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History of syn-glacial and post-glacial sedimentation at the former terminus of the Flathead ice lobe near Polson Montana

Jason R. Braden
The University of Montana

HISTORY OF SYN-GLACIAL AND POST-GLACIAL SEDIMENTATION AT THE FORMER TERMINUS OF THE FLATHEAD ICE LOBE NEAR POLSON, MONTANA

By

Jason R. Braden

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Dean, Graduate School

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Chairman: Marc S. Hendrix MSH

During the last glacial maximum the Flathead Ice Lobe extended south from the Cordilleran Ice Sheet. The ice lobe flowed down the Flathead Valley and terminated near present day Polson, Montana. Sediment deposited at the former ice margin provides a detailed record of the glacial advance and retreat associated with the Cordilleran Ice Sheet. The overall focus of this study has been to describe the sedimentology and geomorphology of the features left behind by at former ice margin and to infer their environments of depositional.

Ten sedimentary facies were recognized through examination of exposures of sediment. Dmm facies is massive clay to silt matrix supported gravels. Gcm, Gh, Gmm and Gmf are conglomeratic facies differentiated by their clast-supporting material and matrix grain size. St, Sr and Sm are sand facies distinguished based upon grain size and sedimentary structures. Fl consists of laminated clay and silt, and Fsc consists of massive clay and silt with scattered gravel.

Quaternary sediments in the map area are classified into thirteen map units. Qgmft, Qgtu, Qgop, Qgd and Qgo represent glacial moraine, undifferentiated till, outwash, delta and outwash-related deposits at the former terminal ice margin of the Flathead Lobe. Qgl, Qlkof and Qpgl represent fine-grained units associated with ancestral Flathead Lake and pro-glacial lake, respectfully. Qglm and Qglmc are thick deposits of massive and coarse-grained diamict, respectfully, that were deposited in glacial Lake Missoula (GLM). Qe is aeolian sand deposited in sand dunes that rest upon outwash-related sediments. Qal consists of alluvial sediment deposited by modern intermittent streams. Sediments deposited in a terrace by the Flathead River upstream of the Kerr Dam is represents the Qalf unit.

Ancestral Flathcad Lake formed during the retreat of the Flathead Lobe. Correlation of glacial varved sequences, associated with ancestral Flathead Lake, constrains the timing of glacial deposition in the region to no later than 14,300±250 cal. years BP. A gravity survey performed across the northern Polson moraine segment suggests a series of bedrock ridges in the subsurface. These ridges caused the glacial lobe to stagnate over this region and caused a portion of the moraine deposition to be sub-aerial.

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Introduction:

Glacial Lake Missoula (GLM) was first recognized by J. T. Pardee (1910) who described shorelines on Mount Jumbo and Mount Sentinel east of Missoula, Montana. However, it wasn't until Bretz (1923) conducted his seminal work on the Channeled Scabland of eastern Washington, and Pardee (1942) recognized giant ripple marks in the GLM basin that scientists realized that the lake was dammed by a lobe of the Cordilleran Ice Sheet. GLM was impounded during the most recent Pleistocene glacial interval when the Purcell Lobe of the Cordilleran Ice Sheet dammed the Clark Fork River. Most of the major valleys in western Montana were flooded by the lake which, at its maximum pool, had a surface area of 5,000 km^2 and an estimated volume of ~2084km^3 (Alden, 1953; Alt, 2002). At least once and perhaps several times, the ice dam failed, causing a rapid draining of the lake. Voluminous amounts of water, escaping toward the Pacific Ocean, scoured an area in Idaho and eastern Washington known as the "Channeled Scabland" (Bretz, 1923, 1969).

A majority of the research and therefore much of the inferred history of glacial Lake Missoula has focused on the sedimentary and erosional record down gradient of the glacial dam that impounded the lake (Bretz, 1923a, Bretz 1923b, Bretz, 1969, Waitt, 1985, Atwater, 1986, Clague et al., 2003). In contrast, until very recently, minimal research has been conducted on the lake sediments in the GLM basin itself (Levish 1997, Hendrix et al., 2001, Hofmann et al., 2003, Hofmann and Hendrix, 2004b, Hofmann et al., 2006, Smith, 2004, Bondurant, 2005, Timmerman, 2005). As a result, uncertainty remains about the timing and terminal history of glacial Lake Missoula and the record of subsequent deglaciation.

One of the major ice lobes that flowed south from the Cordilleran Ice Sheet during the existence of glacial Lake Missoula is the Flathead Lobe (FHL). Various studies have concluded that the FHL extended into the Flathead Lake region of western Montana during the last glacial maxima (Elrod, 1903, Pardee, 1942, Alden, 1953, Smith, 1966; Figure 1). The terminal moraine associated with the FHL generally is considered to be the large arcuate ridge near Polson, MT (Alden, 1953, Levish, 1997, Hofmann and Hendrix, 2004). An important investigation of Pleistocene sedimentation in the GLM basin was conducted by Levish (1997) who re-examined sediments previously interpreted as glacial till (Alden, 1953; Richmond, 1965) and demonstrated them to be glacio-lacustrine deposits. This sedimentological re-characterization fits well with the interpretation that the Polson moraine represents the southernmost advance of the Flathead Lobe. Hofmann and Hendrix (2004) recognized two crests to the terminal moraine to the east of Polson, and two sets of terminal and lateral moraines from the alpine glaciers that extended from the Mission Mountains. Further to the north, near Elmo, MT, terminal and lateral moraines are recognized in the Proctor, Elmo and Big Arm valleys (Smith, 1966, Bondurant, 2005). At the northern end of Flathead Lake, Smith (2004) examined a large number of water well logs and combined this information with surficial geologic mapping in order to better define the stratigraphy of the Flathead Valley and more tightly constrain the history of deglaciation in this region.

Although a consensus among studies in the Flathead Lake region indicate a glacial lobe occupied the valley during the last glacial period, only recently has research on this system focused along the former ice margin (Alden, 1953, Smith 1966, Hofmann and Hendrix 2003a, Hofmann and Hendrix 2003b, Bondurant, 2005). The

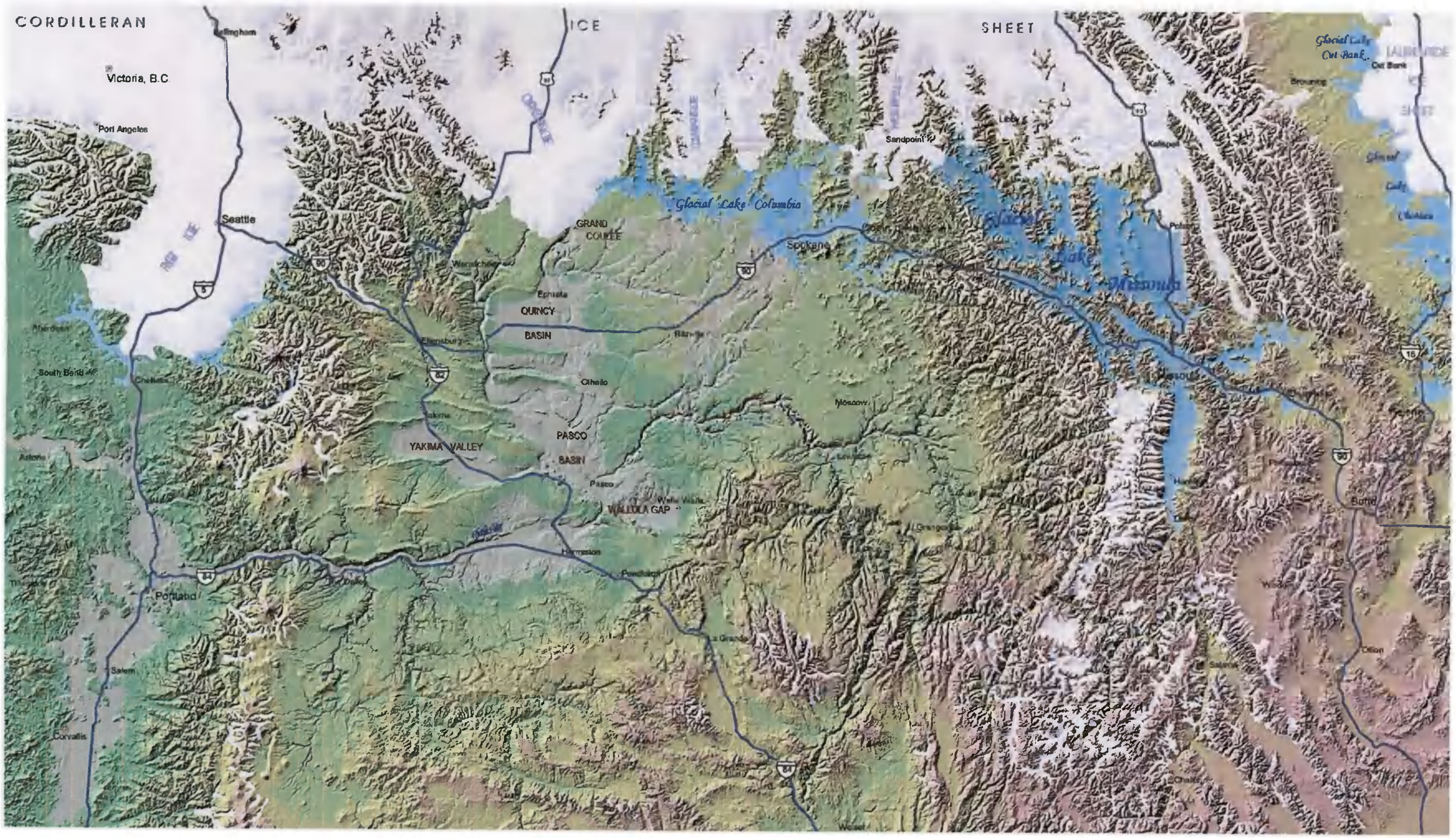
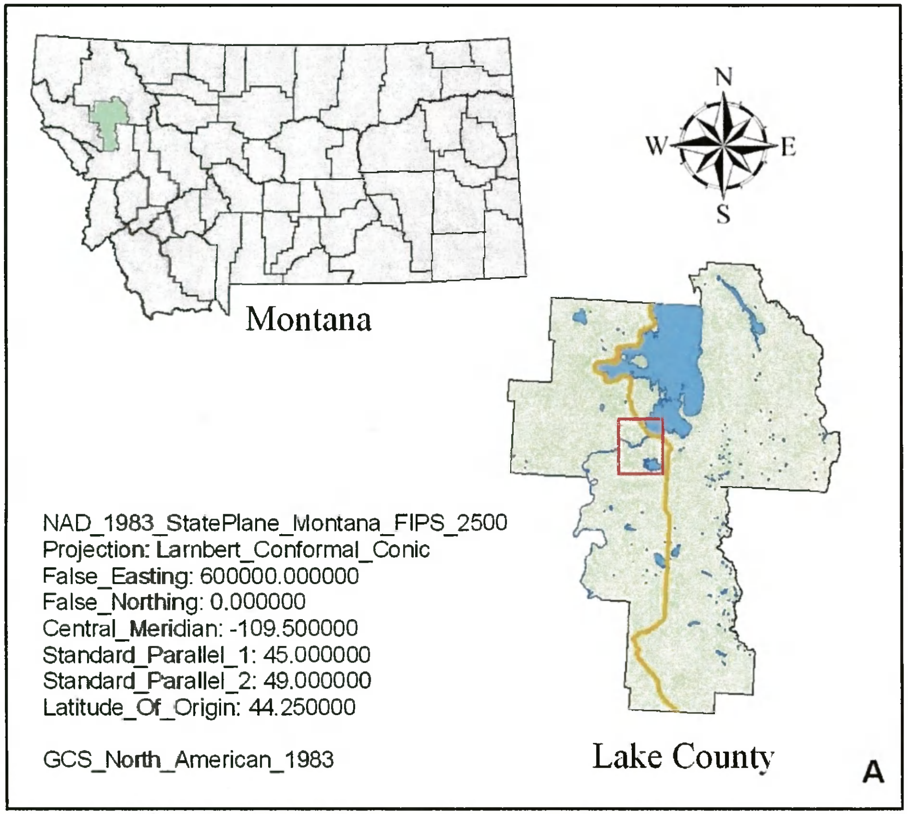


Figure 1. Extent of the Cordilleran Ice Sheet during the last glacial maximum. Note the Purcell Trench Lobe impounding glacial Lake Missoula, and south of Kalispell, MT the Flathead Ice Lobe terminates into glacial Lake Missoula. (Silkwood, 1998)

physical and temporal relationships between glacial Lake Missoula and the Flathead Lobe sediment deposits and landform distribution are essential to understanding the Quaternary history of this region. Specific locations of glacial, glacio-lacustrine and associated deposits record information about the position of the ice margin through time. By documenting the distribution of these sediments and using relative dating techniques to place constraints on the ordering of events, it is possible to significantly refine understanding of the region's history of terminal glacial expansion and retreat, as well as the region's preserved record of post-glacial sedimentation.

The principal focus of this study is to describe the sedimentology and geomorphology of features associated with the former Cordilleran Ice Sheet margin. Specifically, in this thesis, I present results of geologic mapping along the southern perimeter of Flathead Lake in the vicinity of Polson, MT (Figure 2). This mapping displays the distribution of glacial and post-glacial deposits and aides in documenting the history of the former ice margin. Using the distribution of sediment deposits, I was able to determine a relative order of glaciation events. I infer depositional environments of various map units from my sedimentological observations, inferences I can make using available subsurface information, and comparisons with published examples of ancient and modern analogs. These observations suggest that the southern segment of the Polson moraine was deposited in a primarily sub-aqueous environment (Hofmann and Hendrix 2004, Hofmann et al., 2006).

In addition to my facies descriptions and map work, I correlated varved sediment sequences recognized onshore to those found in offshore cores recovered from Flathead Lake (Hofmann et al., 2003). These varved sequences are important because they provide a basis for estimating proximity to the glacial front, as well as providing some indication of the depositional setting and the timing of events associated with certain portions of the ice marginal system. Finally, I performed a small linear gravity survey over a portion of the Polson moraine to better understand the geometry of the underlying bedrock topography and the influence this geometry may have had on the history of ice movement.



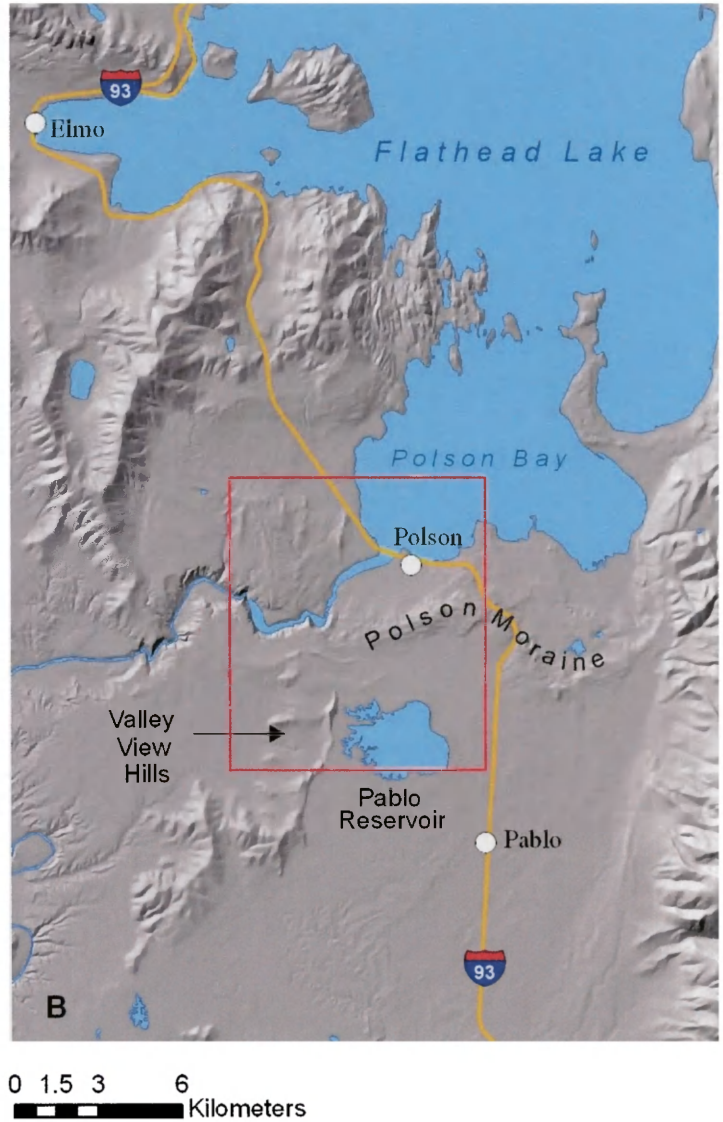


Figure 2. A: Location of study area within Lake County, Montana. B: Hillshade of the northern Mission Valley and southern Flathead Lake Basin. Polson Moraine is the arcuate feature south/southeast of Polson. Red box indicates study area.

Geologic Setting and Physiography

The study area is located at the southern end of the Flathead Valley and the northern part of the Mission Valley (Figure 2). The Flathead Valley is approximately 90 km long and between 15 and 25 km wide, whereas the Mission Valley is ~50 km-long and 25-30 km wide. The southern end of Flathead Lake, near Polson, MT, usually is taken as the border between the two valley systems (Figure 2). Flathead Lake is a large open lake that covers ~500km^2 in the southern Flathead Valley. The deepest parts of the lake are along its eastern edge where maximum depths of 112m occur. In contrast, the Polson Bay typically is 5-10 m deep. Currently draining Flathead Lake is the lower Flathead River. The river exits the lake along the southwest margin of Polson Bay and flows south/southwest to the confluence with the Clark Fork River near Perma, MT.

The Flathead and Mission basins occupy the southern end of the northwest-southeast trending Rocky Mountain Trench (Leech, 1966) (Figure 3). Extending roughly 1500 km from the Lewis and Clark Zone in Montana through British Columbia (Canada), the trench is a series of continuous valleys that extend north to the Laird plain just south of the Yukon Territory (Leech, 1966). Mountains surrounding the study area are comprised of Mesoproterozoic metasedimentary rocks of the Belt Supergroup. Bedrock units were folded and faulted during late Mesozoic and early Cenozoic time (74 – 59 Ma, Sears, 2001). Compressional deformation and ensuing extension during the Cenozoic caused the preliminary north/south trending valleys (Constenius, 1996). The Flathead and Mission Valleys sit in one of these extensional half-graben, bounded on the east by a normal fault system (Mission fault; Osteena, 1995).

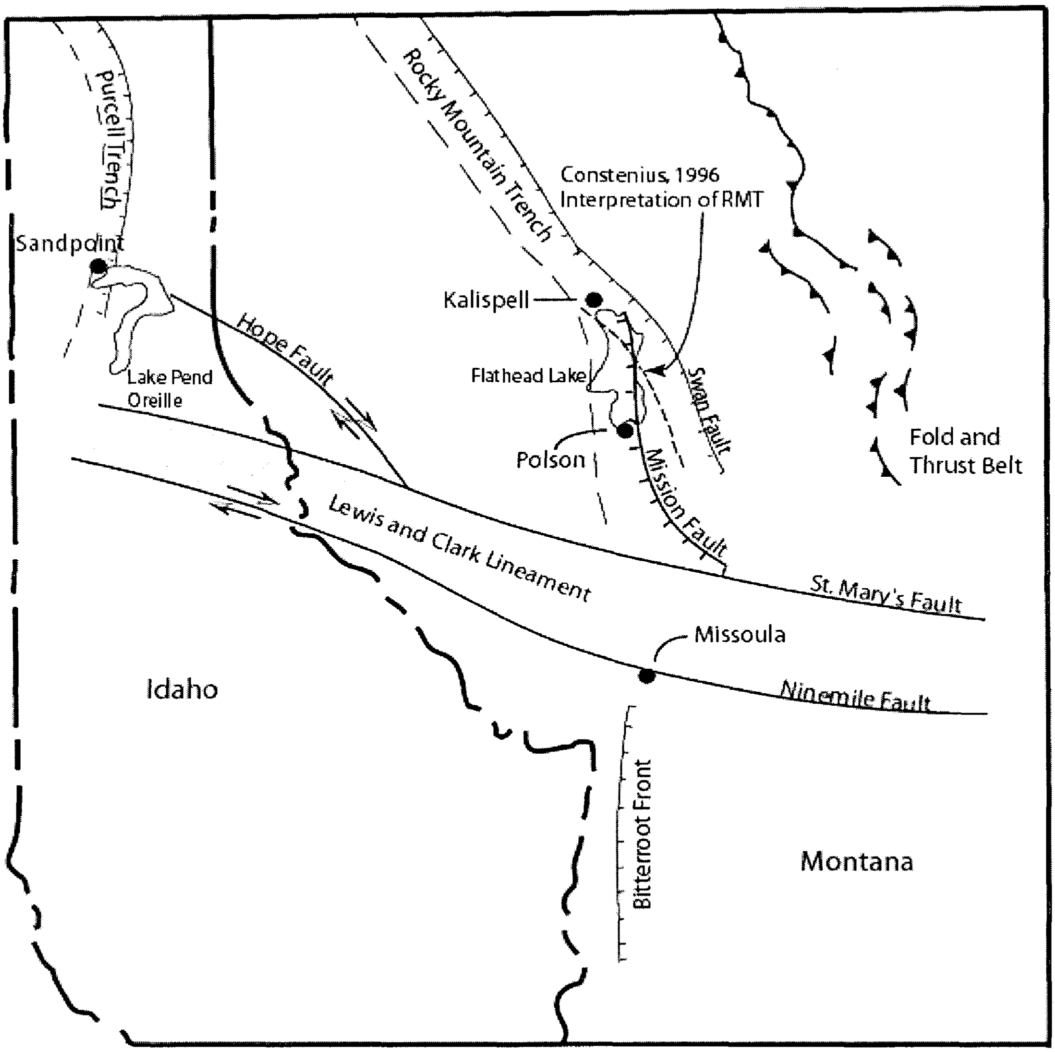


Figure 3. General Structure of Northwestern Montana and Northern Idaho. Flathead Lake is at the southern end of the Rocky Mountain Trench (Redrawn and modified from LaPoint, 1971).

Using regional gravity data LaPoint (1971) interpreted a north/south trending gravity low as representing downdropping of the Mission and Flathead Valleys along the Mission Fault. Bedrock profiles under the Polson moraine were interpreted by the same author, based upon gravity data, to consist of a series of small horst and graben structures. LaPoint (1971) inferred maximum valley fill thicknesses along this profile to be slightly more than 910m.

Bedrock in the area consists of Pre-Cambrian metasedimentary rocks with minor Proterozoic intrusive igneous sills, whereas the valley fill consists of Tertiary and Quaternary sediments (Figure 4). Bedrock exposures around Polson, MT comprise strata of the Belt Supergroup, primarily the Ravalli Group (Figure 5). The Ravalli Group consists mainly of thin to medium bedded, gray to reddish argillite and quartzite (Decker, 1968). In addition to the Ravalli Group, minor exposures of the Empire Formation appear to be present. These exposures consist of calcareous gray, green and purple argillite, limestone and dolomite (Decker, 1968, Salmon, 2005, pers. comm..). Geophysical investigations and interpretation of borehole log data has indicated the presence, upwards of 1500m, of Tertiary sedimentary strata north of the region (LaPoint, 1971, Stickney, 1980, Smith, 2000a). Tertiary deposits are described as brown and orange, medium to coarse grained pebbly sandstone, well-rounded pebble and cobble conglomerate of the Kishenehn Formation and Paola gravel (Constenius, 1996). Constenius (1996) also described sandstone and conglomerate beds as having channelized and erosional bases and locally infilling fractures within rock of the Belt Supergroup. Quaternary sediments in the valleys are derived primarily from glaciers (Smith, 2004). The majority of such deposits consist of moraine, glacio-lacustrine and outwash plain deposits related to the last glacial advance of the Cordilleran Ice Sheet.

Period	Epoch	Name	Description	Interpretation
Quaternary	Holocene	deglacial and postglacial deposits	Sand and gravel with minor silt and clay within major river valleys and in broad sheets.	Outwash, eolian sand sheets and dunes, fluvial, alluvial, and alluvial fan deposits.
Quaternary	Holocene / Pleistocene	ancestral Flathead Lake deposits transitional laminated silt and clay deposits	Brown and gray, laminated, calcareous fine sandy silt, clayey silt, and minor clay; cross-stratified and wave-rippled sand, sandy silt, and gravelly sand exposed near recessional moraines; generally not permeable to groundwater except for beds of sand and gravel; deposit has mostly flat upper surfaces.	Most deposited from suspension in distal positions in lake that was initially pro-glacial; few gravels deposited from melting ice; subaqueous outwash fan deposits near recessional moraines; higher lacustrine deposits were abandoned successively as the lake receded.
Quaternary	Pleistocene	diamicton intermediate alluvium	Massive diamiction: Gravel and boulders in a matrix of gray and brown dense sand, silt, and clay; generally not permeable to groundwater; clasts typically rounded and subrounded metacarbonate, quartzite, argillite, and diorite; more resistant clasts commonly striated; associated landforms include drumlins, terminal moraines, hummocky moraine, and eskers Bedded diamicton: 0.3->2 m diamictons locally interbedded with 0.05-0.2-m-thick beds of sorted sand and sandy gravel. Intermediate alluvium: stratified sand and gravel; single or multiple beds in any given area; permeable to groundwater.	Massive diamicton: mostly till deposited subglacially by lodgement and melt-out processes; surface is marked by englacial or subglacial eskers, supraglacial ablation deposits, drumlins, and moraines; Bedded diamicton: flow till and debris flow deposits; typically reworked in ice-contact environments. Intermediate alluvium: englacial or subglacial alluvial deposits that are encased in till.
Quaternary	Pleistocene	deep alluvium	Brown, yellowish brown, and gray stratified coarse-grained sand and gravel conglomerate; rare calcium carbonate cement; clasts of quartzite, argillite, and metacarbonate.	Outwash deposited during glacial advance; may include some intraglacial alluvium.
			unconformity	
Tertiary	Eocene-Miocene(?)	Tertiary sediment and sedimentary rocks	Brown and orange medium- and coarse-grained pebbly sandstone; pebble and cobble conglomerate; carbonaceous shale and carbonized wood; gray, yellow, and orange mudstone; and orange clayey gravel (diamicton); gravel clasts of argillite, quartzite, and siltstone are mostly well rounded; sandstone and conglomerate beds have channelized, erosional bases; locally infills fractures in Belt Supergroup bedrock; may include strata of the Kishenehn Formation and Paola gravel (Constenius, 1996).	
			unconformity	
Proterozoic		Belt Supergroup	Numerous stratigraphic units composed mostly of metamorphosed siltstones, carbonates, and quartz sandstones and minor amount of igneous rocks; most bedding thicknesses range between less than 1 cm in metasiltstones to a few decimeters or a few meters in metacarbonates and quartzites (Johns, 1970).	

Figure 4 General summary of Flathead Valley Stratigraphy (Smith, 2004)

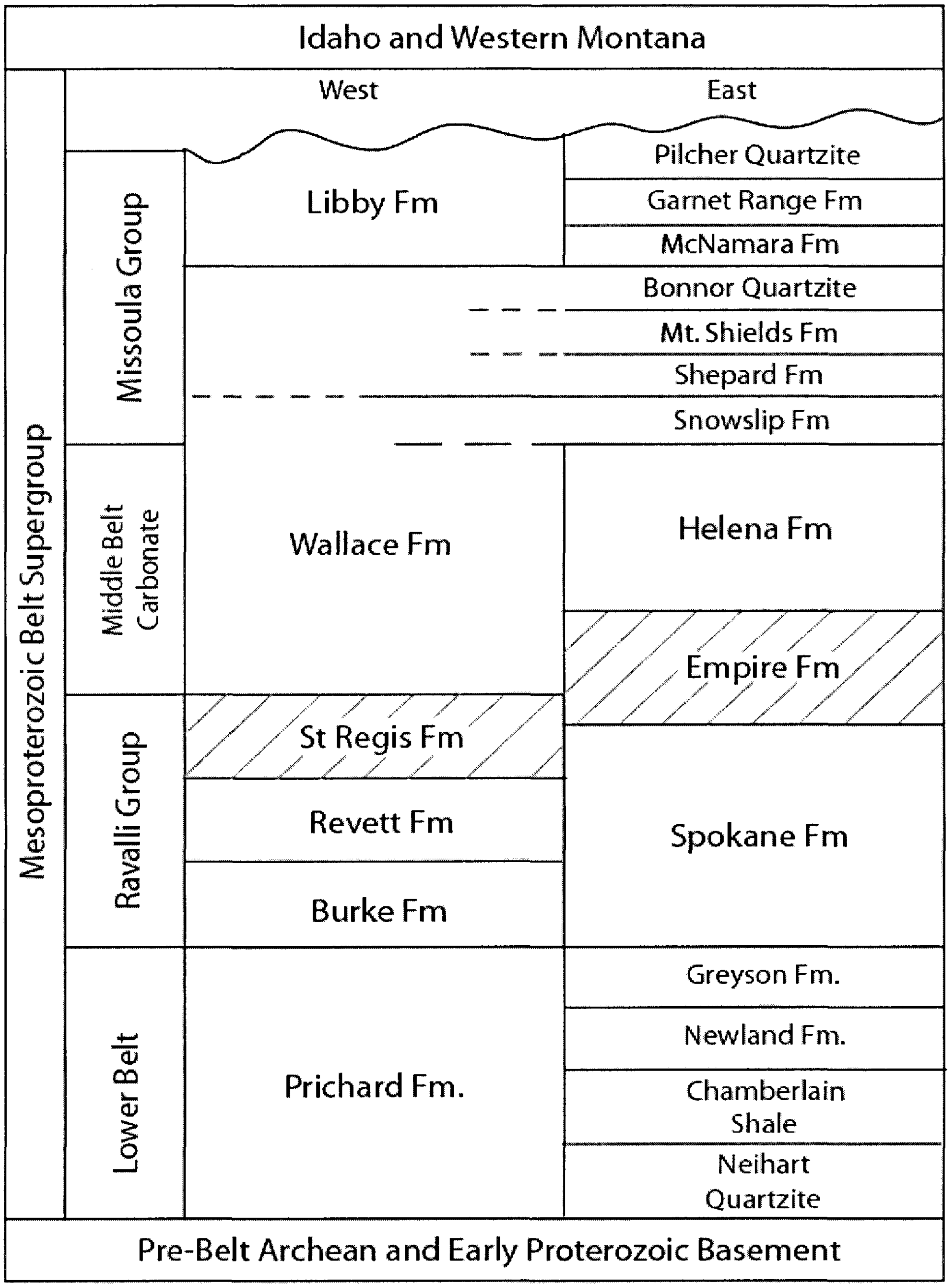


Figure 5. Stratigraphy of the Belt Supergroup. Cross hatch shows formations present in the study area. (Redrawn and modified from Luepke and Lyons, 2002)

Late Wisconsin Glaciation

Supply of glacial ice to the Flathead Lobe came from the Cordilleran Ice Sheet, valley glaciers near Whitefish, MT, valley glaciers in the forks of the upper Flathead River, and from the Swan Range (Smith, 2004). By modeling ice sheet behavior, Locke (1995) concluded that supply of ice to the FHL was derived chiefly from the Middle and South Forks of the Flathead River and from the Swan Range and that contributions from the Cordilleran Ice Sheet were less significant. Glaciers from the river valleys converged northeast of the Flathead Valley and flowed south, eventually combining with the glacier extending northwestward from the Swan Range (Alden, 1953; Locke, 1995). The Flathead Lobe, near the Big Arm Embayment, split into two arms; one moved westward and the other southward. In the Big Arm Embayment the glacier split into three smaller lobes, terminating and depositing moraines in Proctor, Elmo and Big Arm valleys (Smith, 1966, Bondurant, 2005). At the southern end of the Flathead Valley, near Polson, the south moving arm of the Flathead Lobe terminated and deposited the large arcuate Polson moraine.

Formation of glacial Lake Missoula coincided with inundation of the Flathead Valley by the Flathead glacial lobe (Figure 1). During the highstand (1280m) of the lake, GLM covered an estimated 5,000km^2 inundating Missoula, Mission, Bitterroot and other valleys in western Montana. During the existence of GLM, wavecut shorelines developed on the slopes surrounding the lake basin, including those slopes forming the southern and western margins of the Polson moraine. These observations suggest that either the Flathead Lobe terminated into glacial Lake Missoula for at least a portion of its history and/or that the Polson moraine formed prior to terminal draining of GLM

(Richmond, 1965, 1986; Levish, 1997, Smith, 2004). Draining of GLM is a topic of controversy. Some studies have concluded that numerous fillings and drainings of GLM took place (Chambers, 1971; Waitt, 1985; Atwater, 1986) while others have suggested that few draining events occurred during the lake's existence (Levish, 1997; Smith 2004).

The timing of the existence of glacial Lake Missoula, the terminal advance(s) of the Flathead Lobe and subsequent deglaciation in the region is not well determined. In the vicinity of northwestern Montana, the last glacial period (25-14ka ^{14}C y BP) is referred to as the Pinedale glaciation (Figure 6). This time period is tantamount to the Fraser glaciation of British Columbia, Canada and Washington. During Pinedale glaciation, the Purcell Trench Lobe and the Flathead Lobe have been interpreted to be at their maximum extent simultaneously (Smith, 2004). The time interval during which glacial Lake Missoula was impounded has been determined from glacial varves to range from 3240 to 3510 years (Levish, 1997). Different interpretations for the timing of glacial Lake Missoula impoundment have been reported in the literature. Using optically stimulated luminescence analysis on glacial lacustrine sediment, Levish (1997) suggested that the lake existed from ~19,200 to 16,000 cal years before present. In contrast to Levish, dates determined outside of the GLM basin by Atwater (1986) range from 18,000 to 15,500 cal years BP, and those presented by Waitt (1985) range from 17,500 to 15,000 cal years BP.

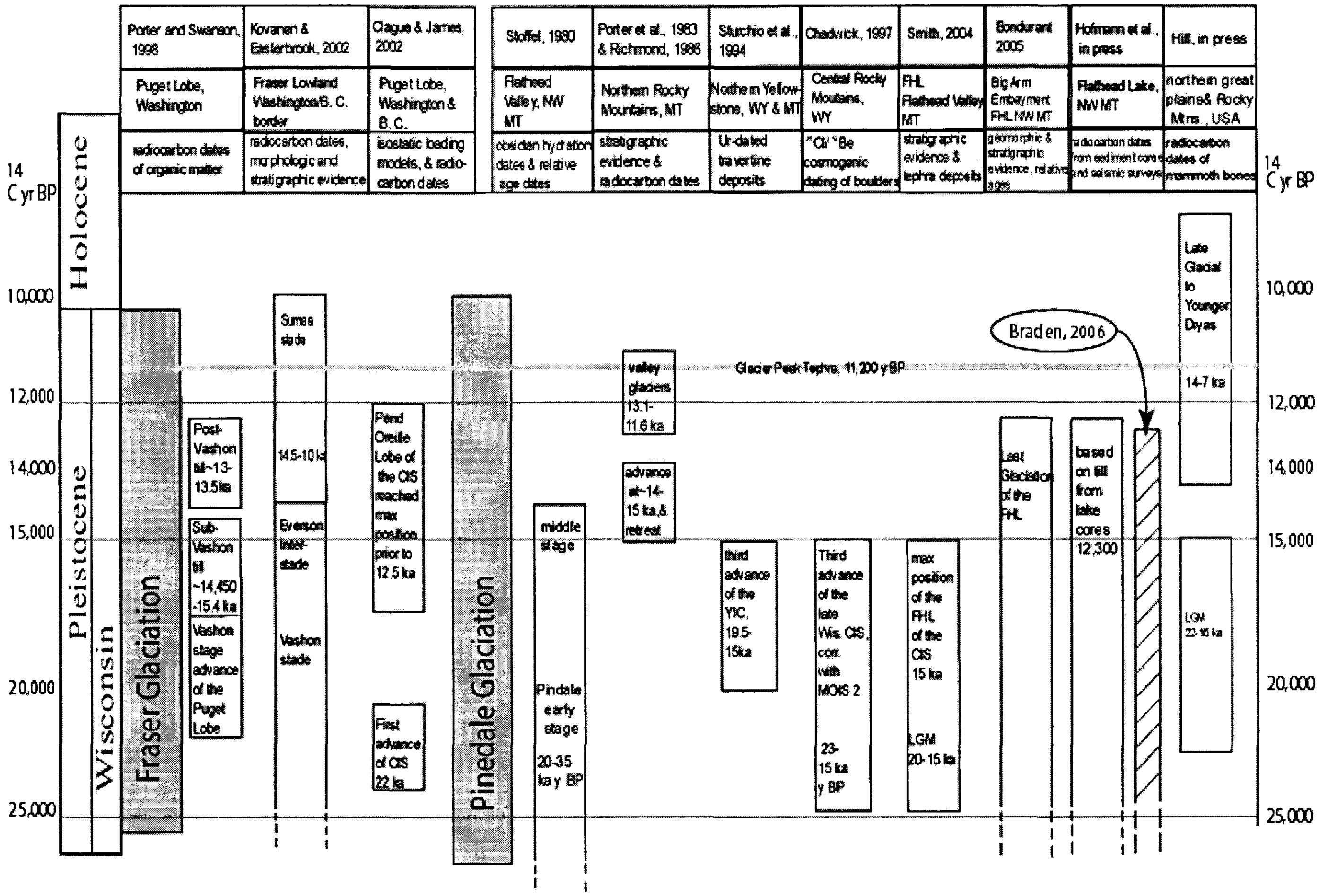


Figure 6. Glacial chronology table of the Cordilleran Ice Sheet during the Wisconsin. (CIS, Cordilleran ice sheet; FHL, Flathead Lobe; LGM, Last Glacial Maximum; YIC, Yellowstone ice cap; MOIS, Marine Isotope age). (Modified from Bondurant, 2005)

Timing of the existence of glacial Lake Missoula and glacial lobes in the Flathead Valley, though imprecise, are constrained by dateable tephra layers. Deglaciation timing is constrained by the deposition of the Glacier Peak tephra (11,200 ^{14}C year BP). Glacier Peak tephra and Mount St. Helens Jy ash (11,400 ^{14}C year BP), both located at Marias Pass, provide timing controls on deglaciation for northwestern Montana (Carrara, 1989). The Glacier Peak tephra additionally has been identified in sediment cores recovered from Flathead Lake in 2000 and 2003 (Hofmann et al., 2003) and in aeolian deposits north of Flathead Lake (Konizeski et al., 1968; Smith, 2004b). Analysis of seismic reflection data from Flathead Lake suggests that retreat within the lake basin took place approximately 13,000 ^{14}C year BP. Dates obtained ~30km north of the USA-Canada border indicate that deglaciation occurred by 12,000 ^{14}C year BP, and may have been as early as 13,500 ^{14}C year BP (Carrara, 1989).

Investigations of stratigraphy and radiocarbon dates throughout British Columbia, Canada indicate the Cordilleran Ice Sheet developed 30,000-25,000 ^{14}C year BP and persisted until 11,000 – 10,500 ^{14}C year BP (Clague and James, 2002). Using relative age dating of geomorphic and stratigraphic features, Bondurant (2005) inferred that the Flathead Valley was deglaciated by 12,300 ^{14}C year BP (14,150 cal years BP), relatively close to the date obtained by Hofmann et al. (2005) from radiocarbon dates from sediment cores and seismic survey analysis. In Flathead Lake sediment cores, rhythmite layers that are interpreted as varves underlie the Glacier Peak tephra (Hofmann et al., 2005). A date of 14,150 ±150 cal. years BP was obtained from ^{14}C dating of carbon material from core FL-03-19K (Hofmann et al., 2006). Although this date is from a pine needle collected from a deformed zone of core sediment, Hofmann (2005) was able to correlate varves sequences above and below the deformed zone to varves in other lake cores. Through this work, Hofmann (2005) concluded that ~100 varves are involved in the distorted section. This 100 years of uncertainty in the position of the pine needle recovered from core FL-03-19K results in 100 years being added into the uncertainty of the absolute dates of the varved sequence. Correlation of varves recognized onshore in the study area to those in the cores aides in constraining the timing of the deposition of glacial landforms. On the basis of stratigraphic relationships, relative ages and varve correlations, I conclude in this study that the glacial sediment and topographic features formed during the last glacial advance occurred after ~25,000 cal. years BP but prior to 14,300 ±250 cal year BP.

General Geography and Glacial Setting

Topographic elevations in the study area range from ~880m at the water surface elevation of Flathead Lake (Polson Bay) to ~1078m at the peak of the Valley View Hills located southwest of Polson (Figure 2). Within the study area, bedrock forms a series of distinct topographic ridges that are located southwest and west of Polson. The main Quaternary feature of the study region is the large arcuate Polson moraine (Figure 2). The moraine is bisected by the Flathead River, as it flows through the incised valley cut into the moraine by post-glacial flows (Figure 2). Located a couple of kilometers west of Polson is Kerr Dam, completed in 1938. This dam controls the present day surface elevation of Flathead Lake. East of the modern Flathead River in the former glacial outwash plain is Pablo Reservoir, a lake used for irrigation and as a wildlife refuge.

Methodology

I used standard geologic mapping techniques and sedimentological descriptions to define Quaternary map units. Those techniques involved drawing contacts on a paper topographic base USGS 1:24,000 Polson Quad and measuring oriented morphologic and geologic features, such as glacial striae, using a Brunton compass. Sedimentological descriptions included color, grain size, sorting, sedimentary structures and any other diagnostic sedimentologic features. The most significant geographic locations within the study area I assigned a field station number. Such stations were primarily at exposures of sediment and places that provided overviews of the surrounding landscape that aided in my geologic interpretations. I used a Trimble Pathfinder Pro XRS GPS device and ArcGIS 9 to determine the latitude and longitude of those field locations (Appendix 1).

In addition to the topographic base map I used a digital elevation map (DEM) of the field area, and aerial orthophotographs, to determine the location of geomorphic landforms. I obtained the base-layer DEM and aerial images of the Polson area from the Montana Natural Resource Information System (NRIS) website (http://nris.state.mt.us/). Using ArcGIS 9, I created a hillshade of the DEM to better delineate topographic features.

To better understand the subsurface stratigraphy, I obtained 89 well logs (Appendix 2) from the Montana's Ground-Water Information Center (GWIC, http://mbmggwic.mtech.edu/). Each well used in this study contained general lithologic descriptions of the material encountered during the drilling process. Several of these wells also penetrated bedrock, thereby providing information useful for constraining the depth to bedrock in cross-sections constructed across the study area (Plate 3), an isopach map (Plate 4) and bedrock elevation map (Plate 5).

Exposures of bedrock were found in numerous locations in the study area, some with glacial striae. At 8 field stations I took a total of 189 measurements of these lineations using a Brunton compass, with an average of 23 measurements per location. I used Golden Software's Grapher 5 to plot the bedrock scour orientations on rose diagrams for each of the various geographic locations. I measured a total of six stratigraphic sections in the study area. Four small (<4 meter) stratigraphic sections are located on the Polson Moraine (Fig. 13-16), one relatively short (~2m) section is located near the Mission Valley Chevrolet-Pontiac car dealership (Figure 19) and a longer (~30 meter) section is located just north of the Flathead River, ~1km east of Kerr Dam (Plate 2). These measured sections are used to assist in determining the facies and map units of the study area. In the stratigraphic sections I measured a total of 143 clast imbrications, with an average of 20 readings per section. I used the imbrication measurements to help determine sediment transport direction.

I digitized my geologic map using ESRI's ArcGIS 9 software by manually drafting the contacts. The map was georeferenced to state plane coordinates and the NAD 1927, ultimately projected in Albers Equal Area projection.

Lithofacies

To define the sedimentary facies present in the study area I described sediment composition, grain size and shape, color, and sedimentary structures. Based on these observations I applied facies codes, following the general descriptions of Eyles et al. (1983) and Miall (1996) (Figure 7).

Facies code	Facies	Sedimentary structures
Gmm	Matrix-supported, massive gravel	Weak grading
Gmg	Matrix-supported gravel	Inverse to normal grading
Gci	Clast-supported gravel	Inverse grading
Gcm	Clast-supported, massive gravel	-
Gh	Clast-supported, crudely bedded gravel	Horizontal bedding, imbrication
Gt	Gravel, stratified	Trough crossbeds
Gp	Gravel, stratified	Planar crossbeds
St	Sand, fine to v. coarse, may be pebbly	Solitary or grouped trough crossbeds
Sp	Sand, fine to v. coarse, may be pebbly	Solitary or grouped planar crossbeds
Sr	Sand, very fine to coarse	Ripple crosslamination
Sh	Sand, v. fine to coarse, may be pebbly	Horizontal lamination, parting or streaming lineation
Sl	Sand, v. fine to coarse, may be pebbly	Low-angle (< 15°) crossbeds
Ss	Sand, fine to v. coarse, may be pebbly	Broad, shallow scours
Sm	Sand, fine to coarse	Massive, or faint lamination
Fl	Sand, silt, mud	Fine lamination, v. small ripples
Fsm	Silt, mud	Massive
Fm	Mud, silt	Massive, desiccation cracks
Fr	Mud, silt	Massive, roots, bioturbation
C	Coal, carbonaceous mud	Plants, mud films
P	Paleosol carbonate (calcite, siderite)	Pedogenic features

[a] *v.*, very; *D*, dimensional.

Figure 7. Facies Codes (Miall, 1996)

Dmm – *Massive, Matrix-Supported Diamict*

Dmm facies is dominated by massively-bedded light grey to light tan clay and silt (Figure 8). Clasts are predominantly sub-angular to sub-rounded pebbles, cobbles, and boulders. Small zones of clast supported conglomerate, interpreted as resulting from iceberg dumps, are present locally.

Gcm – *Massive Clast-Supported Gravel*

Clasts consist of sub-rounded to well-rounded pebbles and cobbles, with uncommon boulders (Figure 8). Sedimentary structures are limited to weak imbrication and crude stratification. Matrix is fine to coarse (0 to 3 phi) brown sand.

Gh – *Open Framework Clast-Supported Gravel*

Clasts consist of pebbles and small cobbles that are sub-rounded to well-rounded. Facies displays crude bedding and imbrication within an open framework.

Gmm – *Massive Matrix-Supported Gravel*

Facies contains sub-rounded to rounded medium to very coarse (-1 to 2 phi) brown sand. Coarser clasts are pebble- to boulder-sized and are predominantly sub-rounded to well-rounded. No imbrication or stratification was observed (Figure 9). This facies occurs primarily in the southern portion of the Polson Moraine.

Gmf – *Massive Matrix-Supported Gravel (fine)*

Matrix is dominated by light grey to tan clay and silt with minor amounts of very fine sand. Clasts are pebble to boulder sized and are sub-rounded to rounded. No imbrication or stratification is displayed within this facies (Figure 9). This facies occurs in the western portion of the Polson Moraine, north of the Flathead River.

Figure 8. A: Image of the Dmm facies, note the weathering pattern, lack of bedding and scattered angular dropstones. B: Image of the Gcm facies, note the weak imbrication and crude foresets.

Figure 9. A: Image of the Gmm facies, note the rounded gravel and sandy matrix. B: Image of the Gmf facies, note the lack of structure and abundance of gravel.

St *– Sand, medium to very coarse, may be pebbly*

Facies comprises sub-rounded to rounded medium to very coarse (-1 to 2 phi) brown sand, minor amounts of small sub-rounded pebbles, thinly bedded with cross-bedding. This facies typically is interbedded with Gmm (Figure 10).

Sr *– Sand, very fine to medium, ripples*

This facies is dominated by well sorted, rounded very fine (3 to 4 phi) tan sand with locally fine to medium (2 to 3 phi) tan sand. Sub-critically to critically-climbing asymmetric ripples and tabular cross-bedding are common (Figure 10). Facies occurs stratigraphically below the Polson moraine in the southwestern portion of the field area and is interbedded with Dmm.

Sm *– Sand, Massive*

This facies comprises well-sorted, rounded fine to medium (1 to 2 phi) sand that is massively bedded with no observed sedimentary structures. Sand is loosely packed and contains no dropstones or gravel. Facies occurs south of and stratigraphically below the Polson moraine.

Fl *– Silt, Mud, Laminated*

Facies comprises light grey to white clay and tan to brown silt in alternating light and dark bands (rhythmites; Figure 11). Few pebble dropstones are present and no deformation of surrounding sediment appears to be associated with dropstones. Average thickness of rhythmites is 3 to 4 cm.

Fsc *– Silt, Mud, Massive*

Facies consists of light grey to tan clay and silt, with few pebbles and cobbles (Figure 11). No bedding or sedimentary structures were observed within this facies.

Figure 10. A: Image of the St facies, note the pebbly sand with cross bedding. B: Image of the Sr facies, note the critically climbing ripples. Scale in centimeters.

Figure 11. A: Image of the Fl facies, note the alternating light and dark layers. B: Image of the Fsc facies, note the lack of structure and few dropstones.

Map Units

Polson Moraine (Qgmft) and Undifferentiated Till (Qgtu)

The moraines deposited at the southern end of Flathead Lake during the Pinedale glaciation are well preserved. Geomorphically, the moraines are represented by long hummocky arcuate and linear ridges consisting of Gcm, Gmm, and Gmf (Map Plate 1) and are bisected by the Flathead River. The southern portion of the moraine extends east/west just south of Polson, Montana and has two main crests, one with a maximum elevation of ~1034m and the other at ~1043m (Map Plate 1). The northern portion of the moraine is located west of Polson and north of the Flathead River. This section of the moraine consists of three crests trending generally north/south. Two of the three crests have similar elevations (~1037m and ~1043m) to those crests of the southern portion of the Polson moraine (Map Plate 1).

The southern portion of the Polson moraine differs sedimentologically from the section north of the Flathead River. Facies Gcm and Gmm dominate exposures of the moraine in the south, although minor interbedding of Gmf facies does occur (Figure 13, 15). Two sections measured in road cuts near the town of Polson (station JB-008-05 – Appendix 1) at the top of the moraine display interbedding of the two main facies (Figure 13, 14). Crude imbrication and faint foresets imply a transportation direction to the south (Figure 13, 14). In contrast, the northern section of the moraine consists of the Gmf facies. This portion of the moraine typically shows no structure or flow direction indicators. One exception is a road-cut measured section along Irvine Flats Road (JB-048 and 51-05 – Appendix 1) that displays faint overall stratification and minimal dip to the east (Figure 15). A more detailed examination of the top meter reveals laminated and very thinly bedded (1cm) brown clay and silt and very thin (2-4cm) beds of very fine to fine tan sand. Interbedded in the clay and silt beds are three reddish brown silt layers with small pebbles resting atop the layer. A set of wavy clay and sand layers is truncated by a bed of reddish brown silt.

East of the northern section of the Polson moraine, Gmf facies are exposed in broad undulating valleys between the main moraine and bedrock ridges (Map Plate 1). These sediments likely are glacially deposited but are not topographically associated with the moraine; therefore, I defined the unit as undifferentiated till.

Glacial Outwash Plain (Qgop)

Located south of the Polson moraine and mainly east of the Valley View Hills is an expansive glacial outwash plain (Map Plate 1) that occurs as a series of gently undulating hills. Active gravel pits are located in the outwash plain, including one within the study area. Unfortunately, I was denied permission to examine these gravel pits. Four wells (Well #3,4,5,6 – Appendix 2) have been drilled into this area and the material described consists of interbedded sand and gravel. These sand and gravel beds are hypothesized to consist of St, Gcm and Gmm facies. Maximum depth of the outwash sediments drilled in the wells is 55m.

Two other significant regions interpreted as representing glacial outwash are located north of the Flathead River. The first is a sinuous channel extending southward from a valley between the two main crests of the moraine. A well drilled (Well #29 – Appendix 2) into this section penetrates interbedded sand and gravel to a depth 67m. At the southern end of the channel (station JB-050-05) the modern topographic surface has

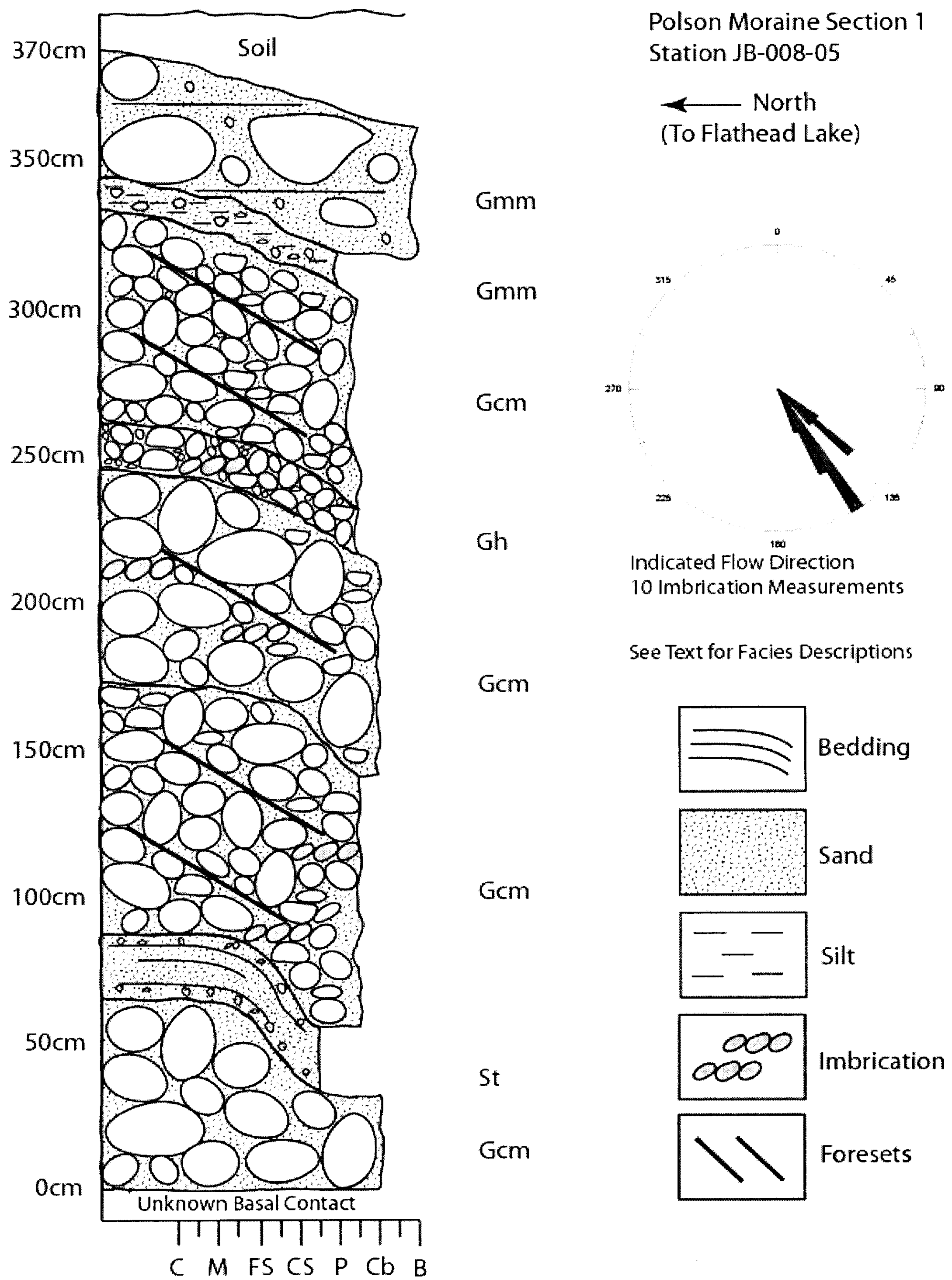


Figure 12. Road-Cut measured section of the Polson moraine, along Highway 93. Foreset beds recognized in exposure represent prograding delta front deposits.

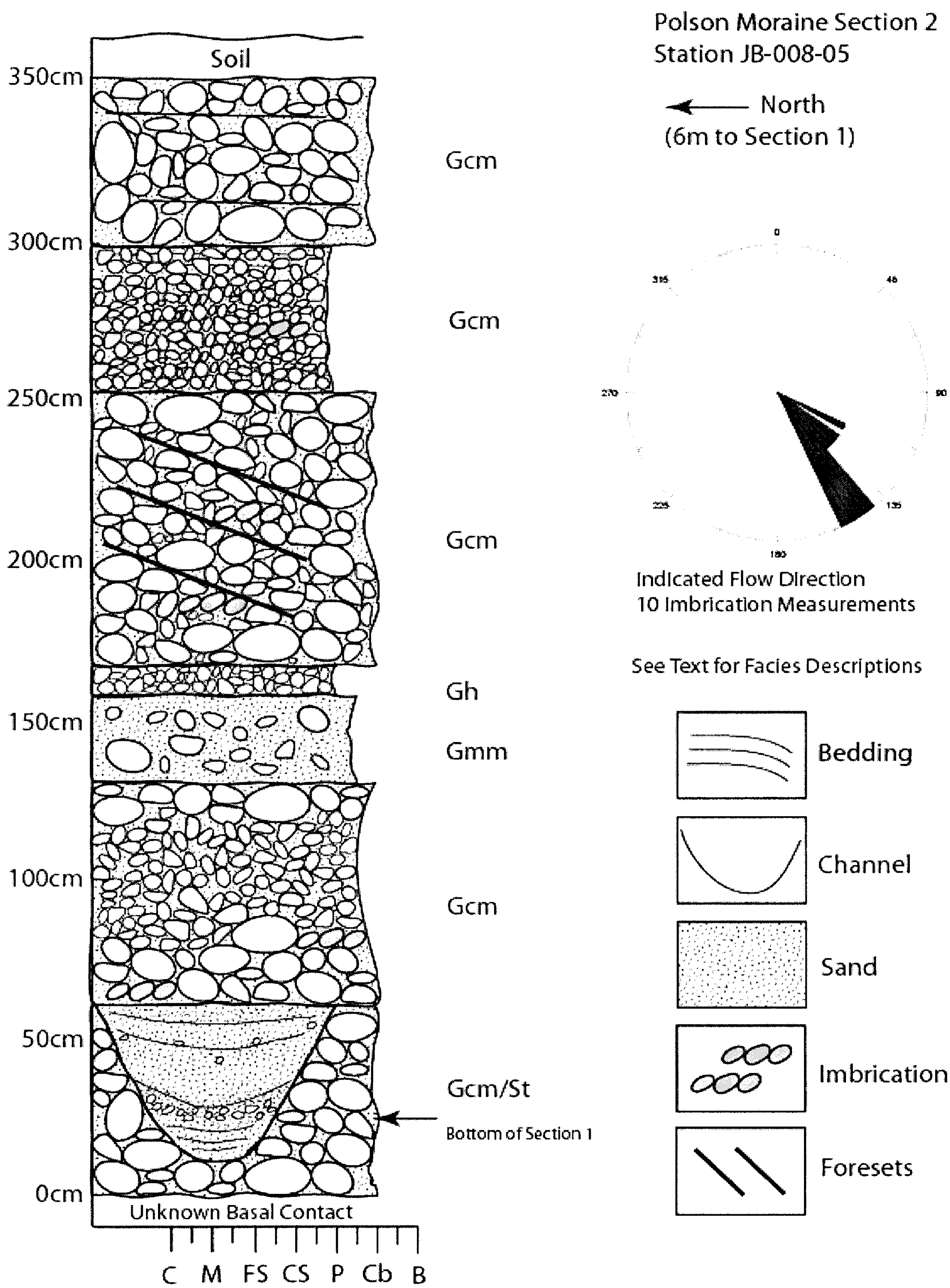


Figure 13. Road-cut measured section of the Polson moraine, ~6m south of section 1. Topset and channel structure indicate a fluvial environment, where the foresets suggest progradational slope of a delta.

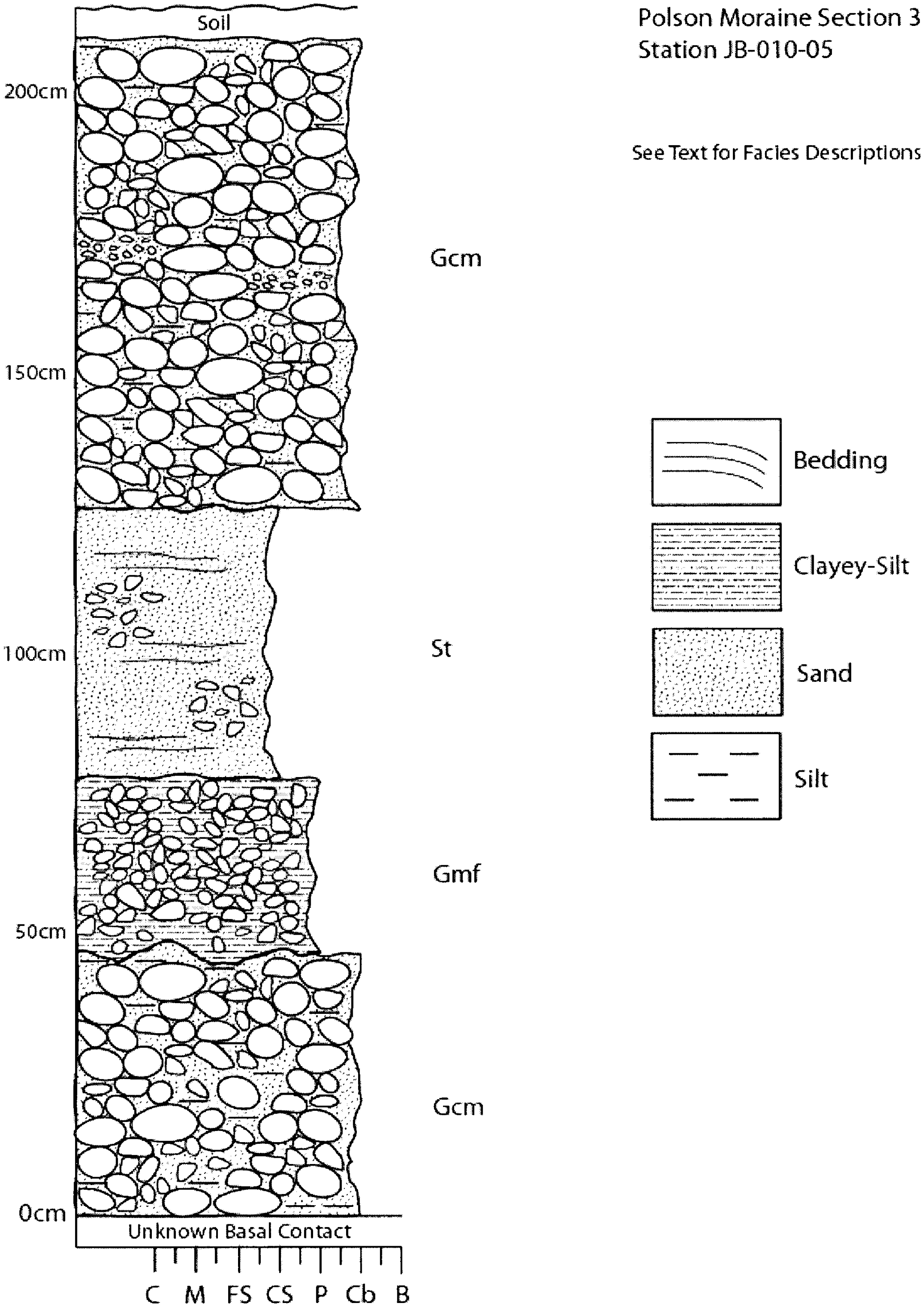


Figure 14. House foundation pit measured section of the Polson Moraine. Deposition in sub-aqueous outwash, small density flows, and fluctuating discharge and flows.

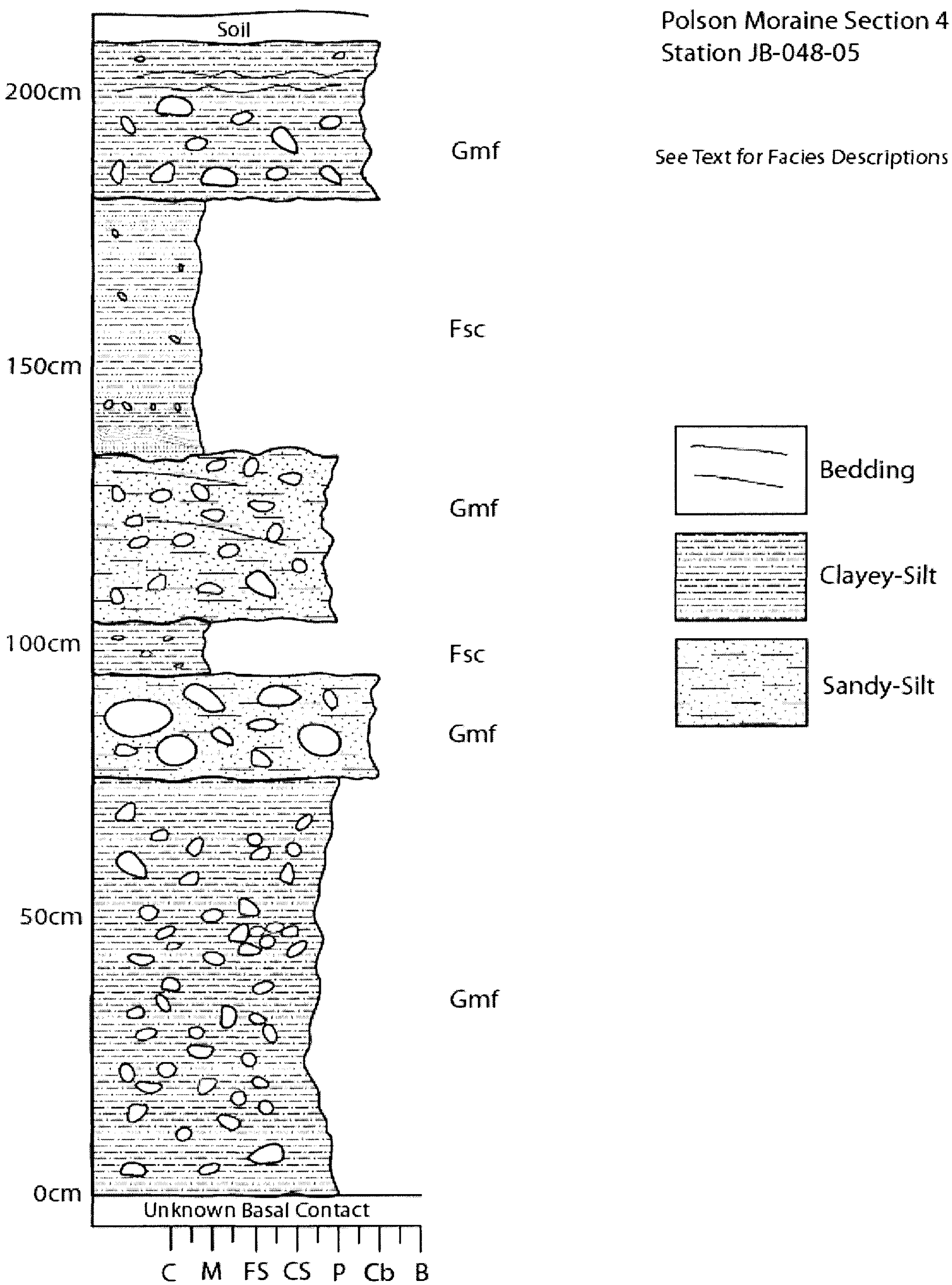


Figure 15. Road-cut measured section of the Polson moraine along Irvine Flats Rd. Weak stratification, gradational contacts and laminated fine grained sediment interpreted to be deposited in low energy (calm water) depositional environment.

many rounded pebbles and cobbles mixed in a sandy soil. Again, the facies hypothesized to exist in this region are those of St, Gcm and Gmm. The other major region of outwash is along the northern border of the moraine. Two well logs (well# 38 and 45 – Appendix 2) report sand and gravel, similar to the material observed in other wells. However, in these locations the sediment thickness is thin; both wells report slightly more than 5m of sand and gravel. This significant decrease in the volume of outwash likely reflects the fact that the sand and gravel was deposited outside of the main outwash channel.

Diamict (Qglm) and Coarse Diamict (Qglmc)

Clay and silt containing coarser grained clasts is interpreted as diamict and can be traced out from just south of Polson to Crow Creek (Levish, 1997). Using facies interpretations from Eyles et al. (1983), Levish (1997), interpreted the diamict to be sublacustrine, deposited into glacial Lake Missoula. Sedimentological descriptions and facies interpretations determined from this study are consistent with descriptions of nearby Quaternary sediments from other studies (Levish, 1997, Timmerman, 2005, Edwards, 2006, in progress). I mapped the steep cliffs along the Flathead River and the undulating plains in the southwest quarter of the study area as diamict (Map Plate 1).

The main constituent of the cliffs along the lower Flathead River is the Dmm facies. Locally there is interbedding of facies Sr, St, Gcm and Gmf. The Dmm facies is easily erodable; however, with interbedded more resistant Gcm and Gmf facies, the erosional profile of the deposit is highly variable. Located along the length of the river, above Sloan Bridge, the diamict forms cliffs with pillars and numerous gullies (Figure 16). Southwest of Rocky Butte and west of the Valley View Hills the geomorphic

Figure 16. Highly variable erosion within the Diamict forming pillars and gullies.

expression of this unit is mostly that of a gently undulating plain. This plain has been dissccted by numerous modern stream gullies that cut into the easily erodable Dmm facies.

Located near the Valley View Hills and Rocky Butte are two topographic benches bordered by south- and west-facing slopes (Map Plate 1). Sediment along these slopes consists of coarse diamict with sedimentologic characteristics slightly different from Qglm. A new housing subdivision, south of Forman Rd, was in the process of being built during the summer of 2005. A 1.5m deep and 350m long utility trench, starting near station JB-004-05 (Appendix 1), descends ~6m over a horizontal distance of ~50m into a small gully, exposing coarse diamict. The Dmm facies is the dominant material in the coarse diamict exposed within the trench. However, sediment in the trench near the bottom of the gully is clayey silt with an increase in gravel content and very fine sand lenses and fines upward to Dmm facies sediment. In addition to the exposed material well log #17 reports claybound sand, gravel and cobbles and well log #33 reports silt, sand, gravel and cobbles overlying tan clay with gravel (Appendix 2). Both wells intersect bedrock at shallow depths which, in conjunction with the bedrock exposure in this area, suggests a bedrock ridge system. I infer that these bedrock ridges served as a 'ponding' area for icebergs, allowing the coarser material to be deposited in this backwater region and contributing to the modern day topographic benches. This interpretation fits well with that of Levish (1997) who first recognized that the Valley View Hills (VVH) partially blocked lacustrine deposition to the west. Levish (1997) reported that the Quaternary sediment column is 75-100 meters thicker east of the VVH than to the west.

Outflow/Sub-Lacustrine Fan (Qgo)

Lønne (1995, 2001) described sediments on the ice-proximal side of a moraine, deposited as a submarine fan as the glacier retreats, as having bedding planes and foresets dipping towards the glacier. Submarine fan material consists of coarse-grained facies deposited by traction transport (Lønne, 1995, 2001). In this region the sediment is typically is also characterized by glaciotectonic features and reworking of the sediment (Lønne, 2001).

At the terminal position of the Flathead Lobe, sediment was being transported southward into the glacial outwash plain. Subglacial fluvial processes also were depositing material north of the Polson moraine beneath and proximal to the glacier. As the lobe retreated to the north, deposition of sediment occurred in the newly forming ancestral Flathead Lake. These sediments sit as a low angle apron on the north slope of the Polson moraine (Map Plate 1). The largest concentration of the outflow-related (sub-lacustrine fan) sediments is located at the eastern end of the study area near US highway 93. Sediment exposed in a temporary outcrop along Highway 93 displayed coarse sand lenses, crudely imbricated gravel, and open framework gravel of Gmc, Gh and St facies (Figure 17).

Across the Flathead River from the Polson airport outcrops of interbedded sand and gravel are exposed in the cliff face. These sediments consist of the facies St, Sr and Gh. The morphology between the river and the highway suggests the continuation of similar facies between these two outcrops; however, no outcrops occur in this region.

Figure 17. Gmc and St facies displayed in highway construction road cut.

Ancestral Flathead Lake Sediments (Qlkof) and Glacial lake Sediments, Undivided (Qgl)

During the retreat of the Flathead Lobe a large pro-glacial lake was dammed against the ice-margin and behind the terminal moraines. This proglacial lake was an ancestral version of Flathead Lake. Typical proglacial lake bottom sediments consist of finer grained material produced by glacial erosion and deposited through suspension settle out to form flat planes (Flint, 1957, 1971). Seasonal variations in sediment production and texture results in coarser grains settling out first during higher discharge (spring), and fines during low discharge periods (winter). The resulting annual accumulation of sediment is a fining-upward bed that is repeated each year, forming a series of glacial rhythmites (Antevs, 1925, Legget and Bartley, 1953). Nearshore sediments are dominated by silt and clay; however, because of proximity to deposition from onshore, gravel and sand are interbedded into the lake sediment (Flint, 1957, 1971). A modern example of glaciolacustrine sediments featuring rhythmitic sequences and littoral deposits have been recognized near Copper River, Alaska (Bennett et al., 2002).

Around the perimeter of modern Flathead Lake and downstream along Flathead River, fine-grained laminated sediments dominate. The sediments deposited consist of the Fl and Fsc facies. Topographically, these sediments are expressed as a plain with little or no undulation. I used well logs in addition to morphology to help define the extent of the Qlkof unit (Well # - 21, 22, 25, 26, 42, 58, 59, 61 – Appendix 2). Driller's logs describe this material as tan clay, tan and brown clay, and in places, tan clay with few pebbles. Near the Polson airport, along the Flathead River (station JB-042-05, Appendix 1), the top few meters of the cliff face are accessible. Similar to the well logs, the sediment is comprised of cm-scale laminated tan and brown clay typical of the Fl facies. Thickness of the rhythmite layers ranges from <1cm to 9cm with an average thickness of ~3cm in this outcrop.

A wave-cut terrace is evident around the perimeter of the town of Polson. The approximate elevation of the terrace is at 902m, ~21 meters above the present day lake surface elevation. The transition from Qlkof and the Qgl map unit is located in the vicinity of the 902m terrace. Few exposures of this material are present within the study area and none show the contact between map units; therefore, morphology is a key indicator of this unit. On the southern side of the town there is a low angle slope connecting the flat plain of the ancestral Flathead lake sediment and the sub-lacustrine fan. North of the Polson Airport, near Tower Road, the present day surface is a low angle slope above the terrace level that leads up to the Polson moraine. Driller's well log lithologic descriptions (Well # - 37, 44, 46, 47, 84, 86, 87) report more gravel in the region mapped as Qgl, with descriptions ranging from tan clay, silt and gravel to gravel imbedded in clay. These sediments differ from diamict in that they are deposited on top of the Polson moraine and most likely received their gravel from littoral deposits. Some of the sediments were most likely derived from deeper lake environments as well.

Eolian Deposits (Qe)

Eolian sands are typified by frosted, well-sorted, well-rounded cross-bedded sand and ventifacts formed from abrasion (Whitney and Dietrich, 1973). Such sediments were temporarily exposed in parts of small hills south of Polson (station JB-011-05) during the summer of 2005. Exposure of the material shows massively-bedded well sorted brown sand, with local areas of thinly bedded sand that is locally cross-bedded (Figure 18.) Analysis of this sand under 10x magnification shows the grains to be well rounded, well sorted and frosted. Overall the outcrop coarsens upward from fine to coarse sand. The sediment represents a combination of the three sand facies in the study area: St, Sr and Sm. Due top their similar morphology I mapped the small hills located south of the Polson moraine, along US highway 93, as eolian sands (Map Plate 1).

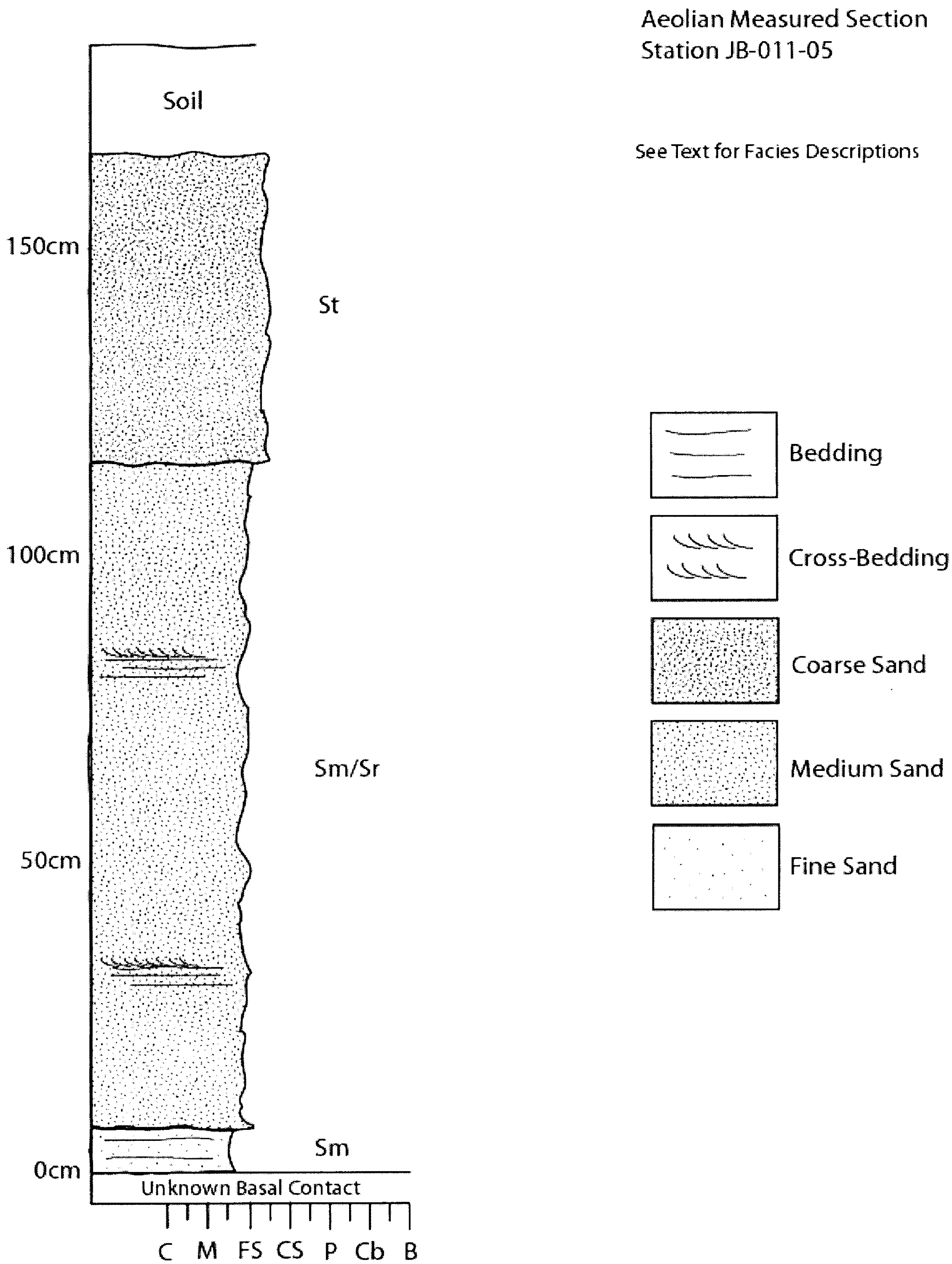


Figure 18. Road-cut measured section, near Mission Valley Chevrolet-Pontiac car dealership, interpreted as aeolian sands.

Delta Sediments (Qgd)

Contemporaneous with the advancement of the ice front, outwash sediment deposited in subaqueous environment can form a fan or delta. Deltas associated with the advancing glacial position typically display coarsening upward subglacial facies, inclined boulder rich foresets and turbidite features (Lønne, 1995, Bennet et al., 2002). Erosion and reworking of the sediment can occur in the fan zone. Interbedding of fine and coarse grained facies does occur because of the complex glacial dynamics, discharge variability and flow changes (Lønne, 1995, 2001; Bennet et al., 2002).

A drainage gully located north of the Flathead River, ~0.8km east of Kerr Dam, has exposed several short sections of Quaternary sediment (Map Plate 1). I measured a ~30m stratigraphic section in the gully (Plate 2). I used one of Trimble's mapping grade GPS systems, the Pathfinder PRO XRS, to determine the elevation of the top of the section. The top of the measured section is at ~983m elevation while the base is at 952m (station JB-021-05 – Appendix 1). This section sits stratigraphically below and is interbedded with sediments of the Polson moraine. The section also is interbedded with diamict sediment at its base. The section shows an upward coarsening sequence followed by an upward fining package consisting of facies Gcm, Sr, Sm and St and minor amounts of Fsc. Large clast supported conglomerate facies occur at the base of each package and locally display imbrication and well defined stratification. One of the gravel layers in the middle of the section displays a channelized form and an overall lack of structure. Imbrication measurements indicate a variable transportation direction with overall transport to the southwest. I interpret the stratification as being foresets that are shallowly dipping beds (<10°) to the south and southwest. The sands vary throughout the section and range from fine- to coarse-grained with some layers displaying ripples and cross-bedding.

The cliff faces along the Flathead River, upstream of the Kerr Dam, expose sediment primarily dominated by the Dmm facies. Starting just upstream from the dam, local exposures of material consist of the St, Sr, and Gmc facies (Figure 19). These sediments are sedimentologically similar to those described in the measured section in the drainage gulley. Stratigraphically these gravels and sands occur below the diamict and therefore below the other deltaic package. The deposits consist of interbedding clast supported conglomerate and sand. No imbrication measurements were obtained because of the inaccessibility of the cliff face. Using photographs of the cliff side, I infer the overall transportation direction to be towards the southwest based on imbrication and gently dipping beds. The contact between the diamict and the delta deposits is sharp and varies from flat to wavy.

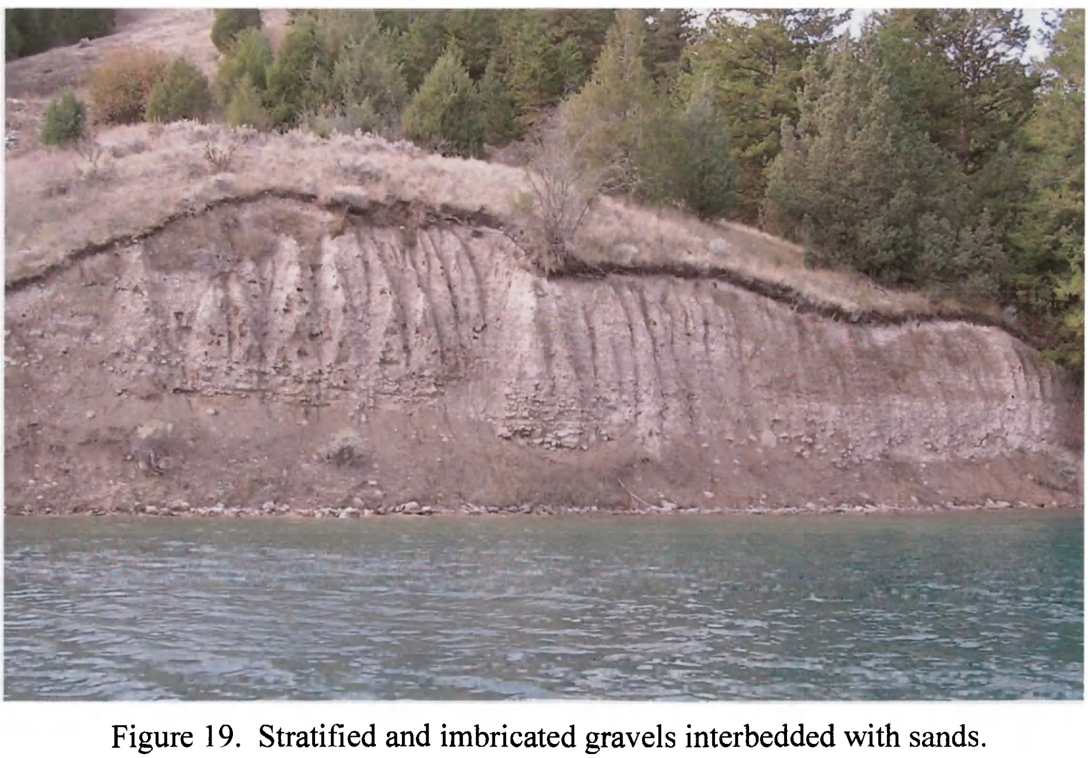


Figure 19. Stratified and imbricated gravels interbedded with sands.

Tertiary Sediments, undifferentiated (Tu)

Smith (2004) recognized Tertiary sediments near the northern end of Flathead Lake, and Alden (1953) described Tertiary material in the Mission Valley region. Tertiary age determination of the material in the Kishenehn Basin, north of the Flathead Valley, was based on fossil mammals, mollusks, leaves and pollen from exposure of the Kishenehn formation in Canada (Russel, 1964; Hopkins and Sweet, 1976). More recently Constenius (1996) reported Eocene mammal fossils in the Coal Creek member of the Kishenehn Formation north of this study area. Unfortunately, no fossilized bone or carbonized wood were discovered within the outcrops along the Flathead River. However thorough investigations of these outcrops were highly limited because of their accessibility and position along the Flathead River.

Near the pump station, along a bend in the Flathead River upstream of Kerr Dam, there are deposits of orange to light brown colored coarse grained sediments that I interpret to be Tertiary in age (Figure 20, 21). These deposits rest upon exposures of Mesoproterozoic bedrock and occur at a stratigraphically lower position in the section than the diamict. Figure 21B displays crudely stratified matrix supported pebble to cobble conglomerate, locally clast supported. Clasts are sub-angular to sub-rounded, the matrix consists of clay to silty fine sand (Figure 20). Tertiary sediments in the Flathead and Mission valleys are described as including brown and orange pebble and cobble conglomerate and orange clayey gravel. Sandstone and conglomerate lithologies appear to be channelized (Alden, 1953, Smith, 2004). The sedimentological descriptions of other exposures recognized in northern Flathead Valley (Alden, 1953; Constenius, 1996) are consistent with the sediment found in this study.

Figure 20. Clay to sand matrix supported sub-angular to rounded pebble to cobble conglomerate of weakly consolidated Tertiary sediments located along the Flathead River next to the Aqueduct Pump Station. The dark bed represents a channel cut and fill contact (arrow).

Figure 21. A: Image shows angular contact with diamict above Jason Edwards' head. B: Image displays coarse grained and rough stratification of Tertiary sediments, note contact with Mesoproterozoic bedrock.

Flathead River Sediments (Qfr)

The lower Flathead River is the outflow for Flathead Lake. Discharge of the lower Flathead River is controlled by the Kerr Dam. Approximately 1 mile upstream from the Kerr dam are a series of 9 terraces (Map Plate 1). The lowest terrace trends NW/SE and the terrace top is between 2 and 3 meters above modern day water level. From rivers edge to the toe of the slope to the next terrace, at the widest point, is approximately 60m. This terrace consists of stratified gravels and sands with crudely imbricated gravels (Figure 22). Outcrops of the terrace material show an interbedding of St and Gcm facies. I interpret this lowermost terrace to consist of mostly coarse-grained sediment deposited by the Flathead River.

Figure 22. Stratified sands and crudely imbricated gravels of the depositional terrace.

Pro-glacial Lacustrine Sediments (Qglp)

Bordering the Pablo Reservoir to the north, within the glacial outwash plain is a small topographic low. The majority of this land is used for agriculture and contains no outcrops. Well log #7 (Appendix 2) drilled into this region describes brown clay from the surface to a depth of ~15m. Inspection of lithologic descriptions from other well logs (#11, 15 and 16) nearby to well #7 indicates the presence of a brown clay layer. Correcting for elevation differences of the well tops suggests that the brown clay layer extends laterally to the northwest beneath the outwash plain. The top of the clay layer is located at an elevation of 975m, whereas the base of the clay layer occurs at an elevation of 960m.

Pablo Reservoir/Marsh (Qpr)

South of Polson, east of the Valley View Hills, is the 1850 acre (US Fish & Wildlife Service, 2006) Pablo reservoir, part of the Pablo National Wildlife Refuge (Map Plate 1). Around the perimeter of the lake marshes and woodlands are common. The sediments consist of organic-rich silts deposited during past flood stages of the lake. Today the reservoir is dam controlled and serves as source water for irrigation of the surrounding agricultural industry and for flood control.

Late Holocene Stream Deposits (Qal)

Many intermittent streams occur in the study area. Deposits within the stream beds generally consist of transported and re-worked material from moraines, outwash plains and lake sediment. The Flathead River is the only major river in the study area, and today the flow is controlled by the Kerr Dam.

Interpretations and Discussion

The former terminus of the Flathead Ice Lobe is expressed topographically as the Polson moraine. Extending from the Mission Mountains, the large hummocky landform arcs toward Kerr Dam then northward where it is cross cut by the present day Flathead River. Sedimentological differences between the northern and southern sections of moraine suggest slightly contrasting depositional environments. The southern portion of the Polson moraine is interpreted to be deposited in a sub-aqueous environment based upon abundant climbing current ripples observed in moraine exposures in the Redi-Mix gravel pit along US Highway 93 (Hofmann and Hendrix, 2004).

I propose that the glaciofluvial delta (outwash fan/sandur delta) model described by Lønne (1995) is a modern day analog (Figure 23) for the Polson moraine material. Ice-proximal glaciofluvial deltas (outwash fan/sandur delta) are typified by well-developed fluvial distributary plain, aerial component, stream-deposited topset, foreset built of outwash material, and glacio-tectonic deformation only within the head-zone (Lønne, 1995). Extending south from the Polson moraine is a broad, south-sloping, undulating plain. Lithologic descriptions for water wells drilled in this region indicate an abundance of sand and gravel units (Well 3, 4, 5, 6 – Appendix 2). Hofmann and Hendrix (2004) illustrated this outwash plain as consisting of clast-supported, silty and sandy gravel and sub-lacustrine fan delta deposits. Sand units overlying glaciolacustrine deposits, recognized during hydrogeological and soil investigations of the proposed expansion area for the Lake County landfill, contain features typical of outwash plains (Damschen & Associates, 1999). In addition Damschen & Associates (1999) recognized a portion of these outwash deposits were overlain by moraine sediments that displayed progradational

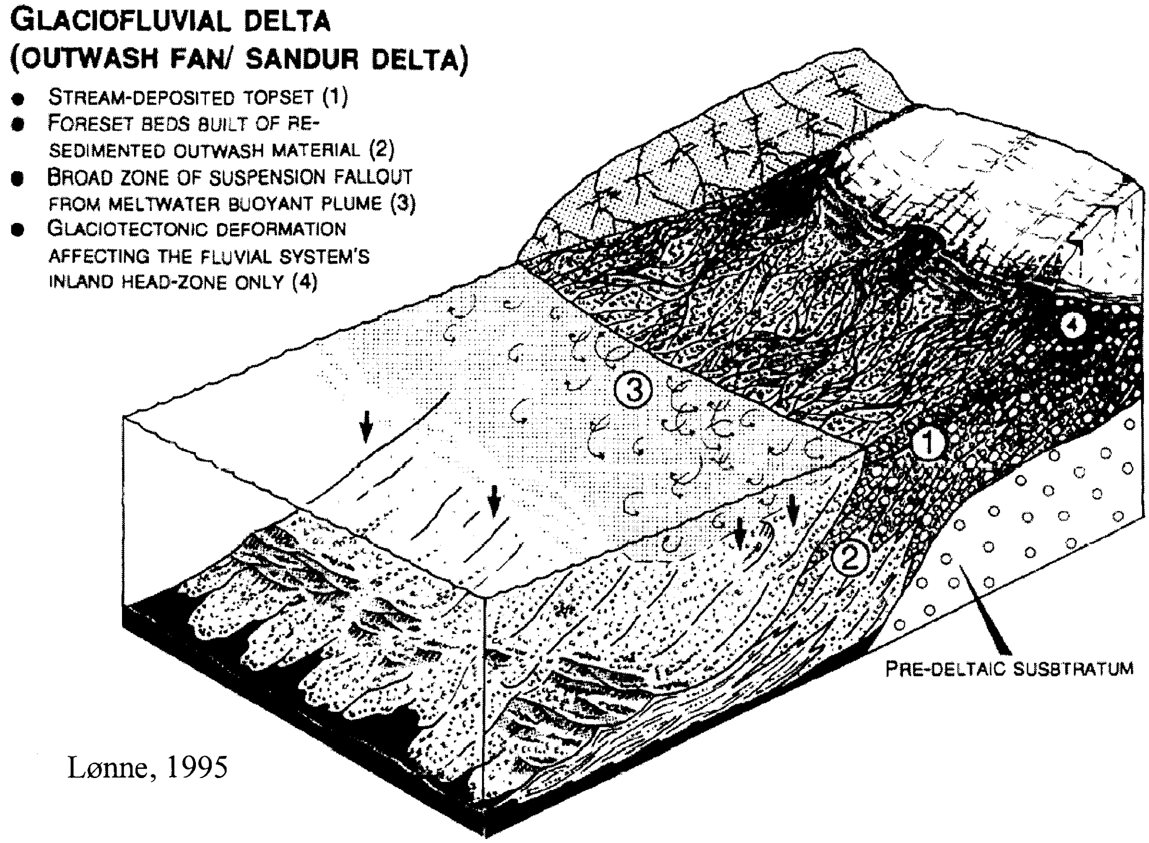


Figure 23. Glaciofluvial depositional system model proposed for the Polson Moraine.

bedding, flame structures, and density flow deposits indicating glacial overriding of outwash sediments in a lacustrine environment. Along US Highway 93, across from the Redi-Mix plant, a portion of the moraine was exposed by earth moving equipment (JB-008-05 – Appendix 1). This exposure is located near the top of the moraine. Examination of the outcrop revealed a primarily clast-supported conglomerate with a matrix of coarse sand. Foreset and topset beds overlay a gravelly erosion layer that truncates a cut and fill channel structure (Figure 13, 14, 25). Topset beds and the channel structures indicate sediment deposition in a fluvial depositional environment overriding deltaic sediment prograding in the pro-glacial lake.

Hofmann and Hendrix (2004) recognized a stratigraphic section that fined upward from gravel beds into sand with well-developed, highly aggradational sub-aqueous current ripples in the Redi-Mix plant. Overlying the gravel and sand deposits is a sequence interpreted to include paleosol horizons and leoss deposits (Hofmann and Hendrix, 2004). Lithologic descriptions of sediment intersected in drilling wells through the Polson moraine describe Gcm, Gmm and St facies to depths of ~140m. I interpret these sub-surface sediments to be morainal and interbedded outwash deposits as they are typical of the surface exposures of the southern segment of the moraine. The sediment exposed within and near the Redi-mix plant, in conjunction with the inferred sub-surface facies indicate deltaic and fluvial-style deposition at a largely sub-aqueous ice margin. I infer that these relations indicate that the Flathead Lobe did indeed calve directly into a lacustrine environment. This interpretation fits well with the glaciofluvial model put forth by Lønne (1995, 2001). Formation of paleosols indicates aerial exposure and is compatible with this depositional model for the Polson moraine and broad sandur delta plain extending southward. On the south facing slope of the moraine, wave-cut terraces strongly suggest that the moraine terminated against glacial Lake Missoula.

Glacio-tectonic deformation is expected only on the ice-proximal slope of the moraine within the head zone of the glacier. The head zone for the Flathead Lobe occupied the location where the city of Polson presently is situated. Expansion of the city of Polson has developed the majority of the land in this local; therefore, very few outcrops of the facies that underlie Polson are available. New exposure located along US

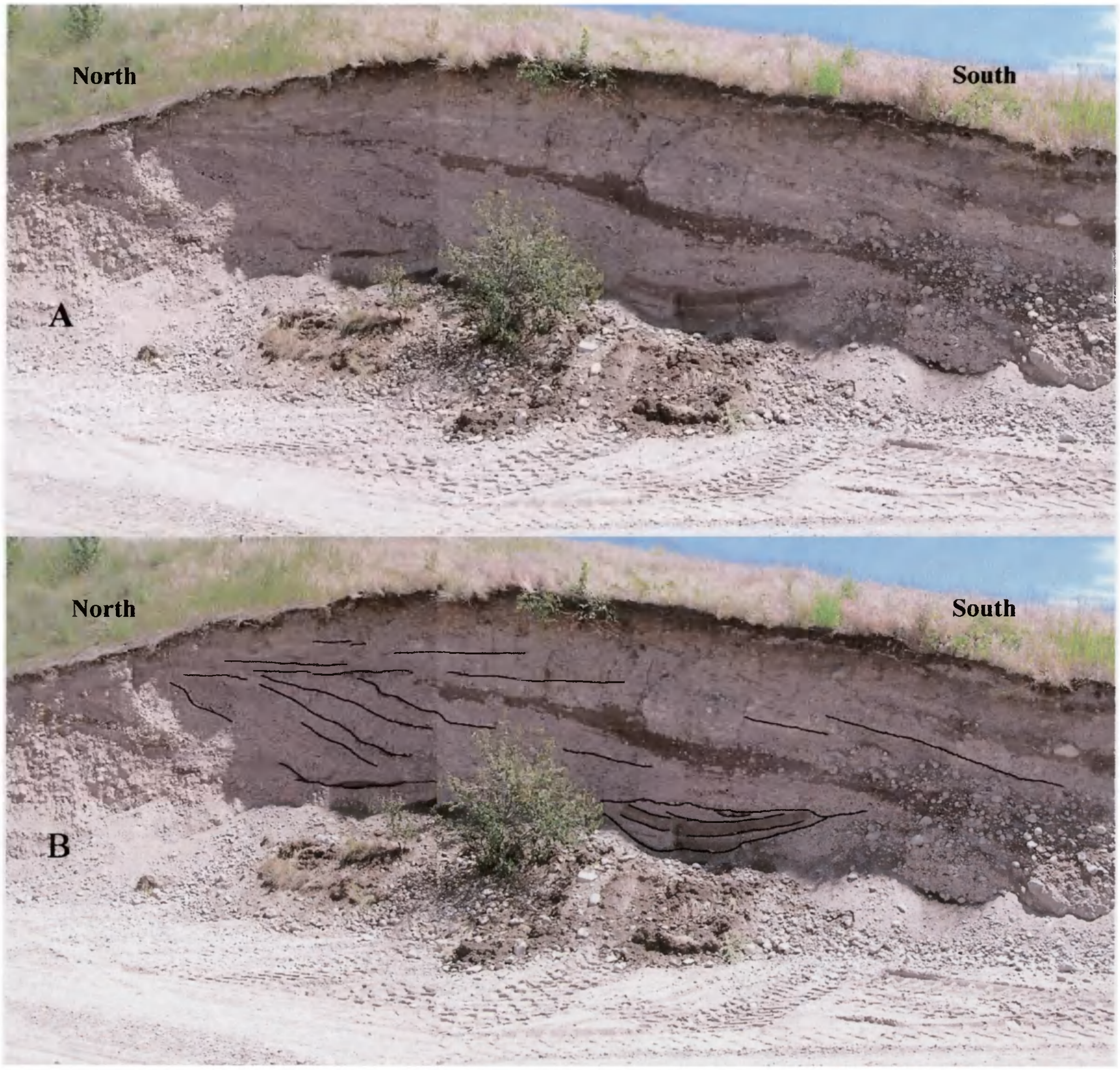


Figure 24. A: Exposed sediment along road-cut near Redi-Mix plant. B: Interpretation of foresets indicating deltaic environment, and stream deposited topsets at station JB-008-05. Looking toward the Northeast.

Highway 93, near the Highway 35 intersection in Polson revealed interbedded sand and clast supported gravel of the sub-lacustrine/outwash related map unit (Map Plate 1). Sand layers are wavy with moderate sorting and numerous small-scale tectonic offsets. A portion of these offset structures potentially were created during the use of heavy construction equipment in this area. However, I conclude that most of the tectonic features are remnants of past glacial dynamics because of their 'protected' location relative to the primary construction zone. The base of gravel layers typically display erosional contacts, and sand units are cross-bedded, suggesting deposition by sub-glacial meltwater flows in a sub-lacustrine fan delta (Hofmann and Hendrix, 2004). Although previous work has demonstrated that these sediments were deposited in an aqueous environment, this is the first recognition of significant glacio-tectonic deformation in the area.

The position of the southern segment of the Polson moraine is determined by relatively shallow bedrock features. Along the Flathead River, near the aqueduct pump station, there are exposures of bedrock at the base of the cliff face. These outcrops of Belt bedrock are 40-50m below the moraine deposits and are locally capped with 2-3m of sediments that I infer to be Tertiary. However, well logs located in Polson, in addition to others located further east along the moraine, describe intersecting bedrock at approximately 6 – 30m. I infer that these bedrock features aided in terminating the glacier at this locality, although the bedrock topography and structure under the southern moraine is not well constrained due to the lack of detailed geophysical information. I suggest that the basin architecture is complicated by the combined effects of erosional topography of the top-bedrock surface, heterogeneity of the ice-lake system, and time-integration of the whole system.

Deposition of the portion of the Polson moraine north of the Flathead River differs from the southern part in terms of its sedimentology and structure. The northern segment of the moraine consists primarily of the Gmf facies. Morainal sediments exposed along Irvine Flats Rd. (station JB-053-05) and near a newly constructed water storage tank (near station JB-035-05) display chaotic and massive bedded sediment.

Sediment associated with the inner moraine crest examined along Irvine Flats Rd. (station JB-051-05) consist of laminated and very thin to thin bedded clay to sand (Figure 15) in the upper meter of section. A few of the layers consist of reddish brown silt and have small pebbles resting on top of the bed I interpret as an erosional surface. One series of wavy beds of laminated clay and thin bedded fine sand are truncated by an erosional surface. I interpret these fine scale bedding and erosional surfaces to be indicative of calm water sediments occasionally exposed sub-aerially. Exposures of bedrock are abundant in this region. The bedrock profile underlying the moraine consists of a series of shallow ridges (see Polson Moraine Gravity Survey) that are expressed topographically along strike to the north. Shallow bedrock caused the glacier to founder and stagnate over the ridges. The outcrop of moraine sediment, near the previously mentioned water tank, rests directly upon bedrock. Influence of the bedrock inhibited the development of sub-aqueous sediment and structures, effectively causing this portion of the moraine to be deposited in a more subaerial (terrestrial) environment. The hummocky morphology of this portion of the moraine, which is typical of subaerially deposited glacial sediment, fits well with the interpretation of the bedrock influences. Small lakes can form in the depressions caused by ice wasting, and could account for sediment deposited in a low energy environment described above.

Stratigraphically below the Polson moraine is diamict (Map Plate 1). Exposures of the diamict along the Flathead River proximal to Kerr dam are massive and laterally continuous. No bedding truncations, erosional surfaces, or change in sedimentology have been recognized that would indicate a change in depositional environment. I suggest, through these observations, that the diamict underlying the moraine was deposited in glacial Lake Missoula and, therefore, represents the bottom of the lake. This is the same interpretation Levish (1997) applied to the diamict deposited throughout the Mission Valley. The topographic expression of the diamict that I interpret to represent the lake bottom, is a relatively flat bench. Emplaced on top of the diamict is the Polson moraine with no observed deformation of underlying material. The inferred contact between these two geologic units is covered by vegetation and erosional material; I cannot rule out the possibility that sediment deformation possibly is present but unexposed. Only one location (JB-021-05) in the study area were the sediments exposed that showed the transition from diamict to moraine deposition. There were no recognized deformation features in a ~30 meter measured section of the exposed material in a drainage gully, approximately 1km upstream of Kerr Dam (Plate 2). Again, this limited view of sediment does not preclude the possibility of deformation, just that it is unexposed.

The interbedding of diamict and deltaic/outwash sediment, grading into morainal sediment indicates a sub-aqueous depositional environment. Stratigraphic successions from diamict to sub-aqueous traction-transport sediments of the northern and southern moraine segments support the interpretation that the Flathead Lobe terminated into glacial Lake Missoula for at least a part of its history (Richmond, 1965, 1986; Levish, 1997; Smith, 2004). Glacial Lake Missoula sediments are not observed to onlap the Polson moraine or outwash sediment, suggesting the lake receded (drained) from the Polson region prior to retreat of the Flathead Lobe. Channels cut into glaciolacustrine sediment and infilled by distal outwash sediment are recognized proximal to the southern segment of the moraine (Damschen & Associates, 1999). Between the Polson moraine and the Pablo Reservoir the Qpgl map unit represents lake sediments that are overlain by outwash sediments. Well logs indicate the brown clay layer is limited laterally indicating a small pro-glacial lake. These observations are consistent with the interpretation that glacial Lake Missoula retreated prior to the development of an extensive outwash plain south of the Flathead Lobe terminus. A large sinuous fluvial channel (just north of Weythman Gulch) cross cutting the northern segment of the moraine and extending southward along the moraine front also suggests the absence of glacial Lake Missoula.

Bondurant (2005) drew environmental interpretations and a similar overall glacial terminal history based upon her interpretation of the sedimentary facies and stratigraphy in the Elmo Valley. Bondurant (2005) interpreted that the Elmo moraine was deposited in a sub-aqueous environment. The portion of the Flathead Ice Lobe that flowed into the Big Arm Embayment terminated into glacial Lake Missoula. Two sets of fluvial channels are recognized extending to the west from the Elmo moraine. Bondurant (2005) interpreted the first channel set as flow from supraglacial waters when the ice lobe was at the terminal position. The second system of well defined channels and point bars cross-cuts the first and is representative of the outflow from a spill point of ancestral Flathead Lake (Bondurant, 2005). The development, and preservation, of the fluvial channels indicates the absence of a pro-glacial lake, therefore, Bondurant (2005) concludes the glacial lobe terminated into glacial Lake Missoula for only the initial portion of its history.

Although the southern limit of the Flathead Lobe appears to be demarcated by the Polson moraine, it remains unclear whether the lobe advanced once or twice during its terminal phase. Studies of glaciation in regions in Idaho, Northern Montana, North Dakota and the present day Yellowstone National Park suggest at least two major advances of ice during the Pinedale (Bogert et al., 1999; Fullerton et al., 2004). Two distinct sets of alpine terminal moraines are recognized in the valleys of the Mission Mountains, and two crest lines of the Polson moraine were identified in the East Bay Quadrangle (Hofmann and Hendrix, 2004). Both the northern and southern segments of the moraine in this study display two prominent crest lines. Three crest lines were at first recognized on the northern segment; however, geophysical analysis of this area indicates the easternmost crest mimics the underlying shallow bedrock ridge (see Polson Moraine Gravity Survey).

Both of the regionally-expressed crest lines of the Polson moraine are prominent topographic ridges; one does not appear more eroded than the other. The interior of the two moraine lines is significantly larger than the most terminal position, implying a longer duration of ice occupancy. Sediments associated with the two crestlines of the southern moraine segment, examined near the Lake County landfill and the Redi-Mix plant, both display similar sub-aqueous related sedimentology and structure. Exposures of chaotic, massively bedded material associated with the two crestlines of the hummocky northern moraine segment display no great differences in sedimentology either. A portion of the sediments located in a road cut at the crest of the inner moraine do display fine scale bedding and erosional truncation surfaces. These features are interpreted to be deposited in small hummock filled lakes that were sub-aerially exposed for short periods of time. Also associated with the inner moraine crest are the sub-aqueously deposited sediments described in the 30m measured section in the drainage gully. However, these sediments sit stratigraphically lower than the small lacustrine and sub-aerially derived material. Sub-aerially deposited moraine sediment resting atop sub-aqueously derived deltaic sediment from the advancing glacial front which in turn rests on diamict fits the interpretation that the ice lobe terminated in glacial Lake Missoula for the initial portion of its history.

It is apparent there were two main stages to the glaciation in order to develop the two-ridgeline moraine complex recognized at the southern end of Flathead Lake. The southern portion of the Polson moraine is a sub-aqueous deposit in a glaciofluvial delta system. North of the Flathead River the moraine displays both sub-aqueous and sub-aerial deposition. The high bedrock ridges influenced the glacier in this locale, causing stagnation of the ice lobe. During the lowering of glacial Lake Missoula, water levels caused sub-aerial exposures along these ridges. The existence of sub-aqueous sediment juxtaposed next to sub-aqueous/aerial moraine segment does not necessarily indicate two separate main advances. However, the lack of absolute dates within the field area does not permit a definite conclusion. Determination of whether the two moraine crests indicate two terminal positions of separate advances or one terminal moraine with a recessional moraine is inconclusive.

The final retreat of the Flathead Lobe initiated the formation of pro-glacial Lake Flathead (ancestral Flathead Lake) initially dammed by the Polson moraine. Recession rates for the Flathead Lobe are variable and have been estimated to range from between 26-150m $year^{-1}$ at the lower end to potentially more than 500m $year^{-1}$ (Smith, 2004). Portions of the glacial lobe over relatively deep water would retreat at significantly greater rates because of the effect increased water depths have on enhancing calving rates (Brown et al., 1982). As the ice lobe retreated further away from the Polson region, sediment deposition in the lake was primarily of fine grained material. The rhythmic sediments described along the Flathead River and found near the Polson Airport are interpreted as varves. These varves represent cyclic deposition of the sediment during annual release of sediment from the glacier.

Based on regional facies relations, ancestral Flathead Lake drained initially through three outlets: 1) the Elmo spillway, approximate elevation of 1000m (Bondurant, 2005); 2) the fluvial channel (Weythman Gulch) along the western slope of the northern moraine segment which is also at an elevation of about 1000m and crosscuts the moraine; and 3) the modern drainage outlet at ~880m. Draining via the Elmo spill point and Weythman Gulch continued until both outlets were abandoned by lowering lake levels, leaving the modern drainage as the sole outlet for Flathead Lake.

The Flathead River presently is the only drainage for Flathead Lake. Kerr dam controls the water surface elevation, stabilizing the maximum lake surface elevation approximately 3m above pre-dam elevation. The river has cut down through the Polson moraine, the initial main dam for ancestral Flathead Lake. Analysis of sediment cores and seismic data from Flathead Lake indicated the presence of turbidite beds interpreted as large scale meltwater surges from the retreating Flathead Lobe (Hofmann et al., 2006). These turbidite beds are time-constrained because they are located stratigraphically between rhythmite sediment packages (14,150 ±150 cal years BP) and the Glacier Peak tephra (13,180 ± 120 cal years BP) (Hofmann et al., 2006). Timmerman (2005) interpreted that these event beds reflected large-discharge glacial meltwater surges, from the retreating Flathead Lobe, that downcut through the moraine and bedrock ridges downstream of the moraine.

I hypothesize that the meltwater surges into ancestral Flathead Lake caused the breakthrough of the dam that ponded ancestral Lake Flathead. Along the Flathead River, the position occupied originally by the moraine, eight large terrace sets occur in Quaternary sediment. These terraces document significant lowering of ancestral Lake Flathead via this channel. Large (53-123cm), angular boulders are deposited primarily along the upper portion of the terrace flights and onto the tread of the terraces. The elevation of the terrace treads are approximately: 886m, 897m, 907m, 910m, 912m, 920m, 938m, and 945m. A well developed shoreline terrace at 902m is visible around much of the perimeter of Flathead Lake. Terraces found upstream of Kerr Dam potentially correspond to several terraces that are located downstream of the dam, signaling the catastrophic draining episodes of ancestral Flathead Lake (Edwards, 2006, in progress).

Glacial Movement

Glacial striations aided in determining the location and overall sense of movement of the Flathead lobe. Bedrock exposures near the Polson moraine and scattered through the study area display striations scoured by glacial movement (Figure 26). Measurements of the striations in the northern portion of the study area display a more east/west movement compared to those in the central area, which are to the southwest (Figure 26). Station JB-049-05 primarily displays a NW/SE transport direction resulting from interaction of the glacier with the bedrock highs in that area. At stations JB-016-05 and JB-039-05, perpendicular sets of striations were recognized. Those striae trending NW/SE display a more weathered appearance and are cross cut by the more prominent

SW/NE striking scour marks. These features of the glacial striae suggest two different advances of the Flathead Lobe. However, variation in glacial striation trends can be considerable. Cross cutting relationships may result from overall changes in flow direction, and basal flow variability of a glacier over irregular surfaces (Benn and Evans, 1998). I infer overall glacial movement and timing based on a combination of overall striation azimuths and weathering appearance, in addition to roche moutonnée orientations. A significant portion of the bedrock outcrops that are striated are streamlined along the same trend as the striae. Trends of striation trends at JB-001-05 are due south and are interpreted to be from a previous glaciation period, perhaps Bull Lake.

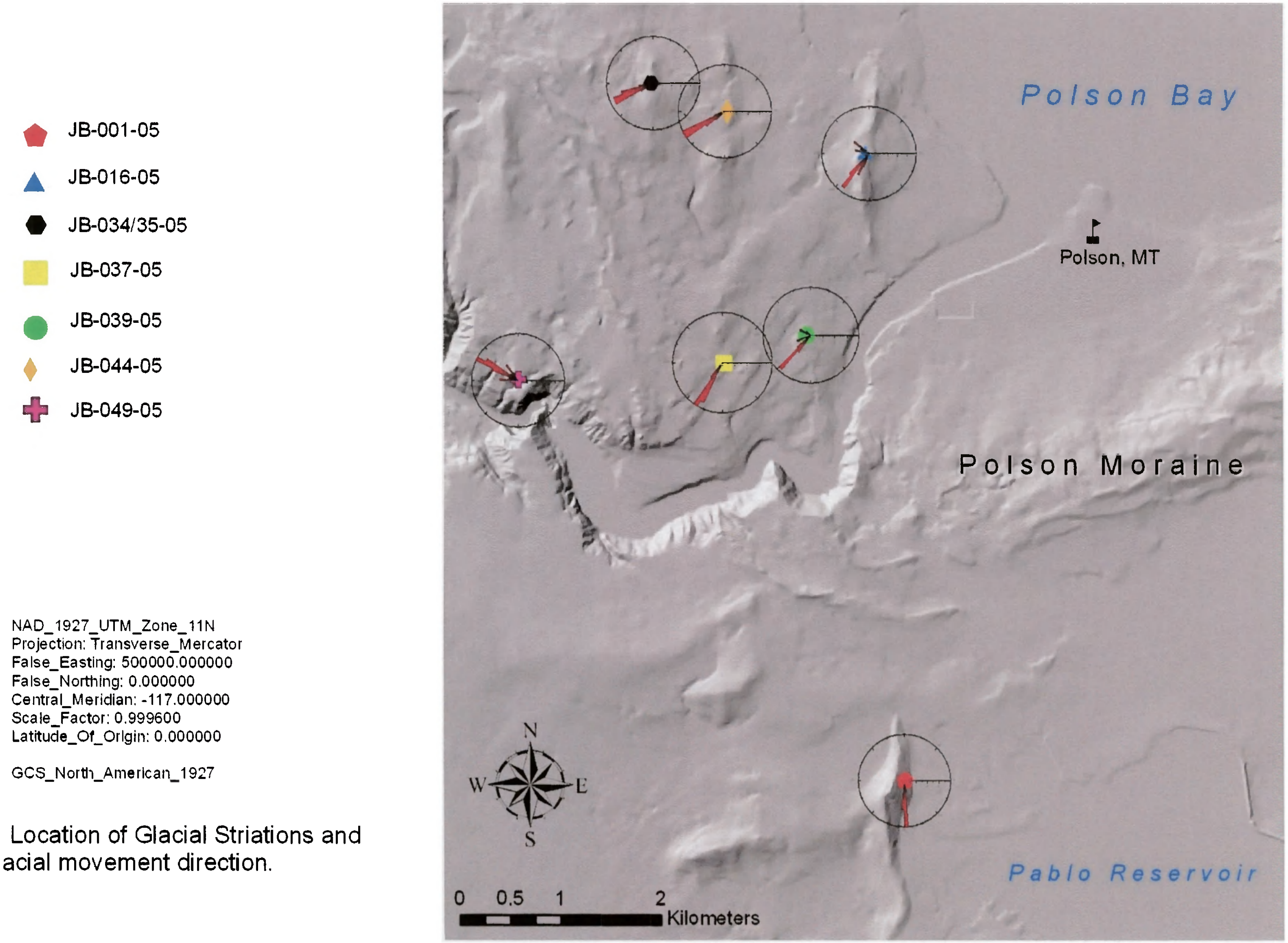


Figure 25. Location of Glacial Striations and inferred glacial movement direction.

Varve Correlation

In 2000 and 2003, a total of 19 piston cores of sediment were retrieved from the Flathead Lake sub-bottom (Hofmann et al., 2003). Thicknesses of the sediment cores ranged from 5m to 11m. Sedimentological analyses of the cores were applied to determine grain size distribution and to constrain deposition rates and potential depositional environments (Hofmann, 2005). Core analysis revealed the presence of the Glacier Peak tephra and rhythmite sequences interpreted as varves (Hofmann et al., 2003). The recognition of the tephra layer, rhythmic sediments and development of a seismic stratigraphic framework allowed correlation between the various cores (Hofmann et al., 2006). Varve thickness curves were created for each of the cores, and correlation between the cores based upon thickness patterns was observed (Hofmann, 2005).

Varve deposition in a lake basin is related to the amount and rates of sediment deposition, localized environmental conditions, and the location of the glacial front (Ashley, 1975). As such, the position of the Flathead Lobe and relative timing of deglaciation in the region can be constrained by understanding regional varve patterns. During the mapping phase, packages of rhythmites were recognized onshore along the Flathead River near the Polson Airport (station JB-042-05 – Appendix 1). I mapped this area as consisting of ancestral Flathead Lake sediments; it is dominated by the Fl facies (Map Plate 1). A weathered, several meter-long section of Fl facies was exposed and accessible at the top of a cliff face along the lower Flathead River. Upon further inspection of these sediments, I interpret them to be glacially-influenced varves. Varved sequences additionally were recognized along US Highway 93 near the airport; however, only about a meter of section was poorly expressed. The presence of glacial varves indicate an aqueous depositional environment and potentially a high-stand of ancestral Flathead Lake. If this is the case, the varve thickness pattern potentially could correlate to the varved sequence recognized in the cores; therefore, adding an absolute age constraint to this portion of the study area.

The varves were exposed by cutting into the outcrop to remove the erosional cover (Figure 27). This was accomplished by using a variety of tools to carve into the outcrop and then smooth the face so it was relatively perpendicular to the varves. Digital pictures were taken of the entire section, with a cm-scale tape measure present in each image so the thickness of the individual varves could be documented (Figure 27). Viewing the digital images in Adobe Photoshop 5.5, I determined the thickness of each varve to the closest millimeter. The varve number and thickness values were entered into a Microsoft Excel spreadsheet, and a thickness plot was created. Varve thickness patterns were determined for the Flathead Lake cores by Hofmann et al. (2003) and I applied a visual based correlation between the onshore varves and those recognized in core FL-03-26K.

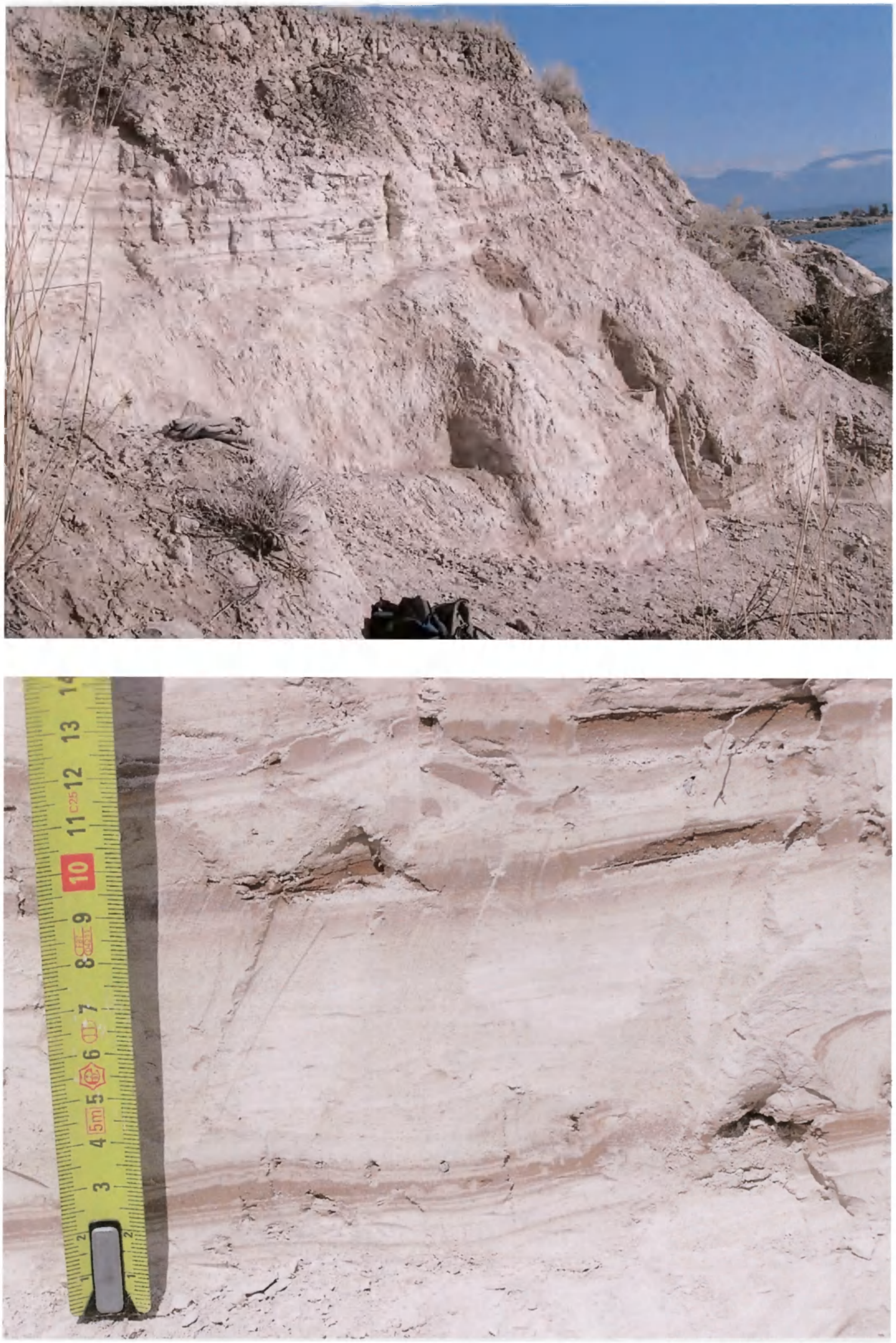


Figure 26. A: Image of the trenched section measured for varve correlation. B: Sample image of varves taken to determine the thickness pattern of the varved sequence.

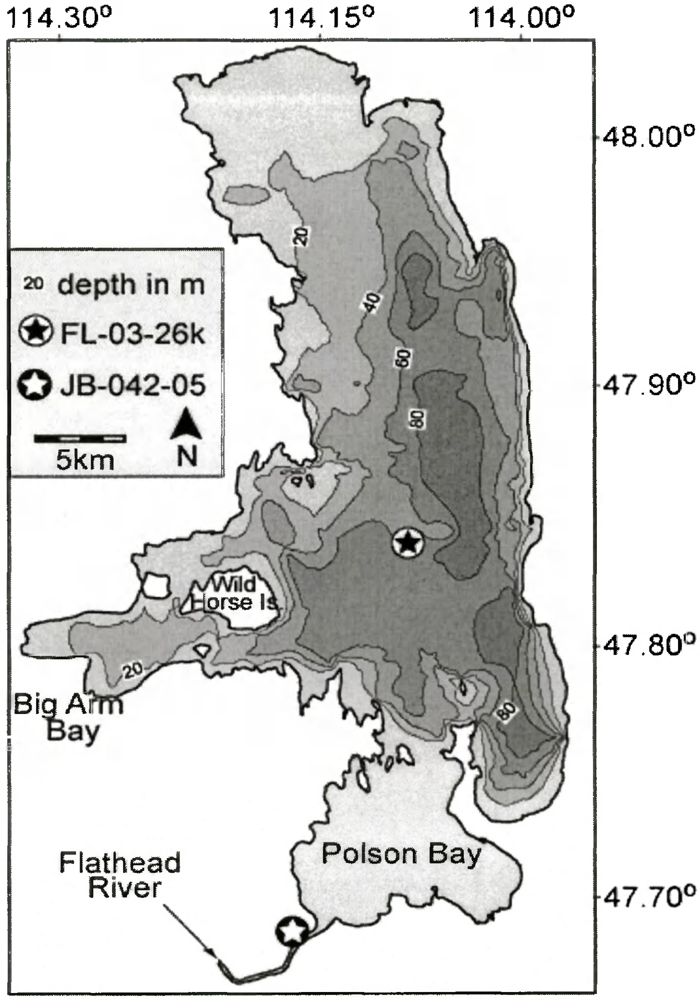


Figure 27. Bathymetric map of Flathead Lake, and the location of core FL-03-26k and the onshore varve location, JB-042-05.

Varve Correlation Results & Interpretation

A total of 60 varves were interpreted from the digital images taken of the exposed sediment. Unfortunately, the 60 varves are not in a continuous section. Trenching of the outcrop uncovered an area of deformed sediment (Figure 28). Approximately 154cm section of deformed sediment separates the top 19 varves and the bottom 41 varves. In this disturbed zone I observed the remnants of the dark brown clay layers; therefore, I infer that there were varves, but that they were disrupted most likely due to dewatering.

Thickness of the upper 19 varves totaled 93.9cm with an average varve thickness of 4.94cm. The lower 40 varves had an average thickness of 2.69cm with a total thickness of 110.2cm. Using the average thickness of the entire varved sequence (3.4cm) I estimated that 45 varves were absent from the disturbed zone. Due to the highly variable (non-linear) nature of the thickness of varves, this number is used only as a guide to help determine the approximate relationship between the upper and lower sections during the correlation. Figure 30 shows the approximate positioning of the two sections and the interpreted thickness patterns for the 60 varves.

Hofmann et al. (2003) interpreted a total of 254 varves in core FL-03-26K. Varve thickness varied from 0.39cm to 9.57cm, with an overall thinning of the varves towards the top of the section (Hofmann et al., 2003). Visual correlation between varves found in the core and those onshore resulted in a strong potential match low in the stratigraphic section. The visual correlation matched the upper section of the onshore varves to varve numbers 158 to 176 in the cored section; visually it was slightly more difficult to correlate the lower onshore varve sequence with the core data.

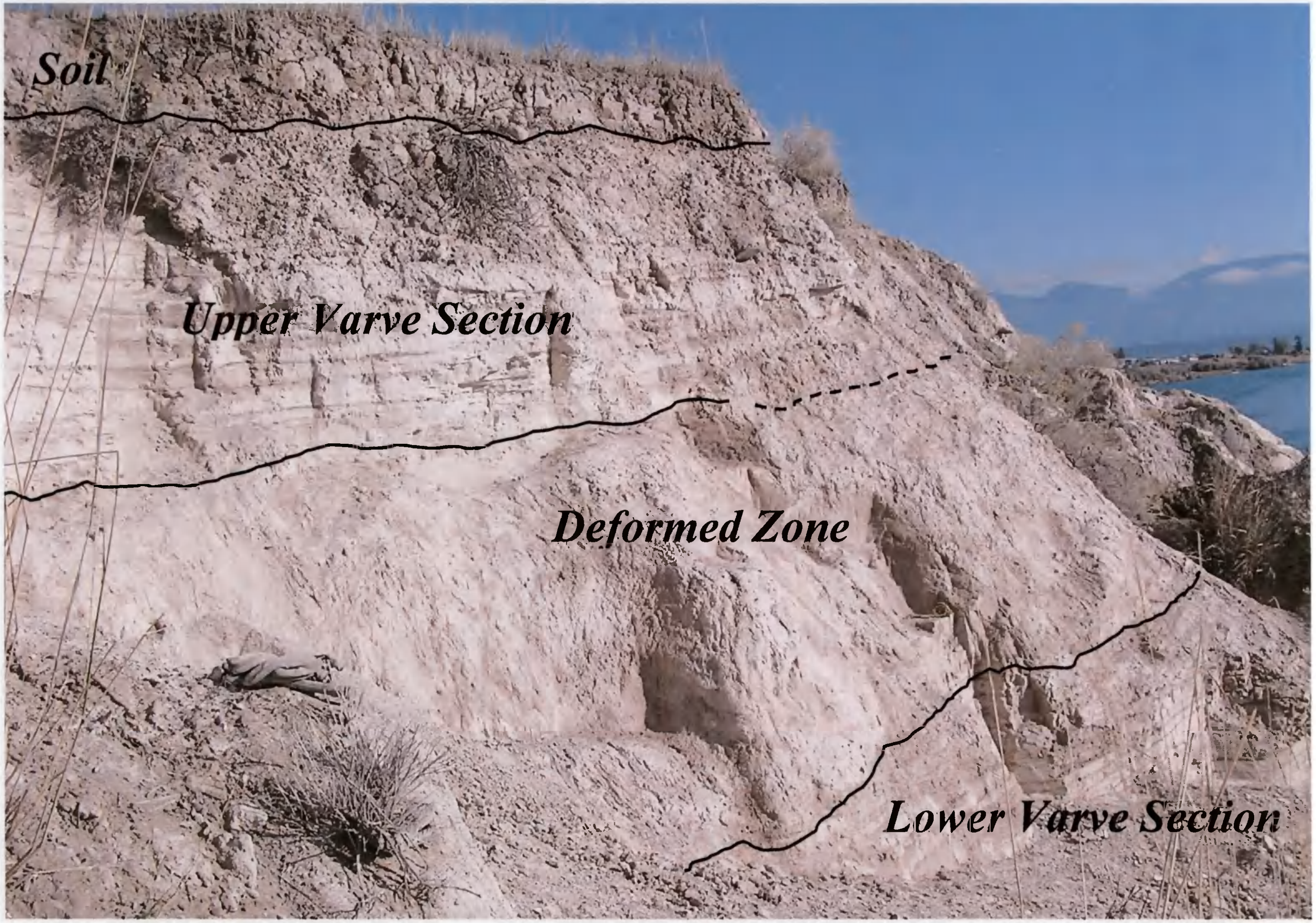


Figure 28. Stratigraphy of the varved sequence. The Upper and Lower sections are separated by a deformed zone

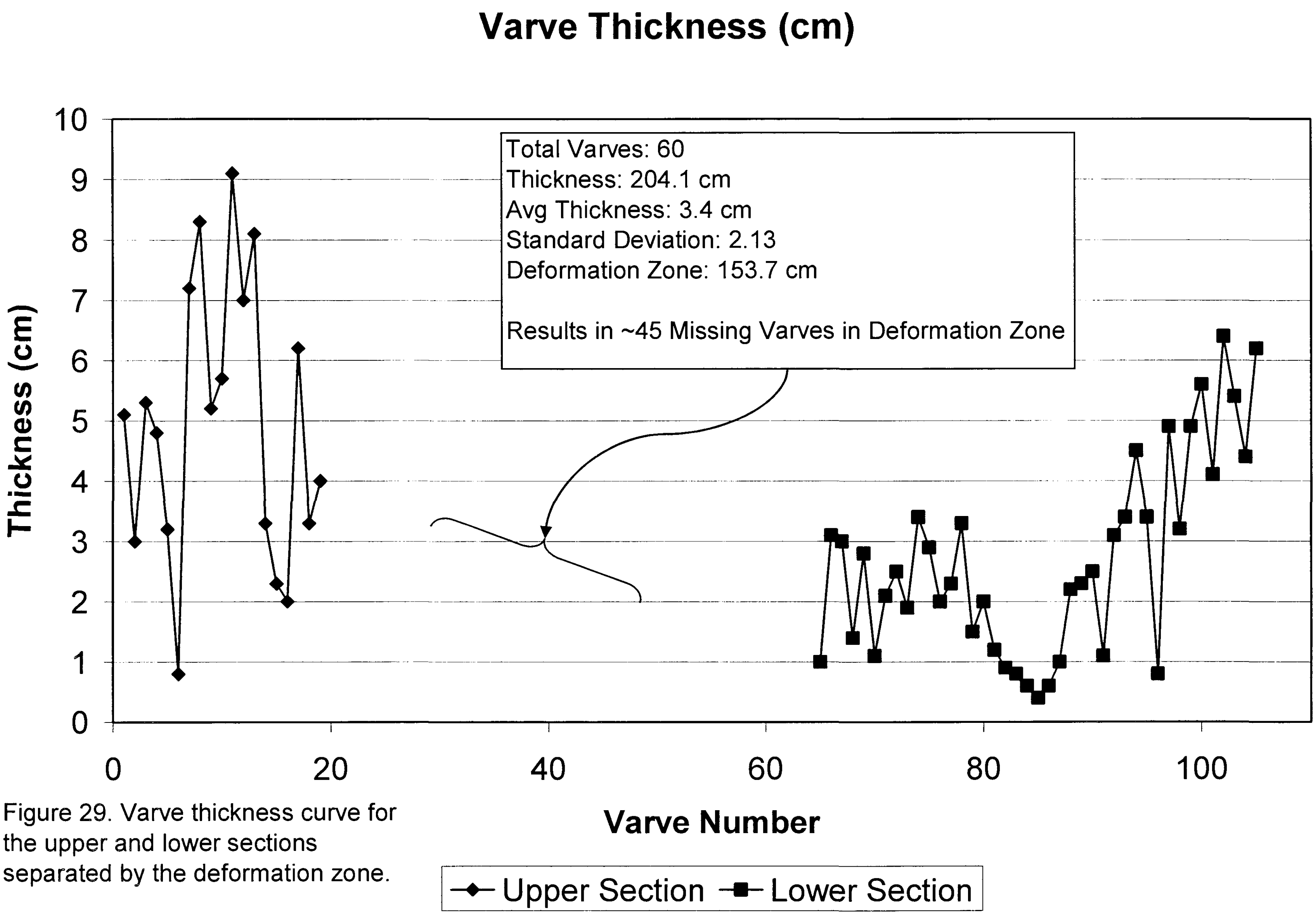


Figure 29. Varve thickness curve for the upper and lower sections separated by the deformation zone.

To test whether the visual match was reasonable, a statistical correlation would aid in determining the quality of the match. Varves not only are a function of proximity to the glacial front and sediment supply from meltwater but also localized environmental conditions within the lake (Ashley, 1975). These variable conditions from one locality in the lake to another can cause a great deal of disparity in the characteristics of one varved sequence when compared to another (Ashley, 1975). This fact precludes the use of a typical Pearson correlation applied to many scientific systems to achieve an R and R^2 value. The other caveat to correlation of the varved sequences is the limited number of samples. Varves recognized in the sediment cores from Flathead Lake contained continuous sections, so long term trends in thickness could be visually matched from core to core (Hofmann et al., 2003). In the case of the onshore varves, two small segments (19 and 41 varves) were determined with an unknown number of varves destroyed by deformation.

With the problems being stated, a qualitative measurement can be achieved simply by visual matching of the thickness pattern. For the 19 upper section varves, 13 of 18 (72.2%) increases or decreases in varve thickness were matched to FL-03-26K varve 158-176. The visually correlated position of the 41 lower section varves to FL-03-26K varve 222-254 results in 8 of the onshore varves lying below the base of the cored interval. Therefore, a match of 19 of the 32 (59.7%) increases or decreases matched. The percentage increases from 59.7% to 68.7% if a few of the varves are re-interpreted as 'false' varves caused by sedimentation processes causing thin clay laminations to occur in the silt layers (Ashley, 1975). It cannot be statistically demonstrated that the correlation of the upper and lower varved sequence exposed onshore is correctly correlated with the record from core 26K. Qualitative results show ~70% match of the thickness pattern between the two varved sequences to their respective positions. Correlation of the curves to their respective positions results in a total of 46 varves separating the two portions of the onshore stratigraphic record, nearly identical to the original rough estimate of 45 missing varves within the deformed zone (Figure 31).

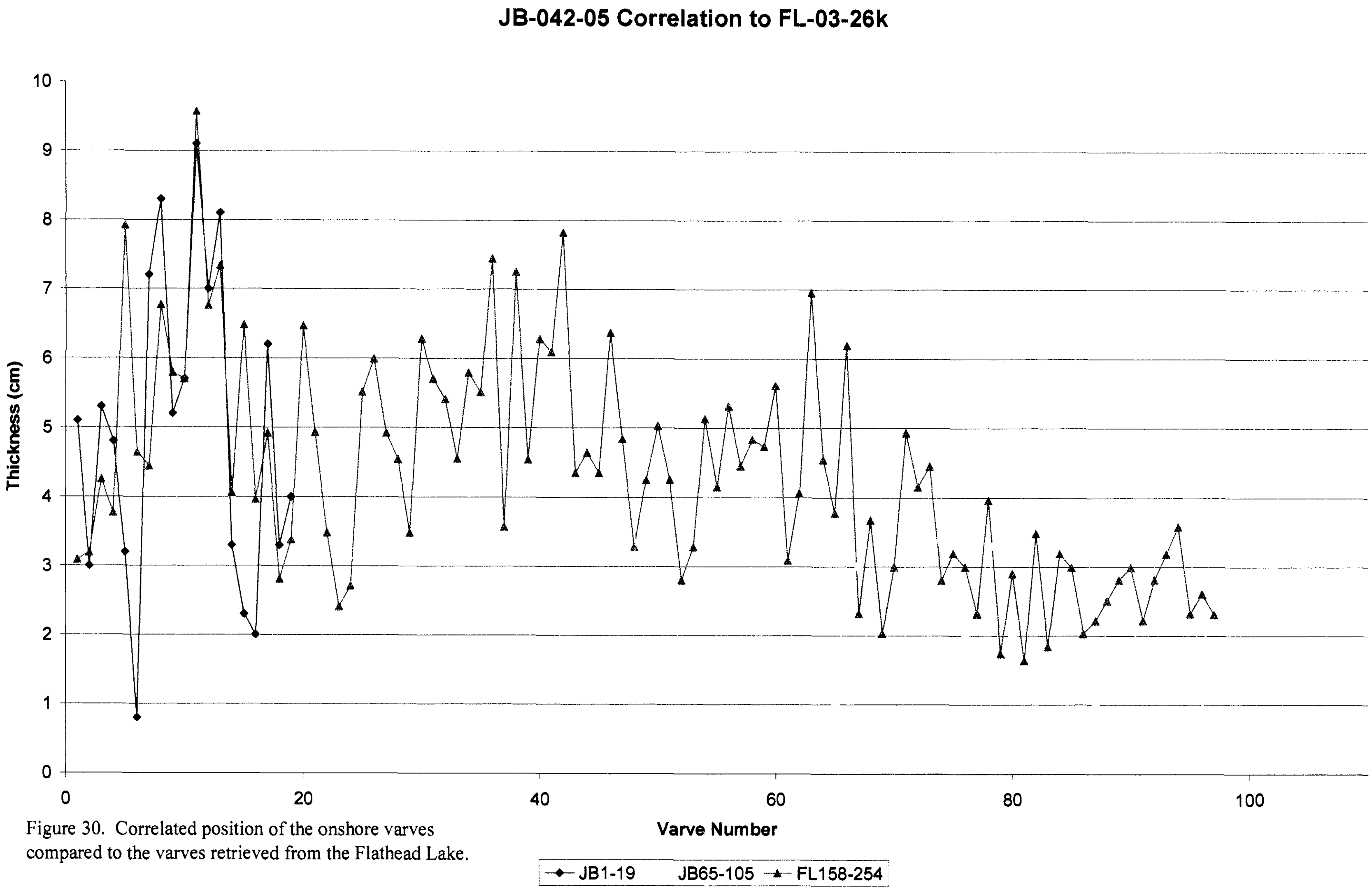


Figure 30. Correlated position of the onshore varves compared to the varves retrieved from the Flathead Lake.

Some portions of the correlated varve count curves match convincingly whereas other portions are questionable. Factors that would contribute to degradation of the correlation quality arise from: 1) local sources of sediment input, 2) missing varves due to sediment bypass, 3) mis-interpretation of varves within a sequence, and 4) outright miscorrelation of the two varve sequences. One varve may contain multiple graded beds and settle out of clay layers from turbidites causing a misinterpretation of these false varves as actual seasonal deposits (Ashley, 1975; Shaw, 1977). Uneven input of sediment from local sources would affect thickness of sediment derived from the glacial front. It is possible that the varves I studied onshore correspond to older varves than those recovered in the Flathead Lake sediment cores, although I am unable to demonstrate this. Therefore, with the available data the onshore varve sequence I infer an annual-scale correlation between varves recognized in core FL-03-26K, beginning at varve number 158 (c.f., Hofmann, 2005). This correlation suggests that varved sediments located on the present day land surface near the Polson Airport were deposited between 14,308 and 14,410 ±250 cal. years BP.

Timing of the Flathead Lobe Glaciation/Deglaciation

The beginning of glaciation of the Flathead and Mission Valleys is not well constrained. Cordilleran Ice Sheet development is estimated to have started in Canada ~25,000 ^{14}C years ago. Use of relative age dating techniques has been the mainstay of estimating the age of deposits in the region, due to the paucity of radiometrically dateable material. Deglaciation in the region has been better constrained by the Glacier Peak tephra, because the ash is interbedded with different facies, each of which is part of the regional deglacial depositional framework. Certain regions were ice free during deglaciation, as for example, aeolian dune sediments from the Whitefish River valley area that include the Glacier Peak tephra as an interbed (Smith, 2004). Better age constraints have been determined by Hofmann et al. (2006) through analysis of sediment cores and seismic data. These age constraints bracket the timing of major discharge events associated with deglaciation as occurring between 14,150 ±150 cal years BP and 13,180 ±120 cal years BP. Correlation of glacially-influenced varves found onshore at JB-042-05 and those recognized in core FL-03-26K constrain the timing of glacially-varved sedimentation in the study area to have begun by at least 14,410 ±250 cal. years BP.

Starting ~28,000 cal years BP (~25,000 ^{14}C years BP) the Cordilleran Ice Sheet formed in Canada. The ice sheet extended southward into the northern portions of Washington, Idaho and Montana. Flowing southward to a location near Sandpoint, ID the Purcell Trench Lobe impounded glacial Lake Missoula by between 19,200 -16,500 cal years BP (Levish, 1997). Diamict sediment and varves associated with glacial Lake Missoula are deposited around this time in the Mission Valley. The Cordilleran Ice Sheet reached maximum extent by ~17,000 cal years BP (~15,000 ^{14}C years BP) (Waitt, 1985, Carrara et al., 1996). Overlapping this time frame is the growth of the Flathead Lobe southward along the Rocky Mountain Trench and into the Flathead Valley, terminating near Polson, MT. The Polson moraine is deposited by an ice-proximal glaciofluvial environment in which Flathead Ice Lobe terminated into glacial Lake Missoula. Two moraine crest lines were formed by either two separate major advances of the ice lobe or by one main advance with a pause during retreat that resulted in deposition of a recessional moraine. By the time the final retreat of the Flathead Lobe began, glacial Lake Missoula had receded, and may have completely drained, from the Polson area. As glacial retreat continued, the large pro-glacial Lake Flathead formed as meltwater was impounded by the Polson moraine. By approximately ~14,300 cal years BP, the glacier had retreated far enough to the north for the varves to be deposited in the study area and at the location of core FL-03-26K.

Turbidite beds identified in the sediment cores from Flathead Lake were deposited between the varved sequence and the Glacier Peak tephra (11,200 ^{14}C years BP; 13,180 ±120 cal years BP; Hofmann et al., 2006). These events beds are interpreted to record large meltwater surges released from the retreating glacial lobe. I infer that these meltwater surges were responsible for downcutting of the Polson moraine spillway. Downcutting through the moraine and bedrock resulted in the formation of substantial terrace flights upstream of the Kerr Dam. Formation of the 902m terrace occurred during the Holocene as did the aeolian sand dune formation south of the Polson moraine.

Conclusions

This study combines geologic mapping, sedimentological analysis of Quaternary deposits, varve correlation and a small linear gravity survey (see Polson Moraine Gravity Survey) to reconstruct the history of syn-glacial and post-glacial sedimentation associated with glaciation and retreat of the terminus of the Flathead Lobe of the Cordilleran Ice Sheet. Based on my analysis, I have the following main conclusions:

1.) The Polson moraine was formed between ~28,000 and 14,300 ±250 cal years BP due to Pinedale glaciation of the southern Flathead Valley and northern

Mission Valley. The moraine represents the southern limit of the Flathead Lobe, and preserves a record of the interaction between the Flathead Lobe and glacial Lake Missoula.

2.) The southern Polson moraine was deposited in an ice-proximal glaciofluvial (outwash fan/sandur delta) setting, indicating that the Flathead Lobe terminated into glacial Lake Missoula for a portion of its history. Using cross-cutting relationships and inferred depositional environments, I determined that glacial Lake Missoula had receded from the Polson region prior to the retreat of the Flathead Lobe.

3.) The moraine consists of two prominent crest lines indicating two separate stabilized points for the former terminus of the Flathead Lobe. It is still unclear whether these crests indicate two advances or one advance with a recessional moraine. The northern segment of the Polson moraine is underlain by shallow bedrock ridges (see Polson Moraine Gravity Survey) that caused the glacier to founder in this position and partially deposit material in a terrestrial environment.

4.) I interpret that varves found onshore visually correlate to a stratigraphically low section of varved sediments recovered in Flathead Lake core FL-03-26K. I correlate the uppermost varve exposed in my onshore sequence to correlate to a position 158 years before the top of the varved sequence in the lake cores, corresponding to a depositional age of ~14,308 ± 250 years cal years BP.

Future Work

Future work in the region should focus on expanding knowledge of the subsurface structure by means of geophysical surveys (gravity, seismic, GPR). These data will aide in constraining the bedrock structure which has been shown to have played an important role in the glacial position. To help to try to constrain the timing of the glacial system, correlation of onshore varves to other Flathead Lake sediment cores should be expanded. Investigation of the sediment exposures near the onshore varves used in the study should be examined to determine if the deformation zone is a small localized feature or more expansive. Varved packages recognized in the Elmo Valley may provide timing constraints for the glaciation within the Big Arm Embayment. Ground penetrating radar profiles of the Polson moraine could result in internal structure of the sediment, aiding in the determination of depositional environments and heterogeneity along the moraine front.

Polson Moraine Gravity Survey
Role of Bedrock in the Emplacement of the Moraine

Introduction

At the southern end of Flathead Lake the Flathead River flows out of the lake to the southwest, where it bisects the Polson moraine. One portion of the moraine lies to the west of the town of Polson and north of the Flathead River (Figure 32, Map Plate 1). The morphology of the moraine is a wide topographic high, trending north/south and containing multiple crests. Metasedimentary rocks of the Belt Supergroup crop out at the northern and southern ends of this portion of the moraine (Map Plate 1). The close physical association of the bedrock and the crests of the moraine indicate that the bedrock could be influencing the morphology of the moraine along its length.

A moraine is an accumulation of drift deposited primarily by direct glacial actions independent of the subsurface topography; furthermore an end, or terminal, moraine is a ridge-like accretion of drift at an active glacial margin in a steady-state condition (Flint, 1971). A series of moraines can be deposited either by multiple re-advances of the glacial front or by relatively short-lived stabilized positions during the glacial retreat (Flint, 1957, 1971). The ability to distinguish between various moraine crests in a complex system is important because it aides in determining the number of re-advances, or pauses in the retreat, associated with the glacial history.

The Mission Fault system is a north/south trending system of west dipping normal faults (Ostenaa et al., 1995; Hofmann and Hendrix, 2003; Hofmann et al., in press). This east/west extension in the region has caused a majority of the topographic features to trend in the same direction as the faults. Smaller bedrock ridges and basins located within the study area strike parallel to this more regional trend. The Valley View Hills, located southwest of Polson, constitute one such ridge system; another sits slightly west of the Polson Airport. Detailed documentation and interpretation of the bedrock geology of the Flathead Lake region is outside the scope of this study. However, the north/south trending topographic ridges of bedrock in the study area may have played a significant role in moraine emplacement. Therefore it is important to consider the relationship between the distribution of morainal sediment and the occurrence and geometry of this bedrock topography.

Gravity Survey

To determine the bedrock topography beneath the western portion of the Polson moraine I conducted a gravity survey across the depositional strike of the moraine (Figure 32). The survey consists of 30 stations aligned east/west along Irvine Flats Road. Average distance between stations is 0.25 km for the easternmost 24 stations and 0.75 km for the western 5 stations. The westernmost station was located 1.6km from the previous in order for the survey to terminate upon bedrock. Total distance covered by the survey is 10.92km. The highest density coverage of stations occurred on the Polson moraine itself. At each station I used a Scintrex CG3 gravimeter. The CG3 has a reading resolution of 0.005 milligals (mgals). At each station the gravimeter was leveled, with aide from the electronic tilt sensor, until the X- and Y-axis readings were less than

NAD_1927_UTM_Zone_11N
Projection: Transverse_Mercator
False_Easting: 500000.000000
False_Northing: 0.000000
Central_Meridian: -117.000000
Scale_Factor: 0.999600
Latitude_Of_Origin: 0.000000

GCS_North_American_1983

Station	Elevation	Latitude	Longitude (W)
2022a	907.72	47.68942	-114.19380
2022b	922.53	47.69188	-114.19115
2022c	922.26	47.68940	-114.19663
2022d	931.32	47.68940	-114.19880
2023a	937.16	47.68941	-114.20096
2023b	943.00	47.68942	-114.20298
2023c	947.34	47.68943	-114.20508
2023d	958.62	47.68944	-114.20726
2023e	973.61	47.68947	-114.20966
2100a	973.45	47.68945	-114.21223
2100b	974.19	47.68945	-114.21435
2100c	977.48	47.68946	-114.21614
2100d	983.15	47.68946	-114.21819
2100e	991.70	47.68948	-114.22052
2100f	994.65	47.68947	-114.22272
2101a	997.28	47.68947	-114.22477
2101b	992.73	47.68946	-114.22695
2101c	982.02	47.68946	-114.22910
2101d	982.50	47.68945	-114.23116
2101f	990.16	47.68945	-114.23321
2101g	991.39	47.68945	-114.23546
2101h	993.65	47.68944	-114.23743
2102a	979.98	47.68943	-114.23964
2102b	970.82	47.68945	-114.24227
2102c	971.39	47.68937	-114.24827
2102d	977.97	47.68938	-114.25511
2102e	976.23	47.68934	-114.26176
2102f	973.59	47.68931	-114.26847
2102g	966.83	47.68929	-114.27438
2103a	972.54	47.68909	-114.28938

Table lists stations from East to West. Stations are denoted by Triangles and reference well drilled to bedrock is marked by the star. The survey endpoints are located upon exposures of Belt rock.

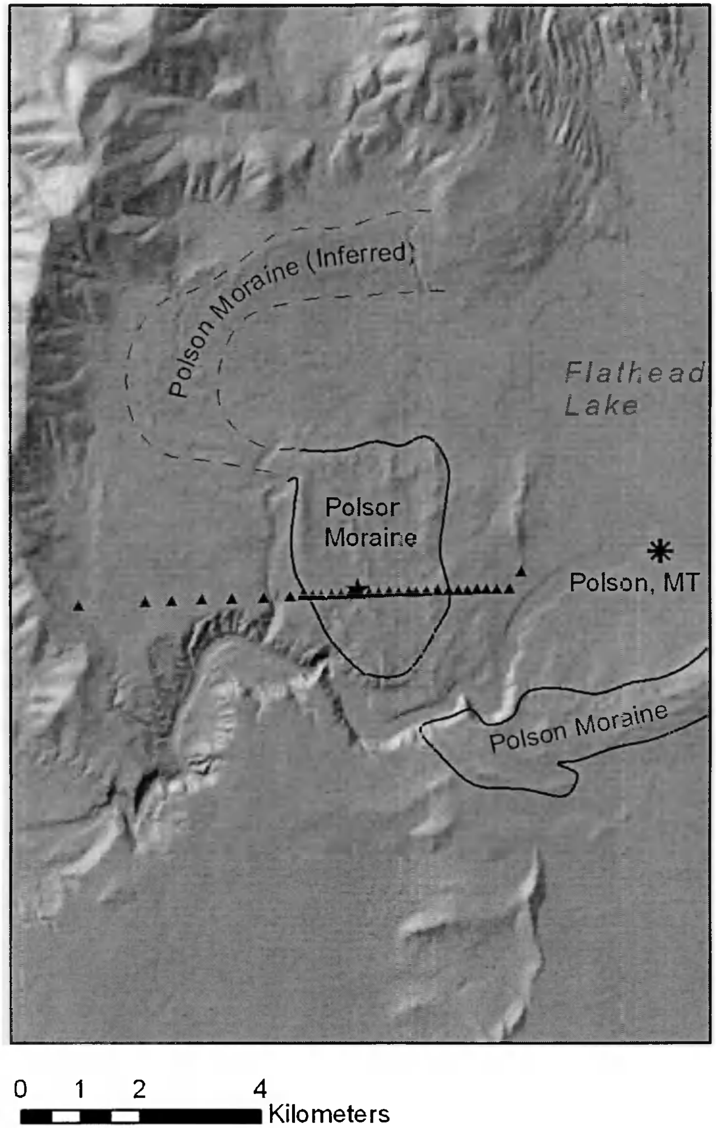


Figure 31. Hillshade of Polson, MT area. Linear gravity survey located west of the town of Polson crossing the Polson Moraine.

magnitude 10. I took two measurements at each station to assure high quality data and if there were any discrepancies between the two measurements, I used the average of the two readings as representing the data for that station (Appendix 3).

Two base stations were used for the survey. These base stations served as control points for the gravity data to construct drift curves, so the hourly change in tidal affects could be countered. I reacquired one of the base stations at least every three hours. As the primary base station, I used the geophysics laboratory, located in the basement of the Clapp Building on the campus of the University of Montana. Absolute gravity value of the laboratory is 980,432.210 mgals. I occupied the primary station twice, once before the survey and once upon the return to campus. The second station of the linear survey served as the field base station. I reacquired the field base station a total of three times while conducting the survey.

In conjunction with the gravimeter I used one of Trimble's mapping grade global positioning systems (GPS), the Pathfinder PRO XRS. The GPS received readings every 10 seconds for a period of ~7 minutes at each of the gravity stations, with an average of 43 data points per station (Appendix 3). Real time corrections, received from the coast guard station in Polson, MT, were applied to the satellite signals. Elevation (height above geoid) was measured in meters while latitude and longitude were measured in UTM and decimal degrees. Station elevations were computed to sub-meter resolution with 1σ standard deviations ranging from 0.087 to 0.698 with an average standard deviation of 0.214. Latitude and longitude positions were found with high precision with typical standard deviations on the order of 1.46×10^{-6} and 1.52×10^{-6} degrees respectively.

Standard crustal density of 2.67g/cm^3 was used for the reduction of the gravity data. Theoretical gravity values were calculated using the 1967 Geodetic Reference System Formula (Appendix 3). Terrain corrections (TC) were applied to all 30 stations because of their proximity to the Mission Mountains, Valley View Hills and other topographic features. HAMMERXYZ, a computer software program by Gradient Geophysics, is based upon terrain correction charts originally designed by Hammer (1939). Hammer charts consist of segmented concentric rings (labeled A-J) that extend outward from the gravity station. Gravity is calculated per ring through a laborious process and added to the Bouguer correction. The computer program calculates the terrain correction for each station out to ring J. Corrections were carried out to 21km from the survey line and results in TC values of less than 1 mgal (Appendix 3).

I used GravCadW, a gravity modeling computer software program by Gradient Geophysics, to model the topography and depth to bedrock. The single control on the model is a water well (Well 29, Appendix 2), located approximately 30m north of the survey line, which intercepts bedrock at ~142m (465ft.).

Interpretation

The complete Bouguer anomaly (CBA) ranges in value from -132.7 to -136.7 mgals (Appendix 3). In the study area the regional gravity is interpreted as being planar. The regional values were determined by plotting the CBA of the survey endpoints and adding a linear trendline. The residual gravity, due to the density variations, was determined by subtracting the regional gravity from the CBA. Resulting residual gravity values range from 0 to -3.43 mgals. Negative Bouguer anomalies suggest the presence of lower density sediments of Quaternary age, and possibly Tertiary age, overlying higher density Belt bedrock.

The gravity anomalies determined in this study are reasonable and comparable to gravity work near Polson conducted by LaPoint (1971) and McCafferty et al. (1998). LaPoint (1971) performed a larger scale gravity survey (~2100km^2) of the southwestern Flathead Lake region including Polson, MT. Data spacing within the survey was variable, but typical spacing was on the order of ½ to 1-mile. The complete Bouguer anomaly determined in the region of LaPoint's (1971) survey ranged from approximately -128 to -132 mgals. The minor discrepancy between CBA values from this survey's and LaPoint (1971) I interpret as resulting from differences in station spacing. Closer data spacing results in higher resolution of the smaller scale gravity fluctuations and can account for the small incongruity. The complete Bouguer anomaly for the state of Montana is maintained by the United States Geological Survey. Data complied to form the map were obtained from the National Geophysical Data Center (from unclassified Department of Defense data), the USGS, and from a number of university thesis and dissertation studies (McCafferty et al., 1998). Approximately 35,000 data points within and adjacent to the state were used to compile the map. Of those 35,000 points, 5 fall along this study's survey line and have complete Bouguer values ranging from -134 to -136 mgals (McCafferty et al., 1998), within the range of gravity data I collected in this study.

The residual gravity values are directly attributable to the topography of the bedrock underlying the lower density material. Gravity data for the study area shows a highly variable bedrock surface with multiple ridges and valleys (Figure 33). As seen in

Figure 3, underlying the Polson moraine is a highly variable bedrock topography. Interpretation of the survey data of LaPoint (1971) and McCafferty et al. (1998) indicate the presence of a large bedrock valley on the western boundary of the moraine, but data from LaPoint (1971) and McCafferty et al. (1998) is too large of scale to display the smaller scale topography beneath the moraine that I infer based on my work.

Most important in the interpretation of the combined gravity data sets is the position of the moraine crests relative to the location of bedrock ridges. There are three prominent crests to this portion of the Polson moraine, and two of those crests are directly over bedrock ridges (Figure 33). The western and eastern moraine crests overlie bedrock highs while the central crest is situated above a prominent bedrock valley.

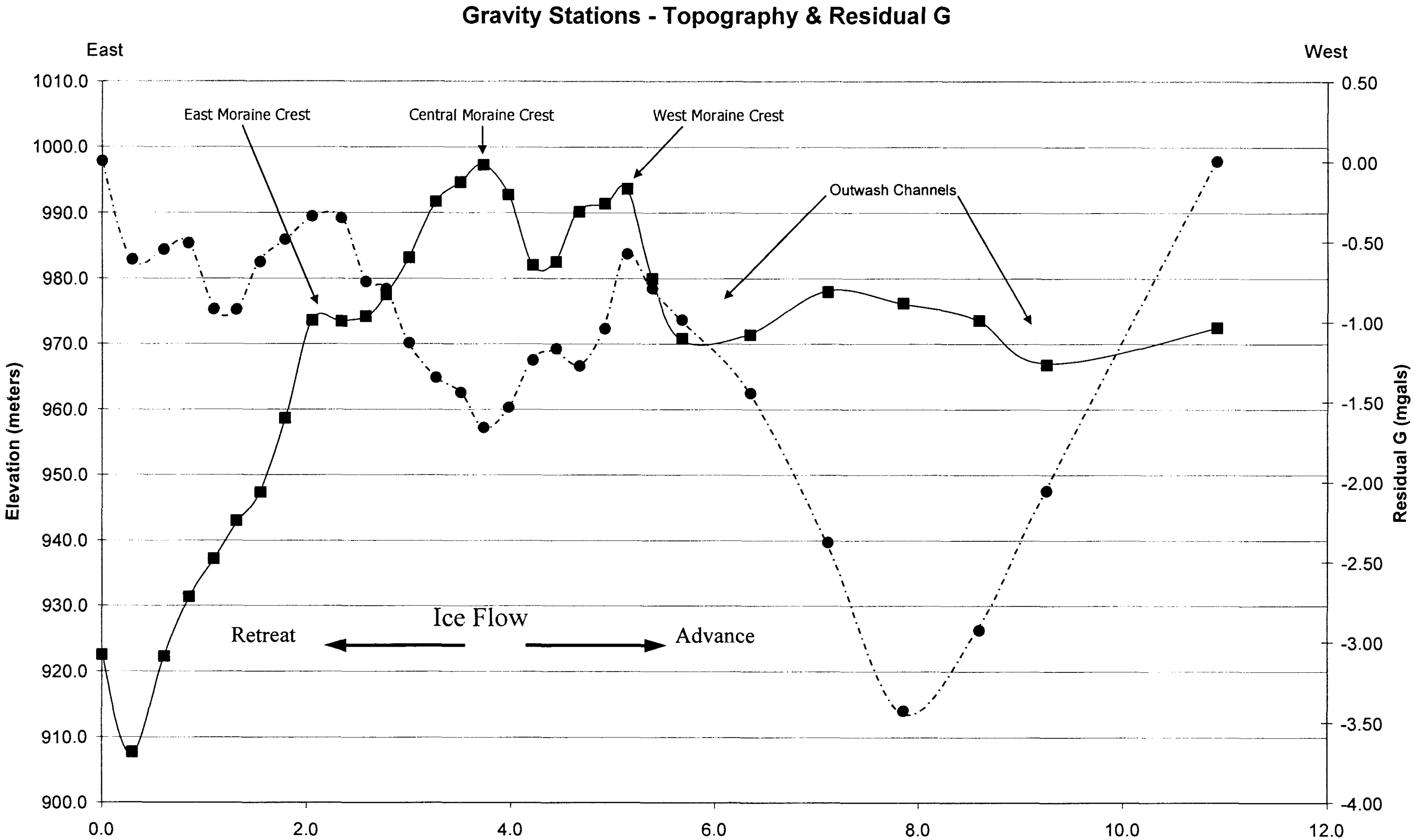


Figure 32. Gravity Station positions and their elevation plotted with the residual gravity value at each station. Note two of the three crests are located over bedrock highs.

Density Values of Modeled Subsurface Material

Determination of sediment and bedrock densities is vital in order to delineate the depth of the interface between fill and bedrock. The most variable and important density value(s) to obtain are those of the basin fill (predominantly glacial till). Morainal material can have a wide range of densities dependant upon percentage of grain sizes and compaction. Glacial till density measurements obtained in Minnesota, South Dakota and Iowa range from 1.83 to 2.24g/cm^3 for dry sediment and from 2.09 to 2.39g/cm^3 for wet sediment (Balco and Stone, 2003). Using the procedure described by Balco and Stone (2003) for sampling till I obtained several samples of the Polson moraine. Samples were collected from near the top of a cut along Irvine Flats Rd. and resulted in density values ranging between 2.15 and 2.24g/cm^3. Because of the stratigraphic location of the samples and the fact that they were mostly dry, the densities are interpreted as representing the lower bound. Using a simple shale compaction equation (Schmoker, 1984) burial to a depth of 142m results in a 7% increase in density. In addition to the compaction, the introduction of water into the pore space and inclusion of Belt rock clasts increase the density; therefore, I used a density value 2.35g/cm^3 for the Quaternary basin fill.

Belt rock in the study area consists primarily of quartzite and argillite. The density of Precambrian rock used in previous work in western Montana range from 2.6 to 2.9g/cm^3 (LaPoint, 1971, Constenius, 1988, Kleinkopf, 1997, Harrison, 2000, Nyquest, 2001, Stalker, 2004). Density values of Belt rock in the study area, determined from collected hand samples, range from 2.69 to 2.72g/cm^3. I chose a value of 2.7g/cm^3 for the bedrock density throughout the survey. Unconsolidated and consolidated Tertiary sands and conglomerates have been described throughout western Montana, including in the Flathead Lake region (Alden, 1953; Constenius, 1996; Smith, 2004). There appears to be no indication of Tertiary material underlying the moraine. Therefore, I have not included a layer of Tertiary sediment in the gravity models. In constructing the models, I used a density contrast between Belt rock and Quaternary basin fill of $0.35 g/cm^3$.

Bedrock Profile

Using a density contrast between bedrock and basin fill of $0.35 g/cm^3$, a model of the basin shape (or bedrock topography) was constructed in GravCadW (Figure 34). The model suggests that the depth to bedrock below the eastern moraine crest along the survey line is ~17m (Figure 33). A water well (Well 38, Appendix 2) drilled a kilometer north along this trend struck bedrock at 5m. To the north of the well and south of the survey point, bedrock is exposed. Combination of Belt rock exposures, well log data and the gravity model indicate a north/south trending bedrock ridge. Depth to the bedrock ridge though variable, from north to south, appears to lie shallowly beneath the moraine. Visually this portion of the moraine directly follows the trend of the bedrock. I interpret the eastern crest as merely mimicking the shallow bedrock ridge; it does not appear to represent a morainal ridge deposited at the ice margin.

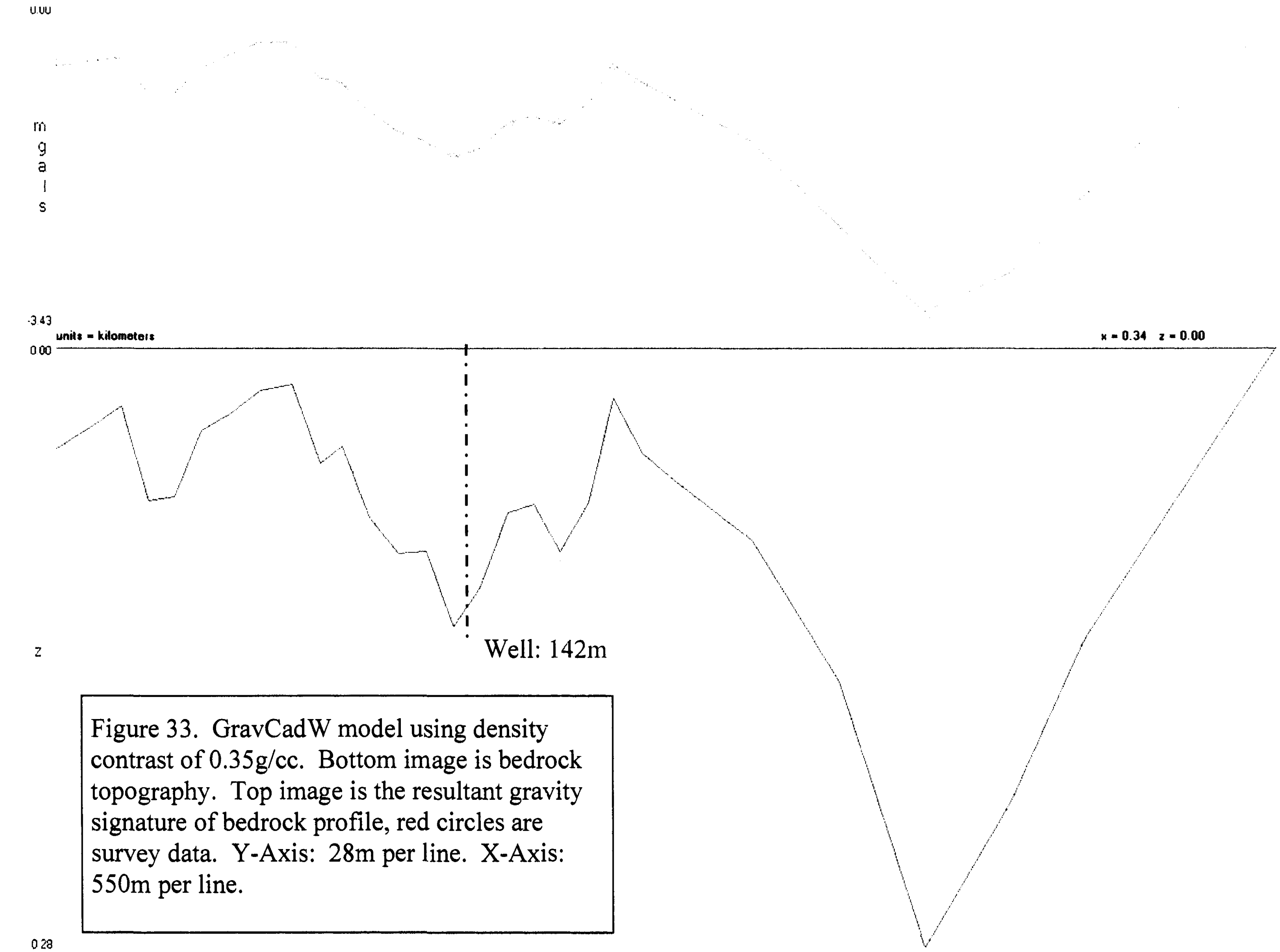


Figure 33. GravCadW model using density contrast of 0.35g/cc. Bottom image is bedrock topography. Top image is the resultant gravity signature of bedrock profile, red circles are survey data. Y-Axis: 28m per line. X-Axis: 550m per line.

The middle crest of the moraine is underlain by a significant bedrock valley (Figures 32, 33). As shown in the gravity model the deepest portion of the valley reaches depths of approximately 130m. Station 17 of the gravity survey is located ~30m south of a water well drilled into bedrock at a depth of 142m (Figure 32, 33). The modeled depth to the bedrock at this survey point is 124m (Figure 33). In the Polson region the exposed bedrock topography is highly variable; therefore, I interpret the difference in the depth to bedrock between the well and station 17 to be within reason. Because the middle moraine crest is situated above a significant bedrock valley; I interpret this as representing the position of the glacial front.

Depth to bedrock under the western crest of the moraine along the survey line is approximately 26m (Figure 33). No exposures of bedrock are found immediately to the north of the survey line; however, from the station location to the north is a relatively prominent topographic ridge. To the south of the survey line at this position is Kerr dam. The dam is built abutting to steep bedrock cliffs found along this stretch of the Flathead River. Bedrock at Kerr dam likely continues northward in the shallow subsurface to Irvin Flats Rd and extends further north under the topographic ridge. The inferred shallow depth of this bedrock ridge suggests that it influenced of the position of the moraine crest. Importantly, to the west of this position no glacial till (moraine) material has been observed (Edwards, 2006, personal comm.); therefore, I interpret the western crest to reflect the true terminal position of the glacial front during its maximum advance. I infer that the glacial lobe was strongly influenced by the bedrock topography and that this topography suppressed glacial movement such that it could not advance beyond this ridge.

Conclusion

The Polson moraine west of the town and north of the Flathead River is a wide, topographic high with three prominent crests. Locations of the bedrock exposures in relation to the moraine crests suggest a potential relationship. I performed a small scale gravity survey orthogonal to the crests to determine the bedrock topography and depth below the moraine. Gravity data indicates two of the moraine crests are underlain by shallow bedrock ridges, while the central crest is located over a significant valley.

Of the three crests, the western and central ridges are interpreted to be directly deposited by glacial activity at the ice margin, while the eastern crest simply is a reflection of the shallow subsurface bedrock ridge. The western crest represents the farthest terminal moraine of the Flathead lobe in this region during the last glacial maximum. Likely the terminal moraine position, though a function of glacial dynamics, was strongly influenced by the bedrock ridge at this locality. East of the terminal moraine crest is the second significant crest. Gravity data indicate a significant bedrock low underlying the moraine crest at this position. A correlation of the crest to a bedrock low indicates this ridge of the moraine is independent of the subsurface features and was formed by direct glacial deposition. Whether this represents a terminal or recessional moraine is not apparent from the gravity survey. The moraine crest farthest to the east directly follows the trend of the shallow bedrock ridge it is deposited upon. Because this topography is dependent on the bedrock ridge, by definition (Flint, 1971), it is not considered to be a moraine ridgeline and is not representative of the glacial front.

Plates

Plate 1: Geologic map of a portion of the Polson Quadrangle. The study area consisted of a large segment of the quadrangle. Remaining area of the Polson quad have been mapped by Edward Salmon and Jason Edwards.

Plate 2: 30m measured section in a drainage gully located at station JB-021-05. The section is a composite of a series of trenches dug into the drainage gully. Sediments from the top of one trench to the bottom of the subsequent higher trench were the same. This indicates lateral continuity between trenches and therefore they can be stacked.

Plate 3: A north/south cross section over the southern Polson moraine beginning at the shore of Flathead Lake to the southern edge of the Pablo Reservoir. Construction of the cross section used data from surface mapping and well-log lithology descriptions.

Plate 4: Depth to bedrock map. The map displays contours of sediment thickness overlying Belt Supergroup bedrock. In other words, the map shows the depth to the bedrock interface throughout the study area.

Plate 5: Bedrock elevation map. The map displays contours of the altitude above sea level of the Belt Supergroup bedrock surface.

References Cited:

Alden, W. C., 1953. Physiography and glacial geology of Western Montana and Adjacent Areas. U.S. Geological Survey Professional Paper 231, 200pp.

Alt, D., 2001. Glacial Lake Missoula and its Humongous Floods. Mountain Press, Missoula.

Antevs, Ernst, 1925. Retreat of the last ice sheet in eastern Canada, Canada Geological Survey Memoirs 146, 142p.

Ashley, G. M., 1975. Rhythmic sedimentation in Glacial Lake Hitchcock, Massachusetts-Connecticut. In: Jopling, A. V., MacDonald, B. C. (eds.), Glaciofluvial and Glaciolacustrine Sedimentation: Soc. Econ. Paleontol. Mineral, Special Publication, v. 23, pp. 304-320.

Atwater, B. F., 1986. Pleistocene glacial-lake deposits of the Sanpoil River Valley, Northeastern Washington. U.S. Geological Survey Bulletin 1661, pp39.

Balco, G. and Stone, J.O., 2003. Measuring the density of rock, sand, till, etc. UW Cosmogenic Nuclide Laboratory, methods and procedures. http://depts.washington.edu/cosmolab/chem.html

Benn, D. I., and Evans, D. J.A., 1998. Glacier and Glaciation, Arnold, London. 734p.

Bennett, M. R., Huddart, D., Geoffrey, S. P. Thomas, 2002. Facies architecture within a regional glaciolacustrine basin: Copper River, Alaska, Quaternary Science Reviews, v. 21, pp. 2237-2279.

Borgert, J. A., Lundeen, K. A., Thackray, G. D., 1999. Glacial Geology of the Southeastern Sawtooth Mountains, in Hughes, S.S., and Thackray, G. D., eds., Guidebook to the Geology of Eastern Idaho: Pocatello, Idaho Museum of Natural History, pp. 205-217.

Bondurant, A. K., 2005. Geologic mapping and sedimentological analysis of Quaternary deposits along the western shore of Flathead Lake, northwest Montana; documenting the record of deglaciation, MS Thesis, University of Montana, Missoula, Montana.

Bretz, J. H., 1923. The Channeled Scablands of the Columbia Plateau, Journal of Geology, v. 31, n. 8, pp. 617-649

Bretz, J. H., 1969. "The Lake Missoula Floods and the Channeled Scabland," Journ. Geology, v.77, pp. 505-543.

Brown, C. S., Meier, M. F., Post, A., 1982. Calving speed of Alaska tidewater glaciers, with application to Columbia Glacier. U.S. Geological Survey Professional Paper 1258-C, 13pp.

Carrara, P. E., Short, S. K., Wilcox, R. E., 1986. Deglaciation of the Mountainous Region of northwestern Montana, USA, as indicated by late Pleistocene ashes. Arctic and Alpine Research, v.18, n.3, pp. 317-325.

Carrara, P. E., 1989. Late Quaternary glacial and vegetative history of the Glacier National Park Region, Montana. U.S. Geological Survey Bulletin, 1902.

Carrara, P. E., Kiever, E. P., Strandling, D. E., 1996. The southern limit of Cordilleran ice in the Colville and Pend Oreille valleys of northeastern Washington during the Late Wisconsin glaciation. Canadian Journal of Earth Sciences, v.33, pp. 769-778.

Chambers, R. L., 1971. Sedimentation in Glacial Lake Missoula, MS Thesis, University of Montana, Missoula, Montana.

Clague, J. J., James, T. S., 2002. History and isostatic effects of the last ice sheet in southern British Columbia, Quaternary Science Reviews, v. 21, pp. 71-87.

Clague, J. J., Barendregt, R., Enkin, R. J., Foit, F. F., 2003. Paleomagnetic and tephra evidence for tens of Missoula floods in southern Washington, Geology (Boulder), v. 31, pp 247-250.

Constenius, K. N., 1988. Structural configuration of the Kishenehn Basin delineated by geophysical methods, northwestern Montana and southern British Columbia, The Mountain Geologist, v. 25, pp. 13-28.

Constenius, K. N., 1996. Late Paleogene extensional collapsc of the Cordilleran foreland fold and thrust belt, Geological Society of America Bulletin, v. 108, pp. 20-39.

Damchen and Associates, Inc., 1999. Hydrogeological and Soils Investigation for the Lake County Landfill Expansion Area, Prepared by: Damschen & Associates, Helena, Montana, January 1999.

Decker, G. L., 1968. Preliminary report on the geology, geochemistry, and sedimentology of Flathead Lake, northwestern Montana, unpublished MS Thesis, University of Montana, Missoula, Montana.

Elrod, M. J., 1903. The physiography of the Flathead Lake region, Lectures at Flathead Lake, Bulletin University of Montana, Missoula, Montana, pp. 197-203.

Eyles, N., Eyles, C. H., Miall, A. D., 1983. Lithofacies types and vertical profile models; an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences, Sedimentology, v. 30, pp. 393-410.

Flint, R. F., 1957. Glacial and Pleistocene Geology, John Wiley and Sons, 553p.

Flint, R. F., 1971. Glacial and Quaternary Geology, John Wiley and Sons, 892p.

Fullerton, D. S., Colton, R. B., Bush, C. A., Straub, A. W., 2004. Map showing spatial and temporal relations of mountain and continental glaciations on the northern plains, primarily in northern Montana and northwestern North Dakota, U.S. Geological Survey Scientific Investigations Map Pamphlet, Map 2843.

Hammer, S., 1939. Terrain corrections for gravimeter stations, Geophysics, v. 4, pp. 184-194

Harrison, N., 2004. Gravity, Radar and Seismic Investigations to help determine geologic, hydrologic and biologic relations in the Nyack valley, Northwestern Montana, MS Thesis, University of Montana, Missoula, Montana.

Hendrix, M. S., Sperazza, M., Gerber, T., Moore, J. N., 2001. Sedimentary record of Late Pleistocene-Holocene transition, Flathead Lake, Montana, American Geophysical Union Abstracts with Programs, v. 82, p. 47.

Hofmann, M. H., Hendrix, M. S., Moore, J. N., Sperazza, M., Shapley, M., Wittkop, C., Stone, J., 2003. Sedimentary indicators of significant late Pleistocene-early Holocene lake level fluctuation: preliminary results from Flathead Lake, Montana, EOS Trans. AGU, 84/87.

Hofmann, M. H., Hendrix, M. S., 2004. Geologic map of the East Bay 7.5' Quadrangle, northwest Montana, Montana Bureau of Mines and Geology Open File Report 496, 10 pages, scale 1:24,000.

Hofmann, M. H., 2005. Using Sediments to infer geologic history of Northwestern Montana during and after the last glacial maximum, the record from Flathead Lake, PhD Dissertation, University of Montana, Missoula, Montana.

Hofmann, M. H., Hendrix, M. S., Moore, J. N., Sperazza, M., 2006. Late Pleistocene and Holocene depositional history of sediments in Flathead Lake, Montana: Evidence from high-resolution seismic reflection interpretation, Sedimentary Geology, v. 184, pp. 111-131.

Hopkins, W. S., Jr, Sweet, A. R., 1976. A microflora from a short section of the Paleogene Kishenehn Formation, Southeastern British Columbia, Geological Survey of Canada Paper no.76-1B, pp. 307-309.

Kleinkopf, M. D., 1997. Geophysical interpretations of the Libby thrust belt, Northwestern Montana, U.S. Geological Survey Professional Paper 1546, 32p.

Konizeski, R. L., Brietkrietz, A., McMurtrey, R. G., 1968. Geology and groundwater resources of the Kalispell Valley, Northwestern Montana, Montana Bureau of Mines and Geology Bulletin, v. 68, 42pp.

LaPoint, D. J., 1971. Geology and geophysics of the Southwestern Flathead Lake region, Montana, MS Thesis, University of Montana, Missoula, Montana.

Leech, G. B., 1966. The Rocky Mountain Trench, Geological Survey of Canada Paper, pp. 307-329.

Legget, R. F., and Bartley, M. W., 1953. An engineering study of glacial deposits at Steep Rock Lake, Ontario, Canada, Econ. Geology, v. 48, pp. 513-540.

Levish, D. R., 1997. Late Pleistocene sedimentation in Glacial Lake Missoula and revised glacial history of the Flathead Lobe of the Cordilleran Ice Sheet, Mission Valley, Montana. PhD Thesis, University of Colorado, Boulder, Colorado.

Locke, W., 1995. Modeling of icecap glaciation of the northern Rocky Mountains of Montana, Geomorphology, v. 14, pp. 123-130.

Lønne, I., 1995. Sedimentary facies and depositional architecture of ice-contact glaciomarine systems, Sedimentary Geology, v. 98, pp. 13-43.

Lønne, I., Nemec, W., Blikra, L. H., and Lauritsen, T., 2001. Sedimentary architecture and dynamic stratigraphy of a marine ice-contact system, Journal of Sedimentary Research, v. 71, pp. 922-943.

McCafferty, A., Bankey, V., and Brenner, K. C., 1998. Montana aeromagnetic and gravity maps and data, U.S. Geological Survey Open File Report 98-333, http://pubs.usgs.gov/of/1998/ofr-98-0333/index.html

Miall, A. D., 1996. Principles of Sedimentary Basin Analysis, 3rd ed., Springer, 616p.

Nyquest, D., 2001. A bedrock model of the Hellgate Canyon and Bandmann Flats area, Montana through constrained inversion of gravity data, MS Thesis, University of Montana, Missoula, Montana

Osteena, D. A., Levish, D. R., Klinger, R. E., 1995. Mission Fault Study, U.S. Bureau of Reclemation, Seismotectonic Report 94-8.

Pardee, J. T., 1910. The glacial Lake Missoula, Montana. Journal of Geology, v.18, pp. 376-386.

Pardee, J. T., 1942. Unusual currents in glacial Lake Missoula, Montana. Geological Society of America Bulletin, v. 53, pp. 1569-1599.

Richmond, G. M., 1965. Glaciation of the Rocky Mountains, in Wright, H. E., Jr, and Frey, D. G., eds., The Quaternary of the United States: Princeton, NJ, Princeton University Press, p. 217-230.

Richmond, G. M., 1986. Tentative correlation of deposits of the Cordilleran Ice Sheet in the northern Rocky Mountains, Quaternary Science Reviews, v. 5, pp. 129-144.

Russel, L. S., 1964. Kishenehn Formation, Bulletin of Canadian Petroleum Geology, v.12, pp. 536-543.

Sears, J. W., 2001. Emplacement and denudation history of the Lewis-Eldorado-Hoadley thrust slab in the northern Montana Cordillera, USA; implications for steady-state orogenic processes, American Journal of Science, v. 301, pp. 359-373.

Shaw, J., 1977. Sedimentation in an Alpine Lake during deglaciation, Okanagan Valley, British Columbia, Canada, Geografiska Annaler: Series A, Physical Geography, v. 59, pp. 221-240.

Silkwood, J., 1998, Glacial Lake Missoula and the Channeled Scabland; A digital portrait of landforms of the last Ice Age, Washinton, Oregon, northern Idaho, western Montana: U.S. Forest Service

Smith, D. G., 1966. Glacial and fluvial landforms adjacent to the Big Arm embayment, Flathead Lake, Western Montana, MS Thesis, University of Montana, Missoula, Montana.

Smith, L. N., 2000a. Altitude of and depth to the bedrock surface in the Flathead Lake Area, Flathead and Lake counties, Montana: Montana, Montana Bureau of Mines and Geology Groundwater Assessment Atlas 2, Map 7, scale 1:150,000.

Smith, L. N., 2000b. Surficial geologic map of the upper Flathead valley (Kalispell valley) area, Flathead County, northwestern Montana, Montana Bureau of Mines and Geology Groundwater Assessment Atlas 2, Map 6, scale 1:70,000.

Smith, L. N., 2004. Late Pleistocene stratigraphy and implications for deglaciation and subglacial processes of the Flathead Lobe of the Cordilleran Ice Sheet, Flathead Valley, Montana, USA, Sedimentary Geology, v.165, pp. 295-332.

Stalker, J., 2004. Seismic and gravity investigation of sediment depth, bedrock topography and faulting in the Tertiary Drummond-Hall Basin, Western Montana, MS Thesis, University of Montana, Missoula, Montana.

Stickney, M. C., 1980. Siesmicity and gravity studies of aulting in the Kalispell valley, northwestern Montana, MS Thesis, University of Montana, Missoula, Montana.

Timmerman, G. K., 2005. Constraining temporal relationships between glacial Lake Missoula, retreat of the Flathead Ice Lobe and development of the lower Flathead River Valley, MS Thesis, University of Montana, Missoula, Montana.

Waitt, R. B., 1985. Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula, Geological Society of America Bulletin, v.96, pp. 1271-1286.

Whitney, M. I., Dietrich, R. V., 1973. Ventifact Sculpture by Windblown dust, Geological Society of America Bulletin, v. 84, pp. 2561-2581.

Appendix 1: Field Station Locations.

JB-Station-05	Longitude (W)	Latitude (N)	JB-Station-05	Longitude (W)	Latitude (N)
1	114.1875	47.6437	47	114.2077	47.6399
2	114.1902	47.6436	48	114.2254	47.6896
3	114.2077	47.6399	49	114.2361	47.6820
4	114.2049	47.6402	50	114.2328	47.6836
5	114.2466	47.6953	51	114.2263	47.6891
6	114.2448	47.6939	52	114.2065	47.7025
7	114.2357	47.6896	53	114.2358	47.6888
8	114.1057	47.6689			
9	114.1637	47.6689			
10	114.1665	47.6680			
11	114.1131	47.6596			
12	114.1950	47.6607			
13	114.1848	47.6647			
14	No Station 14, error in numbering				
15	114.1892	47.6986			
16	114.1899	47.6985			
17	114.1913	47.6980			
18	114.2164	47.6768			
19	114.2156	47.6751			
20	114.2155	47.6719			
21	114.2223	47.6767			
22	114.2107	47.6777			
23	114.2087	47.6722			
24	114.2066	47.6750			
25	114.2051	47.6754			
26	114.2021	47.6745			
27	114.2040	47.6781			
28	114.2099	47.6825			
29	114.1971	47.6732			
30	114.1972	47.6753			
31	114.1955	47.6770			
32	114.1977	47.6786			
33	114.1983	47.6808			
34	114.2182	47.7093			
35	114.2182	47.7078			
36	114.2194	47.7066			
37	114.2099	47.6825			
38	114.2072	47.6853			
39	114.1985	47.6850			
40	114.2000	47.6836			
41	114.1925	47.6853			
42	114.1921	47.6857			
43	114.2172	47.7139			
44	114.2080	47.7092			
45	114.2080	47.7041			
46	114.2190	47.7053			

Appendix 2: Well Logs Examined

Map Well#	GWIC Number	Elevation	Latitude (N)	Longitude (E)
1	130525	3370	47.6771	-114.1303
2	76958	3400	47.6781	-114.1394
3	142468	3241.9	47.6683	-114.135
4	162037	3240	47.6693	-114.1419
5	77000	3210	47.6597	-114.145
6	76990	3195	47.6608	-114.1516
7	188088	3200	47.6511	-114.1633
8	200486	3240	47.6638	-114.1717
9	197421	3275	47.6656	-114.1744
10	76996	3220	47.6634	-114.1807
11	76998	3290	47.6591	-114.1863
12	175582	3250	47.6549	-114.1903
13	148570	3270	47.6549	-114.1959
14	209302	3370	47.6549	-114.2062
15	166706	3260	47.645	-114.1993
16	77014	3265	47.6441	-114.1991
17	205792	3250	47.6441	-114.2063
18	76954	3050	47.6865	-114.138
19	76925	2995	47.6906	-114.1367
20	76923	2935	47.6897	-114.1491
21	200481	2935	47.6875	-114.1579
22	76924	2900	47.6935	-114.1408
23	76918	2980	47.6943	-114.1261
24	76919	3040	47.6906	-114.1261
25	143242	2950	47.6839	-114.1794
26	152773	2915	47.6937	-114.1782
27	76934	3010	47.7002	-114.187
28	200478	3195	47.6918	-114.2134
29	148572	3215	47.69	-114.2272
30	134191	3258	47.6672	-114.2106
31	134197	3251	47.6661	-114.2133
32	148569	3260	47.66	-114.2152
33	199035	3270	47.6376	-114.2021
34	77056	3170	47.6538	-114.2361
35	77016	3078	47.6329	-114.2007
36	198807	3095	47.6984	-114.201
37	200541	2975	47.7055	-114.1961
38	204599	3120	47.6984	-114.2065
39	139325	2970	47.682	-114.1877
40	172467	2960	47.6801	-114.1905
41	76994	3230	47.6712	-114.1932
42	77854	2928	47.7072	-114.1844
43	137592	2950	47.712	-114.1975
44	188069	2960	47.713	-114.201
45	200535	3070	47.7111	-114.2093
46	131990	2965	47.7158	-114.2023

Map Well#	GWIC Number	Elevation	Latitude (N)	Longitude (E)
47	169368	3010	47.7176	-114.2135
48	77948	3120	47.7167	-114.228
49	200489	3280	47.6586	-114.1959
50	156614	3275	47.6586	-114.1903
51	139181	2975	47.682	-114.1662
52	154143	3020	47.6773	-114.178
53	200947	3040	47.6764	-114.1794
54	76951	3060	47.6755	-114.178
55	141486	3110	47.6738	-114.1786
56	25381	3110	47.674	-114.1807
57	24191	3125	47.6745	-114.1835
58	127624	2920	47.6867	-114.1835
59	162036	2955	47.6839	-114.1849
60	76937	3030	47.6783	-114.1822
61	76931	2930	47.7012	-114.181
62	152774	2955	47.6984	-114.1851
63	77061	3020	47.6336	-114.2202
64	77060	3040	47.6422	-114.2249
65	77059	3090	47.6463	-114.2247
66	152783	3190	47.6173	-114.1543
67	141484	3290	47.6975	-114.219
68	77052	3160	47.6585	-114.2494
69	152775	3175	47.6383	-114.1232
70	76962	3280	47.6808	-114.1248
71	148571	3205	47.6254	-114.1903
72	77884	2925	47.7059	-114.125
73	76916	2900	47.699	-114.1275
74	76933	2932	47.7022	-114.1851
75	77049	2970	47.6754	-114.2425
76	77086	2943	47.6267	-114.2422
77	219556	2965	47.6365	-114.2437
78	221193	3205	47.6618	-114.2494
79	76940	2980	47.6811	-114.178
80	212798	2900	47.6839	-114.1905
81	200479	2900	47.6876	-114.1849
82	219554	3320	47.6656	-114.196
83	162045	3220	47.6675	-114.1876
84	77949	3085	47.781	-114.2252
85	77935	3092	47.7293	-114.2252
86	122709	3085	47.7311	-114.2202
87	77937	3055	47.7255	-114.2208
88	77945	3220	47.7175	-114.2426
89	77856	2930	47.7111	-114.188

Lithology descriptions can be viewed by typing in the GWIC number at the Montana Ground Water Information Cite: http://mbmggwic.mtech.edu/

Appendix 3: Gravity Survey Station Data

Station #	GPS Stat.	HAG	Lat	Long	G (mgals)	Theoretical
SC3 Lab					980432.210	
Field Base	2022a	907.715	47.6894	-114.1938	980547.855	980863.037
1	2022b	922.531	47.6919	-114.1911	980545.495	980863.259
2	2022a	907.715	47.6894	-114.1938	980547.855	980863.037
3	2022c	922.256	47.6894	-114.1966	980545.220	980863.035
4	2022d	931.324	47.6894	-114.1988	980543.605	980863.035
5	2023a	937.161	47.6894	-114.2010	980542.190	980863.036
6	2023b	943.004	47.6894	-114.2030	980541.145	980863.037
7	2023c	947.337	47.6894	-114.2051	980540.685	980863.038
8	2023d	958.618	47.6894	-114.2073	980538.660	980863.039
9	2023e	973.606	47.6895	-114.2097	980535.920	980863.041
10	2100a	973.454	47.6895	-114.2122	980536.145	980863.040
11	2100b	974.191	47.6895	-114.2144	980535.690	980863.040
12	2100c	977.479	47.6895	-114.2161	980535.055	980863.040
13	2100d	983.147	47.6895	-114.2182	980533.720	980863.041
14	2100e	991.696	47.6895	-114.2205	980531.850	980863.042
15	2100f	994.647	47.6895	-114.2227	980531.230	980863.041
16	2101a	997.280	47.6895	-114.2248	980530.575	980863.041
17	2101b	992.726	47.6895	-114.2269	980531.625	980863.040
18	2101c	982.023	47.6895	-114.2291	980534.215	980863.040
19	2101d	982.502	47.6895	-114.2312	980534.310	980863.040
20	2101f	990.161	47.6894	-114.2332	980532.750	980863.039
21	2101g	991.394	47.6894	-114.2355	980532.770	980863.039
22	2101h	993.648	47.6894	-114.2374	980532.695	980863.039
23	2102a	979.978	47.6894	-114.2396	980535.430	980863.038
24	2102b	970.825	47.6895	-114.2423	980537.080	980863.040
25	2102c	971.392	47.6894	-114.2483	980536.355	980863.032
26	2102d	977.970	47.6894	-114.2551	980534.565	980863.033
27	2102e	976.230	47.6893	-114.2618	980534.245	980863.030
28	2102f	973.591	47.6893	-114.2685	980535.650	980863.027
29	2102g	966.830	47.6893	-114.2744	980538.070	980863.025
30	2103a	972.536	47.6891	-114.2894	980539.040	980863.007

Theoretical gravity value was calculated by the following equation (Θ is Latitude):

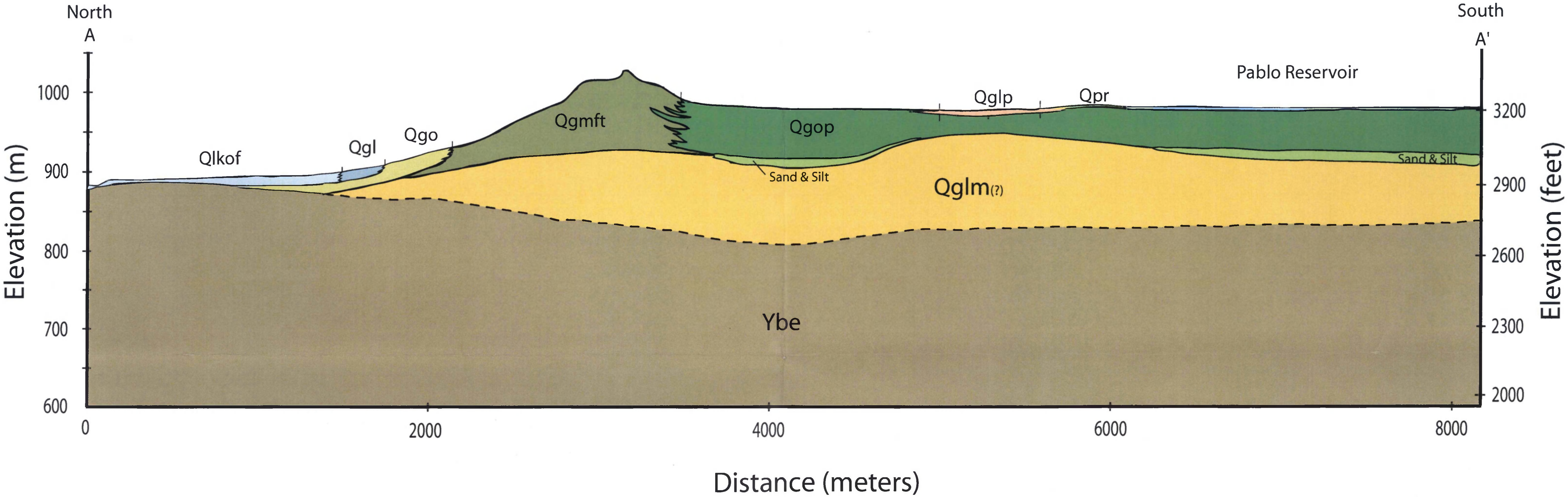
$$9.7803267714*[1+(0.00193185138639(\mathrm{Sin}2\Theta))] / \sqrt{(1-(0.00669437999013(\mathrm{Sin}2\Theta)))}$$

Station #	FAC	FAA	BC	BA	TC	CBA	Residual
SC3 Lab							
Field Base	280.121	-35.061	101.619	-136.680	0.550	-136.130	
1	284.693	-33.071	103.277	-136.348	0.731	-135.617	0.003
2	280.121	-35.061	101.619	-136.680	0.550	-136.130	-0.612
3	284.608	-33.207	103.247	-136.453	0.496	-135.958	-0.548
4	287.407	-32.024	104.262	-136.285	0.451	-135.835	-0.508
5	289.208	-31.638	104.915	-136.553	0.390	-136.164	-0.921
6	291.011	-30.881	105.569	-136.450	0.363	-136.087	-0.922
7	292.348	-30.004	106.054	-136.059	0.348	-135.711	-0.626
8	295.829	-28.549	107.317	-135.866	0.380	-135.487	-0.486
9	300.455	-26.667	108.995	-135.662	0.413	-135.249	-0.340
10	300.408	-26.487	108.978	-135.465	0.303	-135.162	-0.352
11	300.635	-26.715	109.061	-135.775	0.298	-135.477	-0.749
12	301.650	-26.335	109.429	-135.764	0.310	-135.454	-0.794
13	303.399	-25.922	110.063	-135.985	0.274	-135.711	-1.130
14	306.037	-25.155	111.020	-136.175	0.337	-135.838	-1.347
15	306.948	-24.863	111.351	-136.214	0.367	-135.847	-1.440
16	307.761	-24.705	111.646	-136.351	0.362	-135.988	-1.660
17	306.355	-25.060	111.136	-136.196	0.419	-135.777	-1.533
18	303.052	-25.773	109.937	-135.710	0.310	-135.400	-1.238
19	303.200	-25.530	109.991	-135.521	0.272	-135.249	-1.166
20	305.564	-24.725	110.849	-135.574	0.296	-135.278	-1.274
21	305.944	-24.325	110.987	-135.312	0.354	-134.957	-1.040
22	306.640	-23.704	111.239	-134.943	0.526	-134.416	-0.574
23	302.421	-25.186	109.709	-134.895	0.348	-134.546	-0.789
24	299.596	-26.363	108.684	-135.047	0.405	-134.642	-0.986
25	299.772	-26.906	108.747	-135.653	0.784	-134.869	-1.444
26	301.802	-26.666	109.484	-136.150	0.612	-135.538	-2.376
27	301.265	-27.520	109.289	-136.809	0.474	-136.335	-3.427
28	300.450	-26.927	108.993	-135.920	0.345	-135.576	-2.926
29	298.364	-26.591	108.237	-134.828	0.352	-134.475	-2.053
30	300.125	-23.842	108.875	-132.717	0.875	-131.843	0.003

Free Air Correction (FAC) = 0.3086h Where h is height in meters above sea level
Free Air Anomaly (FAA) = Observed G - Theoretical + FAC
Bouguer Correction (BC) = 0.1195h Where h is thickness of rock slab
Bouguer Anomaly (BA) = FAA - BC
Terrain Correction (TC) determined by HAMMERXYZ computer software program based on Hammer Charts
Complete Bouguer Anomaly (CBA) = BA + TC
Residual determined by subtracting regional gravity from CBA, regional is assumed to be planar = 0.3455x - 135.62

A - A' Cross Section - North/South Profile across Southern Polson Moraine

by Jason Braden, 2006



Vertically exaggerated cross-section perpendicular to the southern Polson moraine. Construction of the profile used data from surface mapping, lithology descriptions from driller's well-logs, and the assembled isopach and bedrock elevation maps (Plate 4 & 5). All contacts are estimated from mapping and interpretation of and depth indications from well-logs.

The modern Flathead Lake is located to the north of the cross-section, a small segment is just visible on the extreme left of the profile (~887m). Located at the present day surface, toward the southern portion of the profile, is Pablo Reservoir. The three most prominent units, other than the Belt Supergroup bedrock, are Qgmft, Qgop and Qglm. Qgmft is the Polson moraine. Qgop is glacial outwash and form a significant plain south of the moraine. Qglm is the diamict associated with glacial Lake Missoula and is interpreted to underlie all the other sediment. Glacial front conditions are dynamic and may result in the inter-fingering of the map units.

The two thin layers of sand and silt have been included separatedly from the other map units. This is because interpretation of well-logs that drill through these depths describe these sediments and differ from the overlying gravel, sand, silt and the underlying clay and gravel. Elevation of these two layers matches closely to the depth of a sand/silt layer interpreted in a cross-section in the East Bay Quad (Hofmann and Hendrix, 2004). These sediments may represent glacial Lake Missoula sediment that were sourced from the advancing glacial front.

Plate 3

Composite Measured Section from North of the Flathead River, West of Polson, MT

Station JB-021-05 Long: -114.2223E Lat: 47.6767N

Vertical Scale 1cm=50cm by Jason Braden, 2006

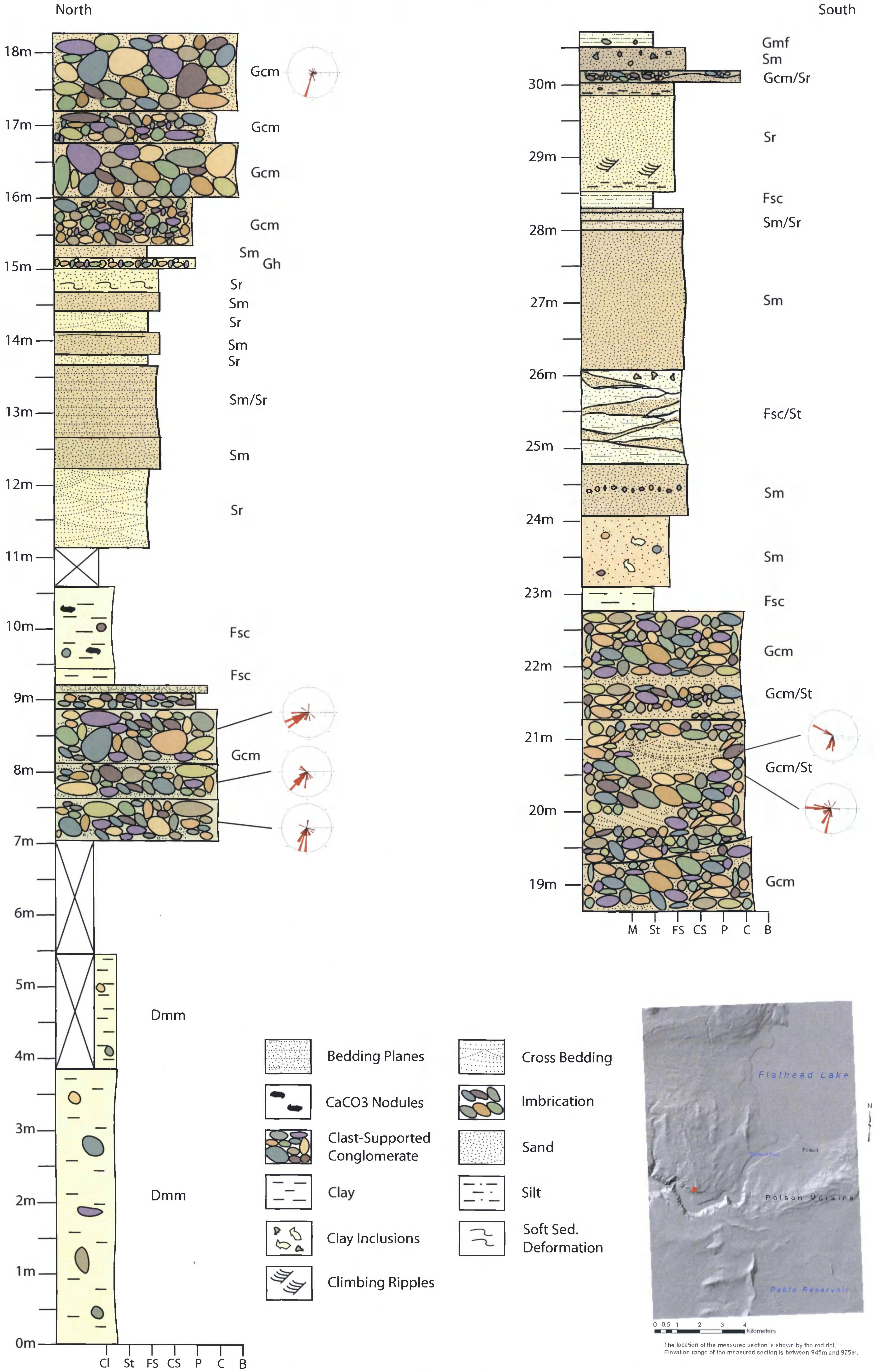
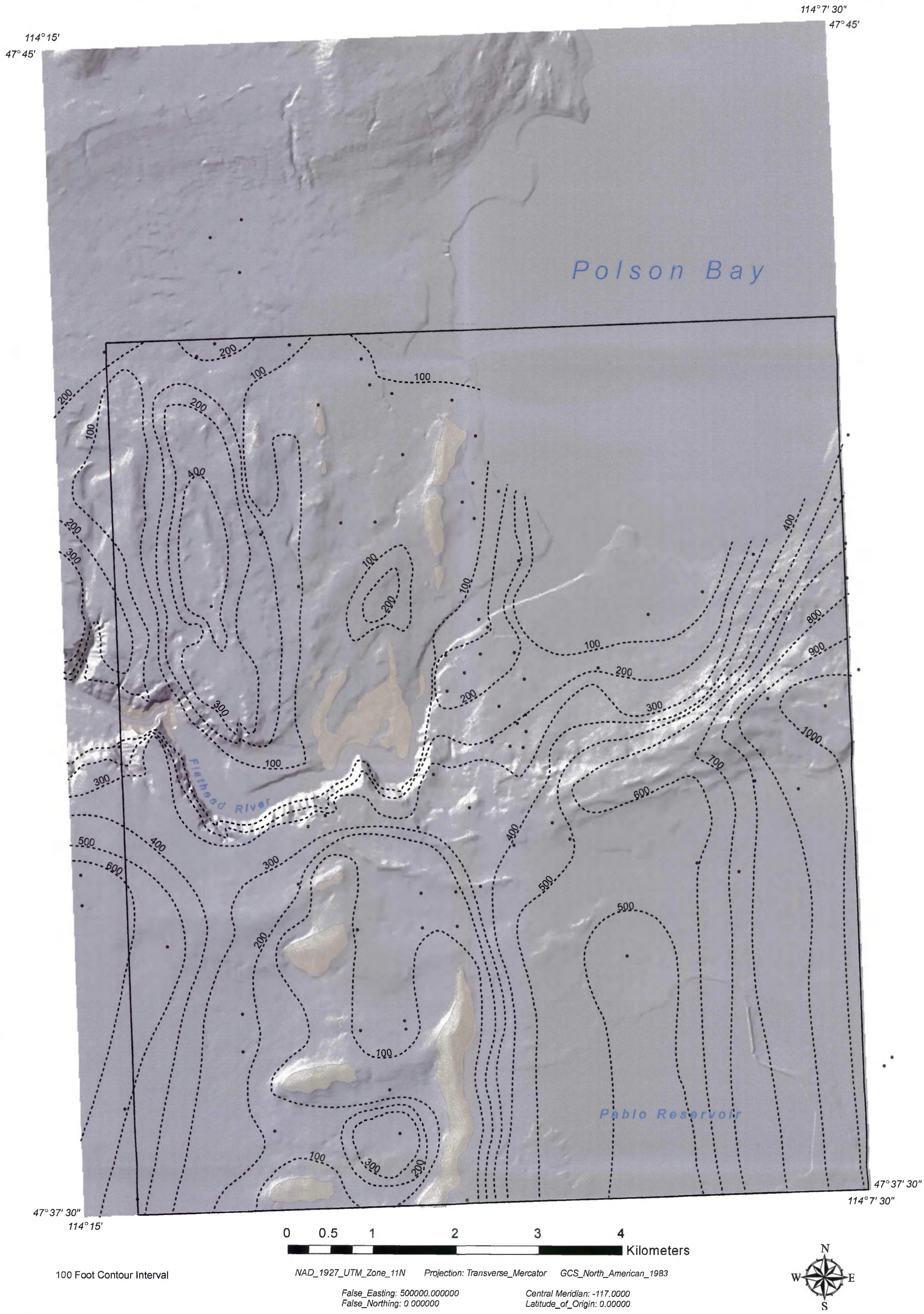


Plate 2



Depth to Bedrock Map

by Jason Braden, 2006

Contour, Estimated Depth to Bedrock

Water Well Location

Surface Exposure of Bedrock

Field Study Area

Map displays the depth to the Belt Supergroup bedrock surface beneath unconsolidated sediments. These sediments consist of gravel, sand, silt and clay. Contour lines represent the estimated sediment thickness overlaying the bedrock surface. Data used in construction of the map was a combination of a surface map of bedrock exposures, driller's well-logs, and gravity data. Depths to bedrock were interpreted from well-log lithology descriptions and basin topography determined by gravity data. The location of the contour lines were determined visually and sketched in manually.

Extensional tectonics in the region, representated by the proximal Mission Fault, has resutled in horst/graben structures in the Flathead and Mission Valleys (LaPoint, 1971; Ostenaa, 1995). Variable sediment thicknesses shown on the map are primarily N/S trending and suggest ridges and valleys. Glaciation in the region additionally has deposited thick packages of sediment. The southern Polson moraine is the large ridgeline extending East to West and contributes to the significant depth to bedrock in this area. The northern Polson moraine, located north of Flathead River, is shown by the thick sediment package extending north from Kerr Dam.

Bedrock Altitude Map

by Jason Braden, 2006

Contour, Estimated Bedrock Elevation

Water Well Location

Surface Exposure of Bedrock

Field Study Area

Map displays the altitude above sea level of the Belt Supergroup bedrock surface beneath unconsolidated sediments. These sediments consist of gravel, sand, silt and clay. Contour lines represent the estimated bedrock surface elevations. Data used in construction of the map was a combination of a surface map of bedrock exposures, driller's well-logs, and gravity data. Depths to bedrock, interpreted from well-log descriptions and gravity data, were subtracted from surface elevations and resulted in bedrock elevation above sea level. The location of the contour lines were determined visually and manually sketching in the lines.

Extensional tectonics in the region, representated by the proximal Mission Fault, has resutled in horst/graben structures in the Flathead and Mission Valleys (LaPoint, 1971; Ostenaa, 1995). Bedrock ridges and valleys shown on the map are primarily N/S trending and suggest formation by faults. Glaciation in the region additionally has sculpted the bedrock as the primary flow direction of the ice sheets has been from the north to the south. The bedrock low near the mouth of the modern Lower Flathead River indicates a paleovalley potentially incised by previous river flow.

Plate 5

Geologic Map of a portion of the Polson Quadrangle

by Jason R. Braden and Marc S. Hendrix, 2006

Contact — Contact, Approximate — Moraine Crestline — Lake/River Terrace — Strike/Dip — Lake — Field Study Area

- Qal - Alluvium of modern streams (latest Holocene to present)
- Qfr - Flathead River Deposits (latest Holocene to present)
- Qpr - Lake deposits of Pablo Reservoir (Latest Holocene)
- Qe - Eolian deposits (Early-Mid Holocene)
- Qlkof - Lake deposits of ancestral Flathead Lake (late Pleistocene - Early Holocene)
- Qgl - Glacial lake deposits, undivided (late Pleistocene - Early Holocene)
- Qgo - Sublacustrine fan/outflow sediments (late Pleistocene)
- Qgmft - Flathead Lobe terminal moraine (late Pleistocene)
- Qgtu - Glacial till, undivided (late Pleistocene)
- Qgop - Glacial outwash deposits (Pleistocene)
- Qgd - Deltaic/outwash deposits (Pleistocene)
- Qglp - Glacial lake Pablo deposits (Pleistocene)
- Qglmc - Coarse diamict (Pleistocene)
- Qglm - Diamict (Pleistocene)
- Tu - Tertiary deposits (undivided)
- Ybe - Middle Proterozoic Belt Supergroup (undivided)

Plate 1