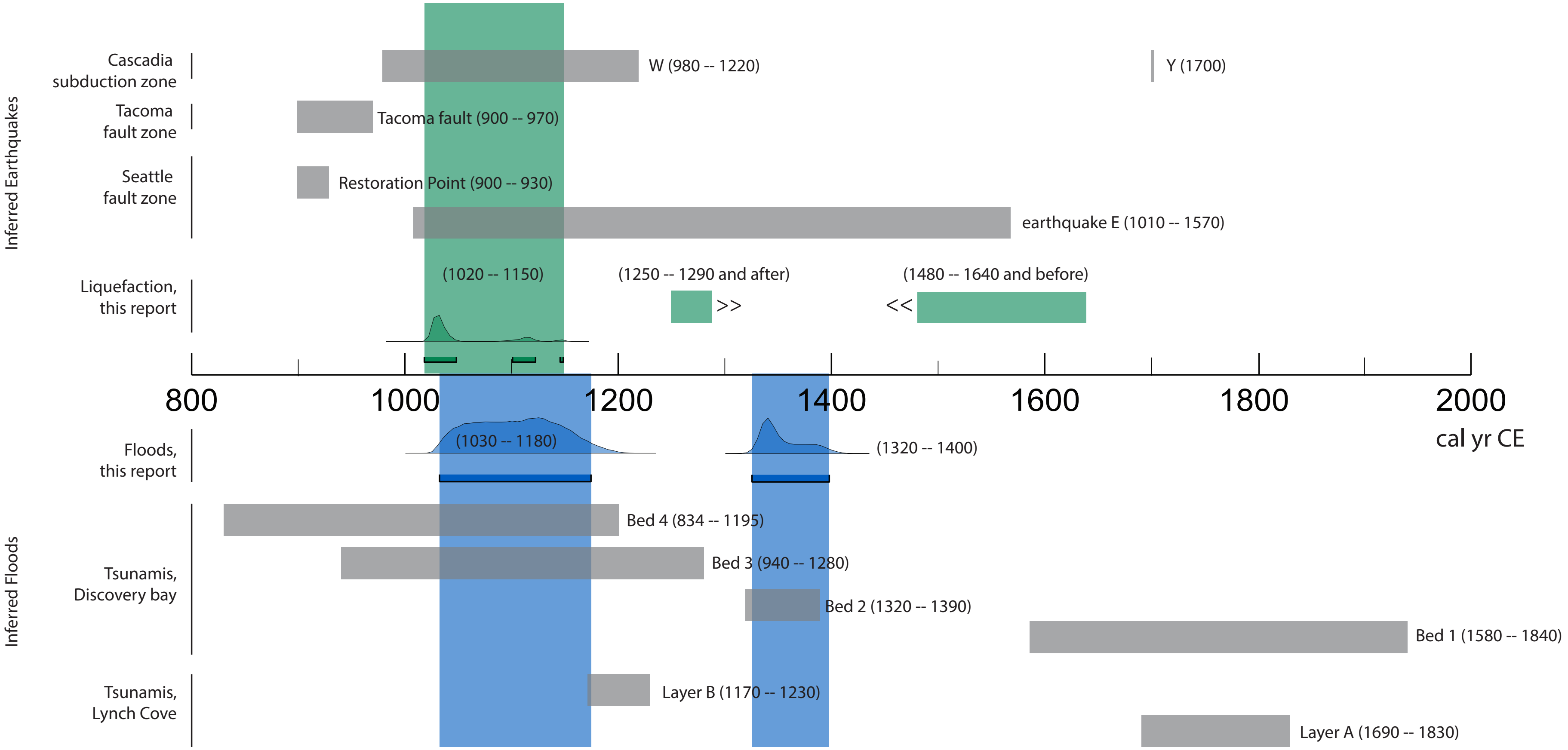


Figure 13. Timeline (cal yr CE) showing inferred events described in this report compared with other regional events. Distributions (2σ) for modelled age ranges of inferred liquefaction events are described in green. Distributions for inferred floods (from land or sea) are shown in blue. Gray bars represent age ranges for other events as described by Nelson et al., 2014 (Seattle fault zone and Tacoma fault zone), Garrison-Laney 2017 (tsunami deposits at Discovery Bay and Lynch Cove), and Jacoby et al., 1997, Yamaguchi et al., 1997, Atwater and Griggs, 2012 (Cascadia Subduction Zone).

Table 1. Summary of outcrops and outcrop investigations. This table presents outcrops along the Duwamish River and the dates and summaries of the field investigations at those outcrops that contributed to this project.

Locale Name	Site number	Coordinates (10T UTM)	Dates of Observations	Persons	Notes by	Summary of Activities
Federal Center	106	0549414, 5267391	3/26/1996	Brian Atwater	Atwater	Leveling, Radiocarbon samples (L1A, L1B)
			4/6/1996	Brian Atwater John Shulene Sarah Konrad Jennifer Zwiebel	Atwater Shulene	Leveling, Set up transect
			5/18/1996	Brian Atwater John Shulene B. Eipert	Shulene	Leveling
			4/4/1998	Brian Atwater Patricia ?	Atwater Patricia (Shulene's book)	Radiocarbon samples (N2, N3), Upper silt leveling
			6/29/2000	Kevin Burrell Brian Atwater John H Richard Kaori Marta	Burell	Small geoslice, Sand samples (00KB1.1, 00KB1.2, 00KB1.3, 00KB1.4)
			8/11/2000	Brian Atwater Susie Fitzhugh Bin Mei Daria Draganova	Atwater	Radiocarbon samples (Q23A, Q23B, Q23C, Q23D)
			6/27/2017	Elizabeth Davis Brian Atwater Belle Philibosian	Davis	Recon
			7/24/2017	Elizabeth Davis Brian Atwater Carrie Garrison-Laney Alyssa Tunelle Johnny Paige J Padgett	Davis Tunelle Paige Atwater	Leveling, Radiocarbon samples (Site 2-1 thru 2-7, Site 3-1 thru 3-9)

			8/7/2017	Elizabeth Davis Brian Atwater Johnny Paige	Davis Atwater Paige	Leveling, Radiocarbon samples (106-25, 26, 27, 29, 30, 31), Sediment samples (olive mud, 106 #24, gray mud, 106 #23, sand blow, 106 #33), gutter sample (sand, lower silt)
			9/8/2017	Elizabeth Davis Alyssa Tunnelle Brian Atwater Carrie Garrison-Laney Sandi Doughton (Seattle Times) Steve ? (Seattle Times) Peter Lape (Burke Museum) Laura Philips (Burke Museum)	Davis Tunnelle Philips	Leveling, tour
			9/20/2017	Elizabeth Davis Brian Atwater	Davis Atwater	Leveling, Gouge coring
Diagonal Park	107	0549287, 5267802	8/7/2017	Elizabeth Davis Brian Atwater Johnny Paige	Davis Atwater Paige	Establish benchmark, Leveling
			9/3/2017	Elizabeth Davis Tina Andry	Davis Andry	Leveling, Radiocarbon samples (107-50, 51, 52), Sediment sample (sand dike, 107 #10)
			9/21/2017	Elizabeth Davis Matt Porter	Davis Porter	Leveling, Gouge coring
Kellogg South	105	0549303, 5267196	8/6/2017	Elizabeth Davis Brian Atwater Alyssa Tunnelle	Davis Tunnelle Atwater	Establish benchmark, Leveling, Radiocarbon sampling (105-1, 2, 3, 4), Sediment samples (sand, 105 #5)
Kellogg Central	109-111	0549096, 5267480	3/19/1998, 3/21/1998	Brian Atwater Greg King Taber Herseen? Stein Bondevik?	Atwater, written 3/22/1998	Leveling, Radiocarbon sampling (N1A, N1B), Photos of shelly deposit at T107, Photos of dikes
			7/19/1997	Brian Atwater	Atwater	Leveling

				Phen M. Deyhim Walter Barnhardt Roger Lewis	Barnhardt Lewis	
			9/16/2017	Elizabeth Davis Kevin Cowell Brian Atwater	Davis	Leveling, Radiocarbon samples (111-80, 81, 112-82,83,84), Gutter sample (silt layer)
Kellogg North	108	0549058, 5267675	7/19/1997	Refer to Kellogg C, same date	-	-
			9/2/2017	Elizabeth Davis Brian Atwater	Davis Atwater	Leveling, Radiocarbon samples (108-10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 28, 32), Sediment samples (sand dike, 108 #1, sand dike 108 #2)
CertainTeed	104	0549800, 5266302	8/6/2017	Elizabeth Davis Brian Atwater Alyssa Tunnelle	Davis Tunnelle Atwater	Establish benchmark, Leveling, Radiocarbon samples (104-3, 4, 7)
NW Seafood	103	0549960, 5265657	8/6/2017	Elizabeth Davis Brian Atwater Alyssa Tunnelle	Davis Tunnelle Atwater	Establish benchmark, Leveling, Radiocarbon samples (103-2, 5, 6), Sediment samples (103 silts)

Table 2. Radiocarbon samples submitted for analysis, prior to use in age models

Sample number	Radiocarbon laboratory number (NOSAMS)	Field locale	Date collected	Radiocarbon age (^{14}C yr B.P.)	Calibrated age, cal yr CE (2σ range)	Material dated	Contextual inference
108-21	148035	Kellogg N	9/2/2017	445 +/- 20	1420—1460	*Bolboschoenus* sp. tuber	Far minimum age for sand layer, age of tuber appearance
108-13	148038	Kellogg N	9/2/2017	445 +/- 30	1410—1490	*Bolboschoenus* sp. tuber	Far minimum age for sand layer, age when tubers were present
Site 3-8	147273	Federal Center	7/24/2017	510 +/- 20	1400—1440	*Triglochin maritima* leaf base	Maximum age for upper silt
104-4	147268	CertainTeed	8/6/2017	515 +/- 15	1400—1440	Forked stick	Minimum age for sand
103-5	147270	NW Seafood	8/6/2017	575 +/- 15	1310—1420	Half leaf	Detrital leaves grew close in time to deposition of silt
Site 3-7	147272	Federal Center	7/24/2017	585 +/- 15	1310—1410	*Triglochin maritima* leaf base	Minimum age for upper silt
107-52	148039	Diagonal Park	9/3/2017	740 +/- 15	1250—1290	*Triglochin maritima* leaf base	Dike cut into this unit, so dike is younger than this
106-25	148036	Federal Center	8/7/2017	890 +/- 20	1040—1220	*Triglochin maritima* leaf base	Minimum age for lower silt
105-4	147269	Kellogg S	8/6/2017	910 +/- 20	1030—1190	*Triglochin maritima* leaf base	Minimum age for sand (grew into sand after it was deposited)
105-3	148037	Kellogg S	8/6/2017	925 +/- 15	1030—1160	*Triglochin maritima* leaf base	Maximum age for silt
106-29	148034	Federal Center	8/7/2017	950 +/- 20	1020—1160	*Triglochin maritima* leaf base	Close maximum age for vented sand
106-31	147271	Federal Center	8/7/2017	1010 +/- 20	980—1040	*Triglochin maritima* leaf base	Close maximum age for vented sand
L1A	Beta-92272	Federal Center	3/26/1996	1260 +/- 100	610—990	*Bolboschoenus maritimus* culm bases, some with parts of corm	Grew prior to sand venting
L1B	Beta-92273	Federal Center	3/26/1996	910 +/- 80	990—1270	*Triglochin maritima*, 30g of leaf bases and attached rhizomes	Grew following lower silt

N1A	QL-4936	Kellogg C	3/19/1997	336 +/- 15 with error multiplier 1.6: 336 +/- 24	No error multiplier: 1480—1540 (28.9%) 1530—1640 (66.5%) With error multiplier: 1470—1640	*Bolboschoenus maritimus* culms, corms, and rhizomes	Grew following sand venting
Q23A	Beta-146056	Federal Center	8/16/2000	920 +/- 40	1020—1210	*Bolboschoenus maritimus* culm with part of corm	Culms formed no earlier than a few years before venting and no later than a few decades after venting.
Q23B	Beta-146057	Federal Center	8/16/2000	1120 +/- 40	770—1020	*Bolboschoenus maritimus* culm with part of corm	Culms formed no earlier than a few years before venting and no later than a few decades after venting.
Q23C	Beta-146058	Federal Center	8/16/2000	890 +/- 50	1020—1250	*Bolboschoenus maritimus* culm with part of corm	Culms formed no earlier than a few years before venting and no later than a few decades after venting.
Q23D	Beta-146059	Federal Center	8/16/2000	990 +/- 40	980—1160	*Bolboschoenus maritimus* culm with part of corm	Culms formed no earlier than a few years before venting and no later than a few decades after venting.

Table 3. Interpreted sand venting events and 2σ age ranges.

SITE	**AGE RANGE, CAL YR CE (2σ)**
FEDERAL CENTER	1010 – 1150
FEDERAL CENTER	> 1010 – 1150
DIAGONAL PARK	> 1250 – 1290
KELLOGG NORTH	unknown
KELLOGG CENTRAL	1450 – 1630

Table 4. Sand dikes observed at the Federal Center outcrop. X-coordinate reported as distance along the face of the outcrop.

x (m)	Width (cm)	Stratigraphic context, highest extent	Strike	Date observed
-1.7	2	Beach in front of face	N-S	7/24/17
1	Small	8cm above lower silt		7/24/17
0.3	Small			7/24/17
14	2	Terminates at sand layer	N10W	4/6/96
16-17	3	Terminates at sand layer	N10W	5/18/96
21.5	<=2	Terminates at sand layer	N-S	4/6/96
35.5-36.5		Beach in front of face	N10W	5/18/96
38.5		Beach in front of face	N10E	4/6/96
43.04	~1	Approaches lower silt from below by ~1cm or less	N30W	4/6/96
43.06	~1	Approaches lower silt from below by ~1cm or less		4/6/96
47.8-49.2	2	Beach in front of face	N10W	5/18/96

Appendix 1. OxCal input and output, by site

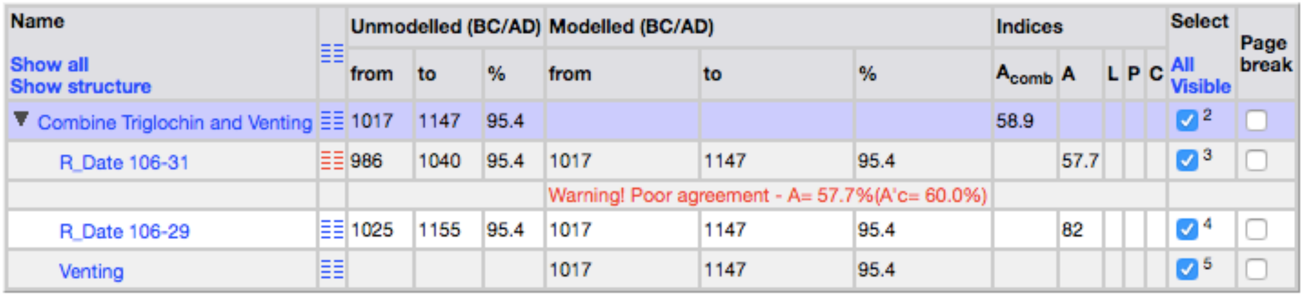
Federal Center

Sand

Input

```
Combine("Triglochin and Venting")
{
 R_Date("106-31", 1010, 20);
 R_Date("106-29", 950, 20);
 Date("Venting");
};
```

Output



Name Show all Show structure	Unmodelled (BC/AD)			Modelled (BC/AD)			Indices					Select	Page break
	from	to	%	from	to	%	A_{comb}	A	L	P	C	All Visible	
▼ Combine Triglochin and Venting	1017	1147	95.4				58.9					☑ 2	☐
R_Date 106-31	986	1040	95.4	1017	1147	95.4		57.7				☑ 3	☐
				Warning! Poor agreement - A= 57.7%(A'c= 60.0%)									
R_Date 106-29	1025	1155	95.4	1017	1147	95.4		82				☑ 4	☐
Venting				1017	1147	95.4						☑ 5	☐

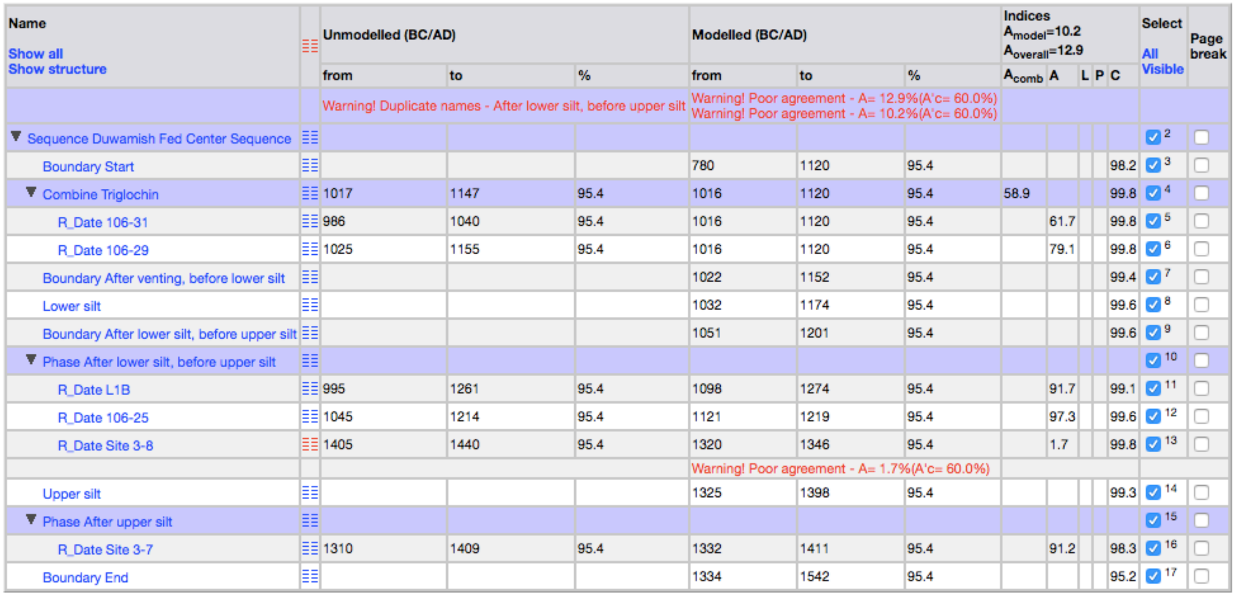
Federal Center

Silt layers

Input

```
Sequence("Duwamish Fed Center Sequence")
{
 Boundary("Start");
 Combine("Triglochin")
 {
  R_Date("106-31", 1010, 20);
  R_Date("106-29", 950, 20);
 };
 Boundary("After venting, before lower silt");
 Date("Lower silt");
 Boundary("After lower silt, before upper silt");
 Phase("After lower silt, before upper silt")
 {
  R_Date("L1B", 910, 80);
  R_Date("106-25", 890, 20);
  R_Date("Site 3-8", 510, 20);
 };
 Date("Upper silt");
 Phase("After upper silt")
 {
  R_Date("Site 3-7", 585, 15);
 };
 Boundary("End");
};
```

Output



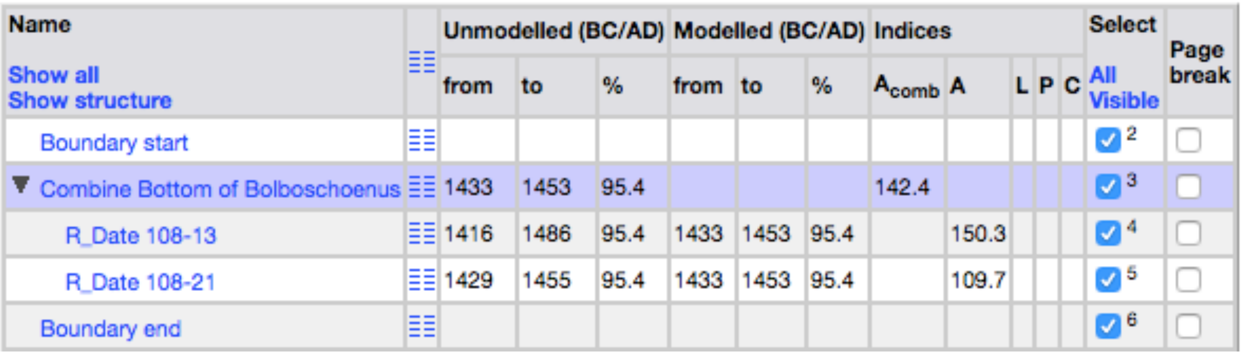
Name Show all Show structure	☰	Unmodelled (BC/AD)			Modelled (BC/AD)			Indices A_{model}=10.2 $A_{overall}$=12.9					Select All Visible	Page break
		from	to	%	from	to	%	A_{comb}	A	L	P	C		
		Warning! Duplicate names - After lower silt, before upper silt			Warning! Poor agreement - A= 12.9%(A'c= 60.0%) Warning! Poor agreement - A= 10.2%(A'c= 60.0%)									
▼ Sequence Duwamish Fed Center Sequence	☰												☑ 2	☐
Boundary Start	☰				780	1120	95.4					98.2	☑ 3	☐
▼ Combine Triglochin	☰	1017	1147	95.4	1016	1120	95.4	58.9				99.8	☑ 4	☐
R_Date 106-31	☰	986	1040	95.4	1016	1120	95.4		61.7			99.8	☑ 5	☐
R_Date 106-29	☰	1025	1155	95.4	1016	1120	95.4		79.1			99.8	☑ 6	☐
Boundary After venting, before lower silt	☰				1022	1152	95.4					99.4	☑ 7	☐
Lower silt	☰				1032	1174	95.4					99.6	☑ 8	☐
Boundary After lower silt, before upper silt	☰				1051	1201	95.4					99.6	☑ 9	☐
▼ Phase After lower silt, before upper silt	☰												☑ 10	☐
R_Date L1B	☰	995	1261	95.4	1098	1274	95.4		91.7			99.1	☑ 11	☐
R_Date 106-25	☰	1045	1214	95.4	1121	1219	95.4		97.3			99.6	☑ 12	☐
R_Date Site 3-8	☰	1405	1440	95.4	1320	1346	95.4		1.7			99.8	☑ 13	☐
					Warning! Poor agreement - A= 1.7%(A'c= 60.0%)									
Upper silt	☰				1325	1398	95.4					99.3	☑ 14	☐
▼ Phase After upper silt	☰												☑ 15	☐
R_Date Site 3-7	☰	1310	1409	95.4	1332	1411	95.4		91.2			98.3	☑ 16	☐
Boundary End	☰				1334	1542	95.4					95.2	☑ 17	☐

Kellogg N

Input

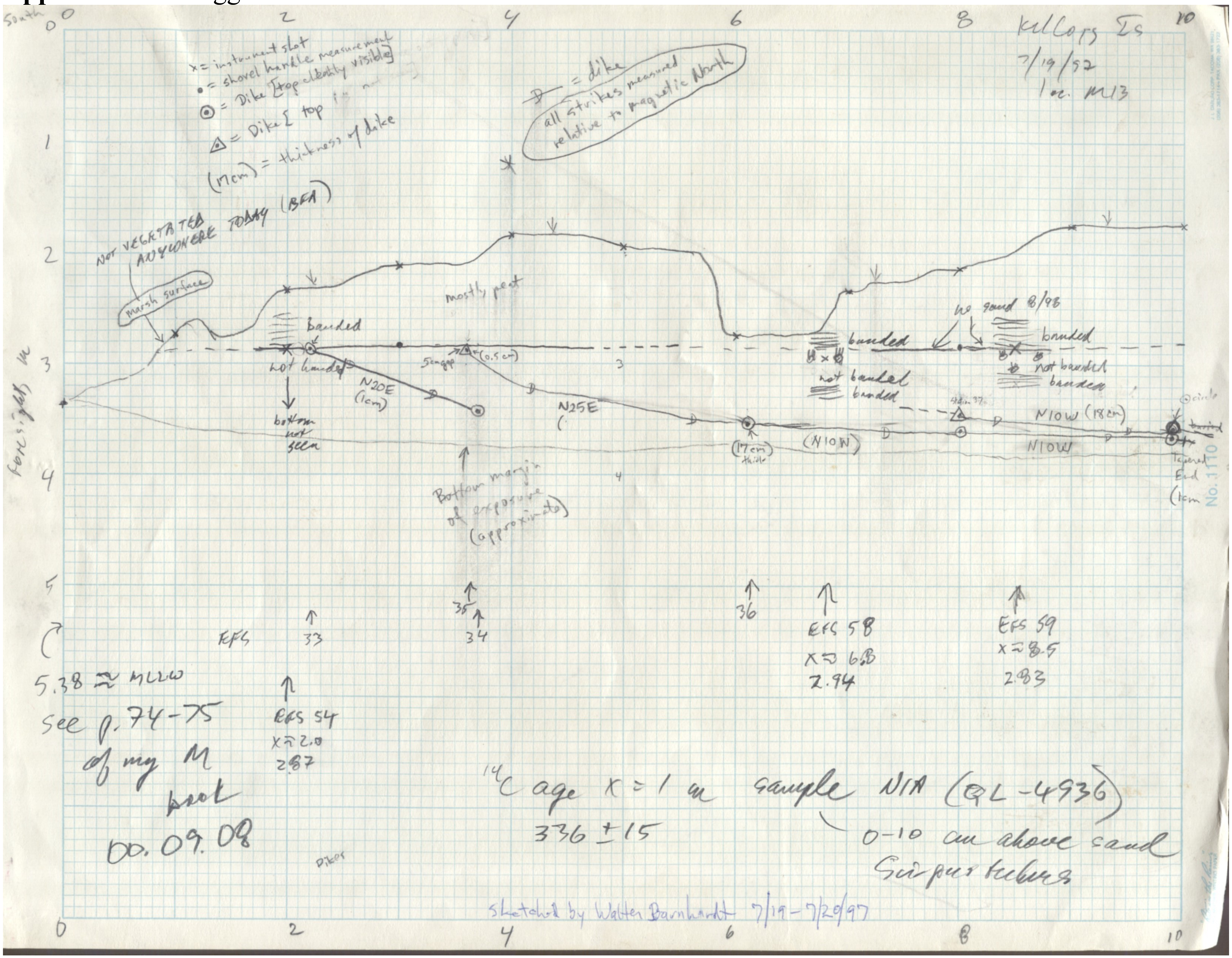
```
Plot()
{
 Boundary("start");
 Combine("Bottom of Bolboschoenus")
 {
  R_Date("108-13", 445, 30);
  R_Date("108-21", 445, 15);
 };
 Boundary("end");
};
```

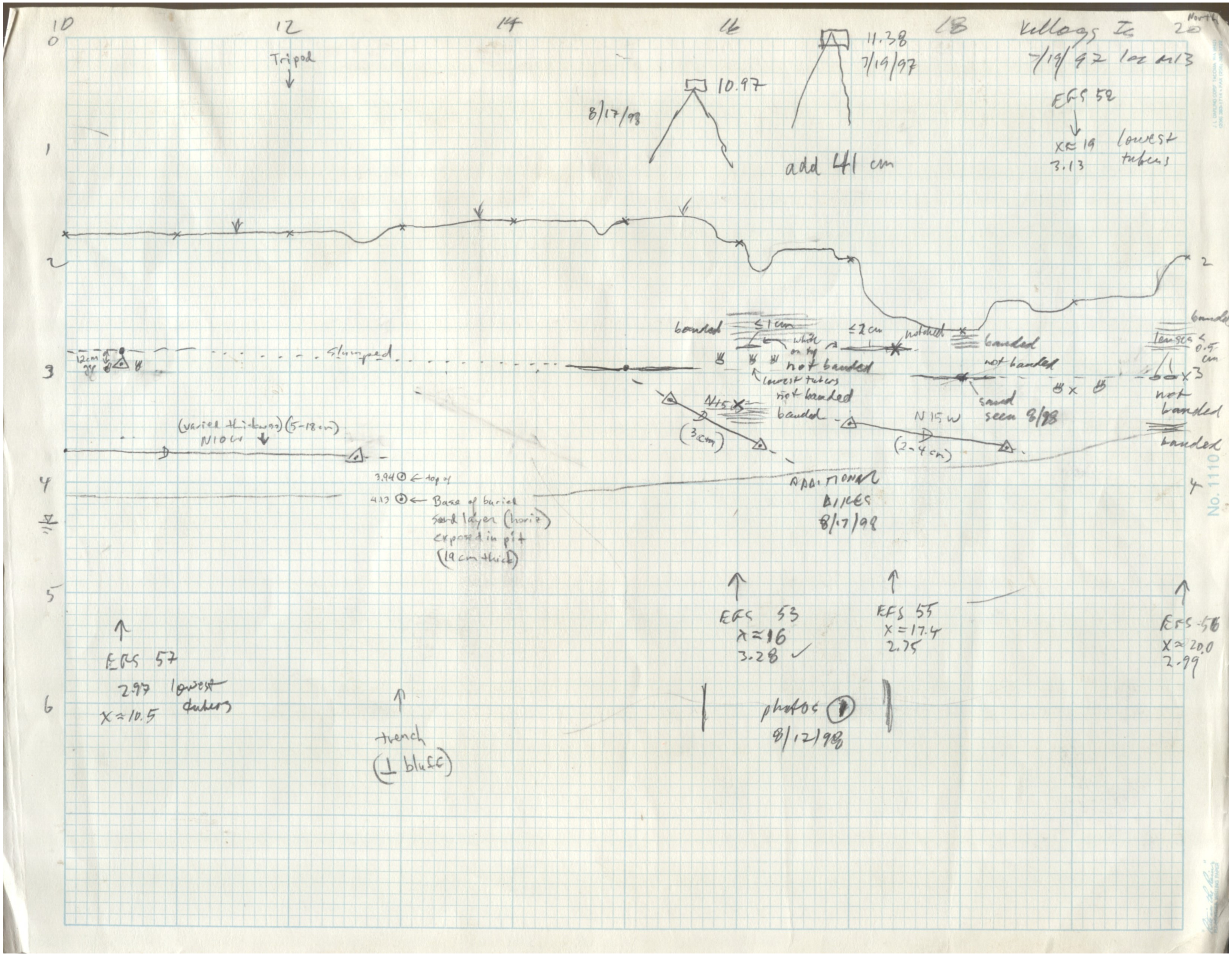
Output

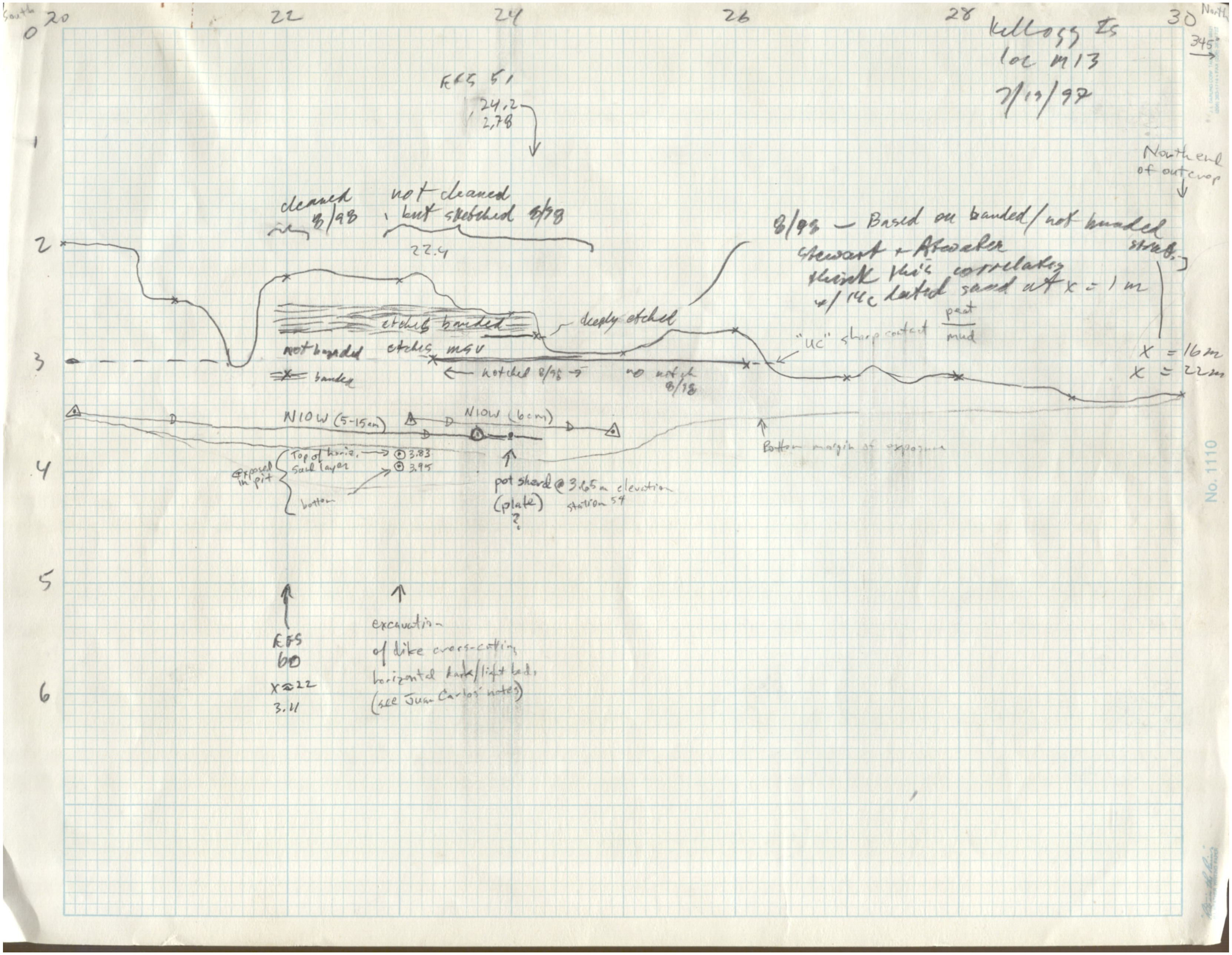


Name		Unmodelled (BC/AD)			Modelled (BC/AD)			Indices					Select	Page break
Show all Show structure	☰	from	to	%	from	to	%	A_{comb}	A	L	P	C	All Visible	
Boundary start	☰												☑ 2	☐
▼ Combine Bottom of Bolboschoenus	☰	1433	1453	95.4				142.4					☑ 3	☐
R_Date 108-13	☰	1416	1486	95.4	1433	1453	95.4		150.3				☑ 4	☐
R_Date 108-21	☰	1429	1455	95.4	1433	1453	95.4		109.7				☑ 5	☐
Boundary end	☰												☑ 6	☐

Appendix 2. Kellogg C Sketch




10
12
14
16
18
Kellogg Is
20
North
0
1
2
3
4
5
6
Tripod
8/17/98
10.97
11.38
7/19/97
add 41 cm
7/19/97 loc m13
EFS 52
X≈19
3.13
lowest
tubes
12cm
slumped
banded
≤1cm
white on top
≤2cm
notched
banded
not banded
lowest tubes
not banded
banded
not banded
sand
seen 8/98
lenses < 0.5 cm
banded
not banded
banded
N45
(3cm)
N 15 W
(2-4 cm)
(varied thickness) (5-18 cm)
N10W
3.94 ⊙ ← top of
4.13 ⊙ ← Base of buried sand layer (horiz) exposed in pit (19 cm thick)
ADDITIONAL DIKES 8/17/98
EFS 57
2.97 lowest tubes
X≈10.5
trench
(⊥ bluff)
EFS 53
X≈16
3.28 ✓
photos ①
8/12/98
EFS 55
X=17.4
2.75
EFS 56
X≈20.0
2.99
No. 1110


South
North
0
1
2
3
4
5
6
20
22
24
26
28
30
345° →
Kellogg Is
loc M13
7/19/97
EGS 51
24.2
2.78
North end
of outcrop
cleaned
8/98
not cleaned
but sketched 8/98
22.4
8/98 — Based on banded/not banded strat.
Stewart + Atwater
think this correlates
w/ 14C dated sand at x = 1 m
X = 16 m
X = 22 m
etched banded
deeply etched
not banded
etches MGV
banded
← notched 8/98 →
no notch
8/98
"UC" sharp contact
peat
mud
N10W (5-15cm)
N10W (6cm)
Top of horiz. sand layer
exposed in pit
bottom
3.83
3.95
pot shard @ 3.65 m elevation
(plate)
?
station 54
Bottom margin of exposure
EGS
60
X≈22
3.11
excavation
of dike cross-cutting
horizontal dark/light beds
(see Juan Carlos' notes)
No. 1110