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DISTRIBUTION OF PRE-QUATERNARY AND QUATERNARY GEOLOGIC UNITS AT THE FORMER TERMINUS OF THE CORDILLERAN ICE SHEET; ANALYSIS OF MAP REALATIONS NORTH OF POLSON, MONTANA

by

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Approved by:

Chairman

Dean, Graduate School

8-30-06

Date

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Distribution of pre-Quaternary and Quaternary geologic units at the former terminus of the Cordilleran Ice Sheet; analysis of map relations north of Polson, Montana

Chairman: Marc S. Hendrix MSH

Analysis of 3.5 kHz seismic data from Flathead Lake, combined with onshore geologic mapping and a literature review from previous and related studies, suggests that northwest trending faults in Big Arm Bay have been active since the last glacial interval. These faults likely have both strike-slip and dip-slip components of movement. Movement of the Chief Cliff fault is suggested by block rotation of Meso-Proterozoic Belt Supergroup bedrock in the Chief Cliff area and involvement of Pleistocene and younger sediments in a probable flower structure imaged in offshore 3.5 kHz reflection seismic data southeast of Chief Cliff in Big Arm Bay. A 3 to 12 meter thick drape of undisturbed sediment above this flower structure indicates a 10,000 year period of post-faulting quiescence.

During the Pleistocene the study area was inundated by the Flathead Lobe of the Cordilleran Ice Sheet. The south-flowing Flathead Lobe split at the Big Arm embayment; one branch continued south as far as Polson and one branch flowed west into the Big Arm, Elmo, and Dayton valleys. Stratigraphic and geomorphologic commonalities between the Polson and Big Arm moraines suggest that these moraines probably are coeval. The northern portion of the Polson moraine as defined in this study lacks the stratification found in the southern Polson moraine, suggesting that the former was deposited sub-aerially. Other features suggestive of sub-aerial deposition in the northern portion of the Polson moraine include hummocky topography and massive matrix supported conglomerate. Laminated silt and clay and stratified gravel features observed in the southern Polson moraine suggest sub-aqueous deposition there. I interpret these relationships as recording partial glacial retreat followed by terminal glacial advance during a low stand of Glacial Lake Missoula. Evidence for this retreat and advance cycle can be seen in glacial scour striae as well as water well log data from the northern Polson moraine itself.

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Introduction

The Upper Flathead Valley currently is being developed at a very rapid rate, and considerable need exists to better understand the distribution of glacial and post-glacial sediments, particularly those facies that might serve as aquifers or sources of other economically-valuable commodities such as gravel and sand. In addition, earlier work (Ostenaa et al., 1995; Hofmann et al., 2006) has shown that considerable prehistoric seismicity has impacted the area, yet little is known about the distribution of major structures, including faults, that may represent ongoing seismic risk to the rapidly growing population in this region.

The objective of this project is three fold: 1) map the Belt bedrock stratigraphy on the west side of Flathead Lake in order to establish the relationship between geology exposed onshore and that imaged in offshore geophysical data, particularly as regards the distribution of faults that may represent significant seismic risk; 2) document the distribution of glacial and post-glacial sediments along I-93 between Polson Montana and Big Arm Bay; and 3) use the results of my field and geophysical interpretation work to infer the history of glacial and post-glacial sedimentation and Pleistocene and younger deformation in the study area. The map area for this project extends from Chief Cliff in the north to Polson in the south, and west as far as Loon Lake (Figure 1).

Prior to the landmark papers by Ostenaa et al (1990, 1995), no late Quaternary faults had been documented within the map area, although historic and instrumented seismicity in the study area has long suggested the presence of active faults. Recorded earthquakes are typically relatively small, usually < 5.5 M, and infrequent (Smith and

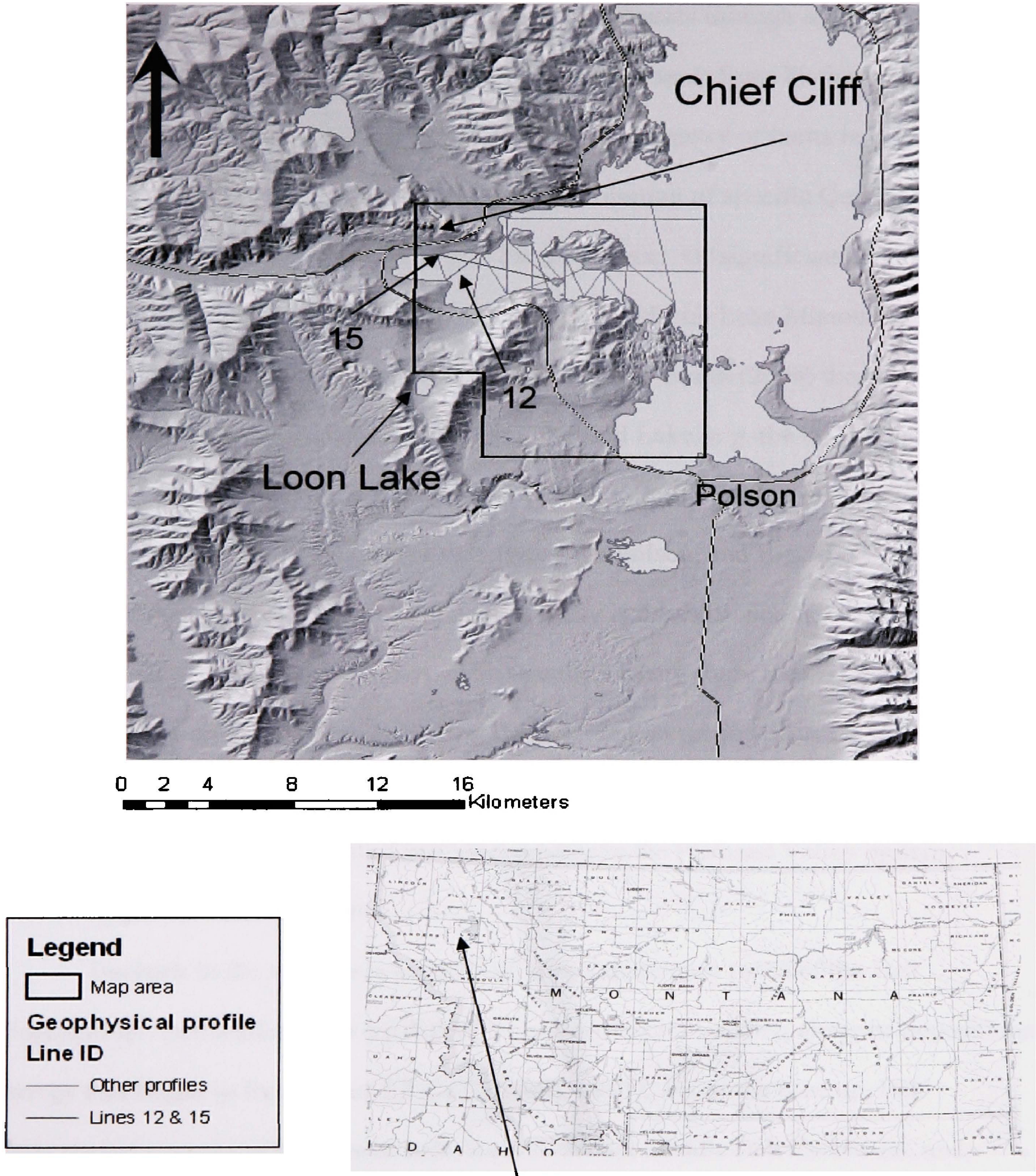


Figure 1
Location of study area.

Arabasz, 1991). Despite the suggestion of fault movements through active seismicity and the imaging of fault-related features in Quaternary sediments from Flathead Lake, very little is known about the specific distribution and the geometry of faults in the map area.

Considerable uncertainty regarding the distribution of specific Quaternary depositional environments remains within the study area. Of significant concern in this regard is the influence that proglacial lakes, including glacial Lake Missoula, may have played during glacial advance and retreat. According to Smith (2004) the till that forms the very conspicuous morainal banks around Flathead Lake (e.g. the Polson moraine) contains definite evidence of sub-aqueous deposition; Smith (2004) also noted a fundamental stratigraphic commonality between the Polson, and Big Arm moraines as well as moraines near Kalispell. That commonality is the existence of lacustrine deposits above, within, and near the moraines. The moraines in my study area north of Polson appear to be much more massive, lacking the stratified lacustrine deposits identified by Smith (2004). Understanding the timing of moraine deposition should help place constraints on the development of pro-glacial lakes in the Flathead Valley system, including glacial Lake Missoula.

Bedrock in the study area consists of metasedimentary rocks of the Belt Supergroup. Belt sediments were deposited in a northwest-trending elongate depositional trough that began to form about 1.5 Ga (O'Neill, 1983). From the base up, Belt Supergroup consists of the Lower Belt, Ravalli Group, Middle Belt Carbonate, and, Missoula Group; only the Ravalli Group and lower Middle Belt Carbonate are exposed in the study area (Winston, 1986). In the study area, the Ravalli group comprises the Burke, Revett, St. Regis, and Empire formations. The Middle Belt Carbonate is represented by the Helena Formation (Winston, 1986).

From Cretaceous through earliest Eocene time the Belt Basin was subject to crustal shortening, followed almost immediately in the middle Eocene by extensional collapse. This extensional deformation formed listric normal faults as well as numerous other normal faults that sole into a reactivated regional detachment (Constenius, 1996). Although extension played a large role in the formation of the study area, map relations suggest it to be relatively devoid of normal faults but instead dominated by strike-slip faults (Figure 1b). One such strike-slip fault trends northwest and is bisected by the east-trending Big Draw fault. LaPoint (1971) suggested that the northwest-trending faults found throughout the Flathead Valley region originated as normal faults. These normal faults were subsequently cut by the east-west trending strike-slip faults (i.e. the Big Draw fault) in the middle Eocene and were later reactivated with a dip-slip component when the major north-south trending normal faults developed (e.g. the Mission fault).

Late Wisconsin glacial Lake Missoula and an ancestral version of Flathead Lake both deposited sediments that are offset by the strike-slip faults in the study area. Sediments in Flathead Lake date at least as far back as 14,150 cal. Yr. B.P., prior to seismic events that produced faults, slump features, and sediment liquefaction imaged on the seismic data from Flathead Lake (Hoffman et al., 2006).

The study area was inundated by the Pleistocene Cordilleran ice sheet which spread over the northern Rocky Mountains between Glacier National Park and the northern Cascade Range (Richmond, 1980; Ward et al, 2004). The Flathead

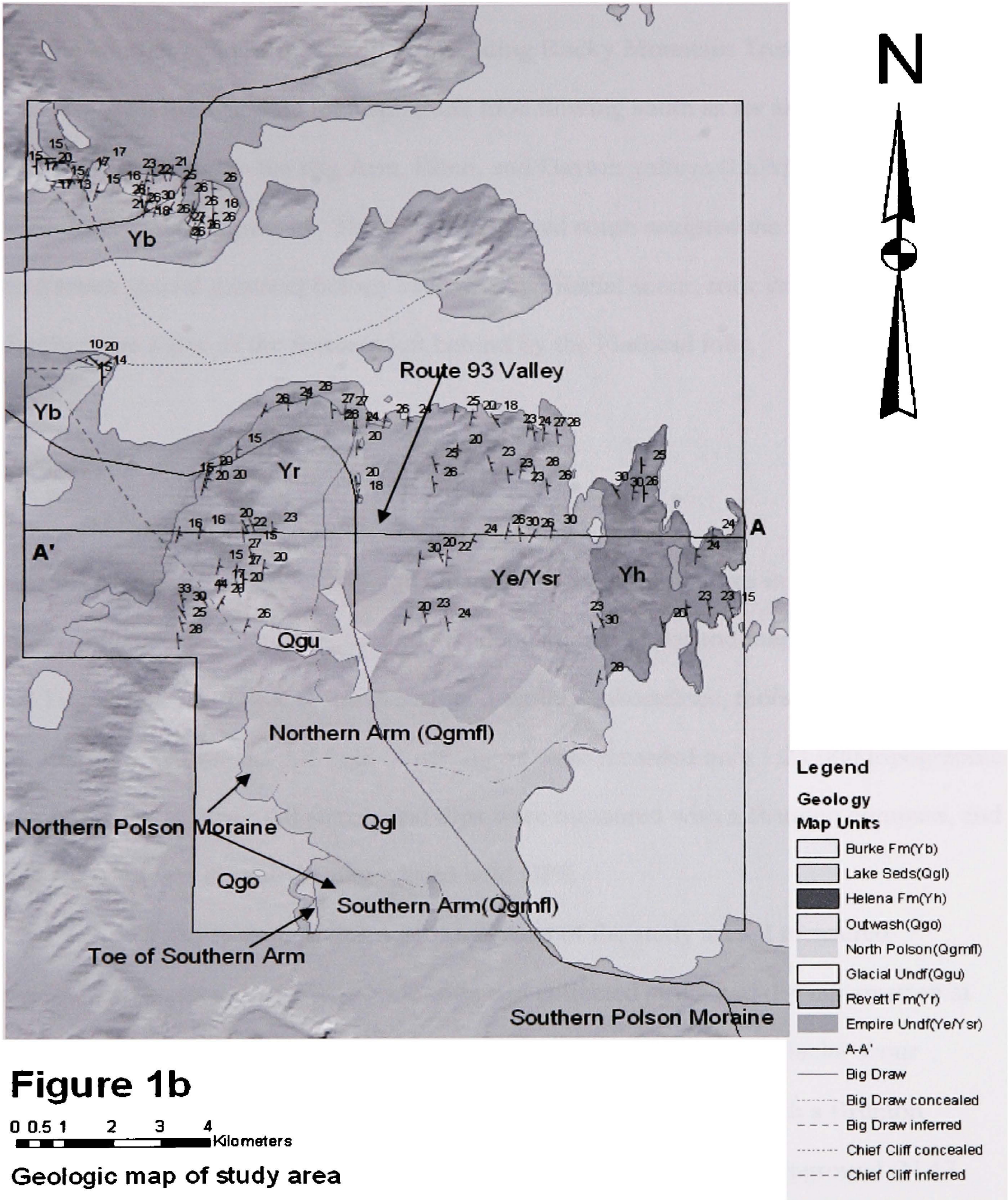


Figure 1b

Geologic map of study area

lobe of the Cordilleran Ice Sheet flowed south down the Flathead Valley which is located near the southern end of the northwest trending Rocky Mountain Trench (Smith, 2004). Near Big Arm the Flathead lobe split, one lobe flowing south as far as Polson and one lobe flowing west into the Big Arm, Elmo, and Dayton valleys (LaPoint, 1971; Bondurant, 2005)(Figure 2). The lobe that moved south sculpted the study area, forming the distinct glacial geomorphology seen today. Glacial scour, rock drumlins and moraines are a few of the features left behind by the Flathead lobe.

1. Methods

A) *Field Methods:*

I mapped pre-Quaternary and Quaternary geologic features in the study area by conducting traverses across structural and depositional strike and mapping the features that I encountered. These features included terraces, shorelines, moraines, scour marks, till, and lake sediments. All field observations were recorded on a 1:24,000 topographic map of the study area. All strikes and dips were measured with a Brunton compass, and each location was recorded using a hand held GPS.

In addition to completing a geologic map of the study area, I measured stratigraphic sections of various rock units and collected strike and dip information at outcrops throughout the study area. I also conducted an analysis of glacial scour orientations by measuring and recording 75 different scour marks with a Brunton compass on an exposed, east facing bedrock hill above the KOA campground (N 47 degrees 42.444 minutes W 114 degrees 14.225 minutes). Throughout the map area, I

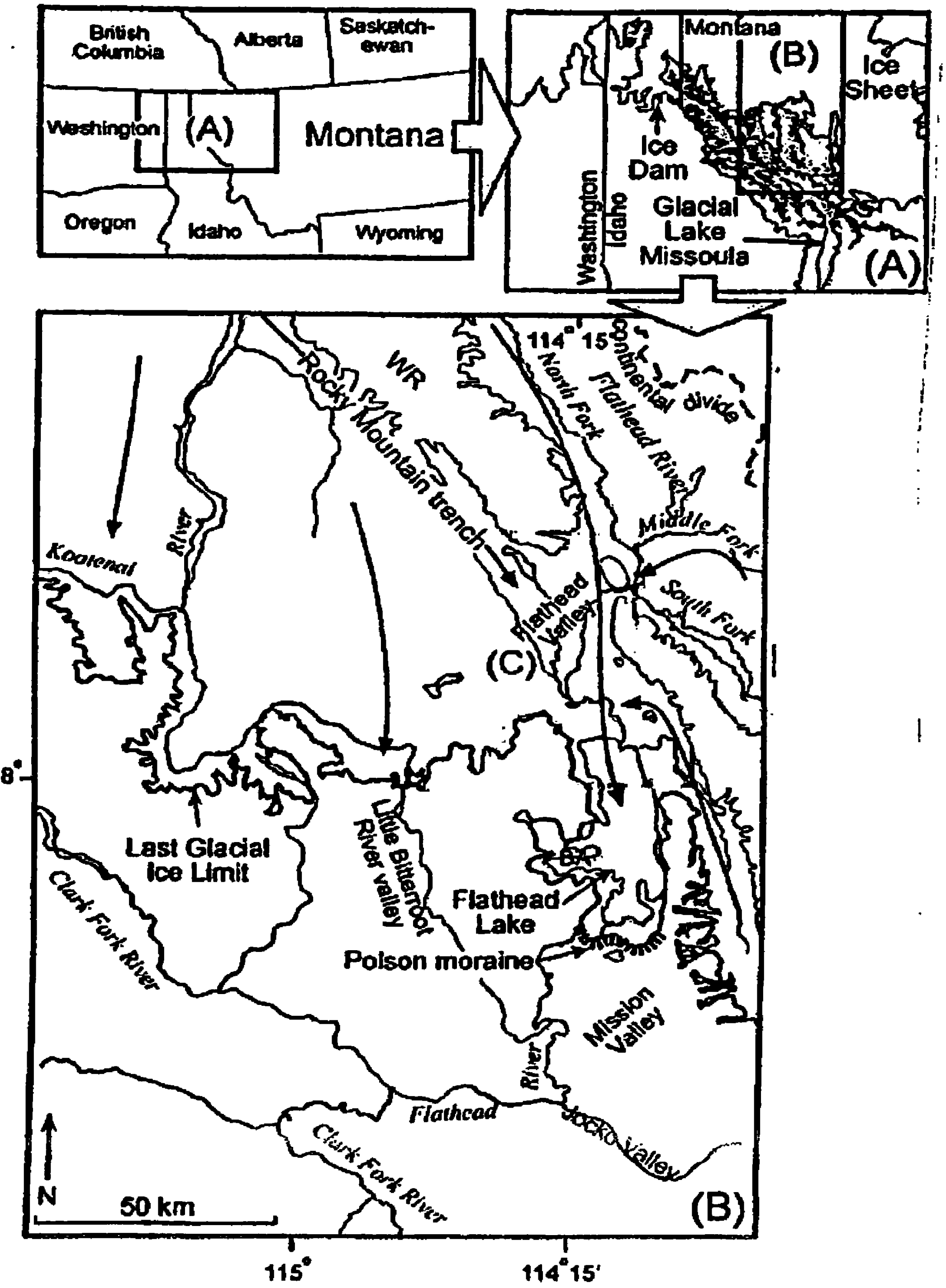


Figure 2
Southern extent of Cordilleran ice sheet in western North America. Shown here is the Polson moraine before small recessional and re-advance phase. Northern Polson moraine in study area not pictured.

measured stratigraphic sections that represent the different Pre-Quaternary stratigraphic units present; the Burke, Revett, St. Regis, and Empire Formations of the Ravalli Group, and the Helena Formation of the lower Middle Belt Carbonate. Measured sections range in length from 6 to 8 meters, depending upon the size and accessibility of the outcrop, and record detailed observations at centimeter scale.

I completed five measured sections of Quaternary sediments, in order to provide a basis for the recognition of facies differences across the map area. I also utilized a 30-meter DEM of the area to refine my mapping, and I revisited sites that needed further attention. Finally, I collected lithology data from water wells drilled throughout my study area in order to define intra-moraine stratigraphy and sedimentology and determine depth to bedrock. I obtained lithology well data from the Montana Bureau of Mines and Geology website (http://www.mbmg.mtech.edu/). In order to determine if water well stratigraphy showed any commonality among wells I assigned different colors to clay, sand, and gravel and performed a simple visual analysis of the color patterns.

(B) *Subsurface analysis:*

Seismic data collected from Flathead Lake by Wold (1982) and analyzed by Hofmann (2006) formed the basis for mapping faults that cut Quaternary and older strata in the lake bottom. Much of the seismic data collected in and around Big Arm Bay does show the presence of a fault so this data was analyzed most closely. Lines 12 and 15 (Figure 1) are the most important lines in this regard. Following onshore and offshore work, the correlation of the two sets of faults was assessed.

Results

A) *Stratigraphy and Sedimentology of Map Units:*

1. Burke Formation

The western edge of the study area is underlain by the Burke Formation, the lowermost member of the Ravalli Group and the oldest stratigraphic unit in the area (Figure 3a). Measuring a section of this unit was hindered by the surface trace of the Big Draw Fault which deformed the outcrop I studied. The outcrop alternates between light green and dark gray microlaminated siltstone. Microlaminae are highlighted by siderite grains along the bedding planes (Figure 3b &c). The microlamina seem to be wavy which may be the result of soft-sediment deformation or sub-aqueous currents. Other diagnostic characteristics of the Burke include the presence of abundant centimeter-scale cubes of pyrite now replaced by iron oxide.

Winston (1986) characterized the Burke as sea-margin-flat and distal-alluvial-apron sediments that prograded into the Belt basin over sub-wave base sediments of the Prichard Formation. The braided stream and sheet flood deposits pass northward to horizontally laminated sheet flood deposits of the distal part of the alluvial apron, where subaerial and subaqueous siltite and argillite deposited on sea margin flats become interstratified with quartzites (Mauk, 1983).

2. Revett Formation

Conformably on top of the Burke is the second oldest member of the Ravalli Group, the Revett Formation. Revett strata in the area consist of fine-grained, well-rounded, well-sorted, gray sandstone with little internal variation (Figure 4a &b).

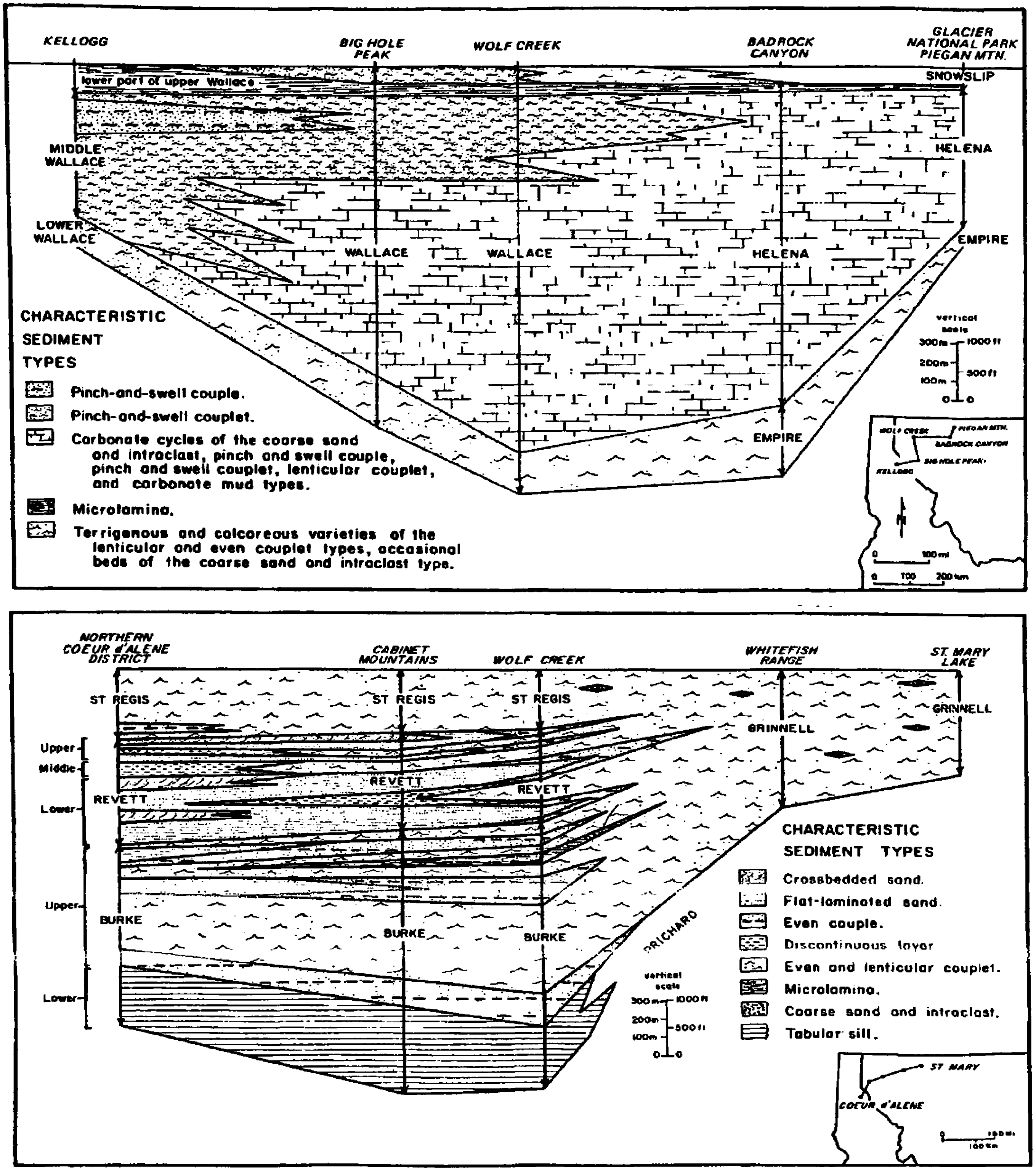


Figure 3a
Generalized cross section of the Ravalli Group and Middle Belt Carbonate. The Empire Formation, currently a member of the Ravalli Group, is included in the Middle Belt Carbonate diagram as the lateral facies of the Wallace Formation (Winston, 1983)

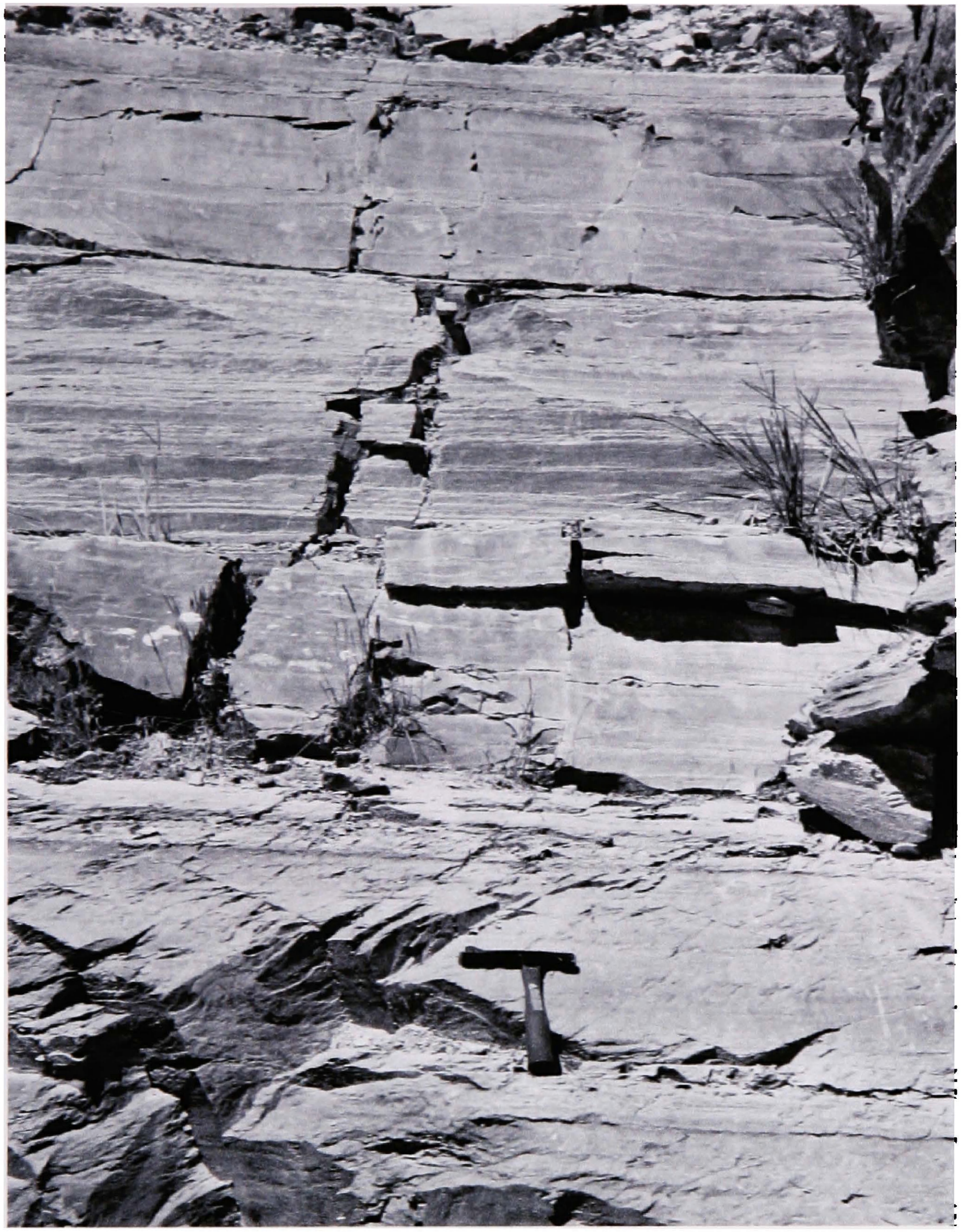


Figure 3b
Burke Formation; hammer rests on lower portion of outcrop where slickensides associated with the Big Draw fault tend to obscure bedding. The upper portion of the outcrop has fewer slickensides and the bedding is much more evident.

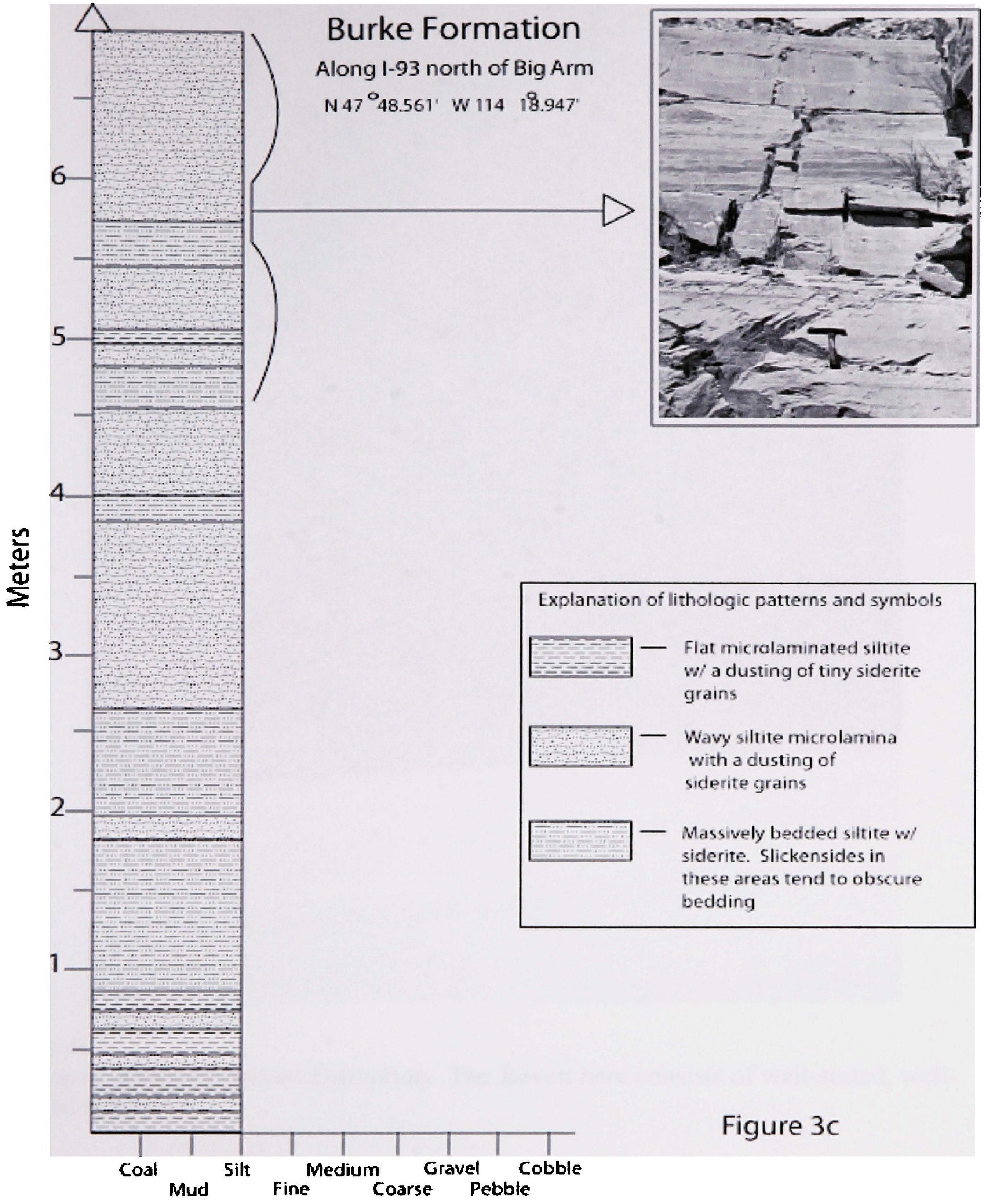

Burke Formation
Along I-93 north of Big Arm
N 47°48.561' W 114° 18.947'
Meters
6
5
4
3
2
1
Coal
Mud
Silt
Fine
Medium
Coarse
Gravel
Pebble
Cobble
Explanation of lithologic patterns and symbols
Flat microlaminated siltite w/ a dusting of tiny siderite grains
Wavy siltite microlamina with a dusting of siderite grains
Massively bedded siltite w/ siderite. Slickensides in these areas tend to obscure bedding

Figure 3c

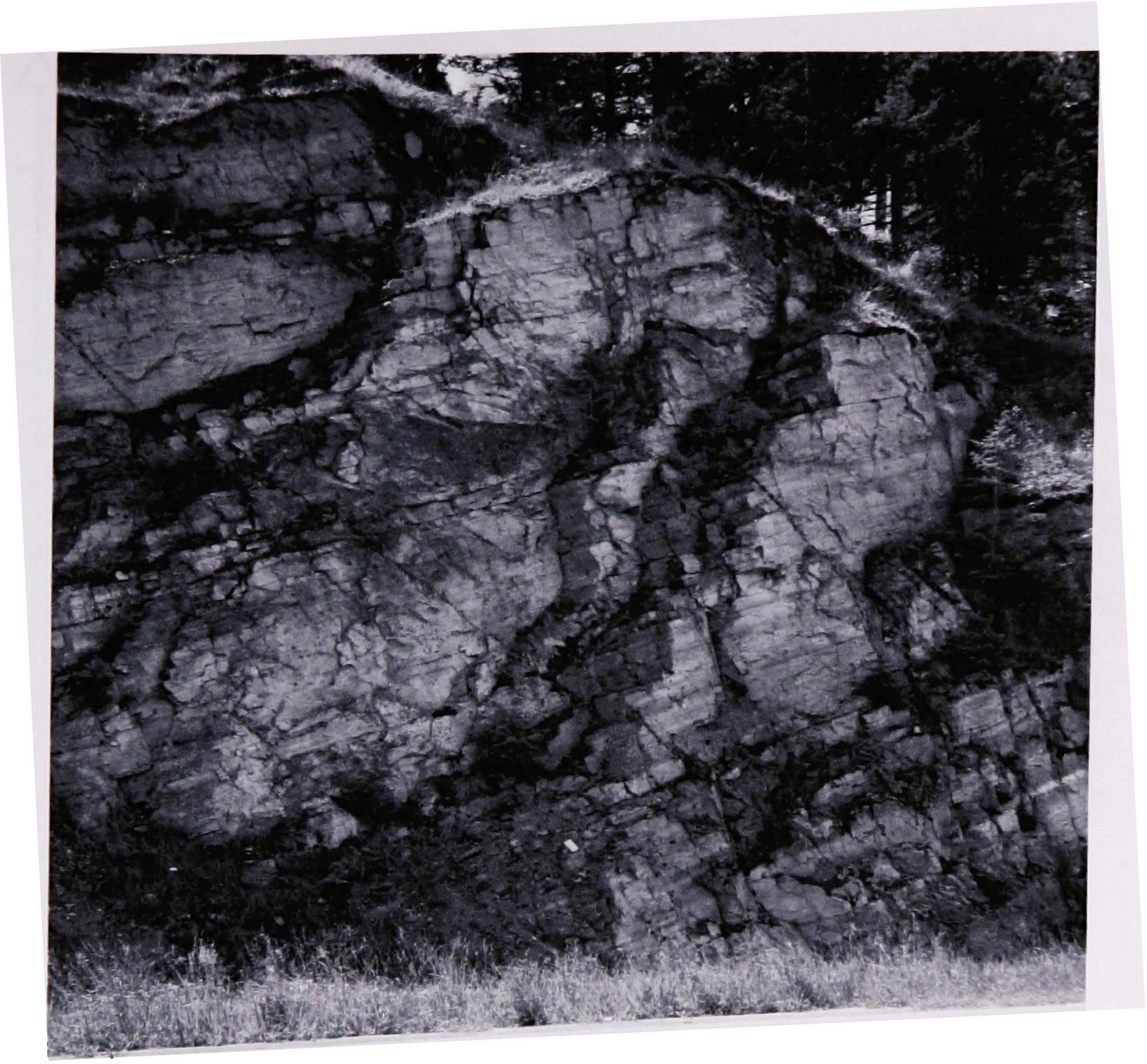


Figure 4a
Outcrop of measured Revett Formation. The Revett here consists of well-sorted, well-rounded sandstone.

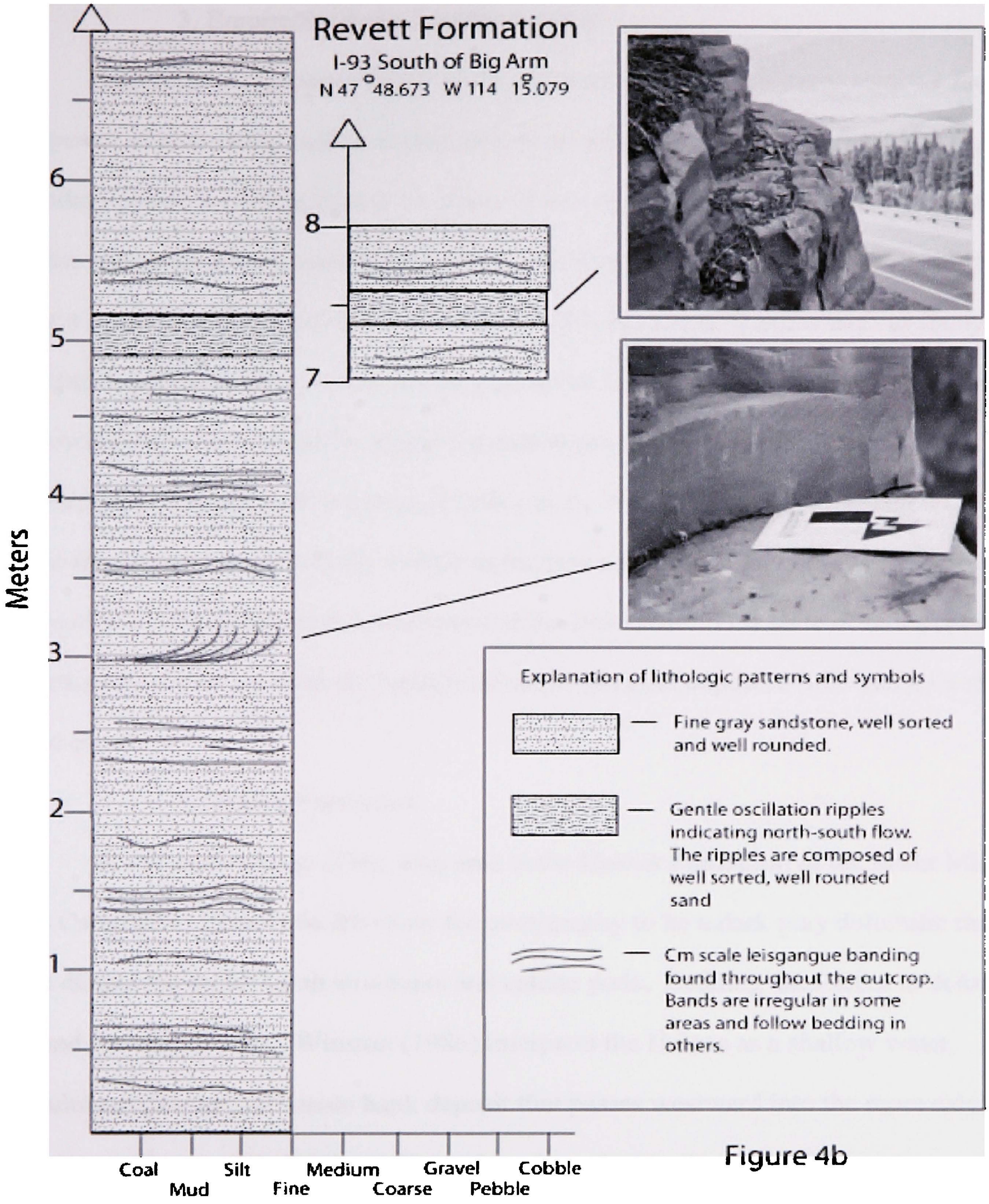

Revett Formation
I-93 South of Big Arm
N 47 °48.673 W 114 15.079
Meters
1
2
3
4
5
6
7
8
Coal
Mud
Silt
Fine
Medium
Coarse
Gravel
Pebble
Cobble
Explanation of lithologic patterns and symbols
Fine gray sandstone, well sorted and well rounded.
Gentle oscillation ripples indicating north-south flow. The ripples are composed of well sorted, well rounded sand
Cm scale leisgangue banding found throughout the outcrop. Bands are irregular in some areas and follow bedding in others.

Figure 4b

3. Empire/St. Regis Undifferentiated

Empire/St. Regis strata in the study area consist of red and green argillite that is composed of alternating light and dark microlamina 1 to 5 cm thick (Figure 5a &b), and abundant calcite pods that tend to be about 10 cm long and 5 cm wide. Sedimentary lamina appear to deform around the calcite pods suggesting that the pods were lithified prior to significant compaction. Soft-sediment deformational features such as flame structures and mudcracks are pervasive and can be found throughout the entire formation. Following deposition of the St. Regis Formation prolonged basin subsidence led to deposition of the Empire Formation (Connor et al, 1983). According to Winston (1986), wave-rippled surfaces generally overlie more desiccated surfaces within the Empire Formation of the eastern and central parts of the Belt basin. This suite of sedimentary structures is consistent with the interpretation of subaerial exposure followed by a sheet flood event.

4. Helena Formation

At the eastern edge of the map area is the Helena Formation of the lower Middle Belt Carbonate. Figures 6a &b show the stratigraphy to be a dark gray dolomitic mud with diagnostic molar-tooth structures and calcite pods. Bedding does seem to deform around the calcite pods. Winston (1986) interprets the Helena as a shallow water, turbulent, dolomitic carbonate bank deposit that passes westward into the more calcitic terrigenous facies of the Wallace Formation, deposited in the deep basin center.

5. Quaternary Facies 1

Just north of Polson, a large arcuate feature sweeps from the Flathead River to the

Figure 5a
Overview of Empire formation shows well-developed stratigraphic layering; white quartzite layer on extreme upper-right-hand portion of outcrop. Empire contains desiccation cracks and calcite pods.

Empire Formation

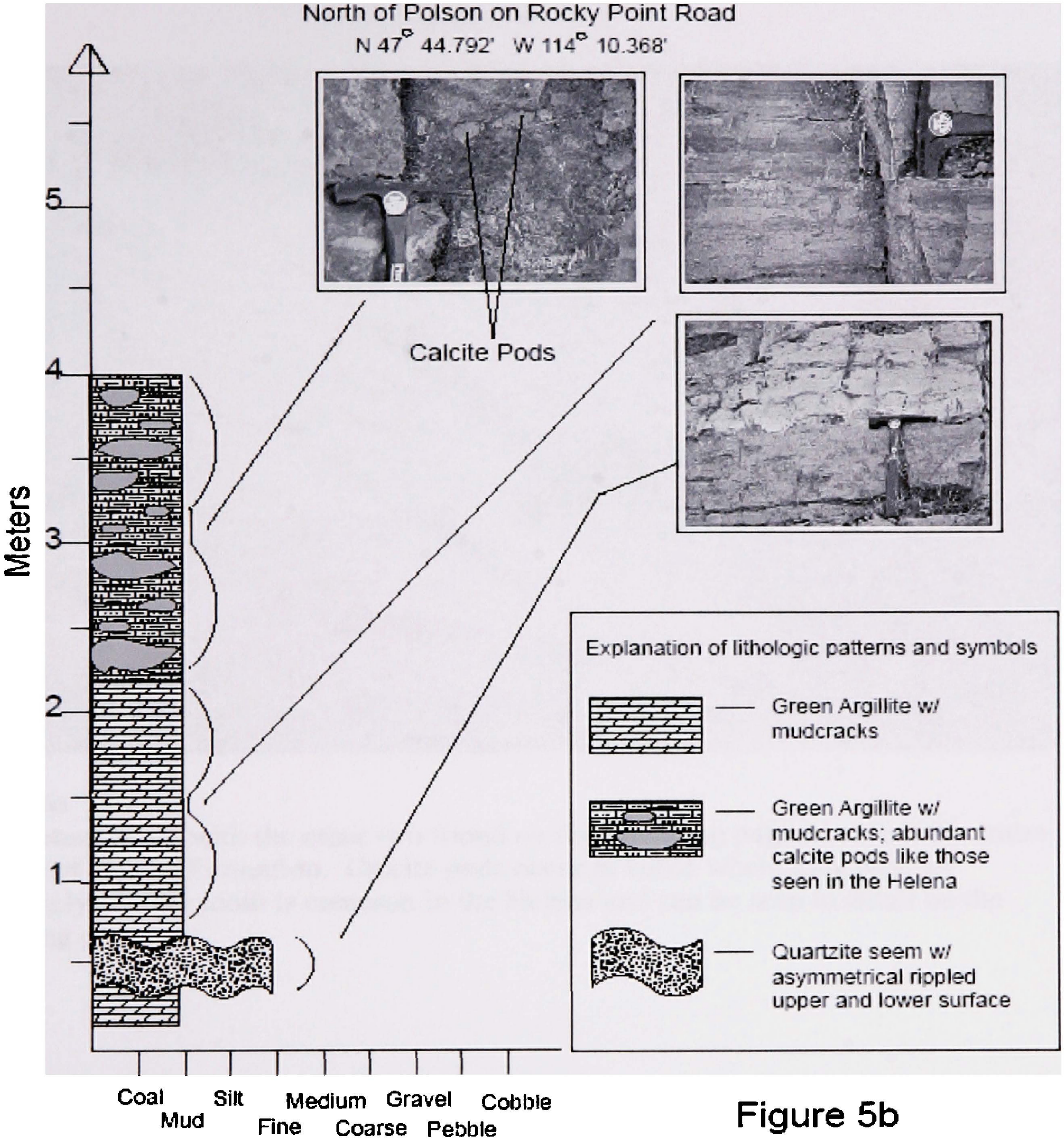


Figure 5b

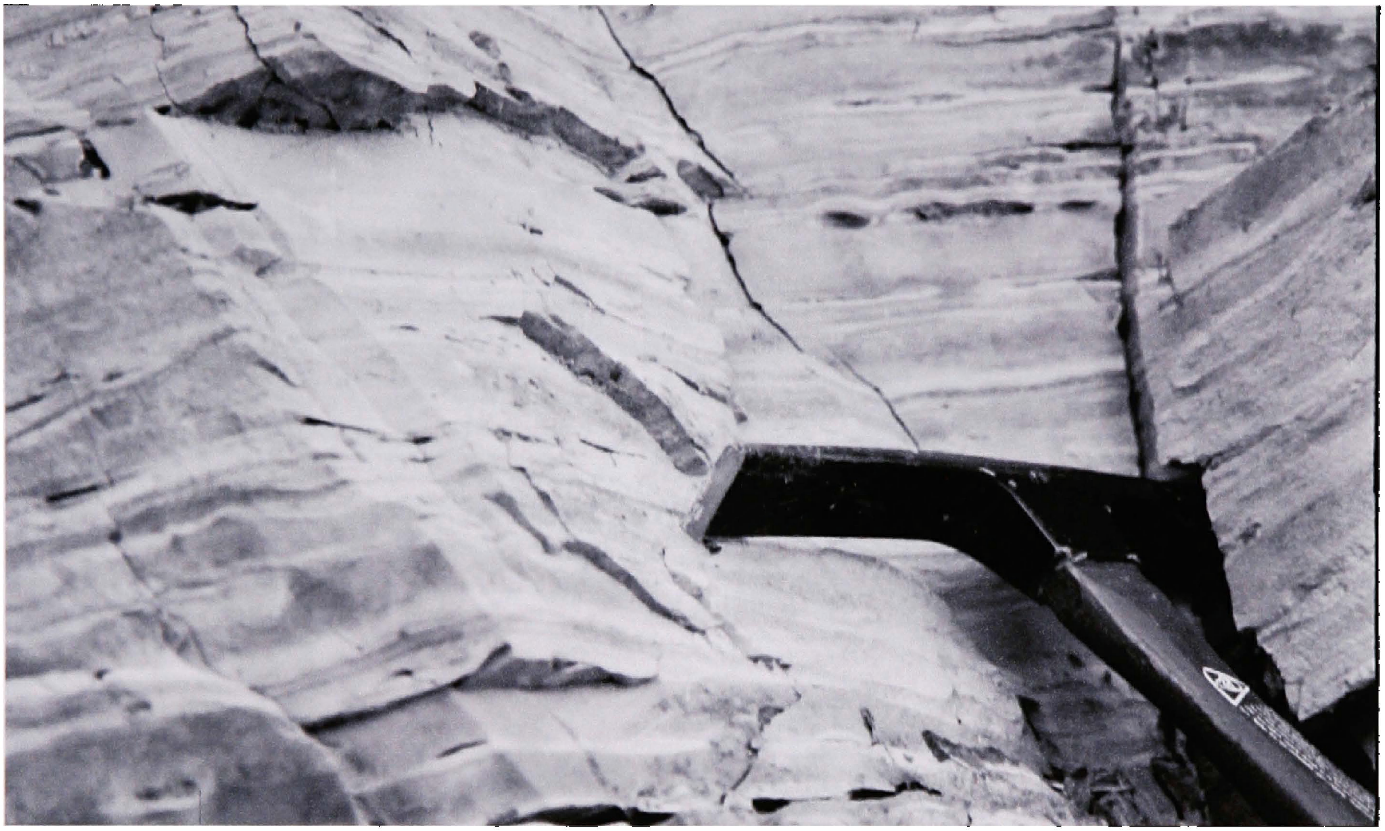


Figure 6a
This picture along with the other two found on the following page represent the entire outcrop of Helena Formation. Calcite pods occur in zones where they weather recessively. Molar tooth is common in the Helena and can be seen in detail on the following page.

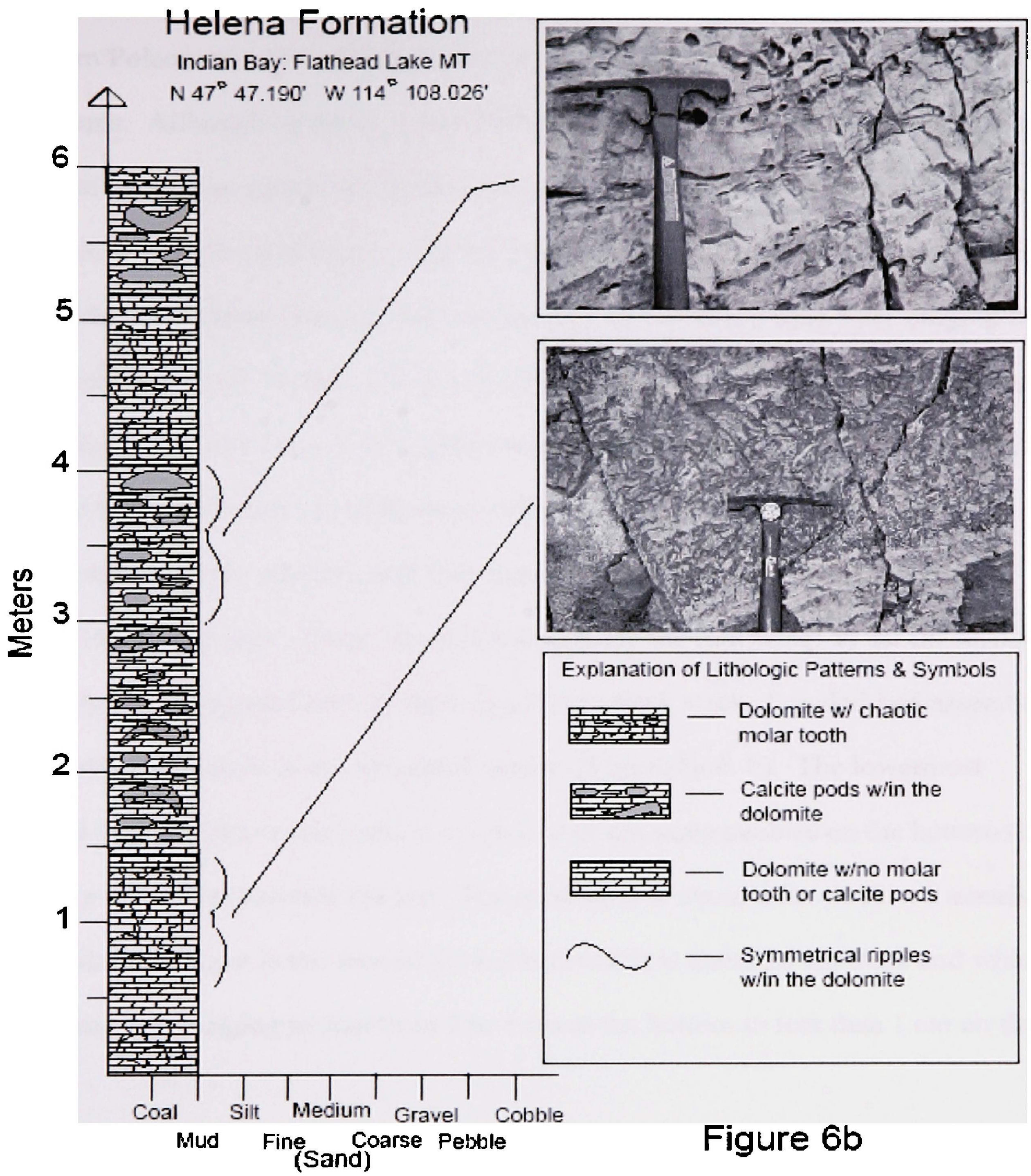

Helena Formation
Indian Bay: Flathead Lake MT
N 47° 47.190' W 114° 108.026'
Meters
6
5
4
3
2
1
Coal
Mud
Silt
Fine
Medium
(Sand)
Coarse
Gravel
Pebble
Cobble
Explanation of Lithologic Patterns & Symbols
Dolomite w/ chaotic molar tooth
Calcite pods w/in the dolomite
Dolomite w/no molar tooth or calcite pods
Symmetrical ripples w/in the dolomite

Figure 6b

bedrock ridge on the north side of the valley (Figure 1b). Hereafter this moraine is termed the northern Polson moraine, and the two arms of this moraine are the southern and northern arms. Although bedrock 'spurs' define part of the southern arm, the occurrence of glacial till as well as glacial erosional features on the spurs themselves suggest that the arcuate feature is a glacial moraine. The till along the southern margin of the moraine is dominated by light brown clay, is matrix supported, and contains clast sizes ranging from gravel to cobble (Figure 7a &b). There are apparently no sedimentary structures here, but the till is more clay-rich than on either the northern arm or other moraines in the area, such as the Route 93 valley moraine discussed below.

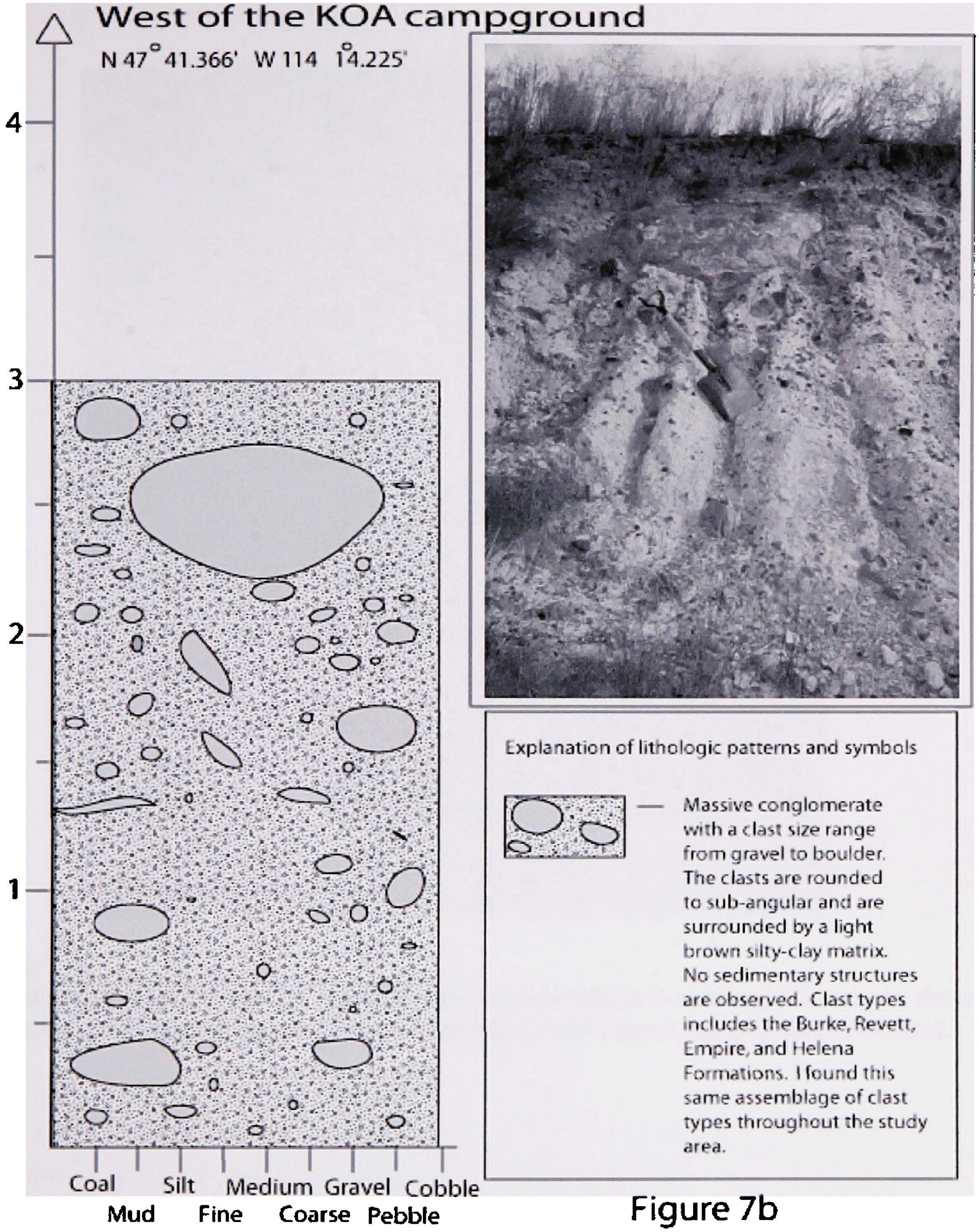
At the toe of the southern arm I observed features that I did not encounter elsewhere in my map area. These observations include the following: 1) the till seems to be generally clast supported and, 2) there is a 30-cm thick stacked graded-bed assemblage located at the 2.3 m mark in the measured section (Figure 8a & b). The lowermost graded bed is about 10 cm thick and is composed of cm scale pebbles on the bottom that grade into a sand layer towards the top. The sand layer is about 6 cm thick and massive. On top of the sand layer is the second graded bed which is about 20 cm thick and which grades from clasts ranging in size from 3 to 5 cm at the bottom to less than 1 cm on the top.

The north arm of the Polson Moraine is similar to the south arm in that the till is chaotic and seems to lack sedimentary structures. Clasts in the southern arm make up about 40% of the till and clearly are in matrix support. Along the northern arm the clasts comprise about 60% or more of the till and are also in matrix support. Clast sizes range

Figure 7a

Chaotic till at the top of southern arm of north Polson moraine. I infer that this till was deposited in a subaerial setting, based on absence of lacustrine deposits within and on top of till as well as characteristic hummocky topography.

Southern Arm of the Northern Polson Moraine



Explanation of lithologic patterns and symbols

— Massive conglomerate with a clast size range from gravel to boulder. The clasts are rounded to sub-angular and are surrounded by a light brown silty-clay matrix. No sedimentary structures are observed. Clast types includes the Burke, Revett, Empire, and Helena Formations. I found this same assemblage of clast types throughout the study area.

Figure 7b

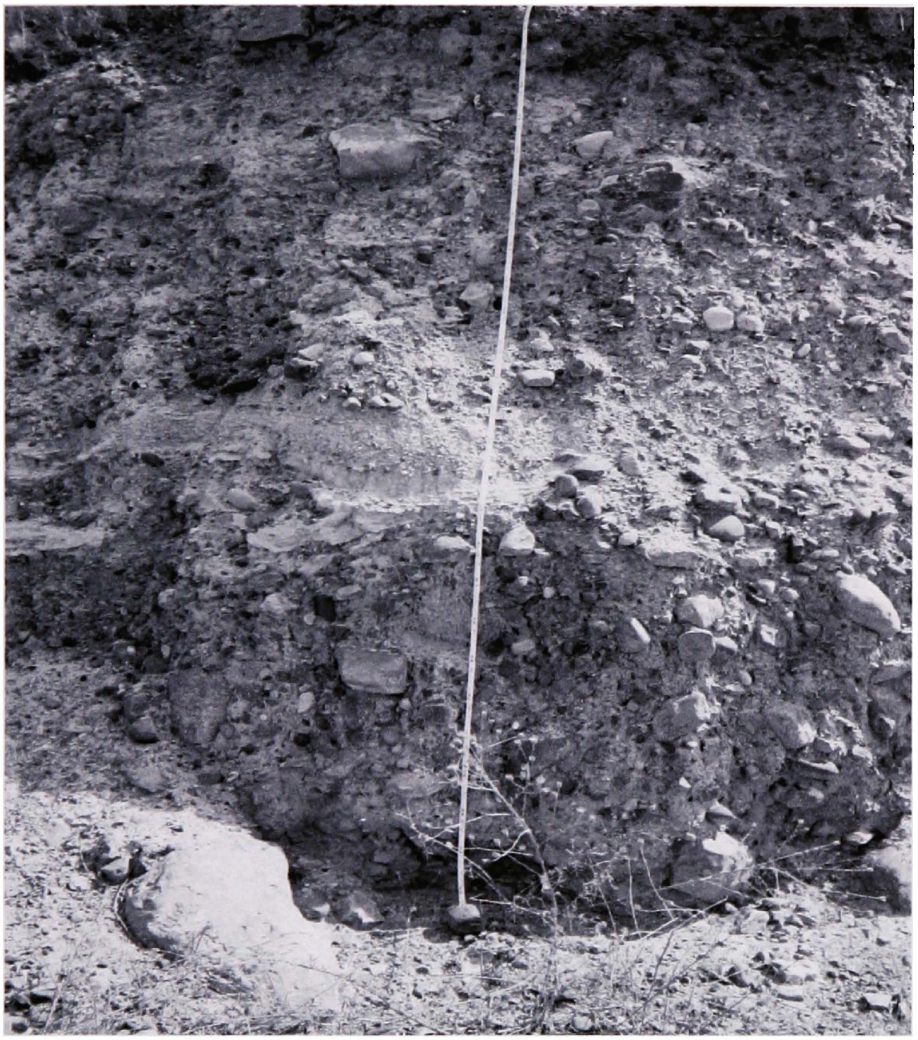


Figure 8a
Measured section of Figure 8b. Note break in clast-supported conglomerate in the center of the photo. The fine-grained strata within the break consist of pebbles and sand.

Toe from the southern arm of the northern Polson Moraine

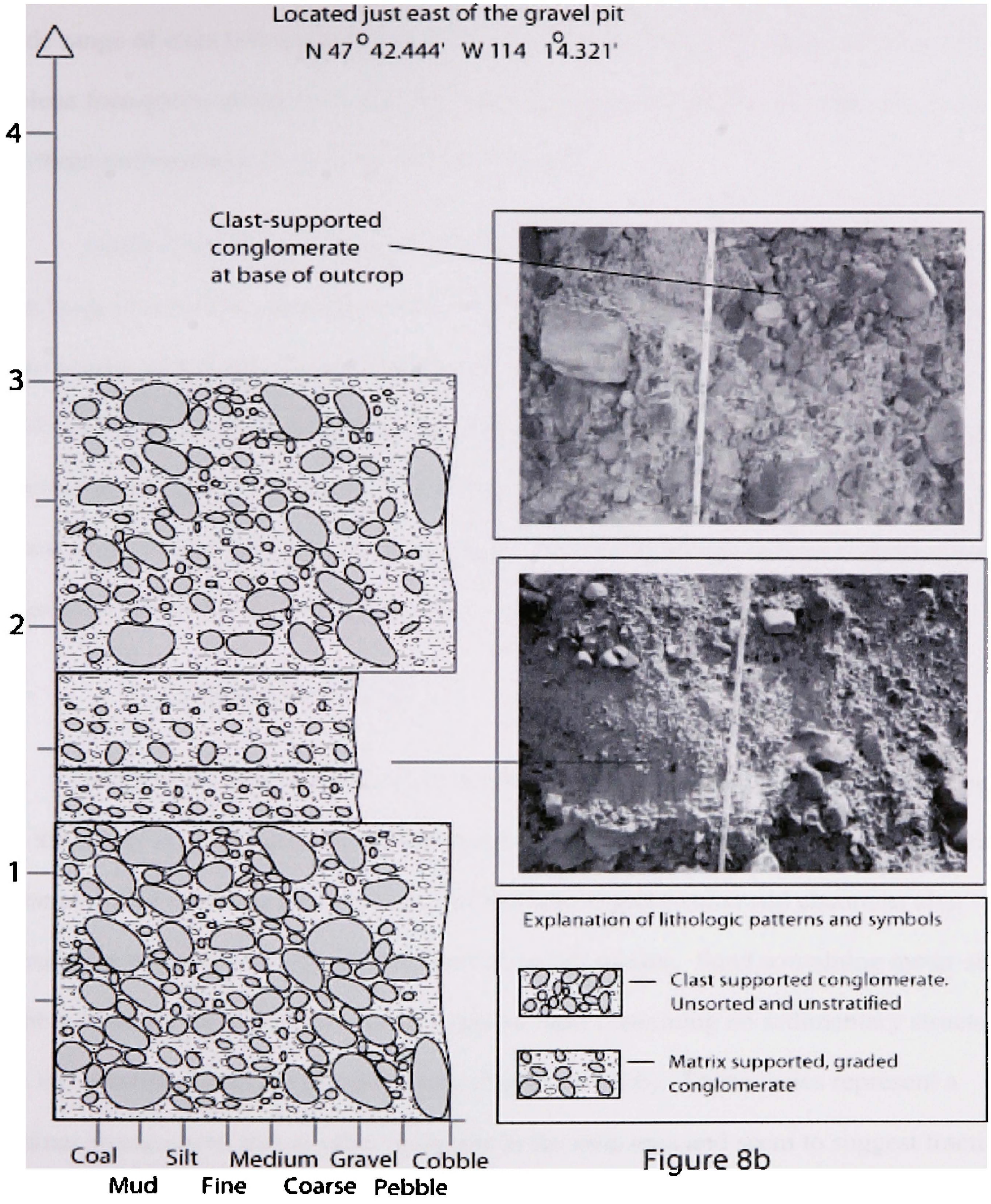


Figure 8b

from gravel to boulder; some clasts are rounded while others are angular, and there is a wide range of clast lithologies (Figure 9). The Burke, Revett, St. Regis, Empire, and Helena formations all appear to be represented in clast assemblages observed in both the northern and southern arms of the Polson moraine.

North of the Polson moraine, Route 93 passes through a 300-meter wide corridor that leads to a narrow, glaciated valley. Till is present in road cuts along Route 93 and is very similar to that found on the north arm of the Polson moraine in the study area. This till is unsorted and unstratified and generally is devoid of sedimentary structures. It is in matrix support and is comprised of rounded to sub-angular, striated clasts that make up about 60 to 70% of the unit. Clast type is the same as mentioned above (Figure 10a &b). Figure 1b shows the location of this till.

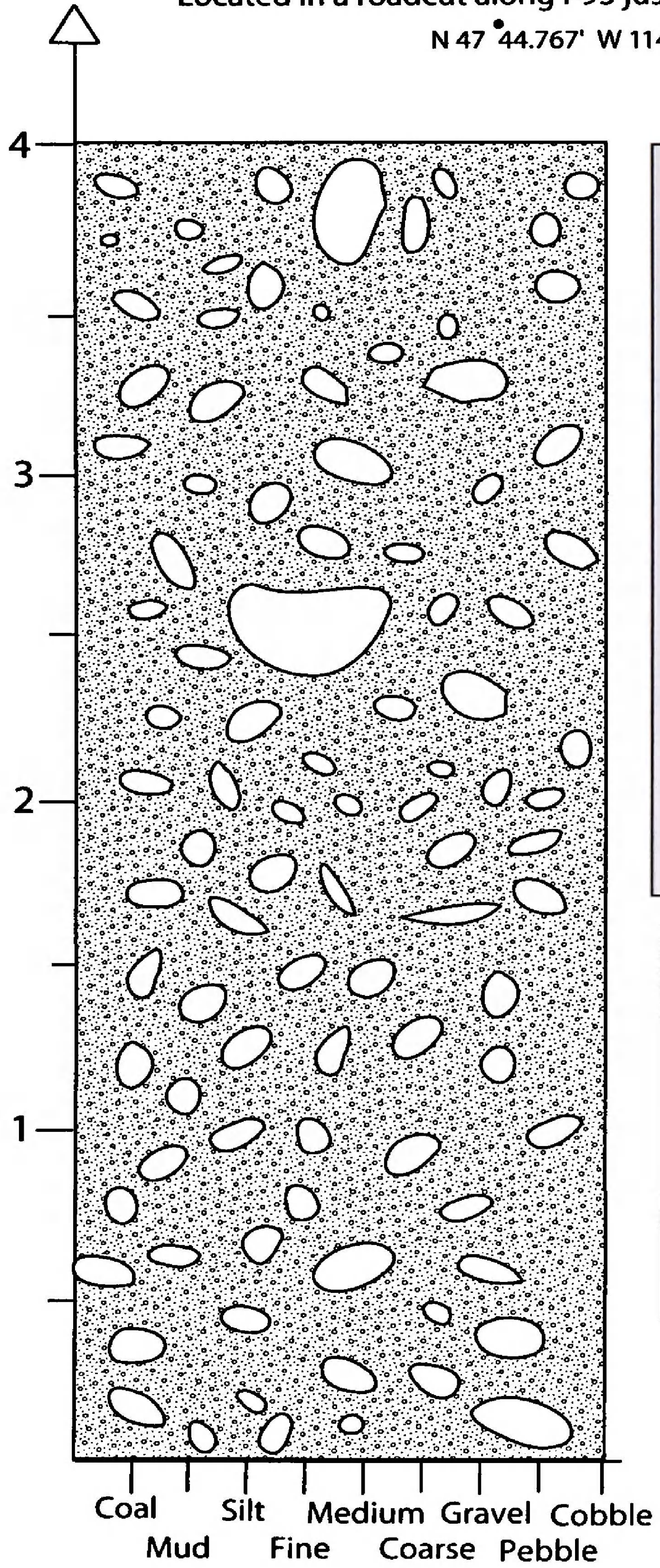
6. Quaternary Facies 2

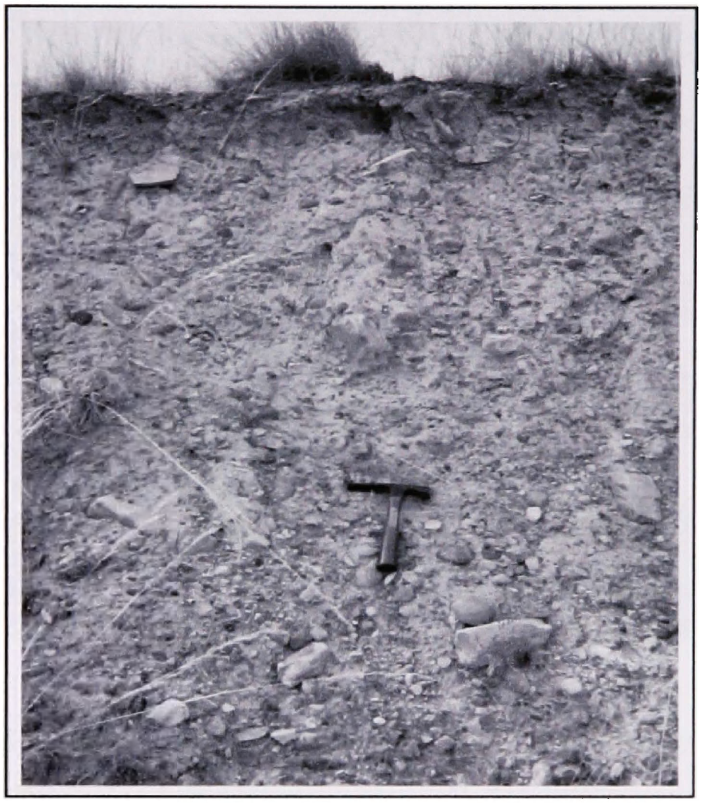
West of the northern arm of the northern Polson moraine, a large gravel pit occurs on the valley floor. Exposures within the gravel pit on the valley floor contain several generations of climbing ripples, gravel cross beds, ripple marks, and channels; also present are massive, clast-supported beds of conglomerate. Sand containing meter-scale cobble-mantled cross-beds as well as massive sand containing no sedimentary structures are interstratified with the conglomerate (Figure 11a &b). These facies represent a distinct change from that at other locations in the map area and seem to suggest traction-transport deposition in a sub-aqueous setting.

North arm of the northern extension of the Polson moraine

Located in a roadcut along I-93 just south of the Country Store

N 47°44.767' W 114°13.785'





Explanation of lithologic patterns and symbols

▨ — Massive poorly sorted matrix supported conglomerate with a range in clast size from gravel boulder. Matrix is composed of a light brown silty-clay. Clasts, rounded to sub-angular, comprise about 60% of the conglomerate.

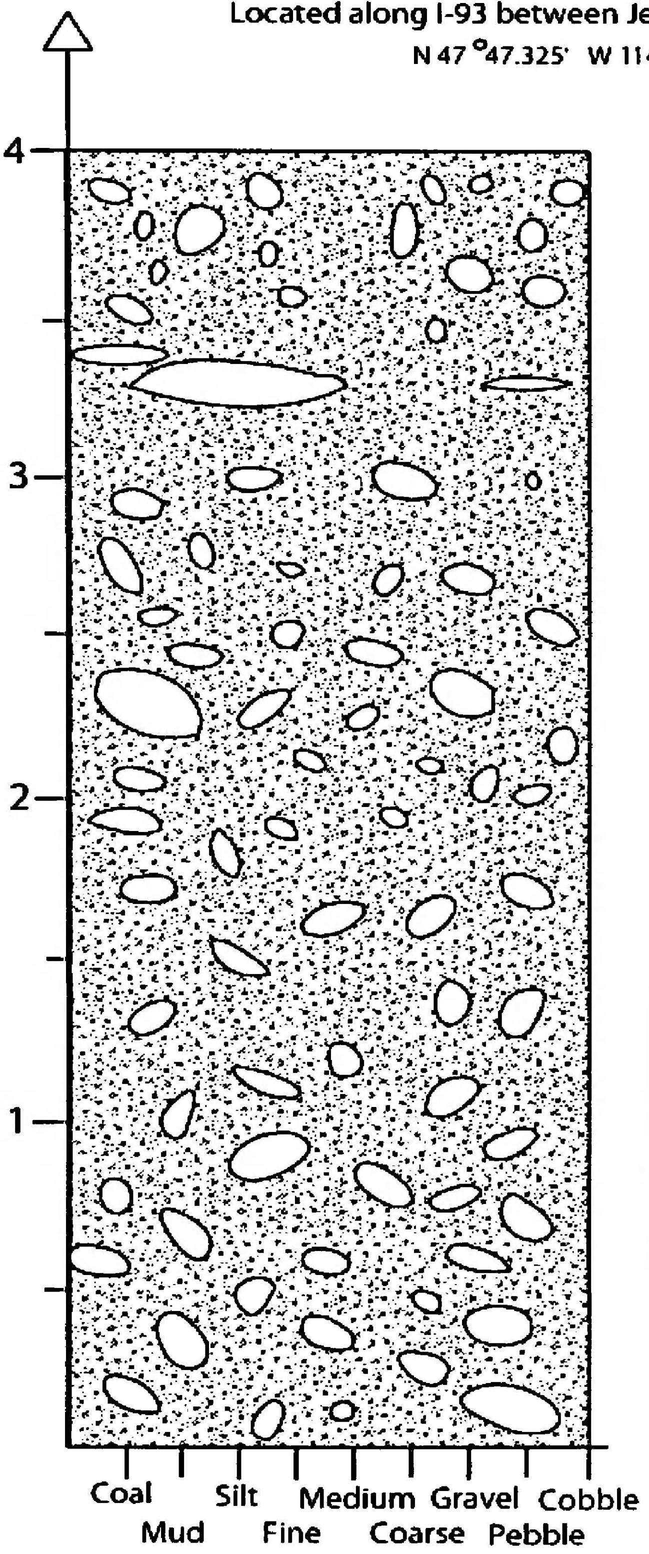
Figure 9

Figure 10a
Measured section of Route 93 valley moraine. Moraine is massive and lacks sedimentary structures. Wide variety of clast lithologies match clast lithologies of other moraines. This observation suggests that the cirque in Jette Lake area was not the source of the conglomerate, because if it were, the moraine in this photograph would consist mainly of clasts from the Revett Formation.

Route 93 Valley Moraine

Located along I-93 between Jette Lake and Big Arm

N 47 °47.325' W 114 1°4.383'



Explanation of lithologic patterns and symbols

▨ — Massive matrix supported conglomerate with a range in clast size from gravel to boulder and a matrix comprised of a light brown silty clay. Clasts are rounded to sub-angular.

Figure 10b

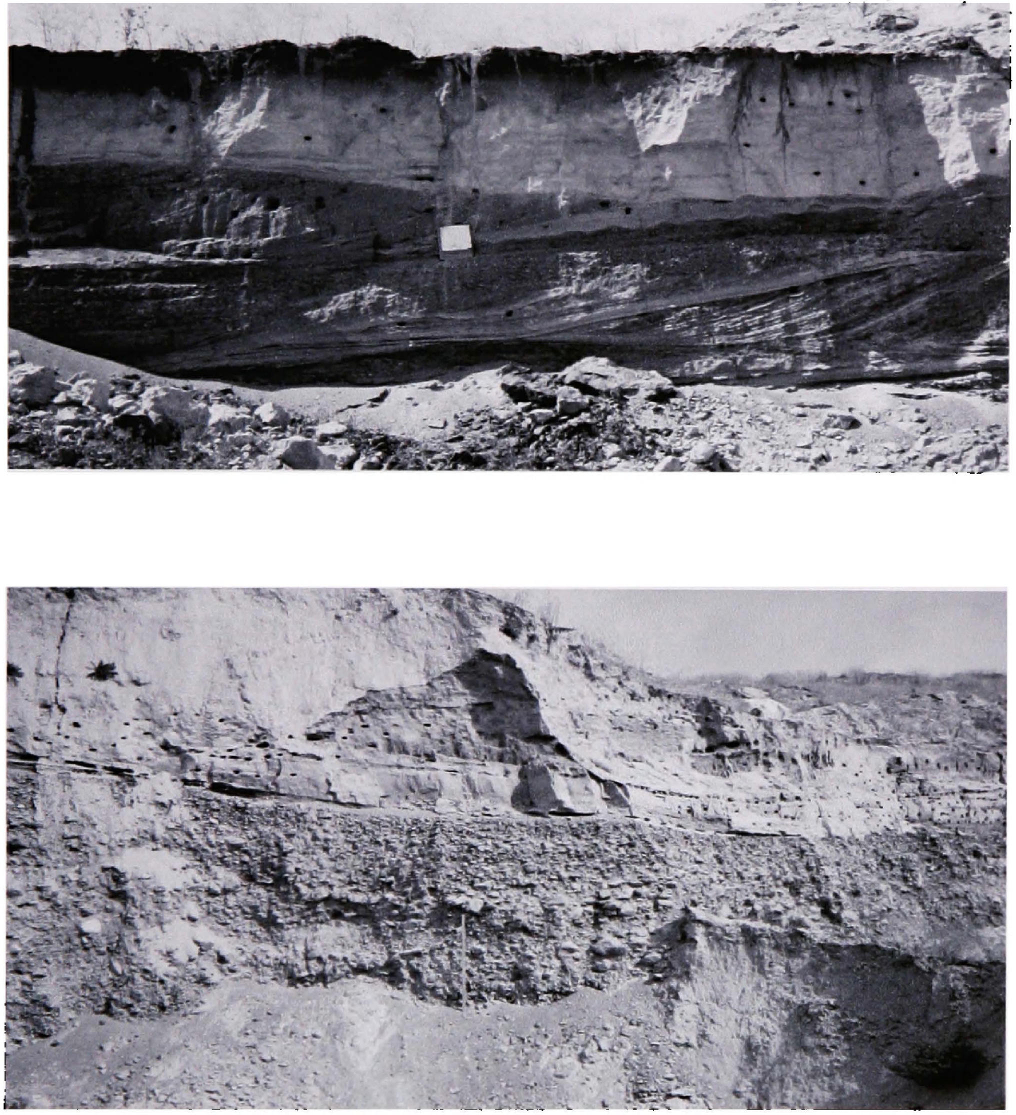


Figure 11a
Two photographs taken from gravel pit (just west of southern arm) showing diversity of structures and grain sizes of outwash. Upper photograph represents measured section. Map board for scale. The lower photograph is from opposite wall of gravel pit, about 20 meters from measured section. Two meter long wooden pole in center of outcrop for scale.

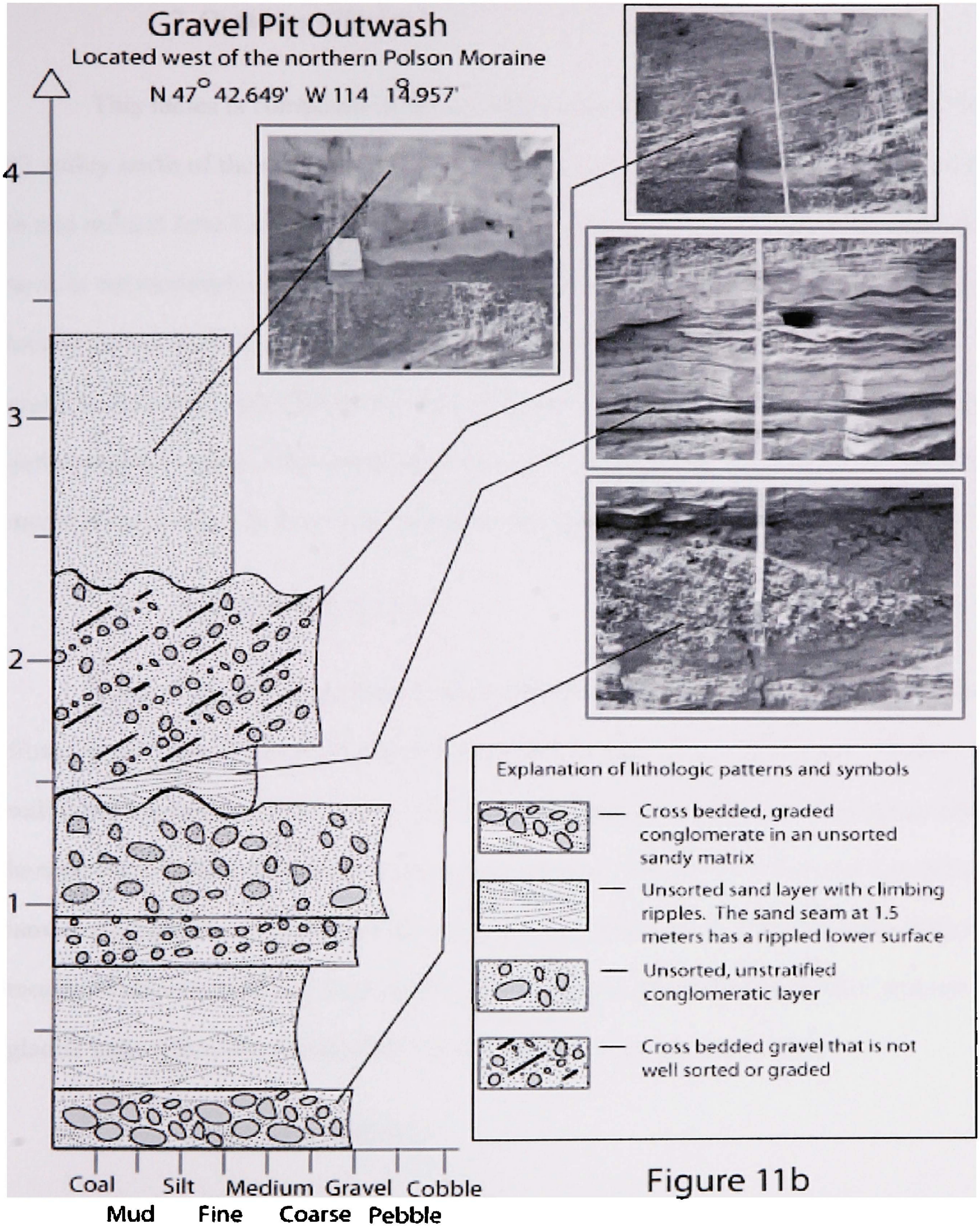

Gravel Pit Outwash
Located west of the northern Polson Moraine
N 47° 42.649' W 114 1°4.957'
4
3
2
1
Coal
Mud
Silt
Fine
Medium
Coarse
Gravel
Pebble
Cobble
Explanation of lithologic patterns and symbols
— Cross bedded, graded conglomerate in an unsorted sandy matrix
— Unsorted sand layer with climbing ripples. The sand seam at 1.5 meters has a rippled lower surface
— Unsorted, unstratified conglomeratic layer
— Cross bedded gravel that is not well sorted or graded

Figure 11b

7. Quaternary Facies 3

This facies is composed of the undifferentiated Quaternary sediment in the Route 93 valley north of the northern Polson moraine, as well as the Quaternary sediment found in and around Jette Lake (Figure 12). This sediment contains the same clast assemblage seen in the moraines of the study area but is loosely scattered on the surface and only locally forms mounds about 3 to 4 meters tall and 5 or 6 meters in diameter. The mounds, however, occur along the side of Route 93 and therefore I cannot rule out an anthropogenic origin. This material does not lend itself to the production of a detailed measured section; it is, however, prevalent enough to warrant its own distinct facies.

8. Quaternary Facies 4

East of the two arms of the northern Polson moraine are lake sediments either from glacial Lake Missoula or from an ancestral version of Flathead Lake. These sediments are composed of alternating layers of light and dark brown centimeter-scale lamina with distinct centimeter-scale dropstones that deform the otherwise flat-lying lamina (Figure 13). The distinct absence of these lamina west of the northern Polson moraine indicates that they may be the result of the ancestral Flathead Lake and not glacial Lake Missoula which likely would have covered the entire area.

9. Glacial Landforms

Other glacial-related features in the map include distinct terraces at an elevation of 1,066 meters, and rock-sculpted features known as rock drumlins or whale backs (refer

Figure 12
Example of sediment found around Jette Lake and along Route 93 between the two moraines.

Figure 13
Lake sediments along Route 93 south of the northern Polson moraine. The unit contains cm-scale dropstones.

to Figure 1b). The degree to which the study area is overgrown with pine forests and underbrush hampers more refined description of the glacial features, although the terminal moraine for the Route 93 valley glacier is distinct in figure 1b.

Because the till in the map area appears to be similar to that encountered by Bondurant (2005) immediately to the north, I decided to employ her map unit terminology. Qgmfl (Flathead Lobe lateral moraine) is unstratified, white to light-tan till with sub-rounded to rounded pebble- to boulder-sized clasts in a light-tan silt matrix. In the map area only one outcrop had interbedded sand lenses while in Bondurant's (2005) map area they appeared to be more abundant. Qgmfl represents the till found on the southern arm of the northern Polson moraine, the till encountered along the northern arm of the northern Polson moraine and the till found in the Route 93 valley to the north of both Polson arms. Qgo (Flathead Lobe outwash) I interpret to be fluvial outwash containing climbing ripples, graded gravel cross beds, and clast supported conglomerate. This facies is evident at the toe of the southern arm of the northern Polson moraine. Qgl (Glacial Lake deposit) consists of glacially influenced lacustrine deposits with laminated silt and abundant dropstones. Lacustrine deposits such as this are located east of the northern Polson moraine. Qgu (Glacial till undivided) is an unstratified, massively bedded clast supported conglomerate found in the Jette Lake area as well as the Route 93 valley area.

B) *Major Structures:*

Harrison's (1986) structural geology map of the area contains about 13 normal faults for which I have found no supporting field evidence (Figure 14 & 15). Figure 1b shows the placement of faults in the map area according to my measured sections, my interpretations of the geophysical data, and numerous strike and dip measurements. These include the Big Draw Fault, which trends east west and ends in a series of splays on Wild Horse Island (Power, 2005 – senior thesis project), and a smaller strike-slip fault - the Chief Cliff fault - that has been bisected by the Big Draw. The placement of these faults is mostly based on large changes in strike and dip orientations across linear traverses over bedrock. Available 3.5 kHz seismic reflection profiles from Big Arm Bay also were crucial for fault identification (e.g., Figure 16; Hofmann et al., 2006). Figure 16 shows an example of a 3.5 kHz seismic reflection profile from Big Arm Bay. Imaged sediments contain numerous deformational structures and liquefaction likely associated with compression due to movement along an underlying strike-slip fault. Hofmann et al. (2006) interpret this feature to be a flower structure associated with strike-slip movement. Lines 12 and 15 are the only seismic profiles in the map area that include a large flower structure. I infer that the fault system imaged in these two lines is a single fault.

2. Discussion

A) *Pre-Quaternary History:*

Winston (1983, 1986) proposed that partitioning of the basement into 5 separate blocks controlled deposition in the Belt Basin. Stratal assemblages thickened or thinned across block boundaries according to the relative amount of uplift or subsidence among blocks. For example, the Middle Belt Carbonate thickens into the Lewis and Clark Line

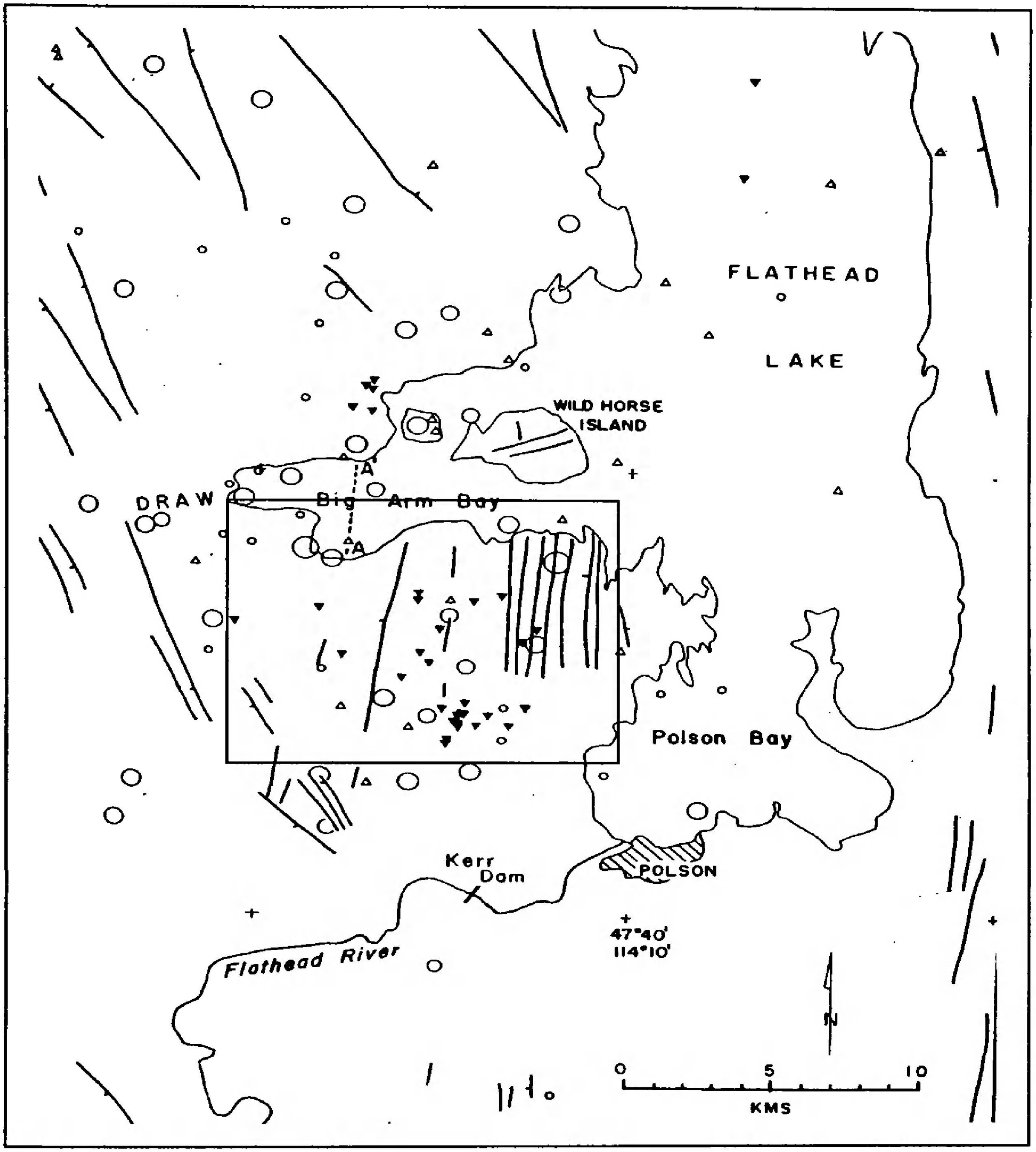


Figure 14
Faults mapped by Harrison et al. (1986). Outlined by the box are 11 normal faults in the study area. I have not observed evidence of these faults and infer the bedrock stratigraphy there to consist of the Burke, Revett, St. Regis, and Empire Formations of the Ravalli Group, and the Helena Formation of the Middle Belt Carbonate unit.

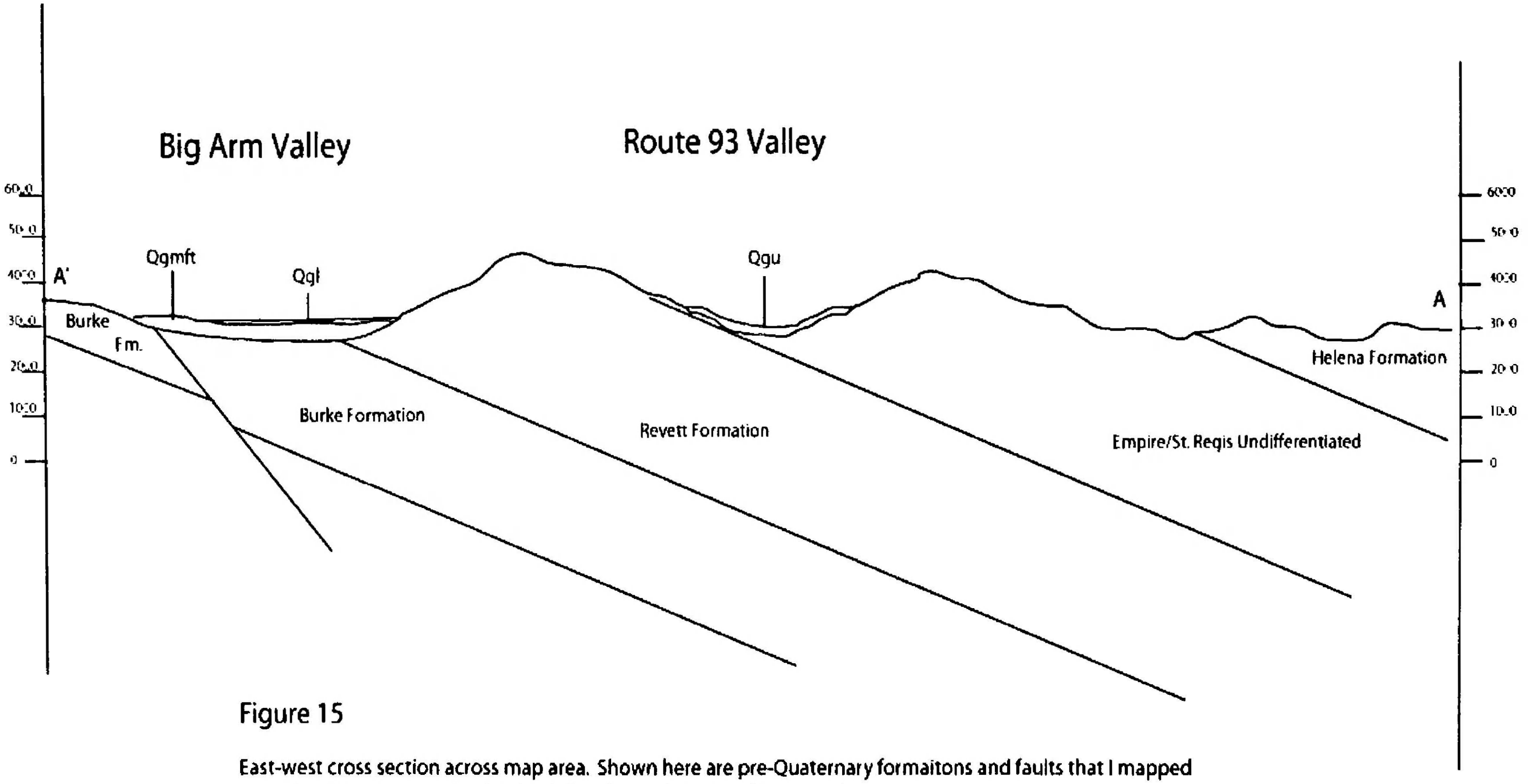


Figure 15

East-west cross section across map area. Shown here are pre-Quaternary formaitons and faults that I mapped as well as Quaternary units that both Bondurant (2005) and I mapped.

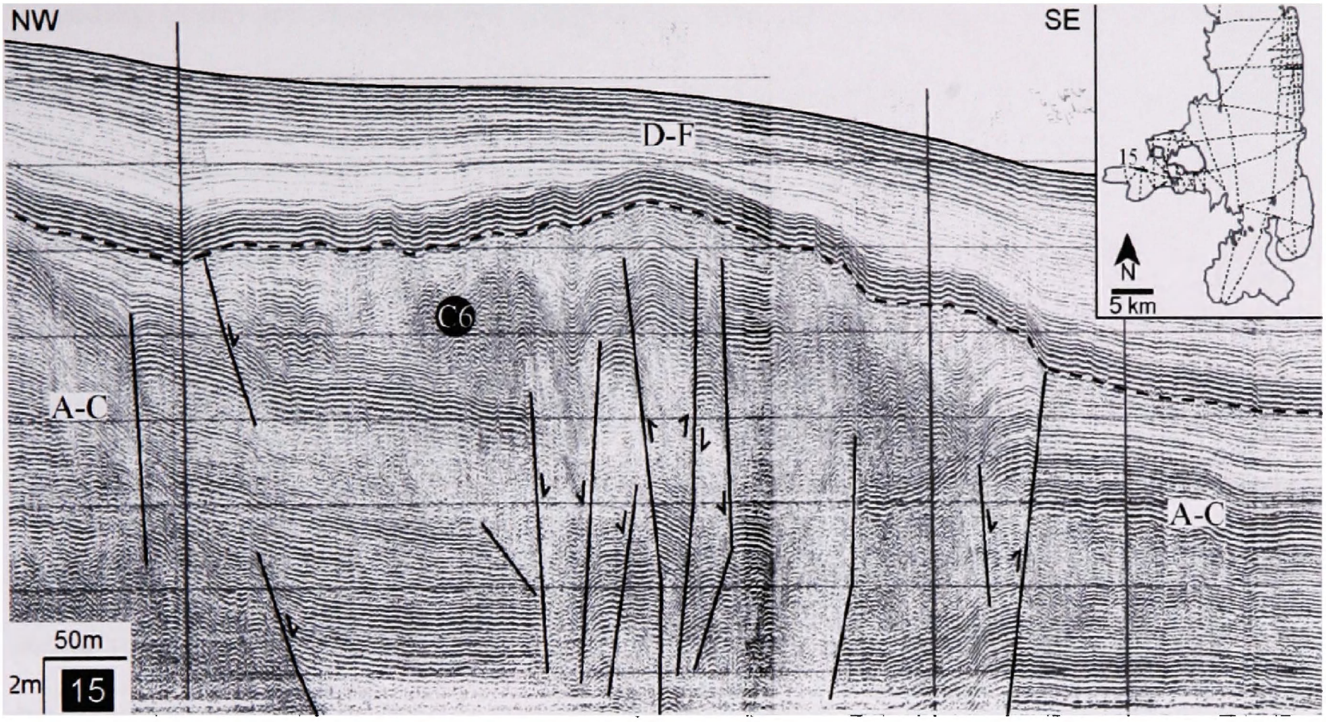


Figure 16
Flower structure imaged along seismic lines 12 and 15. This zone is comprised of small faults with normal and reverse motion typical of a strike-slip fault. Rotation of outcropping bedrock to the north is the main evidence for left-lateral motion along this fault.

and then thins dramatically south of it (Connor, 1984). Although the large basin-bounding faults are absent in the study area, faults are nonetheless present and their influence on sedimentation is both striking and well documented. According to LaPoint (1971), northwest- and northeast-trending faults in the map area formed first (e.g., Chief Cliff fault), followed closely in time by the east trending strike-slip faults (e.g., Big Draw fault). LaPoint's (1971) interpretation is supported by the observation that the northwest and northeast trending faults are cross-cut by the east-west trending faults. Later, major north-south trending faults (e.g., Mission fault) developed along with reactivation and dip-slip movement of the northwest and northeast trending faults. Such a scenario would account for the observations made in the field area. The large east trending Big Draw fault appears to cross-cut the northwest-trending Chief Cliff fault. The Chief Cliff fault contains a major splay that trends northwest and is located about 1 km east of the Chief Cliff face. I infer that vertical-axis block rotation between the splay and the Chief Cliff fault, as well as the seismically-imaged flower structure, point to reactivation of the northwest trending Chief Cliff fault.

Reactivation of normal faults with a strike-slip component of movement is quite common and typically represents a change in the direction of extensional stress (Ring et al., 1992). Ring et al. (1992) used the Malawi rift in East Africa to study normal vs. strike-slip faulting during rifting and found that a second phase was dominated by strike-slip movement along older normal faults, thereby generating dextral strike-slip and dextral oblique-slip offsets. A similar scenario is likely the case in the map area north of Polson. Ring et al. (1992) described the formation of several synthetic faults with a right-lateral component of movement. With continued strike-slip deformation, they documented clockwise rotation of sedimentary strata about a vertical axis. The map I generated of the study area contains a synthetic right-lateral fault as well as clockwise rotation. The rotation that I infer is supported by strike and dip orientation data that I collected from Chief Cliff. East of the Chief Cliff fault strike is generally north, while west of the fault strike is generally east.

Figure 16 depicts a large flower structure imaged in Pleistocene and Holocene sediments within the Big Arm Bay of Flathead Lake, immediately offshore of the map area. Hofmann et al.(2006) describe this feature as a zone of liquefaction related to a fault trace; in Figure 16 it appears as though the amount of offset decreases with depth to the point at which it can no longer be resolved, although this observation may be an artifact of the relative orientation of the seismic profile with respect to the dipping fault (Hofmann et al., 2006). The fault trace that I mapped, the Chief Cliff fault, is a left-lateral strike-slip fault, as demonstrated by the strike and dip orientations collected east of the fault. I interpret the offshore flower structure to be the result of compression along this fault. Hofmann et al. (2006) pointed out that the zone of liquefaction comprises small faults with both normal and reverse local sense of motion typical of strike-slip faults. Stevenson (1976) concluded that the focal mechanism studies he conducted in the Big Arm Bay region clearly indicated a strike-slip component there. Qamar et al. (1982) imaged a very similar structure on the north side of Big Arm Bay and interpreted the structure as not showing definite offset of beds (Figure 17). Rather, Qamar et al. (1982) inferred that it was related to slumping on a 1 or 2 degree slope. I cannot completely

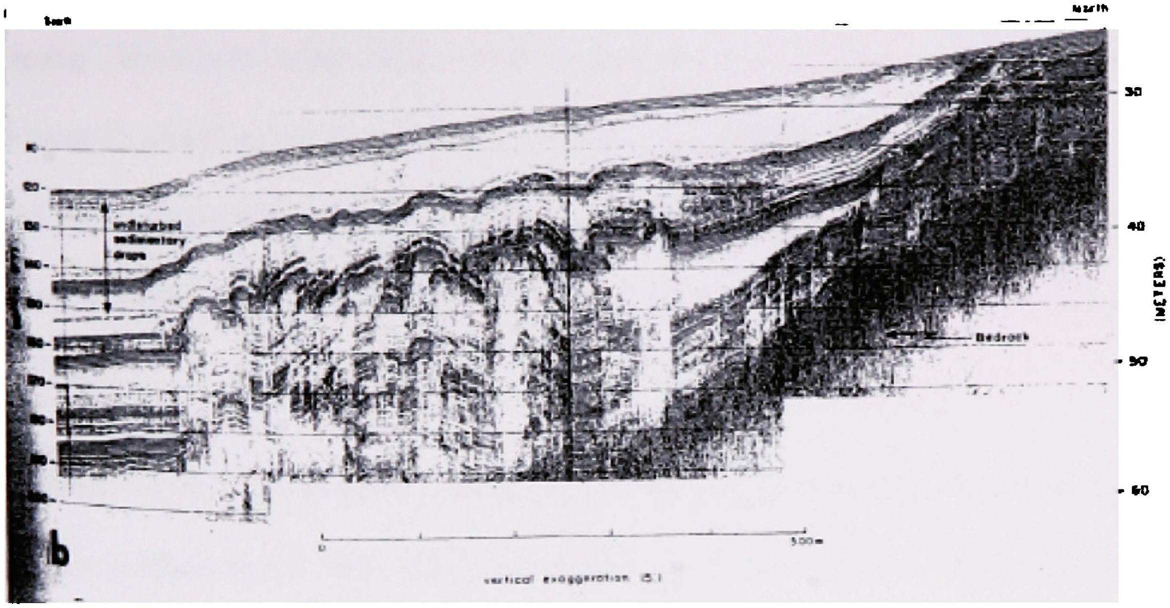


Figure 17
3.5 kHz seismic reflection profile #15 from Big Arm Bay showing deformed Quaternary sediment that Qamar et al. (1982) interpreted to be the result of slumping. The lack of a failure scar and the offset of beds outlined by Hofmann et al. (2006) suggest that this feature is in fact related to compression along a strike-slip fault.

discount this idea, because the disturbed sediment clearly is located on a slope. Accordingly the flower structure imaged in the geophysical data may very well be related to slumping. However, slides leave distinct failure scars (Schnellman et al., 2005), and no such scar is observed in the seismic profiles. Schnellman et al. (2005) also pointed out that mass flows generally appear as confined bodies that commonly have transparent seismic reflection characteristics, and this also is not the case with the feature imaged in Big Arm Bay.

Qamar et al. (1982) noted that in the 3.5 kHz seismic reflection profiles from Big Arm Bay, as well as in all other seismic profiles collected from the lake, the disrupted beds are covered by an undisturbed drape of sediment 3 to 12 meters thick. A sedimentation rate of 1 mm/yr places an age of at least 10,000 years on this structure (Qamar et al., 1982). Hofmann et al. (2006) also concluded that the faulting in Big Arm Bay is at least 10,000 years old.

B) Quaternary History:

1. Northern Polson Moraine

As the Flathead lobe of the Cordilleran Ice Sheet advanced through the area during the late Pleistocene it left behind evidence both of its travel direction and its routes. One such region is the broad valley just north of Polson. There, two sets of glacial scour striae can be found on outcrops of the Empire/St. Regis Formation just west of the KOA (Figure 18). One set of scour indicates that the ice moved in a southwesterly direction while the other set indicates that the ice was moving due west.

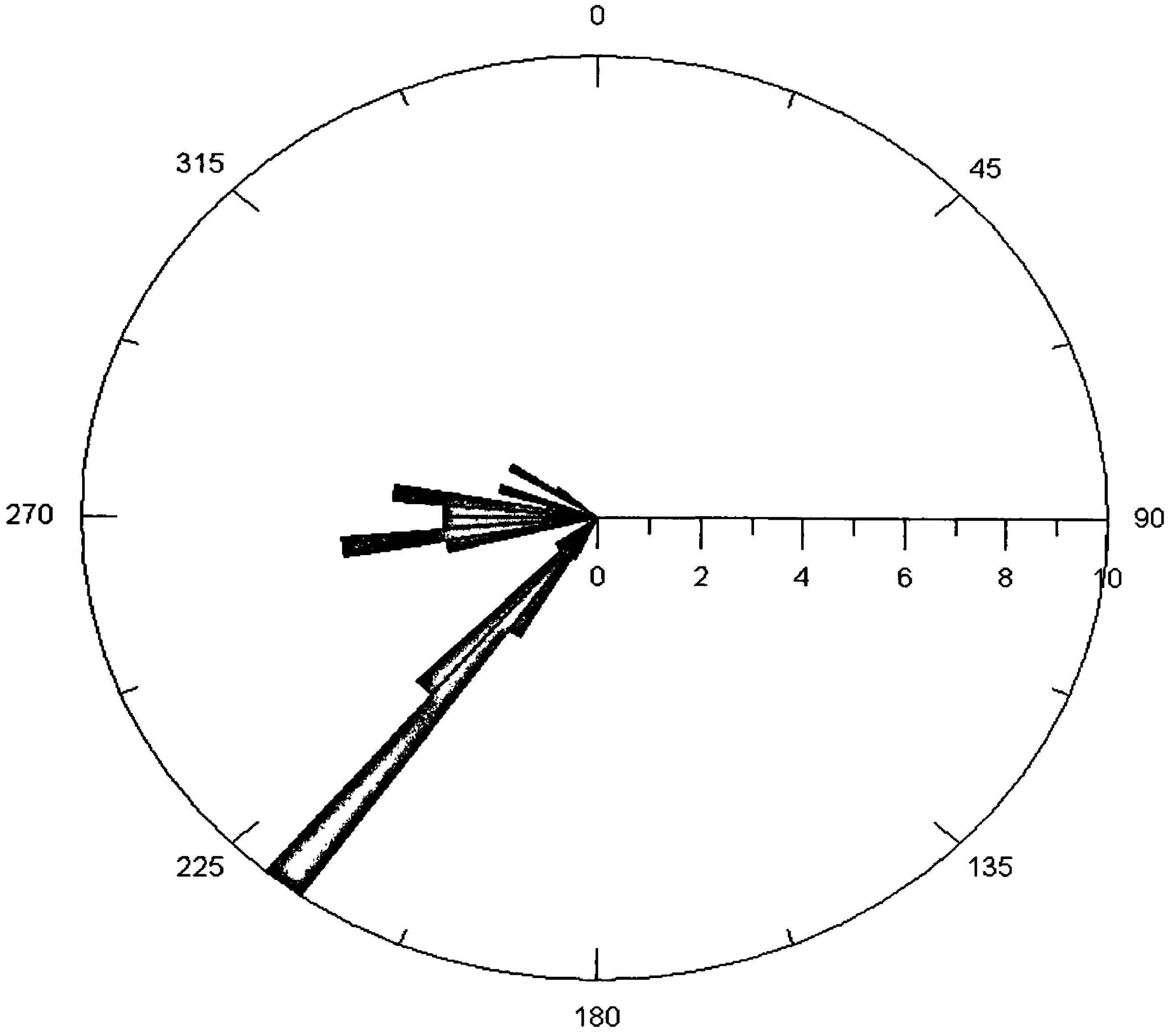


Figure 18
Rose diagram of glacial scour measurements collected from the bedrock immediately west of the KOA north of Polson. These data suggest the presence of two very distinct ice flow directions with possibly a third.

As described previously the till in the study area is of two distinct types: that found along the southern and northern arms of the northern Polson Moraine, and that found at the toe of the northern Polson moraine's southern arm. The till east of the southern Polson moraine toe, near the KOA campground, is chaotic and in matrix-support. Clasts range in size from gravel to cobble, are rounded to sub-angular, and contain the same range of clast lithologies previously mentioned (refer to figure 7b). This description is consistent with Smith's (2004) description of a massive, matrix supported diamicton deposit in the area of Polson with 40-60% sub-rounded to sub-angular, commonly striated clasts. According to Smith (2004) and Levish (1997) the Polson moraine, of which the moraine in the map area appears to be a continuation, is thought to have been deposited subaqueously.

Smith (2004) described tills in his study area north of Polson as containing silt and clay, silty sand, sand and gravel that include climbing ripples, dropstones, foresets, and shallow channels all of which permit sub-aqueous deposition. Other descriptions of sub-aqueous moraine tills are very similar: sandy gravel and sand, laminated sand, silt and clay, and a ripple or cross-laminated sand (McCabe, 1986; Paterson et al., 1997). Massive laterally extensive beds also are characteristic of sub-aqueous moraines and can be interpreted as the direct product of debris rainout with each unit representing a debris pulse. Interbeds of silt represent periods when the supply of debris is minimal and suspension settling dominates (Bennett et al., 2002). None of the till in this area, except for that found at the toe of the southern arm, displays such evidence of subaqueous deposition. Eight or so exposures in the northern Polson moraine contained no channels, cross beds, or climbing ripples of any kind, all of which are clearly visible in the southern Polson moraine.

Hummocky topography characterizes the entire southern arm of the northern Polson moraine. Hummocky topography associated with moraines is commonly associated with processes of ice disintegration in a stagnant glacier. Namely, hummocky topography results from topographic inversion associated with wasting glacial ice, and hummocky topography is produced wherever debris mantled ice existed previously (Attig, 1983; Ciner et al., 1999) (Figure 19). These authors posited that a 'sea' of hummocky topography typically marks regions of former ice cover. In contrast, Eyles et al. (1999) and Gravenor and Kupsch (1975) proposed that hummocky topography results from compression and squeezing of basal till into depressions with in the basal ice.

I do not think that the process described by Eyles et al. (1999) and Gravenor and Kupsch (1975) formed the hummocky topography in my area for the following reasons; (1) as the authors stipulate the till must be saturated with water to allow for it to squeeze into the cavities at the base of the ice. Such a process likely would create flow structures in the till and none were observed, and (2) observed exposures do not have the fine grained characteristics (clasts of about 10 cm or less) more typical of deformation till (Eyels et al., 1999). The only departure from the scenario proposed by Ciner et al. (1999) and Attig (1983) is that I only observed hummocky topography on the moraine itself; the 'sea' of hummocks typical of a wasting glacier is not present.

The broad portion of the moraine that forms the southern arm was deposited

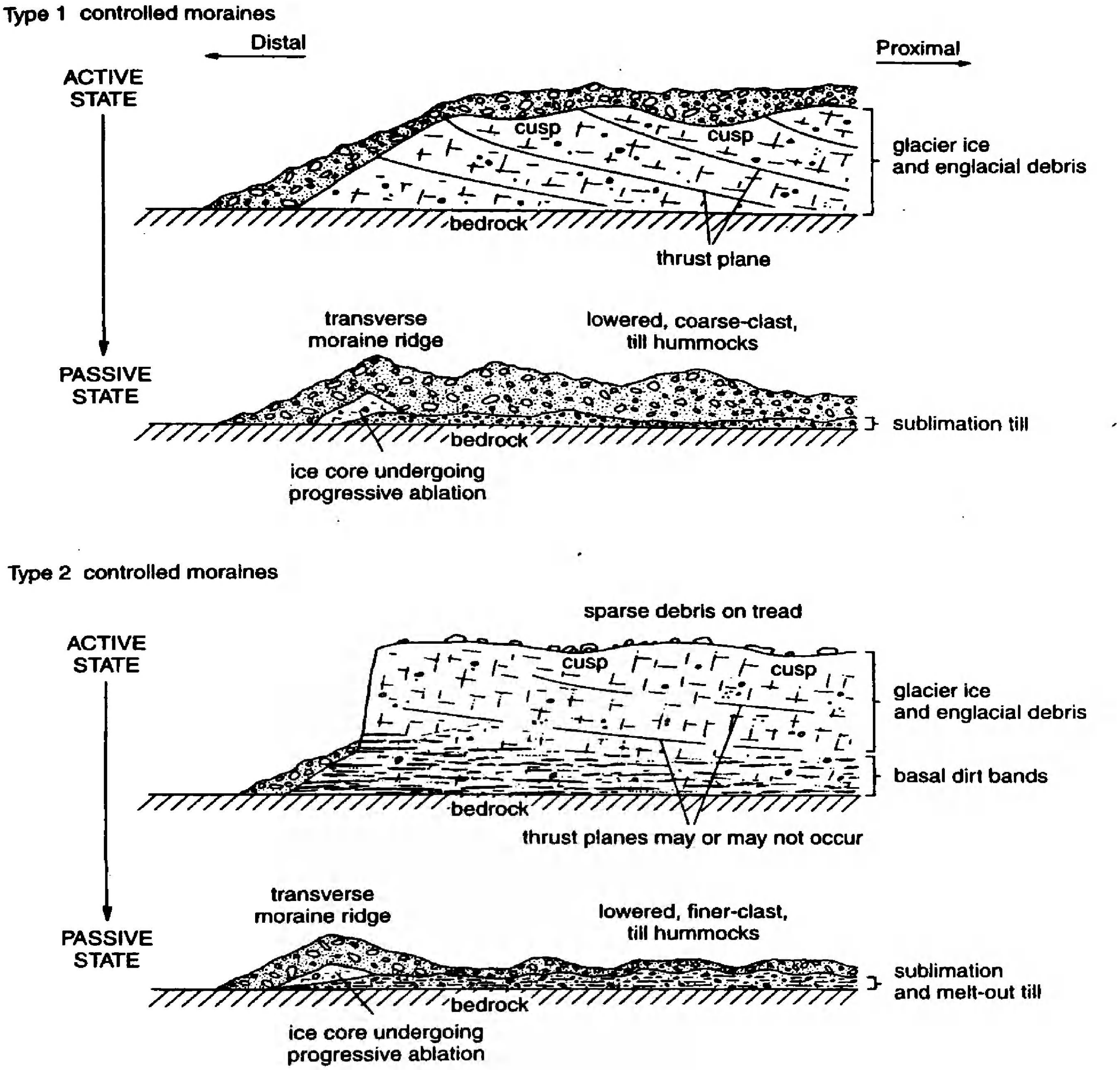


Figure 19
This schematic from Glaciers and Glaciation (Benn and Evans, 1998) shows the process by which hummocky topography is formed. It results from the wasting of a foundering ice sheet in a subaerial environment.

between and on top of several bedrock ridges that crop out at various places along the moraine (Braden, 2006). I think that these ridges played an important role in the formation of this part of the moraine by acting as a baffle or a dam; the ice probably foundered here, allowing for the formation of hummocky topography through wasting and topographic inversion. Although small lakes can form in the depressions, this process of wasting and topographic inversion is decidedly subaerial. I interpret the hummocky topography associated with the till on top of the southern arm in the study area to result from this sort of mechanism.

The topographically lower portion of the southern arm of the northern Polson moraine exhibits sedimentary structures that appear to suggest a sub- aqueous environment of deposition (refer to Figure 8a & b). There, the till clearly contains a 30 cm thick graded bed. Beneath the graded bed the till is in clast support. The graded bed is an indicator of sub-aqueous settling and the clast support may possibly indicate winnowing by currents coming out from underneath the ice. One possible explanation for this observation is that the moraine terminated in glacial Lake Missoula when elevation of the lake surface was such that the Flathead Lobe reached the lake shoreline but was completely grounded. This situation might result in a moraine with a subaerial top and a sub-aqueous bottom. A glacier such as this in a 'tidewater' type environment might not founder long enough for stagnant ice features to develop and this might explain the lack of hummocky topography on the northern arm of the northern Polson moraine.

The sub-aqueous structures I observed at the toe of the southern arm of the northern Polson moraine might be the result of a small pond formed in a depression during the process of topographic inversion. Material avalanching into the pond from the surrounding highs may have formed the clast-supported conglomerate as well as the graded beds. As melting and topographic inversion continued the surrounding highs may have lowered leaving this portion of the moraine exposed at the front.

Tidewater glacier margins are frequently unstable and produce rapid flow normal to the ice margin. The rapid rate of flow, in time, might contribute to high erosion rates and common glacially-eroded land forms (Kaplan, 1999). This scenario might account for the lack of a continuous morainal bank from the south arm to the north arm of the northern Polson moraine in this study area. Alternatively, the form of this moraine might be the result of erosion by glacial Lake Missoula or that of a Proto Flathead Lake, although the lack of lake sediments on top of the glacial outwash immediately to the west of the northern Polson moraine suggests that this is not the case.

I did not observe well-developed hummocky topography on the northern arm of the northern Polson moraine, most likely because of erosional deletion by glacial outwash flow from the Route 93 valley glacier. It is also possible that the ice was not stagnant long enough here for widespread hummocky topography to develop. If the ice were stagnant long enough to produce hummocky topography on the northern arm of the northern Polson moraine itself, it should be stagnant long enough to produce the ‘sea’ of hummocky topography mentioned by Eyles et al. (1999). According to Gravenor and Kupsch (1974) stagnant ice will produce a round, broad moraine and the northern Polson moraine does not quite fit that description. The evidence seems to point to a subaerial moraine that was stagnant only where it was trapped by the belt rock spurs.

The northern arm of the northern Polson moraine comprises till, characterized by gravel, and boulders supported by a matrix of light brown silt and clay. Clasts are rounded to sub-angular and striated and represent the same wide range of lithologies mentioned earlier. The till is generally devoid of subaqueous sedimentary structures. The lack of such sedimentary structures is consistent with my interpretation that the moraine was likely deposited in a subaerial setting.

North of the Polson moraine, Route 93 passes through a small topographic corridor in the bedrock. There, a moraine was formed by ice flowing south up the narrow valley within about 1 km of the northern extension of the northern Polson moraine. The geomorphology of the valley suggests that the ice did not flow through to the south side (refer to Figure 1b), although the outwash from this glacier probably did. The till in this area is very similar to that found on the northern arm of the northern Polson Moraine, being composed of clasts ranging in size from gravel to boulder and being supported in a matrix of light brown clay and silt. Cobbles are striated, rounded to sub-angular, and contain the same wide range of clasts encountered at the other moraines in the study area; the till is relatively devoid of sedimentary structures. Apparently, the glacier occupied the entire valley and terminated about 1 km from the outlet of the valley; the sub-aerial nature of this till may be explained by the displacement of lake water as the glacier flowed up the small valley or more simply a lack of lake water as the glacier flowed up the small valley. In both cases I think that the massive till, lacking interstratified lacustrine deposits, suggests a subaerial setting.

2. Glacial Outwash

The gravel pit located at N 47 degrees 42.444 minutes and W114 degrees 14.321 minutes also exhibits classic subaqueous structures that I interpret as fluvial (refer to Figure 11). Climbing ripples in large sand seams, and small and large graded gravelly cross beds, some with up to a meter of relief, were encountered throughout the gravel pit. Typical fluvial outwash facies include ripple cross laminated sands, cross bedded sands and gravels, tabular sheets of massive gravel, and sets of trough and planar cross bedded gravel (Benn and Evans, 1998). All of these facies are found in abundance in the gravel pit. This fluvial outwash, which appears overall to fine upwards, is located at the toe of the southern arm of the northern Polson moraine.

The sand facies, which is very prevalent here, has been observed in pro-glacial meltwater environments as most commonly being associated with the downstream migration of bars and the formation of dunes and ripples (Maizels, 2002). Rippled sands may accumulate locally during shallow flows across bar tops or with in shallow channels, however the preservation potential of such deposits is relatively low (Maizels, 2002). The cut-and-fill nature of the deposits at this gravel pit are striking in that a half meter thick rippled sand seam is eroded and cut into by a large meter scale gravel layer (Figure 11). Massive sands, which can be found at the top of the gravel pit, are characteristic of suspension flows, in which rapid deposition occurs with in the deeper channels (Figure 11) (Maizels, 2002).

The gravel facies, which is the most prevalent facies found in the gravel pit, is massive in some areas, imbricated in others, and shows definite centimeter- to meter-scale bedding in still other locations. The massive gravel, which does not show imbrication but which does exhibit a wide range of clast sizes, is characteristic of a torrential flood (Maizels, 2002). The areas that are imbricated and that show distinct bedding probably were deposited during more moderate flows (Maizels, 2002).

The outwash in the study area strongly exhibits the characteristic features of a braided system in a pro-glacial setting. The lack of lake sediments and dropstones with in and on top of this section strongly indicate that the glacier that released this sediment did so entirely under sub-aerial conditions, and the fining upward nature possibly suggests deposition as the glacier began its final retreat.

3. Undifferentiated Quaternary Sediment

Jette Lake is located adjacent to the toe of the Route 93 valley moraine. The Jette Lake area is littered with gravel and cobbles but does not contain outcrops of till. The Jette Lake basin is an overdeepened basin about 250 meters across with a steep back wall, an upward-concave slope, and an arcuate plan-view. These characteristics are consistent with erosion by a small cirque glacier (c.f., Benn and Evans, 1998). Abundant gravel, including meter scale erratics occur in the Jette Lake basin as well as along Route 93. This gravel contains clasts from the Burke, Revett, St. Regis, Empire, and Helena Formations, suggesting derivation from a more integrated source than the Jette Lake cirque basin alone.

Coupled with observations of north-south oriented glacial striae along the main Rt. 93 valley glacier, I infer that the gravel observed in the area was introduced through south-directed flow of the main valley glacier, rather than local derivation from erosion of the cirque itself. Outwash from the cirque as well as the Rt. 93 valley glacier flowed through the narrow corridor to the south. This narrow 300-meter passageway slopes down to the south and is littered with cobbles and boulders (refer to Figure 12). Scour orientations in this location, as well as in the Big Arm, Elmo, and Dayton valleys, along with rock drumlin elongation direction and the till composition, all suggest that this glacier was moving due south through the region.

4. Other Glacial Features

East of the northern arm of the Polson Moraine, Quaternary strata include varved lake sediments with numerous drop stones (refer to figure 13). Two plausible scenarios account for the occurrences of these facies: 1) the sediments represent deposition from a small pro-glacial lake dammed behind the moraine and formed as the glacier retreated and; 2) the sediment represents deposition by Glacial Lake Missoula. It is most likely the former of the two interpretations that is most plausible because of the lack of varved lake sediments west of the northern Polson moraine itself.

East of the northern extension of the northern Polson moraine the bedrock topography has been ice-sculpted into a very distinct pattern of rock drumlins or whalebacks. Rock drumlins and whalebacks are elongate, smoothed bedrock bumps which lack the characteristic quarried ice faces of roches moutonnees. Whalebacks are approximately symmetrical, whereas rock drumlins are asymmetrical with steeper stoss faces (Benn and Evans, 1998). The importance of the rock drumlins and whalebacks is that they are elongate in the direction of ice flow and therefore serve as good ice flow directional indicators. Here the ice was moving due south over the peninsula before it broke into the lobes that formed the Polson moraine.

Terraces are present on both sides of the Rt. 93 valley at an elevation of 1066 meters (refer to Figure 1b). The terraces may be kame terraces although the lack of outcrops in the area makes this assessment difficult; it is certainly possible that the terraces are sculpted bedrock features. A kame terrace is a gently sloping depositional terrace perched on a valley side and deposited by melt water streams flowing between the glacial margin and the adjacent valley wall; it is composed predominantly of fluvial sand and gravel (Benn and Evans, 1998). I also found north-south trending glacial scour on Belt rock exposures just below the terraces.

C) *Evidence for Multiple Flathead Lake Advances:*

One possible explanation for the interpretation that a sub-aerial moraine was deposited next to, and seemingly adjoining, a sub-aqueous moraine is that the sub-aqueous southern extension of the northern Polson moraine was first deposited in glacial Lake Missoula as Levish (1997) and Smith (2004) inferred. The Flathead Lobe retreated temporarily and then underwent readvance to its terminal position during a low stand of glacial Lake Missoula or possibly following terminal draining of the glacial lake.

Licciardi et al. (2001) and Sturchio et al. (1994) documented that the last Pinedale glacial maximum of a Yellowstone outlet glacier occurred between 30 and 22.5 thousand years ago followed by a recessional phase between 22.5 and 19.5 thousand years ago. There is some disagreement about the recessional phase. Licciardi et al. (2001) call this a ‘restrictive ice phase’, while Sturchio et al. (1994) surmised this to be an outright recessional phase. The Flathead Lobe was quite possibly retreating and advancing essentially in phase with the Yellowstone glacial system. The recessional phase of the Flathead Lobe may have been followed by a small glacial advance; this advance would have correlated with a low stand in glacial Lake Missoula as the sub-aerial characteristics of the moraine suggest.

Sturchio et al. (1994) recognized a small glacial event in Yellowstone National Park occurring between 19.5 and 15.5 thousand years ago; this glacial event may correlate with the advance that formed the northern Polson moraine. The existing southern Polson moraine may have acted as a dam channeling the ice westward towards the present position of the northern extension of the northern Polson Moraine. Glaciers probably had receded well up-valley from the study area of Licciardi et al. (2001) and Sturchio et al. (1994) no later than 14-13 thousand years ago; the Glacier Peak ash in the area around Flathead Lake also suggests that the glaciers were gone by this time.

The timeline of events outlined above is in agreement with that of Ward and Thompson (2002). The subaqueous till of the southern Polson moraine and the sub-aerial till of the northern Polson moraine, taken in conjunction with the two distinct directions of glacial scour indicating both southwesterly and westerly flow, suggest the development of two separate glacial advances. The southern Polson moraine in the study areas of Smith (2004) and Levish (1971) shows evidence for sub-aqueous deposition throughout the entire sequence; as I have discussed the northern extension of the Polson moraine appears to show no such evidence. I infer that the southern Polson moraine was deposited during a high stand while the northern Polson moraine was deposited during a low stand when lake water was not present, or was low enough that the glacier was not floating.

I also utilized well log data from wells drilled in the study area to determine till thicknesses and depth to bedrock. The well log descriptions provided insufficient detail to distinguish between Quaternary gravels and gravels that might have been older so I was not able to determine with any confidence the thickness of the till. I was able, however, to correlate a large clay layer across the northern extension of the Polson moraine (Figure 20). This clay layer likely represented lake deposition during a glacial retreat. Two wells found along the apex of the moraine (number's 177507, and 6273) exhibit the clay layer, at a depth of 67 feet, between layers that fit the description of till. Well 77923 also has a clay layer at this depth but the clay layer there has gravel embedded in it. The well data is not conclusive but it does seem to suggest that at least a few of the wells recorded a period of glacial retreat and lake sedimentation. This lake would have to have been gone as the ice began its re-advance to allow for a sub-aerial moraine.

Well ID: 77923

Top	Bottom	Description
0	1	Topsoil
1	64	Tan clay w/ gravel
64	66	Tan clay & gravel
66	141	Tan clay w/ gravel
141	151	Silty gravel
151	159	Tan clay w/ gravel

Well ID: 177507

Top	Bottom	Description
0	3	Topsoil
3	49	Gravel in gray clay
49	67	Gray Clay
67	122	Tan silty clay w/ gravel
122	133	Tan silty clay w/ gravel
133	146	Blue Rock

Well ID: 6273

Top	Bottom	Description
0	1	Topsoil
1	23	Small boulders in sandy clay
23	25	Large gravels in sandy clay
25	27	Sand
27	61	Gravel in tan clay
61	67	Tan clay

Figure 20
Location and cross section of three wells located at the apex of the northern Polson moraine. Borehole logger distinguished the layer from 64 to 66 feet in well 77923. I cannot be sure if there was more or less gravel in the interval which led to this.

Conclusions:

1. The Chief Cliff fault that I mapped probably began as a normal fault that was subsequently reactivated with a left-lateral strike-slip component. I infer that the Big Draw fault originated as a strike-slip fault. The Chief Cliff fault was mapped on the basis of abrupt changes in strike and dip as well as the presence of a large flower structure imaged in the offshore 3.5 kHz seismic reflection data of Big Arm Bay. Observed fault block rotation of bedrock, as well as the fact that the flower structure contains numerous small faults with normal and reverse senses of motion strongly suggests that this fault is a strike-slip fault that has been reactivated. The undisturbed drape of sediments overlapping the fault suggests that it has been locked for about 10,000 years.

2. Sub-aerial till deposits on the northern Polson moraine indicate that the ice may have advanced to its terminal position during a low stand of Glacial Lake Missoula. The juxtaposition of the subaerial deposition of the northern Polson moraine adjacent to the subaqueous deposition in the southern Polson moraine seems to suggest that the two moraines were formed separately at different times. A small glacial retreat and re-advance during a low stand of glacial Lake Missoula is a plausible explanation for the observations made in the field. The fining upward outwash just beyond the toe of the north Polson moraine appears to be fluvial in character, consistent with deposition following terminal retreat of glacial Lake Missoula from the study area.

3. Other evidence for glacial activity in the map area can be seen in the many rock drumlins and whale backs, as well as terraces, till, and glacial scour along I-93. This

evidence suggests that ice was moving due south before it foundered and formed the different lobes of the Polson moraine.

References

Attig, J.W., 1983. The origin of hummocky topography in end moraines. Abstracts with Programs-Geological Society of America. Boulder, CO, USA, p. 250.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold, London.

Bennett, M.R., Huddert, D., Thomas, G., 2002. Facies architecture with in a regional glaciolacustrine basin: Copper River, Alaska. Quaternary Science Reviews 21, 2237-2279.

Bondurant, A., 2005. Geologic mapping and sedimentologic analysis of Quaternary deposits along the western shore of Flathead Lake, Northwest Montana, documenting the record of degalciation. MSc Thesis, University of Montana.

Braden, J., 2006. History of syn-glacial and post-glacial sedimentation at the former Terminus of the Flathead Lobe near Polson Montana. MSc Thesis, Universtiy of Montana.

Ciner, A., Deynoux, M., Corekcioglu, E., 1999. Hummocky moraines in the Nameras And Susam valleys, central Taurids, southwest Turkey. Quaternary Science Reviews 18, 659-669.

Connor, J.J., Reynolds, M.W., Whipple, J.W., 1983. Stratigraphy of the Ravalli Group, Belt Basin, Montana and Idaho. MBMG Special Publication 90, pp. 13-15.

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

Eyles, N., Boyce, J.I., Barendregt, R.W., 1999. Hummocky moraine: sedimentary record of stagnant Laurentide ice sheet lobes resting on soft beds. Sedimentary Geology 123, 163-174.

Gravenor, C.P., Kupsch, W.O., 1975. Ice-disintegration features in western Canada. Geology 67, 48-64.

Harrison, J.E., Cressman, E.R., Whiple, J.W., 1986. Geologic and structure maps of the Kalispell 1x2 quadrangle, Montana, and Alberta British Columbia. USGS Miscellaneous Investigations Series Map I-2267, scale 1:250,000.

Hofmann, M., Hendrix, M.S., Sperazza, M., Moore, J.N., 2006. Neotectonic evolution and fault geometry change along a major extensional fault system in the Mission and Flathead Valleys, NW-Montana. Journal of Structural Geology 184, 111-131

Kaplan, M.R., 1999. Retreat of a tidewater margin of the Laurentide ice sheet in eastern Coastal Maine ca. 14,000 and 13,000 Cal. Yr. B.P. Geological Society of America Bulletin 3, 620-632.

LaPoint, D.J., 1971. Geology and Geophysics of the southwestern Flathead Lake region, Montana. MSc Thesis, University of Montana.

Levish, D.R., 1971. Late Pleistocene sedimentation in glacial lake Missoula and revised Glacial history of the Flathead lobe of the Cordilleran ice sheet, Mission valley, Montana. Ph.D. thesis, University of Colorado.

Licciardi, J.M., Clark, P.U., Brook, E.J., Kurz, M.D., Elmore, D., Sharma, P., 2001. Cosmogenic He and Be chronologies of the late Pinedale northern Yellowstone ice cap, Montana, USA. Geology 29, 1095-1098.

Lonne, I., 2001. Dynamics of marine glacier termini: from moraine achitecture. Geology 29, 199-202.

Maizels, J., 2002. Modern and Past Glacial Environments. Jordan Hill, Oxford.

Mauk, J.L., 1983. Stratigraphy and sedimentology of the Proterozoic Burke and Revett Formations, Belt Supergroup, western Montana. Abstracts with Programs-Geological Society of America. Boulder, CO, USA, p. 424.

McCabe, A.M., Eyles, N., 1998. Sedimentology of an ice contact glaciomarine delta, Corey valley, northern Ireland. Sedimentary Geology 59, 1-14.

O'Neill, J.M., Ferris, D.C., Schmidt, C.J., Hanneman, D.L., 1986. Recurrent movement along northwest trending faults at the southern margin of the Belt Basin, Highland mountains, southwestern Montana. MBMG Special Publication 94, pp. 209-216.

Paterson, J.T., Cheel, R.J., 1997. The depositional history of the Bloomington complex, an ice contact deposit in the Oak Ridges moraine, southern Ontario, Canada. Quaternary Science Reviews 16, 705-719.

Power, D., 2005. Geologic mapping of Wildhorse Island Flathead Lake, Montana. Senior Thesis, University of Montana.

Qamar, A.I., Kogan, J., Stickney, M.C., 1982. Tectonics and recent seismicity near Flathead lake, Montana. Bulletin of the Seismological Society of America 71, 1591-1599.

Richmond, G.M., 1980. Tentative correlation of the Cordilleran Ice-Sheet in the northern Rocky mountains. Quaternary Science Reviews, 129-134.

Ring, R., Betzler, C., Delvaux, D., 1992. Normal vs. strike-slip faulting during rift development in East Africa: the Malawi Rift. Geology 20, 1015-1018.

Schnellman, M., Anselmetti, F., Giardini, D., McKenzie, J., 2005. Mass movement induced fold-and-thrust belt structures in unconsolidated sediments in Lake Lucerne: Switzerland. Sedimentology 52, 271-289.

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 165, 295-232.

Stevenson, P.R., 1976. Microearthquakes at Flathead Lake, Montana; a study using automatic earthquake processing. Bulletin of the Seismological Society of America 66, 61-80.

Sturchio, N.C., Pierce, K.L., Murrell, M.T., Sorey, M.L., 1994. Uranium series ages of travertines and timing of the last glaciation in the northern Yellowstone area, Wyoming – Montana. Quaternary Research 41, 265-277.

Ward, B.C., Thomas, B., 2004. Late Pleistocene stratigraphy and chronology of the Lower Chehalis River southwestern British Columbia: evidence for a restricted Coquitlam Stade. Canadian Journal of Earth Sciences 41, 881-895.

Winston, D., White, B.G., Mauk, J., 1983. Stratigraphy of the Revett Formation. MBMG Special Publication 90, pp. 209-216.

Winston, D., 1986. Sedimentology of the Ravalli Group, Middle Belt Carbonate and Missoula Group, Middle Proterozoic Belt Supergroup. MBMG Special Publication 94, pp. 85-124.