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QUATERNARY GEOLOGY OF THE CABINET, HERON AND SMEADS BENCH 7.5’ QUADRANGLES, WITH EMPHASIS ON GLACIAL LAKE MISSOULA SEDIMENTS

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by

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Abstract

The primary scientific purpose of this project was to improve geologic knowledge of valley-fill units in the most downstream portion of the Clark Fork River valley in Montana. This was done to help understand the history of glacial Lake Missoula filling and draining cycles in the vicinity of the dam. The secondary purpose was to make a geologic map of the Cabinet, Heron and Smeads Bench 7.5-minute quadrangles and to resolve differences between detailed maps of Idaho (Lewis and others, 2008) and the old map of the Smeads bench, Heron and Cabinet quadrangles in Montana (Harrison and others, 1992; mapping was done 1977-87).
Improving knowledge as to the timing and history of glacial Lake Missoula in this area was done by delineating the valley fill sediments and flood gravel deposits from newer alluvial gravels and glacial outwash. There are two large glaciolacustrine outcrops in the field area that were analyzed in detail. Stratigraphic sections show sections of repeating sequences of silt and clay couplets, that are unconformably separated by a thicker layer of fine grained, crossbedded sand and silt. Sands from both sections were sampled for Optically Stimulate Luminescence and Infrared Stimulated Luminescence burial age-analysis. The burial-age of our successful sample was 16.02 +/- 1.08ka, which is consistent with having been buried during the final stages of glacial Lake Missoula. The other sample was determined to be in error due to scatter in the signal. In the field area, massive gravel deposits were found in streamlined bars mid-channel along the banks of tributary channels and in areas protected from stream erosion such as meanders and topographical highs. The gravels were deposited by one or more massive floods that flowed through the valley when the ice dam broke. The gravel deposits are buttressed and mantled by glaciolacustrine sediments of glacial Lake Missoula and thus can be assumed to be the older of the two deposits. The preservation of the lake beds in the field area indicates that the final draining of the lake was much slower and less erosive. The laminated couplets represent annual deposits laid down while the lake was increasing in depth. The basal sand beds represent high-energy influx of sediment in shallow water. This suggests that lake levels fluctuated around 16.02 +/- 1.08ka before draining completely.

Keywords: Glacial Lake Missoula, rhythmites, flood gravels, Cordilleran Ice Sheet, Optically Stimulated Luminescence, Infrared Stimulated Luminescence

Dedication

I want to first and foremost thank my Mom and Dad for always encouraging me to continue educating myself for reasons beyond getting a degree. I want to thank my Grandpa and Uncles for inspiring me to pursue geology and for always wanting to talk things through with me. My advisor Larry Smith was the best person I could have asked for to learn about this amazing subject and I want to thank him for putting up with me. Dean Hartline was a big advocate to me and pushed me harder than I thought I could go. Thank you all very much.

Acknowledgements

I would like to acknowledge fellow Geoscience graduate student Michael Chambers for assisting in the mapping portion of this report. Professor Dr. Larry Smith from the Montana Tech Geoscience department who advised me on this project, providing materials such as a Brunton compass, handheld GPS, geologic maps, aerial photos, etc. He also assisted in portions of the mapping and helped me with revisions to the final draft of this thesis. Jeff Lonn, field geologist for the Montana Bureau of Mines and Geology came to the field area to teach us about the Belt rocks in the area, which was very useful as Belt units can be hard to distinguish. Financial support was provided by the U.S. Geological Survey, National Cooperative Geologic Mapping Program: Award No. G15AC00153, 2015. The Geological Engineering department and the Dean of Students at Montana Tech, Bev Hartline, provided grant assistance for my tuition and I am humbled and profoundly grateful.

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1. Introduction

During the Wisconsin Era of the Pleistocene, the Purcell Lobe of the Cordilleran Ice Sheet descended south from Canada into Idaho and Montana. The lobe of ice created a massive ice dam on the Clark Fork River that backed up 2,200 to 2,600 km^3 of water into the intermontane valleys of Western Montana (Pardee, 1910, Smith, 2006). As the water rose, tunnels beneath the ice formed and the dam eventually failed (Clarke et al., 1984) Flood waters of the largest magnitude ever recorded cascaded through Idaho, Washington and Oregon, eroding resistant bedrock into channels and coulees, depositing massive amounts of gravel and creating what's known as the Channeled Scablands (Bretz, 1923, Bretz et al., 1956).

Geologic maps that show accurate extents of Quaternary units in intermontane valleys of western Montana are needed to understand the history of glacial Lake Missoula filling and draining cycles. Correlation of glaciolacustrine deposits within the lake basin contributes to the knowledge of the lake in its final stages.

One goal of this project was to make a geologic map of the Montana portion of the Cabinet 7.5 minute quadrangle, the Smeads Bench and the Heron 7.5-minute quadrangles at a scale of 1:24,000 (Figure 1). To date, published maps in this area are at smaller scales: 1:250,000 (Harrison et al., 1983), 1:250,000 (Harrison and Cressman, 1993) and 1:100,000 (Lewis et al., 2008). A 1:24,000 scale map was published in the Idaho portion of the Cabinet Quadrangle (McFadden, et al., 2006).

The primary goal of mapping was to delineate unconsolidated Quaternary units and improve the precision of contact placement of these units abutting bedrock. Sand and gravel deposits in the lake Missoula basin are key aquifers across Western Montana, so knowing their distribution and sedimentology in the field area is useful for understanding the groundwater resources in this area. The Montana Bureau of Mines and Geology's (MBMG) Groundwater Characterization Program (GWCP) plans to begin a multi-year study across economically developing northwestern counties of Montana in the near future.

1.1. Previous Geologic Mapping

Previous mapping of this area in Northwestern Montana has only been carried out at a 1:100,000 scale and smaller. The most detailed map that includes the quadrangles mapped in this project is Harrison and Cressman's (1993) map of the Libby Thrust Belt. On this map, most river valley sediments, including the smaller channel offshoots joining the valley from adjacent mountains, were mapped as Qg, Quaternary glacial deposits. No delineation was made between Qg, as all the sediments were lumped together as glacially deposited or influenced. Holocene and Pleistocene alluvium, proglacial lake sediments or flood gravels, glacial outwash and till were not differentiated on previous maps in Montana (Harrison and Cressman, 1993; Harrison et al., 1983; Lewis et al., 2008; and McFadden et al., 2006).

On the 1:100,000 scale map by Lewis et al. (2008), gravel and flood related deposits are divided further than on our map. On this map multiple terraces of flood gravel deposits are delineated as old, middle, and young. This map includes the Montana portion of the Cabinet quadrangle. Quaternary units that are on this map that are not on Plate I are Qfgb (flood gravel bars), and Qgu (undivided). Lewis et al. (2008) mapped most the valley as glacial till.

1.2. Previous Research on glacial Lake Missoula

In 1910, Joseph Pardee proposed that a large ice-dammed lake filled the intermontane valleys of western Montana. The evidence he cited was large strandlines on the side of Mt Jumbo in Missoula. Bretz (1925) studied the origin of the Grand Coulee in Washington and deduced that the coulee and the channeled scablands were carved out by floods from glacial Lake Missoula. This was evident to Bretz because of the location of the dam and the volume and height of the lake, stating that it contained all the necessary elements for catastrophic draining.

Although it is unknown how many times the ice dam formed and broke, Pardee (1910, 1942) proposed that it did so at least twice and that the later draining(s) were much slower. This is due is the closely spaced the shorelines are and that they were faint enough that each lake stand must have been of short duration. The wave cut shorelines are not necessarily chronological though, and are difficult to correlate (Smith, 2017). The highest shoreline is a marker for the highstand of the lake at its maximum volume to be 1,260 – 1,298 m asl, not accounting for post-glacial isostatic adjustment (Smith et al., 2016).

Glacial Lake Missoula sediments are found preserved on valley floors at 610 m in elevation near the ice dam to 100 m below the top strandline in Missoula (Smith et al., 2016). Constraining the ages of different glacial Lake Missoula deposits is important for understanding the history and chronology of the lake. This is difficult due to the lack of organic material. The most effective way of dating these sediments has been Optically Stimulated Luminescence dating (Hanson et al., 2012.; Smith, et al., 2016; Smith et al., 2018).

The outcrop of glacial Lake Missoula sediments that has been studied the most in the glacial Lake Missoula basin is called the Ninemile section (Alt and Chambers, 1970; Chambers, 1971, 1985; Waitt, 1980, 1985; Fritz and Smith, 1993; Shaw et al., 1999, 2000; Atwater et al., 2000; Booth et al., 2004; Hanson et al., 2012). The Ninemile creek section is near the confluence of Ninemile Creek and the Clark Fork River. It is approximately 250 meters long and 23 meters thick (Hanson et al., 2012). The sedimentology here consists of sections of clay and silt laminations that thin up-section until they are unconformably covered by a thicker deposit of silt, sand and/or gravel. These sections have been interpreted to be rhythmites: draining and filling cycles of glacial Lake Missoula (Chambers, 1971, 1984; Fritz and Smith, 1993; Hanson et al., 2012).

Ninemile has been interpreted as showing evidence for up to 40 filling and draining cycles by Waitt (1980, 1985), and Atwater (1986) counted 89 transgressions of glacial Lake Missoula. The section has been correlated with slackwater deposits of catastrophic flood events in Idaho, Washington and Oregon (Waitt, 1980, 1985; Atwater et al., 2000). Fritz and Smith (1993) argued that the sedimentology of the Ninemile section shows patterns of lake level fluctuations, without indication of catastrophic flooding. In 2006, analysis by Smith attributed these glaciolacustrine deposits to later stage, less energetic drainings of the lake. He stated that the large-scale gravel bars that underlie these lake beds in other places along the Clark Fork River such as Tarkio and Garden Gulch, are evidence for catastrophic flood events (Lonn and Smith, 2007), much like the Stout and Paradise bars along the Flathead River and lower Clark Fork River of Pardee (1942).

Hanson et al. (2012) compared the Ninemile section to another outcrop of glaciolacustrine sediment in Missoula coined the Rail Line section. In both the Rail Line and the Ninemile sections, the rhythmites begin with a thin layer of gravel (only 2 of the rhythmites at the Rail Line section have the gravel layer), followed by a layer of fine crossbedded sand, and then clay and silt couplets that thin up-section. They showed evidence for soft sediment deformation and subaerial exposure surfaces near the base of many of the rhythmite sections. Hanson et al. (2012) concluded that the upwardly thinning varves, climbing ripple-drift sequences, soft sediment deformation structures and erosive lower contacts suggests that the silt beds found in the Ninemile and Rail Line sections were deposited by turbidity currents at relatively shallow depth. This conclusion was also reached by Chambers (1971, 1984) at the Ninemile site.

Shaw et al. (1999) suggested that the crossbedded basal sand layers were high energy turbidite deposits activated by jokulhlaups beneath the Cordilleran ice sheet. Hanson et al. (2012) reasoned that this did not explain the exposure surfaces and convoluted and micro-faulted bedding just above the sand-silt contact or the fact that the varves thin up-section, representing a deepening of water and further distance from the sediment source. Instead, the climbing rippled basal sands were deposited in high energy, high deposition flows, i.e. turbidity currents, in a shallow Lake Missoula (Hanson et al., 2012; Chambers, 1971, 1984).

In Montana, previous analysis done on glacial Lake Missoula sediments has been primarily along the Upper Clark Fork and Flathead Rivers. Until now, analysis of glacial Lake Missoula sediments has not been done in the proximity of where the Pleistocene glacial lobe blocked the Clark Fork River. That is what we set out to do in this project, in order to gain knowledge as to the timing and behavior of glacial Lake Missoula in its last stage.

1.3. Regional Geologic Setting

The area of research in this paper is located in the Clark Fork River Valley between the Cabinet Mountains and the Bitterroot Range within the Kootenai National Forest, in Sanders County, MT. Its boundaries are defined by the extent of three 7.5-minute quadrangles in NW Montana: the Montana portion of the Cabinet quadrangle (the Idaho portion of the Cabinet Quadrangle was previously mapped at 1:24,000 by the Idaho Geological Society (McFaddan et al., 2006); the Heron quadrangle; and the Smeads Bench quadrangle. These three quadrangles include the most downstream portion of the Clark Fork River in Montana, and three tributaries: Bull River, Blue Creek, and Elk Creek. The Cabinet Quadrangle straddles the border of Montana and Idaho, and the map area begins just east of the Cabinet Gorge Dam and Lake Pend Oreille, at the Montana border. It is at this approximate location that the ice damn was formed ~20 ka ago (Pardee, 1910, 1942; Bretz, 1925, Booth et al., 2004).

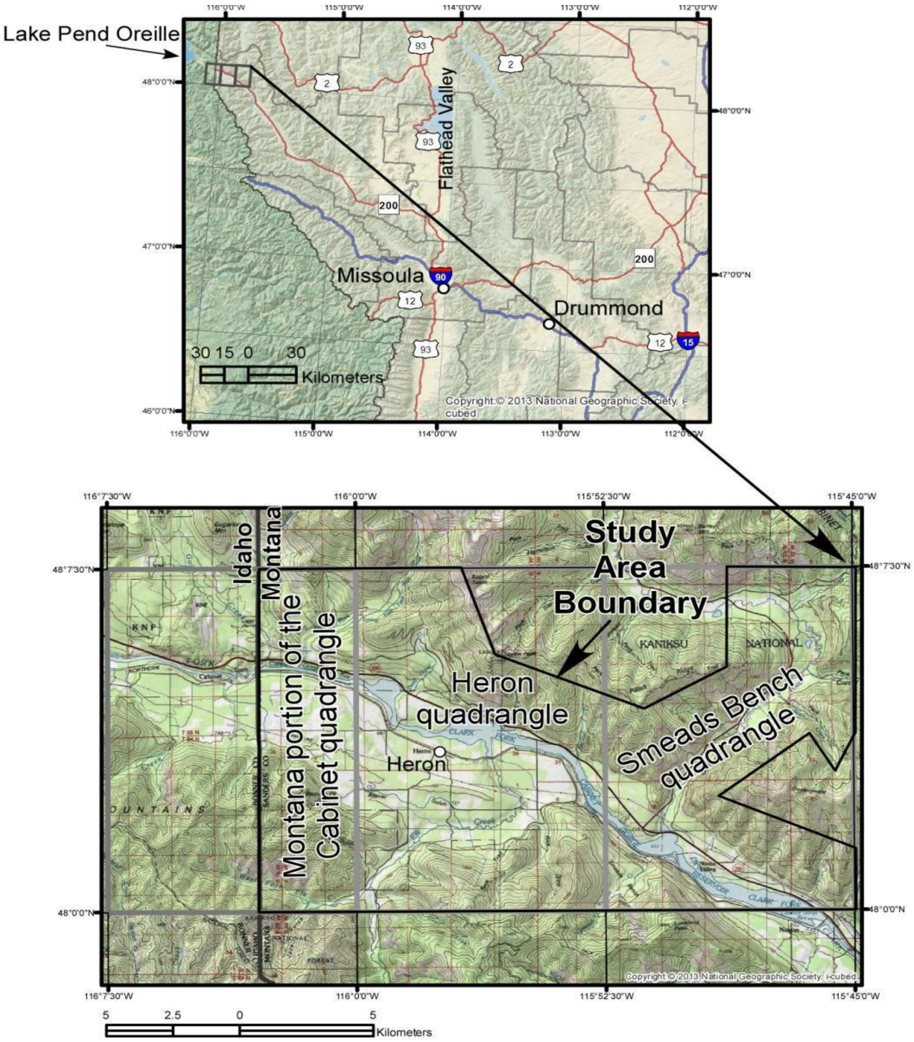


Figure 1: Map showing the boundary and extent of the field area in the Cabinet, Heron and Smeads Bench 7.5' quadrangles in Northwestern Montana.

1.4. Structure

The study area is located within a complex zone of thrust faults and high-angle normal faults that is about 24 km wide and 161 km long and extends from the Canadian Border just west of the Idaho/Montana border to the Hope Fault. This zone is called the Libby Thrust Belt (Harrison and Cressman, 1993).

The Hope Fault is a W-NW trending dextral strike slip fault more than 160 km long that extends from Hope, Idaho to Heron, Montana. This transform fault has apparent right-lateral horizontal displacement of 26 km and 6.7 km of apparent vertical displacement to the south (Harrison and Cressman, 1993).

Evidence of Proterozoic sills across the Hope Fault indicates that the fault may have existed in the Proterozoic (Harrison et al., 1972). The Hope Fault has been linked to the Lewis Thrust Belt by Harrison and Cressman (1993) stating that since this is the southern terminus of the thrust belt, it possibly formed a tear fault through Mesozoic thrusting. Displacement along the Hope Fault occurred during Mesozoic thrusting~100 m.y. ago when the Libby Thrust Belt was formed, and it remained active until about 60 m.y. ago

2. Methods

The Cabinet, Heron and Smeads Bench quadrangles were mapped at 1:24,000 scale using a combination of field analysis, aerial photo interpretation, and referencing from other geologic maps of various scales. The field mapping was carried out during the summer of 2015, in multiple 10-day segments, as well as during reconnaissance work after the map was in the stage of being digitized. Standard geologic tools were used for mapping, including a Brunton compass, a handheld GPS, and paper topographic base maps of the Smeads Bench, Heron and Cabinet quadrangles at 1:24,000 scale. Mapping was completed on foot, one quad at a time, in north and south sections to systematically gather information. Due to dense vegetation on many hillslopes, roadcut exposures were traversed and strike and dip was taken where possible.

The contacts of Belt Supergroup formations and faults on Plate 1 were compiled by referencing three previously published maps: Geology of the Libby thrust belt of northwestern Montana and its implications to regional tectonics (Harrison and Cressman, 1993); Preliminary geologic map of part of the Kalispell 1 degree X 2 degree quadrangle, Montana (Harrison et al., 1983), and the Preliminary Geologic Map of the Sandpoint 30 x 60 Minute Quadrangle, Idaho and Montana, and the Idaho Part of the Chewelah 30 x 60 Minute Quadrangle (Lewis et al., 2008), (Figure 2).

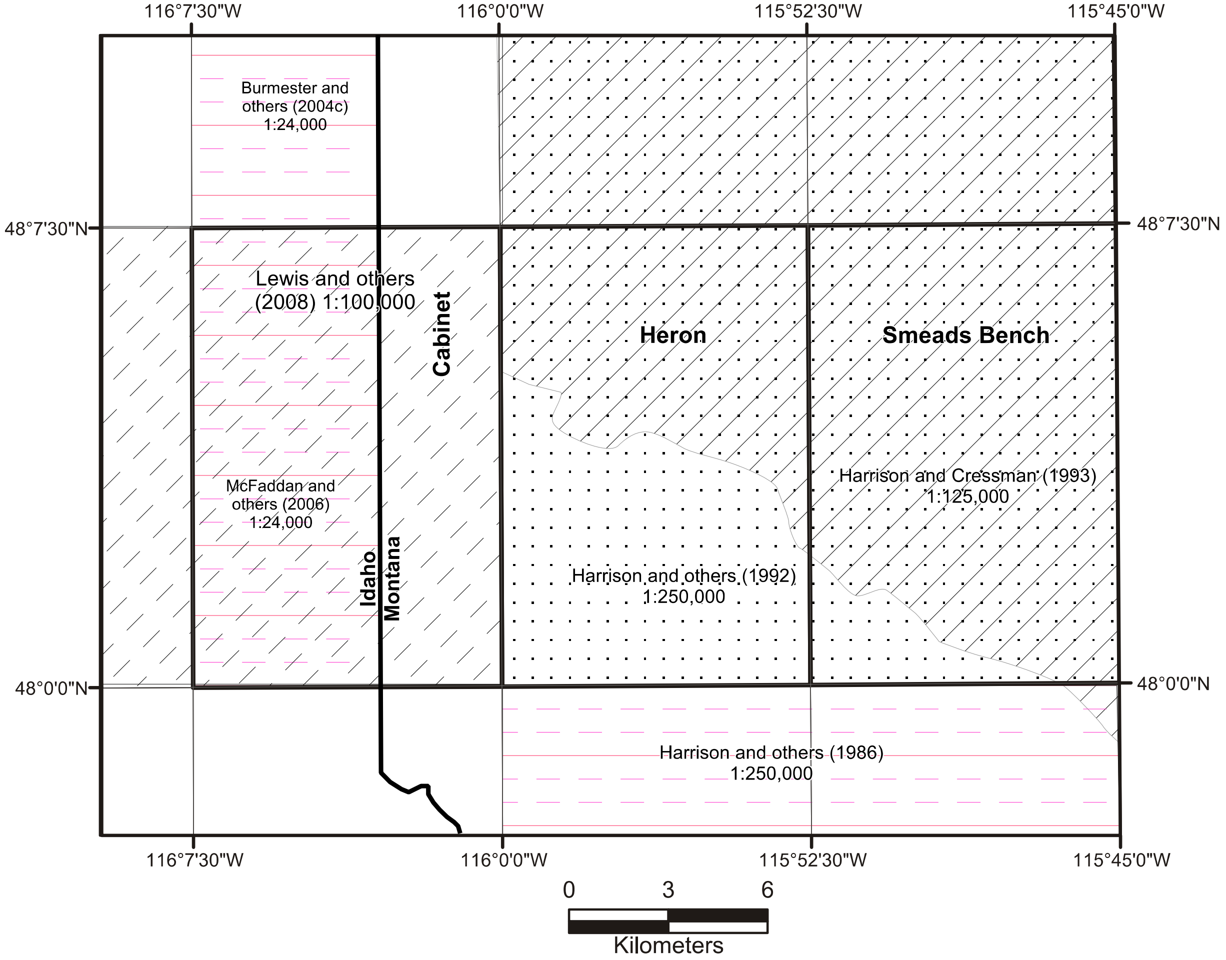


Figure 2: This map is showing previously mapped areas that intersect the field area. The authors and scales of each map is labeled within the mapped outlines.

The map of the geology of the Libby Thrust (Harrison and Cressman, 1993) shows the entire length of the field area, north of the Clark Fork River, at 1:250,000 scale. It is very detailed in showing the complex structure of the area and the attitude of bedding planes. This map contributed to our placement of the Hope Fault and thrust and normal faults in the northwestern region of the map (Plate 1), as well as Belt Supergroup formation contacts. The geologic map of the Sandpoint and Chewelah quadrangles (Lewis et al., 2008) was mapped at a 1:100,000 scale and includes the area at the western edge of our map to ~2.25 km east of Bull

River. The map covers south and north of the Clark Fork River and aided in our placement of contacts between Belt formations in the mountainous areas. The geologic map of the Kalispell quadrangle, 1:250,000 scale, shows most of the field area, starting about where the Libby Thrust map cut off to the east. It shows both the north and south of the river. This map was referenced when adding contacts between Belt formations south of the valley, and in corroboration with the Libby Thrust map for the northern contacts.

2.1. Analysis of valley and glacial Lake Missoula deposits

A good portion of the mapping was done in an effort to understand the path of glacial Lake Missoula during high-energy flood stages. Mapping the distribution and morphology of the gravel deposits throughout the field area was done by analyzing the geology from the channels outward and walking along edges of the bedrock cliffs. Holocene alluvium was analyzed along Bull River at the Bull River Campground and along the Clark Fork River near the Heron bridge. The Clark Fork River's flood plain extends farther south than it does north, and many roads head south from Highway 200, across most of the valley. We traversed on foot and by car down the roads, analyzing the morphology of the flood plain as we moved south away from the river and beyond a river-cut terrace.

Old alluvium (Pleistocene) deposits were differentiated from Holocene alluvium by factors such as sorting, matrix, grain size and overall abundance of clasts. It was essential to distinguish between the Pleistocene alluvium, Pleistocene flood gravels and glacial outwash. The alluvium was differentiated from flood gravels by clast size and roundness, stratigraphic features, pathways and shapes of the deposits. We visited several massive gravel deposits that had well-exposed surfaces with which to see imbrication and crossbedding. The gravel deposits in the middle of the valley were traversed to determine their extent and stratigraphy. Glacial outwash was harder to delineate, as it is very similar to flood gravel characteristically. Geologic interpretation of potentially glaciated alpine regions was used as a guide to possible depositional processes having taken place.

Of equal importance to studying the gravel deposits was to analyze the glaciolacustrine deposits left over from glacial Lake Missoula. The valley terrain was thickly forested, and exposures of this sediment was topical in most places. The thickest outcrop of these sediments that we found in the field area is on a road cut on Elk Creek Road in Heron, MT (Location 1, Plate 1). The exposure was steep and so a stair-step exposure was cut into and diagonally up the exposure to provide fresh, reachable surfaces. The tools used to expose the sections were trowels, a pick axe and a shovel. Stratigraphic analysis of these sediments was done using a Jacob staff to measure the overall thickness, and a metric compass-ruler to measure the individual laminations in detail. This section was measured vertically on a millimeter scale, to the point where bioturbation and soil interference was present.

A thinner section of glacial Lake Missoula sediments was found at the top of a large gravel deposit along Highway 200, next to Blue Creek Road. I refer to this outcrop as the Blue Creek Road section, and it was also measured in detail. Two stratigraphic sections of these locations were used to infer glaciolacustrine sedimentation in the area.

In addition to mapping the surficial deposits, well logs were used to get a picture of the subsurface. The object was to get a general picture of the thickness and stratigraphy of glacial Lake Missoula sediments and gravels in the valley, as well as improve knowledge as to the groundwater potential in the area.

2.2. Geochronology of glaciolacustrine sediments

Optical dating is the prevalent method used to determine the timing of burial and deposition of quartz and feldspar grains in glacial Lake Missoula deposits (Levish, 1997; Hanson et al., 2012; Smith et al., 2018). Optically stimulated luminescence dating (OSL) and Infrared Stimulated Luminescense (ISRL) are techniques used to determine the time elapsed since quartz and feldspar grains were last exposed to sunlight. During aerial, glacial or fluvial sediment transport the sand grains' luminescence signal is commonly zeroed out, or "bleached", due to exposure of sunlight.

Determining the burial age of the sand in the 2 glaciolacustrine outcrops we sampled in the field area will add to the knowledge of the history of the lake that has been inferred by others downstream and upstream of the dam.

2.2.1. Sample Locations

Two samples were taken for optical dating in the field area, and their locations are on the corresponding stratigraphic sections (Plate 2 and Figure 9). Beds that had visible quartz sand grains were chosen for our sample locations. The first sample, Sample #: EC-01, was collected from the Elk Creek Road Section (Location A on Plate 1 from the sand-silt facies). Sample #: BC-01 was taken from the Blue Creek Road section (Location B on Plate 1) in sand-silt facies at the base of the section where it contacts the underlying gravel-sand facies. When choosing the sample points on these sections, beds that showed signs of post-depositional mixing processes such as bioturbation, soil formation, desiccation cracks were avoided. For the lab to determine the dose rate of radiation, we provided a quart-sized sample of the sediment ~30 cm surrounding the tube, and the latitude and longitude of the location, elevation, and the burial depth of the sample were noted for processing, following the techniques of Rittenour (2008).

2.2.2. Sampling Methods

Outcrops were excavated to depths of about 50-75 cm in order to expose un-weathered sediment. Samples were then collected by hammering in a 25 cm long, 4cm diameter aluminum tube into the gravel-sand/sand-silt horizons (Figures 3 and 4), into the exposure, ensuring the entire tube was filled. The end of the tube was taped off with electrical tape to limit further light exposure, preserve water content and prevent mixing. The other end was taped off upon removal of the tube. An arrow was drawn on the tube pointing to the end that was driven into the sediment and the site and date in which we had taken the sample were labeled. A Ziploc bag filled with sediment from ~30 cm around the hole (over a quart) where the sample had been taken was collected.

Figure 3: At the Blue Creek Road section, the OSL sample was taken at the contact between overlying sandy silt and underlying sandy-gravel facies. A 25cm long aluminum tube was pounded in the sediment and capped off at the ends.

Figure 4: At the Elk Creek Rd section the sample tube is shown in place and capped. A sample bag of surrounding sediment for dose rate measurements was collected from around the tube where the outcrop has been scraped flat

Using a Jacob staff and a Brunton compass, I measured the stratigraphic height to the sample site location from the base of the section to the land surface.

2.2.3. Sample Preparation Procedures

The samples we collected were processed for OSL and IRSL dating at the Luminescence lab at Utah State University. This was done in a dark room, illuminated by standard photographic darkroom light, to prevent the luminescence signature from bleaching.

2.2.3.1. Optically Stimulated Luminescence Dating (OSL) Procedures

At the lab I completed the steps below to prepare my samples for OSL dating. All lab activities were guided and supervised by Dr. Tammy Rittenour in August of 2015.

1. The outer 2-3 cm of sediment was removed from each end of the tube. The end material has more potential to have been exposed to solar radiation, so this portion was instead used to measure water content.
2. The sample of surrounding sediment was split so as to fill a ~50-gram bag. This sample must be dry and without coarse grained material (pebbles or gravels).

3. The remaining sediment in the tube was then wet-sieved into three grain-size fractions. The sieve sizes were <63µm, 63-150µm (target grain size), and >150µm because very-fine to fine-grained sand is preferred (Nelson et al., 2015).
4. Carbonates were removed from the target sand by soaking it in 10% HCl for at least an hour and until there was no bubbles when stirred.
5. The target sample was dried in the oven.
6. Heavy minerals were removed using DI water and Sodium Polytungstate.
7. Heavy liquid separation was used to separate the quartz from the feldspar.
8. To remove remaining feldspar grains, the quartz grains were etched using HF for at least an hour.
9. The quartz grains were rinsed with deionizing water to remove any precipitant residuals from the HF.
10. The target sample was transferred to a canister for lab analysis and instrumental luminescence dating.

2.2.4. Environmental Dose Rates and Dose Equivalent Rates

Calculating the time elapsed since burial using OSL is a matter of calculating the environmental radiation dose rate (Gy/ka) and the dose equivalent (D_E) to the burial dose. To calculate the equivalent dose the sediment received during burial, the natural luminescence of the sample was measured using the single-aliquot regenerative (SAR) method of Murray and Wintle (2000).

Due to the presence of radioactive isotopes in minerals, radiation causes electrons to become trapped in their crystal lattice (King et al., 2014). Upon burial, this radiation causes the luminesce signal to accumulate. Freed “traps” are excited by ionizing radiation. Exposing these grains to a stimulus of blue-green light releases these trapped electrons and they emit a photon of light or luminescence, upon recombination (Aitken, 1998; Murray and Wintle, 2000).

Using the SAR method, a bracket of D_E values was determined by irradiating the bleached sediment at 5 different doses (Appendix A, Procedures). These values were then fit to a saturation exponential and plotted on a luminescence dose-response curve (Figure 5, for example). The intercept of this curve is the D_E. Multiple aliquots must be used to obtain a statistically accurate D_E value.

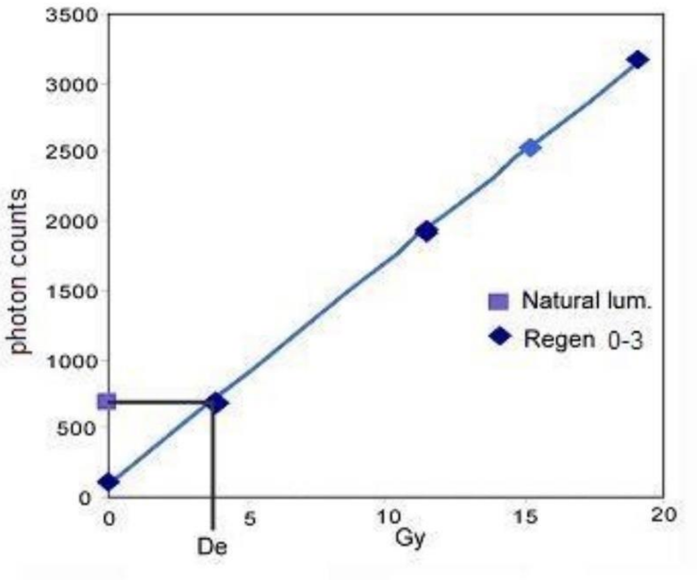


Figure 5: An example luminescence dose-response curve chart from the USU Luminescence Lab, showing a single dose plot for one aliquot of one sample.

For OSL dating, dose rates were calculated by chemical analysis of the U, Th, K, and Rb content in the sediment. This was done using ICP-MS and ICP-AES techniques by ALS Chemex, Elko, NV and conversion factors from Guerin et al. (2011).

Soil moisture must be considered when calculating age because intergranular water absorbs radiation and decreases the effective dose rate of sediment, affecting the calculated age. The pore water content was estimated to determine the water attenuation of the dry sample. This was done by placing a sample of the sand we collected and a saturated sample in a 40° C oven and measuring the drying rates. The burial depth, elevation, latitude and longitude of the sample location was noted for the calculation of the cosmic contribution.

Dose rates on K-feldspar were determined by adding the internal grain beta dose rate assuming 12.5% K (Huntley and Baril, 1997) and 400 ppm Rb (Huntley and Hancock, 2001) attenuated to grain size using Mejdahl (1979). Alpha dose rate contribution was determined using an ‘a’ factor of 0.10 ±0.05 of Reese-Jones (1995)

Burial age was calculated by dividing the equivalent dose by the dose rate of the sediment surrounding the sample:

Equation 1: Calculating Burial Age

Age (kyr) = Equivalent Dose (Gy) / Dose Rate (Gy/kyr)

2.3. Infrared Stimulated Luminescence (IRSL) Dating Procedures

Infrared Stimulated Luminescence dating was used as a backup method to account for possible underestimation of age of quartz due to scatter error in OSL, and to corroborate results (Appendix A: Final Luminescence Age Report).The SAR method was used to measure the IRSL signal at 50˚C (Wallinga et al., 2000). Sieving, HCL and bleach treatments, and heavy mineral separation with no HF treatment isolated the K-feldspar component with grain sizes between 63-150µm. D_E values and age data were determined using the Central Age Model (CAM) of Galbraith and Roberts (2012).

Feldspars luminescence signal decays over time, known as anomalous fading. So fading rate and D_E had to be considered to produce accurate results. (Nelson et al., 2015). Anomalous fading was accounted for using the fading method of Auclair et al. (2003) and the age correction model of Huntley and Lamothe (2001).

3. Results

3.1. Geologic Map

A geologic map was completed of portions of the Cabinet, Heron and Smeads Bench quadrangles at a scale of 1:24,000 (Plate 1). This is the largest scale geologic map produced for this area in the state of Montana. Previously published maps in this area are at a scale of 1:250,000 (Harrison et al., 1983); 1:125,000 (Harrison and Cressman, 1993); and 1:100,000 (Lewis et al., 2008), while maps adjacent to and west of the field area in Idaho are published at 1:24,000 (McFaddan et al., 2006).

The map area boundary was chosen to portray the area that was inundated by the lake at some point, up to at least 1,280 m in elevation and to include the areas where the bedrock comes in contact with the valley sediments. The map accompanying this report will be used by the Montana Bureau of Mines and Geology's (MBMG) Geologic Mapping and Groundwater Characterization programs as a reference for future research pertaining to Sanders County, Montana.

3.2. Valley Topography

The valley that extends west to east in the field area (on Plate 1) surrounds the 25-km-long reach of the Clark Fork River from its exit from Montana into Idaho, to the edge of the Smeads Bench quadrangle just southwest of the town of Noxon, MT (Figure 1). The valley ranges in elevation from 2,200 – 2,500 ft (670 – 760 m) and has a maximum width of 6 km.

In his field trip guidebook, Breckenridge (1989) describes the region between Noxon, MT to Clark Fork, ID along the Clark Fork River as having striations and glacially-scoured cliffs along the south side of the valley. He describes the north side of the valley as a bedrock bench covered in till interpreted as ice margin deposits.

The map area encompasses the reach of the Clark Fork River that has been flooded by the construction of the Cabinet Gorge Dam in 1952 (Breckenridge,1989). This ice-marginal till that Breckenridge describes was not found in our mapping. This may be because the water level is higher than the till deposits due to the flooding of the river. Further study of these deposits on the north side of the river and glacial scour on the south side of the valley would be useful in tracking the paths of the Purcell Lobe in the Clark Fork River Valley.

The valley floor is primarily covered in clayey-silt, gravelly-sand and sandy-gravel. There are large gravel bars in the lees of bedrock knobs and in streamlined deposits mid-valley, paralleling the river. These deposits range from 24 m (at the meander deposit mentioned below) to140 meters higher than the valley floor. To the east of the Cabinet Gorge Dam, in the Heron Quadrangle, the Clark Fork river meanders south and buts up against bedrock. A large gravel deposit fills in the meander. Close to the river's perimeter is an alluvial plain. This extends out from the river up to a kilometer in places. At the southern outside edge of the alluvium, the elevation steps up by 100-200 feet to a terrace of glaciolacustrine sediments that cover the valley middle, along with streamlined gravel bars and deposits behind bedrock knobs. At the northern edge of the valley, gravels follow the river's edge and butt up against the steep bedrock.

Bull River is a tributary that branches off to the north at the Bull River Campground on Highway 200. The banks of this river and East Bull River are almost completely covered in gravel. Elk Creek is a tributary that joins the Clark Fork River from the south through a bedrock channel. When the creek reaches the valley, it flows north east traversing the edge of a gravel deposit before connecting with the Clark Fork. This gravel was built up to ~85 meters high around a bedrock knob adjacent to where Elk Creek enters the valley from the south.

The small active and inactive streams that exit the mountains have wide flood plains' relative to the stream size and gravel backfill deposits.

3.3. Bedrock

3.3.1. Belt Supergroup, Middle Proterozoic (1,400 – 900 Ma)

The predominant bedrock in the study area is a thick sequence of Proterozoic meta-sedimentary deposits called the Belt Supergroup. Figure 6 shows the geographical coverage of these depositions.

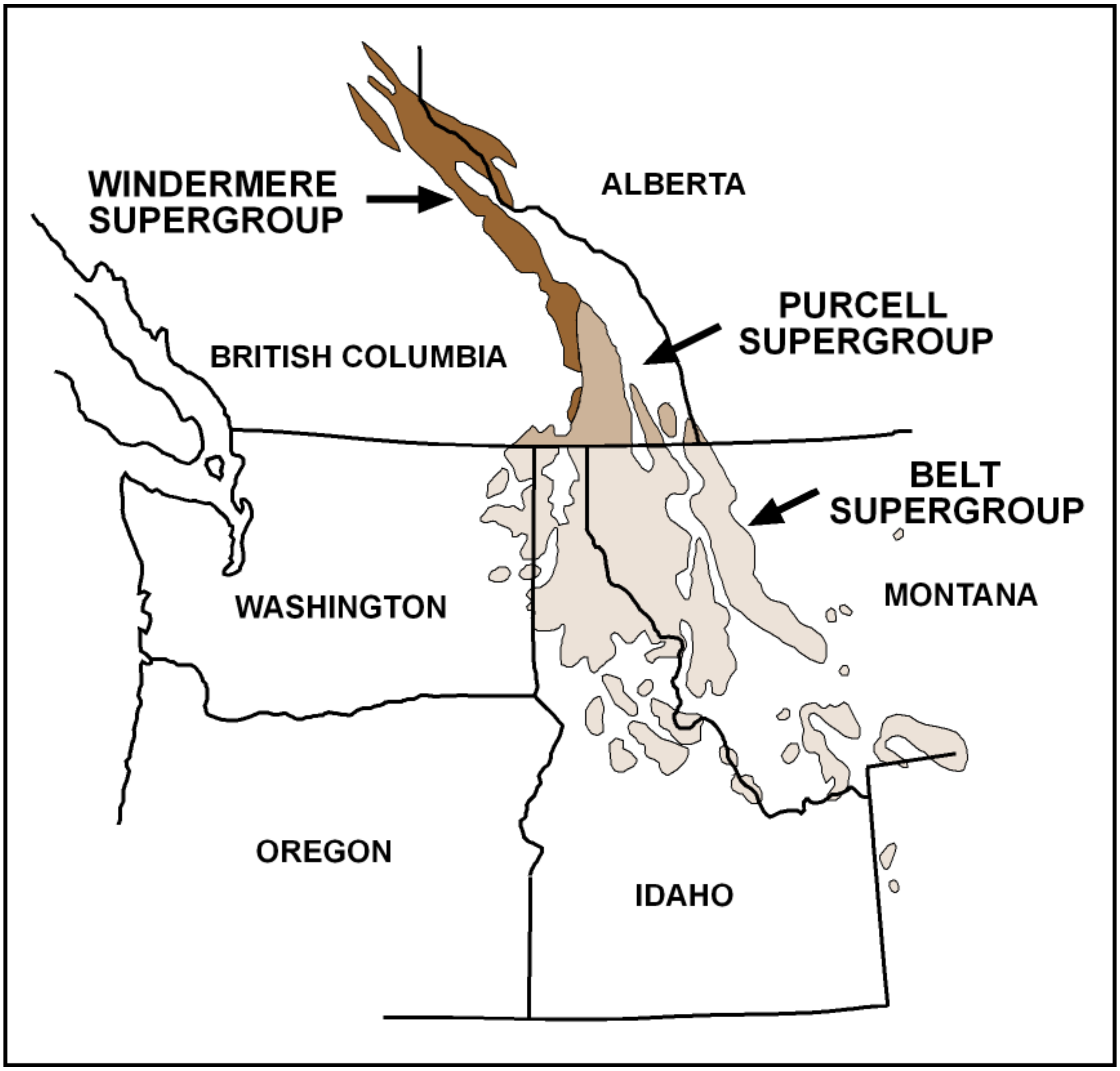


Figure 6: This map from Burchfiel et al. (1992) shows the approximate extent of the Belt Supergroup and the equivalent Purcell Supergroup in the United States and Canada.

The Belt Supergroup is divided into groups in order of deposition: the Purcell Formation, the Ravilli Group, the Piegan Group, and the Missoula Group. Below (Figure 7-9) is an overview of the formations exposed in the field area. The rock descriptions in the following tables are modified from Harrison and Cressman (1993) by descriptions of outcrops in the field area.

Group	Formation	Rock Descriptions
Missoula Group	**Libby Formation**	This formation consists of alternating dark grey to black graded siltite and argillite laminae, and chert-like olive green quartzite to pale green siltite. The laminae contacts are sharp and wavy to planar and break easily along bedding planes. Mud/clay chips, mudcracks, ripples, pinch and swell, stromatolites and synerisis cracks are present in the upper member.
	Bonner Formation	Pink, red and green fine-to-medium-grained feldspathic quartzite, siltite and argillite make up this formation in the map area. It is micaceous along bedding planes and creates flaggy talus.
	Mt Shields Formation	This formations consists of thin-to-medium laminations of dark-light grey siltites with argillite interbeds. Mud and clays chips, mudcracks, ripple marks, raindrop imprints, salt casts and pinch and swell features are abundant.
	Shephard Formation	This formation is dolomitic light green argillite with dark green siltite flat laminations. Platey, micaceous layers are present between bedding planes. Weathering produces a tan outer color. Cherty mud chips were found in places.
	Snowslip Formation	The green facies of this formation was found in the map area. This facies consists of green, thin-bedded, interlaminated argillite and siltite.

Figure 7: Missoula Group is the uppermost sequence of Belt Supergroup formations. The formations within this group that are in the map area are shown above along with descriptions of the lithology and sedimentary structures found in each.

Group	Formation		Rock Descriptions
Piegan Group	Helena-Wallace Formation	Wallace Formation	This formation consists of light-colored siltite and very-fine-grained quartzite that fines upward to black argillite. The black layers are hummocky with variable thickness. It weathers tan due to an abundance of muddy carbonates, algal mats and molar tooth structures.
		Helena Formation	The formation consists of cyclical, gray limestone and dolomite sequences, with white quartzite laminae in places. Molar tooth structures are abundant. Thick beds of weathered-orange dolomite and thin interbeds of green to tan argillite characterize the lower portion of this formation.
Ravilli Group	Empire Formation		Dark to light green dolomitic and silty argillite make up this formation. Locally found were fluid escape structures and calcite-filled voids.
	Revett Formation		Gray, medium-grained, blocky quartzite and siltite, with interbeds of argillite in places.
	Burke Formation		Green and purple flat laminae of argillite interbedded with siltite. Erosion forms steep bedded cliffs with flaggy detritous that collects downslope.

Figure 8: Table of rock descriptions for the middle Belt groups and their associated formations.

Formation	Rock Descriptions
Prichard Formation	This formation consists of thinly-interbedded siltite and argilite , occurring as graded couplets (Cressman, 1985). The color is typically grey but oxidizes to a rusty brown. It forms cliffs and has platey weathering. Biotite flakes are abundant in the laminae.

Figure 9: Rock descriptions of the lowest and thickest formation in the Belt Supergroup: the Prichard Fm.

3.4. Cambrian Bedrock Units

There are two outcrops of limestones with shale interbeds are mapped along Highway 200 north of Heron as Cambrian (undivided). This description is used when thickness is uncertain (Harrison and Cressman, 1993). The limestone is grey, fossiliferous and interbedded with black shale (USFS, 1979).

3.5. Quaternary Deposits

3.5.1. Gravel-dominated deposits

Gravel-dominated deposits have been differentiated into 4 separate units in this paper: Holocene alluvium and older alluvium, Quaternary glacial outwash, and Quaternary glacial Lake Missoula flood gravel deposits. These units were delineated according to location, sorting, matrix, consolidation, geographic position, stratigraphy and relative age as inferred from topographic position. The lithology of the gravel deposits consists mostly of rocks from the Belt

Supergroup (quartzite, siltite, argillite) with lesser amounts of igneous rocks such as granite and granodiorite.

Delineating between alluvium, outwash and flood gravel was not always obvious. Most areas of interest were heavily forested. In places, there was layering of different gravel units, such as the Holocene alluvium and Older alluvium overlying Quaternary flood gravels along the banks of the Clark Fork River and its tributaries. Calcite cementation was found in the top layers of different gravel units, portraying consolidation and cement. Digging deeper into the different formations would aid in understanding the flood and glacial history of the area.

Below are descriptions of the gravel units in the map area that are based on our field observations.

3.5.1.1. Glacial Outwash (Qgo)

A deposit of glacial outwash was found overlying flood gravels at the Bull River Campground, near the junction of Bull River and the Clark Fork River. The deposit covers a flat bench >35m above the modern floodplain. It contacts with sharply steepening bedrock of the Wallace Fm to the northeast. The outwash consisted of gravels that were poorly to moderately sorted with a sandy/silty matrix. The clasts were rounded to subangular and of Belt and igneous origin. The deposit was coarsely-to-moderately stratified. Conglomerates cemented with calcitic were abundant in the top layers of the deposits and in areas influenced by groundwater percolation.

3.5.1.2. Flood Gravel Deposits

Flood gravel found in this area is predominantly clast-supported, pebble-to-boulder sized, poorly-to-moderately sorted and rounded-to-subrounded. The lithology of the gravels is generally of the Belt Supergroup (quartzite, siltite, argillite) as well as lesser amounts of igneous rocks such as granite and granodiorite. In places, gravel is mantled by silt which has infiltrated into the top layers.

Flood gravels cover much of the outer channel banks in the field area, adjacent to and mixed in with modern alluvium. Bull River has flood gravels on both sides of its flood plain and is locally overlain by alluvium at the meander where the river turns southwest toward the Clark Fork River. Down-cut mountain channels in the Snowslip and Wallace Formations along Bull River are infilled with flood deposits in most places. A large, moraine-like feature that trends toward the Clark Fork is covered in flood gravel and overlies alluvium.

East of the junction of Bull River and the Clark Fork River, flood gravels lie along the base of the steep Wallace Fm north of the river on the outer flood plain. South of the river on top of the Shephard Fm, is a planed off mound called Smeads Bench that is overlain by flood gravel. West of Smeads Bench, a large expansion gravel deposit fills the inner meander of the main river where the valley widens. Elk Creek’s western path is forced to turn northward to join with the Clark Fork (figure 9) upon reaching this gravel barrier. This deposit also fills in a large draw (Rice Draw) that that opens into the Shephard Fm - ~40 m west of Smeads Bench – and wraps around the base of a knob of the bedrock. Here the gravel is overlain by glaciolacustrine and alluvial deposits. Northeast of where Rice Draw exits the mountains are large scale dune deposits that can be seen on Google Earth (figure 10). Two streamlined gravel bars up to 4 km long parallel the river in the middle of the valley (Plate 1). They are adjacent to and mantled in glaciolacustrine sediments, have characteristically large-scale crossbedding, and erratics of up to more than a meter wide.

Figure 10: Flood gravels form a large expansion bar deposit where the valley widens. Large-scale dune deposits are distinct features on the unwooded area of this deposit. Notice where Elk Creek is forced to turn north at the west flank of the gravel deposit. Smeads Bench and Rice Draw are also shown, which are also covered in flood gravels.

Elk Creek forms a narrow channel that heads into the bedrock to the south. Again, there are flood gravels wrapped around the bedrock knobs where the narrow stream exits the mountains into the valley. On the east side of the creek there is a relatively large down-cut stream channel that is filled with gravel. The gravel extends along the bedrock to the southwest until the channel splits into 3 branches and beyond that the banks are covered in older alluvium. Along the sharp edge of the bedrock on the south side of the valley and to the west of Elk Creek, there are outcrops of flood gravel either as infill of down-cut channels or as benches slightly higher in elevation than the glaciolacustrine sediments adjacent to them.

North of the Town of Heron, flood gravel covers a large part of the map area. It dominates the river bank and reaches far into the mountains surrounding and overtopping the

Shephard formation, filling in the down-cut mountain channels in the Prichard Fm, the Helena-Wallace Fm, the Libby Fm and the Snowslip Fm in the northwest corner of the map.

At Blue Creek, these gravels are locally overlain by glaciolacustrine sediments and cover the banks of the east and west fork of the creek. At the Blue Creek Roadcut section (Location 2, Plate 1), the contact between the gravel with the sand above it is irregular, with cobbles protruding up into the sand and sand infiltrating around the cobbles below it. The basal gravel consists of poorly sorted cobble gravels with open-work gravel texture. The gravel below the lake beds has boulders, cobbles and pebbles throughout. The cobbles are of Belt Supergroup and igneous origin, are poorly sorted and of variable sizes and roundness. The erratic boulders measured up to ~90cm wide on their A-axis, were subrounded and randomly emplaced.

Gravel fills the valley to depths of >90 m deep (Figure 25) according to well log lithology data (Appendix C).

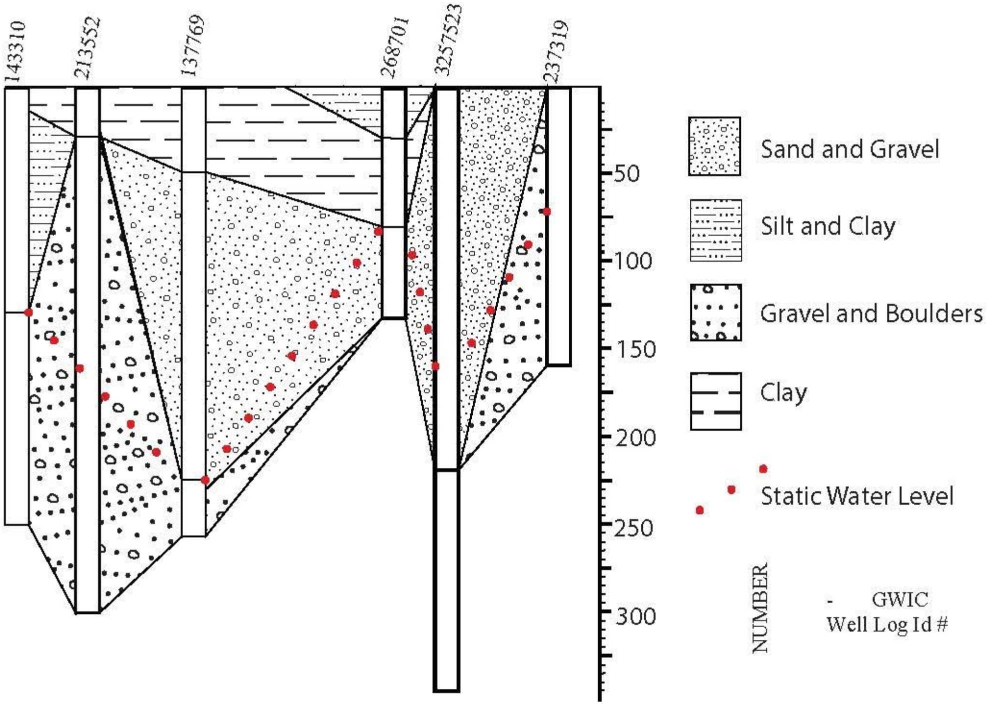


Figure 11: This cross section extends down-valley, parallel to the river. The primary surface geology is glaciolacustrine and gravel deposits. This diagram was made from well logs identified by their GWIC Id, (Appendix C). Reference Plate 1 for cross-section line.

Gravel deposits were well exposed in the multiple gravel pits within the field area. deposits were well exposed in the multiple gravel pits within the field area. These outcrops are described in a supplementary table in Appendix B, with their corresponding map locations.

Figure 12: Gravel Pit outcrop location G on Plate 1. This exposure shows poorly sorted gravels with large scale crossbedding. Flow direction is to the northwest.

Figure 13: Location F on Plate 1, this picture shows a gravel pit exposure along Bull River. These gravels are trending toward the river out of a down-cut channel in the Wallace Formation. The formation is very steep, so slope failure disrupts the bedding. The gravels here are poorly sorted, unconsolidated and crossbedded.

Figure 14: The Blue Creek Road gravel deposit is located across Highway 200 from the furthest western reach of the Clark Fork River in the map area. The junction of Blue Creek and the river is directly east of this picture.

Figure 15: Erratics as big as 90cm were found toward the top of the Blue Creek gravel deposit. A thin layer of lake beds mantles the deposit. This deposit is at location 2 on Plate 1.

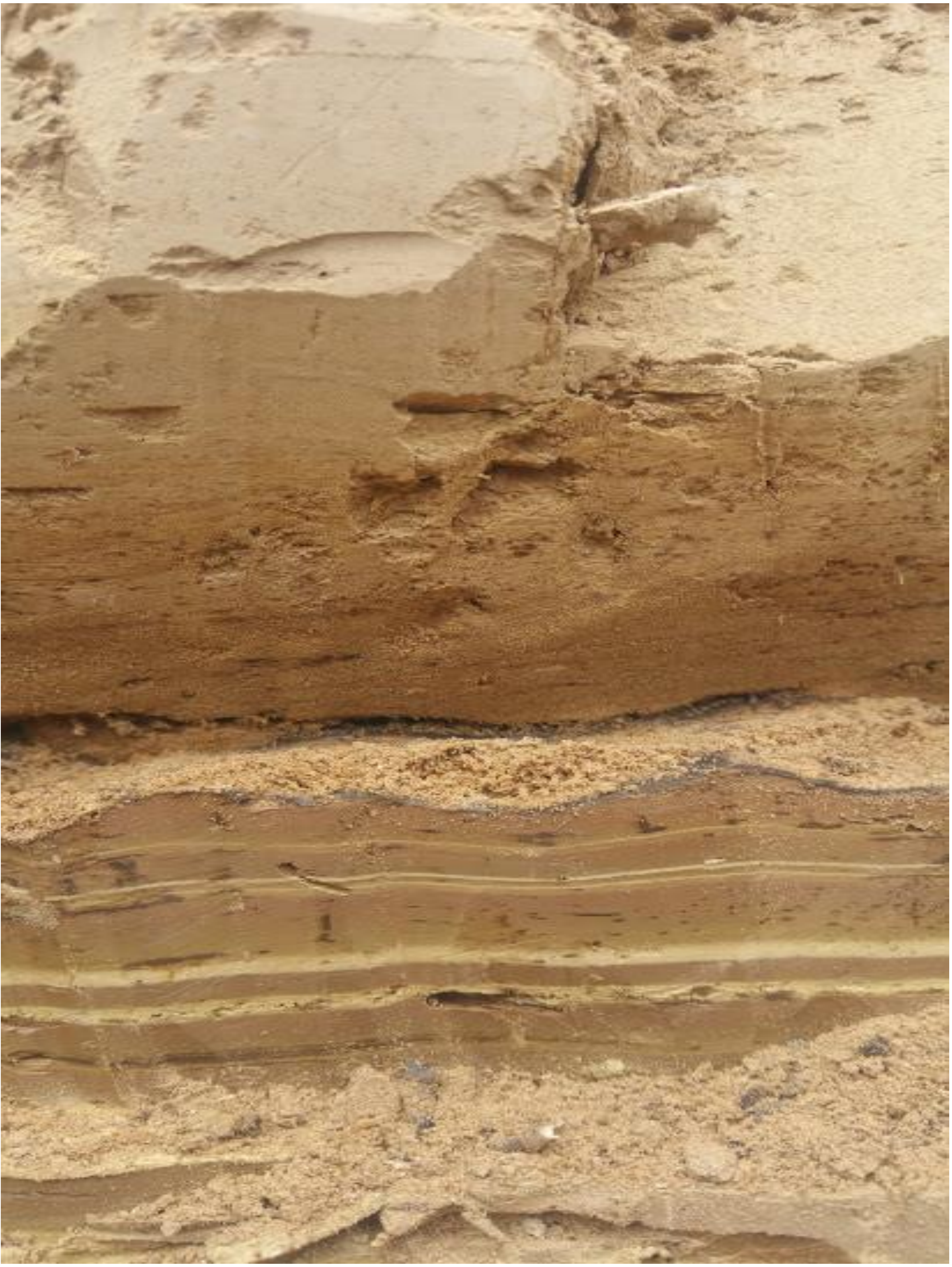
3.5.1.3. Glaciolacustrine Deposits (Qgl)

Glaciolacustrine sediments recognized in this study area are rhythmically bedded coarsening-upward sequences including sand, silt and clay. Each rhythmite consists of basal sections of a sandy silt facies that is bounded on the base by an erosional contact, overlain by the silt-clay facies that includes microlaminated couplets of silt and clay, with a lower gradational contact. Bedforms such as soft sediment deformation, load and dewatering structures, and moderate crossbedding are present in the basal sands in most cases. Figure 16 shows an outcrop of these sediments that has stairs dug into the slope to expose unweathered sediments and provide a climbable surface.

Figure 16: Vertical staircase I dug into the slope to analyze the glaciolacustrine sediments at the Elk Creek Rd section.

3.5.1.3.1. Sand-silt facies

The sand-silt facies are present in each of the 12 rhythmite units at the Elk Creek Road section. This facies consists of cross-bedded fine-grained quartz arenite sand, which grades to very fine sand and to silt. The base of these beds is typically crossbedded (figure 17a) and mudclasts (figure 17e) are present around the sand-silt transition. These sand-silt beds are thicker than the varved couplets above them. The range of thickness of the basal sand layers is 1.1 – 15 centimeters. Other defining features found in the sand-silt facies are erosive bottom contacts (figure 17b), load structures, (figure 17a), soft-sediment deformation (figure 17a, c), and micro-faulting (figure 17d).



a)

b)

c)

d)

e)

Figure 17: a.) A wavy, erosive contact between the sand-silt facies and the silt-clay facies. b.) A load structure at the contact between the silt-clay sub-facies and the sand-silt sub-facies. c.) Soft-sediment deformation mixed in silt from below into the clay at the base of the silt-clay facies. d.) Microfaulting of clay and silt beds. e.) Crossbedded basal sand with mudclasts at the sand-silt transition.

3.5.1.3.2. Silt-Clay Facies

The silt-clay facies consist of rhythmically sequenced couplets of silt and clay laminae (Figures 18a-d). These couplets have the same characteristics of the lake beds found in the upstream areas of the glacial Lake Missoula basin, i.e. Ninemile Creek, Tarkio, Rail Line, Mission Valley., etc.

The clay laminations in this section are predominantly thicker than the silt layers. The thickness of the silt laminations is variable but predominantly 0.2 – 6cm thick. The number of couplets per rhythmite ranges from 3 to 80. The average number of couplets per rhythmite section is 21, discounting the two rhythmites previously mentioned.

The contacts between the silt and clay laminations are gradational, and the contacts between couplets is sharp and planar. Other distinctive characteristics of these sequences is micro-faulting toward the top of the section and rip up clasts of sediment found in the sand-silt beds (Figure 18d).

There are places where microlaminations may be present but were eroded, faulted or too thin to be measured (18a).

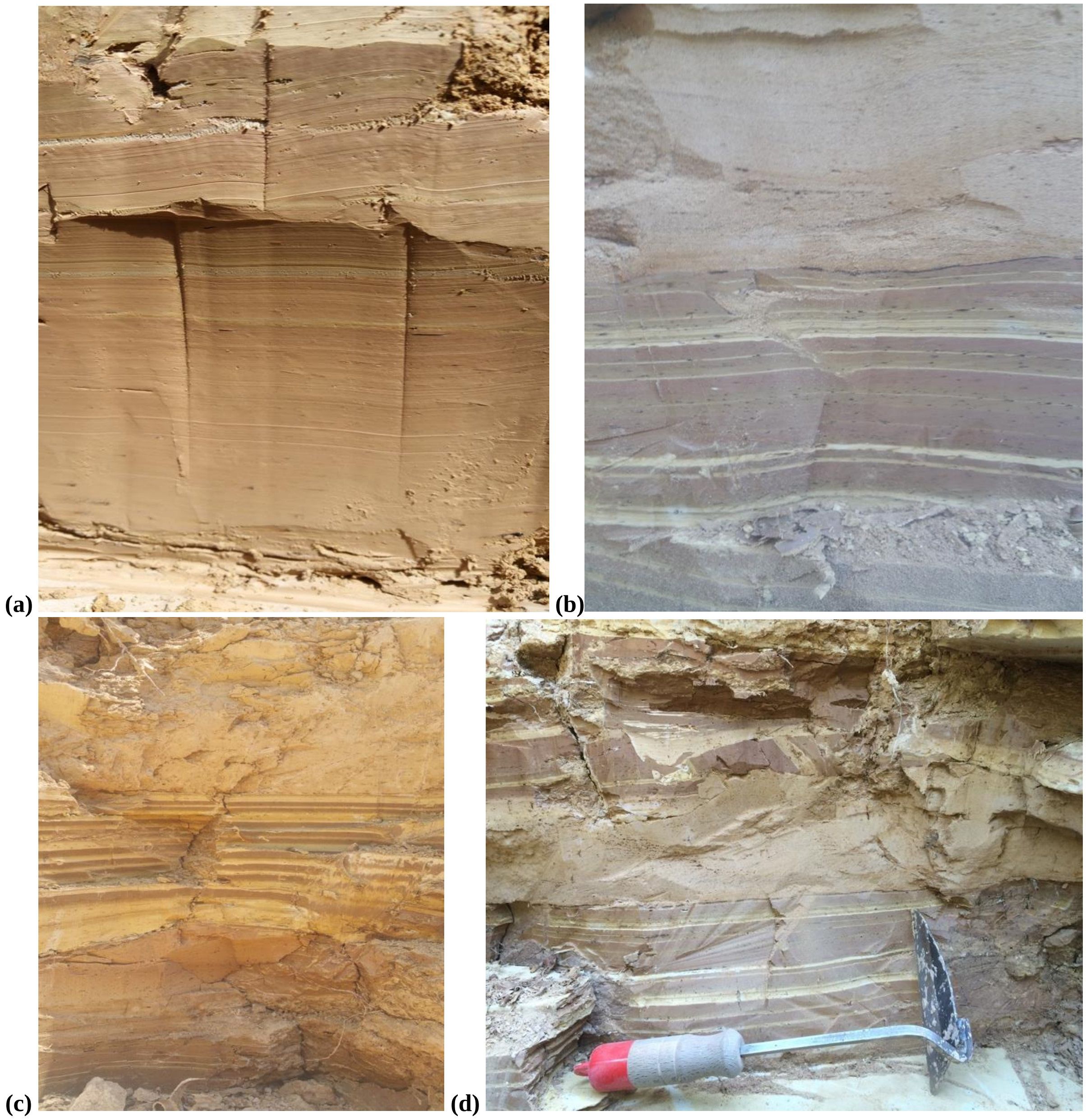


Figure 18: (a) Above the first basal sand measured was a thick layer of clay. (b) Silt-clay varves at a contact with a basal sand. This shows a possible ice wedge cast but it is unconfirmed. (c) 8 varve couplets and the basal sand of the next rhythmite are showing. This shows an example of varves thinning up-section. (d) Micro-faulting and varve inclusions are above the sand-silt contact.

3.5.1.3.3. The Elk Creek Rd Section

The Elk Creek Road section is a northeast-trending outcrop of glaciolacustrine sediment exposed at a road cut along Elk Creek Road, in the town of Heron, Montana. It is located just south of the Cabinet Gorge Reservoir and just east of the Montana/Idaho border This section is labeled 1 on the map (Plate I). The elevation of the glaciolacustrine beds at the Elk Creek Road

Section is ~719m, which is the lowest point in elevation of all the deposits documented. For reference to the descriptions provided, refer to the stratigraphic section, Plate II, in pocket.

The height of the Elk Creek Road exposure is ~9 meters from ground surface at its maximum and it tapers down toward an alluvial bench to the north. The exposed section is nearly vertical, so I dug diagonal steps to allow for the most complete stratigraphic analysis (Figure 16). This section was only measured and analyzed to ~4.5 meters above the road, as the upper part of the section was disturbed by plant roots and burrowing of insects.

The Elk Creek Road lake beds consist of sections of alternating silt and clay couplets. At the base of each section there is a bed of fine/very-fine, crossbedded sand that fines to silt, then the silt grades to clay. The sections with the basal sands are delineated in rhythmite units. At the Elk Creek Road section, the clay laminations are thicker than the silt laminations in general. The contacts between the clay and the silt are consistently sharp and planar, while the silt laminations grade normally to clay. Contacts between rhythmites are wavy and erosional. A flame structure invades the lower sediment at the base of the section. Mudclasts and broken pieces of the laminated sediment are incorporated into the sand in places along with microfaulting of couplets. These features are generally found directly above the sand/silt – silt-clay facies' contacts. Mudclasts were also found in the sand bed of the second rhythmite.

The top few meters of sediment was bioturbated and had root interference and so it was not analyzed in the section. A sample was collected from the sand-silt facies about 3.5 meters up from the base of the section for burial age-dating analysis. The exact location of where the sample was taken can be seen on Plate 2. The base of the sequence of rhythmites, where glaciolacustrine sediments are underlain by gravel, was not found.

3.5.1.3.3.1. Blue Creek Lake Beds

The Blue Creek Road Section is an east-west-trending blanket of glaciolacustrine sediments on top of a thick gravel deposit. The exposure is located at a road cut along Highway 200, north of the Cabinet Gorge Reservoir and is labeled location 2 on the map (Plate 1). The top of the section is at an elevation of ~731.5 meters and the lake sediments are <0.5 meters thick at this location.

The Blue Creek roadcut section has only one rhythmite above its contact with gravel (Figure 15). The glaciolacustrine sediments consists of a basal, cross-bedded sand layer that grades to laminated silt and then to clay. The rest of the sequence consists of 12 silt-clay couplets.

Figure 19: This picture shows the Blue Creek Road rhythmite section beginning with the sand-gravel facies at the base, then a fine sand-to-silt layer below a section of 12 varve couplets.

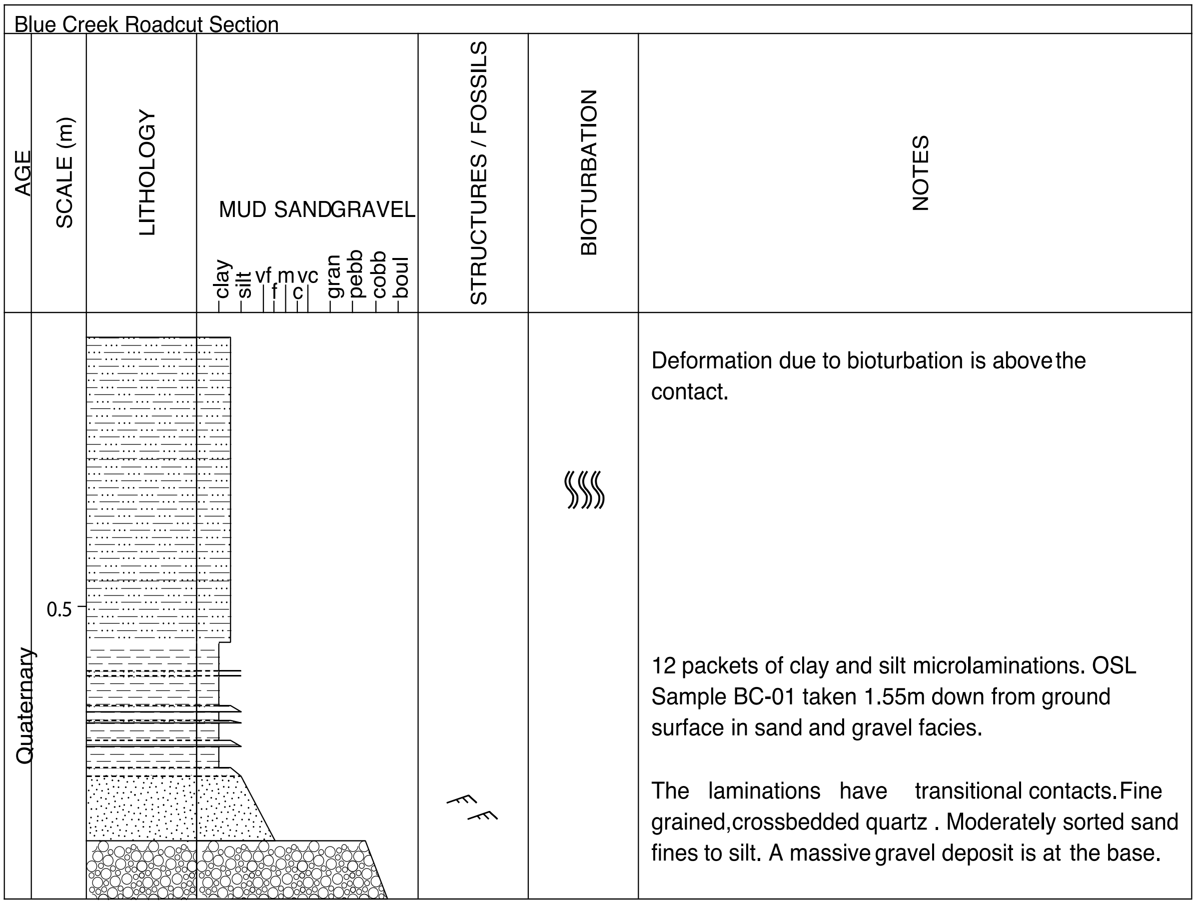


Figure 20: Stratigraphic section of the one rhythmite unit at the Blue Creek Road Section. A gravel deposit is the base of the section. The symbol next to the sand bed represents crossbedding. The symbol toward the upper part of the section indicates bioturbation.

3.5.1.4. Holocene Alluvial Deposits

3.5.1.4.1. Older Alluvium (Qalo)

Old alluvium was mostly found adjacent to the larger streams in areas outside of (stream) flood plains, but inset into the older flood gravel deposits. The rocks are of Belt Supergroup and igneous lithology The gravel is well-sorted, rounded to subrounded and normally graded. Older alluvium is generally less consolidated than active alluvium and is covered in overgrowth.

3.5.1.4.2. Active Alluvium (Qal)

The young alluvium in the field area is found along the banks of the main river and its tributaries. It consists of well-sorted, rounded to subrounded, normally graded gravel and gravelly-sand deposits. Silt infiltrations and calcite cementation is common due to groundwater influence.

Figure 21: This picture faces north towards the river over the alluvial plain adjacent to the Elk Creek Road lakebeds.

3.5.1.4.3. Alluvial Fans (Qaf)

There are three alluvial fans in the field area. Two are downstream of the Bull River outlet and the third is west of where Elk Creek enters the valley. They consist of unconsolidated deposits of unsorted tallus and gravel. The rocks were transported out of the mountains by water and piled up in a conical shape at its base where the stream reached the open valley. The lithology of these deposits is reflective of the formation the stream emptied out of.

3.6. Optical Ages

Optical dating of basal sands in the rhythmic glaciolacustrine sequences gives an approximate age of when the sediment was buried. These results can then be compared with the ages of other similar deposits within the lake basin.

Quartz luminesce age dating depends on the dose rate and the dose equivalent of the samples. The dose rates for the quartz samples are shown on Table I. 14 aliquots were used to determine bracketed D_E values for both samples, but only 12 were analyzed for BC-01. The estimated values are shown in Table I and distribution radial plots used in determining these values are shown in Appendix A. The following data was produced by Tammy Rittenour after processing the EC-01 and BC-01 samples in the lab at USU.

Table I: Small-Aliquot Optically Stimulated Luminescence (OSL) Age Information.

Sample number	USU num.	Depth (m)	Num. of aliquots[1]	Dose rate (Gy/ka)	D_E[2] ± 2σ (Gy)	OD[3] (%)	OSL age ± 2σ (ka)
EC-01	USU-2128	4.27	14 (14)	4.71 ± 0.21	59.61 ± 3.22	2.3 ± 8.1	12.65 ± 1.414
BC-01	USU-2129	1.55	12 (14)	4.00 ± 0.18	70.42 ± 5.57	9.1 ± 4.1	17.60 ± 2.20

[1] Age analysis using the single-aliquot regenerative-dose procedure of Murray and Wintle (2000) on 2mm small-aliquots of quartz sand. Number of aliquots used in age calculation and number of aliquots analyzed in parentheses.

[2] Equivalent dose (D_E) calculated using the Central Age Model (CAM) of Galbraith and Roberts (2012).

[3] Overdispersion (OD) represents variance in D_E data beyond measurement uncertainties, OD >20% may indicate significant scatter due to depositional or post-depositional processes.

[4] Quartz OSL age is underestimating burial age, see IRSL results in Table 2.

The sand sample (EC-01) collected from the Elk Creek Road section yielded a burial age of 12.65 ± 1.414 ka using the OSL dating technique on quartz grains. Dr Rittenour tested the luminescence and concluded that the intensity of the signal was too weak and likely underestimated the age. Using IRSL on this sample yielded an age of 16.02 ± 1.08 ka after correcting for anomalous fading (Table II). Dr. Rittenour reported that this represents an accurate estimate for the burial age of this sediment.

TheBC-01 sample collected from the Blue Creek Roadcut section yielded a final burial age of 17.60 ± 2.20 ka using OSL on the quartz grains and 18.28± 3.67 using IRSL on feldspar (Table II). The test showed that IRSL over-dispersion (OD %, Appendix A) was >20%, which indicates scatter that may have overestimated the results.

Table II: Infrared Stimulated Luminescence (IRSL) Age Information

Sample num.	**USU num.**	**Num. of aliquots[1]**	**Dose rate (Gy/ka)**	**D_E[2] ± 2σ (Gy)**	**OD[3] (%)**	**IRSL age[4] ± 2σ (ka)**	**Fading Rate g_{2days} (%/decade)**
EC-01	USU-2128	11 (13)	6.74 ± 0.33	79.02 ± 7.18	9.8 ± 4.8	**16.02 ± 1.08**	3.4 ± 1.0
BC-01	USU-2129	13 (14)	5.89 ± 0.30	78.99 ± 13.97	29.3 ± 6.7	**18.28 ± 3.67**	3.7 ± 0.7

[1] Age analysis using the single-aliquot regenerative-dose procedure of Wallinga et al. (2000) on 1-2mm small-aliquots of feldspar sand at 50°C IRSL. Number of aliquots used in age calculation and number of aliquots analyzed in parentheses.

[2] Equivalent dose (D_E) and IRSL age calculated using the Central Age Model (CAM) of Galbraith and Roberts (2012), unless otherwise noted.

[3] Overdispersion (OD) represents variance in D_E data beyond measurement uncertainties, OD >20% may indicate significant scatter due to depositional or post-depositional processes.

[4] IRSL age on each aliquot corrected for fading following the method by Auclair et al. (2003) and correction model of Huntley and Lamothe (2001).

Table III: Dose Rate Information

Sample num.	USU num.	In-situ H_2O (%)[1]	Grain size (µm)	K (%)[2]	Rb (ppm)[2]	Th (ppm)[2]	U (ppm)[2]	Cosmic (Gy/ka)
EC-01	USU-2128	2.4	63-150	3.14±0.08	147.5±5.9	13.3±1.2	2.8±0.2	0.14±0.01
BC-01	USU-2129 [3]	4.7	63-150	2.35±0.06 2.60±0.07	109.0±4.4 124.0±5.0	12.3±1.1 11.6±1.0	2.6±0.2 2.7±0.2	0.20±0.02

Assumed 5±2% for moisture content over burial history.

Radioelemental concentrations determined by ALS Chemex using ICP-MS and ICP-AES techniques; dose rate is derived from concentrations by conversion factors from Guérin et al. (2011). For IRSL dose rate, grain-size based internal beta dose rate determined assuming 12.5% K and 400ppm Rb using Mejdahl (1979). Alpha contribution to dose rate determined using an ‘a’ factor of 0.10±0.05 after Rees-Jones (1995).

Dose Rate for USU-2129 is average of sediment dose rate sample (top values) and rock dose rate sample (bottom values).

4. Geologic History

4.1. Precambrian

During the Mid-Proterozoic (1,470 – 1,400 Ma), an accumulation of ~15-20 km (Winston and Link, 1993) of sedimentary rocks were deposited into a rifted intracratonic basin on the edge of North America. These sediments make up what is known as the Belt Supergroup, which is the predominant bedrock in the field area. The basin was mostly a lacustrine environment but was periodically connected to the ocean (Winston and Link, 1993).

At the base of the Belt Supergroup is the Prichard Fm, which is the thickest of all the Belt units, and its thickest known exposure is near the field area in Plains, MT (Cressman, 1985). The Prichard Fm was deposited during the first marine progradation of deltaic complexes into the basin (Cressman, 1989). The Ravilli Gp. is stratigraphically above the Prichard Fm. The units in the Ravilli Gp have been interpreted to represent marine transgression and progradation of beaches, deltas, tidal flats and alluvial plains (Winston and Link, 1993). Above the Ravilli Gp, is the Peigan Gp., also referred to as the Middle Belt Carbonate. It has been interpreted to represent another transgressive-regressive sequence in and out of the basin. Dolomitic to siliciclastic cycles of the Helena Fm. have been interpreted to suggest a marine/lacustrine environment. The uppermost group of the sequence is the Missoula Gp. It is interpreted to be intertidal and subtidal, due to evidence of traction transport, suspension settle out, and desiccation (Horodyski, 1983).

4.2. Phanerozoic (541 Ma to present)

Paleozoic (541 to 252 Ma)

The early Paleozoic was a period of uplift folding and faulting. The Cambrian Period (541-485Ma) took place during a time of sea level rise when water inundated the entire area, depositing limestone and shale in a transgressive sequence (USFS, Kootenai National Forest, 1979). Evidence of this unit in the field area are two small outcrops about one-mile northeast of Heron.

4.2.1. Mesozoic (252 – 66 Ma)

There is no sedimentary record of Mesozoic rocks in the field area, though the time frame is significant in the formation of the landscape. The Laramide Orogeny took place from about 100 Ma. in the Late Cretaceous into the Middle Tertiary (Cenozoic period about the 40 Ma.) as a result of plate interactions along the western continental margin. This orogeny built the Rocky Mountains and the Lewis Thrust Belt. Tectonic forces uplifted and deformed the Belt rocks into northwest-trending folds and faults. Right-lateral movement was active along the Hope fault during this period of thrusting.

4.2.2. Cenozoic (66 Ma – present)

The Quaternary Period, Pleistocene Epoch (2.6 Ma – 12,000yr)

In the Quaternary, during the Bull Lake Glaciation (200ka – 130ka) and the Pinedale Glaciation (25ka – 11.2ka) the Cordilleran Ice Sheet descended southward from Canada, covering much of the Northern Rocky Mountains.

During the Bull Lake glaciation, The Bull River lobe of the Cordilleran Ice Sheet flowed down Bull River, possibly reaching as far as the Clark Fork River (Richmond, 1965; Alden, 1953). Alden (1953, p. 140) cited evidence for a flood-gravel-covered moraine, just south of the junction of Bull River and East Bull River.

During the Pinedale glaciation, the Purcell Lobe extended eastward through the Purcell Trench, past the Idaho-Montana border, and merged with local alpine glaciers (Richmond et al., 1965), damming glacial Lake Missoula. The history of glacial Lake Missoula in the study area will be presented in detail below.

5. Discussion

Mapping the geology of the area where the ice dam once impounded glacial Lake Missoula allowed for a big picture perspective on the history of the lake and the geomorphic expression that the ice and water left in their wake. It did not prove easy to map, due to the density of the forest cover and steep slopes. For this reason, walking out contacts of bedrock was treacherous in some places. We focused on delineation between Belt units to try to improve upon precision of contact placement, while mostly staying close to the valley margins. The placement of the Belt unit contacts in other areas was done using the previously published maps mentioned earlier, predominantly The Geology of the Libby Thrust Belt, Northwest Montana by Harrison and Cressman (1993). This map was also referenced when expanding on the rock descriptions from what we saw in the field area, and in fault-line placement.

Distinguishing between alluvium and flood gravels was not always obvious due to calcitic cement in the top layers of the deposits closest to the rivers. This gave an impression of consolidation in areas where the gravels were most likely conglomerated by ground water percolation. We didn’t have the equipment with which to dig into these deposits to determine thicknesses of alluvium and old alluvium deposits. Such equipment and effort would possibly uncover multiple layers of flood and lake deposits, as was done by the Washington Water Power Company when they built the Cabinet Gorge dam. The company drilled monitor wells that showed that the terrace north of the river had several cycles of clay till with interbedded lake deposits, which Breckenridge (1989) believes is indicative of several episodes of ice damming.

Upon construction of the Cabinet Gorge Dam in 1952, the length of the Clark Fork River in the field area was flooded and much of the channel bank sediment cannot be reached. Breckenridge (1989) reported abundant till cover along the north side of the valley west of the dam, interpreting it to be ice marginal deposits. Drilling into the flooded sediment would most likely uncover the same ice marginal till. Breckenridge proposed that the flood drainage may have been pushed to the south side of the valley by ice on the north during smaller late-glacial floods. If this is true, then the gravels that were deposited north of the river and up Blue Creek may represent an earlier flood deposit than the gravels south of the river. The burial age for the sand sample at Blue Creek Rd indicates that they are likely the same age as the valley gravels, as the age was most likely an overestimation, but this is not definitive.

There are two moraine-like features north of the Bull River Campground and across the valley on Smeads Bench that are covered in flood gravel. The shape of the deposits suggests that they may have been formed by the terminus of the Purcell lobe in one or two advances and were then covered in gravel by flooding.

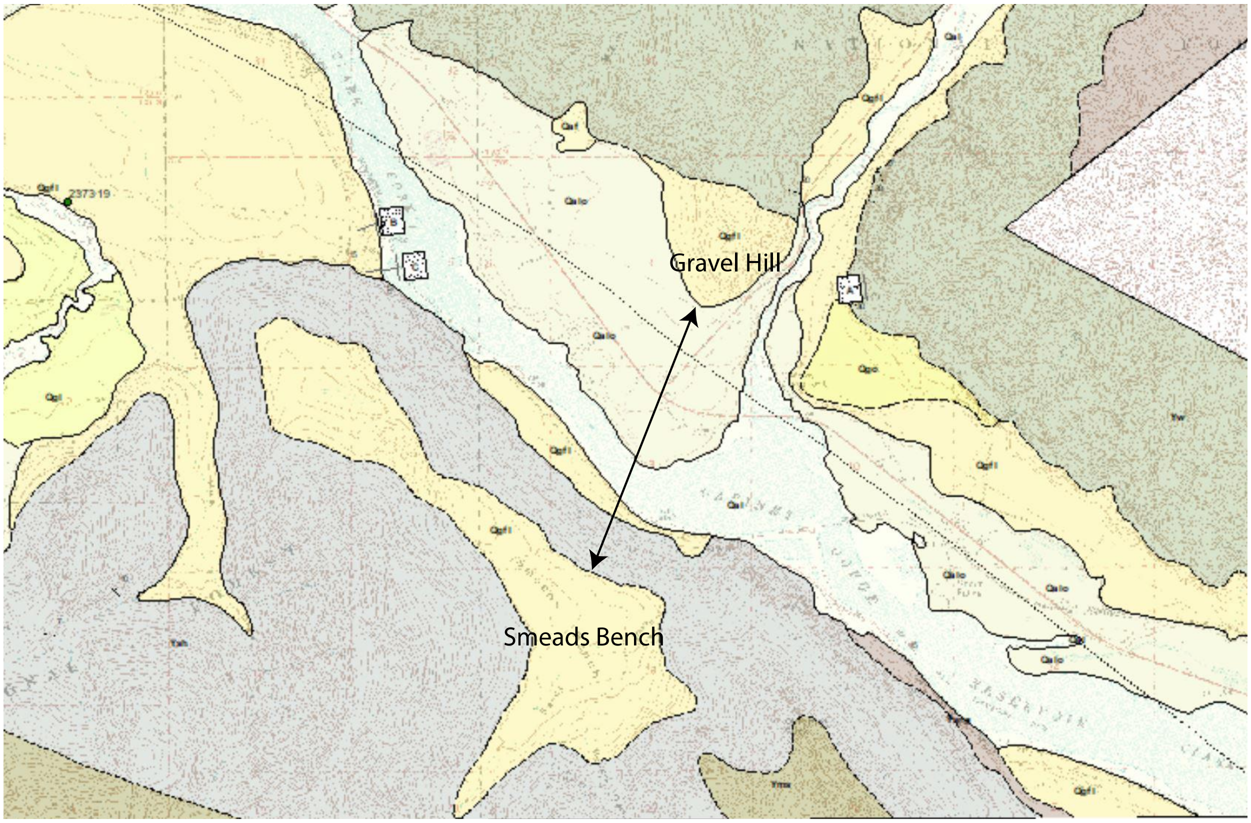


Figure 22: Portion of the geologic map (Plate I) showing the position of Smeads Bench and a moraine-like hill of gravel near the confluence of Bull River and Clark Fork River. The “A” symbol shows the location of the Bull River Campground mentioned in the text.

Figure 23: Picture showing the gravel mound across the river from the Bull River Campground that is depicted above in Figure 23.

West of Bull River and Smeads Bench (Figure 22), the valley widens significantly, which provided room for the floodwaters to spread out and the flood velocity to decrease. This allowed for large deposits of gravel to accumulate in the western half of the valley. The giant current dunes that formed on an expansion gravel bar where the valley first widens (Figure 10), and the streamlined gravel bars in the mid-valley show that the flow was still cascading at relatively high velocities during this particular flood. Eddy deposits are found accumulated at bedrock knobs. The gravel was pushed laterally to lap up against the steep bedrock at the edges of the valley and along tributary stream valleys. It infilled areas protected from stream erosion, and filled the valley >90 m deep according to well log lithology data (Appendix C). This thick deposit could be representative of one or multiple floods.

After the catastrophic flooding took place that deposited the gravels currently found in the field area, the dam reformed and the lake refilled. This is evident because glaciolacustrine sediments overlie flood gravels throughout the Clark Fork River valley and up Blue Creek and are therefore the younger of the deposits. This was probably the last stage of glacial Lake Missoula, unless evidence is found for subaerial exposure in the lake beds in the field area, of which I found nothing conclusive. Another high-velocity flood would have eroded away all evidence of the lake sediments in the field area, though it is possible that some of it was eroded.

While the river was impounded, glaciolacustrine silt and clay laminae were deposited on the lake bottom via settling out from the water column and underwater currents. The silt grades to clay which is commonly associated with turbidity currents causing a layer of water full of suspended sediment to flow across the bottom of the basin. Coarser grains settle out as bed load first, then finer grains settle out from the water column. These deposits are commonly referred to as varves and they are seasonally variable. Cooler temperatures cause varves to be thinner due to less runoff. Composite varves have thin clay laminae within the lighter silt layer, making intermittent couplets that resemble varves (Antevs, 1951). What I found was the opposite, thin silt laminae inside the thicker clay layers, still making the separation of true varves an inexact science.

The thinness of the silt laminae in the varved sequences at Elk Creek Rd suggests there were less high-energy turbidity currents during the summer months. This could be related to why the clay laminations were generally thicker because more sediment was being deposited by settling out of the water column. Climate may also have had an influence if colder temperatures, possibly due to proximity to the ice, produced less melt and more rock flour.

I found no conclusive evidence for subaerial exposure at the Elk Creek Road site, although this may be subject to interpretation. Micro-faulting, broken varve and dewatering structures have been cited as desiccation features from subaerial exposure (Hanson et al., 2012). They could also be due to dewatering and erosion due to rapid loading of the overlying sand-silt units (Shaw et al., 2000). I found one feature at the bottom contact of second basal sand that looked similar to an ice wedge cast, but I couldn’t find it the next day and it may have been caused by sediment disturbance from digging. I cannot conclusively say it was a subaerial exposure and I did not see any more features like it in the section.

The crossbedded, erosive sand beds at the base of each rhythmite section were likely deposited by higher-energy, higher-density currents produced following a fluctuation in the lake’s depth. The basal sand and silt beds grade upward into silt-clay varves that were deposited in deeper water (Hanson et al., 2012), further away from the sediment source.

5.1. OSL Discussion

Once correcting for anomalous fading in the IRSL K-Spar dose rate, the age of the sand sample from the Elk Creek Road section was approximately 16.02 +-1.08 for sample EC-01. When the feldspar was not corrected for anomalous fading, the lower IRSL K-Feldspar ages indicates that the quartz was well bleached. Dr. Rittenour (2016) found that the OSL signal intensity in the quarts for EC-01 was low and that the IRSL results were more accurate.

The Over Dispersion (OD) as shown on Table 2 of the Full Luminescence Report (Appendix A) for the BC-01 sample had a value >20% which indicates significant scatter due to processes during and after deposition. Due to the closeness of the sampled sand to the underlying gravels at the Blue Creek Roadcut section, we believe that there was mixing of the glaciolacustrine sand with sand in the gravel deposit below causing the age to be overestimated.

5.1.1. Susceptibility for Error

The contrasts of ISRL to OSL are that K-feldspar has a stronger and more stable luminescence signal when responding to near-infrared light. It also saturates slower than quartz. Yet quartz is preferred to feldspar because it is much more rapidly bleached when exposed to sunlight.

When a grain of quartz is fully bleached, the OSL signal was reset completely prior to burial. Partial bleaching occurs when a grain of sand is not exposed to enough direct sunlight prior to being buried. This can commonly happen when sediment is remobilized in a lake by turbidites, where sunlight is limited, and thus the OSL signal is not fully reset. This results in an age underestimation (Nelson et al., 2015).

If it is suspected that the OSL signal was not reset in all grains prior to deposition and burial, scatter must be considered. Although, it has now been shown through experiment that it takes <1 minute of direct sunlight to completely reset the signal (Godfrey-Smith et al., 1988) in quartz grains.

Moisture content, post-depositional mixing and partial bleaching are all sources of error when undertaking the processing of samples for burial dating. Water content impacts the bulk density of sediment and decreases the effective exposure to radiation from the surrounding sediment. Climate and grain size are twos factors in estimating soil moisture content. The effects of these are figured into a model that compares the results of both and provides a dose rate variability (Nelson and Rittenour, 2015).

Post-depositional mixing is caused by occurrences such as erosional contacts, bioturbation, soil formation, desiccation cracks, and frost wedging. All of these and more can mix grains of different age and origin. This flaws the dating results by causing scatter in the signal.

See Appendix A for the complete Final Luminescence Age Report from the USU luminescence laboratory. (Appendix A).

5.2. Hydrogeologic Implications

Many areas of influence of the lake Missoula floods benefit from the flood gravels for their primary aquifers. West of the field area, the Spokane Aquifer consists of coarse sand gravel, cobble and boulders left over from one or more flood events. This is one of the most productive aquifers in the United States (Molenaar, 1988). The gravels fill the valley > 90 meters in places and have good aquifer potential due to their lack of sorting and openwork texture. See Appendix B for a description of different gravel deposits that were exposed and their aquifer potential.

5.3. Comparison of our data with previous studies

Two significant sites that had burial ages similar to the Elk Creek Road section are the Ninemile and Rail Line sections, about 250km upstream along the Clark Fork River. Hanson et al. (2012) used the SAR method and CAM models for determining the OSL burial age of the quartz samples taken at the Rail Line and Ninemile sections. At the Ninemile section, subaerial exposures were found at 936 m a.s.l. and the crossbedded basal sand at the base of the section was buried 15.1 +- 0.6 kya. At the Rail Line section, at around 970 meters a.s.l the basal sand was dated at 14.8 +- 0.7 ka. The burial ages between these sites and the age of the Elk Creek Rd section are comparable when their analytical uncertainties are taken into account.

Burial-age date analysis of transgressive sand beds at different elevations has been done in order to better interpret glacial Lake Missoula filling and draining cycles. The current interpretation of this data by most who study it is that the last glacial Lake Missoula did not drain catastrophically but fluctuated in depth during its last stages. These findings are supported in this research. Each of the sand beds that are sampled represents a period of time in which the lake had either drained completely or fluctuated in depth in already shallow water.

A notable difference from the Elk Creek Road section and the Ninemile and Rail Line sections is a presumed lack of subaerial exposures in the lake sediments in the field area. Since the other two locations are 200-300 meters higher in elevation, the presence of subaerial exposures means that the water drained completely below an elevation of 936 meters around 15,000 – 16,000 years ago. The lack of evidence for these features at the Elk Creek Road section shows that the lake did not drain below 720 meters at that time.

6. Conclusions

During the Wisconsin age of the Pleistocene era, the Purcell Lobe of the Cordilleran Ice Sheet blocked the flow of the Clark Fork River and created glacial Lake Missoula. The location of one or two positions of this ice dam is the area of study in this paper.

We found geomorphic and sedimentological evidence for catastrophic flooding in the field area. In the valley, high velocities of water shaped streamlined gravel bars and eddy deposits. Gravel covers the outer banks of all the main streams in the field area and in alpine channel reaches. Well logs show that the gravel reaches depths of over 90 meters within the valley. The gravels are overlain by glaciolacustrine sediment, so they are the older of the two deposits. Both glacial Lake Missoula sediments and flood gravels were preserved throughout most of the Clark Fork River Valley in the field area, and thus were not eroded by subsequent flooding.

On the floor of glacial Lake Missoula, varved couplets of glaciolacustrine sediment were deposited. The varves thin up-section and represent a period when the lake was deepening. Unconformable and erosive crossbedded sand beds are at the base of each section of varves. These layers represent a high-energy influx of sediment into the lake after it had dropped in water level and was closer to the sediment supply.

OSL burial-date analysis of a basal sand bed in the field area yielded an age of 16.02 +-1.08 ka. This is within error margins of being consistent with OSL ages from the Ninemile and Rail Line sections ~200 km upstream. Correlation of transgressive sands across the glacial Lake Missoula basin helps to interpret the nature of the lake's filling and draining cycles.

Subaerial exposures were found by others in basal sand layers of glacial Lake Missoula deposits ~200 meters higher in elevation and ~200 km upstream from the current map area.There were no features to conclusively indicate subaerial exposure in the map area, yet the sands are within the same age bracket as those found at the Ninemile and Rail Line sections. The lack of these features in the Elk Creek Road section suggests that the lake was not completely draining during each cycle of lake-level change at this time.

Around 16,000 years ago, glacial Lake Missoula was fluctuating in depth in shallow water and did so until it drained completely. Preservation of fine-grained lake sediments in the map area, likely less than 5 km upstream of the last ice dam, suggests that the lake that deposited the sediments did not drain catastrophically.

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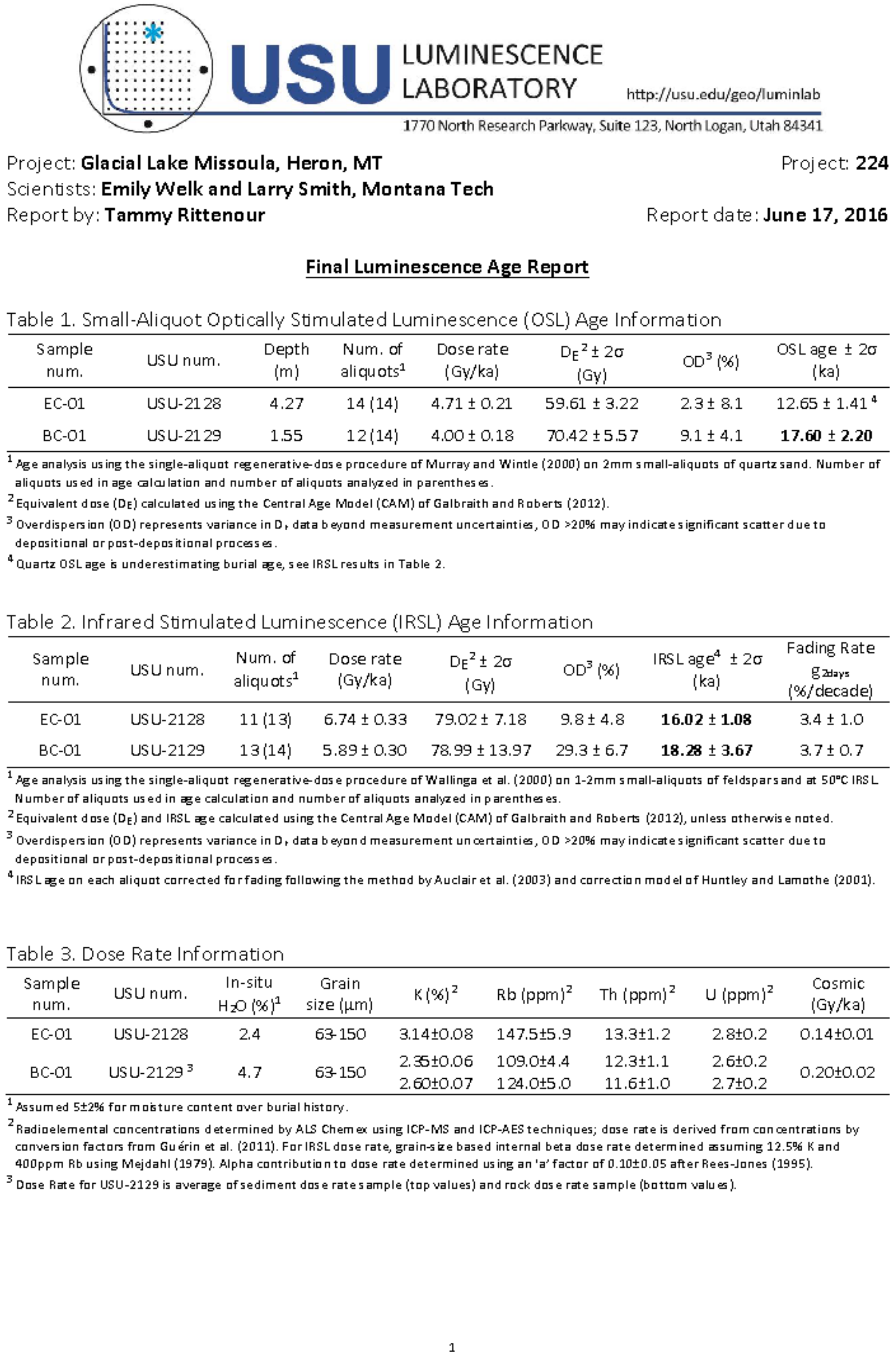
8. Appendix A: Final Luminescence Age Report



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Project: **Glacial Lake Missoula, Heron, MT** Project: **224**
Scientists: **Emily Welk and Larry Smith, Montana Tech**
Report by: **Tammy Rittenour** Report date: **June 17, 2016**

Final Luminescence Age Report

Table 1. Small-Aliquot Optically Stimulated Luminescence (OSL) Age Information

Sample num.	USU num.	Depth (m)	Num. of aliquots[1]	Dose rate (Gy/ka)	D_E[2] ± 2σ (Gy)	OD[3] (%)	OSL age ± 2σ (ka)
EC-01	USU-2128	4.27	14 (14)	4.71 ± 0.21	59.61 ± 3.22	2.3 ± 8.1	12.65 ± 1.41[4]
BC-01	USU-2129	1.55	12 (14)	4.00 ± 0.18	70.42 ± 5.57	9.1 ± 4.1	**17.60 ± 2.20**

[1] Age analysis using the single-aliquot regenerative-dose procedure of Murray and Wintle (2000) on 2mm small-aliquots of quartz sand. Number of aliquots used in age calculation and number of aliquots analyzed in parentheses.

[2] Equivalent dose (D_E) calculated using the Central Age Model (CAM) of Galbraith and Roberts (2012).

[3] Overdispersion (OD) represents variance in D_E data beyond measurement uncertainties, OD >20% may indicate significant scatter due to depositional or post-depositional processes.

[4] Quartz OSL age is underestimating burial age, see IRSL results in Table 2.

Table 2. Infrared Stimulated Luminescence (IRSL) Age Information

Sample num.	USU num.	Num. of aliquots[1]	Dose rate (Gy/ka)	D_E[2] ± 2σ (Gy)	OD[3] (%)	IRSL age[4] ± 2σ (ka)	Fading Rate g_{2days} (%/decade)
EC-01	USU-2128	11 (13)	6.74 ± 0.33	79.02 ± 7.18	9.8 ± 4.8	**16.02 ± 1.08**	3.4 ± 1.0
BC-01	USU-2129	13 (14)	5.89 ± 0.30	78.99 ± 13.97	29.3 ± 6.7	**18.28 ± 3.67**	3.7 ± 0.7

[1] Age analysis using the single-aliquot regenerative-dose procedure of Wallinga et al. (2000) on 1-2mm small-aliquots of feldspars and at 50°C IRSL. Number of aliquots used in age calculation and number of aliquots analyzed in parentheses.

[2] Equivalent dose (D_E) and IRSL age calculated using the Central Age Model (CAM) of Galbraith and Roberts (2012), unless otherwise noted.

[3] Overdispersion (OD) represents variance in D_E data beyond measurement uncertainties, OD >20% may indicate significant scatter due to depositional or post-depositional processes.

[4] IRSL age on each aliquot corrected for fading following the method by Auclair et al. (2003) and correction model of Huntley and Lamothe (2001).

Table 3. Dose Rate Information

Sample num.	USU num.	In-situ H_2O (%)[1]	Grain size (μm)	K (%)[2]	Rb (ppm)[2]	Th (ppm)[2]	U (ppm)[2]	Cosmic (Gy/ka)
EC-01	USU-2128	2.4	63-150	3.14±0.08	147.5±5.9	13.3±1.2	2.8±0.2	0.14±0.01
BC-01	USU-2129[3]	4.7	63-150	2.35±0.06 2.60±0.07	109.0±4.4 124.0±5.0	12.3±1.1 11.6±1.0	2.6±0.2 2.7±0.2	0.20±0.02

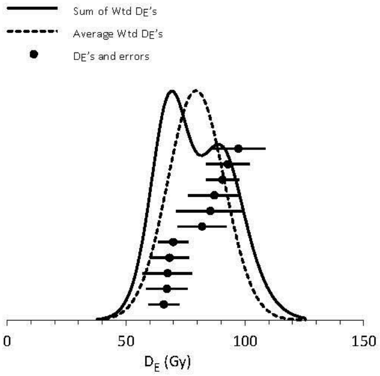
[1] Assumed 5±2% for moisture content over burial history.

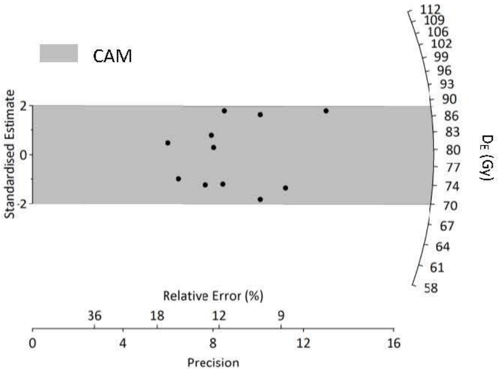
[2] Radioelemental concentrations determined by ALS Chemex using ICP-MS and ICP-AES techniques; dose rate is derived from concentrations by conversion factors from Guérin et al. (2011). For IRSL dose rate, grain-size based internal beta dose rate determined assuming 12.5% K and 400ppm Rb using Mejdahl (1979). Alpha contribution to dose rate determined using an 'a' factor of 0.10±0.05 after Rees-Jones (1995).

[3] Dose Rate for USU-2129 is average of sediment dose rate sample (top values) and rock dose rate sample (bottom values).

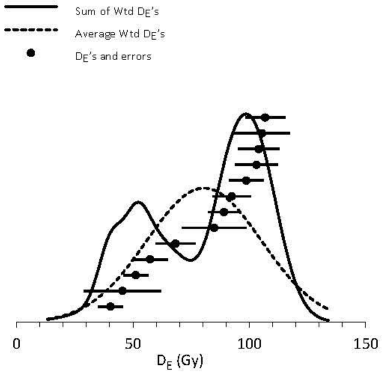
IRSL Equivalent Dose (D_E) Distributions: Probability density functions and radial plots

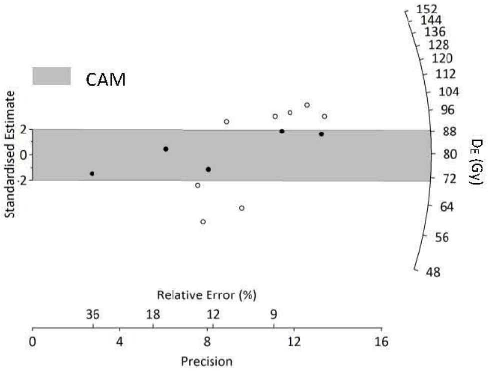
1. EC-01, USU-2128

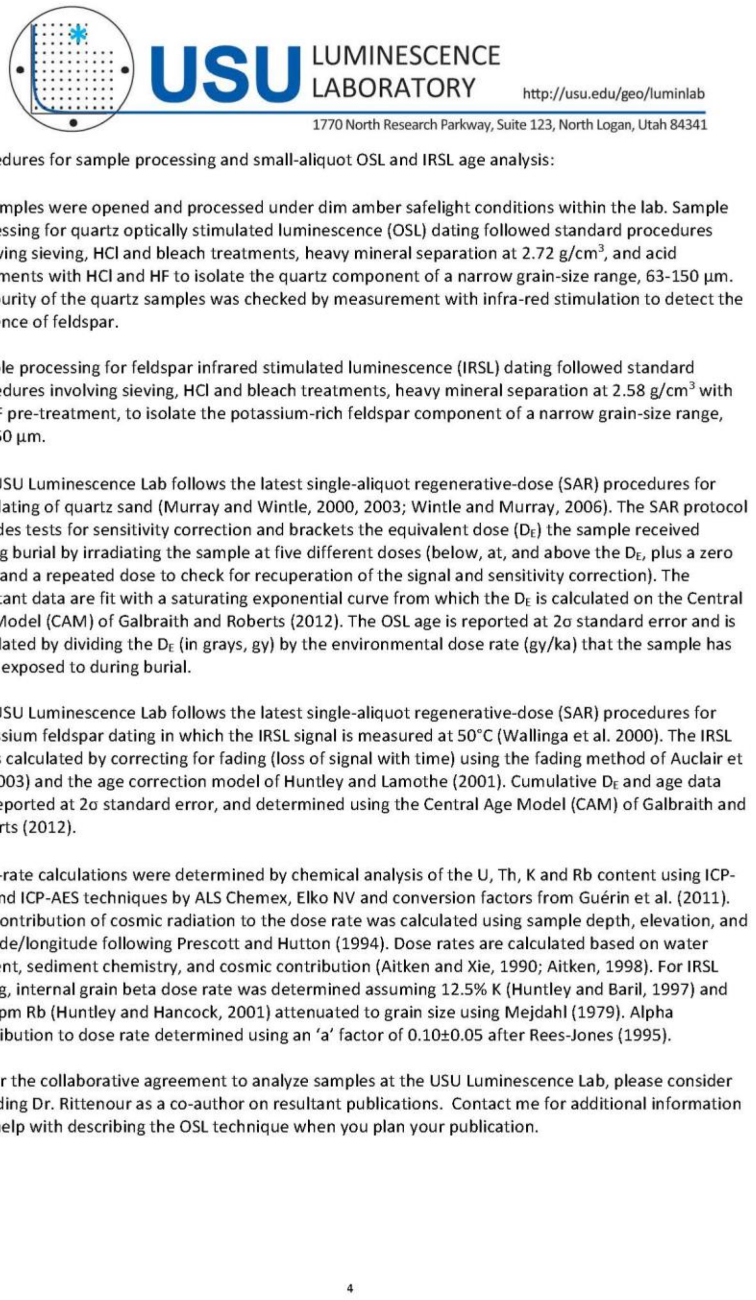




2. BC-01, USU-2129







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Procedures for sample processing and small-aliquot OSL and IRSL age analysis:

All samples were opened and processed under dim amber safelight conditions within the lab. Sample processing for quartz optically stimulated luminescence (OSL) dating followed standard procedures involving sieving, HCl and bleach treatments, heavy mineral separation at 2.72 g/cm^3, and acid treatments with HCl and HF to isolate the quartz component of a narrow grain-size range, 63-150 µm. The purity of the quartz samples was checked by measurement with infra-red stimulation to detect the presence of feldspar.

Sample processing for feldspar infrared stimulated luminescence (IRSL) dating followed standard procedures involving sieving, HCl and bleach treatments, heavy mineral separation at 2.58 g/cm^3 with no HF pre-treatment, to isolate the potassium-rich feldspar component of a narrow grain-size range, 63-150 µm.

The USU Luminescence Lab follows the latest single-aliquot regenerative-dose (SAR) procedures for OSL dating of quartz sand (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006). The SAR protocol includes tests for sensitivity correction and brackets the equivalent dose (D_E) the sample received during burial by irradiating the sample at five different doses (below, at, and above the D_E, plus a zero dose and a repeated dose to check for recuperation of the signal and sensitivity correction). The resultant data are fit with a saturating exponential curve from which the D_E is calculated on the Central Age Model (CAM) of Galbraith and Roberts (2012). The OSL age is reported at 2σ standard error and is calculated by dividing the D_E (in grays, gy) by the environmental dose rate (gy/ka) that the sample has been exposed to during burial.

The USU Luminescence Lab follows the latest single-aliquot regenerative-dose (SAR) procedures for potassium feldspar dating in which the IRSL signal is measured at 50°C (Wallinga et al. 2000). The IRSL age is calculated by correcting for fading (loss of signal with time) using the fading method of Auclair et al. (2003) and the age correction model of Huntley and Lamothe (2001). Cumulative D_E and age data are reported at 2σ standard error, and determined using the Central Age Model (CAM) of Galbraith and Roberts (2012).

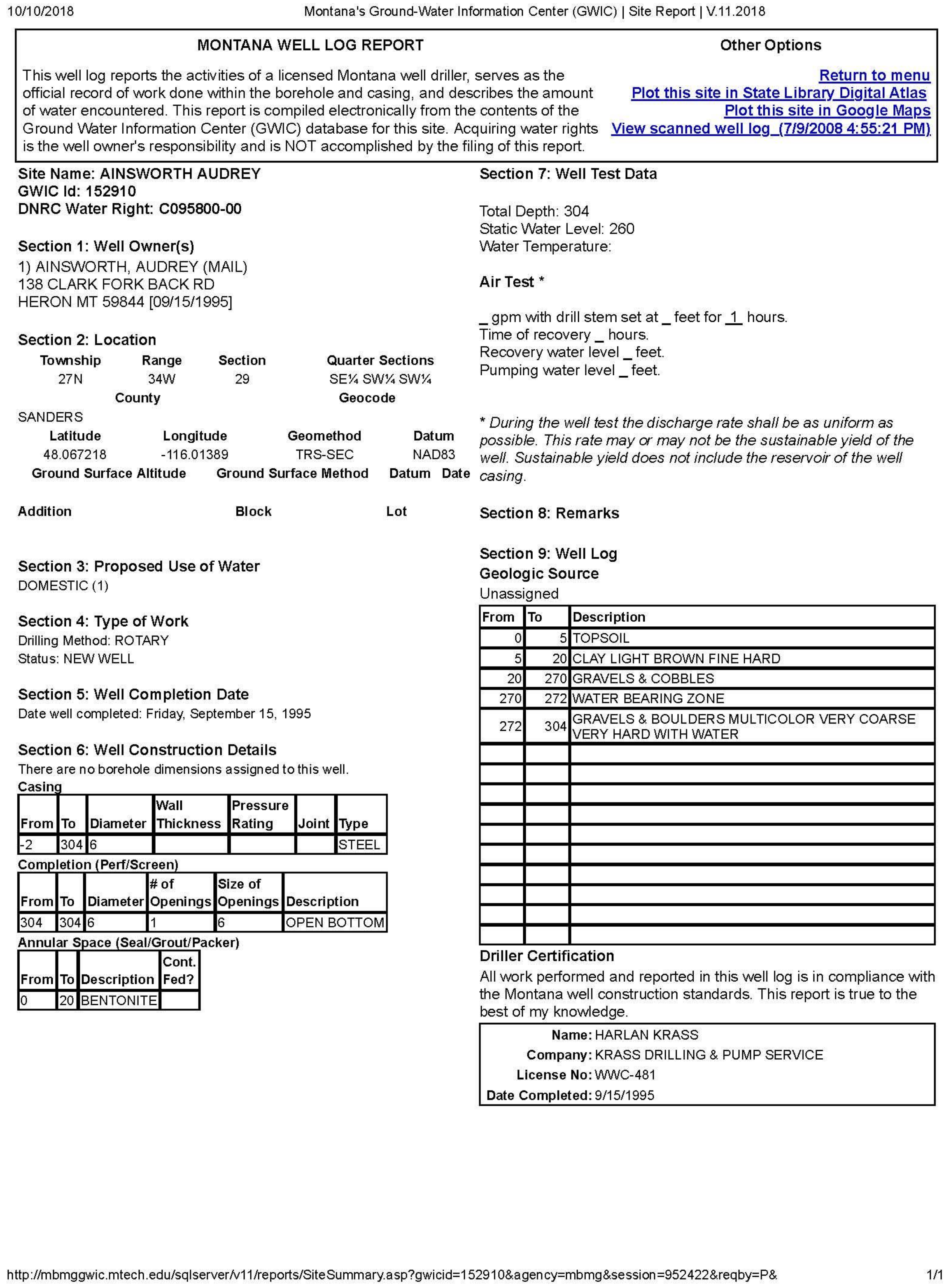
Dose-rate calculations were determined by chemical analysis of the U, Th, K and Rb content using ICP-MS and ICP-AES techniques by ALS Chemex, Elko NV and conversion factors from Guérin et al. (2011). The contribution of cosmic radiation to the dose rate was calculated using sample depth, elevation, and latitude/longitude following Prescott and Hutton (1994). Dose rates are calculated based on water content, sediment chemistry, and cosmic contribution (Aitken and Xie, 1990; Aitken, 1998). For IRSL dating, internal grain beta dose rate was determined assuming 12.5% K (Huntley and Baril, 1997) and 400ppm Rb (Huntley and Hancock, 2001) attenuated to grain size using Mejdahl (1979). Alpha contribution to dose rate determined using an 'a' factor of 0.10±0.05 after Rees-Jones (1995).

Under the collaborative agreement to analyze samples at the USU Luminescence Lab, please consider including Dr. Rittenour as a co-author on resultant publications. Contact me for additional information and help with describing the OSL technique when you plan your publication.

9. Appendix B: Supplementary Flood Gravels

Location	Clast Sizes	Lithologies	Roundness and Sorting	Matrix	Bedding/Imbrication	Aquifer Potential
A	Granule to cobble	Belt Supergroup, volcanics	R/WR and poorly sorted	Fine sand/silt	None	Good
B	Pebble to cobble	Belt Supergroup, volcanics	Angular-WR, Poorly sorted	Course sandy, matrix supported	None	Good
c	Pebble to boulder	Belt Supergroup, volcanics	Angular-WR, Poorly sorted	Fine Sand/silt, matrix supported	None	Moderate
D	Pebble (dominant) to cobble, erratics in places	Belt Supergroup, volcanics	WR/SR and moderately to well-sorted	Course sandy, matrix supported	Stratified/rhythmic bedding with large-scale crossbedding	Good
F	Dominantly pebbles, cobbles in places	Belt Supergroup, volcanics	WR/SR, 10% angular, moderately sorted	Sandy/silt and carbonate, rice crispy texture, well-cemented clast supported	None	Poor to moderate
G	Granules-pebble-cobble beds, boulders in places	Belt Supergroup, volcanics	Angular-subrounded, well sorted	Silt and carbonate, rice crispy texture, well-cemented, clast supported	Stratified/rhythmic bedding large scale crossbedding, alternating ~10-20 cm	Poor to moderate
H	Pebble to cobble	Belt Supergroup, volcanics	Sub-angular, poorly sorted	Silt and carbonate, rice crispy texture, well-cemented, clast supported	None	Poor to moderate

10. Appendix C: Well Logs used



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MONTANA WELL LOG REPORT

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Other Options

Return to menu
Plot this site in State Library Digital Atlas
Plot this site in Google Maps
View scanned well log (7/9/2008 4:55:21 PM)

Site Name: AINSWORTH AUDREY
GWIC Id: 152910
DNRC Water Right: C095800-00

Section 1: Well Owner(s)

1) AINSWORTH, AUDREY (MAIL)
138 CLARK FORK BACK RD
HERON MT 59844 [09/15/1995]

Section 2: Location

Township	Range	Section	Quarter Sections
27N	34W	29	SE¼ SW¼ SW¼

County	Geocode
SANDERS	

Latitude	Longitude	Geomethod	Datum
48.067218	-116.01389	TRS-SEC	NAD83

Ground Surface Altitude	Ground Surface Method	Datum	Date

Addition	Block	Lot

Section 3: Proposed Use of Water

DOMESTIC (1)

Section 4: Type of Work

Drilling Method: ROTARY
Status: NEW WELL

Section 5: Well Completion Date

Date well completed: Friday, September 15, 1995

Section 6: Well Construction Details

There are no borehole dimensions assigned to this well.

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	304	6				STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
304	304	6	1	6	OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	20	BENTONITE	

Section 7: Well Test Data

Total Depth: 304
Static Water Level: 260
Water Temperature:

Air Test *

_ gpm with drill stem set at _ feet for 1 hours.
Time of recovery _ hours.
Recovery water level _ feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source

Unassigned

From	To	Description
0	5	TOPSOIL
5	20	CLAY LIGHT BROWN FINE HARD
20	270	GRAVELS & COBBLES
270	272	WATER BEARING ZONE
272	304	GRAVELS & BOULDERS MULTICOLOR VERY COARSE VERY HARD WITH WATER

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	HARLAN KRASS
Company:	KRASS DRILLING & PUMP SERVICE
License No:	WWC-481
Date Completed:	9/15/1995

http://mbmggwic.mtech.edu/sqlserver/v11/reports/SiteSummary.asp?gwicid=152910&agency=mbmg&session=952422&reqby=P& 1/1

MONTANA WELL LOG REPORT

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Other Options

Return to menu
Plot this site in State Library Digital Atlas
Plot this site in Google Maps
View scanned well log (7/9/2008 4:55:01 PM)

Site Name: ROCCO MARY C
GWIC Id: 137769

Section 1: Well Owner(s)

1) ROCCO, MARY C. (MAIL)
BOX 82
HERON MT 59844 [08/28/1993]

Section 2: Location

Township	Range	Section	Quarter Sections
27N	34W	29	NW¼ SW¼

County	Geocode
SANDERS	

Latitude	Longitude	Geomethod	Datum
48.071879	-116.01528	TRS-SEC	NAD83

Ground Surface Altitude	Ground Surface Method	Datum	Date

Addition	Block	Lot

Section 3: Proposed Use of Water

DOMESTIC (1)

Section 4: Type of Work

Drilling Method: ROTARY
Status: NEW WELL

Section 5: Well Completion Date

Date well completed: Saturday, August 28, 1993

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	280	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	278	6				STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
278	278	6	1	6	OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	20	BENTONITE	

Section 7: Well Test Data

Total Depth: 280
Static Water Level: 227
Water Temperature:

Air Test *

25 gpm with drill stem set at _ feet for 2 hours.
Time of recovery _ hours.
Recovery water level _ feet.
Pumping water level 227 feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source

Unassigned

From	To	Description
0	50	WET-STICKY CLAY
50	65	SAND AND GRAVEL FEW COBBLES
65	75	LARGE BOULDER OR ROCK- LIMESTONE
75	226	SAND AND GRAVELS FEW COBBLES AND SMALL BOULDERS SOME CLAY MATRIX
226	233.5	LARGE BOULDER OR ROCK- LIMESTONE
233.5	260	GRAVEL AND BOULDERS VERY COURSE
265	280	SAND AND GRAVEL SOME CLAY

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name: WILLIAM HAYES
Company: RUEN DRILLING, INC
License No: WWC-361
Date Completed: 8/28/1993

MONTANA WELL LOG REPORT

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Other Options

Return to menu
Plot this site in State Library Digital Atlas
Plot this site in Google Maps
View scanned well log (7/10/2008 7:02:44 AM)

Site Name: MOSLEY MILTON H & DIANE
GWIC Id: 143310

Section 1: Well Owner(s)

1) MOSLEY, MILTON H. AND DIANE (MAIL)
109 COTTONWOOD
HERON MT 59844 [04/27/1994]

Section 2: Location

Township	Range	Section	Quarter Sections
27N	35W	24	SE¼ SE¼

County	Geocode
SANDERS	

Latitude	Longitude	Geomethod	Datum
48.082846	-116.039953	TRS-SEC	NAD83

Ground Surface Altitude	Ground Surface Method	Datum	Date

Addition	Block	Lot
CHAR-RAY RANCHES		9

Section 3: Proposed Use of Water

DOMESTIC (1)

Section 4: Type of Work

Drilling Method: CABLE
Status: NEW WELL

Section 5: Well Completion Date

Date well completed: Wednesday, April 27, 1994

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	250	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
0	250	6				STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
250	250	6	1	6	OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	250	BENTONITE	

Section 7: Well Test Data

Total Depth: 250
Static Water Level: 215
Water Temperature:

Bailer Test *

7 gpm with _ feet of drawdown after 4 hours.
Time of recovery _ hours.
Recovery water level _ feet.
Pumping water level 215 feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source

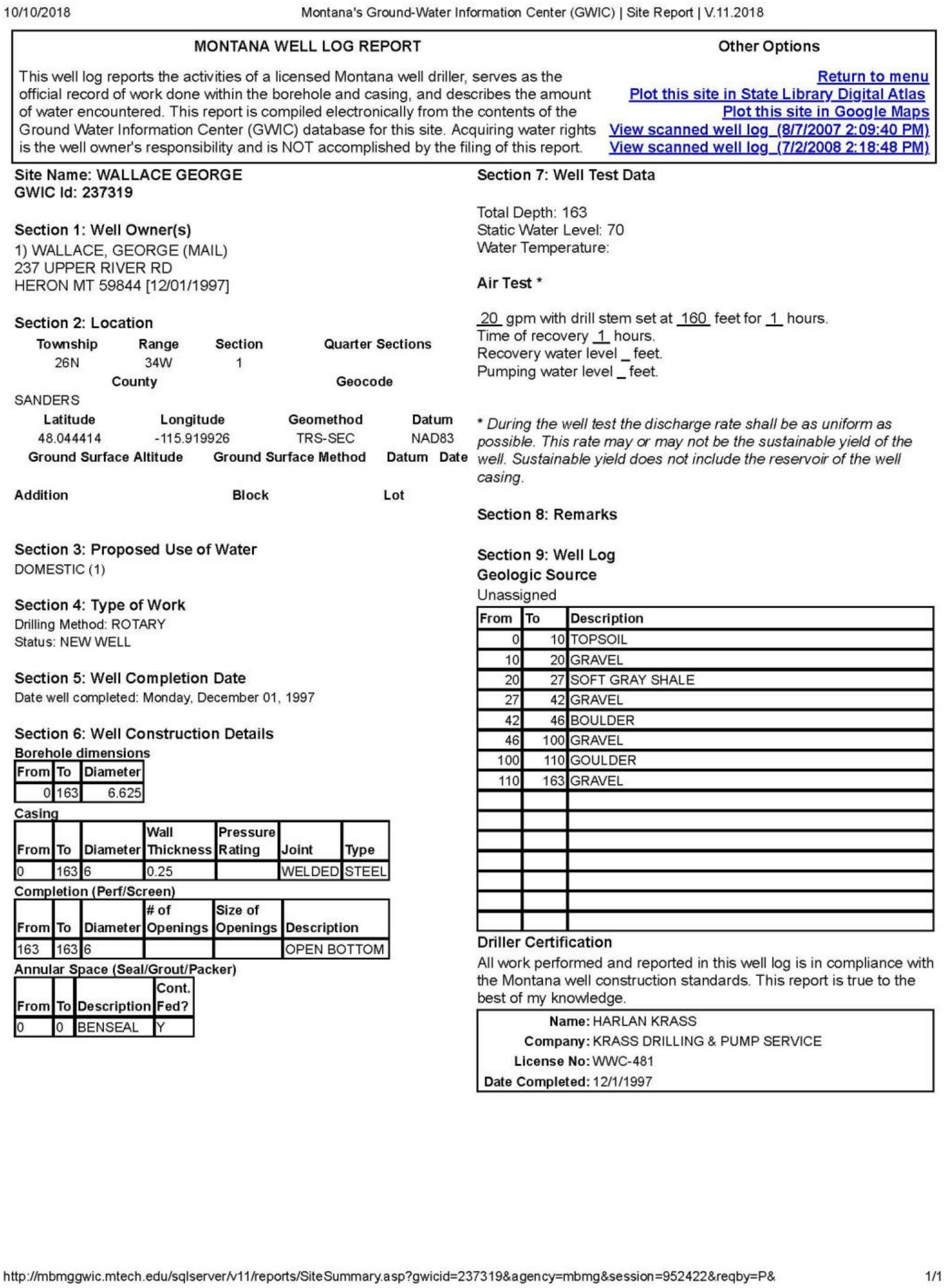
Unassigned

From	To	Description
0	1	TOPSOIL
1	14	CLAY
14	130	CLAY GRAVEL
130	185	CLAY GRAVEL BOULDERS
185	250	GRAVEL

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	ROBERT L. VETTER
Company:	RL VETTER CONTRACTING
License No:	WWC-549
Date Completed:	4/27/1994



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MONTANA WELL LOG REPORT

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Other Options

Return to menu
Plot this site in State Library Digital Atlas
Plot this site in Google Maps
View scanned well log (8/7/2007 2:09:40 PM)
View scanned well log (7/2/2008 2:18:48 PM)

Site Name: WALLACE GEORGE
GWIC Id: 237319

Section 1: Well Owner(s)

1) WALLACE, GEORGE (MAIL)
237 UPPER RIVER RD
HERON MT 59844 [12/01/1997]

Section 2: Location

Township	Range	Section	Quarter Sections
26N	34W	1	

County	Geocode
SANDERS	

Latitude	Longitude	Geomethod	Datum
48.044414	-115.919926	TRS-SEC	NAD83

Ground Surface Altitude	Ground Surface Method	Datum	Date

Addition	Block	Lot

Section 3: Proposed Use of Water

DOMESTIC (1)

Section 4: Type of Work

Drilling Method: ROTARY
Status: NEW WELL

Section 5: Well Completion Date

Date well completed: Monday, December 01, 1997

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	163	6.625

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
0	163	6	0.25		WELDED	STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
163	163	6			OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	0	BENSEAL	Y

Section 7: Well Test Data

Total Depth: 163
Static Water Level: 70
Water Temperature:

Air Test *

20 gpm with drill stem set at 160 feet for 1 hours.
Time of recovery 1 hours.
Recovery water level _ feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source

Unassigned

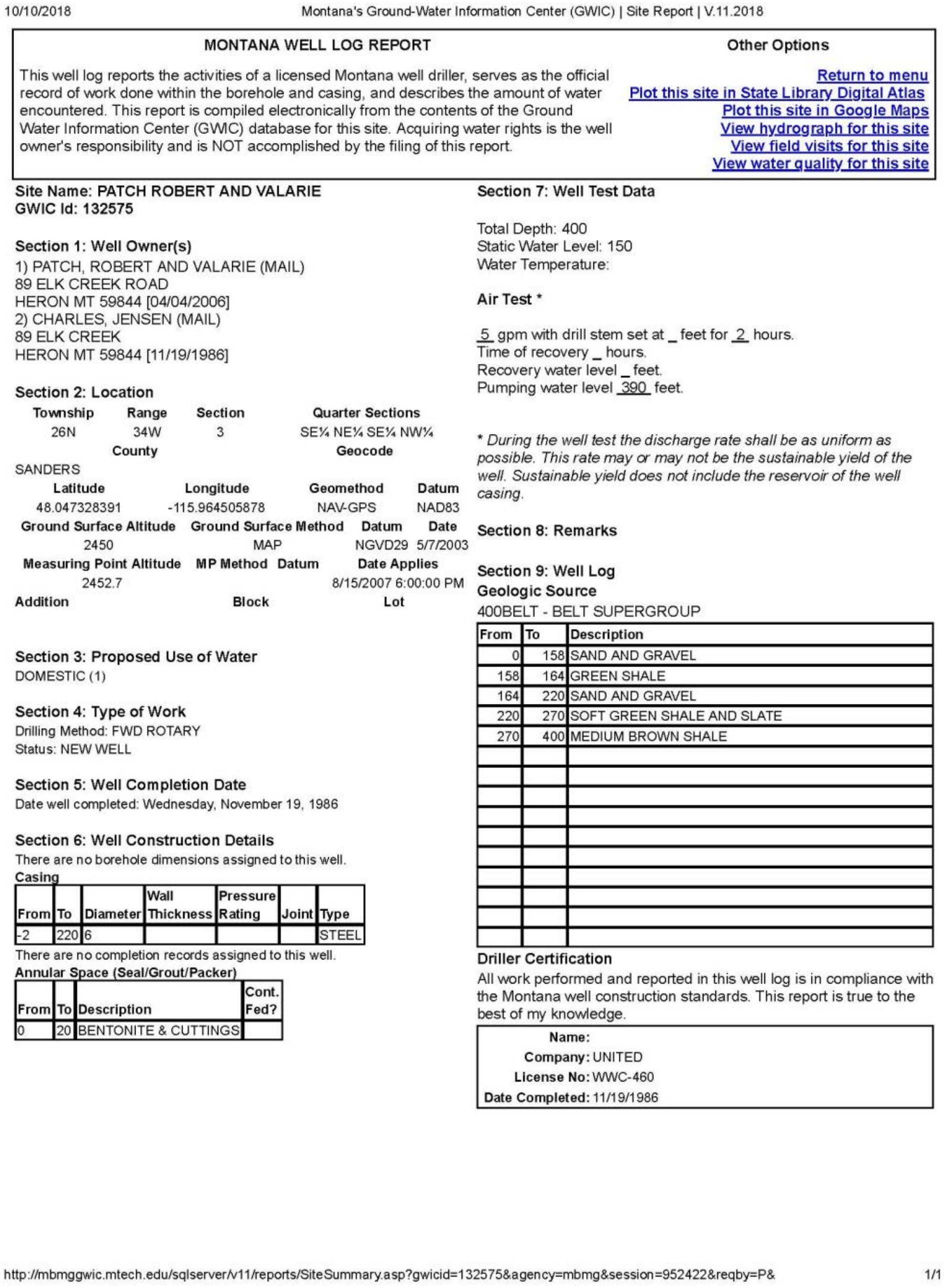
From	To	Description
0	10	TOPSOIL
10	20	GRAVEL
20	27	SOFT GRAY SHALE
27	42	GRAVEL
42	46	BOULDER
46	100	GRAVEL
100	110	GOULDER
110	163	GRAVEL

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	HARLAN KRASS
Company:	KRASS DRILLING & PUMP SERVICE
License No:	WWC-481
Date Completed:	12/1/1997

http://mbmggwic.mtech.edu/sqlserver/v11/reports/SiteSummary.asp?gwicid=237319&agency=mbmg&session=952422&reqby=P& 1/1



MONTANA WELL LOG REPORT

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Other Options

Return to menu
Plot this site in State Library Digital Atlas
Plot this site in Google Maps
View hydrograph for this site
View field visits for this site
View water quality for this site

Site Name: PATCH ROBERT AND VALARIE
GWIC Id: 132575

Section 1: Well Owner(s)

1) PATCH, ROBERT AND VALARIE (MAIL)
89 ELK CREEK ROAD
HERON MT 59844 [04/04/2006]
2) CHARLES, JENSEN (MAIL)
89 ELK CREEK
HERON MT 59844 [11/19/1986]

Section 2: Location

Township	Range	Section	Quarter Sections
26N	34W	3	SE¼ NE¼ SE¼ NW¼

County	Geocode
SANDERS	

Latitude	Longitude	Geomethod	Datum
48.047328391	-115.964505878	NAV-GPS	NAD83

Ground Surface Altitude	Ground Surface Method	Datum	Date
2450	MAP	NGVD29	5/7/2003

Measuring Point Altitude	MP Method	Datum	Date Applies
2452.7			8/15/2007 6:00:00 PM

Addition	Block	Lot

Section 3: Proposed Use of Water

DOMESTIC (1)

Section 4: Type of Work

Drilling Method: FWD ROTARY
Status: NEW WELL

Section 5: Well Completion Date

Date well completed: Wednesday, November 19, 1986

Section 6: Well Construction Details

There are no borehole dimensions assigned to this well.

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	220	6				STEEL

There are no completion records assigned to this well.

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	20	BENTONITE & CUTTINGS	

Section 7: Well Test Data

Total Depth: 400
Static Water Level: 150
Water Temperature:

Air Test *

5 gpm with drill stem set at _ feet for 2 hours.
Time of recovery _ hours.
Recovery water level _ feet.
Pumping water level 390 feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source

400BELT - BELT SUPERGROUP

From	To	Description
0	158	SAND AND GRAVEL
158	164	GREEN SHALE
164	220	SAND AND GRAVEL
220	270	SOFT GREEN SHALE AND SLATE
270	400	MEDIUM BROWN SHALE

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	
Company:	UNITED
License No:	WWC-460
Date Completed:	11/19/1986

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Other Options

Return to menu
Plot this site in State Library Digital Atlas
Plot this site in Google Maps

Site Name: HUSSELL, THORNING, EARLE & EARLENE MARIE
GWIC Id: 268701

Section 1: Well Owner(s)

1) HUSSELL, THORNING, EARLE & EARLENE MARIE (MAIL)
P.O. BOX 225
HERON MONTANA 59844 [09/15/2012]

Section 2: Location

Township	Range	Section	Quarter Sections
27N	34W	34	NW¼ SW¼

County	Geocode
SANDERS	

Latitude	Longitude	Geomethod	Datum
48.0570395416	-115.971634923	TRS-SEC	NAD83

Ground Surface Altitude	Ground Surface Method	Datum	Date

Addition	Block	Lot

Section 3: Proposed Use of Water

DOMESTIC (1)

Section 4: Type of Work

Drilling Method: ROTARY
Status: NEW WELL

Section 5: Well Completion Date

Date well completed: Saturday, September 15, 2012

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	116	8

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
0	116	6	0.25		WELDED	A53B STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
116	116	6			OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	20	BENTONITE	Y

Section 7: Well Test Data

Total Depth: 116
Static Water Level: 77.9
Water Temperature:

Air Test *

30 gpm with drill stem set at 111 feet for 1.5 hours.
Time of recovery _ hours.
Recovery water level _ feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source

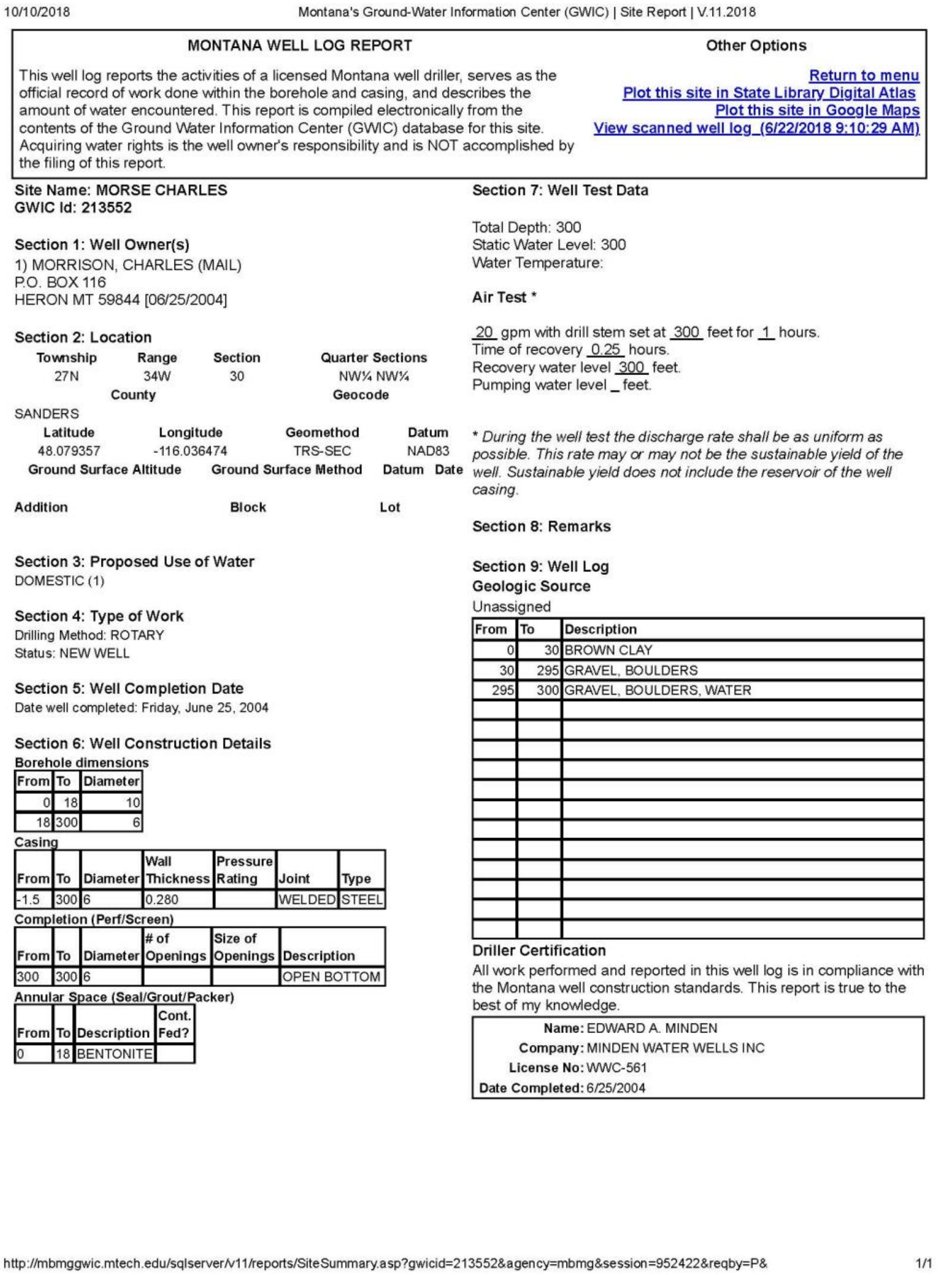
Unassigned

From	To	Description
0	12	SAND
12	32	SAND AND CLAY
32	82	CLAY AND GRAVEL
82	116	GRAVEL, H2O

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	JOSEPH WILLIAMS
Company:	WILLIAMS WELL DRILLING
License No:	WWC-567
Date Completed:	9/15/2012



MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is compiled electronically from the contents of the Ground Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Return to menu
Plot this site in State Library Digital Atlas
Plot this site in Google Maps
View scanned well log (6/22/2018 9:10:29 AM)

Site Name: MORSE CHARLES
GWIC Id: 213552

Section 1: Well Owner(s)

1) MORRISON, CHARLES (MAIL)
P.O. BOX 116
HERON MT 59844 [06/25/2004]

Section 2: Location

Township	Range	Section	Quarter Sections
27N	34W	30	NW¼ NW¼

County	Geocode
SANDERS	

Latitude	Longitude	Geomethod	Datum
48.079357	-116.036474	TRS-SEC	NAD83

Ground Surface Altitude	Ground Surface Method	Datum	Date

Addition	Block	Lot

Section 3: Proposed Use of Water

DOMESTIC (1)

Section 4: Type of Work

Drilling Method: ROTARY
Status: NEW WELL

Section 5: Well Completion Date

Date well completed: Friday, June 25, 2004

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	18	10
18	300	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-1.5	300	6	0.280		WELDED	STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
300	300	6			OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	18	BENTONITE	

Section 7: Well Test Data

Total Depth: 300
Static Water Level: 300
Water Temperature:

Air Test *

20 gpm with drill stem set at 300 feet for 1 hours.
Time of recovery 0.25 hours.
Recovery water level 300 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source

Unassigned

From	To	Description
0	30	BROWN CLAY
30	295	GRAVEL, BOULDERS
295	300	GRAVEL, BOULDERS, WATER

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name: EDWARD A. MINDEN
Company: MINDEN WATER WELLS INC
License No: WWC-561
Date Completed: 6/25/2004

SIGNATURE PAGE

This is to certify that the thesis prepared by Emily Welk entitled "Quaternary Geology of the Cabinet, Heron, and Smeads Bench 7.5′ Quadrangles, with Emphasis on Glacial Lake Missoula Sediments" has been examined and approved for acceptance by the Department of Geological Engineering, Montana Technological University, on this 1st day of May, 2019.

Larry N. Smith, PhD, Professor and Department Head
Department of Geological Engineering
Chair, Examination Committee

Glenn Shaw, PhD, Associate Professor
Department of Geological Engineering
Member, Examination Committee

David Reichhardt, Assistant Professor
Department of Petroleum Engineering
Member, Examination Committee