Geomorphology and sedimentology of selected areas along the eastern and southern margins of Yellowstone Lake, Yellowstone National Park, Wyoming: Results from the 2010 and 2011 field season

Michael H. Hofmann, Ph.D.
Assistant Research Professor of Geology

Marc S. Hendrix, Ph.D.
Professor of Geology

Department of Geosciences
The University of Montana
Missoula, MT 59812

March 7, 2012

1. INTRODUCTION AND MAIN FINDINGS

The main objective of this project is to provide a geomorphologic and geologic framework for the analysis and interpretation of archaeological sites located along the eastern and southern shores of Yellowstone Lake, Yellowstone National Park, Wyoming. The work was undertaken during two one week excursions in 2010 (08/01/10-08/07/10) and 2011 (09/07/11-09/11/11).

This report summarizes the preliminary findings of these field excursions and is based mainly on detailed sedimentologic descriptions from outcrops and trenches and geomorphologic measurements from total station and high resolution GPS surveys. A total of 10 stratigraphic sections were measured at 5 locations. Of these, the most revealing are located along Columbine Creek/Alluvium Creek, Clear Creek, and west of Trail Creek (Fig. 1) and are presented in this report. Total station surveys were acquired along Alluvium Creek/Columbine Creek, and near Columbine Creek. High resolution GPS surveys were conducted along Alluvium Creek/Columbine Creek and west of Trail Creek.

The main findings from this field excursion are:

- An extensive, triangular-shaped morphologic bench bounded on the north by Columbine Creek eastward approximately to Brimstone Basin, then southwest to the Yellowstone Lake shoreline is the remnant delta plain/flood plain of a Gilbert-style delta that formed along the margin of ancestral Yellowstone Lake when it had a surface elevation ~21 m above the present day lake level. This Gilbert-style delta, previously mapped as Pinedale age coarse grained lacustrine deposits (Richmond and Pierce, 1972), currently is being incised by Alluvium Creek.
- A prominent geomorphologic bench west of Trail Creek with bench heights and morphologies similar to the Alluvium/Columbine Creek delta is also interpreted as a Gilbert style delta resulting from a similar lake level history. The Trail Creek Gilbert delta has previously been mapped as Pinedale age ice contact deposits (Richmond and Pierce, 1972),
- A radiocarbon date of 10,390 +/-150 cal yr BP from charcoal collected from a measured section in coarse gravels that form the proximal part of the Alluvium

Creek Gilbert-style delta along Columbine Creek indicates that the delta was undergoing active construction at this time..

- A radiocarbon date of 2795+/-55 cal yr BP from a sample of charcoal collected in a section measured in an abandoned channel wall ~50m from modern-day Columbine Creek and ~2m above the modern creek surface provides a depositional age constraint for these elevated floodplain deposits.
- A radiocarbon date of 4100 +/- 130 cal yr BP from charcoal recovered from low energy deposits inferred to be floodplain or lacustrine and located ~ 4m above the present day lake surface and 2 m above present day Clear Creek suggests that lake level was elevated by at least 2 m and as much as 5 m at that time.
- Preliminary geologic/geomorphologic evidence, combined with the results of three radiocarbon ages, suggest that, relative to the modern ground surface, the surface elevation of Yellowstone Lake was significantly higher along its southeastern shore than outlined by Pierce et al. (2002, 2007), but in line with a lake level model published by Locke and Meyer (1994). However, other radiocarbon ages and duplicate samples are needed to confirm these findings.

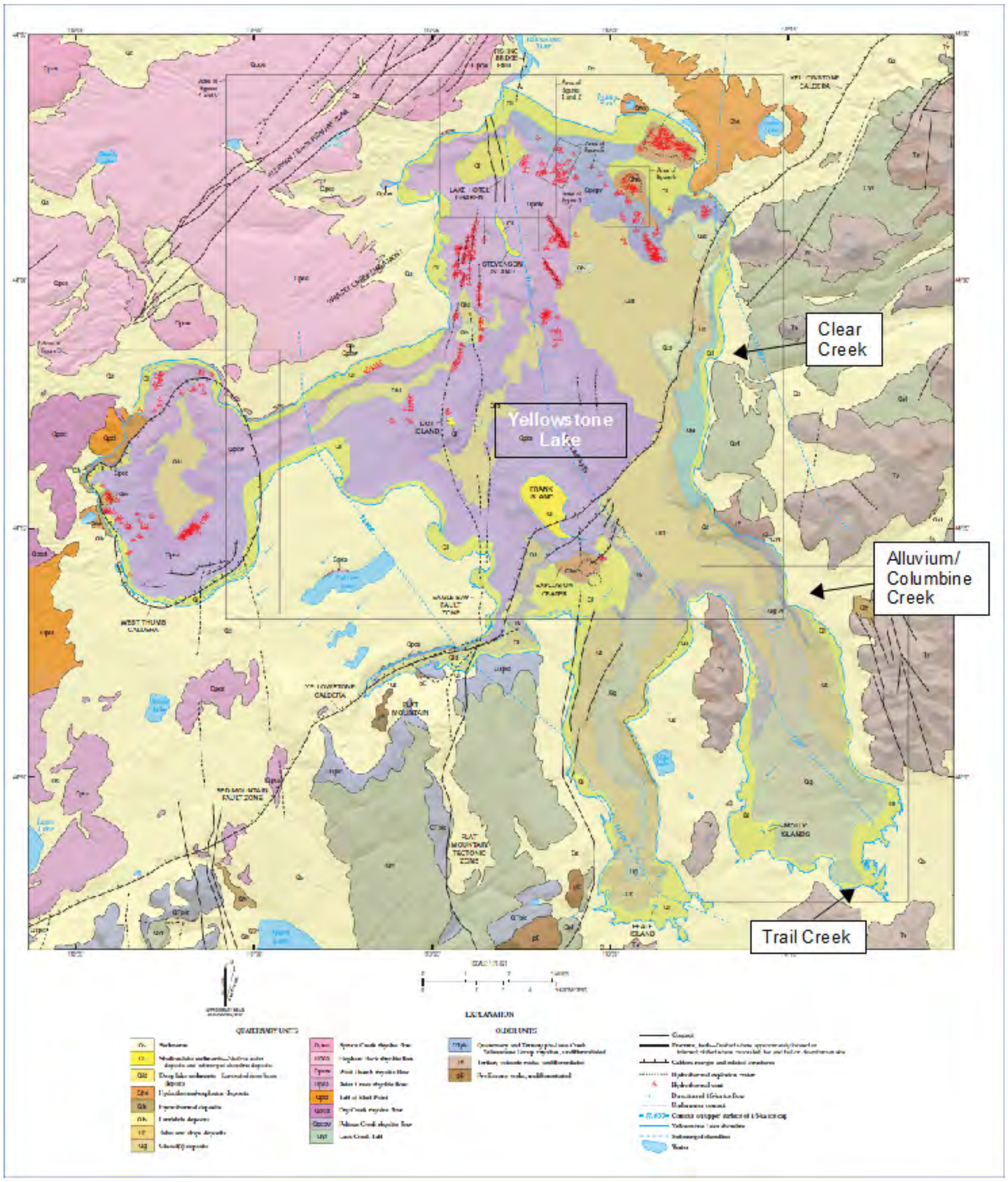


FIGURE 1: Geologic map of Yellowstone Lake and surrounded areas. Main study areas along the eastern and southern shores of the lake are highlighted. Map modified from Morgan et al., 2007.

2. METHODS

Stratigraphic sections:

A total of ten stratigraphic sections were measured over the course of our field work of which eight are presented in this report. With the exception of the upper Columbine Creek sections, which were well exposed in the headwaters of this drainage, and the Columbine Creek N section, which was exposed in an abandoned channel wall, each of the measured sections required hand-digging. The Alluvium Creek, Clear Creek, and Trail Creek sections were exposed by hand-digging and troweling a series of pits that were offset laterally and that did not overlap stratigraphically. The pits were dug along the sides of slopes formed by post-depositional erosion and overall incision of the stream network on the eastern and southern shores of Lake Yellowstone.

Upon digging of the pits and troweling of at least one and in some cases three of the interior sides of the pit, the stratigraphy was described and measured. Sedimentary units observe in each pit were described at cm- to dm- scale, meaning that individual beds of this thickness or other sedimentary features existing at this scale were resolved. Observations made during section description included grain size, grain sorting, grain texture (form, rounding), grain composition, presence of biogenic debris including charcoal and/or wood, and presence and nature of biogenic or sedimentary structures. Dip direction and dip angle measurements of sedimentary structures were conducted using a standard compass.

Wood or charcoal samples for radiometric dating were recovered from several of the measured stratigraphic sections. In each case, the organic sample was photographed in situ, then carefully removed from the exposure and placed into an individual sample bag. Samples were labeled and transported back to camp on foot. Following field work, samples were transported to Missoula and refrigerated for about three weeks until arrangements for radiometric analysis could be made. Four of the organic samples were sent to Beta Analytic, Inc. for AMS-C14 dating. Detailed results of this work are in Appendices B-E of this report.

Total Station and GPS Survey:

We conducted two digital topographic surveys using a Leica TC307 total station, and 2 surveys using a Trimble GeoXH GPS unit. Vertical and horizontal accuracy of the Total Station survey is ~0.2 mm/30 m Rod-TS distance. GPS information from the

Trimble GeoXH GPS unit was post-processed following field work using three permanent UNAVCO base station at Yellowstone National Park; eastgate, Wyoming; and . Both point data and line data were collected. Point data were acquired by maintaining a constant position for ~100 individual measurements, all of which were post-processed and averaged. Vertical accuracy of these data is about 0.2m. Line data were collected by walking along a topographic surface and acquiring one measurement every 2 or 3 seconds, depending on the terrain. Data were post-processed in Trimble Pathfinder Office using six separate base stations in the Yellowstone region. Collectively, the base stations surround the study site. The following base stations were used: 1) UNAVCO, Yellowstone National Park (p709), located at the northern tip of Promontory Point (44°23'30.46614"N, 110°17'09.61825"W); 2) UNAVCO East Gate, WY (p717), located on a small hill east of Yellowstone’s East Entrance (44°29'07.46527"N, 109°53'50.24393"W; 3) UNAVCO, Wyoming (hvwy), located on the southern side of Yellowstone Park’s Hayden Valley (44°36'48.96421"N, 110°32'09.45251"W); 4) UNAVCO Yellowstone National Park (p716), located on the northern side of the Hayden Valley (44°43'05.73060"N, 110°30'41.43611"W); 5) UNAVCO, Moose, WY, located along the Ashton-Flagg Ranch Road south of Yellowstone (44°05'44.71764"N, 110°43'55.70303"W); and 6) CORS, Mammoth Wyoming (mawy), located in northern Yellowstone (44°58'24.34263"N, 110°41'21.47906"W). A total of 9221 individual GPS measurements were collected, including all point and line data. Following post-processing of all point and line data, the estimated accuracy for the entire data set was as follows: 0-15cm 36.80% of data set; 15-30cm 13.37% of data set; 30-50cm 36.72% of data set; 0.5-1m 10.90% of data set 1-2m 1.65% of data set; 2-5m 0.55% of data set; >5m 0.01% of data set. Thus, of the 9221 individual measurements collected, over 85% had an estimated vertical accuracy of 50cm or less.

Visualization for both survey data sets was performed by using Golden Surfer and Golden Voxler software. Gridding algorithms were chosen to apply to minimize smoothing of the data in order to maintain the highest resolution information acquired during the surveys.

3. RESULTS

3.1 Alluvium Creek / Columbine Creek

3.1.1 Geomorphology (GPS survey data and Total Station survey CO-AC; FIGURE 2; APPENDIX A):

The total station survey in the headwaters of Alluvium Creek was conducted a few hundred meters below Brimstone Basin at a point where two separate active channels are incised and separated by <100m by an unusual ridge-forming interfluve that had longitudinal dimensions of ~1km (Fig. 2). Our survey ran transverse to the interfluve at its downstream end just above the point at which Alluvium Creek turns orthogonally to the southwest (left) from which point it continues southwest for 1.6 km to the Yellowstone Lake shoreline (Figs. 2, 3). The total station was set up and leveled on the crest of the interfluve so that data could be collected in both the Alluvium and Columbine Creek main channels. All of the total station data for the survey were collected with the instrument at one location. Individual shot points were located 2-3 m apart except in parts of the survey characterized by steep or highly variable topography where shot points were more closely spaced.

In addition to the total station survey we conducted a GPS transect running along the top margin of the Alluvium Creek incised canyon from the previously described Total Station survey area to the shore of Yellowstone Lake (Fig. 4). This GPS line was chosen to acquire additional information about the broad morphologic changes of the Alluvium Creek system from a proximal location near the bedrock contact to the distal location near the mouth of Alluvium Creek. The GPS transect also provides a tie line connecting the total station survey area, measured stratigraphic sections, and modern Yellowstone Lake surface. The latter was chosen as the reference level for all of the geomorphologic data acquisition.

FIGURE 2: Satellite image with detailed location information of the Alluvium Creek (AC) and Columbine Creek CO) area.

Results from our survey data show that the main geomorphologic feature in the Alluvium Creek / Columbine Creek area is a wide, low gradient bench starting at an elevation of ~2379 m (~7806 ft) or ~ 21 m (68 ft) above the present day lake level of 2358 m (7736 ft) and extending eastward away from the lake for 1.6 km before reaching exposed bedrock (Figs. 2, 4). The average slope on top of this surface is <3.5°. This wide bench is bounded by a steeply dipping slope (max. slope angle ~14°) along its western margin that drops down to the present day Yellowstone Lake shoreline (Fig. 4). A similar morphology extends for more than 3 km parallel to the shoreline (Fig. 2). The low gradient bench narrows towards the east to an apex located a few hundred meters below Brimstone Basin at a point where Alluvium and Columbine Creeks diverge. The surface area of the trianglular-shaped bench is ~ 3km^2. The shape and morphology of this feature resembles that of a modern day delta.

The formation of this larger delta clearly predates the incision of the modern Alluvium Creek and Columbine Creek. Although only separated by a relatively narrow ridge (~50m; Fig. 3), our total station data shows that both creeks are incised to exactly the same elevation (Fig.3), suggesting that incision of these two creeks near the apex of the large delta occurred simultaneously and in response to a regional change in base level.

To investigate the genesis of the sediment making up the broad triangular bench, we measured several stratigraphic sections along the modern, incised channel walls of Columbine Creek and Alluvium Creeks. The first two sections, Columbine Creek 1 and Columbine Creek 2 (Fig. 2) are located near the eastern narrow apex of the delta feature about 1.5 km east of the mouth of Columbine Creek Creek and ~100 m above the point at which Alluvium Creek makes an orthogonal turn to the left (southwest). Both the Columbine Creek 1 and Columbine Creek 2 measured sections consist mainly of proximal delta deposits.

The third stratigraphic section was measured in the Alluvium Creek valley and is located ~ 250m northeast of the present day mouth of Alluvium Creek near the western margin of the 2379m terrace (Figs. 2, 4). This stratigraphic section consists of very well-preserved distal delta top and proximal delta front deposits.

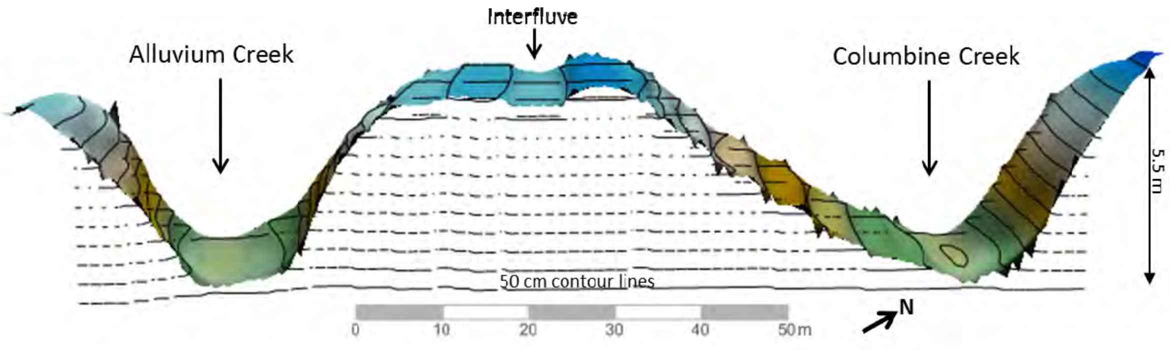


FIGURE 3: CO-AC Total Station Survey transect (see Fig. 2 for location). Incision depth of both creeks is within <50cm of the same elevation, suggesting a consistent incision history. The interfluve is a remnant of the previous, original delta surface.

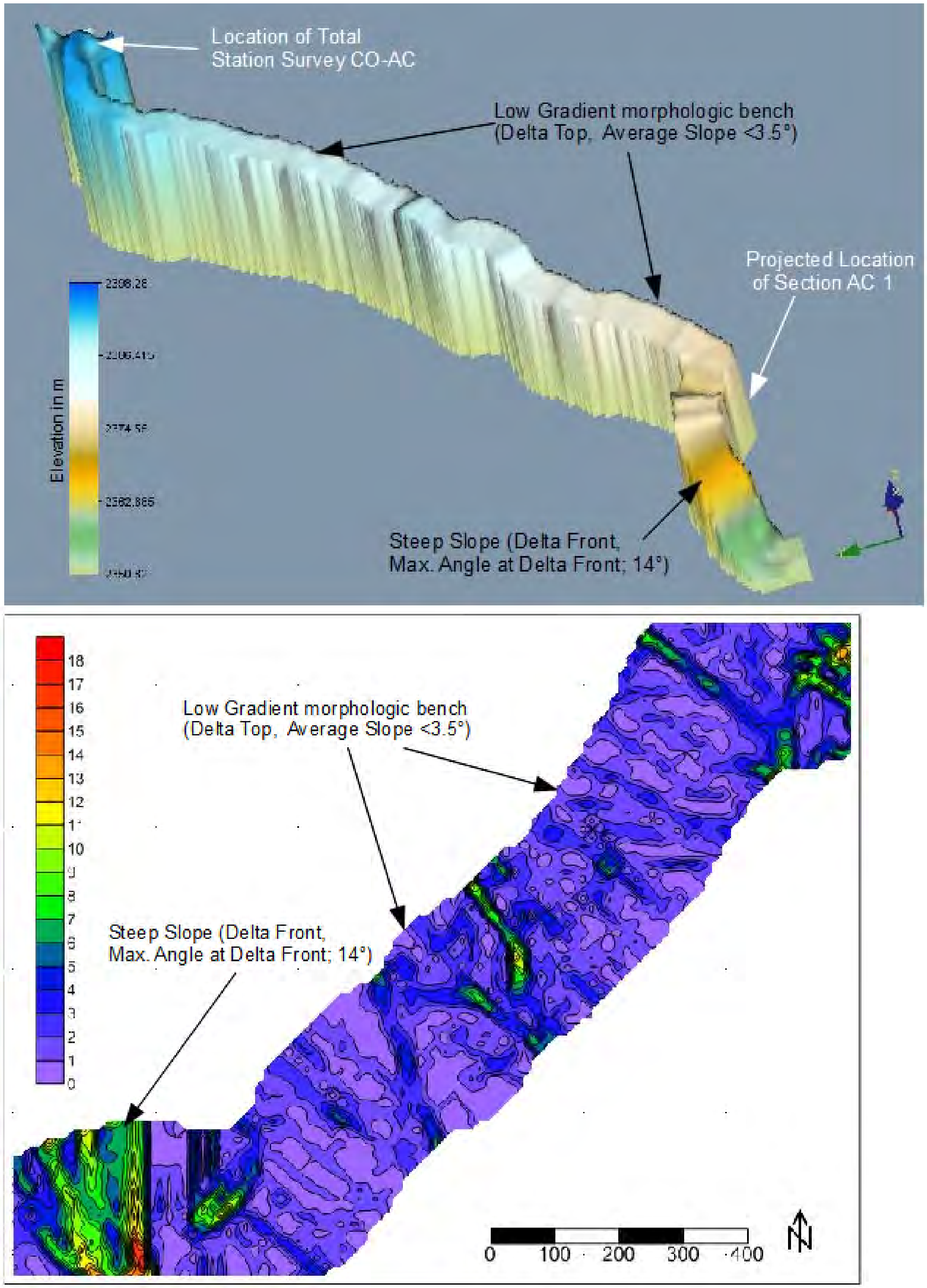


FIGURE 4: Topographic profile (oblique view) from GPS survey (top) and slope map (bottom) of the Alluvium Creek Gilbert delta (for location information of these lines see figure 2).

3.1.2 Upper Columbine Creek Section #1 (APPENDIX B-1)

Location: Along the northern bank of Columbine Creek ~ 1.5 km upstream (east-southeast) of its mouth (Fig. 2; GPS: MSHWPT131)

Outcrop: 7.5 m high natural exposure; the basal 3 m are naturally outcropping along the river bank (Fig. 5), the upper 4.5 m was hand-dug and exposed through a series of shallow laterally offset pits.

Description:

The basal 1.5 m in this section consists of laminated very fine sand and silt alternating in color from dark greenish gray to light greenish gray (Figs. 5 and 6) The laminae are tilted and dip to the northeast. Laminae in the upper 50 cm are faint, display orange iron(?) staining and are less silty than laminae in the lower part of the interval. The fine grained laminae are dissected by a series of nearly vertical clastic gravel-filled dikes containing mainly pebble sized clasts. The width of the dikes ranges from a few cm to almost 1 m (Fig. 7). The total length of the dikes is unknown, because their bases are not exposed and the tops are truncated.

FIGURE 5: Section CO1 along Columbine Creek; box outlines area shown in Fig. 6

The basal fine-grained section described above is truncated by an erosional unconformity. The unconformity has erosional relief of ~ 20 cm that also marks the base of a poorly sorted, massive (crudely stratified?), 3.5 m thick interval dominated by gravel (Fig. 6). Gravel clasts are sub-angular to sub-rounded, grain supported, and poorly sorted. The median gravel size is in the cobble fraction, but clast sizes range from pebble to boulder sized. The largest boulder exposed in the outcrop walls is 40 cm in diameter. Some clasts are imbricated with intermediate-long axis planes dipping to the NE (~40°). Matrix is sparse but where present typically consists of medium sand.

The top 2.5 m of the stratigraphic section consists of alternating, dm thick layers of partially open framework pebble conglomerate interstratified with fine sand (Fig. 8). Clasts are commonly sub-angular to sub-round and medium well sorted. The maximum pebble size is 3 cm. Many of the framework gravel layers are weakly iron(?) stained. The alternating sandy intervals are well sorted. Grain size in these layers ranges from very fine sand to fine sand. Sandy layers become more common towards the top, suggesting a fining upward trend within the entire interval.

FIGURE 6: Basal exposure of section CO1. Hammer (circled in yellow) for scale.

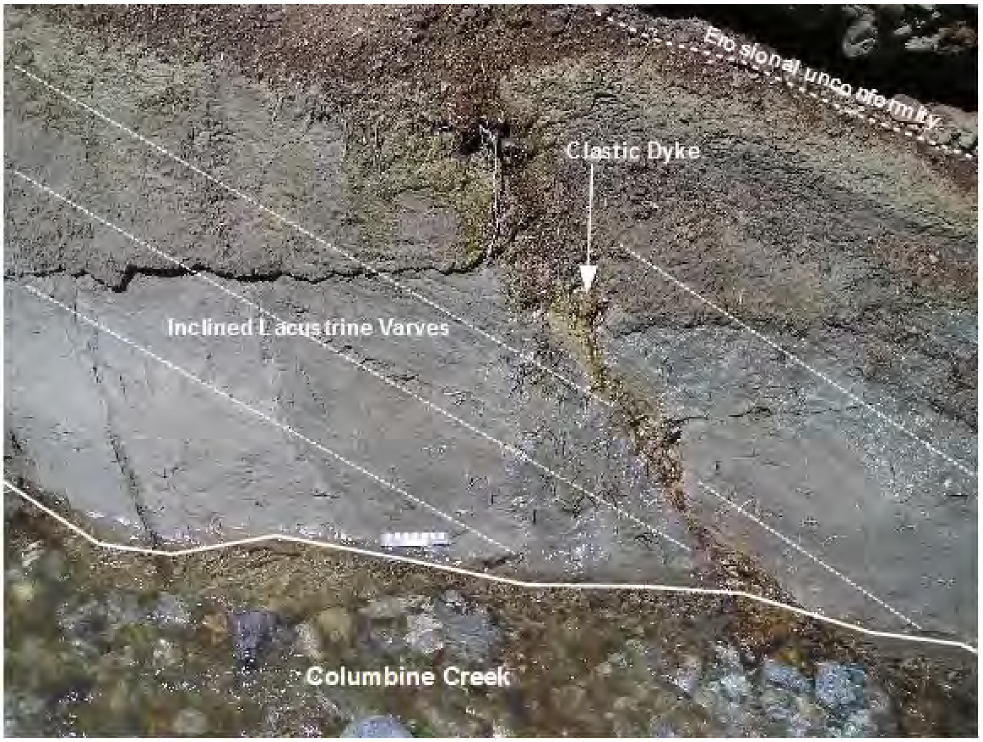


FIGURE 7: Clastic dikes and inclined laminae in basal part of section CO 1. In lower photograph, 1 dm scale located just above waterline (smallest increments = 1 cm).

FIGURE 8: Typical facies in upper part of section CO 1. 1 dm scale located in shadow (left); smallest increments = 1 cm.

3.1.3 Upper Columbine Creek Section #2 (APPENDIX B-2)

Location: Along the northern bank of Columbine Creek ~ 200 m upstream (east) of Upper Columbine Creek Section #1 (Fig. 2; GPS: MSHWPT132)

Outcrop: 7m thick high natural exposure (Fig. 9). Only the lowermost 1 m is well exposed, the rest of the section was accessed by hand-digging a series of offset shallow pits.

Description:

The Upper Columbine Creek stratigraphic section #2 has a tripartite stratigraphy very similar to that observed in Upper Columbine Creek section #1. The basal 80 cm exposed along the creek at section #2 consist of greenish gray laminated very fine sand and silt. Woody debris is common, and some wood fragments range up to 20 cm. A well-preserved log that was encased in the silt was sampled for C-14 dating (sample 10-CO-10; Appendix E). Results indicated that the age was outside the range of the C-14 technique and that the log is older than 43,500 yr BP.

At Upper Columbine Creek section #2, the basal silty unit containing the log is truncated by an erosional unconformity. The overlying coarse-grained gravelly interval downcuts into this unit. Relief on the exposed unconformity is ~ 20cm (Fig. 10). The poorly sorted gravelly interval is dominated by sub-rounded cobble-sized clasts, although boulder sized clasts up to ~40cm also are present locally. Fine-grained matrix is subordinate and clast support is dominant. We did not observe any clast imbrication in this unit, but the quality of exposure was poor and sedimentary structures easily could have been missed.

The youngest stratigraphic interval in this section consists of alternating layers of very fine sand and sandy gravel. Most layers are ~1dm thick. The fine-grained layers are composed of poorly-consolidated white-colored volcanic airfall (ash) mixed with other sand-sized clastic detritus. The coarser intervals consist of granule and pebble conglomerate (max. clast size ~3cm) with a fine- to medium-sized sandy matrix. Clast to clast contacts are dominant and iron(?) staining is common. We interpret these orange-colored sandy beds as ferricretes forming in overbank deposits. A sample of charcoal (10-CO-11; Appendix E) was recovered from this interval (6m above section base) and yielded a C-14 date 10,390 +/-150 cal yr BP.

FIGURE 9: Upper Columbine Creek #2 stratigraphic section. Approximate location of C-14 samples shown.

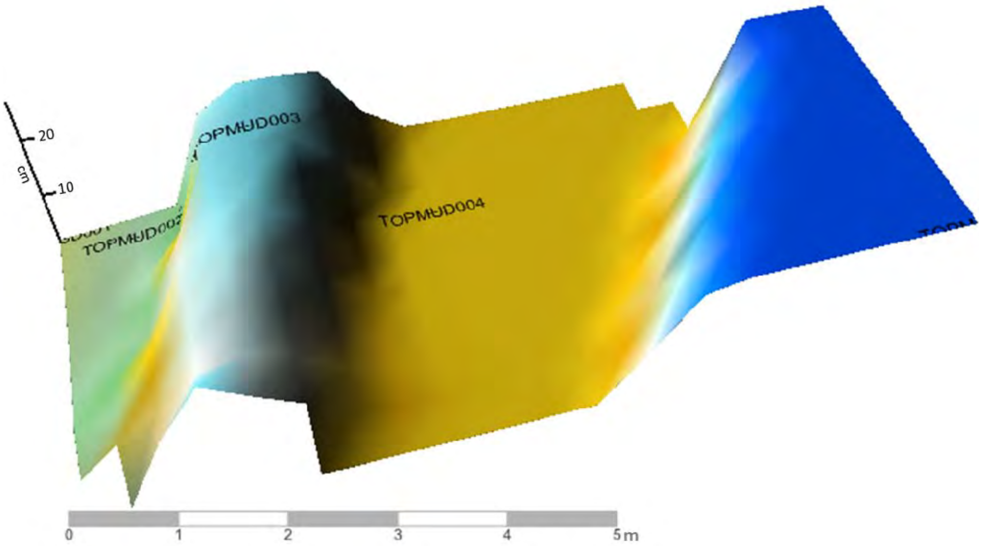


FIGURE 10: Topography of erosional surface at the base of the coarse grained gravely unit exposed in stratigraphic section Columbine Creek #2. The relief along this surface is ~ 20cm.

3.1.3.1 Interpretation of Columbine Creek sections #1 and #2:

Columbine Creek sections #1 and #2 contain a very similar stratigraphic succession. Given this facies similarity, the spatial proximity of these sections, and the almost horizontal layering of the younger stratigraphic units, we interpret these two sections to have been deposited in similar depositional environments at approximately the same time.

The basal, laminated fine grained unit was deposited in an environment with suppressed current activity as is common in floodplain and/or lacustrine settings. Based on the radiocarbon date for sample 10-CO-10, we infer that such a subaqueous, relatively quiet water environment existed at these locations sometimes before 43,500 BP. After deposition, these fine-grained deposits were tilted and dissected by clastic dikes (Fig. 7). Our preferred interpretation for the tilting of the basal silt section and presence of the clastic dikes is that these reflect paleo-seismic activity. Alternatively, the tilting and dikes could be related to loading by glacial ice.

The unconformity that truncates the silt section is clearly erosional (Fig. 10). Its age is inferred to be at least 10,390 +/-150 cal yr BP, the age of the charcoal sample from the top of Columbine Creek section #2. The locally imbricated, partially open-framework gravel overlying the unconformity suggests the presence of water as a flow agent. Interbedded finer-grained (sandy) units within the conglomerate suggest fluctuating flow strength through time. We interpret the coarser-grained deposits to reflect deposition in or near the center of a stream and the finer-grained, better stratified units to reflect deposition outside the main flows or during a phase of lower discharge. These flow processes were probably not too dissimilar to those in the modern Columbine Creek channel during large runoff events.

The stratigraphic units above the unconformity are interpreted to be genetically related and to reflect a decrease in overall flow strength, likely as the main channel migrated laterally away from the sites of the measured sections. We interpret the tuffaceous, sandy, iron-oxide cemented upper portion of both sections to reflect deposition in a fluvial overbank setting that was influenced by run-off from Brimstone Basin thermal area, located <1 km upslope.

The observed stratigraphic relationships and our environmental interpretations suggest that the age of 10390+/-150 cal yr BP for charcoal recovered from the upper fine grained unit at Columbine Creek section #2 can reasonably be taken as a close approximation of the age of the upper part of the measured sections. We infer the underlying coarse conglomerate to be part of the same fluvial depositional system and the erosional unconformity separating these genetically-related units from the underlying laminated very fine sand and silt to span at least 35,000 years.

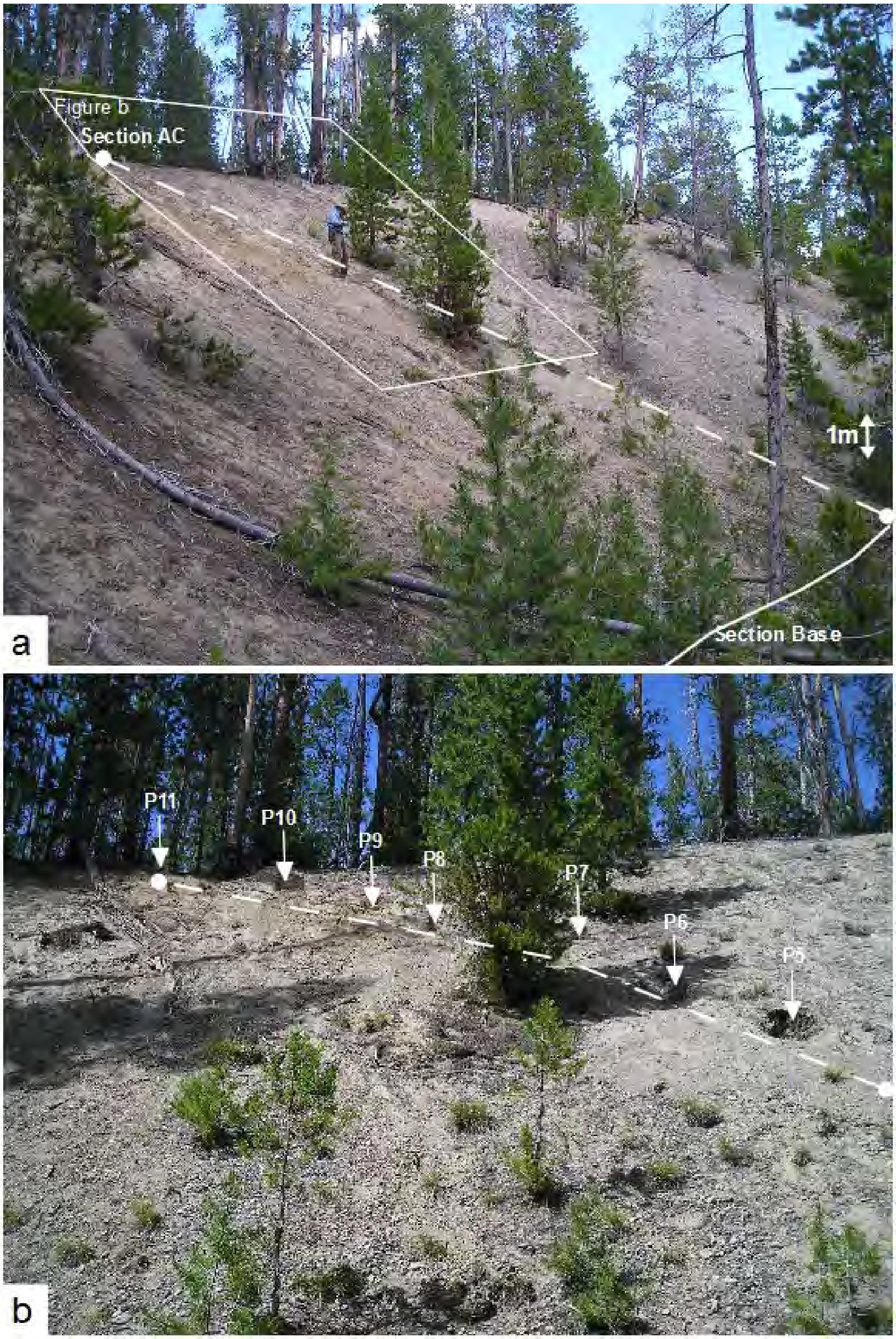


FIGURE 11: Alluvium Creek section. Hand-dug pits labeled and highlighted by arrows.

3.1.4 Alluvium Creek Section (APPENDIX B-3)

Location: On the northern cut bank of Alluvium Creek ~ 250 m upstream of the present day mouth of Alluvium Creek (Fig. 2; GPS: MSHWPT146-149).

Outcrop: 10 m high colluvium-draped incised channel wall in Alluvium Creek drainage. Measured section starts ~ 2 m above modern day Alluvium Creek (Fig. 11a). Section is not continuous but is composed of series of 11 pits that were hand-dug into the hillside and hand-troweled prior to measurement. Individual pits were, on average, ~ 50 - 70cm deep with ~ 50 cm gaps (covered intervals) in between (Fig. 11b).

Description: Sediments exposed in the lowest pits (P1, P2, base of P3) are massive, dark brown, medium grained pebbly sands. Pebbles are up to 3 cm in diameter and increase in abundance from P1 to P2. Grains are sub-angular to sub-round and sorting is poor. No stratification was observed.

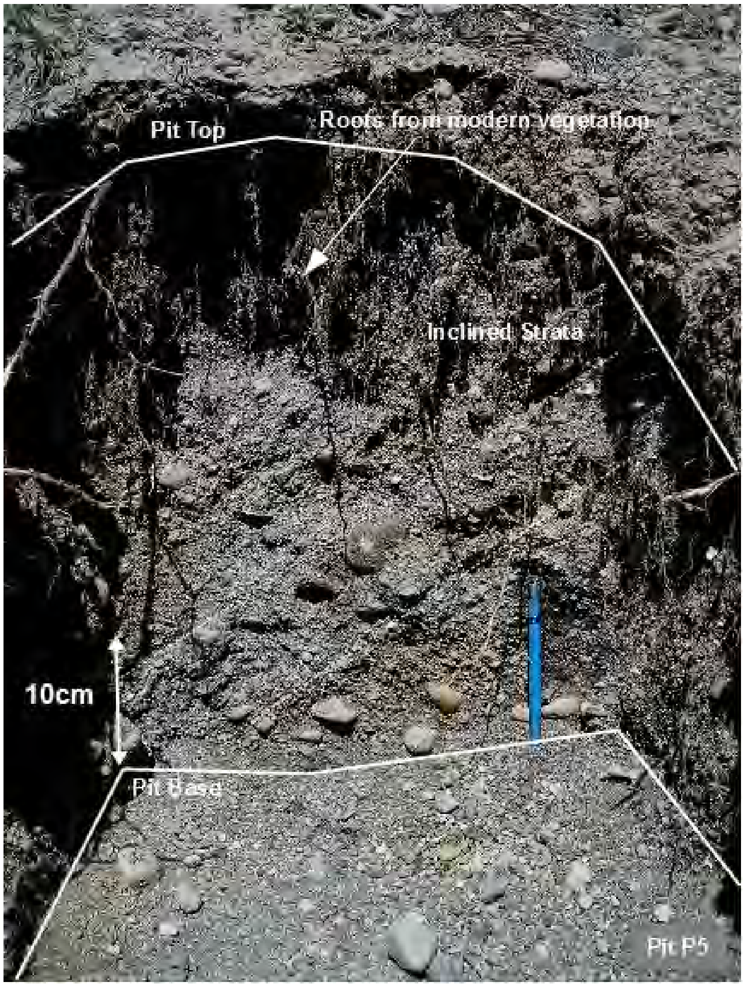


FIGURE 12: Sediments of pit P5

Above these massive sands and beginning at the top of P3 is an interval of well layered fine to very fine sand that lacks pebbles. The average thickness of the sand layers is ~5 cm and layers are gently inclined ~ 8° to the SW (210°). Sand grains are angular to sub-angular and color ranges from light gray to yellowish-brown.

This sandy interval is overlain by grayish, medium- to coarse-grained, poorly sorted sand in pits P4 and P5. Granules and pebbles are abundant, range in size up to 8 cm and are well rounded. Sand grains forming the surrounding matrix are sub-angular to sub-rounded and in general medium-sized. Maximum pebble sizes increase towards the top of pit 5. These pebbly sand deposits display faint lamination that is steeply dipping to the WSW (258° - 268°). Dip angle increases from ~12° in P4 to ~26° in P5 (Fig. 12).

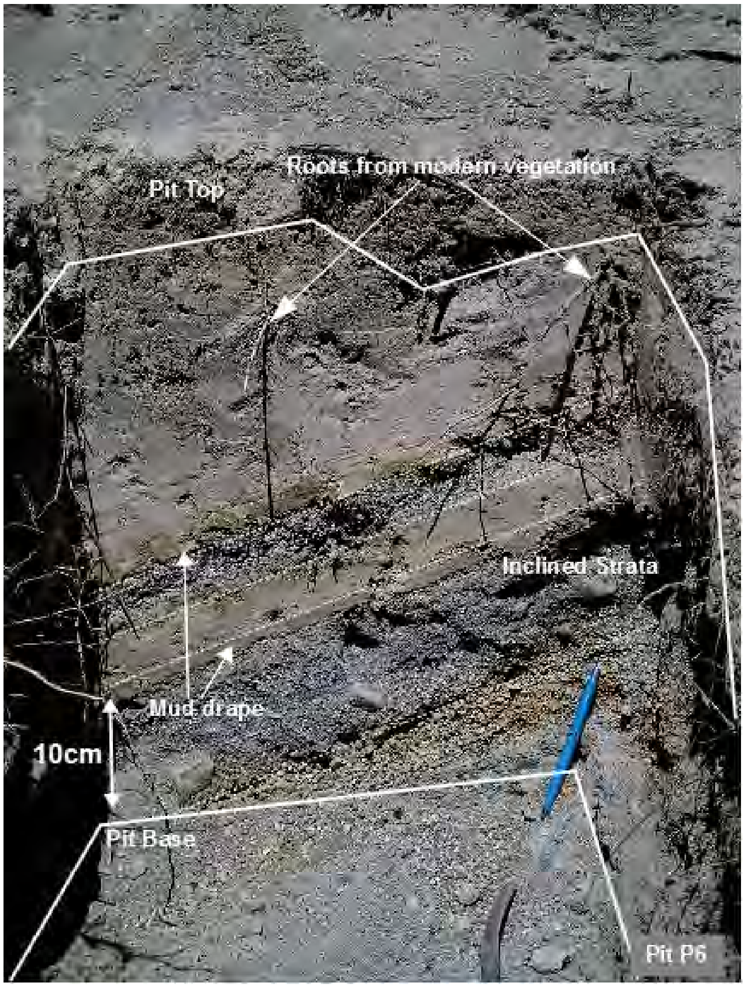


FIGURE 13: Sediments exposed in pit P6

Sediments exposed in pits P6 upward to the base of P8 are dominated by cm- to dm-scale thick upward-fining layers of granule-bearing sand (Fig. 13). Cm thick layers of interbedded mud commonly separate individual upward-fining sand layers. Pebble-sized clasts are well rounded, reach up to 3 cm in diameter, and are embedded in a sandy matrix except at the base of two upward-fining layers (base pit 6, pit 7) where cm-sized (“pea gravel”) clasts display an open framework. Upward-fining layers with smaller overall grain sizes are well sorted and contain fewer outsized clasts (~1 cm diameter) than coarser-grained layers which are medium sorted and contain local cm-sized clasts. The finer sandy layers also are distinctly laminated. The color of the coarser-grained layers is predominantly grayish; the finer-grained intervals are darker brownish-gray. Dip decreases from 26° in pit P6 to 16°-20° in pit P7 and P8. Along with the dip angle change is a change of azimuth from W (268°) in P6 to SW (222°-224°) in P7 and P8.

The most significant stratigraphic contact in the entire Alluvium Creek section is visible in pit P8. There the steeply dipping beds so prominently displayed in the underlying pits are unconformably truncated by nearly horizontal beds (Fig. 14).
The stratigraphic unit above the unconformity is dominated by a series of cm thick fine and very fine sand deposits that are particularly well exposed in pits P8 – P10 (Fig. 14). Grading in the horizontal beds that overlie the unconformity is not as pronounced as in the underlying steeply dipping beds, and both upward-coarsening and upward-fining sedimentary packages with dm-scale thickness occur in this succession. Some beds have rust colored iron(?) staining, others contain small woody debris. Fine sandy sediments exposed in pit 9 display faint unidirectional ripples. Ripples were not observed above pit 9, very fine to fine sand interbeds with thickness at a multi-cm scale were observed in pits 10 and 11. Most layers dip < 5° to the NNW (330°). Only the uppermost layers in pit P10 have increased dip angles of 10°-12°. The uppermost 50 cm of pit 11 contains well-rounded pebbles and consists of the modern surface colluvium and soil.

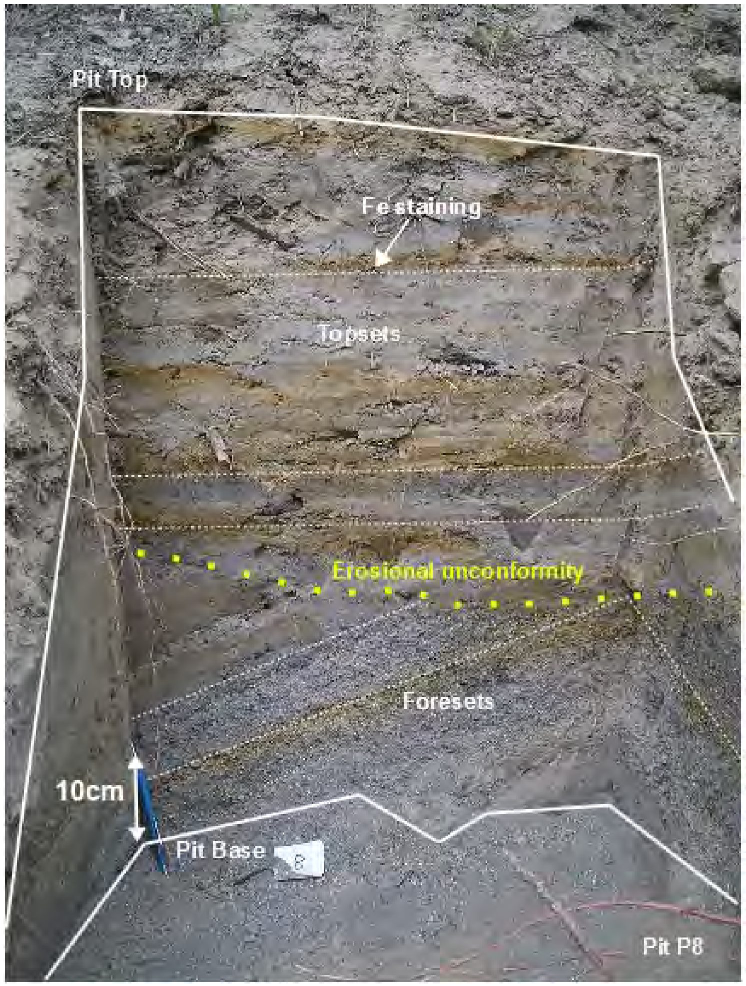


FIGURE 14: Contact between delta foresets and topsets in pit P8

Interpretation:

The sediments exposed in the Alluvium Creek section are interpreted to be the deposits of a Gilbert type fan-delta (Fig. 15) rather than coarse grained lacustrine beach deposits as previously suggested (Richmond and Pierce, 1972). Gilbert deltas are coarse grained (gravel-bearing) deltas with steeply inclined, relatively straight foresets (Gilbert, 1885, 1890). Their development requires a high gradient basin margin, and they are often found in lake environments and in particularly glacial lake environments characterized by high gradient margins following glacial retreat. In addition to their characteristic steeply dipping foresets, Gilbert type deltas also typically contain lower gradient subaerial topsets and lower gradient subaqueous bottomsets, all of which were observed in the Alluvium Creek section.

The bottomset deposits associated with the inferred Gilbert-style delta exposed in the Alluvium Creek section were observed in pits 1 and 2. These relatively low-gradient bottom sets typically result from a variety of sediment gravity flow types that include debris flows and turbidity currents with additional sedimentation taking place through suspension settle out. The steeply dipping foresets observed in pits P4-P8 resulted from subaqueous density currents containing a high sediment load. In modern Gilbert-style deltas, foreset slope gradients can reach up to 35° in coarser gravelly foresets but more commonly range between 20°-27° in finer grained, sand-dominated foresets (Nemec, 1990). In the upper part of the delta front (e.g. lower part of P8), these sediment-laden flows were dominated by inertia associated with the slowing fluvial current. These inertial flows also likely triggered subsequent gravitational avalanching of grain flows, frictionally-dominated debris flows, and turbidity currents further down the delta front. In addition to the inertia-dominated flows are hyperpycnal flows which reflect semi-continuous delivery of sand- and silt-dominated sediment to the lower delta front and beyond. These hyperpycnal flows can be the dominating flow process in some Gilbert-style deltas, typically leaving behind stratified silty and sandy deposits associated with the lower foresets and bottomsets (i.e., lower delta front and beyond). The topsets in Gilbert type deltas truncate and overlie the foreset deposits and result from avulsing channel systems and overbank deposition. We interpret the gently-inclined beds exposed in pits P8-P10 as representing deposition on the delta top.

The wealth of stratigraphic heterogeneity (inverse and normal grading, presence of massive beds, variable dip azimuth and magnitude, and spatial distribution of sedimentary structures) documented from the Alluvium Creek measured section is interpreted to reflect variation in flow dynamics and basin configuration during deposition. The occurrence of fine (mm-scale) lamination in the silt-bearing fining upward units (e.g. P6; Fig. 13) permit the interpretation that these beds are Tb deposits according to Bouma's classification of fine grained turbidites.

The poorer sorting and crude normal grading of the coarser, pebbly intervals (e.g. P5; Fig. 12), together with the presence of outsized pebble clasts locally floating in sandy matrix, are typical for laminar gravity flows. The flows never completely disaggregated when flowing down the steeply inclined surface and sediments were deposited as poorly sorted and coarse grained. This alternating occurrence of debrites and turbidites is typical of Gilbert-style delta front environments where flows are flashy and flow processes neither steady nor uniform and capable of high sediment delivery rates.

These various sediment gravity flow deposits are separated by muddy interbeds interpreted to represent either the fine grained tail of turbidity currents (Td deposits after Bouma), or the background sedimentation in the lake (Te deposits after Bouma; e.g. P6; Fig. 13).

The minor change in dip angle visible between pit P6 and pit P7 is interpreted to reflect avulsion of the main sediment delivery channel system from this area to a more southerly channel system. Deltas switch lobes frequently, especially in a high density fan delta environment similar to the one inferred to be represented here. Such a switch in the deposition center could produce the change of the dip azimuth and magnitude observed between pits 6 and 8. The observed shift to finer grain size at this stratigraphic level is consistent with our interpretation of an avulsion event that shifted the locus of deposition southward.

The most significant change in depositional environment is represented by the erosional unconformity clearly visible in P8 (Fig. 14). Beds exposed in the bottom part of this pit are interpreted as delta front deposits, whereas the more gently-inclined deposits above the erosional unconformity are interpreted to be delta topsets. These topsets were deposited after the break in slope associated with the transition from delta front to delta top had prograded basinward of the section location (Fig. 15). Cm-scale sandy rhythmites, ripples, and burrows all are consistent with deposition on a delta plain (fan surface) characterized by occasional standing water (shallow lake/s). The observed iron staining in several intervals is interpreted to reflect weak soil development at times when the water table dropped below the land surface, allowing draining of the shallow subsurface and precipitation of iron oxide cements and grain coatings.

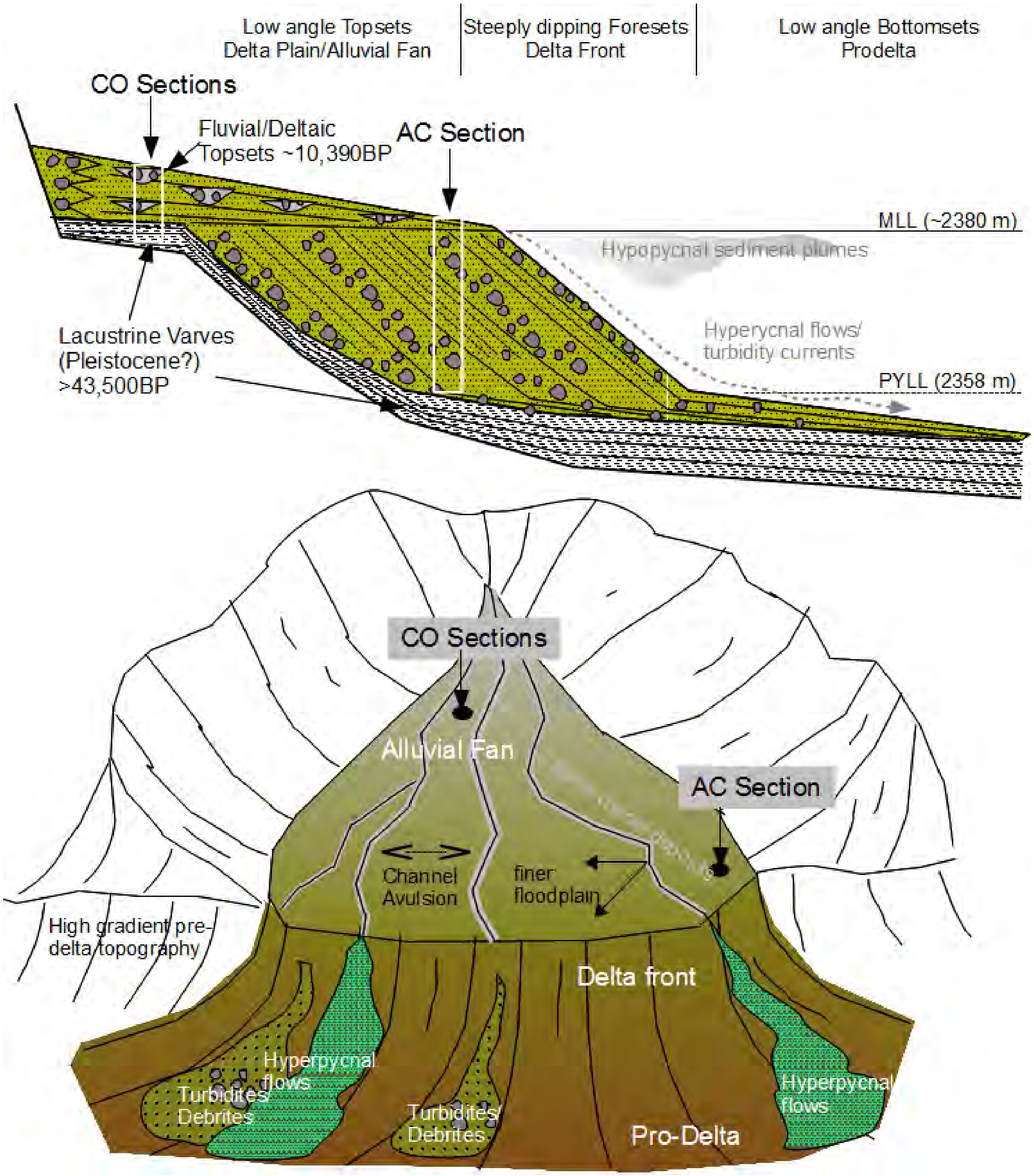


FIGURE 15: Gilbert Delta model for the Columbine/Alluvium Creek Delta. MLL = Maximum Lake Level at delta formation; PYLL = present day Yellowstone Lake level

3.1.5 Columbine Creek Section N (APPENDIX B-4)

Location: Cutbank of a distributary channel of Columbine Creek ~50 m south of Columbine Creek (Fig. 2; GPS: WPTMSH150)

Outcrop: 1.3m high exposure in a scour (cut bank) of a Columbine Creek flood channel. The base of the section is approximately 1m above the present day base of Columbine Creek

Description:

Sediments in this section are dominantly coarse grained, although the basal 10 cm are composed of yellowish-brown mud (silt and clay). The overlying 70cm are dominated by weakly stratified coarse-grained sand with abundant floating pebbles (max. 2 cm diameter). Individual beds are ~20cm thick and fine upward. This coarse grained succession is topped by a 10 cm thick layer of fine sand with mud. We were able to recover a sample of charcoal from this unit (10-CO-100; Appendix E) that yielded a radiocarbon age of 2660+/-40 BP (2795+/-55 cal yr BP). Above this fine grained unit is another ~20cm thick bed of sand with abundant pebbles floating in the matrix. The uppermost 30cm exposed in the cut bank is a pebbly gravel with pebble sizes up to 4cm in diameter. This youngest unit displays apparent downcutting into the underlying sediments.

Interpretation:

The limited exposure makes a detailed interpretation difficult. The overall coarse grain size of the sediments and their similarity to modern Columbine Creek deposits, however, suggests a depositional environment very similar to those found in or near a creek bed. The fact that these sediments are presently exposed in a cutbank of a flood channel also suggests that deposition of these units occurred at a time when the surface level of Yellowstone Lake (i.e., local base level) was higher than at present.

3.1.6 Columbine Creek - Total Station Survey (APPENDIX A)

Location: The Columbine Creek total station survey started at the Yellowstone Lake shoreline ~125m southeast of NPS campsite 5E9 and trended northeasterly for ~600m to the first outcrop of volcanic bedrock (Figs. 2, 16). GPS WPTMSH151 marks the location of the total station instrument throughout the entire survey.

Description:

The purpose of shooting the Columbine Creek total station survey was to document the presence of a series of low relief shoreline parallel ridges in this part of the field area. The ridges are well expressed on aerial and/or satellite images and cut across a network of meadows and clearings.

The total station was positioned approximately in the middle of the transect and was not moved. At the conclusion of the survey, the location of the first survey point was reshot in order to provide a basis for measurement uncertainty. The discrepancy between the first and last survey shots was 6mm easting, <1mm northing, and 1mm elevation, indicating that our measurement uncertainty in each of these directions was <1 cm. We used a flat-bottomed base for the survey rod. Individual points were shot following placement and leveling of the rod base onto the ground surface and communicating by 2-way radio that the rod was in position. Individual survey points were typically 4-5 m apart.

In the field, we recognized at least five prominent paleo-shoreline positions marked by constructional beach ridge deposits (Fig. 17). In addition to their positive topographic relief and association with rounded gravel (Fig. 18) the beach ridge deposits in the survey area are characterized by relatively heavily vegetated sage separated by grassy swales. The sage evidently is growing in better drained soils forms by the beach ridge gravels, relative to the more poorly-drained intervening swales.

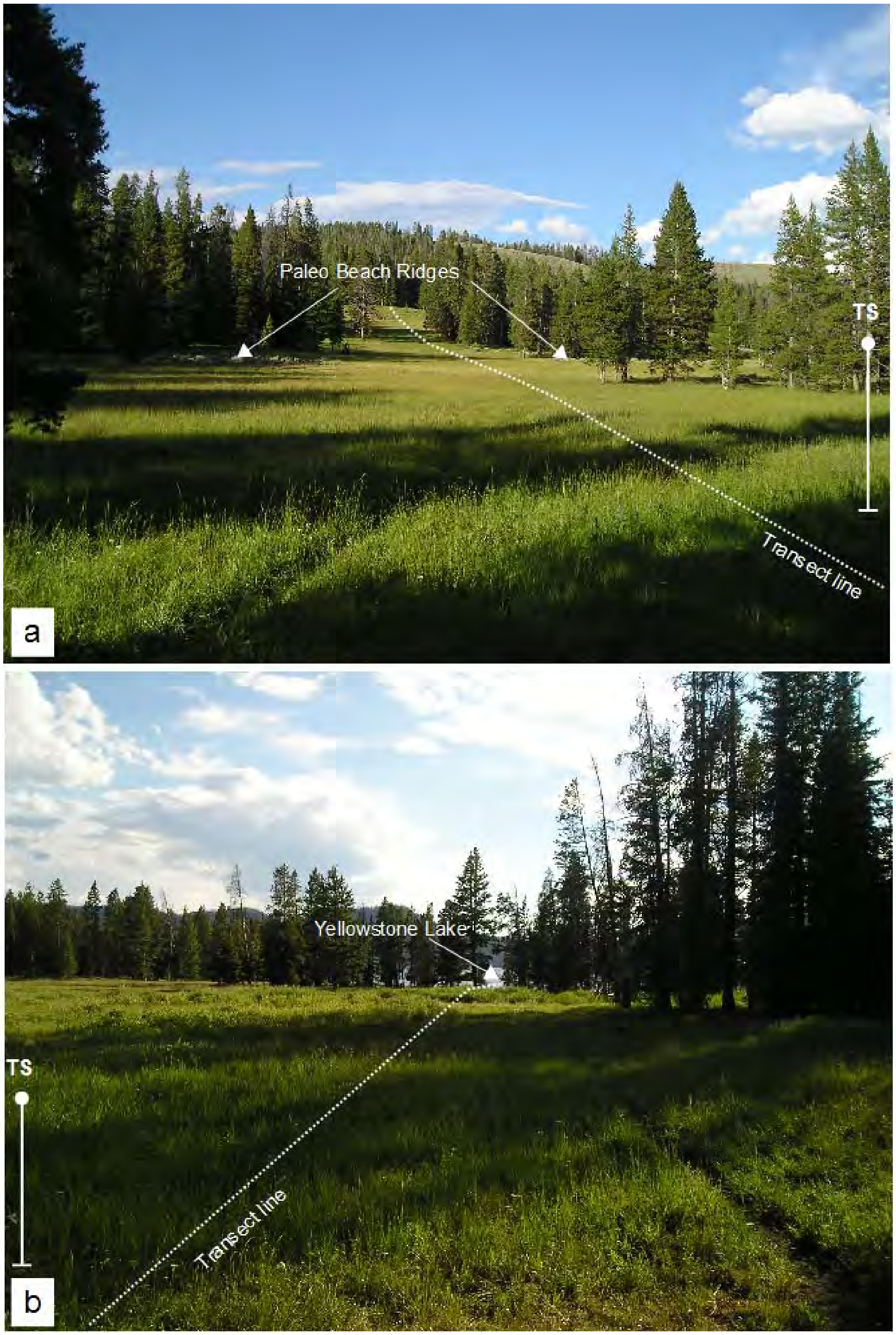


FIGURE 16: View of Total Station transect line from Total Station location (TS). View in a is to the east, view in b is west towards the lake. The eastern end of the line (a) is at a contact with bedrock, the western end of the line (b) is at the shoreline.

The highest of the beach ridges along the line of transect is located at ~ 2368 m, ~ 10m above the present day lake level (Fig. 17a). Results from the Columbine Creek total station survey transect suggest that lake levels were situated in a stable position at elevations near 2368 m, 2363 m, 2362 m, 2361 m, and 2360 m, respectively, relative to the modern day shoreline elevation of 2358 m and prior to the lake level dropping to its present elevation. These paleo beach ridges rise prominently 20 cm – 100 cm above the surrounding areas, suggesting only minor erosional degradation since their formation (Fig. 17b). We did not, however, recover any dateable material and therefore can only speculate about the age of the individual shoreline terraces.

The grain size and texture of the ancient beach ridges (Fig. 18a) is very similar to that of modern beach deposits on the eastern shore of Yellowstone Lake (Fig. 18b and 19). These similarities suggest a wave climate during formation of the beach ridges that was very similar to that present today on the eastern shoreline of Lake Yellowstone. These similarities also imply that the paleo-beach deposits were related to shoreline processes and wave energy associated with discrete lake level positions rather than being event deposits related to caldera eruptions or other singular events.

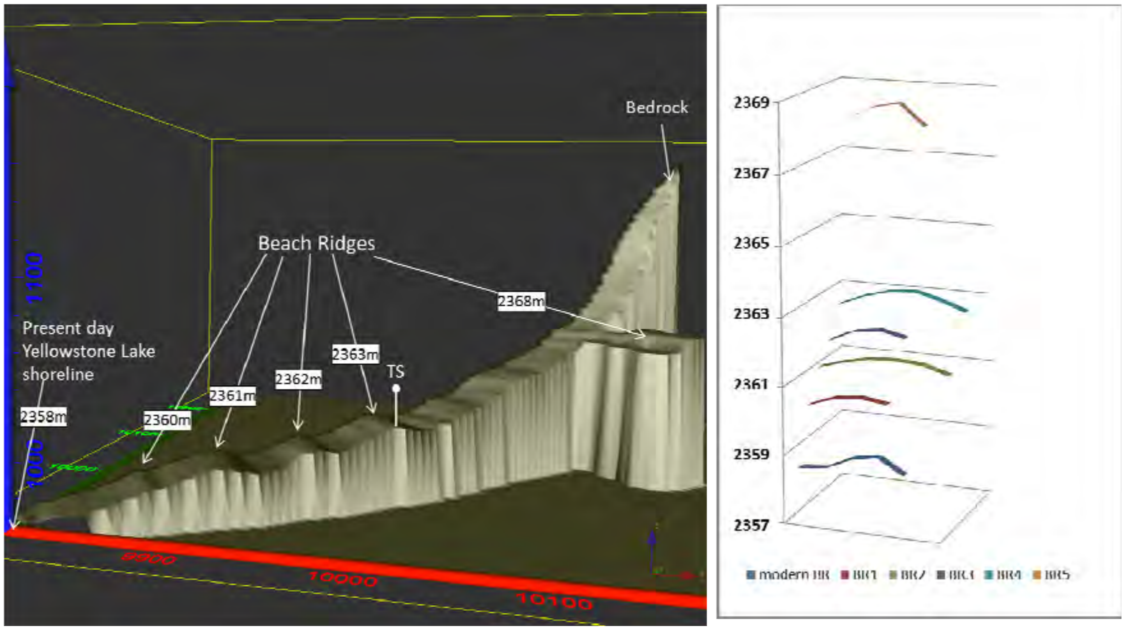


FIGURE 17: a (left): Total Station transect. Paleo-beach ridges are prominent morphologic ridges (arrows). TS = Total Station position during survey.
b (right): Beach ridge cross-sections. Paleo beach ridges (BR) are labeled in ascending order from lowest elevation (BR1; 2360m) to highest elevation (BR5; 2368m)

FIGURE 18: Comparison of paleo- and modern beach ridge deposits along Columbine Creek total station transect. a: Deposits of paleo beach ridge at 2363m; b: Deposits of modern (active) beach ridge. Note similar size and composition between ancient and modern deposits.

FIGURE 19: Morphology of present day beach and beach ridge at the west end of the total station transect line. Photo taken looking southeast.

3.2 Clear Creek

3.2.1 Geomorphology: The Clear Creek study area is located adjacent to the modern floodplain associated with Clear Creek, a significant tributary to the eastern shore of Yellowstone Lake. The mouth of Clear Creek is located roughly halfway between the mouth of Columbine Creek and the East Entrance Road to the north. From its mouth, where a modest spit is developed with evidence of pre-historic human activity (an ancient hearth is exposed at the shoreline), Clear Creek enters a thickly-wooded area and flows for ~100m over exposed bedrock for a straight section after flowing through several long sinuous meanders where exposed bedrock is not observed. The margins of the stream valley in this thickly-wooded section are marked by several subtle topographic benches that step down towards the modern stream channel and appear to be erosional in nature. Further upstream, Clear Creek passes through a more open clearing with dimensions ~600 x ~250m. In this clearing, the stream is clearly alluvial (i.e., flowing over fluvial/alluvial sediment, not bedrock) and is considerably more sinuous. The northeastern edge of the clearing is marked by a prominent slope separating the modern Clear Creek floodplain from a topographic bench ~5m higher.

In the Clear Creek area, we focused our efforts on documenting the sedimentology and stratigraphy of sediments exposed by hand-digging along the margins of the modern floodplain in the rises separating it from higher elevation terraces.

3.2.2 Clear Creek Section 1 (APPENDIX C-1)

Location: On the northern cut bank of the Clear Creek floodplain ~ 800 m inland (upstream) of the present day mouth of Clear Creek (Fig. 20; GPS: WPTMSH158-159)

Outcrop: 7 m high hillslope. The stratigraphic section measured here is not continuous but is composed of series of 6 pits that we hand-dug into the hillside. Individual pits were, on average, ~ 50 – 70 cm deep with ~ 50-100 cm gaps (covered intervals) in between. The base of the section is ~ 2 m above the base of the present day Clear Creek floodplain. Pits 1-3 are located downhill of the pack trail, pits 4-6 uphill of the pack trail.

FIGURE 20: Location map of Clear Creek (CC) sections.

Description:

The hill side is covered by thick modern colluvium. In pit P1 we were not able to dig through the surface cover. Therefore this pit is not considered in terms of stratigraphic results. The modern colluvium, exposed in all pits, is uniformly composed of poorly sorted sand with cobbles and pebbles. Grain size of the matrix varies from fine to coarse grained sand, large clasts are sub-angular to rounded and up to 7cm in diameter. Modern roots are common in this unit.

Pit P2 was the first in which pre-colluvium stratigraphy was exposed. The bottom 50 cm of this pit are composed of massive, poorly sorted medium- to coarse-grained sand. Pebbles floating in the matrix are rounded and have diameters up to 1cm. Modern colluvium makes up the upper 70cm of the exposed stratigraphy in pit P2.

The basal 50 cm in pit P3 are composed of weakly stratified, poorly sorted, fine to coarse grained sand. Sand grains are angular to sub-rounded. Well rounded granules and pebbles 1-2 cm in diameter float in the sandy matrix. Individual layers are ~ 10 cm thick and have an apparent dip of 8°-10° to the NNW (328°). A similar facies is exposed in the basal 50 cm of pit P4, but the weakly stratified layers in this pit do not show any apparent dip. A change in facies and stratification is visible in pit P4, 50-90 cm above the pit bottom. Weakly layered strata have an apparent dip of 18° to the W (270°). Individual layers fine upward from a medium-coarse sand with few clasts (max diameter 1 cm) to better sorted medium sand in the upper part of each layer. Similar facies and upward-fining stratification continues in the basal 30 cm of pit P5, where beds also dip steeply (18°) to the W (290°). These dipping beds are truncated by a series of thinly layered sandy beds. Grains size ranges from medium- to coarse-grained sand with variable clast contents. Beds in this interval are not graded but poorly sorted with a medium-coarse sand matrix and alternation of pebble-bearing sand with well-sorted sand lacking pebbles.

Pit P6 contains the most complex stratigraphy. The basal 5 cm in this pit are composed of medium-fine sand with a few granules floating in a generally fine-grained, well sorted matrix. The overlying 15 cm have a similar matrix composition, but lack granules. These fine grained units are erosionally truncated by a 20 cm thick fining upward layer. Coarse/medium sand with an abundance of pebbles and cobbles (up to 7cm diameter) fines upward into medium/coarse sand with clasts of less than 1cm in diameter and medium/coarse sand without any clasts. The matrix is sub-rounded, whereas coarser clasts are rounded. Stratigraphic layers dip gently ~4° to the W (240°).

Another 15 cm thick layer of poorly sorted medium/coarse sand with pebbles and cobbles forms the next stratigraphic unit that in turn is overlain by a 15 cm thick layer of medium/coarse sand without any clasts.

3.2.3 Clear Creek Section 2 (APPENDIX C-2)

Location: ~ 100m northwest (downstream) of Clear Creek Section 1 (Fig. 20)

Outcrop: One test pit was dug in an attempt to find a hillside with less surface cover. The thickness of the surface cover in this pit exceeded 40 cm and contained pervasive modern rooting. No other pits were dug. The stratigraphic position of the one test pit in this second Clear Creek section is approximated as equivalent to pit P3/4 in the Clear Creek Section 1

Description:

The 60 cm thick section exposed in the one test pit is crudely stratified into 4 layers. The basal ~ 15cm thick layer is composed of well sorted lower medium (upper fine) sand. The upper 3 beds are formed by individual fining upward packages with a medium/coarse-grained sand matrix. Grading is the result of variable clast density within the matrix, with the maximum clast size being 1 cm.

3.2.3.1 Interpretation of Clear Creek sections 1 and 2

The poor exposure in Clear Creek sections 1 and 2 and thick modern colluvium hinders a reliable interpretation, as does the presence of non-diagnostic facies assemblages. Facies composition and stratigraphic relationships exposed in sections CC1 and CC2 permit the interpretation of this section as reflecting sedimentation in deltaic, alluvial fan, and/or fluvial environments.

3.2.4 Clear Creek Section 3 (APPENDIX C-3)

Location: On the northeastern cut bank of Clear Creek ~ 300 m inland (upstream) of the present day mouth of Clear Creek (Fig. 20; GPSMSH162) and also upstream of an exposed bedrock knickpoint along Clear Creek.

Outcrop: Stratigraphic section consists of two pits hand dug into the hillside on the cutbank site of Clear Creek. The lower pit is located ~ 2m above the valley floor, the upper pit it located ~ 2m above the lower pit. The two pits are separated by a clearly defined erosional fluvial terrace (Fig. 21).

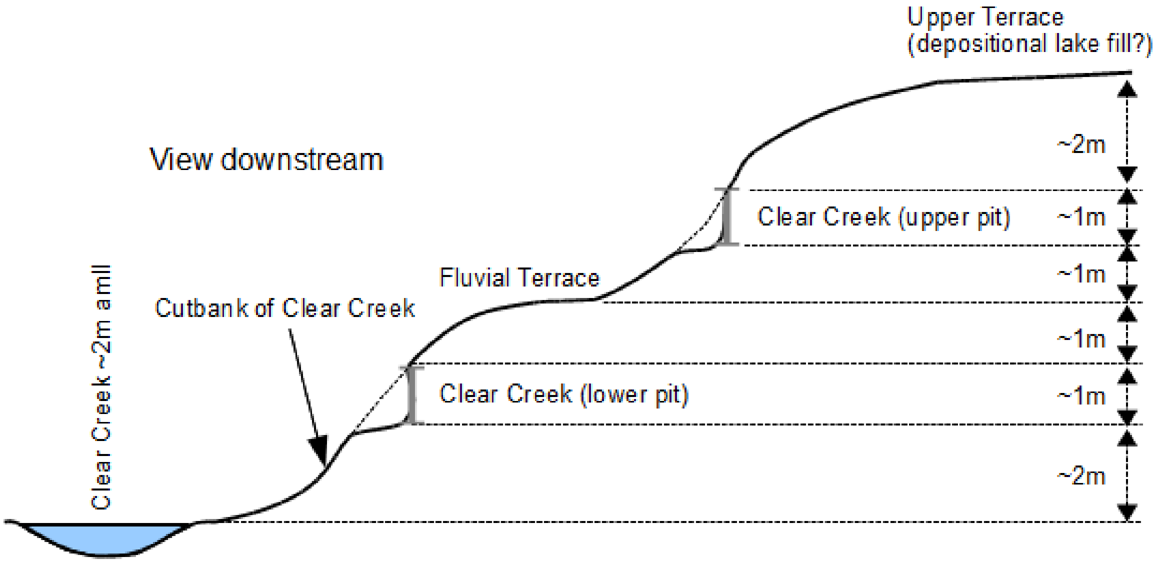


FIGURE 21: Schematic cross-section of pit position in Clear Creek section 3.

Description:

Sediments in the lower pit are dominantly very fine grained. The basal 20 cm are composed of mud (silt and clay) with a few outsized pebble clasts (max. 18 cm diameter) floating in the fine grained matrix. The next 23 cm are dominated by gray-brown fine sand with sub-rounded granules and pebbles (max. diameter 2cm) floating in this fine-sand matrix. This interval contains abundant charcoal, and one sub-sample of this charcoal (10-CC-10) yielded a radiocarbon age of 3730+/-40 BP (4100 +/- 130 cal yr BP; Appendix E).

Sediments in the upper pit also are dominated by gray-brown fine sand and silt. The basal 25 cm in the upper pit consist of three thin layers of clay (each less than 0.5 cm thick) separated by layers of very fine sand/silt. The very fine sand and silt layers are between 3 and 10 cm thick (Fig. 22). Above this basal interval is a 45 cm thick interval of massive well sorted, well rounded fine to very fine sand.

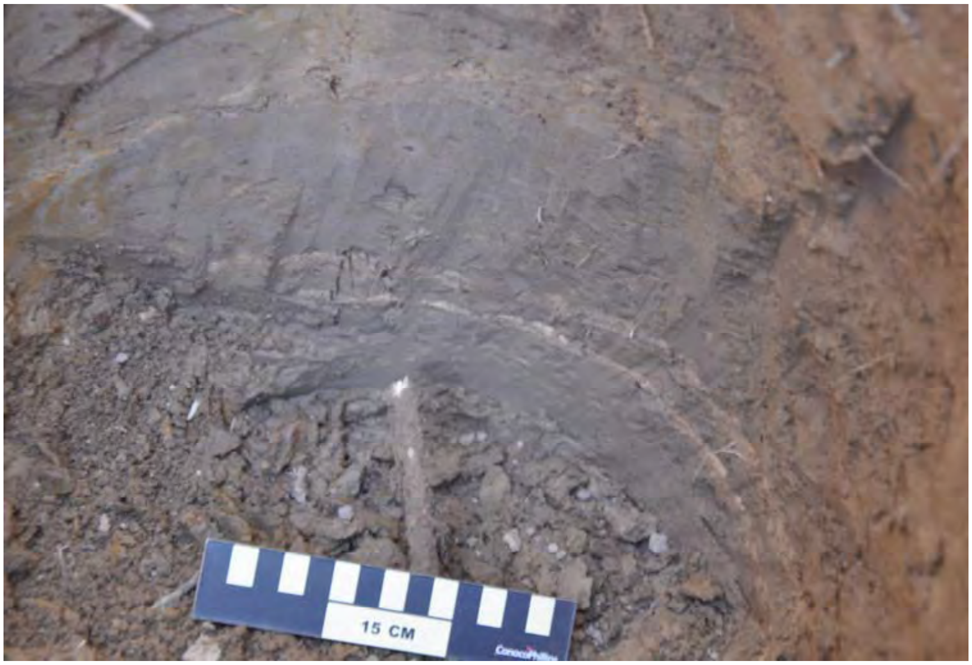


FIGURE 22: Photograph of clay lamina (light brown, >1cm thick) interstratified with silt and fine sand (darker gray-brown) in the upper pit at Clear Creek section 3.

Interpretation:

The limited exposure renders a detailed interpretation of these sediments difficult. The generally very fine grain size requires deposition in a low energy environment, and lamination observed in the muddy portions of the exposed pits (Fig. 22) further suggest episodic sediment delivery followed by suspension settle out under low-energy conditions. Such hydrologic regimes can exist in a variety of depositional environments including lacustrine settings and floodplains of fluvial systems.

Based on observed sediment grain sizes, preservation of laminae, and location of the CC-3 pits immediately upstream of one of several small bedrock knickpoints, we infer that the sediment exposed in the pits was deposited either in standing water on the Clear Creek Floodplain or in a low-energy environment within Yellowstone Lake.

The fact that the two pits expose sediments that today clearly are undergoing erosional incision is significant. This observation indicates that when the muddy sediments exposed in the CC-3 section were deposited, base-level (lake surface elevation) must have been at least 2m higher than present assuming that the fine-grained deposits are related to floodplain deposition along Clear Creek. If the muddy sediments at CC-3 were deposited in a low-energy environment associated with Yellowstone Lake, the lake surface must have been high enough at least to inundated the CC-3 study area to an elevation as high as the lower pit, located ~5m above the modern lake surface. If fine-grained deposits in the upper pit were deposited in the same depositional environment as the fine-grained deposits of the lower pit this lake elevation had to be even higher, and may have been as high as 10m (elevation of upper terrace) above the present day lake surface (Fig. 21).

FIGURE 23: Clay-silt laminae in Clear Creek section 3

To summarize, we infer the muddy sediments exposed in the CC-3 section to have been deposited in low energy subaqueous conditions that require either standing water on the floodplain and a high enough base-level (lake surface elevation) to overtop the bedrock knickpoint and possibly the CC-3 section by water from Yellowstone Lake. The first scenario requires a minimum ~2m rise in lake surface elevation, and the latter scenario requires a rise of at least 5m and potentially up to 10m around the time of 4100 cal yr BP. After the sediment at CC-3 had been deposited, the lake surface elevation dropped to its present level and incision of the Clear Creek drainage commenced, forming the erosional terraces of the CC-3 site.

3.3 Trail Creek

3.3.1 Geomorphology (GPS survey data; FIGURE 24; APPENDIX A):

A high resolution GPS transect was conducted perpendicular to the Yellowstone Lake shoreline from the modern-day shoreline southward up a well defined slope to and across a prominent flat topped bench located just west of Trail Creek (Fig. 24, 25).

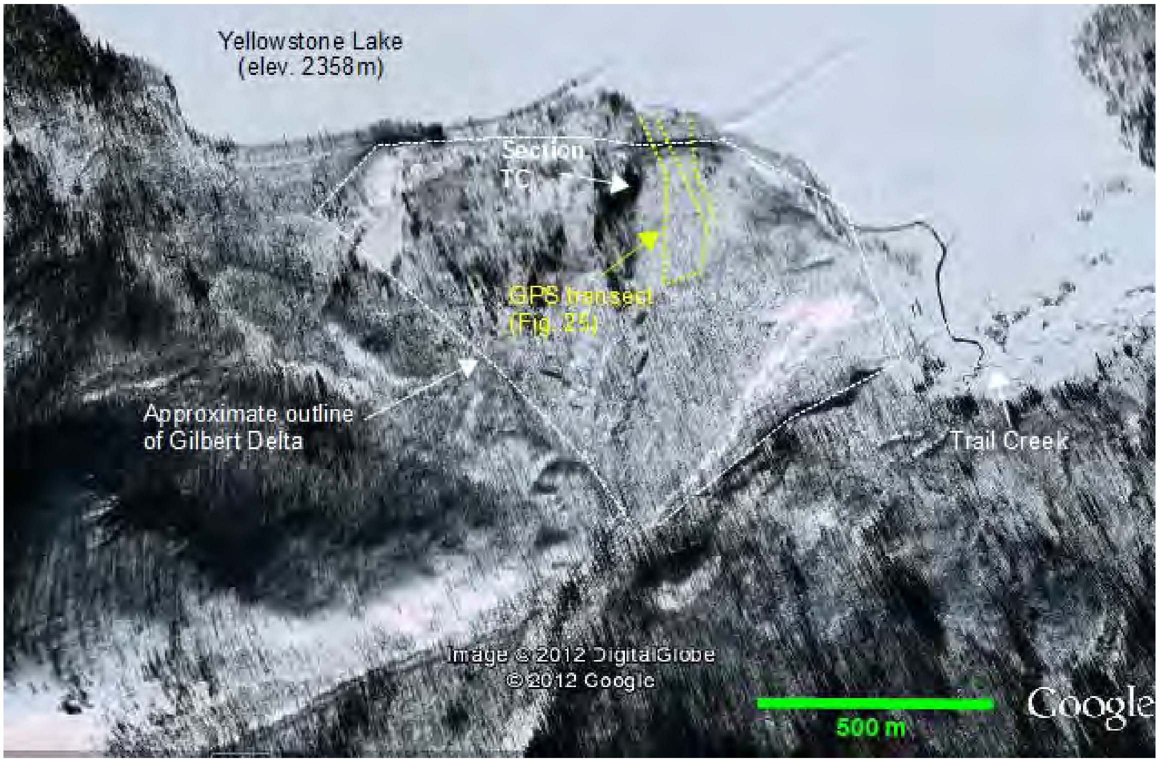


FIGURE 24: Satellite image of Trail Creek study area

Results from the Trail Creek survey data show that the main geomorphologic feature is a wide, low gradient bench starting at an elevation of ~2379 m (~7806 ft) or ~ 21 m (68 ft) above the present day lake level of 2358 m (7736 ft). The average slope on top of the bench is generally <1.5°. To the north this wide bench is bounded by a steeply dipping slope (max. slope 25°) that drops down to the present day Yellowstone Lake shoreline (Fig. 25). The break in slope between the flat topped bench and the steeply dipping slope parallels the modern day shoreline for more than 1.5km and is interrupted only by some modern-day creek incisions. The low gradient bench extends southward away from the lake and coalesces at an apex about ~0.9 km from the shoreline. In general the outline and morphology of this feature resembles that of a modern day Gilbert style delta (Fig. 24), and we interpret it as such.

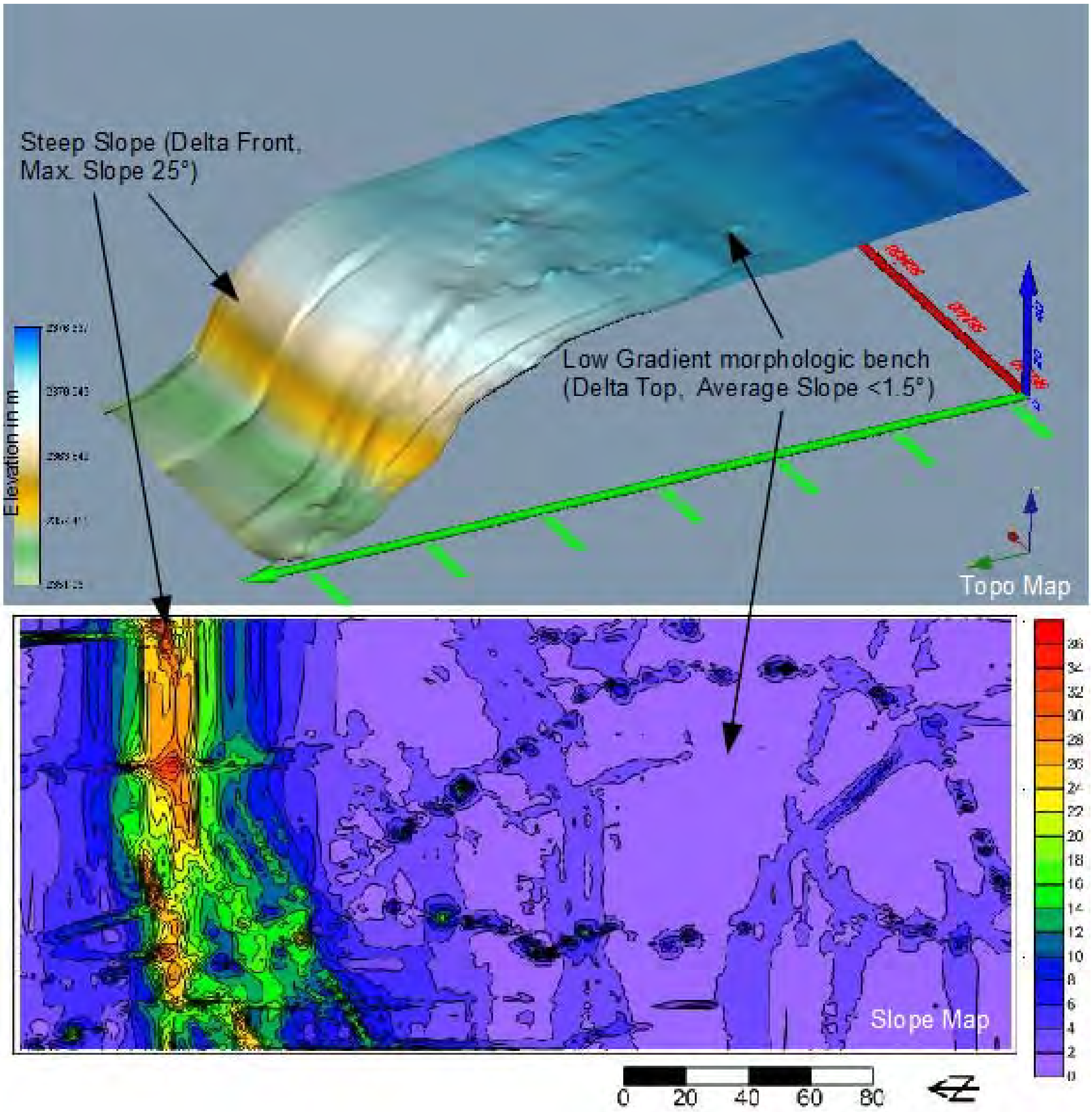


FIGURE 25: Topographic profile (top) and slope map (bottom) of the Trail Creek Gilbert delta. For location of section line see figure 24.

The formation of the Trail Creek Gilbert style delta clearly predates the incision of the modern Trail Creek as well as the incision of a series of smaller, unnamed creeks dissecting this prominent morphologic feature (Fig. 24). The downcutting of one of these unnamed creeks approximately along the center axis of the delta resulted in a steep cutbank wall that exposed the delta sediments described in the following chapter.

3.3.2. Trail Creek Section (Appendix D1)

Location: Along the southern shore of Yellowstone Lake west of Trail Creek, ~ 1100 m east of historic Trail Creek Ranger Cabin (Fig. 24; GPS: YE0911 St1a).

Outcrop: ~6 m high colluvium-draped incised channel cutbank wall along unnamed drainage. The Trail Creek measured section starts ~ 3 m above the modern day floodplain of an unnamed creek ~500m west of Trail Creek (Fig. 26). The Trail Creek section is not continuous but is composed of a series of 5 pits that were hand-dug into the hillside and hand-troweled prior to measurement. Individual pits were, on average, ~ 45 – 80cm deep with ~ 80 cm gaps (covered intervals) in between.

FIGURE 26: Location of Trail Creek measured section. The flat-topped bench (Delta Top) and the steeply dipping delta front morphologies are clearly visible on this photograph. The measured section is not continuous but is composed of a series of 5 individual short sections that were aligned along the highlighted section line. View is to the east.

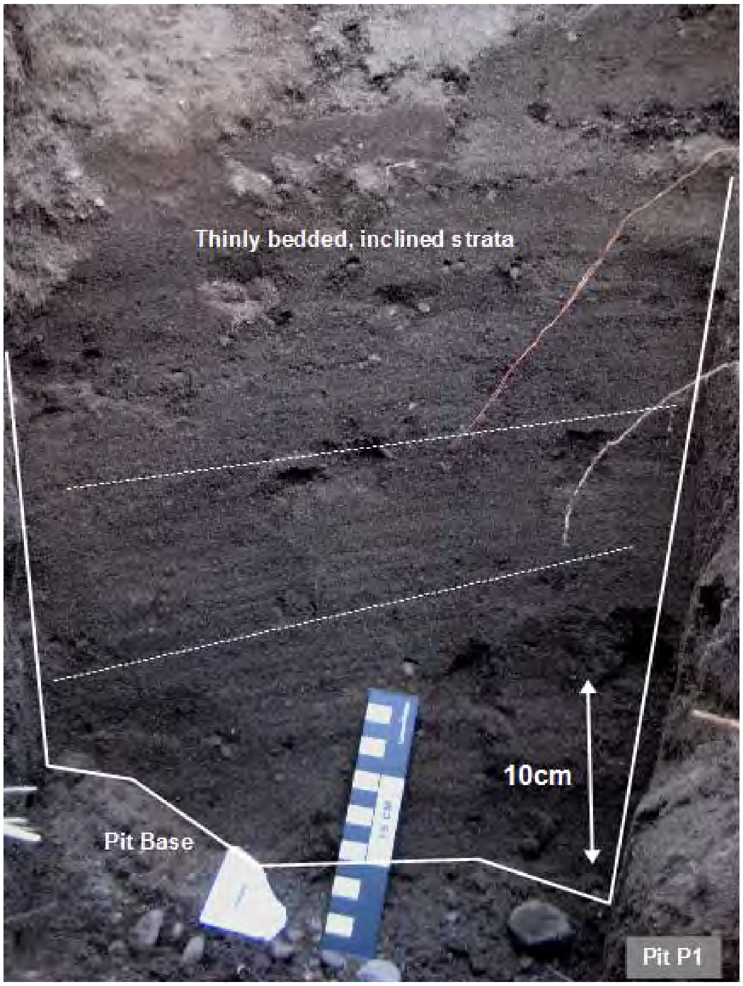


FIGURE 27: Gilbert style delta deposits exposed in Trail Creek pit 1

Description:

Sediments exposed in pits P1 to P4 are dominated by dark brown, medium to coarse grained pebbly sand (Figs. 27, 28). Pebbles are commonly smaller than 3 cm in diameter, but sporadically coarser outsized clasts are present in some of the pits (P2 and P3). Grains are sub-angular to sub-rounded and the matrix is medium well sorted. Grain size and pebble abundance increases slightly from bottom to top. Most beds are stratified on a cm to dm scale. Some beds fine upward, some others have a poorly defined coarsening upward trend. Stratification is commonly inclined dipping to the NNW with dip angles increasing from ~ 15° in pit 1 to ~ 22° in pits 3 and 4.

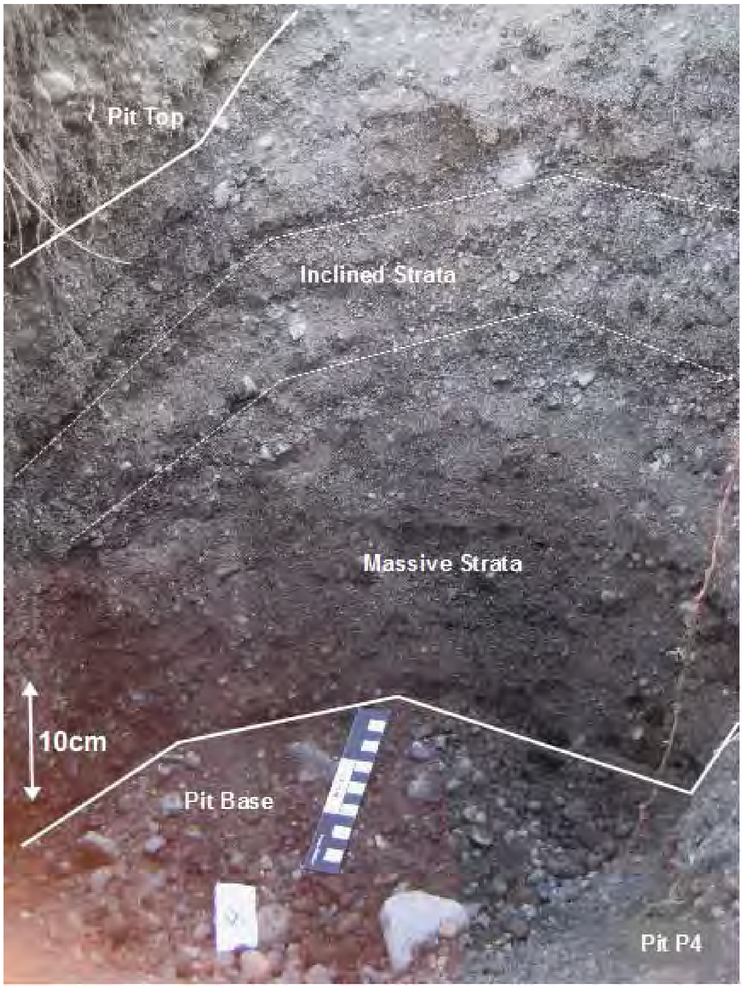


FIGURE 28: Sedimentary deposits exposed in Trail Creek pit 4. Inclined strata dip oblique towards viewer.

This general coarsening upward trend combined with the increase in dip angle of inclined beds is abruptly interrupted by dark brown, medium grained, well sorted sediments exposed in pit 5 (Fig. 29). The basal strata in this pit is massive upper fine- to medium-grained sand without any significant number of outsized grains and clasts. Twenty cm above the base of this pit, gently dipping inclined strata overlie this basal unit along a well-defined unconformity. The 2 cm thick basal layer of inclined strata is dominated by coarse sand and pebbles up to 1cm in diameter. Above this basal layer the remaining layers of inclined strata in pit 5 are much finer-grained and coarsen upward from upper fine sand to upper medium/lower coarse sand. The abrupt change of grain size observed in pit 5 is accompanied by an abrupt decrease in dip angle of the inclined strata (~15°) as well as a change in dip direction from predominant NNW (310° to 330°) in pits P1 to P4 to WNW (280°) in pit P5.

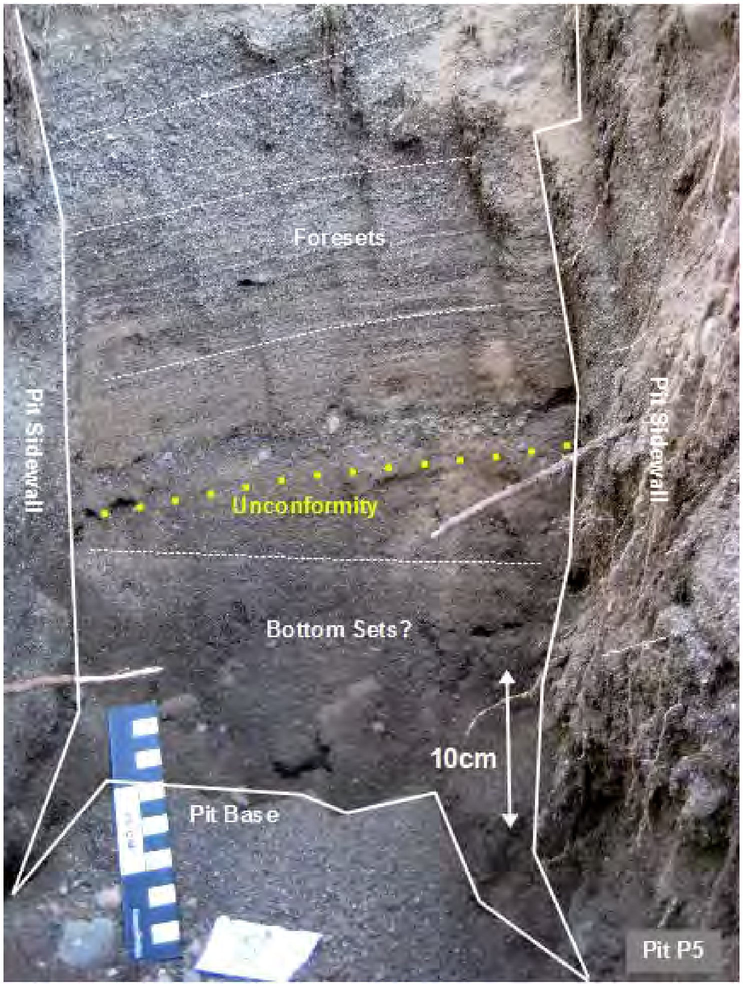


FIGURE 29: Gilbert style delta sediments exposed in Trail Creek pit 5. The absence of flat lying delta top strata can be explained by the position of the measured section on the lakeward site of the ancient shoreline location.

Interpretation:

The sediments exposed in the Trail Creek section are interpreted to be deposited by a Gilbert type fan-delta, similar to the deposits described from the Alluvium Creek section (Fig. 15), rather than ice contact deposits (kame terraces) as previously suggested (Richmond and Pierce, 1972).

The general depositional processes and stratigraphic architectures observed in Gilbert style deltas have been described and illustrated for the Alluvium Creek section and won't be repeated here.

One difference between the Alluvium Creek and Trail Creek sections is the apparent lack of bottom and topset beds in the Trail Creek section, although a thin layer of well sorted sediment lacking inclined stratification in pit P5 might represent bottom set beds of a small delta lobe. The absence of top set sediments is largely expected as the measured section was located on the lakeward side of the topographic break between the gently dipping morphologic bench and the steeply dipping slope and interpreted as the final position of the delta top and delta front of the Gilbert style delta, respectively.

Deposition of the steeply dipping inclined strata that as is predominantly exposed in the Trail Creek section resulted from subaqueous density currents. Dip angles change such that steeper dip angles (up to 22°) are mainly associated with the coarse grained sand and pebbly intervals, and more gently dipping strata (15°) are associated with the finer grained sediments. In general deposits in the Trail Creek section are finer grained than deposits in the Alluvium Creek section, but sedimentary characteristics ranging from outsized clasts floating in finer matrix to normally graded and laminated beds still suggests vacillations between laminar and turbulent flow processes typical for Gilbert style delta deposition.

The present-day morphology of the Trail Creek Gilbert delta with its steep delta front and gently dipping delta top likely reflects the last stage of delta evolution that has not been significantly altered since the delta was active. A maximum slope angle of ~25° compared to the 22° measured from the inclined strata is a close fit and supports this interpretation. In contrast, the shallower dip angle observed for the Alluvium Creek modern-day delta front morphology is likely a function of secondary wave reworking in this part of the lake. The stronger wave reworking is also evident by a series of beach berms present in the vicinity of the Alluvium Creek study site. While primary depositional processes were primarily fluvial and are preserved in the stratigraphic record, a secondary reworking of these sediments by wave processes is suggested by the beach berms.

3.4 Radiocarbon Dates and Lake Level Model (APPENDIX E)

Based on the limited age data from the measured sections and our sedimentologic, stratigraphic and geomorphologic observations, we infer the following model for lake level variation through time within the study area (Fig. 30). We fully expect that this model will be refined with additional information from subsequent work, and we emphasize here that the model presented below is preliminary.

Data and interpretations based on the 2010 and 2011 field seasons suggest that, relative to the modern ground surface, the surface of Yellowstone Lake was at a level of ~ 21 m above its modern level (that is, ~23m above datum as defined by Pierce et al., 2002, 2007) at the time of deposition of sample 10-CO-11 (10,390+/- 150 cal yr BP or 9,220+/-50 BP C14 yr BP). This lake level assumes a constant gradient from the sample location in Columbine Creek section #1 to the change in slope between delta topsets and foreset. The slope break at Trail Creek is equivalent to the slope break near the Alluvium Creek section location and is highlighted on the GPS profile presented in figure 4. Sample 10-CO-11 was collected ~ 1.5m below the modern ground surface, thus the surface elevation of Yellowstone Lake was ~ 1.5m below the morphologic break in slope. This linear relationship is deemed to be a valid assumption given the consistent grain size and composition of sediments exposed in the topsets of the Alluvium Creek section as well as the consistent grain size and composition of the alluvial deposits in the Columbine sections that collectively suggest a consistent hydrologic regime throughout the time of deposition. Although we weren't able to recover any dateable material from the Trail Creek site, striking similarities in morphology and sedimentary record suggest a similar lake level history as described for the Alluvium Creek site. Most notable, the slope break, the transition from delta top to delta front, for both deltas is at exactly the same elevation thus deposited most likely at a time when lake level was at a steady height ~21m above the present day lake surface.

Sample 10-CC-10, sampled ~ 2 m above the stream bed of the modern Clear Creek (GPS: WPTMSH163) and ~ 5 m above the present day lake level (7m above datum), was taken from thinly layered deposits of either lacustrine or floodplain origin (Fig. 22). This sample suggests a depositional age of these sediments of 4,150+/- 80 cal BP (3730+/-40 BP C14) in the Clear Creek area.

The youngest data sampled during this field season comes from an outcrop near the modern day river bed of Columbine Creek (sample 10-CO-100). This sample was measured at 2795+/-55 cal yr BP (2660+/-40 BP C14) and suggests that the surface elevation of Yellowstone Lake was ~ 1-2m above the present day at that time. This inference assumes a constant gradient for Columbine Creek, which we deem as valid given the similar composition of these late Holocene to the modern flood plain and fluvial deposits. These three data points collectively suggest that lake level dropped continuously at a constant minimum rate of ~ 2.5 – 3.0 mm/yr dependent on whether the sediments in the Clear Creek interval are lacustrine or fluvial. This rate is similar to rates calculated by Locke and Meyer (1994) for the low frequency post glacial lake level decline (2.5-3mm/yr).

Although our preliminary lake level history is very similar to that of Locke and Meyer (1994), significant differences exist between our preliminary model and that published by Pierce et al. (2002, 2007). Although our limited data does not provide a basis for further refinement of our lake elevation model relative to that of Pierce et al. (2002, 2007), understanding these difference should be an important objective for future studies. Understanding these differences is particularly important because our data and interpretations suggest a much younger formation of many of the lake terraces than suggested by Pierce et al. (2007) and, therefore, a much later timing of for inhabitation of the study site by humans.

The timing of a relative consistent lake level lowering throughout most of the Holocene (~10,000 - ~3,000), as we infer from our preliminary results, also coincides with a dryer and warmer climate in central Yellowstone area (Huerta et al., 2009). The decrease in the rate of lake lowering over the last ~ 3,000 years coincides with the onset of wetter and cooler conditions in the region (Huerta et al., 2009). The abundance of coal fragments in the Clear Creek section also is in agreement with the interpretation of decreased fire frequency in the central Yellowstone area at around this time (Millspaugh et al., 2000; Huerta et al., 2009). Huerta et al. (2009) reported a fire frequency of ~ 7 fires/1000 yrs ending at ~ 4000 yrs, compared to only 2 fires/1000 years for the time thereafter. Higher frequency changes of sedimentation and incision, particularly in the Clear creek area, seem to have potentially strong correlations to some of the incision rates and terrace formations reported by Meyer et al. (1995) for the NE part of Yellowstone National Park. These relationships between our lake level model and existing climate records should be a focal point of future investigations.

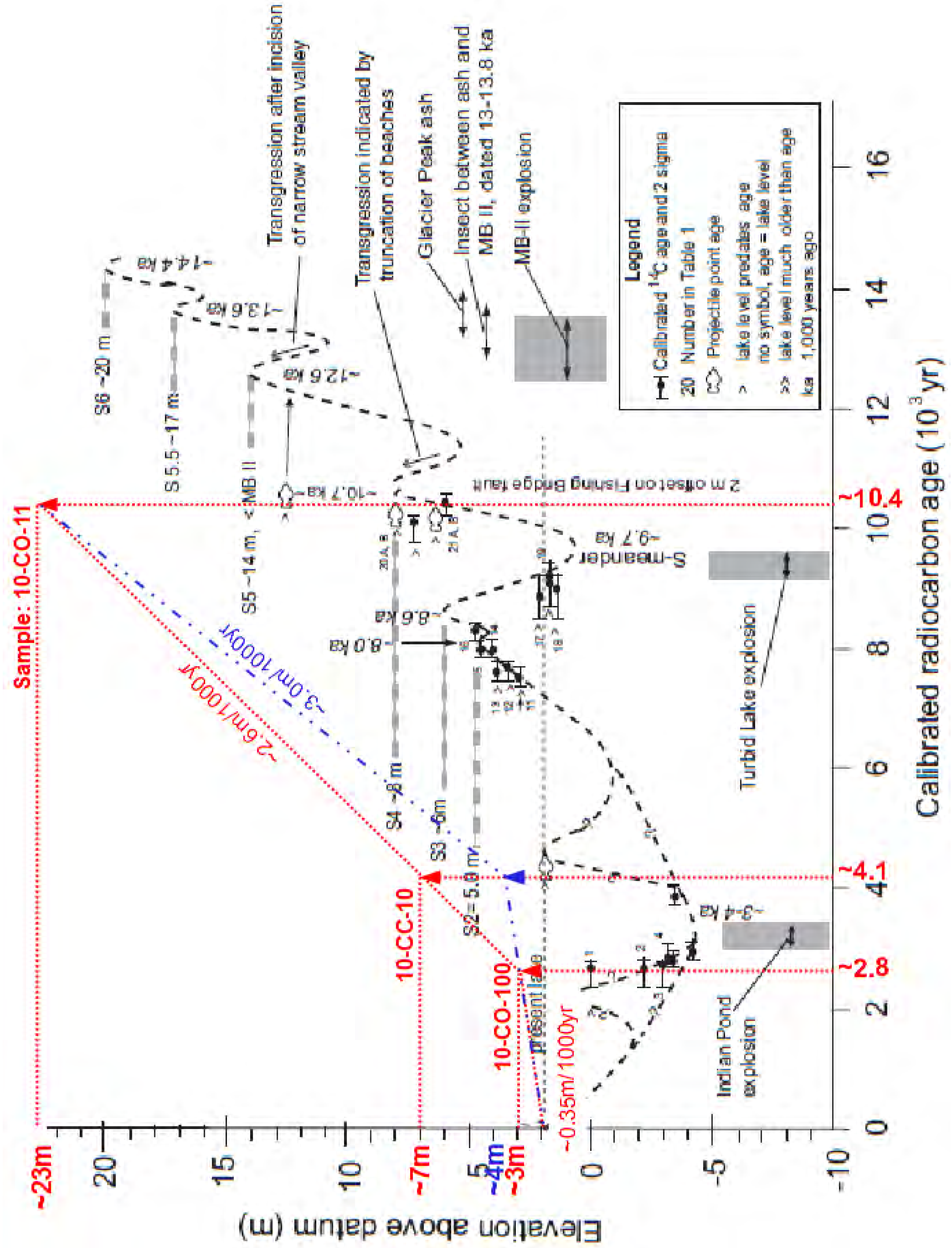


FIGURE 30: Comparison of a lake level models based on data from this study (blue/red) to the lake level model published by Pierce et al. (2002, 2007). The red model assumes that the deposits in the Clear Creek section 3 are lacustrine sediments and therefore lake level was at or near the top of the section and the upper terrace there (7-10m amll; Fig. 21); The blue model assumes that the fine-grained deposits are of fluvial origin and the river level and lake level was ~ 2m above the present level.

4 SUMMARY AND RECOMMENDATIONS

Based on preliminary sedimentologic, geomorphologic, and geochronologic information resulting from the 2010 and 2011 field seasons, we conclude the following:

1) The broad, triangular-shaped bench immediately up slope from the mouth of Alluvium Creek and bounded to the north by Columbine Creek is the preserved remnant of a Gilbert-style fan-delta that was actively constructing ~10ka, around the Pleistocene-Holocene boundary.
2) The elevation of documented topset to foreset transition near the youngest part of the Gilbert-style fan-delta requires a lake surface elevation ~21m higher than present, relative to the ground surface, around 10ka, based on radiocarbon dating of proximal fan-deltaic sediments near the fan apex.
3) A similar morphologic feature west of Trail Creek is also interpreted as a Gilbert style fan delta. Its topset to foreset transition occurs at exactly the same elevation as at the Alluvium Creek site, thus was likely responding to a similar lake level history as the Alluvium Creek Gilbert delta.
4) A series of constructional beach ridges near NPS campsite 5E9 are well-preserved, as much as 10m above the modern lake surface elevation, and very similar in sedimentary style to the modern beach in this area.
5) Radiocarbon dating of charcoal from flood plain deposits exposed in an abandoned channel near the mouth of Columbine Creek indicates active fluvial deposition ~2m above modern Columbine Creek elevation by ~2.8ka.
6) Radiocarbon dating of muddy sediment exposed along an erosionally-terraced portion of Clear Creek indicate deposition in a low energy environment we infer to be either standing water on the Clear Creek flood plain or water associated with a higher stand of Yellowstone Lake.
7) Radiocarbon dating of the Clear Creek muddy sediments indicate a higher base level (lake surface elevation) of at least ~2m and possibly >5m at ~4.1ka, followed by lowering of base level and incision to form the modern terraces associated with the Clear Creek study site.
8) We recommend that future work in the area provide for additional documentation of the sedimentology and sedimentary architecture associated with the Alluvium Creek fan-delta, the Trail Creek fan delta, and the Clear Creek 3 locations and concentrated effort investigating the geomorphology,

sedimentology, and stratigraphy of the shoreline region around the Southeast Arm of Lake Yellowstone.

9) We recommend the initiation of a sediment coring program for selected locations that were formerly connected to Yellowstone Lake during higher lake levels. These locations should include small lakes and swamps at elevations up to 21m above the modern-day lake surface. Coupled with sedimentologic analyses, dateable material from these sites would provide temporal constraints on their separation from the open lake, thus providing additional information about the lake level history of Yellowstone Lake.

5 REFERENCES

Gilbert, G.K., 1885, The topographic features of lake shores. Annual Report of the United States Geological Survey 5, p. 75-123.

Gilbert, G.K., 1890, Lake Bonneville. Monograph of the United States Geological Survey 1, 438p.

Huerta, M.A., Whitlock, C., Yale, J., 2009, Holocene vegetation–fire–climate linkages in northern Yellowstone National Park, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 271, p. 170-181.

Locke, W.W., Meyer, G.A., 1994, A 12,000-year record of vertical deformation across the Yellowstone caldera margin: The shorelines of Yellowstone Lake. Journal of Geophysical Research 99, p. 20079-20094

Meyer, G.A., Wells, S.G., Timothy Jull, A.J., 1995, Fire and alluvial chronology in Yellowstone National park: Climatic and intrinsic controls on Holocene geomorphic processes. Geological Society of America Bulletin 107, p. 1211-1230.

Millspaugh, S.H., Whitlock, C., Bartlein, P.J., 2000, Variations in fire frequency and climate over the past 17000 yr in central Yellowstone National Park. Geology 28, p. 211-214.

Morgan, L.A., Shanks, W.C., Lee, G.K., Webring, M.W., 2007, Bathymetry and ecology of the floor of Yellowstone Lake, Yellowstone National Park, Wyoming, Idaho, and Montana. U.S. Geological Survey Scientific Investigations Map 2973.

Nemec, W., 1990, Aspects of sediment movement on steep delta slopes. In: Colella, A., Prior, D.B., eds., Coarse grained deltas. Special Publication of the International Association of Sedimentologists 10, p.29-73.

Pierce, K.L., Cannon, K.P.,Meyer, .A., Trebesch, M.J., Watts, R.D., 2002, Postglacial Inflation-Deflation Cycles, Tilting, and Faulting in the Yellowstone Caldera Based on Yellowstone Lake Shorelines. U.S. Geological Survey Open File Report 02-0142, 62p.

Pierce, K.L., Cannon, K.P.,Meyer, .A., Trebesch, M.J., Watts, R.D., 2007, Postglacial Inflation-Deflation Cycles, Tilting, and Faulting in the Yellowstone Caldera Based on Yellowstone Lake Shorelines, in Morgan, L.A., ed., Integrated Geoscience Studies in the Greater Yellowstone Area— Volcanic, Tectonic, and Hydrothermal Processes in the Yellowstone Geoecosystem. U.S. Geological Survey Professional paper 1717, p. 131-168.

Richmond, G.M., Pierce, K.L., 1972, Surficial Geologic Map of the Eagle Peak Quadrangle, Yellowstone National Park and adjoining area, Wyoming. U.S. Geological Survey

6 APPENDICES

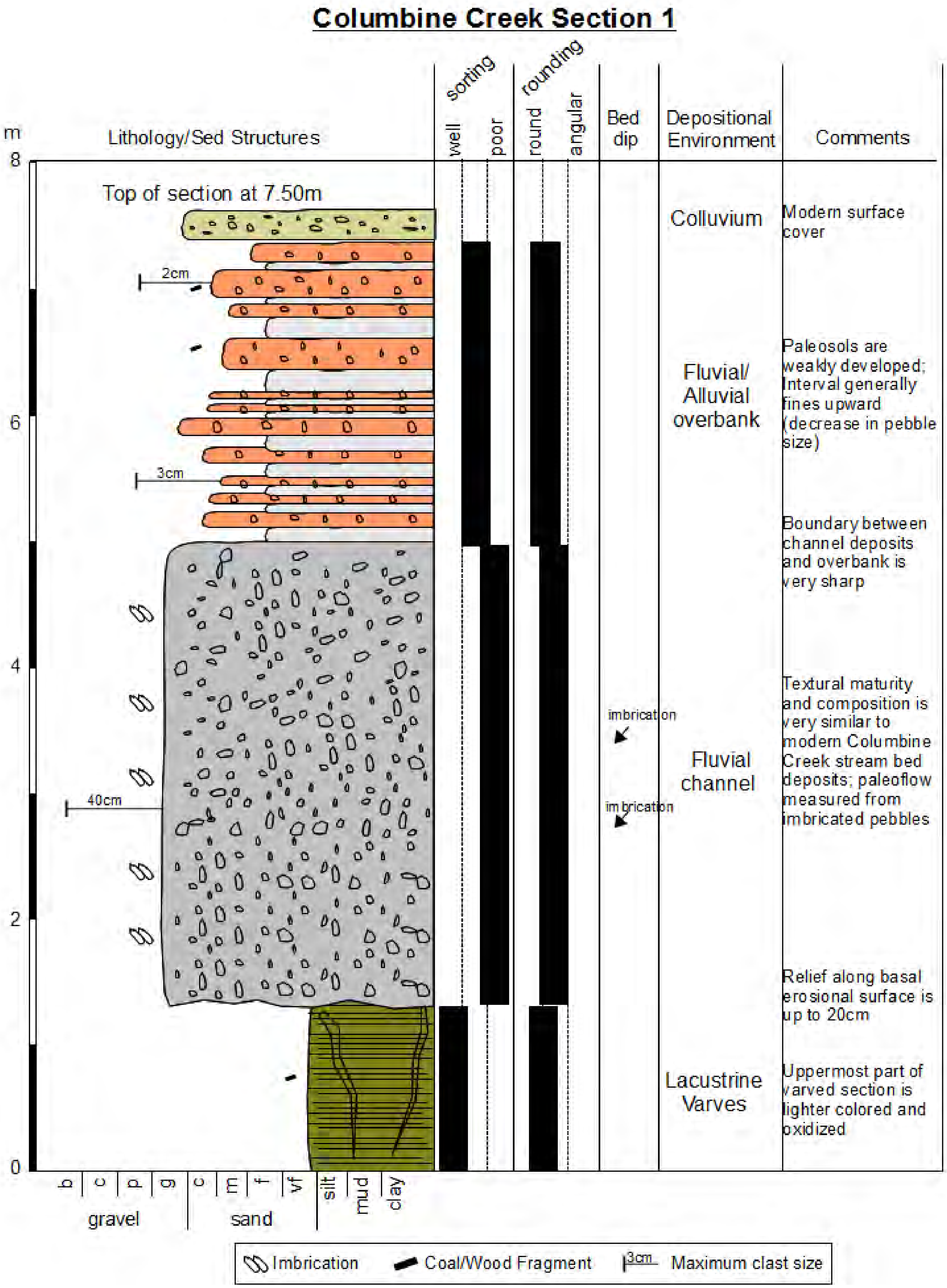
Appendix A: Data of Total Station Surveys

Total Station transect CO-AC			
Station	**x**	**y**	**z**
HOME2	9992.109	9904.504	992.914
BS1	9980.343	9938.349	996.175
BS2	9997.172	9963.489	994.741
BS3	9985.545	9886.02	992.421
BS4	9991.653	9998.187	999.764
T0001	10057.26	10057.395	1000.767
T0002	10054.996	10055.325	1000.748
T0003	10053.501	10053.923	1000.426
T0004	10052.39	10052.831	1000.047
T0005	10050.978	10051.289	999.452
T0006	10049.668	10049.876	998.904
T0007	10048.455	10048.547	998.29
T0008	10047.541	10047.542	997.641
T0009	10046.632	10046.652	996.972
T0010	10045.795	10045.9	996.339
T0011	10044.704	10045.058	995.71
T0012	10043.972	10044.424	995.391
T0013	10043.564	10043.891	995.158
T0014	10041.984	10041.663	994.944
T0015	10039.844	10039.895	995.068
T0016	10036.931	10037.398	995.556
T0017	10034.117	10034.429	995.825
T0018	10030.483	10030.483	996.301
T0019	10026.96	10026.708	997.208
T0020	10022.492	10021.965	997.921
T0021	10019.108	10018.596	998.722
T0022	10016.757	10016.329	999.484
T0023	10014.523	10014.003	1000.134
T0024	10010.872	10011.219	1000.335
T0025	10005.947	10006.878	999.841
T0026	10001.594	10002.105	1000.062
T0027	9996.179	9996.368	999.857
T0028	9992.967	9992.374	999.122
T0029	9990.958	9990.186	998.622
T0030	9989.514	9988.796	997.78
T0031	9988.446	9987.76	997.136
T0032	9986.938	9986.745	996.357
T0033	9985.399	9985.582	995.678
T0034	9984.618	9984.996	995.46
T0035	9982.554	9984.654	995.392
T0036	9981.744	9983.9	995.194
T0037	9979.621	9982.308	995.08
T0038	9977.604	9980.521	995.064
T0039	9975.046	9978.912	995.28
T0040	9972.795	9977.71	996.139
T0041	9971.312	9976.793	997.201
T0042	9969.758	9976.238	998.196
T0043	9967.989	9974.539	999.025
T0044	9965.997	9973.115	999.588
T0045	9962.87	9970.878	999.74
T0046	9960.1	9966.953	999.377
TOPMUD001	10040.019	10055.107	995.412
TOPMUD002	10039.763	10055.843	995.424
TOPMUD003	10039.436	10057.099	995.625
TOPMUD004	10038.844	10058.695	995.488
TOPMUD005	10036.383	10062.696	995.664

Total Station transect CO								
Station	x	y	z		Station	x	y	z
TRANSECT0001	9993.143	9985.921	999.693		TRANSECT0054	10067.56	10063.25	1001.789
TRANSECT0002	9886.368	9811.122	995.284		TRANSECT0055	10072.15	10066.96	1002.149
TRANSECT0003	9886.743	9811.941	995.376		TRANSECT0056	10076.84	10071.49	1002.273
TRANSECT0004	9887.243	9812.937	995.623		TRANSECT0057	10080.64	10076.42	1002.53
TRANSECT0005	9887.519	9813.439	995.697		TRANSECT0058	10085.7	10082.64	1002.632
TRANSECT0006	9887.955	9814.369	996.032		TRANSECT0059	10090.07	10088.53	1002.744
TRANSECT0007	9888.673	9815.847	996.182		TRANSECT0060	10096.29	10094.62	1003.126
TRANSECT0008	9890.147	9818.733	995.73		TRANSECT0061	10102.47	10100.8	1003.441
TRANSECT0009	9891.758	9822.084	995.851		TRANSECT0062	10108.52	10106.66	1003.743
TRANSECT0010	9895.518	9826.392	996.091		TRANSECT0063	10114.03	10111.87	1003.997
TRANSECT0011	9898.371	9831.554	996.276		TRANSECT0064	10120.4	10118	1004.483
TRANSECT0012	9901.483	9836.351	996.362		TRANSECT0065	10124.32	10123.28	1004.797
TRANSECT0013	9905.006	9841.775	996.491		TRANSECT0066	10129.27	10127.52	1005.31
TRANSECT0014	9908.023	9846.616	996.568		TRANSECT0067	10135.3	10133.35	1005.425
TRANSECT0015	9910.879	9852.655	996.787		TRANSECT0068	10141.76	10139.3	1005.675
TRANSECT0016	9914.444	9858.42	996.976		TRANSECT0069	10148.26	10144.3	1006.061
TRANSECT0017	9917.931	9864.069	997.242		TRANSECT0070	10154.28	10149.56	1006.745
TRANSECT0018	9921.309	9869.347	997.523		TRANSECT0071	10158.1	10152.58	1007.249
TRANSECT0019	9923.819	9874.017	997.591		TRANSECT0072	10163.5	10157.47	1008.203
TRANSECT0020	9925.552	9877.098	997.477		TRANSECT0073	10169.51	10162.69	1008.953
TRANSECT0021	9928.144	9881.915	997.739		TRANSECT0074	10175.04	10167.06	1009.683
TRANSECT0022	9931.439	9887.393	997.935		TRANSECT0075	10179.09	10170.31	1010.455
TRANSECT0023	9934.842	9892.889	998.14		TRANSECT0076	10183.34	10173.75	1011.597
TRANSECT0024	9938.069	9899.589	998.37		TRANSECT0077	10187.34	10176.63	1012.547
TRANSECT0025	9940.978	9905.573	998.519		TRANSECT0078	10192.92	10180.55	1013.455
TRANSECT0026	9943.974	9912.121	998.55		TRANSECT0079	10199.38	10185.26	1014.329
TRANSECT0027	9945.887	9916.367	998.488		TRANSECT0080	10206.31	10189.58	1014.99
TRANSECT0028	9947.392	9919.828	998.26		TRANSECT0081	10211.98	10194.76	1015.769
TRANSECT0029	9947.784	9921.105	998.256		TRANSECT0082	10218.88	10199.96	1016.565
TRANSECT0030	9951.263	9926.838	998.115		TRANSECT0083	10224.41	10205.05	1017.465
TRANSECT0031	9955.563	9932.716	998.172		TRANSECT0084	10230.95	10210.72	1018.351
TRANSECT0032	9960.941	9935.923	998.223		TRANSECT0085	10230.95	10210.67	1018.324
TRANSECT0033	9963.675	9940.616	998.3		TRANSECT0086	10237.2	10215.95	1019.07
TRANSECT0034	9966.409	9945.009	998.731		TRANSECT0087	10242.64	10220.58	1019.858
TRANSECT0035	9968.608	9950.494	999.065		TRANSECT0088	10248.91	10225.18	1020.837
TRANSECT0036	9971.976	9957.751	999.166		TRANSECT0089	10250.43	10227.13	1021.83
TRANSECT0037	9976.404	9964.218	998.987		TRANSECT0090	10253.64	10229.8	1022.453
TRANSECT0038	9982.975	9972.084	999.08		TRANSECT0091	10258.37	10233.86	1024.151
TRANSECT0039	9987.249	9977.949	999.275		TRANSECT0092	10264.06	10238.01	1025.319
TRANSECT0040	9991.684	9983.884	999.614		TRANSECT0093	10269.7	10242.08	1026.559
TRANSECT0041	9995.745	9989.318	999.913		TRANSECT0094	10274.55	10247.42	1027.961
TRANSECT0042	10000.21	9994.892	1000.125		TRANSECT0095	10276.15	10256.87	1028.564
TRANSECT0043	10004.47	10001.11	1000.178		TRANSECT0096	10279.35	10260.79	1028.783
TRANSECT0044	10009.19	10007.97	999.974		TRANSECT0097	10115.09	10147.39	1004.909
TRANSECT0045	10014.69	10014.61	999.707		TRANSECT0098	10118.44	10150.13	1005.278
TRANSECT0046	10021.52	10019.31	999.956		TRANSECT0099	10122.98	10154.65	1005.429
TRANSECT0047	10027.06	10026.05	1000.063		TRANSECT0100	10101.16	10162.44	1004.814
TRANSECT0048	10033.52	10031.84	1000.386		TRANSECT0101	10104.62	10167.34	1005.548
TRANSECT0049	10039.91	10037.22	1000.617		TRANSECT0102	10111.3	10176.34	1005.758
TRANSECT0050	10046.02	10041.76	1000.778		TRANSECT0103	10083.53	10178.98	1004.775
TRANSECT0051	10052.36	10047.24	1000.812		TRANSECT0104	10088.15	10185.6	1005.667
TRANSECT0052	10058.06	10053.28	1001.145		TRANSECT0105	10091.56	10192.1	1005.796
TRANSECT0053	10063.26	10059.25	1001.498		TRANSECT0106	9993.137	9985.921	999.692

Appendix B: Logs of stratigraphic sections Columbine Creek/Alluvium Creek

B-1: Columbine Creek Section 1



Modern surface cover

Paleosols are weakly developed; Interval generally fines upward (decrease in pebble size)

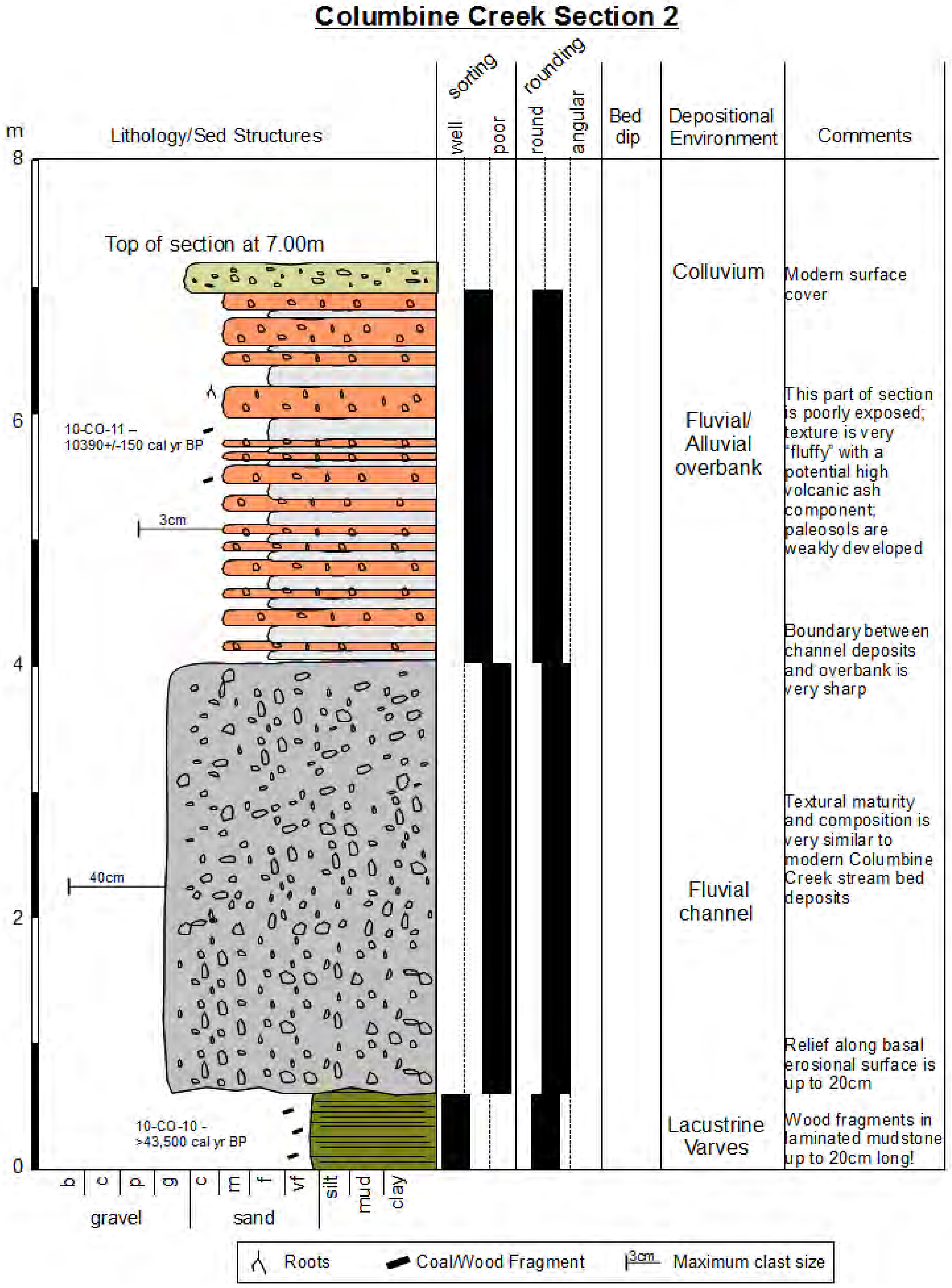
Boundary between channel deposits and overbank is very sharp

Textural maturity and composition is very similar to modern Columbine Creek stream bed deposits; paleoflow measured from imbricated pebbles

Relief along basal erosional surface is up to 20cm

Uppermost part of varved section is lighter colored and oxidized

B-2: Columbine Creek Section 2



Columbine Creek Section 2

Modern surface cover

This part of section is poorly exposed; texture is very "fluffy" with a potential high volcanic ash component; paleosols are weakly developed

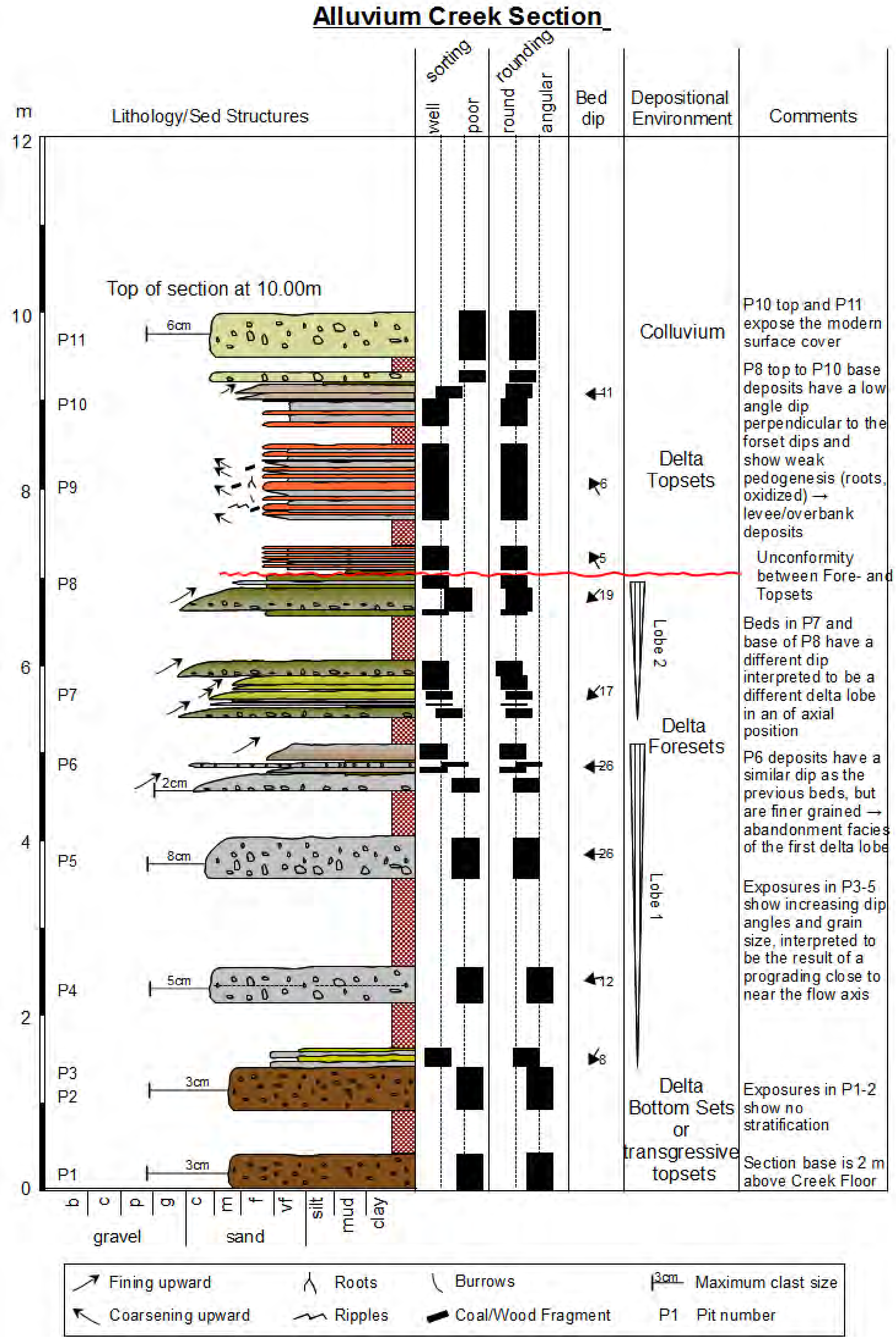
Boundary between channel deposits and overbank is very sharp

Textural maturity and composition is very similar to modern Columbine Creek stream bed deposits

Relief along basal erosional surface is up to 20cm

Wood fragments in laminated mudstone up to 20cm long!

B-3: Alluvium Creek Section



P10 top and P11 expose the modern surface cover

P8 top to P10 base deposits have a low angle dip perpendicular to the forset dips and show weak pedogenesis (roots, oxidized) → levee/overbank deposits

Unconformity between Fore- and Topsets

Beds in P7 and base of P8 have a different dip interpreted to be a different delta lobe in an of axial position

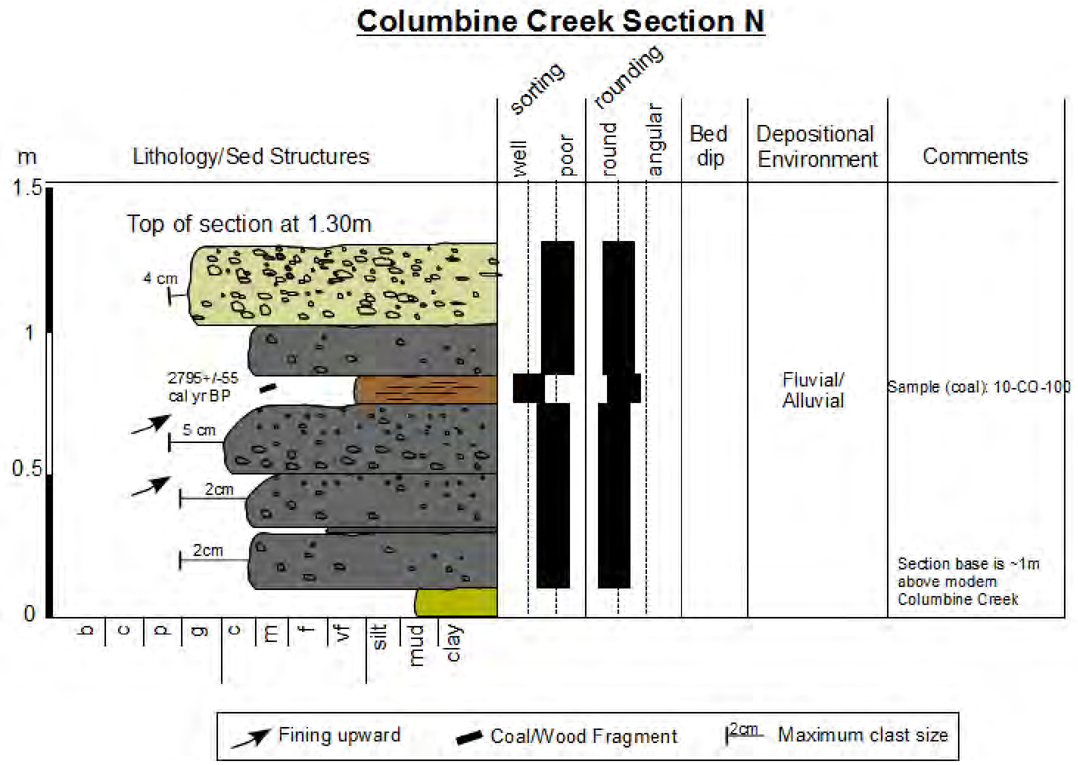
P6 deposits have a similar dip as the previous beds, but are finer grained → abandonment facies of the first delta lobe

Exposures in P3-5 show increasing dip angles and grain size, interpreted to be the result of a prograding close to near the flow axis

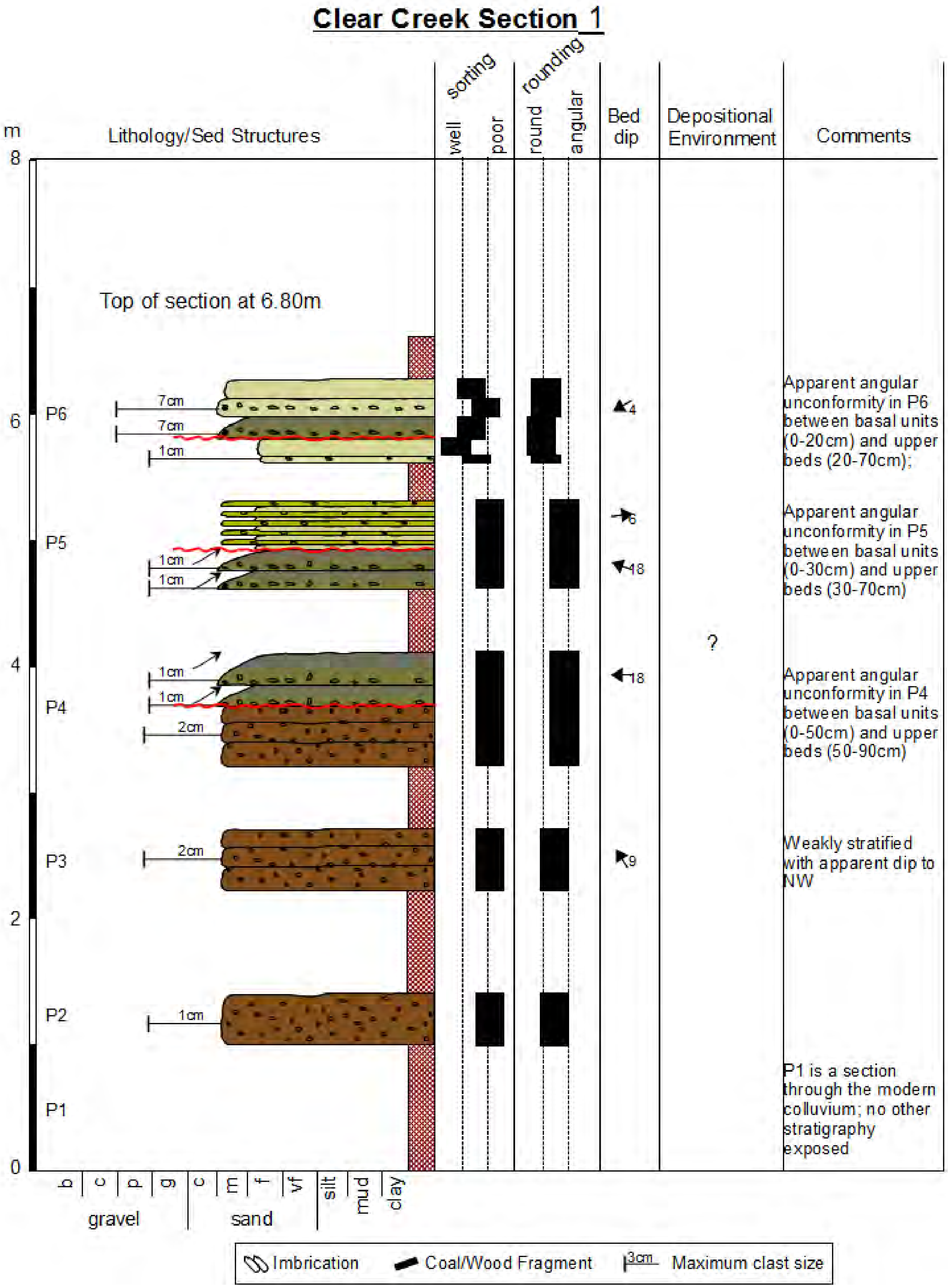
Exposures in P1-2 show no stratification

Section base is 2 m above Creek Floor

B-4: Columbine Creek Section N



Appendix C: Logs of stratigraphic sections Clear Creek
C-1: Clear Creek Section 1



Apparent angular unconformity in P6 between basal units (0-20cm) and upper beds (20-70cm);

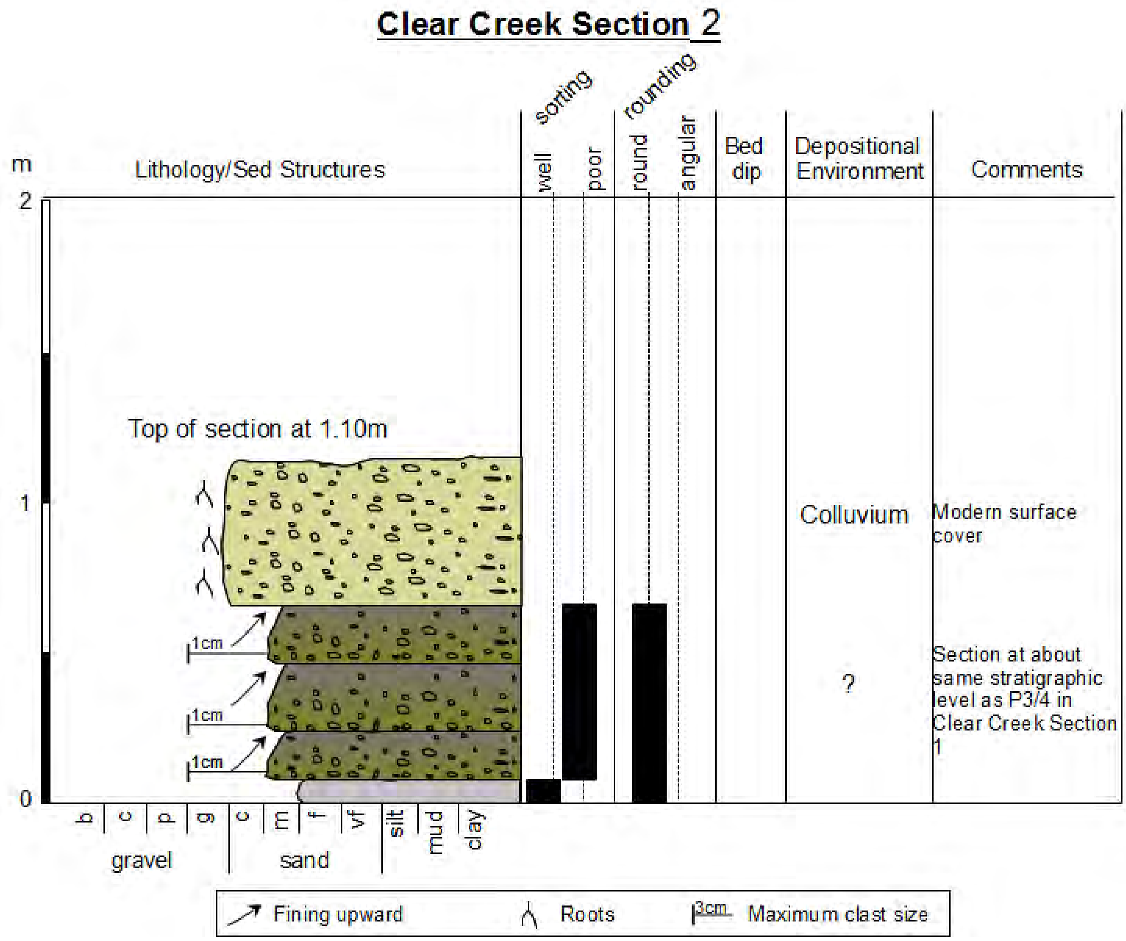
Apparent angular unconformity in P5 between basal units (0-30cm) and upper beds (30-70cm)

Apparent angular unconformity in P4 between basal units (0-50cm) and upper beds (50-90cm)

Weakly stratified with apparent dip to NW

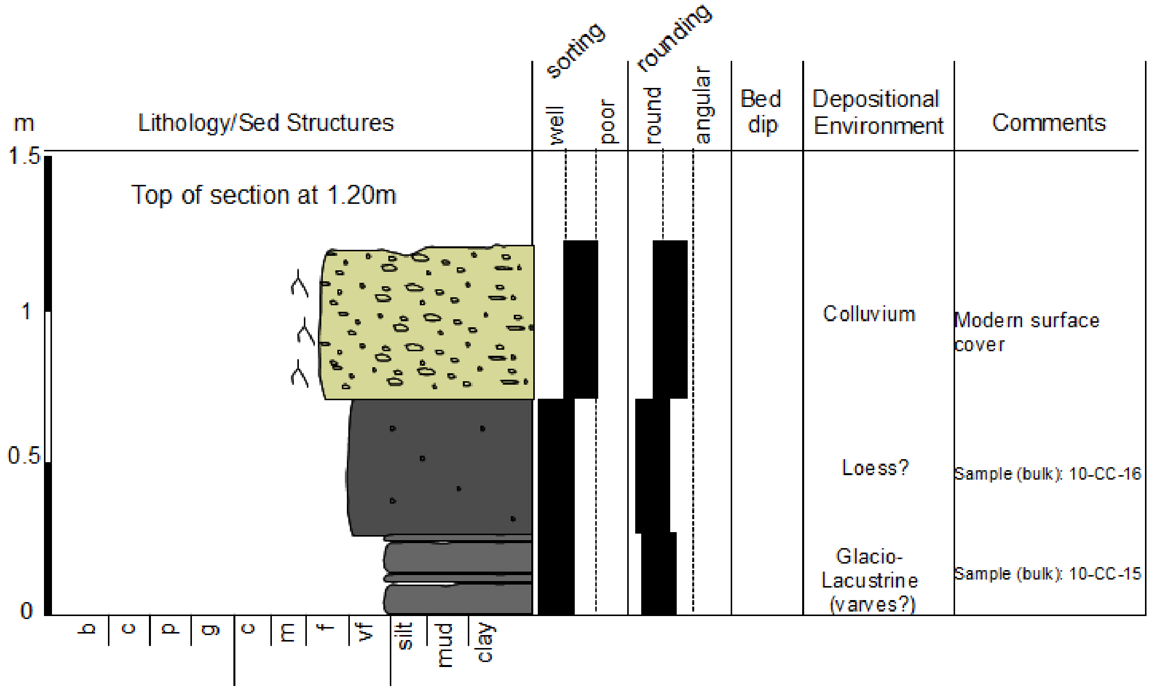
P1 is a section through the modern colluvium; no other stratigraphy exposed

C-2: Clear Creek Section 2

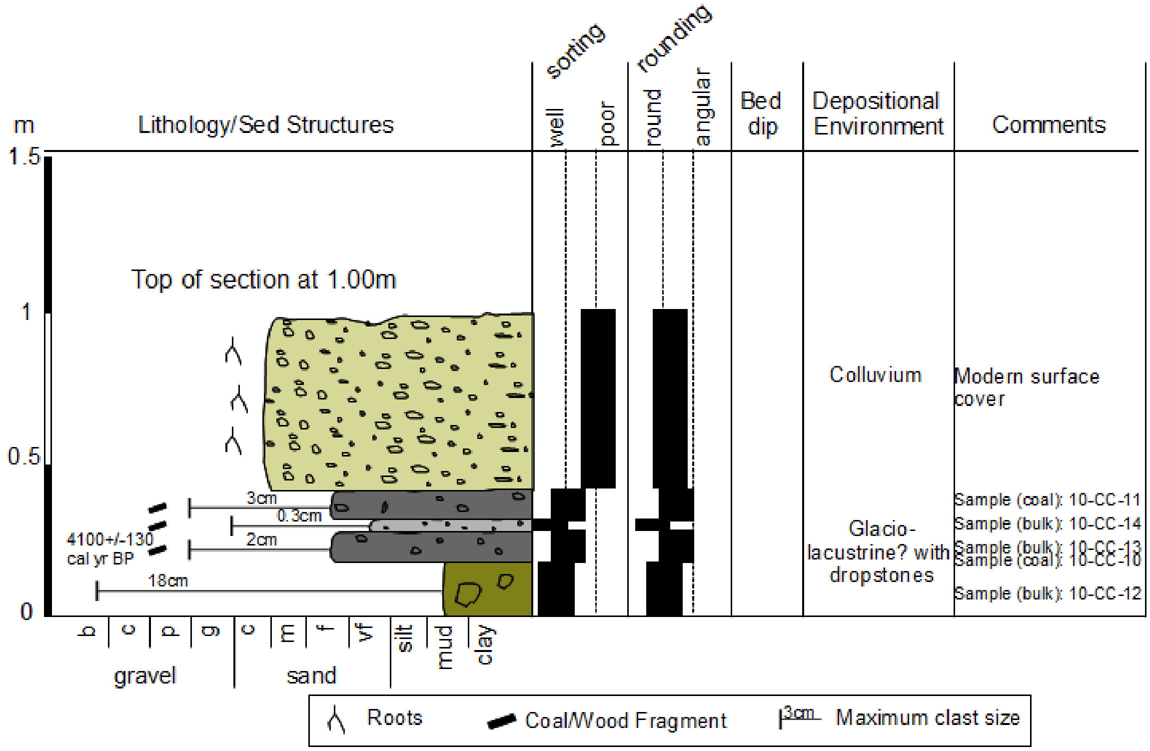


C-3: Clear Creek Section 3

Clear Creek Section 3 (upper pit)

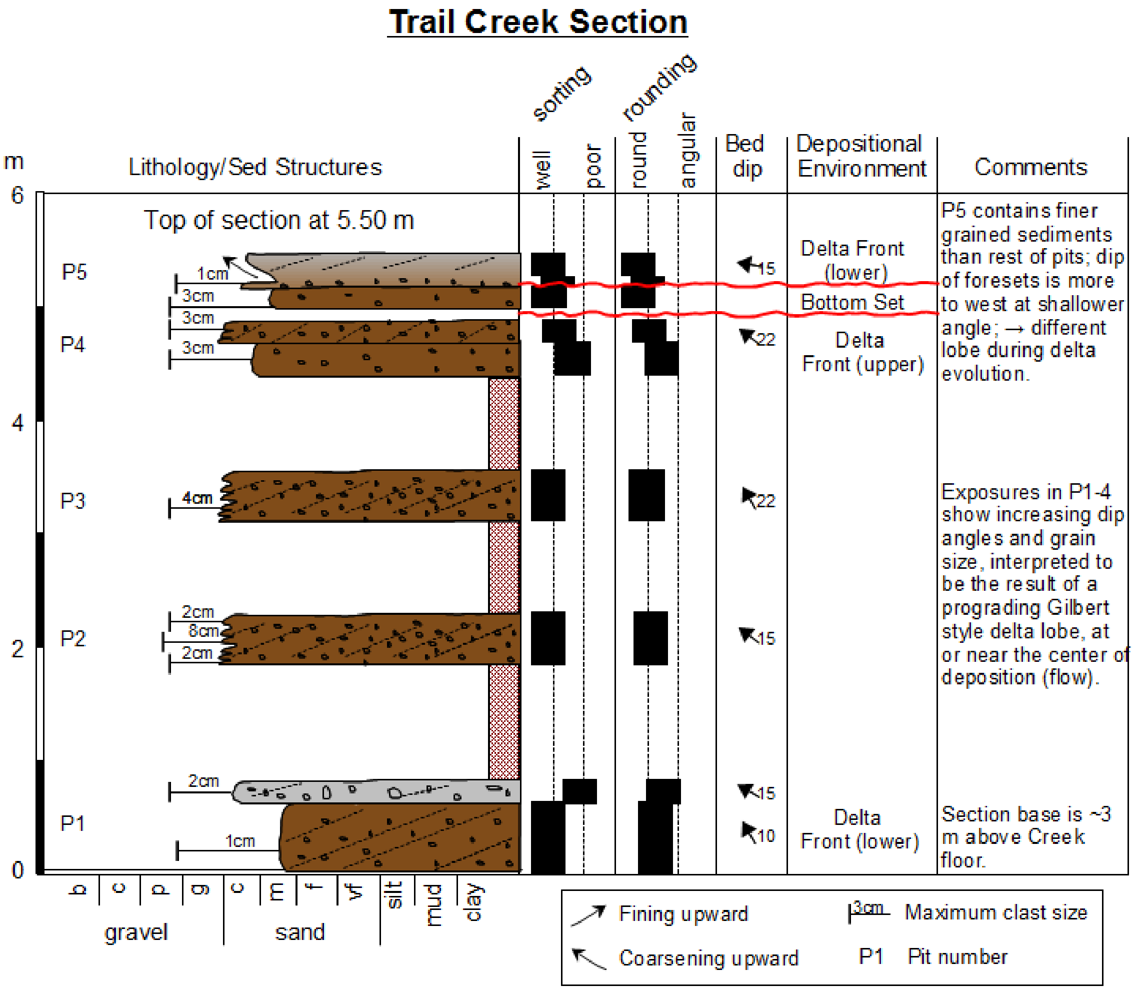


Clear Creek Section 3 (lower pit)

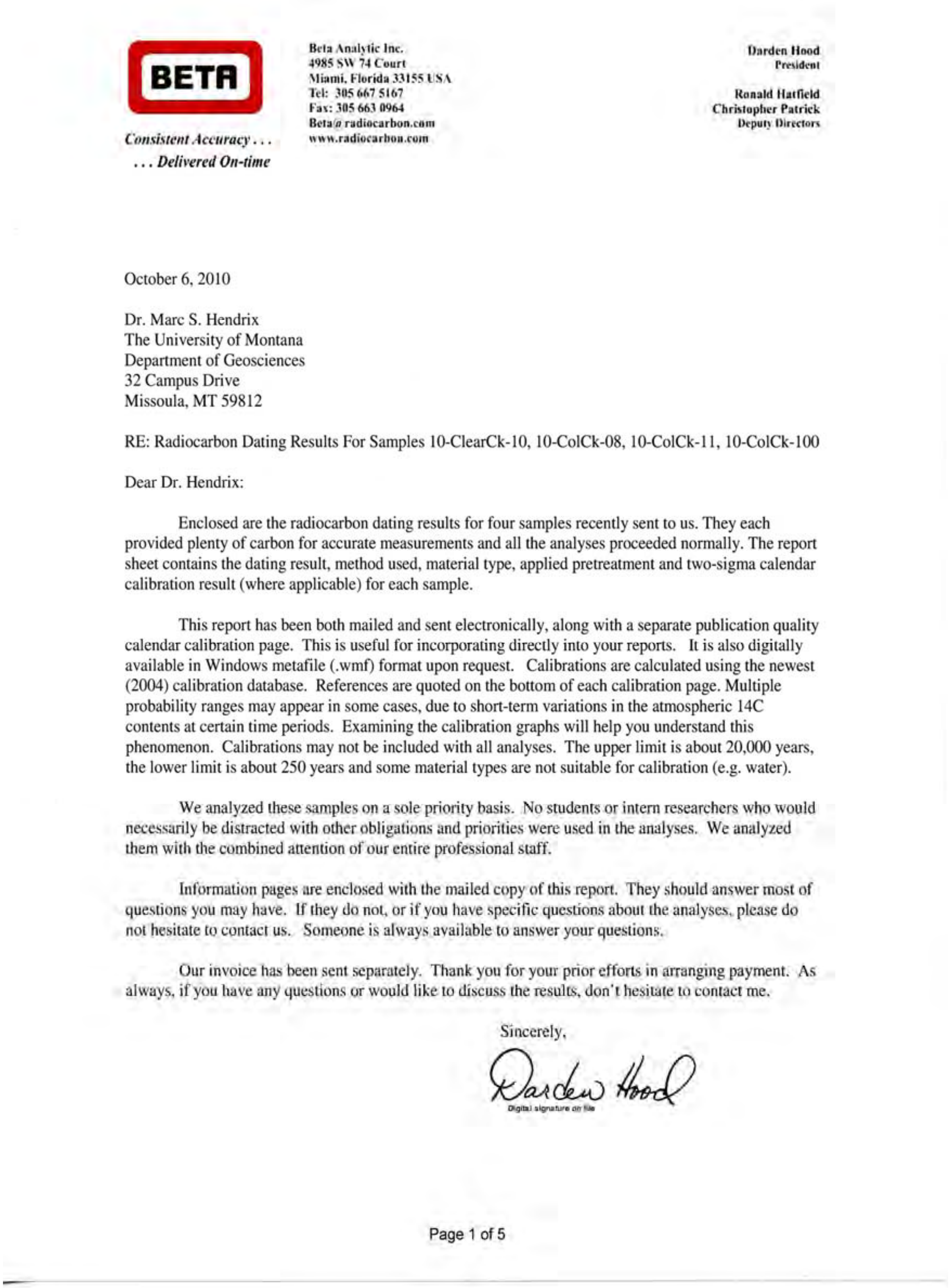


Appendix D: Logs of stratigraphic sections Trail Creek

D-1: Trail Creek Section 1



Appendix E:



BETA

Consistent Accuracy . . .
. . . Delivered On-time

Beta Analytic Inc.
4985 SW 74 Court
Miami, Florida 33155 USA
Tel: 305 667 5167
Fax: 305 663 0964
Beta@radiocarbon.com
www.radiocarbon.com

Darden Hood
President

Ronald Hatfield
Christopher Patrick
Deputy Directors

October 6, 2010

Dr. Marc S. Hendrix
The University of Montana
Department of Geosciences
32 Campus Drive
Missoula, MT 59812

RE: Radiocarbon Dating Results For Samples 10-ClearCk-10, 10-ColCk-08, 10-ColCk-11, 10-ColCk-100

Dear Dr. Hendrix:

Enclosed are the radiocarbon dating results for four samples recently sent to us. They each provided plenty of carbon for accurate measurements and all the analyses proceeded normally. The report sheet contains the dating result, method used, material type, applied pretreatment and two-sigma calendar calibration result (where applicable) for each sample.

This report has been both mailed and sent electronically, along with a separate publication quality calendar calibration page. This is useful for incorporating directly into your reports. It is also digitally available in Windows metafile (.wmf) format upon request. Calibrations are calculated using the newest (2004) calibration database. References are quoted on the bottom of each calibration page. Multiple probability ranges may appear in some cases, due to short-term variations in the atmospheric 14C contents at certain time periods. Examining the calibration graphs will help you understand this phenomenon. Calibrations may not be included with all analyses. The upper limit is about 20,000 years, the lower limit is about 250 years and some material types are not suitable for calibration (e.g. water).

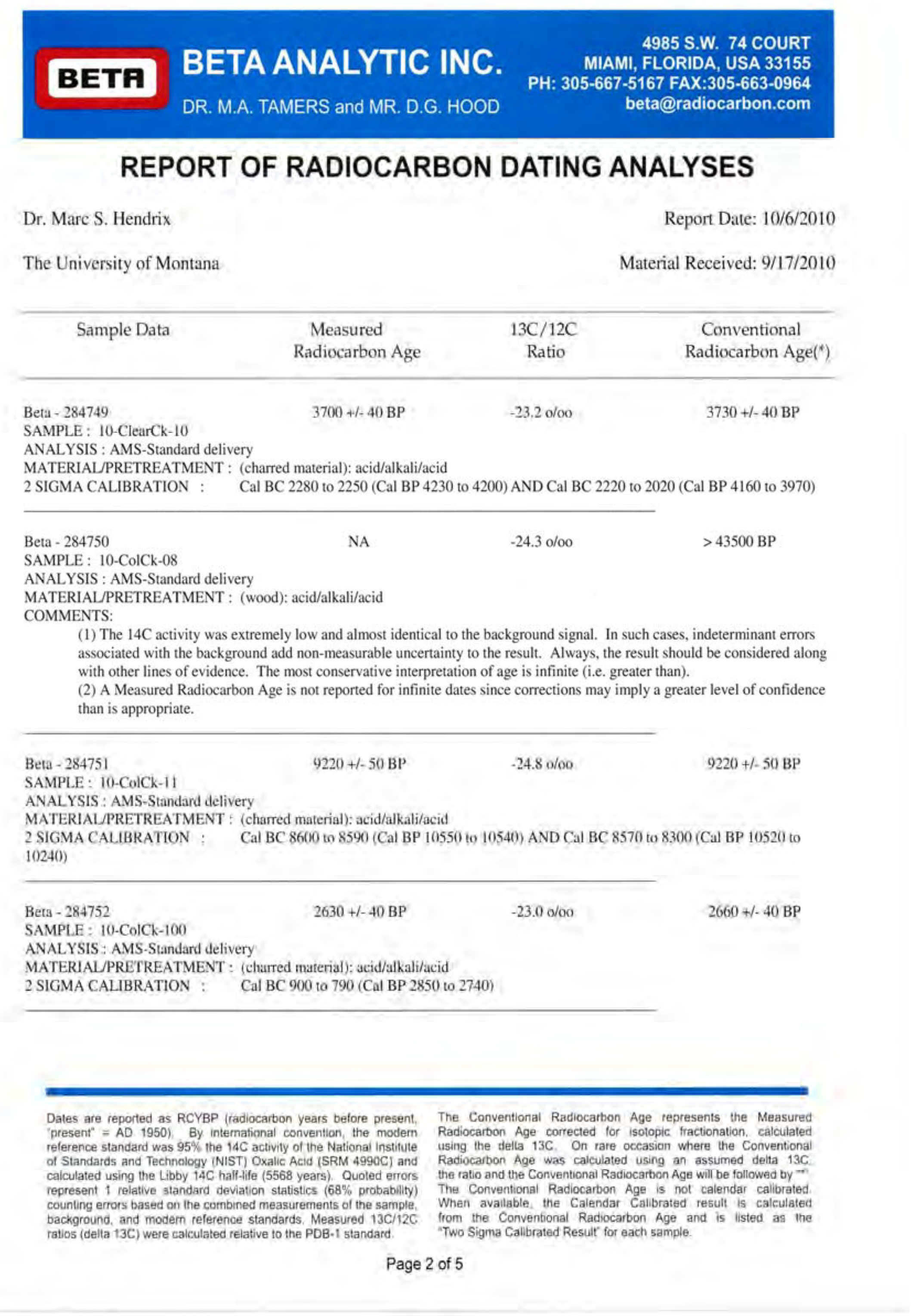
We analyzed these samples on a sole priority basis. No students or intern researchers who would necessarily be distracted with other obligations and priorities were used in the analyses. We analyzed them with the combined attention of our entire professional staff.

Information pages are enclosed with the mailed copy of this report. They should answer most of questions you may have. If they do not, or if you have specific questions about the analyses, please do not hesitate to contact us. Someone is always available to answer your questions.

Our invoice has been sent separately. Thank you for your prior efforts in arranging payment. As always, if you have any questions or would like to discuss the results, don't hesitate to contact me.

Sincerely,

Darden Hood
Digital signature on file



BETA ANALYTIC INC.

DR. M.A. TAMERS and MR. D.G. HOOD

4985 S.W. 74 COURT
MIAMI, FLORIDA, USA 33155
PH: 305-667-5167 FAX:305-663-0964
beta@radiocarbon.com

REPORT OF RADIOCARBON DATING ANALYSES

Dr. Marc S. Hendrix
The University of Montana

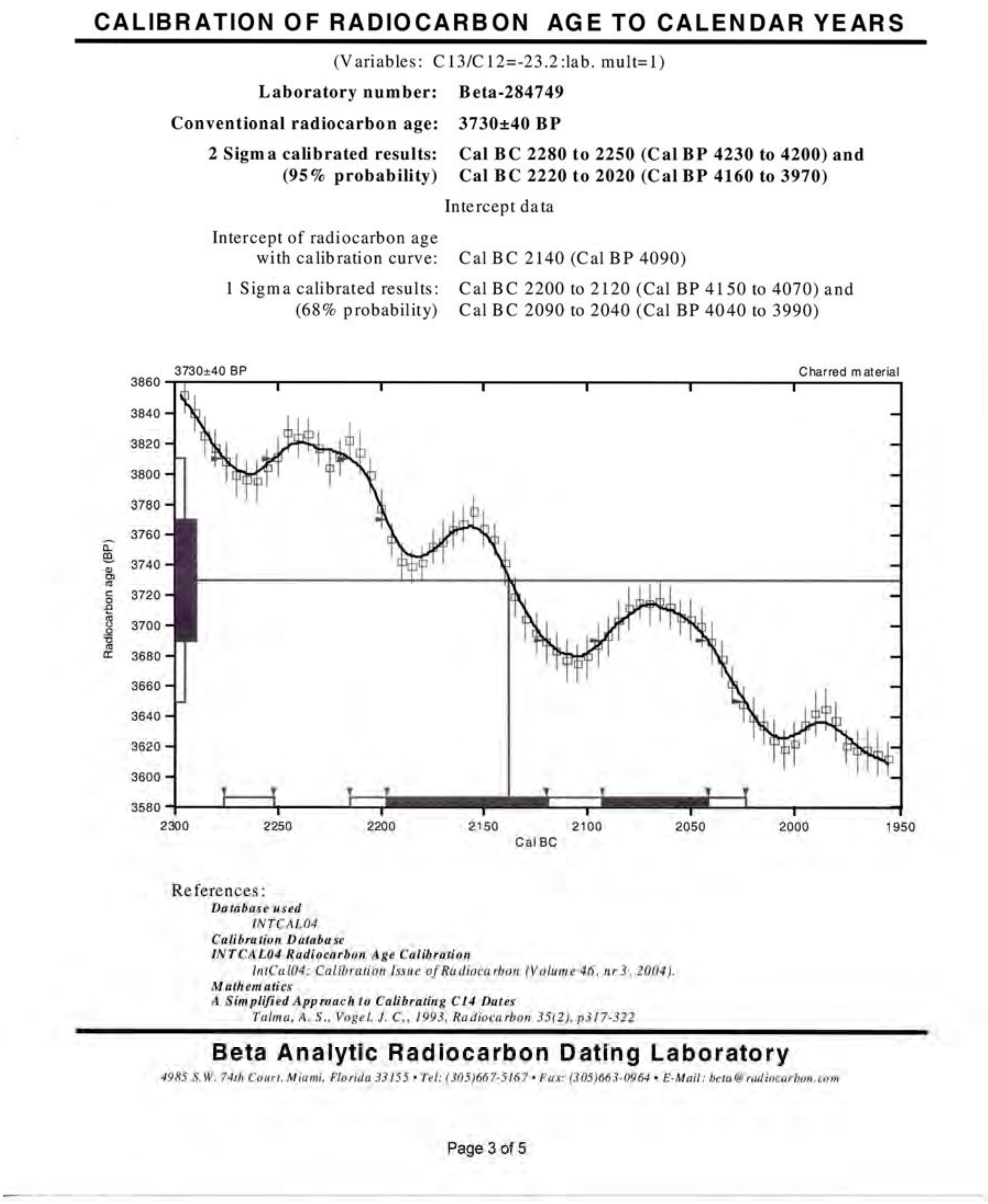
Report Date: 10/6/2010
Material Received: 9/17/2010

Sample Data	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age(*)
Beta - 284749 SAMPLE : 10-ClearCk-10 ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 2280 to 2250 (Cal BP 4230 to 4200) AND Cal BC 2220 to 2020 (Cal BP 4160 to 3970)	3700 +/- 40 BP	-23.2 o/oo	3730 +/- 40 BP
Beta - 284750 SAMPLE : 10-ColCk-08 ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (wood): acid/alkali/acid COMMENTS: (1) The 14C activity was extremely low and almost identical to the background signal. In such cases, indeterminant errors associated with the background add non-measurable uncertainty to the result. Always, the result should be considered along with other lines of evidence. The most conservative interpretation of age is infinite (i.e. greater than). (2) A Measured Radiocarbon Age is not reported for infinite dates since corrections may imply a greater level of confidence than is appropriate.	NA	-24.3 o/oo	> 43500 BP
Beta - 284751 SAMPLE : 10-ColCk-11 ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 8600 to 8590 (Cal BP 10550 to 10540) AND Cal BC 8570 to 8300 (Cal BP 10520 to 10240)	9220 +/- 50 BP	-24.8 o/oo	9220 +/- 50 BP
Beta - 284752 SAMPLE : 10-ColCk-100 ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 900 to 790 (Cal BP 2850 to 2740)	2630 +/- 40 BP	-23.0 o/oo	2660 +/- 40 BP

Dates are reported as RCYBP (radiocarbon years before present, "present" = AD 1950). By international convention, the modern reference standard was 95% the 14C activity of the National Institute of Standards and Technology (NIST) Oxalic Acid (SRM 4990C) and calculated using the Libby 14C half-life (5568 years). Quoted errors represent 1 relative standard deviation statistics (68% probability) counting errors based on the combined measurements of the sample, background, and modern reference standards. Measured 13C/12C ratios (delta 13C) were calculated relative to the PDB-1 standard.

The Conventional Radiocarbon Age represents the Measured Radiocarbon Age corrected for isotopic fractionation, calculated using the delta 13C. On rare occasion where the Conventional Radiocarbon Age was calculated using an assumed delta 13C, the ratio and the Conventional Radiocarbon Age will be followed by "*". The Conventional Radiocarbon Age is not calendar calibrated. When available, the Calendar Calibrated result is calculated from the Conventional Radiocarbon Age and is listed as the "Two Sigma Calibrated Result" for each sample.

Page 2 of 5



CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-23.2:lab. mult=1)

Laboratory number: **Beta-284749**

Conventional radiocarbon age: **3730±40 BP**

2 Sigma calibrated results: **Cal BC 2280 to 2250 (Cal BP 4230 to 4200) and**
(95% probability) **Cal BC 2220 to 2020 (Cal BP 4160 to 3970)**

Intercept data

Intercept of radiocarbon age
with calibration curve: Cal BC 2140 (Cal BP 4090)

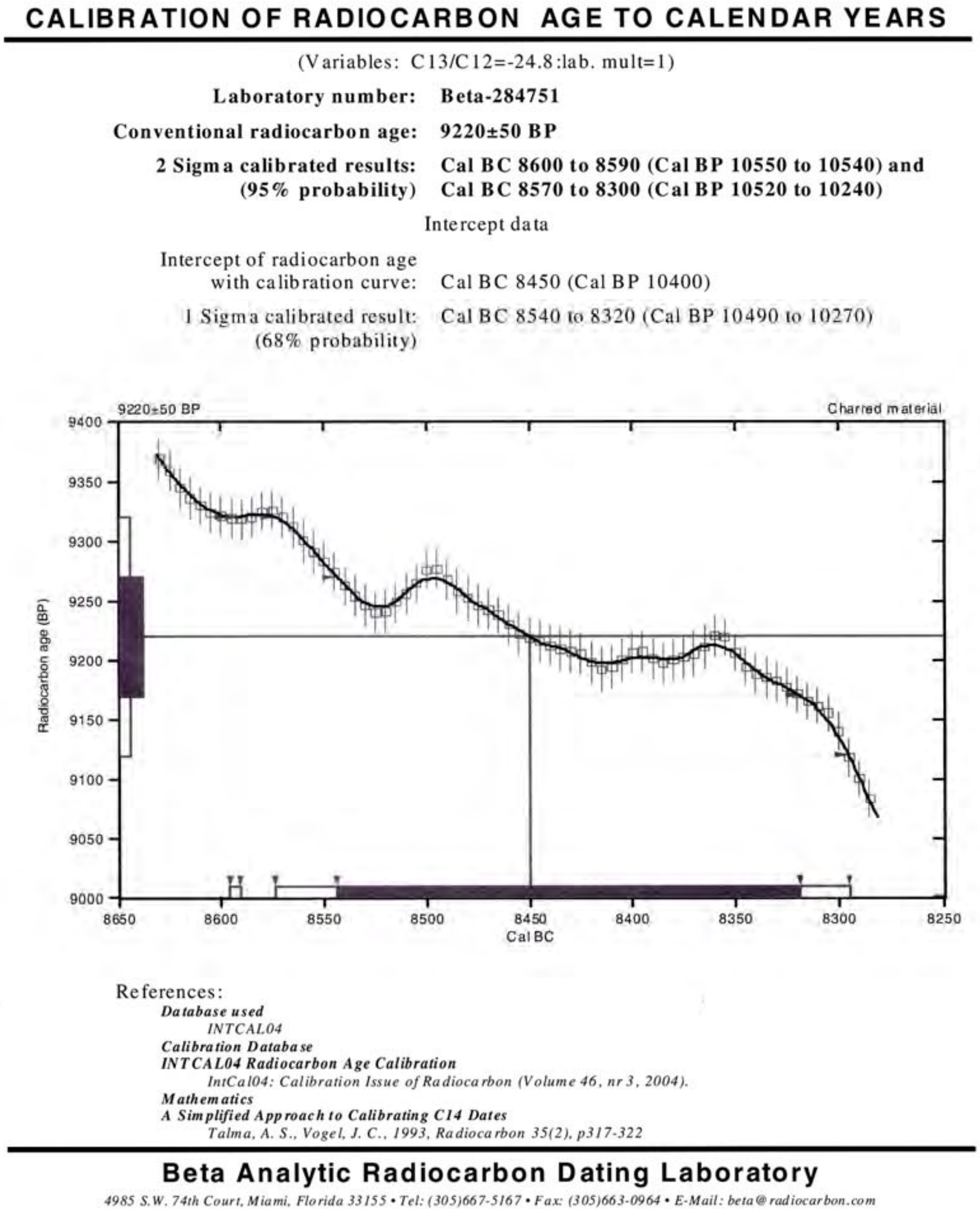
1 Sigma calibrated results: Cal BC 2200 to 2120 (Cal BP 4150 to 4070) and
(68% probability) Cal BC 2090 to 2040 (Cal BP 4040 to 3990)

References:
Database used
INTCAL04
Calibration Database
INTCAL04 Radiocarbon Age Calibration
IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).
Mathematics
A Simplified Approach to Calibrating C14 Dates
Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2), p317-322

Beta Analytic Radiocarbon Dating Laboratory

4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • E-Mail: beta@radiocarbon.com

Page 3 of 5



CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-24.8:lab. mult=1)

Laboratory number:	**Beta-284751**
Conventional radiocarbon age:	**9220±50 BP**
2 Sigma calibrated results: **(95% probability)**	**Cal BC 8600 to 8590 (Cal BP 10550 to 10540) and** **Cal BC 8570 to 8300 (Cal BP 10520 to 10240)**

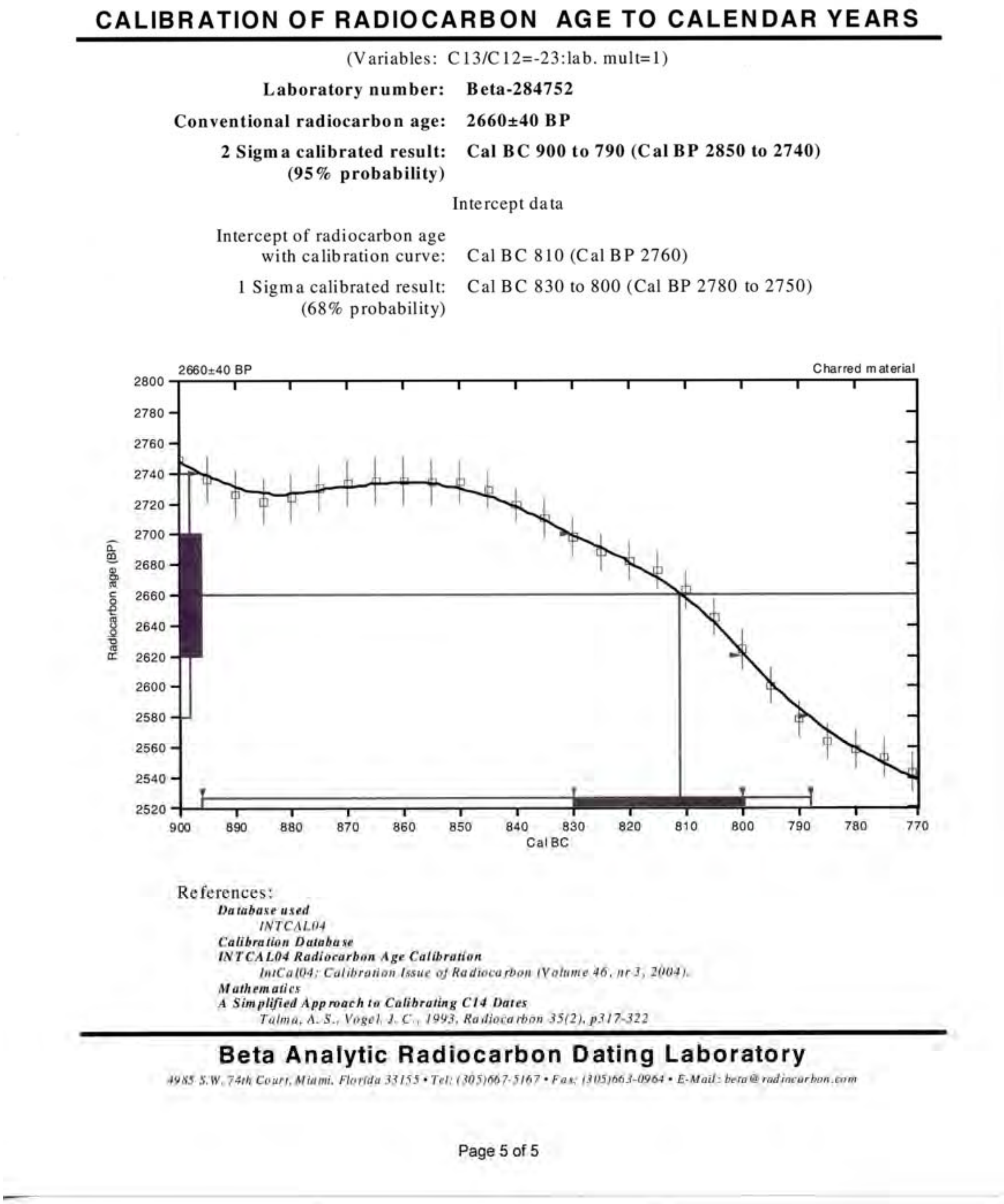
Intercept data

Intercept of radiocarbon age with calibration curve:	Cal BC 8450 (Cal BP 10400)
1 Sigma calibrated result: (68% probability)	Cal BC 8540 to 8320 (Cal BP 10490 to 10270)

References:
Database used
INTCAL04
Calibration Database
INTCAL04 Radiocarbon Age Calibration
IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).
Mathematics
A Simplified Approach to Calibrating C14 Dates
Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2), p317-322

Beta Analytic Radiocarbon Dating Laboratory

4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • E-Mail: beta@radiocarbon.com



CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-23:lab. mult=1)

Laboratory number: **Beta-284752**

Conventional radiocarbon age: **2660±40 BP**

2 Sigma calibrated result: (95% probability) **Cal BC 900 to 790 (Cal BP 2850 to 2740)**

Intercept data

Intercept of radiocarbon age with calibration curve: Cal BC 810 (Cal BP 2760)

1 Sigma calibrated result: (68% probability) Cal BC 830 to 800 (Cal BP 2780 to 2750)

References:

Database used

INTCAL04

Calibration Database

INTCAL04 Radiocarbon Age Calibration

IntCal04: Calibration Issue of Radiocarbon (Volume 46, nr 3, 2004).

Mathematics

A Simplified Approach to Calibrating C14 Dates

Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2), p317-322

Beta Analytic Radiocarbon Dating Laboratory

4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • E-Mail: beta@radiocarbon.com

BETA

Consistent Accuracy
Delivered On Time

Beta Analytic Inc
4985 SW 74 Court
Miami, Florida 33155
Tel: 305-667-5167
Fax: 305-663-0964
beta@radiocarbon.com
www.radiocarbon.com

Mr. Darden Hood
President

Mr. Ronald Hatfield
Mr. Christopher Patrick
Deputy Directors

The Radiocarbon Laboratory Accredited to ISO-17025 Testing Standards (PJLA Accreditation #59423)

Final Report

The final report package includes the final date report, a statement outlining our analytical procedures, a glossary of pretreatment terms, calendar calibration information, billing documents (containing balance/credit information and the number of samples submitted within the yearly discount period), and peripheral items to use with future submittals. The final report includes the individual analysis method, the delivery basis, the material type and the individual pretreatments applied. The final report has been sent by mail and e-mail (where available).

Pretreatment

Pretreatment methods are reported along with each result. All necessary chemical and mechanical pretreatments of the submitted material were applied at the laboratory to isolate the carbon, which may best represent the time event of interest. When interpreting the results, it is important to consider the pretreatments. Some samples cannot be fully pretreated, making their ^{14}C ages more subjective than samples, which can be fully pretreated. Some materials receive no pretreatments. Please look at the pretreatment indicated for each sample and read the pretreatment glossary to understand the implications.

Analysis

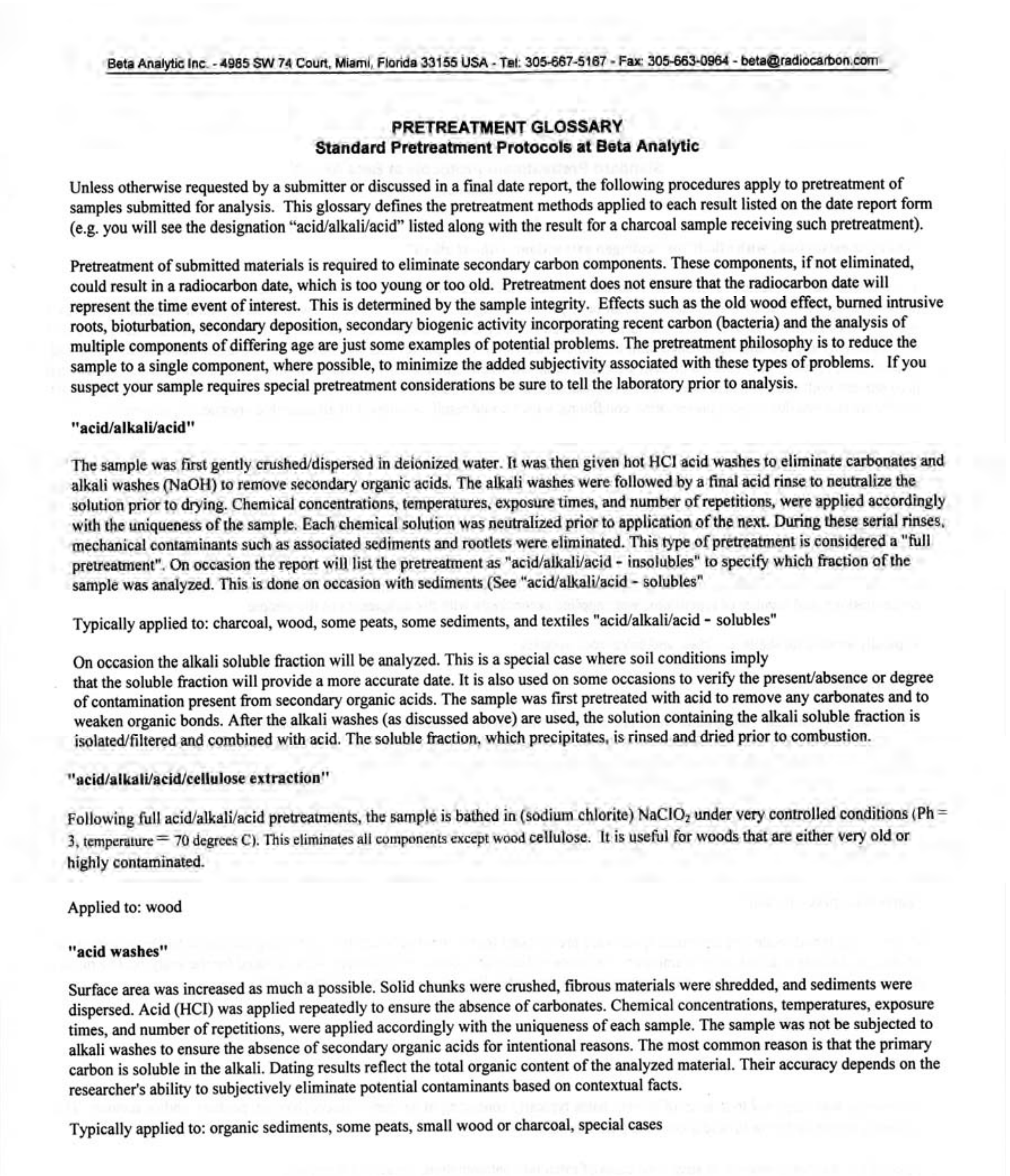
Materials measured by the radiometric technique were analyzed by synthesizing sample carbon to benzene (92% C), measuring for ^{14}C content in one of 53 scintillation spectrometers, and then calculating for radiocarbon age. If the Extended Counting Service was used, the ^{14}C content was measured for a greatly extended period of time. AMS results were derived from reduction of sample carbon to graphite (100 %C), along with standards and backgrounds. The graphite was then detected for ^{14}C content in one of 9 accelerator-mass-spectrometers (AMS).

The Radiocarbon Age and Calendar Calibration

The "Conventional ^{14}C Age (*)" is the result after applying $^{13}C/^{12}C$ corrections to the measured age and is the most appropriate radiocarbon age. If an "*" is attached to this date, it means the $^{13}C/^{12}C$ was estimated rather than measured (The ratio is an option for radiometric analysis, but included on all AMS analyses.) Ages are reported with the units "BP" (Before Present). "Present" is defined as AD 1950 for the purposes of radiocarbon dating.

Results for samples containing more ^{14}C than the modern reference standard are reported as "percent modern carbon" (pMC). These results indicate the material was respiring carbon after the advent of thermo-nuclear weapons testing and is less than ~ 50 years old.

Applicable calendar calibrations are included for materials between about 100 and 19,000 BP. If calibrations are not included with a report, those results were too young, too old, or inappropriate for calibration. Please read the enclosed page discussing calibration.



Beta Analytic Inc. - 4985 SW 74 Court, Miami, Florida 33155 USA - Tel: 305-667-5167 - Fax: 305-663-0964 - beta@radiocarbon.com

PRETREATMENT GLOSSARY

Standard Pretreatment Protocols at Beta Analytic

Unless otherwise requested by a submitter or discussed in a final date report, the following procedures apply to pretreatment of samples submitted for analysis. This glossary defines the pretreatment methods applied to each result listed on the date report form (e.g. you will see the designation "acid/alkali/acid" listed along with the result for a charcoal sample receiving such pretreatment).

Pretreatment of submitted materials is required to eliminate secondary carbon components. These components, if not eliminated, could result in a radiocarbon date, which is too young or too old. Pretreatment does not ensure that the radiocarbon date will represent the time event of interest. This is determined by the sample integrity. Effects such as the old wood effect, burned intrusive roots, bioturbation, secondary deposition, secondary biogenic activity incorporating recent carbon (bacteria) and the analysis of multiple components of differing age are just some examples of potential problems. The pretreatment philosophy is to reduce the sample to a single component, where possible, to minimize the added subjectivity associated with these types of problems. If you suspect your sample requires special pretreatment considerations be sure to tell the laboratory prior to analysis.

"acid/alkali/acid"

The sample was first gently crushed/dispersed in deionized water. It was then given hot HCl acid washes to eliminate carbonates and alkali washes (NaOH) to remove secondary organic acids. The alkali washes were followed by a final acid rinse to neutralize the solution prior to drying. Chemical concentrations, temperatures, exposure times, and number of repetitions, were applied accordingly with the uniqueness of the sample. Each chemical solution was neutralized prior to application of the next. During these serial rinses, mechanical contaminants such as associated sediments and rootlets were eliminated. This type of pretreatment is considered a "full pretreatment". On occasion the report will list the pretreatment as "acid/alkali/acid - insolubles" to specify which fraction of the sample was analyzed. This is done on occasion with sediments (See "acid/alkali/acid - solubles"

Typically applied to: charcoal, wood, some peats, some sediments, and textiles "acid/alkali/acid - solubles"

On occasion the alkali soluble fraction will be analyzed. This is a special case where soil conditions imply that the soluble fraction will provide a more accurate date. It is also used on some occasions to verify the present/absence or degree of contamination present from secondary organic acids. The sample was first pretreated with acid to remove any carbonates and to weaken organic bonds. After the alkali washes (as discussed above) are used, the solution containing the alkali soluble fraction is isolated/filtered and combined with acid. The soluble fraction, which precipitates, is rinsed and dried prior to combustion.

"acid/alkali/acid/cellulose extraction"

Following full acid/alkali/acid pretreatments, the sample is bathed in (sodium chlorite) $NaClO_2$ under very controlled conditions (Ph = 3, temperature = 70 degrees C). This eliminates all components except wood cellulose. It is useful for woods that are either very old or highly contaminated.

Applied to: wood

"acid washes"

Surface area was increased as much a possible. Solid chunks were crushed, fibrous materials were shredded, and sediments were dispersed. Acid (HCl) was applied repeatedly to ensure the absence of carbonates. Chemical concentrations, temperatures, exposure times, and number of repetitions, were applied accordingly with the uniqueness of each sample. The sample was not be subjected to alkali washes to ensure the absence of secondary organic acids for intentional reasons. The most common reason is that the primary carbon is soluble in the alkali. Dating results reflect the total organic content of the analyzed material. Their accuracy depends on the researcher's ability to subjectively eliminate potential contaminants based on contextual facts.

Typically applied to: organic sediments, some peats, small wood or charcoal, special cases

PRETREATMENT GLOSSARY
Standard Pretreatment Protocols at Beta Analytic
(Continued)

"collagen extraction: with alkali" or "collagen extraction: without alkali"

The material was first tested for friability ("softness"). Very soft bone material is an indication of the potential absence of the collagen fraction (basal bone protein acting as a "reinforcing agent" within the crystalline apatite structure). It was then washed in de-ionized water, the surface scraped free of the outer most layers and then gently crushed. Dilute, cold HCl acid was repeatedly applied and replenished until the mineral fraction (bone apatite) was eliminated. The collagen was then dissected and inspected for rootlets. Any rootlets present were also removed when replenishing the acid solutions. "With alkali" refers to additional pretreatment with sodium hydroxide (NaOH) to ensure the absence of secondary organic acids. "Without alkali" refers to the NaOH step being skipped due to poor preservation conditions, which could result in removal of all available organics if performed.

Typically applied to: bones

"acid etch"

The calcareous material was first washed in de-ionized water, removing associated organic sediments and debris (where present). The material was then crushed/dispersed and repeatedly subjected to HCl etches to eliminate secondary carbonate components. In the case of thick shells, the surfaces were physically abraded prior to etching down to a hard, primary core remained. In the case of porous carbonate nodules and caliches, very long exposure times were applied to allow infiltration of the acid. Acid exposure times, concentrations, and number of repetitions, were applied accordingly with the uniqueness of the sample.

Typically applied to: shells, caliches, and calcareous nodules

"neutralized"

Carbonates precipitated from ground water are usually submitted in an alkaline condition (ammonium hydroxide or sodium hydroxide solution). Typically this solution is neutralized in the original sample container, using deionized water. If larger volume dilution was required, the precipitate and solution were transferred to a sealed separatory flask and rinsed to neutrality. Exposure to atmosphere was minimal.

Typically applied to: Strontium carbonate, Barium carbonate
(i.e. precipitated ground water samples)

"carbonate precipitation"

Dissolved carbon dioxide and carbonate species are precipitated from submitted water by complexing them as ammonium carbonate. Strontium chloride is added to the ammonium carbonate solution and strontium carbonate is precipitated for the analysis. The result is representative of the dissolved inorganic carbon within the water. Results are reported as "water DIC".

Applied to: water

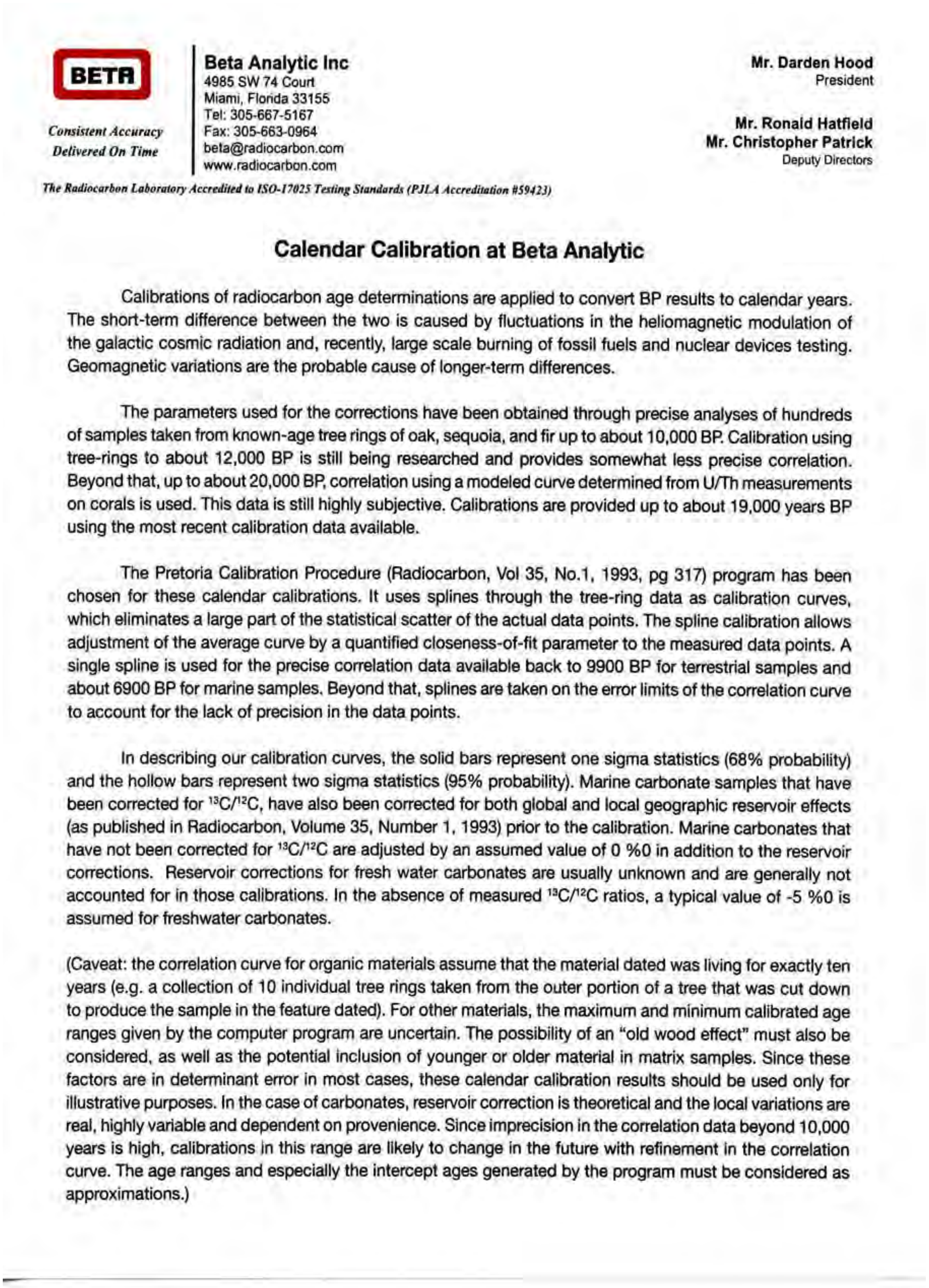
"solvent extraction"

The sample was subjected to a series of solvent baths typically consisting of benzene, toluene, hexane, pentane, and/or acetone. This is usually performed prior to acid/alkali/acid pretreatments.

Applied to: textiles, prevalent or suspected cases of pitch/tar contamination, conserved materials.

"none"

No laboratory pretreatments were applied. Special requests and pre-laboratory pretreatment usually accounts for this.



Consistent Accuracy
Delivered On Time

Beta Analytic Inc
4985 SW 74 Court
Miami, Florida 33155
Tel: 305-667-5167
Fax: 305-663-0964
beta@radiocarbon.com
www.radiocarbon.com

Mr. Darden Hood
President

Mr. Ronald Hatfield
Mr. Christopher Patrick
Deputy Directors

The Radiocarbon Laboratory Accredited to ISO-17025 Testing Standards (PJLA Accreditation #59423)

Calendar Calibration at Beta Analytic

Calibrations of radiocarbon age determinations are applied to convert BP results to calendar years. The short-term difference between the two is caused by fluctuations in the heliomagnetic modulation of the galactic cosmic radiation and, recently, large scale burning of fossil fuels and nuclear devices testing. Geomagnetic variations are the probable cause of longer-term differences.

The parameters used for the corrections have been obtained through precise analyses of hundreds of samples taken from known-age tree rings of oak, sequoia, and fir up to about 10,000 BP. Calibration using tree-rings to about 12,000 BP is still being researched and provides somewhat less precise correlation. Beyond that, up to about 20,000 BP, correlation using a modeled curve determined from U/Th measurements on corals is used. This data is still highly subjective. Calibrations are provided up to about 19,000 years BP using the most recent calibration data available.

The Pretoria Calibration Procedure (Radiocarbon, Vol 35, No.1, 1993, pg 317) program has been chosen for these calendar calibrations. It uses splines through the tree-ring data as calibration curves, which eliminates a large part of the statistical scatter of the actual data points. The spline calibration allows adjustment of the average curve by a quantified closeness-of-fit parameter to the measured data points. A single spline is used for the precise correlation data available back to 9900 BP for terrestrial samples and about 6900 BP for marine samples. Beyond that, splines are taken on the error limits of the correlation curve to account for the lack of precision in the data points.

In describing our calibration curves, the solid bars represent one sigma statistics (68% probability) and the hollow bars represent two sigma statistics (95% probability). Marine carbonate samples that have been corrected for $^{13}C/^{12}C$, have also been corrected for both global and local geographic reservoir effects (as published in Radiocarbon, Volume 35, Number 1, 1993) prior to the calibration. Marine carbonates that have not been corrected for $^{13}C/^{12}C$ are adjusted by an assumed value of 0 %0 in addition to the reservoir corrections. Reservoir corrections for fresh water carbonates are usually unknown and are generally not accounted for in those calibrations. In the absence of measured $^{13}C/^{12}C$ ratios, a typical value of -5 %0 is assumed for freshwater carbonates.

(Caveat: the correlation curve for organic materials assume that the material dated was living for exactly ten years (e.g. a collection of 10 individual tree rings taken from the outer portion of a tree that was cut down to produce the sample in the feature dated). For other materials, the maximum and minimum calibrated age ranges given by the computer program are uncertain. The possibility of an "old wood effect" must also be considered, as well as the potential inclusion of younger or older material in matrix samples. Since these factors are in determinant error in most cases, these calendar calibration results should be used only for illustrative purposes. In the case of carbonates, reservoir correction is theoretical and the local variations are real, highly variable and dependent on provenience. Since imprecision in the correlation data beyond 10,000 years is high, calibrations in this range are likely to change in the future with refinement in the correlation curve. The age ranges and especially the intercept ages generated by the program must be considered as approximations.)