# University of Alberta

Stratigraphy, sedimentology and chronology of the Eagle River meltwater channel and braid delta, northern Yukon

by

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# Chapter 1: Introduction

The Eagle River meltwater channel is a 140 km glacial lake spillway oriented north-northwest through an unglaciated region of northern Yukon. The channel, now occupied by the under-fit Eagle River, diverted water from glacial Lake Hughes in the Bonnet Plume Depression to the inter-connected drainages of the Bluefish, Old Crow and Bell basins (Figure 1-1; Hughes, 1969). The timing of meltwater diversion northward via the Eagle River meltwater channel has been used as a proxy for the timing of the maximum position of the northwest lobe of the Laurentide Ice Sheet, however, records of meltwater channel activation have so far largely been obtained from the more distal Old Crow and Bluefish basins. While the mechanism behind the formation of the channel is largely known, the channel itself has never been examined in detail for evidence of its age, flood dynamics, or depositional environments. The channel remains the keystone of a controversial chronology for the northwest margin of the Laurentide Ice Sheet, despite a lack of detailed information regarding its genesis. This thesis reports on characteristics of the Eagle River meltwater channel and attempts to resolve some of the outstanding issues surrounding its timing and genesis.

## Regional Setting

The study area lies within the physiographic regions of the Eagle Lowland and Porcupine Plateau, described by Bostock (1948) as a long, shallow depression between the Richardson, British, and Ogilvie mountains (Figure 1-1). Structural depressions developed in the region include the Bell, Bluefish and Old Crow basins. Along the northeast edge of the study area, the Richardson Mountain belt is a broad, northwest-trending anticline bounded by a series of north-trending strike-slip faults with up to 40 km of dextral displacement (Norris, 1985). Uplift of the Richardson Mountains took place primarily by east-west convergence during the Cordilleran Orogeny of the latest Cretaceous or Early Tertiary (Lane, 1996). Strong seismicity has been recorded in the

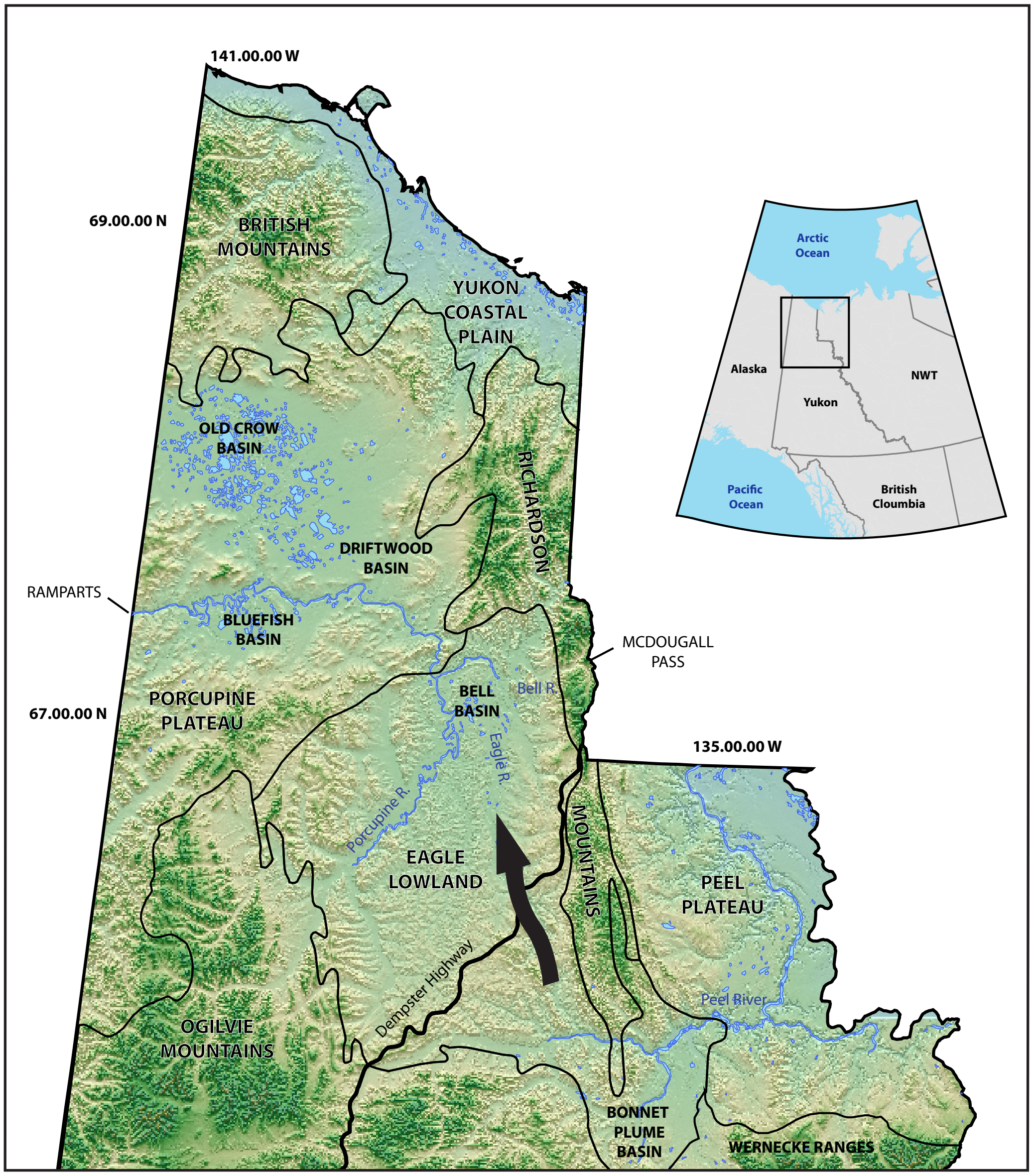


*Figure 1-1: Study area location map with regional physiographic regions outlined. Eagle River meltwater channel indicated with arrow.*

Richardson Mountains and neo-tectonic movement is likely in the form of strike-slip faulting at a rate of ~4 mm/year (Hyndman et al., 2005).

The Eagle River meltwater channel lies on the western edge of the Richardson Anticlinorium within the Richardson Trough; a Paleozoic deep water basin characterized by shale and slope-debris breccias shed off the flanking carbonate banks of the Eagle and Interior Platforms (Figure 1-2; Gabrielse and Yorath, 1991). The upper meltwater channel is cut into soft shale of the Early Carboniferous Ford Lake Formation which has resulted

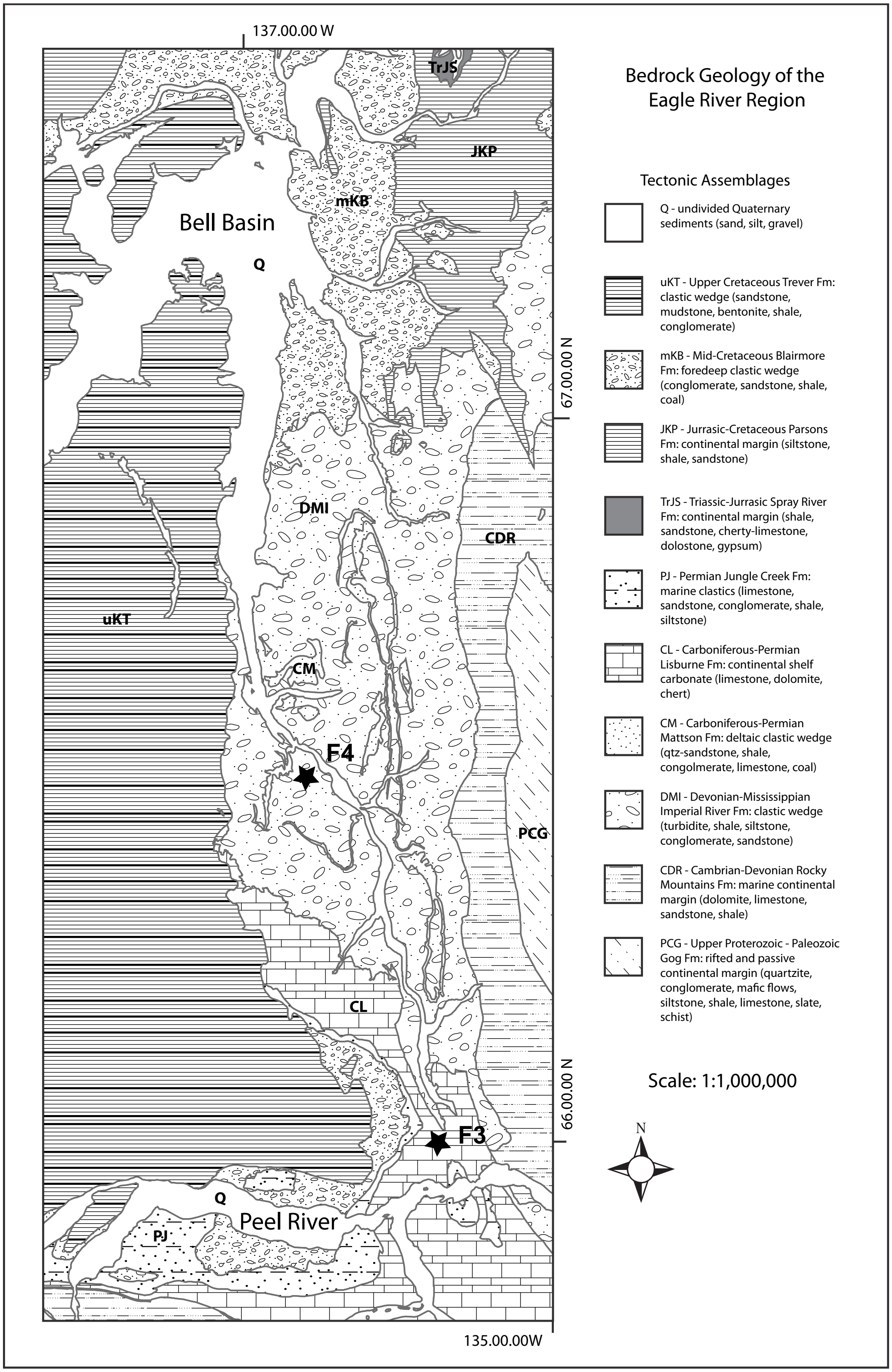


*Figure 1-2: Distribution of primarily shale and carbonate lithologies along the Eagle River melt-water channel (modified from Gordey and Makepeace, 1999). The locations of Figures 3 and 4 are shown by F3 and F4, respectively.*


Figure 1-3: Box-shaped canyon of upper meltwater channel in soft Ford Lake shale.

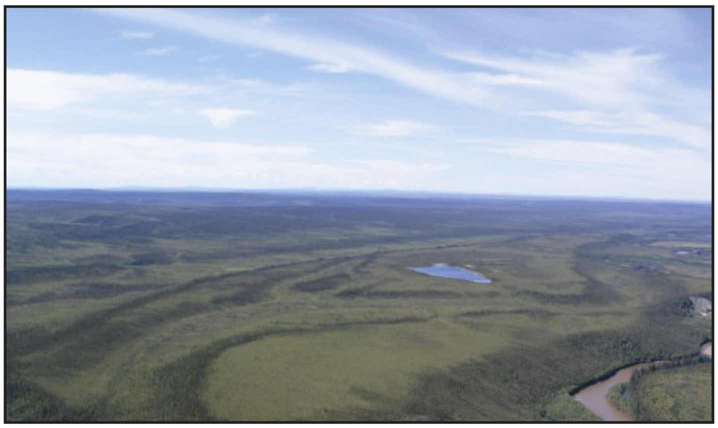
Figure 1-4: Broader and shallower mid-channel developed in coarser-grained Tuttle Formation.

in a distinctive box-shaped canyon (Figure 1-3). Mid-way along the channel the lower Ford Lake Formation grades into underlying interbedded sandstone and shale of the Late Devonian to Early Carboniferous Tuttle Formation (Lane et al., 2007). Beginning as thin sand ribs interbedded with shale and siltstone laminea, the Tuttle Formation coarsens into a chert-pebble conglomerate and quartz and chert sandstone toward its lower contact with the Late Devonian sandstone-dominant Imperial Formation (Lane et al., 2007). The morphology of the channel changes with the increasing resistance of coarser-grained bedrock units and becomes broader and shallower toward its northern conclusion (Figure 1-4).

The confluence of the Eagle and Bell Rivers marks the termination of the Eagle River meltwater channel. The lower Eagle and Bell rivers join the Porcupine River in the Bell Basin; a low, flat area ~45 kilometres in diameter whose surface is dotted with ponds, lakes and swamps. This flat surface is the result of lakes that were impounded in the basin during the Pleistocene and is matched by flat-lying wetlands in the Driftwood, Bluefish and Old Crow basins. Pre-glacial drainage of the Bell, Porcupine, Eagle, and Old Crow basins was eastward through McDougall Pass (Figure 1-1) in the northern Richardson Mountains and ultimately into the Arctic Ocean via the paleo-Porcupine

River (Duk-Rodkin and Hughes, 1995).

The unique landscape of flat bogs and thermokarst ponds in the northern Yukon basins is supported by near continuous frozen soils and mean annual air temperatures of -7.5 °C (Yukon Ecoregions Working Group, 2004). Soils are typically Turbic Cryosols in low lying areas with active layer depths ranging from 30 cm to 90 cm (Smith et al., 1991). Well-drained south-facing slopes and alluvial deposits support Dystric Brunisols and can be free of permafrost (Tarnocai, 1987). Soil capacity is relatively low and summer rain storms are frequently responsible for hydrographic peaks (Yukon Ecoregions Working Group, 2004). Annual precipitation is limited (~400 mm) and falls primarily as summer rain. Winter stream flow is very low and many streams in the region are dry in the late fall and winter (Yukon Ecoregions Working Group, 2004).

Economic development in the region is limited to services along the Dempster Highway corridor. However, many of the Yukon's petroleum reserves are located in the Eagle Plains area and are likely to experience increasing development pressure in the future. Recently, the North Yukon Land Use Planning Commission identified the development of aggregate resources in the region as a priority to facilitate future and ongoing development (North Yukon Planning Commission, 2007).

**Quaternary Geology**

The earliest recorded observations of Quaternary sediments in northern Yukon resulted from an 1888 exploration of the Mackenzie, Bell, and Porcupine rivers by R.G. McConnell (McConnell, 1889). McConnell documented the lack of glacial sediments west of the Richardson Mountains and proposed that continental ice sheets did not extend west of the Cordillera in this region (McConnell, 1889). However, specific glacial source areas and limits did not become clear until Bostock's (1948) descriptions of the northern Canadian physiography compiled with the aid of aerial photographs. Bostock (1948) demonstrated the Richardson Mountains had never supported local ice and that continental ice had affected only their eastern flanks. He also documented the maximum westerly advance of the Laurentide Ice Sheet in the Bonnet Plume Depression, describing a west-flowing lobe occupying the flat plateau between the Richardson and Mackenzie Mountains (Bostock, 1948).

Following this early work, Hughes (1969) described flights of paleo-shorelines and thick, unconsolidated deposits in the Bell, Bluefish and Old Crow basins and suggested a glacial lake mechanism to explain them. Hughes outlined the maximum extent of the Laurentide Ice Sheet along its northwestern margin and identified at least one less-extensive limit (Hughes, 1972). The maximum western limit follows the eastern

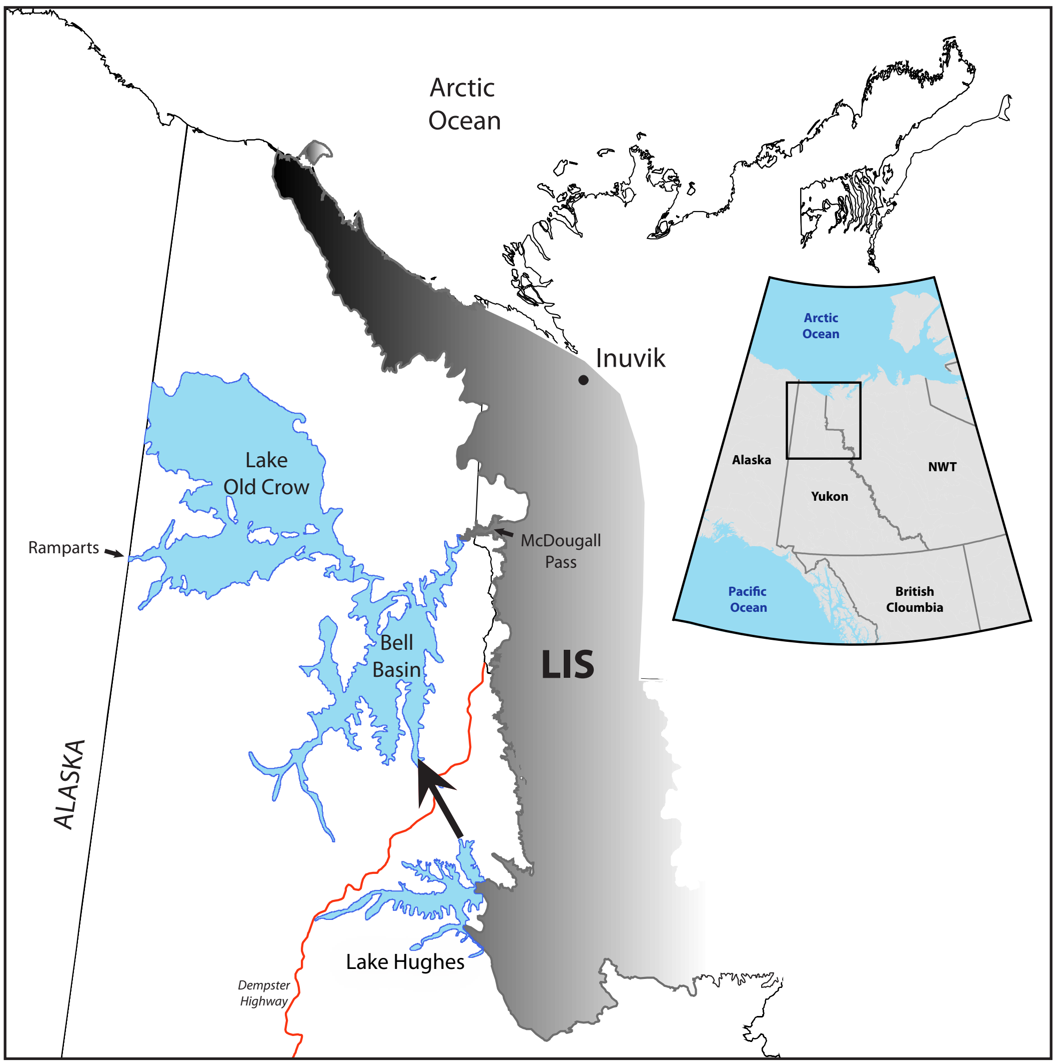


*Figure 1-5: Laurentide glacial limits (LIS) following the Yukon Coastal Plain, along the Richardson Mountain front and into the Bonnet Plume Basin. Hypothesized glacially-impounded lakes are shown in the Old Crow, Bell and Bonnet Plume basins. Routing of the Eagle River meltwater channel is indicated with arrow oriented NNW between Lake Hughes and the Bell Basin.*

flanks of the Richardson Mountains from the Yukon Coastal Plain south into the Bonnet Plume basin with smaller lobes extending into the Upper Rat River drainage to the summit of McDougall Pass, and into tributaries of the Peel River (Figure 1-5).

Based on sediments in Old Crow Basin, Hughes (1969) proposed two separate phases of ice advance and glacial lake impoundment in the Bonnet Plume, Bell and Old Crow basins and suggested these events took place in the early- or pre-Wisconsin (90-70,000 years BP) and late-Wisconsin (~20,000 years BP). More recent work in these basins has modified, but not significantly changed the original scenario outlined by Hughes (1972). Although Hughes (1969) defined nine stratigraphic units in the Old Crow basin, they are generally simplified into four primary units (Figure 1-6).

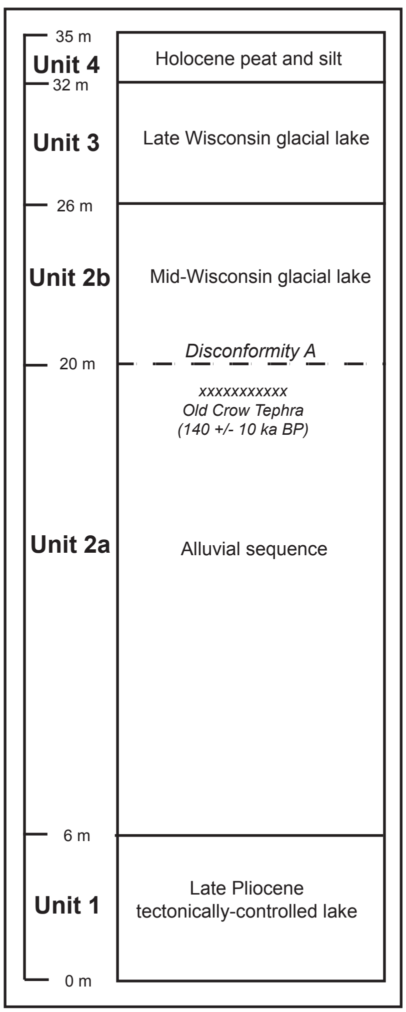


*Figure 1-6: Simplified stratigraphy of the Old Crow Basin based on Hughes (1972).*

The lowermost unit (Unit 1), originally interpreted as the first transgression of glaciolacustrine water into the basin (Hughes, 1972), has since been reinterpreted to be a tectonically-controlled period of sedimentation during the non-glacial Pliocene or early Pleistocene (Pearce et al., 1982; Westgate et al., 1985; Schweger, 1989). Unit 2 was described by Hughes (1972) as 20-30 m of bedded sand, silt, and minor gravel, and interpreted to represent a period of non-glacial fluvial, deltaic and lacustrine sedimentation. Large-scale cut-and-fill structures, ice wedge casts, cryoturbation structures and paleosols are common throughout the unit (Matthews et al., 1987), and indicate periods of sub-aerial exposure. Old Crow tephra, dated at 140 ± 10 ka BP (Westgate et al., 1990), occurs approximately 1-2 m below a widespread erosional unconformity, documented by Morlan (1980) as Disconformity ‘A’. This disconformity is associated with both ice wedge casts and laterally extensive paleosols that potentially represent warmer conditions than present (Matthews et al., 1987; Schweger and Matthews, 1991). Above the disconformity, the alluvial sediments of Unit 2b were originally interpreted by Hughes (1972) to represent a renewal of alluvial basin filling following the erosional event responsible for Disconformity ‘A’, but have subsequently come to be interpreted as a mid-Wisconsin glaciolacustrine unit (Matthews et al., 1987). Unit 3, unfossiliferous glaciolacustrine clay, overlies Unit 2b conformably and is interpreted as a late-Wisconsin glacial lake deposit (Hughes, 1972). The sediments of Units 2b and 3 are generally referred to as deposits of a 13,000 $km^2$ glacial ‘Lake Old Crow’ (Lemmen et al., 1994; Duk-Rodkin et al., 2004; Zazula et al., 2004) that occupied the inter-connected basins of the Bell, Bluefish and Old Crow rivers (Figure 1-5). The uppermost unit in this sequence (Unit 4) consists primarily of peat, silt and organic sediments of Holocene age (Hughes, 1969).

The reinterpretation of Unit 2b sediments as glaciolacustrine (rather than alluvial) is based largely on pollen samples collected through Units 2 and 3 by Walde (1985). Incision of the upper Eagle meltwater channel into soft shale of the Ford Lake Formation was suggested to have supplied the pre-Quaternary palynomorphs found in sediments above Disconformity ‘A’ in the Old Crow Basin (Walde, 1985). Initial incision of the meltwater channel requires impoundment of the Peel River drainage, a situation possible only when the northwest lobe of the Laurentide Ice Sheet is near its maximum position. Subsequently, Disconformity ‘A’ was interpreted to represent the onset of glacial conditions and the transgression of a mid-Wisconsin glacial meltwater lake into the Old Crow basin (Matthews et al., 1987). The interpretation of Unit 2b as glaciolacustrine sedimentation has resulted in the unit being used as a chronostratigraphic proxy in the Old Crow basin for the maximum advance of the Laurentide Ice Sheet in northwestern North America. Problematically, radiocarbon dating of Unit 2b has provided a maximum for the northwest margin that is largely asynchronous with other regions of the ice sheet (Dyke et al., 2002).

The most recently published chronology of glacial Lake Old Crow results from detailed dating of plant macrofossils in Bluefish basin and suggests the upper lake sediments (Unit 3) were deposited by a late-Wisconsin glacial lake that flooded the basins between 16-18 $^{14}$C ka BP (Zazula et al., 2004). This date is in agreement with a southwestern LIS maximum after 20 $^{14}$C ka BP (Dyke et al., 2002) and the recessional Katherine Creek Phase of the Mackenzie Mountains *ca*. 21 $^{14}$C ka BP (Duk-Rodkin and Hughes, 1995). These dates are further constrained by ice free conditions in central Alberta prior to *ca*. 21 $^{14}$C ka BP and after *ca*. 11 $^{14}$C ka BP (Burns, 1996).

However, Zazula et al. (2004) attribute the lower lake sediments (Unit 2b) to a mid-Wisconsin (at least 30 $^{14}$C ka BP) maximum advance of the Laurentide Ice Sheet into the Richardson Mountains and Peel Plateau that activated the Eagle River meltwater channel and resulted in a series of short-lived lakes in the Old Crow and Bell basins. The timing of this event is based on mapping and dating of 'all-time' glacial limits by Duk-Rodkin et al. (1996) to *ca*. 30 $^{14}$C ka BP, and radiocarbon ages from Unit 2b ranging from ~31 to 36 $^{14}$C ka BP (Lichi-Federovich, 1973; Lowdon and Blake, 1979; Morlan, 1980, 1986; Walde, 1986; Morlan et al., 1990; Schweger and Matthews, 1991).

Elsewhere in North America the mid-Wisconsin (27-30 $^{14}$C ka BP) is a time of reduced ice cover, when the margins of the ice sheet were thought to have roughly followed the outline of the Canadian Shield (Dyke et al., 2002; Dyke and Prest, 1987). The interpretation of Laurentide ice near its maximum position in the Richardson Mountains at *ca*. 30 $^{14}$C ka BP is significantly out of phase with continental-scale reconstructions of the ice sheet. In the Old Crow Basin, a continuous series of AMS radiocarbon ages of 24-40 $^{14}$C ka BP on allochthonous mammal bones are evidence that any glacial lakes prior to 24 $^{14}$C ka BP must have been short-lived (Morlan, et al., 1990). Furthermore, plant macrofossils collected from within sediments of Unit 2b during the summer of 2006 were dated by D. Froese and have returned dates between 40-44 $^{14}C$ ka BP, indicating deposition may be much older for that unit than previously considered (Froese et al., 2007). Coupled with other evidence from the region these new dates on the sediments of Unit 2b present the possibility that Unit 2b may not represent sedimentation by a pro-glacial lake created by the advance of Laurentide ice.

The glaciolacustrine interpretation of Unit 2b is based on the presence of Paleozoic palynomorphs identified by Walde (1985); however, the connection between these palynomorphs and the Eagle River meltwater channel remains tenuous. If the pre-Quaternary palynomorphs of Units 2b could have provenance elsewhere than the strata cut by the Eagle meltwater channel, there is no necessary link between the sediments of Unit 2b in the Old Crow basin and Laurentide-induced drainage diversions into the Bell Basin. The Eagle River meltwater channel and braid delta complex provide an alternative and more direct proxy for the northwest Laurentide maximum than does the stratigraphy of the Old Crow Basin. Characterizing the timing and nature of meltwater flooding along the Eagle River meltwater channel will contribute to reconstructing the timing of the northwest Laurentide maximum, and may also serve to elucidate ongoing investigations of the Old Crow Basin's stratigraphy.

**Thesis Objectives**

The objective of this thesis is to characterize the timing and genesis of the Eagle River meltwater channel using stratigraphy, sedimentology and regional mapping as a basis of investigation. In accomplishing this objective, the thesis will provide a model of flood channel development and describe the distribution of surface materials related to the flood. The surface materials will be assessed for their suitability as aggregate resources to facilitate economic development in the region. The thesis will also employ stratigraphy and sedimentology to characterize the depositional environment of fine-grained rhythmically-bedded sediments in the Bell Basin. Radiocarbon dating will be used to establish the age of these sediments, infer their relations to the Laurentide Ice

Sheet, and attempt to correlate them with other fine-grained sediments in adjacent basins in northern Yukon.

The first chapter of the thesis has introduced the regional setting of the study area, outlined previous Quaternary research, identified problems with the existing chronologies, and provided rationale for the pursuit of this thesis. The second chapter is in the form of a paper titled "*Aggregate resource exploration using a process-depositional model of meltwater channel development in the Eagle Plains area, northern Yukon*", and describes results related to flood channel development and related surface deposits. The paper assesses the aggregate resource potential of Quaternary deposits along and adjacent to the Eagle River meltwater channel and outlines exploration targets for future development. The third chapter of the thesis is a paper titled "*LGM age for the NW Laurentide maximum from the Eagle meltwater channel and braid delta complex, northern Yukon*". This paper details the fine-grained stratigraphy and sedimentology of Bell Basin sediments and provides an explanation for these deposits. The timing of meltwater channel development is discussed in the third chapter and evidence for its age is presented. Finally, using chronologies from around the northwest margin, the third chapter will discuss the relationships between the Eagle River meltwater channel, the Laurentide Ice Sheet, and the glacial lake histories of the unglaciated basins in northern Yukon. The fourth and final chapter of the thesis summarizes results presented in both paper-based chapters and relates these to the thesis motivation and objectives.

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## Chapter 2: Aggregate resource exploration using a process-depositional model of meltwater channel development in the Eagle Plains area, northern Yukon[1]

### Introduction

The Eagle River lies on the eastern edge of Beringia– the landmass including northern Yukon, Alaska and Siberia that remained ice-free throughout the Pleistocene (past 2 million years). Soft bedrock (predominantly shale) in the area has been subjected to an extended period of in-situ weathering that has produced a landscape characterized by frozen, deeply weathered, silt-rich soils. These fine-grained soils, coupled with continuous permafrost, have made road and infrastructure development expensive, logistically challenging, and difficult to maintain. This study examines deposits associated with the late Pleistocene Eagle River meltwater channel and the application of a process-depositional model to aggregate resource exploration in the Eagle Plains region (Figure 1).

Hughes (1969), following earlier work by McConnell (1889) and Bostock (1948), described flights of paleo-shorelines and thick, unconsolidated deposits in the Bell, Bluefish and Old Crow basins, and suggested the area had formerly contained large glacial lakes (Figure 2). Hughes (1969) proposed that one or more advances of Laurentide ice against the Richardson Mountains and onto Peel Plateau, blocked easterly drainage of the Mackenzie River tributaries in northern Yukon. Glacially-dammed water in the Bonnet Plume basin was diverted into Bell basin through a meltwater channel occupied by the modern Eagle River (Figure 2). This diversion rapidly incised the Eagle channel and initiated drainage of meltwater from the Bonnet Plume basin into the Bell, Bluefish and Old Crow basins, forming glacial Lake Old Crow. The surface of this lake eventually overtopped the divide of the paleo-Porcupine River system establishing

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1 A version of this chapter has been published as: Kennedy, K. and Froese, D., 2008. Aggregate resource exploration using a process-depositional model of meltwater channel development in the Eagle Plains area, northern Yukon. *In:* Yukon Exploration and Geology 2007, D. S. Emond, L. R. Blackburn, R. P. Hill and L. H. Weston (eds.), Yukon Geological Survey, p. 169-178.

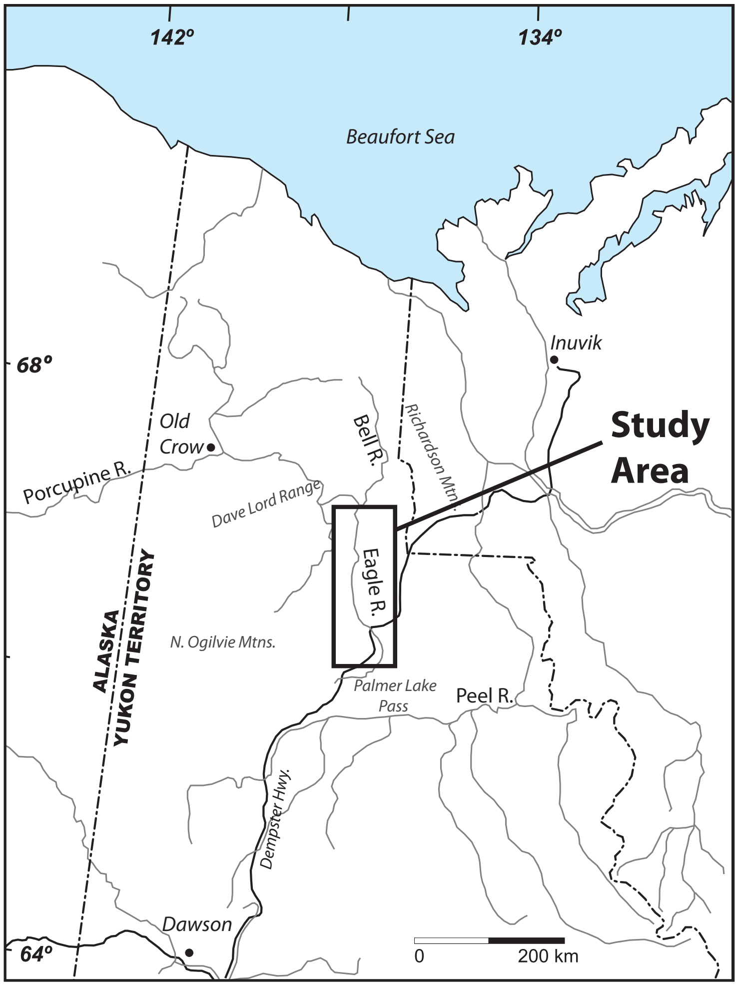


*Figure 2-1: Location of study area.*

westerly drainage of the Porcupine River into central Alaska (Thorson and Dixon 1983; Duk-Rodkin et al., 2004).

*Pleistocene chronology*

Flooding of the Eagle River meltwater channel is intimately connected with extensive continental ice in the western Mackenzie basin blocking drainage from the Richardson Mountains south to the Bonnet Plume basin. Meltwater flooding in the Eagle River channel requires the Laurentide Ice Sheet in northwestern North America to be near its maximum extent. Radiocarbon dates have been collected from the eastern Richardson Mountains, and Bell, Old Crow and Bluefish basins, and applied to the stratigraphy in Old Crow basin to produce a chronology for the northwestern Laurentide Ice Sheet. These dates suggest an extensive advance occurring at least 30,000 $^{14}$C yrs BP (ka BP), followed by a later, less extensive advance *ca.* 16-18 ka BP (Duk-Rodkin et al., 2004; Zazula et al., 2004). Both advances are thought to have activated the Eagle River meltwater channel and created continuous, glacially-dammed lakes in the Bell, Bluefish and Old Crow basins. Recent investigations in the Old Crow area suggests that lake sediments in Old Crow basin, originally thought to represent the maximum advance of the Laurentide Ice Sheet at *ca.* 30 ka BP, may have been deposited more than 40 ka BP and be non-glacial in origin (Froese et al., 2007). This suggests that a tectonically-controlled basin existed in the Old Crow area prior to meltwater additions associated with the Laurentide Ice Sheet, and only a single late Pleistocene advance may have affected the area (Froese et al., 2007).

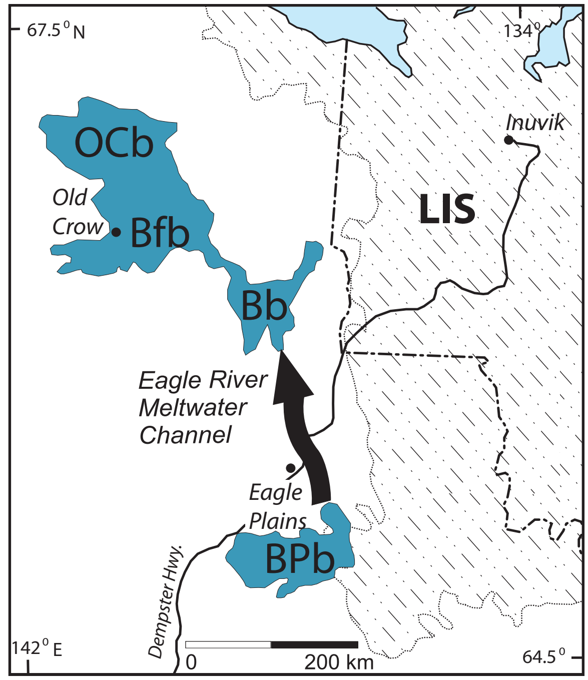

*Figure 2-2: Glacial lakes (shaded areas) formed by the impoundment of east-flowing drainages by the Laurentide Ice Sheet (LIS-hatched pattern). The Eagle River meltwater channel linked a lake in Bonnet Plume basin (BPb) with a continuous lake in Bell (Bb), Bluefish (Bfb) and Old Crow (OCb) basins.*

**Regional setting**

The Eagle Plains ecoregion is a rolling lowland between the Richardson, North Ogilvie and Dave Lord Mountain ranges (Figures 1 and 3). Relief is subdued and draped with colluvial deposits that thicken downslope from veneer-covered ridges. West of the Eagle River, drainages are dendritic with broad v-shaped valleys separated by long rounded ridges (Thomas and Rampton, 1982). East of the Eagle River, drainages are more deeply incised with distinct pediment surfaces related to late-Tertiary uplift of the Richardson Mountains (McNeil et al., 2001). Regional bedrock is dominated by deep marine basinal rocks. Early Carboniferous shale of the Ford Lake Formation is exposed along most of the upper Eagle River and grades laterally into the underlying Tuttle Formation that outcrops on lower reaches of the Eagle River (Norris, 1997; Lane, 2007). Continuous permafrost underlies all materials in the region and can reach local depths of at least 89 m with active layer depths of 20 to 90 cm (Yukon Ecoregions Working Group, 2004).

**Process-depositional models**

Process-depositional models have been developed to understand the formative

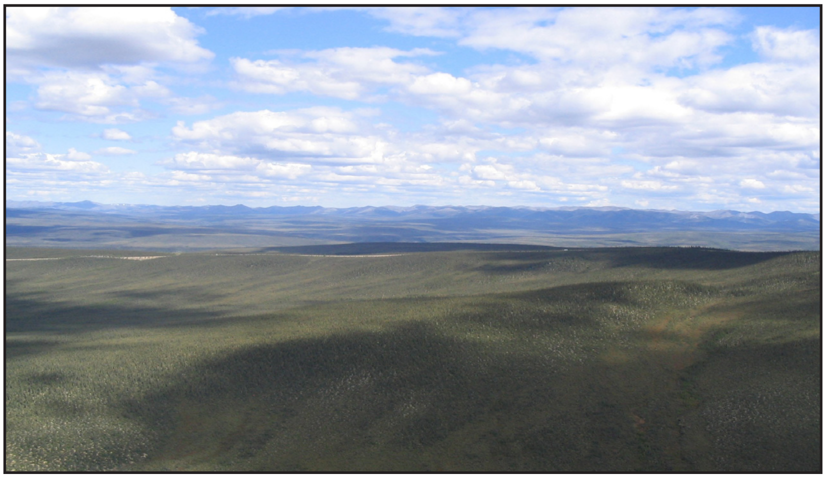

*Figure 2-3: Easterly view of the Eagle Plains area toward the Richardson Mountains. The Dempster Highway is visible in the middle of the photo.*

mechanisms of surficial geologic units and to explain and predict their distribution (Fisher and Smith, 1993). This method has been used successfully to understand the distribution of aggregate resources associated with catastrophic flooding along the margins of the Laurentide Ice Sheet in North Dakota (Lord and Kehew, 1987) and northeastern Alberta (Fisher and Smith, 1993). Process-depositional models for meltwater channels incorporate unique hydrological characteristics of glacial lake outburst floods that differ from traditional paleohydraulic calculations (Lord and Kehew, 1987). Glacial lake outburst channels have relatively consistent channel widths, high depth-to-width ratios, discrete cutbanks, and limited deposition as a result of highly erosive hyper-concentrated flow (Lord and Kehew, 1987).

Development of meltwater outburst channels is thought to occur in three phases (Lord and Kehew, 1987; Fisher and Smith, 1993; O'Connor, 1993). First, initial incision and channel expansion. This is the most erosive phase of flooding and will often dominate for significant distances beyond the drainage divide. Sediment is entrained and carried in suspension with little deposition taking place. Second, development of channelized flow; likely caused by changes in paleo-topography or flood energy, erosive capability is reduced as energy decreases and channel incision begins. This often results in deposition in areas of reduced velocity along channel margins with deposition of pendant bars (channel-attached bars) and back-flooding of tributary junctions (slackwater sedimentation). The final phase in the development of meltwater channels is the deposition of remaining fine-grained suspended sediments (sand, silt and clay). This final deposition may occur in the form of an extensive delta plain if the flows go into a proglacial lake; otherwise, slackwater sedimentation may occur where flow is impinged through a narrowing of the channel. The ultimate distribution of erosion and sedimentation in individual channels is dependent on the nature of bedrock composition and resistance to erosion, surficial geology cover materials and thickness, flood power, duration and volume, and the presence and characteristics of pre-existing valley systems occupied by the flood (Lord and Kehew, 1987; O'Connor, 1993).

**Methods**

We identify aggregate resources along the Eagle meltwater channel using a process-depositional model of flood channel evolution following similar work by Fisher and Smith (1993) applied to the Fort McMurray region. In order to do this, landforms and surficial materials were identified along the length and breadth of the spillway channel using 1:60 000 and 1:70 000-scale aerial photography along with previously published surficial and bedrock geological maps at scales ranging from 1:100 000 to 1:250 000. Landforms were identified, mapped and field-checked during the summer of 2007. At select sites, detailed sedimentologic descriptions were completed to record surficial units exposed in section along the Eagle River and its tributaries. The distribution, composition and characteristics of landforms were then used to reconstruct paleohydraulic conditions and predict zones of coarse aggregate deposition.

**Results**

The Eagle meltwater channel can be divided into three distinct reaches (upper, middle and lower) based on the distribution of erosion and deposition along the meltwater channel, and quality and quantity of aggregate deposits along its length. (Figure 4)

*Upper Reach (~50 km)*

The upper reach of the Eagle channel is characterized by a narrow, steep-walled canyon almost entirely void of flood deposits (Figure 5). The flood channel begins ~60

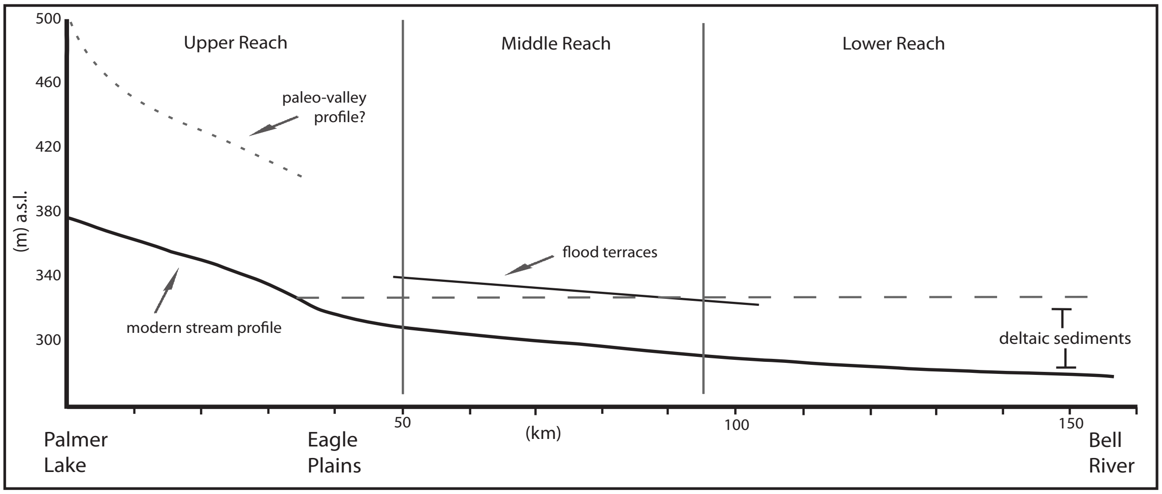


*Figure 2-4: Longitudinal cross section of the modern Eagle River stream profile and the hypothesized paleo-Eagle River profile with locations of flood terraces and the area of deltaic sedimentation. The distribution of erosion and deposition along the channel results in three distinct (upper, middle and lower) reaches for aggregate resource assessment. Vertical scale is exaggerated four times the horizontal scale (VE = 4x).*

*Figure 2-5: Steep valley sides and flat valley floor of the upper channel at Palmer Lake Pass. View is to the south.*

km upstream of the Dempster Highway bridge near the drainage divide at Palmer Lake (Figure 1). The valley bottom is flat and ranges from 500-1500 m wide with steep-sided valley walls up to 200 m high. The valley bottom is poorly drained and organic soils are thick and well-developed. Above the escarpment, surficial materials are composed of thick colluvial deposits, with only minor evidence of flood erosion (Figure 6). Pediment surfaces are well-developed on the slopes above both margins of the channel's upper reach, suggesting this area may have been a high drainage divide prior to meltwater re-routing. The upper reach has the highest topographic relief in the study area.

*Middle Reach (~45 km)*

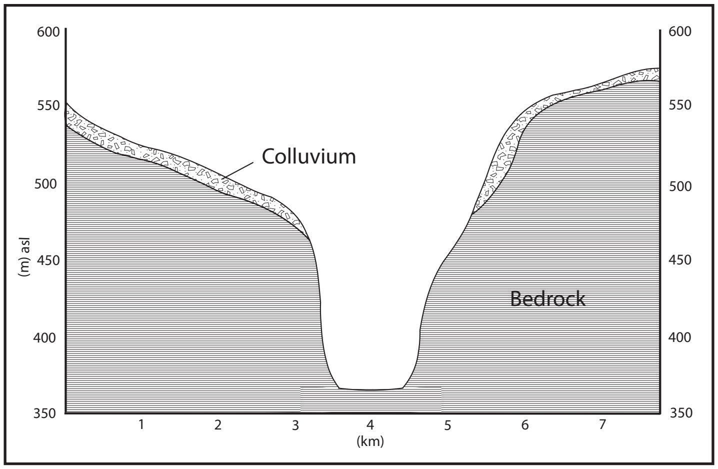


*Figure 2-6: Schematic cross-section of the upper reach of the Eagle meltwater channel. Steep bedrock on the valley sides is blanketed by colluvial deposits that have likely been formed over long periods of periglacial weathering. (VE = 20x)*

The middle reach contains the most prospective aggregate deposits in the Eagle River meltwater channel. Beginning ~10 km upstream of the Dempster Highway bridge the middle reach of the channel is characterized by high, broad bedrock terraces often overlain with flood-deposited gravel and sand (Figures 7 and 8). Terraces are located at elevations of 340-360 m a.s.l. (20-30 m above the modern alluvial plain) and are well-developed on the outside bends of the channel and at the junctions of tributary valleys (Figure 9). Observed thicknesses of terrace deposits range from <1 m to >5 m, and are generally between 1 and 3 m. Terraces near Eagle Plains are ~500 m wide by up to 2 km long.

Terrace deposits are composed of pebble-cobble gravel (clast sizes with b-axis lengths ranging from 0.5-30 cm with rare boulders up to 50 cm), with a coarse sand matrix-fill. Results of limited sampling of terrace deposits for grain size distributions are shown in Table 1. Clasts are imbricate downvalley, rounded-to-tabular in shape, and most deposits are moderate-to-well-sorted.

*Figure 2-7: View downstream of the Eagle River channel, highlighting multiple terrace levels of middle reach with scoured surfaces including shallow lakes. Channelized flow in the middle reach initiated deposition of coarse aggregate deposits.*

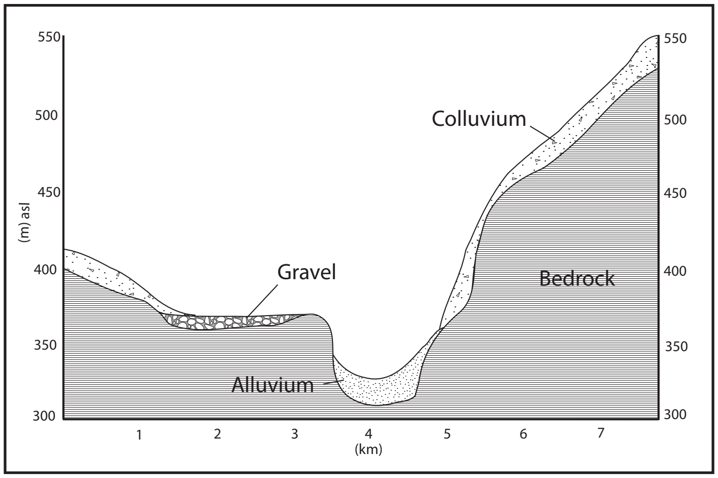


*Figure 2-8: Schematic cross-section of the middle reach of the Eagle meltwater channel. The broader channel in this reach allows for coarse gravel deposits to be preserved above bedrock terraces. (VE = 20x)*

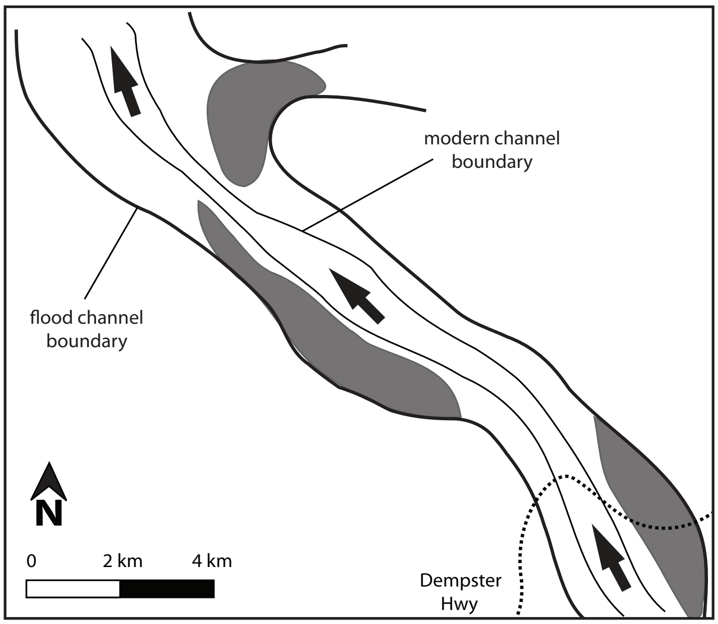


*Figure 2-9: Schematic view of the middle reach of the Eagle meltwater channel with shaded areas outlining coarse gravel deposits on the outside bends and at tributary junctions of the channel.*

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Gravel (>4.75 mm) | 80% | 67% | 59% | 61% |
| Sand (<4.75 mm & >0.075 mm) | 16% | 30% | 37% | 35% |
| Silt (<0.075 mm & >0.002 mm) | 2% | 2% | 2% | 2% |
| Clay (<0.002 mm) | 2% | 1% | 2% | 2% |

*Table 2-1: Grain size distribution (% by weight) of four aggregate samples from terraces in the middle reach of the Eagle River.*

Field observations of clast lithology indicate about 90% of deposits are composed of locally-derived sandstone lithologies, with about 10% of clasts being shale or limestone with rare granite and gneiss.  These latter crystalline rocks are derived from the Canadian Shield and were transported by the Laurentide Ice Sheet and subsequent high-energy flooding along the channel, probably as ice-rafted clasts. Slackwater sediments were


*Figure 2-10: Upstream-trending slackwater deposits above an erosional bedrock contact on a tributary to the Eagle River. Tributary flow is toward the left, and steep cross-beds in sandy slackwater deposits indicate flow was to the right (upstream) when they were deposited. Section is approximately 30 m high.*


*Figure 2-11: View of deltaic sediments blanketing the lower reach of the Eagle River. Flow of the river is toward the bottom of the photo, and the delta top is ~20 m above the river surface.*

documented in the middle reach of the Eagle River channel 30 km downstream from the Dempster Highway bridge with surface elevations of ~340 m a.s.l. (Figure 10). Importantly these deposits are identified by their up-stream paleo-current indicators, representing back-flooding of tributary valleys. This provides a robust elevation for the flood water surface in this reach.

Valley bottom sediments in the middle reach of the channel are coarser than those found in the upper reach due to contributions of coarse material from tributary streams. The channel bottom is armored in cobbles, most of which is likely a local lag associated with downcutting of tributaries and reworking of terrace gravel remnants.

*Lower Reach (~65 km)*

Terraces of the lower reach of the Eagle channel are dominated by fine-grained deltaic and lacustrine deposits (Figure 11). Beginning ~25 km downstream of the

*Figure 2-12: Stratified deltaic deposits within the lower reach. Massive clay alternating with ripple cross-laminated silt and fine sand.*

Dempster Highway bridge, the increasing thicknesses of fine sand, silt and clay obscure underlying deposits of flood material. Fine-grained deposits thicken downvalley reaching a thickness of at least 20 m near the junction with the Bell River. These deposits range from stratified sand and silt with rare clasts in the upstream part of the reach to massive clay beds alternating with beds of ripple cross-laminated fine sand and silt in the downstream reach (Figure 12). Massive clay beds have thicknesses up to 2 m near the base of exposures and thin upward as coarser-grained ripple crossbeds become thicker and more frequent. The top of the sediments display evidence of sub-aerial exposure (ice-wedge casts) and are overlain by up to 1 m of aeolian sand below a cap of modern peat deposits. Coarse aggregate materials may be present at depth, but are not visible where fine-grained sediments are thick.

**Interpretation of flood dynamics**

*Upper Reach*

The narrow canyon in the upper reach of the Eagle channel represents rapid erosion of bedrock and high-energy flooding. Following initial breach of the drainage divide, flood water was likely contained within the canyon in the upper reach and erosion was focused on downward incision. This incision is typical of early phase catastrophic flooding (*e.g.* Lord and Kehew, 1987) and was likely only minimally influenced by pre-existing topography. This initial phase of meltwater flow would likely have begun as a broad sheet of sediment-poor flood water as the divide between the Bonnet Plume and

Eagle basins was overtopped by proglacial meltwater associated with the Laurentide Ice Sheet. Rapid incision into underlying shale would have quickly incorporated large volumes of sediment, carried as suspended load, and flood water may have reached sediment loads typical of a hyper-concentrated flow (intermediate between clear stream flow and sediment-dominated debris flow).

*Middle Reach*

The broad terraces and coarse deposits of the middle reach of the Eagle channel represent a change in flow regime from a single channel to a distributed pattern with one primary channel and multiple secondary channels (Figure 7). This likely reflects changes in paleo-valley alignment or slope that initiated overtopping of the channel margins by flood water. These changes may also have been initiated as flood waters became channelized in a pre-existing paleo-Eagle valley system.

The middle reach of the Eagle channel remained dominantly erosional; however, lower velocity flow along the margin of the channel and into tributary junctions initiated deposition of coarse, cobble-pebble terraces and pendant (bank-attached) bars. Bedrock terraces are often, but not always, overlain by significant gravel deposits and can be found concentrated along outside bends of the meltwater channel reflecting expansion of flow onto these surfaces. Eddy or alcove bars are probably formed in tributary mouths as the result of deposition from back-flooding into valleys (Baker, 1973; O'Connor, 1993) (Figure 13). Upstream-trending cross-beds in slackwater sediments of tributary valleys (Figure 10) provide a minimum elevation of the flood surface, and additional support for the catastrophic nature of channel formation. Flooding likely remained hyper-concentrated in this reach, and deposition is largely limited to coarse material in areas of flow expansion.

Along the present-day Eagle River, continued adjustments in the base level of tributary valleys provide an important source of aggregate material to the alluvial plain of the Eagle River and those of its tributaries. Aggregate deposits in the active Eagle River

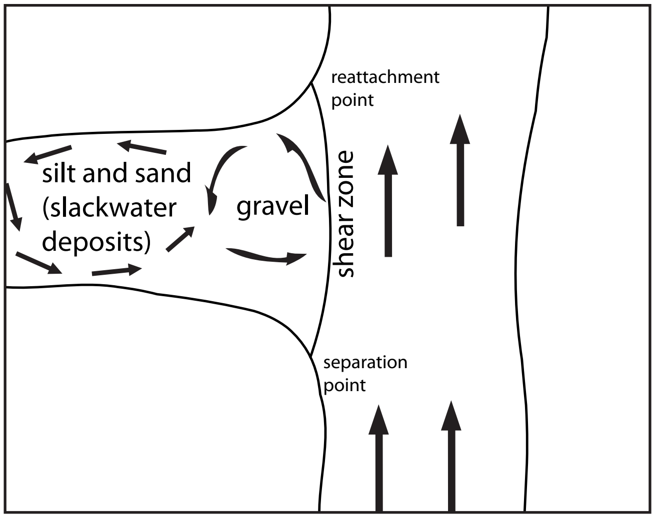

*Figure 2-13: Flow conditions associated with the formation of slackwater deposits. Flood water in the main channel inundates tributary valleys with turbulent flow that deposits coarse materials near the point of separation (at tributary junction) and finer material further up-valley in the tributary. Figure modified from O'Connor (1993).*

alluvial plain are concentrated at tributary junctions, and decrease in concentration downstream from the tributary, producing small fans of coarse deposition into the modern valley. Aggregate development on tributary alluvial plains may be preferred due to the low water levels present on these streams in the summer months.

*Lower Reach*

Thick occurrences of horizontally-stratified sand with interbedded silt up to 20 m thick are found across the lower reaches of the Eagle and Bell rivers and are interpreted as a braid delta built into the upstream extension of glacial Lake Old Crow. Crudely inverse (coarsening upward) grading of these deposits suggests these sediments represent the progradation of deltaic sedimentation into a shallow lacustrine basin. The deltaic sediments lack large cross-beds (foresets) further suggesting a shallow basin that likely aggraded as meltwater influx from the Eagle channel raised lake levels. These sediments and landforms are similar to the Athabasca braid delta at the mouth of the Clearwater-Athabasca meltwater channel in northeastern Alberta (Rhine and Smith, 1988).

Coarse aggregate deposits may be present below lacustrine and deltaic sediments in this reach, but would only be accessible near the basin margins where fine-grained deposits are thinner. Radiocarbon dating of lake sediments in Bluefish basin indicate a lake existed at ~300 m a.s.l. from 18-16 ka BP and may have extended into the Bell basin (Zazula et al., 2004). Flooding of the Eagle River meltwater channel likely contributed to the volume of the lake, and combined with meltwater-related sedimentation, raised lake levels in Bell basin to at least 340 m a.s.l. based on the elevations of deltaic deposits in this study.

**Discussion**

The distribution of erosional area, flood deposits, and deltaic sedimentation in the Eagle meltwater channel is consistent with existing models of flood channel evolution in a proglacial setting (Lord and Kehew, 1987; Fisher and Smith, 1993; O'Connor, 1993). Depositional and erosional features along the Eagle River meltwater channel closely resemble those of the late Pleistocene Clearwater-Athabasca spillway in northeastern Alberta (Fisher and Smith, 1993). The primary depositional landforms associated with both channels are deltaic and fine-grained, with relatively minor amounts of coarse deposition in middle reaches, and virtually no coarse deposition in upper and lower reaches.

The Eagle River meltwater channel differs from other documented spillways and meltwater channels because of the relatively small clast size in coarse deposits (boulders are common in most meltwater channel deposits). The presence of soft Ford Lake shale in much of the upper channel resulted in a deeply incised valley and few resistant clasts available for transport and deposition in the channel. Rare clasts of granite and gneiss occur in the basin, but likely represent ice-rafted deposition of material from the Bonnet Plume basin. The large volume of shale removed from the upper channel was likely carried as suspended sediment and transported through to the downstream lacustrine basins. Coarse deposits are mostly (>90%) sandstone, concentrated from limited availability in regional bedrock.

*Implications for aggregate resources*

Preferred road construction materials are 10-14% silt and clay (for binding), 35-70% sand and 20-60% gravel (Jeff Marynowski, pers. comm., 2007). The low percentages of silt and clay in sampled terrace deposits (Table 1) require that additional fine-grained materials are added to the deposits before they can be used for road construction. However, most terrace deposits in the middle reach of the Eagle meltwater channel are overlain by fine-grained lacustrine sediments that could easily be mixed at the time of extraction. Although sandstone is not a preferred granular material for aggregate resources, few other options exist in this region, other than crushing of local bedrock.

Economic development on the Dempster Highway corridor could be facilitated by additional research along the Eagle River meltwater channel to further define the quality and quantity of aggregate resources available in the channel's middle reach. Specifically, ground penetrating radar surveys, coupled with auger drilling and textural analyses would be useful in defining thicknesses, extents and materials available on different terraces or terrace levels in the area.

**Conclusions**

Aggregate in the Eagle Plains region is found primarily on high terraces formed by late Pleistocene flooding along the Eagle River associated with rerouting of Peel River drainage by the Laurentide Ice Sheet. These deposits, along with those found in the mouths of tributary valleys, are the result of specific paleohydraulic conditions that are typical of glacial meltwater channels. This study demonstrates the erosional and depositional features of the Eagle River meltwater channel fit well within the framework of process-depositional models used to describe meltwater channels. Process-depositional models have proven to be applicable to northern regions and a cost-effective model for developing aggregate resources.

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## Chapter 3: LGM age for the NW Laurentide maximum from the Eagle River meltwater channel and braid delta complex, Northern Yukon[1]

### Introduction

Reconstruction of the timing and dynamics of continental glacial events is important for the correlation of terrestrial stratigraphic and paleoenvironmental records with climate events recognized at the global scale, such as ice and marine cores. This is of particular importance for the Laurentide Ice Sheet where previous reconstructions of the northwestern lobe suggest its maximum extent was reached by *ca.* 30,000 $^{14}C$ yrs BP, or at least 10,000 yrs earlier than areas to the south along the western margin of the ice sheet (Lemmen et al., 1994; Duk-Rodkin et al., 2004; Zazula et al., 2004). This timing would indicate the northwestern margin of the Laurentide Ice Sheet was at its maximum during the late part of marine isotope stage (MIS) 3, a time of reduced global ice volume (Martinson et al., 1987). Alternatively, it has been argued on the basis of maximum ages of *ca.* 25,000 $^{14}C$ yr BP in the Old Crow basin, that this margin can be constrained as being 'broadly Last Glacial Maximum (LGM)' (Dyke et al., 2002). This latter view has been reconciled as only one stage in a prolonged Laurentide maximum that fluctuated along the margin giving an 'early Laurentide' model that may have persisted from 30,000 $^{14}C$ yrs BP to *ca.* 16,000 $^{14}C$ yrs BP (Duk-Rodkin et al., 2004; Zazula et al., 2004). Both models indicate the ice sheet was in retreat from its maximum position by ~16 ka $^{14}C$ BP.

These variant chronological models for the northwest margin of the ice sheet largely reflect differing interpretation of a series of radiocarbon ages associated with meltwater diversion of pre-Laurentide drainage into the unglaciated Old Crow Basin of northern Yukon, through its intermediary, the Eagle River meltwater channel. This paper focuses on the Eagle River meltwater channel complex which has been invoked as recording this early Laurentide maximum at *ca.* 30 $^{14}C$ ka BP in fine-grained sediments

1 A version of this chapter will be submitted for publication to the journal of Quaternary Science Reviews under the same title with additional authors: D.G. Froese, G.D. Zazula, and S. Kuzmina.

occupying the lower meltwater channel (Zazula et al., 2004; Duk-Rodkin et al., 2004). In particular it has been argued that these fine-grained sediments record an oscillating ice margin with repeated drainage of meltwater via McDougal Pass. Here, we report detailed geomorphic and sedimentologic descriptions of the Bell Basin and Eagle River meltwater channel to establish the origin of the sediments, their relations to the northwest Laurentide Ice Sheet, and the depositional setting of a new series of radiocarbon ages which provides an LGM age for the northwest Laurentide maximum extent.

**Regional Setting**

The study area lies within the physiographic region of the Eagle Lowland, a long, shallow depression between the Porcupine and Peel plateaus to the north and south, and the Richardson and Ogilvie Mountains to the east and west (Bostock, 1948; Figure 3-1). Along the northeast edge of the study area, the Richardson Mountain belt is a broad, northwest-trending anticline bounded by a series of north-trending strike-slip faults with up to 40 km of dextral displacement (Norris, 1985). Uplift of the Richardson Mountains took place primarily by east-west convergence during the Cordilleran Orogeny of the latest Cretaceous or Early Tertiary (Lane, 1996). Strong seismicity has been recorded in the Richardson Mountains and neo-tectonic movement is likely in the form of strike-slip faulting at a rate of ~4 mm/year (Hyndman et al., 2005).

The Eagle River lies on the western edge of the Richardson Mountains within a Paleozoic deep water basin characterized by shale and slope-debris breccias shed off the flanking carbonate banks of the Eagle and Interior Platforms (Gabrielse and Yorath, 1991). The bedrock geology between the Bonnet Plume and Bell basins grades northward from soft shale of the Early Carboniferous Ford Lake Formation into coarser-grained siltstones, fine sandstones and coarse lithic (primarily chert) sandstones of the Late Devonian to Early Carboniferous Tuttle and Imperial formations (Lane et al., 2007).

The lower Eagle and Bell rivers join the Porcupine River in the Bell Basin; a low, flat-lying area ~45 kilometres in diameter whose surface is dotted with ponds, lakes

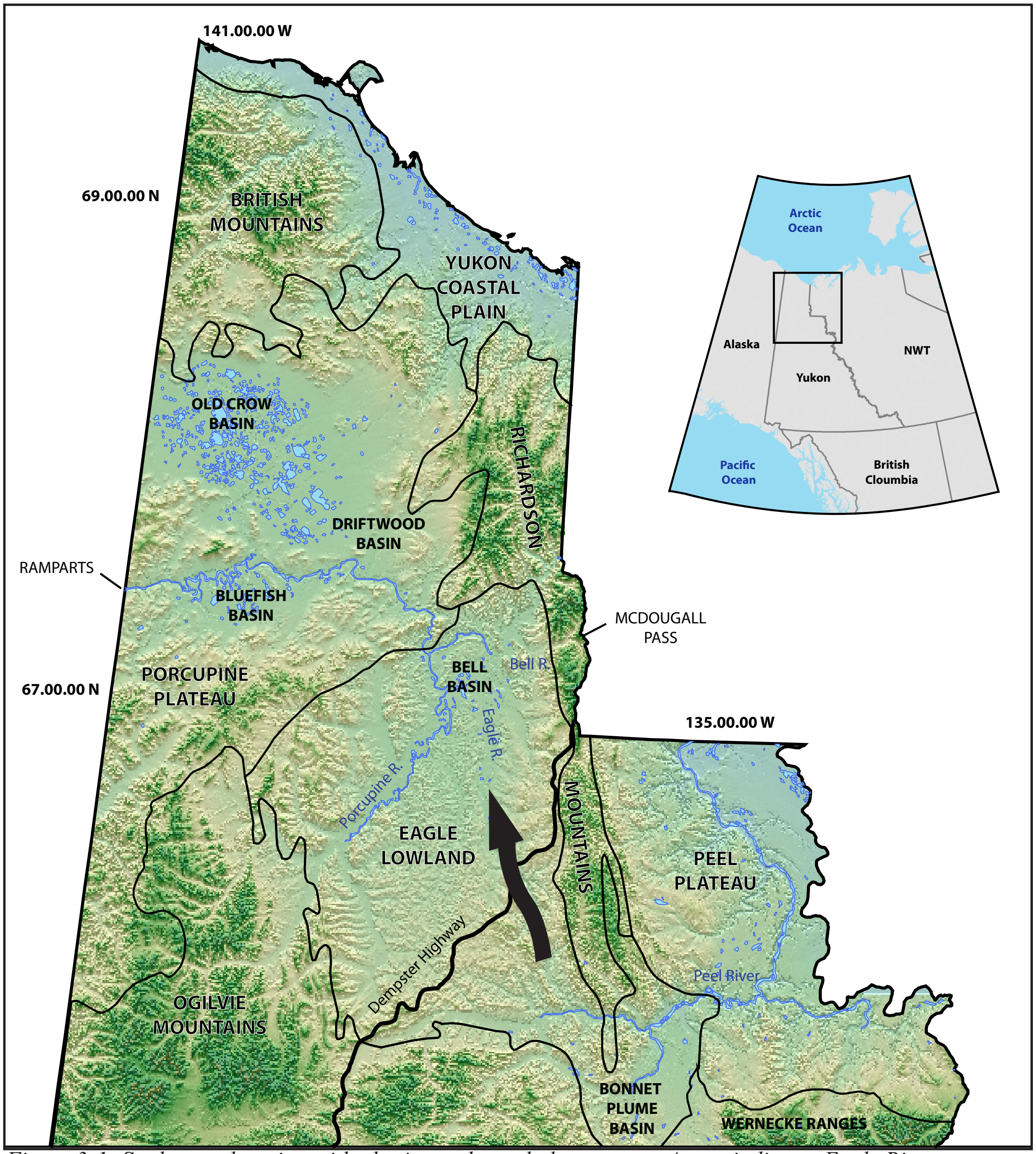



*Figure 3-1: Study area location with physiography and place names. Arrow indicates Eagle River meltwater channel.*

and swamps. This flat surface is the result of meltwater that was impounded in the basin during the Pleistocene and is matched by flat-lying wetlands in the Driftwood, Bluefish and Old Crow Basins. Pre-Laurentide drainage of the Bell, Porcupine, Eagle, and Old Crow basins was eastward through a low pass in the northern Richardson Mountains (McDougall Pass) and ultimately into the Arctic Ocean via the paleo-Porcupine River (Duk-Rodkin and Hughes, 1995). This drainage was antecedent to the uplift of the

Richardson Mountains, and was maintained throughout uplift (McNeil et al., 2001). Late Pleistocene advances of the Laurentide Ice Sheet westward against this regional drainage caused the impoundment of lakes in the western basins and the eventual establishment of western drainage through the Ramparts of the Porcupine River into Alaska and the Yukon River drainage (Figure 3-2; Duk-Rodkin and Hughes, 1995; Thorson and Dixon, 1983).

The landscape of flat bogs and thermokarst ponds in the northern Yukon basins is supported by near continuous frozen soils and mean annual air temperatures of -7.5º C (Yukon Ecoregions Working Group, 2004). Soils are typically Turbic Cryosols in low lying areas with active layer depths ranging from 30 to 90 cm (Smith et al., 1991). Well-drained south-facing slopes and alluvial deposits support Dystric Brunisols and can be free of permafrost (Tarnocai, 1987). Soil capacity is relatively low and summer rain

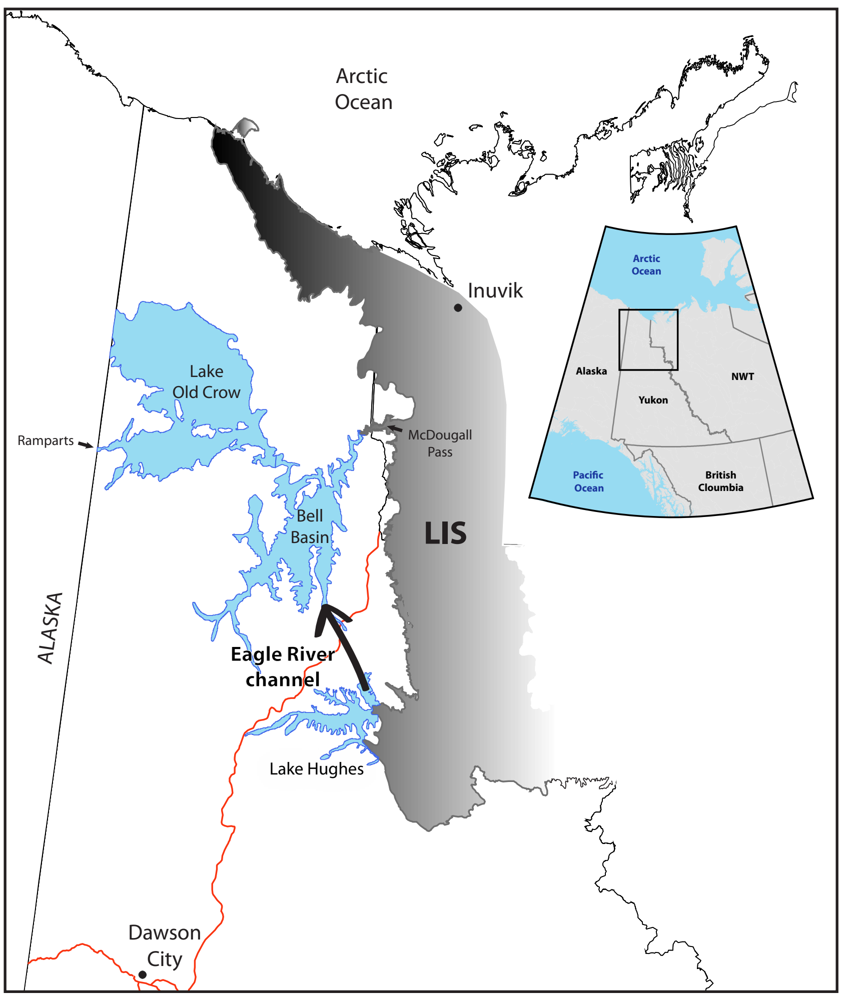



*Figure 3-2: Study area at glacial maximum conditions with Laurentide Ice Sheet (LIS) at its maximum position and associated proglacial lakes filling regional basins.*

storms are frequently responsible for hydrographic peaks (Yukon Ecoregions Working Group, 2004). Annual precipitation is ~400 mm and falls primarily in summer. Winter stream flow is low and many streams in the region are dry in late fall and winter (Yukon Ecoregions Working Group, 2004).

**Eagle River Meltwater Channel**

During the maximum of the Laurentide Ice Sheet, the Bonnet Plume Basin was impounded by a lobe of Mackenzie valley ice that blocked regional east-flowing drainages, creating an ice marginal lake known as glacial Lake Hughes (Figure 3-2; Hughes, 1972; Duk-Rodkin and Hughes, 1995). North of the Bonnet Plume Basin, the Laurentide Ice Sheet advanced onto the eastern margin of the Richardson Mountains up to elevations of ~885 m a.s.l. along valley sides and ~830 m a.s.l. in valley bottoms (Hughes, 1987; Duk-Rodkin and Hughes, 1995). This ice position included narrow tongues of valley-constrained ice that blocked east-flowing drainages of Bell Basin including the paleo-Porcupine River in McDougall Pass (Figure 3-2; Hughes et al., 1981; Catto, 1986). At the glacial maximum, Lake Hughes over-topped its northern divide (at ~560 m a.s.l.), and created a 140 km long meltwater channel, presently occupied by the Eagle River. Meltwater supplied by the channel contributed to a continuous lake in the Bell, Bluefish, and Old Crow basins confined by an ice margin in McDougall Pass less than 3 km across (Lemmen et al., 1994). Evidence of this lake continues into the Old Crow Basin to the north, where strandlines at 366 m a.s.l. mark a high stand of glacial Lake Old Crow (Hughes, 1972). Final drainage of the lake was accomplished by the incision of an outlet near the Yukon/Alaska border (Ramparts on Figures 3-1 and 3-2 at ~370 m a.s.l.), reversing pre-Laurentide drainage and establishing a new western route for the Porcupine River (Hughes, 1972; Thorson and Dixon, 1983; Zazula et al., 2004).

An ‘early LGM’ chronology for the Laurentide maximum in the Bonnet Plume Basin and Richardson Mountains is based predominantly on depositional records and radiocarbon ages obtained from the adjacent Old Crow, Bell, and Bluefish basins. Zazula et al. (2004) propose that intermittent lakes filled the basins beginning *ca.* 30 ka BP. Periodic drainage is suggested to have been controlled by an oscillating ice margin in McDougall Pass and reflected in cyclical sedimentation in the Bell Basin (Schweger, 1989; Duk-Rodkin and Hughes, 1995). A distinctive Paleozoic spore assemblage that appears in intermittent lake sediments in the Old Crow Basin has been suggested to have been retransported from shale containing a similar assemblage (the Ford Lake Formation) in the upper meltwater channel. The lithology was incised during formation of the meltwater channel, and palynomorphs of the same age have since been used to mark the first Laurentide-induced diversion of glacial meltwater into the basins (Walde, 1985). The existing model suggests the 'early' intermittent phase of meltwater diversion was responsible for incision of the Eagle River meltwater channel, and a later, deep water phase of glacial Lake Old Crow created during a readvance of the margin *ca.* 16-18 ka BP is responsible for lacustrine sediments at elevations of ~300 m a.s.l. in the Bluefish Basin, and ultimate diversion of Porcupine River drainage into Alaska (Zazula et al., 2004).

Much of the evidence for the timing of the 'early' northwest Laurentide maximum is related to the Eagle River meltwater channel and flood deposit complex, which ultimately contributed to the sedimentary records of the unglaciated Bell, Bluefish and Old Crow basins of northern Yukon. In particular, reconstruction of sediments along the braid delta complex of the lower meltwater channel provides a record of meltwater diversion and ice damming caused by the Laurentide Ice Sheet at its maximum position in the Bonnet Plume Basin and Richardson Mountains.

**Methods**

Meltwater channel characteristics were observed and documented over a 140 km length of the Eagle and Bell rivers accessed by canoe during June and July of 2007. Unit thicknesses and section elevations were measured with decimeter resolution using a Lasertech 100XL laser range finder with reference to the high-water mark on the Eagle River. Relative elevations are considered correct to ± 1 m, while absolute elevations are considered correct to ± 10 m from topographic maps. Lithostratigraphic logs were compiled on a bed-by-bed basis at exposures along the Eagle River, including detailed description of the fine-grained deltaic and lacustrine sediments along the lower channel. At each location, descriptions included composition, grain size, shape, and sorting; in addition, lithology, imbrication, sedimentary structures, bed contacts, geometry, thickness, lateral continuity and paleocurrent orientations were recorded.

**Meltwater channel development**

The Eagle meltwater channel can be divided into three distinct reaches (upper, middle and lower) based on the distribution of erosion and deposition along the channel. (Figure 3-3)

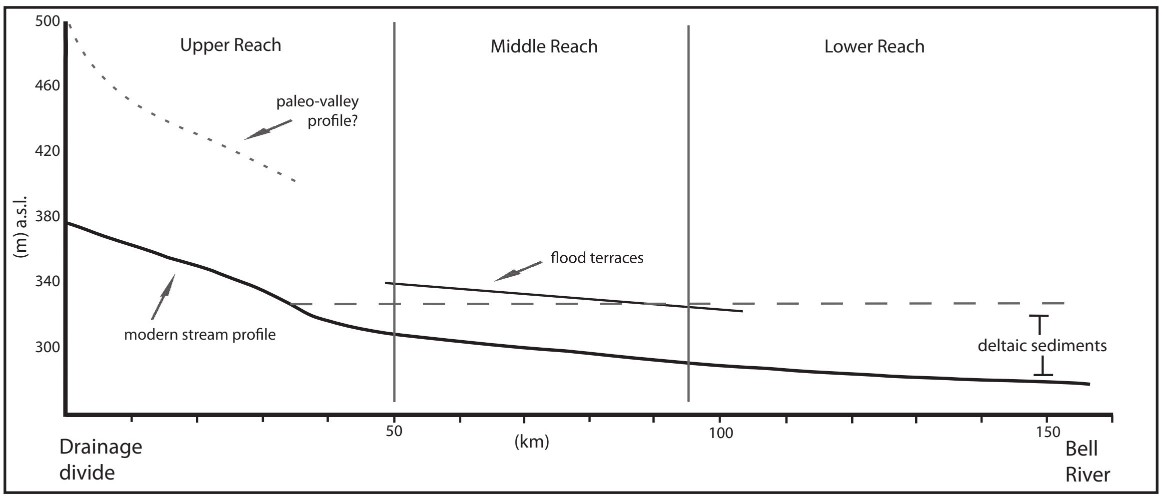



*Figure 3-3: Longitudinal cross section of the modern Eagle River stream profile and the hypothesized paleo-Eagle River profile with locations of flood terraces and the area of deltaic sedimentation. The distribution of erosion and deposition along the channel results in three distinct (upper, middle and lower) reaches for aggregate resource assessment. Vertical scale is exaggerated four times the horizontal scale (VE = 4x).*

*Upper Reach (~50 km)*

The upper reach of the Eagle channel is characterized by a narrow, steep-walled canyon almost entirely void of sedimentary deposits (Figure 3-4). The valley bottom is flat and ranges from 500-1500 m wide with steep-sided valley walls up to 200 m high. Pediment surfaces are well-developed on the slopes above both margins of the channel's upper reach, suggesting this area was likely the former drainage divide prior to meltwater re-

*Figure 3-4: Steep valley sides and flat valley floor of the upper meltwater channel. View is to the south.*

*Figure 3-5: High bedrock terraces (outlined in black) in the middle reach of the channel are often overlain with coarse gravel.*

routing.

The narrow canyon in the upper reach of the Eagle channel represents rapid erosion of bedrock and high-energy flooding (Kennedy and Froese, 2008). Following initial breach of the drainage divide, flood water was likely contained within the canyon in the upper reach and erosion was focused on downward incision. This incision is typical of early phase catastrophic flooding (*e.g.* Lord and Kehew, 1987) and was probably only minimally influenced by pre-existing topography.

*Middle Reach (~45 km)*

The middle reach of the channel is characterized by high, broad bedrock terraces often overlain with ~1-3 m of flood-deposited gravel and sand (Figure 3-5). Terraces are located at elevations of 340-360 m a.s.l. (20-30 m above the modern alluvial plain) and are well-developed on the outside bends of the channel and at the junctions of tributary valleys. Terrace deposits are composed of pebble-cobble gravel (clast sizes with b-axis lengths ranging from 0.5-30 cm with rare boulders up to 50 cm), with a coarse sand matrix-fill. Clasts are imbricate down-valley, rounded-to-tabular in shape, and most deposits are moderate-to-well-sorted. Field observations of clast lithology indicate about 90% of deposits are composed of locally-derived sandstone lithologies, with about 10% of clasts being shale and limestone


*Figure 3-6: Upstream-trending slackwater deposits above an erosional bedrock contact on a tributary to the Eagle River. Steep cross-beds in sandy slackwater deposits indicate flow was to the right (upstream) when they were deposited. Section is approximately 30 m high.*

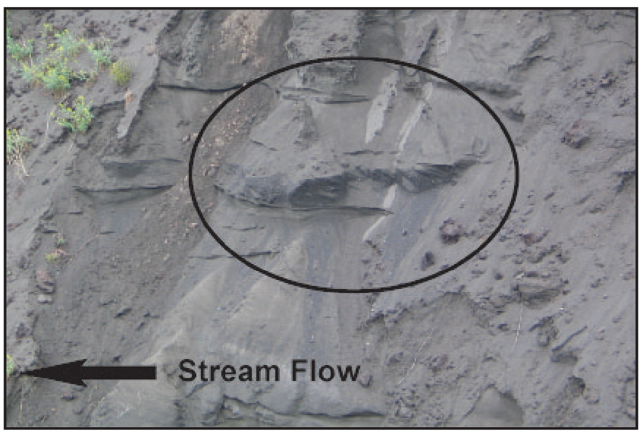



*Figure 3-7: Upstream trending crossbeds in slackwater sediments. Tributary flow is to the left. Cross-beds visible in middle of photo are trending to the right (upstream). Section in view is ~5 m high, with the top of section is at ~340 m asl.*

*Figure 3-8: View downstream of the Eagle River channel, highlighting distributed flow of middle reach with scoured surfaces including shallow lakes.*

with rare granite and gneiss clasts.

Slackwater sediments were documented in the middle reach of the Eagle River channel with surface elevations of ~340 m a.s.l. (Figures 3-6 and 3-7). These deposits are identified by their up-stream paleo-current indicators and represent back-flooding of tributary valleys (Kennedy and Froese, 2008). Upstream-trending cross-beds in slackwater sediments of tributary valleys provide a minimum elevation of the flood surface, and additional support for the catastrophic nature of flow.

The broad terraces and coarse deposits of the middle reach of the Eagle channel are the result of a change in flow regime from a single channel to a distributed pattern with one primary channel and multiple secondary channels (Figure 3-8). This likely reflects changes in paleo-valley alignment or slope that initiated overtopping of the channel margins by flood water. These changes may

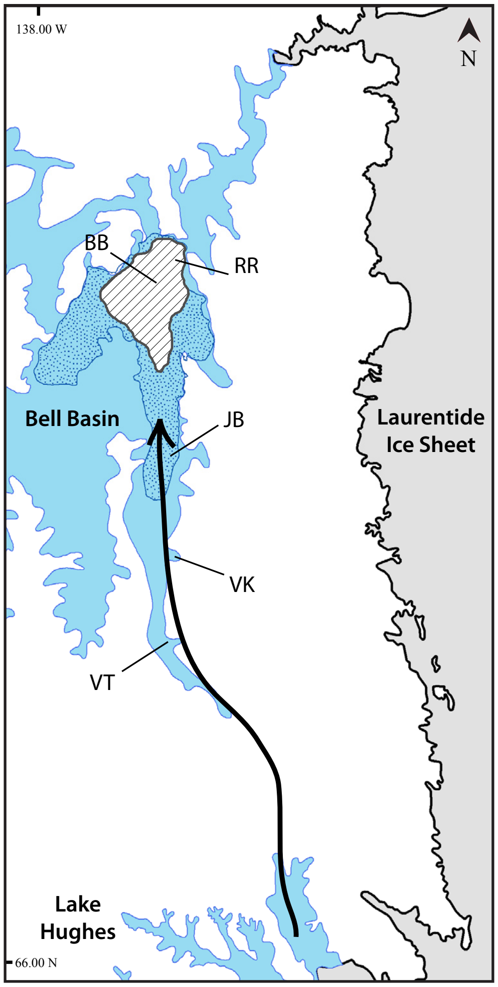



*Figure 3-9: Eagle River meltwater channel (flow path indicated with arrow) with hypothesized extent of lake at glacial maximum. Stippled pattern outlines maximum extent of deltaic deposits, with cross-hatch outlining probable more limited extent. Letters refer to locations of section logs in Figure 10 (VT: Vichi Tik Tsiivii Creek; VK: Vadziah Kan Creek; JB: Jurassic Bluff; BB: Bog Bluff; RR: Rock River).*

also have been initiated as flood waters became channelized in a pre-existing paleo-Eagle valley system. The middle reach of the Eagle channel remained dominantly erosional; however, lower velocity flow along the margin of the channel and into tributary junctions initiated deposition of coarse, cobble-pebble terraces and pendant (bank-attached) bars.

*Lower Reach (~45 km)*

The primary depositional feature of the Eagle River meltwater channel is a downstream-thickening sequence of sand, silt and clay that dominates the lower reach of the channel (Figure 3-9). These sediments occur over distances of 38 km, range in thickness from 10 to 40 m and cover an area of ~860 km$^2$. The feature is fan-shaped and only weakly confined by topography. Based on observations along the Eagle and Bell Rivers, an along-river cross-section was constructed to display the likely sub-surface geometry of the channel deposits (Figure 3-10). Observations of bedrock, gravel and lacustrine contacts fit well with records of shot-hole logs that extend to bedrock in the area (Smith et al., 2007). The total depth of sediments in the middle of the basin is unknown, however, an occurrence of an interstadial assemblage along the lower Rock River (Figure 3-9, RR; Schweger and Matthews, 1991) suggests the pre-flood deposits were near modern river level (*ca.* 290 m a.s.l.), and the deltaic complex aggraded over this surface. The fine-

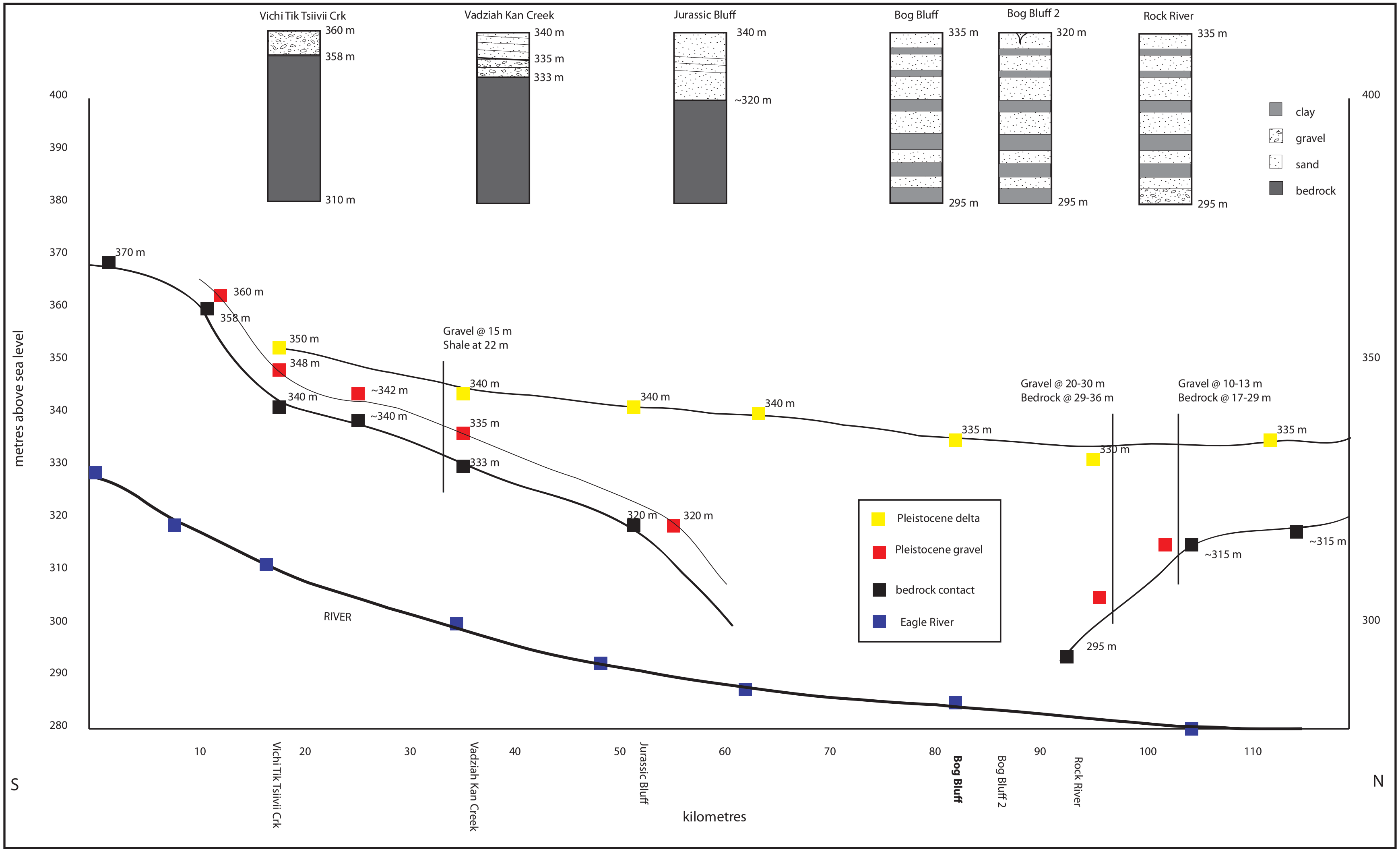



*Figure 3-10: Cross-section of meltwater channel deposits compiled through along-river observations, and shot-hole logs (vertical lines) from the region (Smith et al., 2007). Representative generalized section logs from various locations along the Eagle and Rock rivers (Rock River adapted from Schweger and Matthews, 1991) are presented along the top of the figure.*

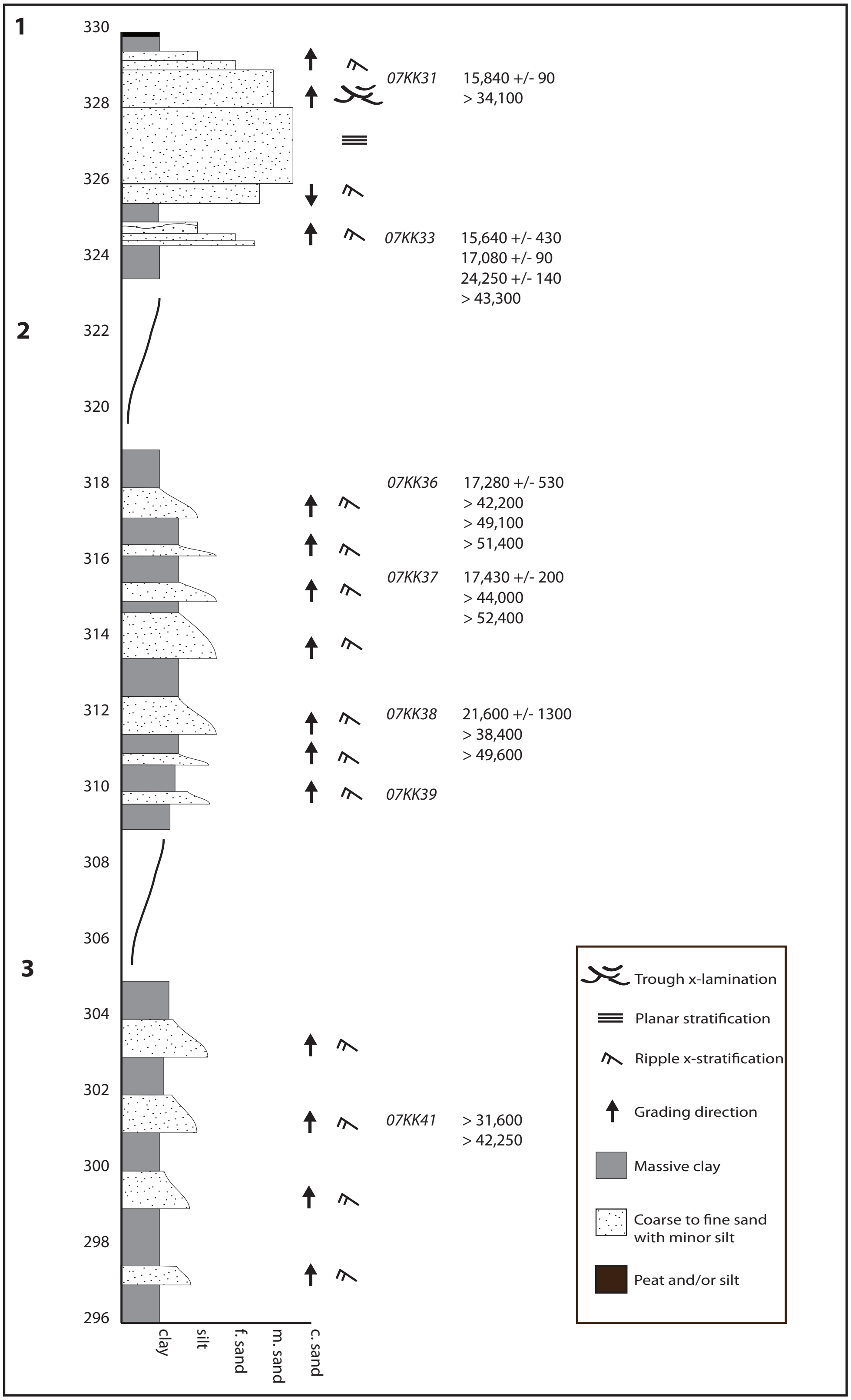



*Figure 3-11: Stratigraphic log of sediments observed at the Bog Bluff exposure. Numbers along left column (1,2,3) refer to composite section locations outlined on Figure 12. Radiocarbon dates and sample numbers are listed along right side at approx. locations where samples were collected.*

grained sediments of the lower reach of the meltwater channel are described below to assist in interpreting their genesis. A detailed section log from the Bog Bluff exposure is representative of lower reach sediments (Figure 3-11).

**Eagle River delta complex**

The Bog Bluff exposure consists of 34 m of unconsolidated Quaternary sediments deposited along the lower reach of the Eagle River meltwater channel. Overall, the section is crudely coarsening upward from alternating beds of massive clay and silt, to ripple-cross bedded sand. The lower surface is not exposed at this site; therefore the total thickness of sediment in this package is unknown. The composite stratigraphic log (Figure 3-11) is based on 3 partial sections within the exposure (Figure 3-12).

*Unit 1: Interbedded silty sand and clay*

An alternating sequence of massive clay and ripple cross laminated silty sand make up the lower 24 m of the Bog Bluff section, and form the main deposit on the lower Eagle River. Massive clay is most common at lower elevations and decreases in thickness and frequency toward the top of exposures as bed thicknesses of cross-laminated sediments increase. The vertical transition from individual beds of ripple cross-laminated sediments upward to massive clay is rapid, but gradational, with clay beds frequently draped over underlying ripples. Upper contacts of clay beds are sharp and become increasingly contorted by loading from overlying sediments at higher elevations in the exposure. Both sub-units are grey in colour and Unit 1, as a whole, is normally graded. Individual beds of Unit 1 are continuous laterally for distances up to 200 m.

Clay beds range in thickness

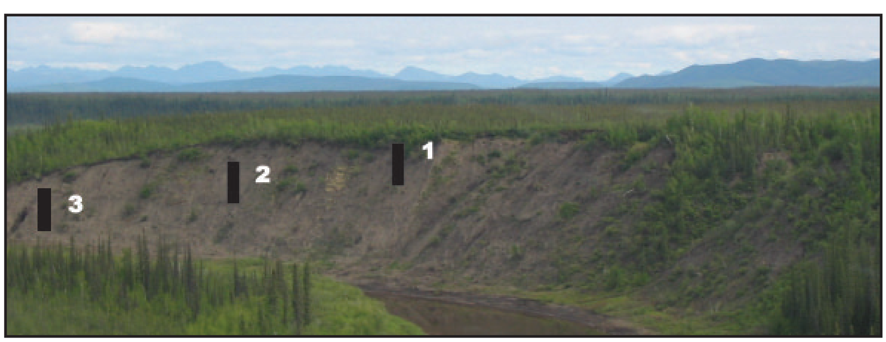


*Figure 3-12: Overview photo of the Bog Bluff exposure with locations of individual sections studied for composite stratigraphic log (Figure 11).*

from a few centimeters to more than 2 m. Beds are generally massive, however, mm-scale partings of fine sand or silt occur commonly at intervals of 10 to 30 cm (Figure 3-13). No frost cracks, ice wedge casts or animal burrows were observed. Normally-graded packages of (high-angle) erosional-stoss planar tabular cross-beds and sinuous packages of (low-angle) depositional-stoss climbing ripples occur in bed thicknesses ranging from a few tens of centimeters to a few metres throughout Unit 1 and commonly grade into intermediate cross-stratified ripple forms (Figure 3-14 and 3-15).

High angle climbing ripple amplitudes range from ~5 cm to ~15 cm, with individual laminations from 1-5 mm thick. Low angle climbing ripples are found in sets ranging in thickness from 10 cm to ~1 m. These beds commonly dip from < 5˚ to ~15˚ indicating flow toward the north. Laminae are 1-5 mm thick, with typical lee-side angles up to 30˚. Stoss-side erosion varies between intermediate forms, but all climbing ripples display pronounced climb northward (downstream). Abundant organic material is preserved on cross laminations in all forms of ripple cross-stratification, but is most pronounced on lee-sides, in troughs, and on low angle surfaces (Figure 3-15).

Unit 1 is interpreted as a sub-aqueous climbing ripple sequence with interbedded

*Figure 3-13: Millimetre-scale partings of fine sand and silt (arrow) occur in intervals of ~10-30 cm within massive clay beds of Unit 1. Trowel handle is ~20 cm.*

*Figure 3-14: Intermediate forms of high angle erosional-stoss climbing ripples display a steep climb downstream (north toward the left side of photo). Trowel handle is ~20 cm.*

*Figure 3-15: Abundant organic material is concentrated on lee-sides and troughs of sinuous, largely depositional-stoss (i.e. low-angle) climbing ripples of Unit 1. Trowel handle is ~20 cm.*

massive clay and silt deposited under fluctuating flow conditions. Climbing ripples along inclined bedding planes indicate high rates of sedimentation under unidirectional flow (Harms et al., 1982), while massive clay beds are typical of suspension settling in lacustrine or distal-deltaic environments (Smith and Ashley, 1985). The high sediment input and reduced transport required to produce climbing ripples indicates energetic sediment-rich water being input into standing or slow moving water, and can occur as the result of turbidity currents, overbank sedimentation, or in deltaic environments (Harms et al., 1982). The lack of erosive contacts and prevalence of massive clay beds suggests overflow sedimentation of sediment-rich water from the Eagle River channel into standing water occupying the Bell Basin. Changes in sediment supply and current velocity would produce variations in ripple cross-stratification from suspension-dominant low-angle climbing ripples to transport-dominated high-angle climbing ripples and planar tabular cross-lamination (Harms et al., 1982). Gradational boundaries between forms of cross-stratification and massive clay beds likely represent fluctuations in water or sediment supply over short time intervals rather than separate flood events.

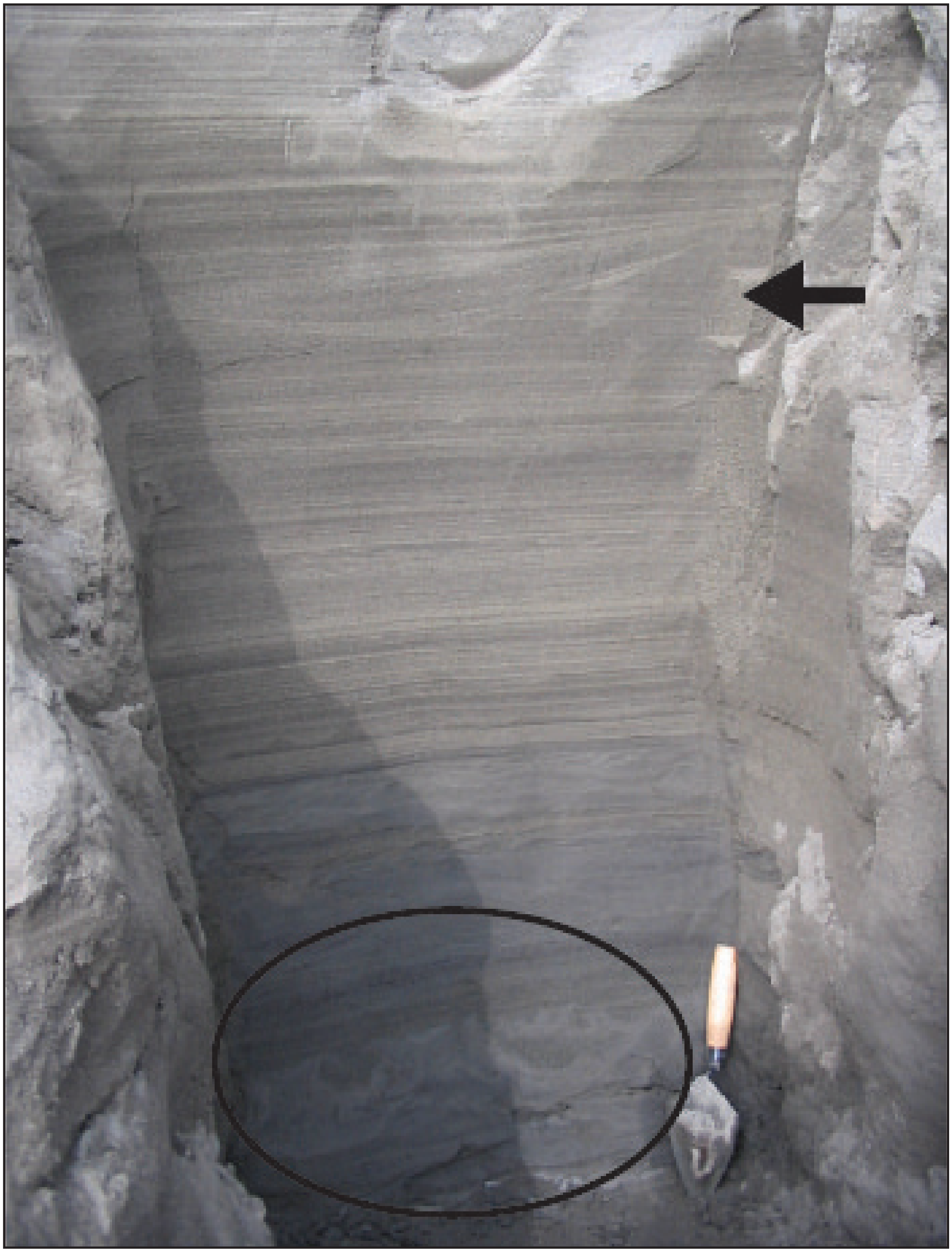
Flume experiments producing realistic sequences of climbing ripples suggest naturally deposited climbing-ripple stratification sequences of tens of metres in thickness could be produced in a matter of hours (Ashley et al., 1982). The sharp transitions between cross-bedded sand and clay suggests a shallow basin relative to the size of the associated river supplying sediment (Smith, 1991), while the coarsening upward of the unit is indicative of a progradation of the sediment source. The lower 24 m of sediment in the Bog Bluff exposure consists of alternating sequences of massive clay and ripple cross-laminated silt and sand which we interpret as rapid deposition of sediment-rich water into a shallow lake that occupied the Bell Basin.

*Unit 2: Planar stratified sand*

Unit 2 is comprised of the coarsest sediment observed at the *Bog Bluff* section. Laminations of medium to coarse planar stratified sand vary widely in colour from tan to black, but the bulk of the sediment is a light grey colour and similar in appearance to Unit 1. Unit 2 is a 2 m thick bed, grading from coarse to medium sand (Figure 3-16). Individual laminations range in thickness from a few millimeters to ~5 cm. The unit is slightly wedge-shaped (tapering downstream) over 200 m of exposure with a sharp lower contact descending northward (downstream) (Figure 3-17). Significant soft sediment deformation is present along the lower contact (Figure 3-16). Organic material is present as individual laminations containing spruce (*Picea*) needles, bark and weathered wood.

Although planar bedding can form under low flow regimes, the relatively coarse-grained texture and sharp lower contact suggest Unit 2 was deposited under high-energy conditions. Planar laminated deposits forming under high-energy conditions typically reflect flash discharge in braided river settings or low-density turbidity flows in delta or slope front basins (Miall, 1977; Nemec et al., 1999). Planar laminated sand in braided river settings is typically thin, and frequently capped by ripple cross laminated sand indicating waning flow and is interpreted as the result of shallow or intermittent high energy flows (Turnbridge, 1981; Miall, 1985).

Planar laminated sand deposited in low-density turbidity flows is characterized by coarse-grained loading or erosion of underlying sediments indicating rapid emplacement, followed by a normally graded transition to planar and ripple laminated sand and silt (Nemec et al., 1999; Winesmann et al., 2004). Turbulent flow generated by slumping or river effluent can be sustained over relatively long durations and produce density sorted, normally-graded packages of sediment ranging from 70-200 cm thick (Lowe, 1982; Nemec et al., 1999; Winesmann et al et al., 2007; Sumner et al., 2008). This mechanism requires deep water conditions (relative to braided river deposits) which could have been created by a transgression of the basin following deposition of Unit 1. The presence of loading, density sorting, and the transition of Unit 2 from coarse planar sand to fine silt and ripple cross-laminations suggest this unit was deposited by a rapid, high-energy subaqueous flow. This flow likely developed following a transgression to a deeper water



*Figuree 3-16: The lower half (~1 m) of Unit 2 sediments where they were observed overlying Unit 1 with a loaded contact (circled). Planar stratified sand displays density sorting (minerals delineated by colour) and a small cut and fill structure near the top of the figure (arrow). Trowel handle is ~20 cm.*


*Figure 3-17: View to the northeast, the contact between planar sand of Unit 2 and trough cross-bedded sand and silt of Unit 3 is sharp and descends gradually northward (downstream). Camera case is ~20 cm long.*

lacustrine phase.

*Unit 3: Trough cross-stratified sand and silt*

Trough cross-stratified grey sand and silt of Unit 3 is ~1 m thick and normally graded from medium sand to fine sand and silt. The lower contact of the unit with underlying planar laminated sand is gradational on the edges of individual troughs and erosive in trough bottoms (Figure 3-18). The unit grades upward into ripple cross-laminated fine sand and silt toward the top of the exposure and contacts with Units 4 and 5 (Figure 3-19). The highest concentration of organic material is found in this facies, particularly along troughs and lee-side surfaces near the bottom of the unit (Figure 3-20).
Although the close vertical association of planar and trough cross-laminated stratification is a common sequence in braided river deposits (Miall, 1977), the separation of these units into a normally-graded package is more typical of the waning stages of a high-energy subaqueous flow such as turbidite sedimentation (Sumner et al., 2008; Harms et al., 1982). Unit 3 is interpreted as the upper (late) stages of turbidite emplacement and is gradational from underlying Unit 2 sediments.

*Unit 4: Laminated silty clay*

Thinly-laminated dark gray massive silty-clay overlies Unit 3 with thicknesses up to

4 m along the lower Rock River, but is poorly preserved along the Eagle River where thicknesses are generally less than ~60 cm. Lower contacts with Unit 3 sediments are sharp, while upper contacts grade into modern peat deposits (Figure 3-19) or Unit 5. The massive grey silt and clay observed on the Eagle and Rock Rivers is similar to the sediments associated with glacial Lake Old Crow, and is considered to represent lacustrine sedimentation during transgression of an upper lake phase.

*Unit 5: Massive tan silt*

Massive tan silt of Unit 5 is poorly preserved, and if present, is the uppermost unit in the basin with a gradational lower contact. This unit is weakly developed where it overlies the dark grey silty-clay of Unit 4 and rarely reaches thicknesses of more than 30 cm. However, in two locations where Unit 4 was absent, massive tan silts contained ice wedge casts and reached a thickness of >1 m. Both casts were formed in massive silt of Unit 5 and the larger cast (~1 m deep) extends into stratified silt and fine sand of Unit 3 (Figure 3-21). Casts are infilled with massive to vertically stratified tan silt with minor

*Figure 3-18: Erosive trough bottoms in Unit 3 interrupt bedding planes in Unit 2, while trough edges are gradational with underlying planar laminations. Scale card is marked in centimeter intervals.*

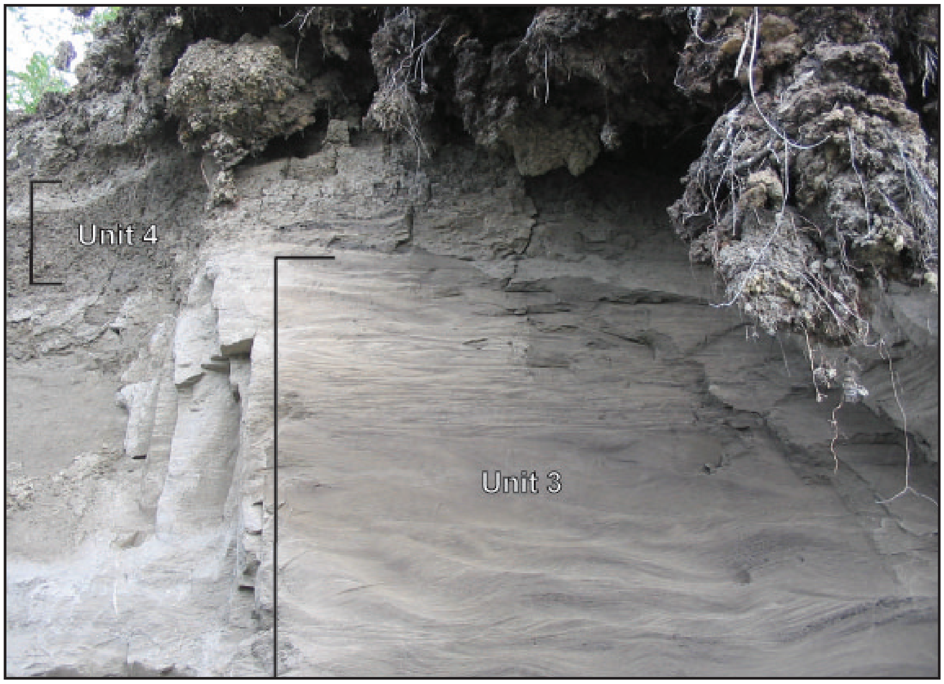



*Figure 3-19: Unit 3 grades upward from trough cross-beds into waning stage planar tabular cross-laminations toward the top of the unit. Unit 4 overlies Unit 3 with a sharp contact ~30 cm below the top of the section. Height of sediments in photo is ~1.5 m.*

*Figure 3-20: Troughs and lee-side surfaces in lower Unit 3 sediments preserve high concentrations of organic materials (circled). Scale card is marked in centimeter intervals.*

peat inclusions.

Sediments of Unit 5 are interpreted as deposition following final drainage of the lake in Bell Basin. The ice wedge casts observed in the massive silt deposits of Unit 5 mark the first evidence for extended sub-aerial exposure of the lower Eagle River meltwater channel sediments.

*Figure 3-21: The largest ice wedge cast observed in Unit 5 massive tan silt extends into stratified silt of Unit 3. Cast is infilled with massive to vertically laminated tan silt and peaty organic material. Trowel handle is ~20 cm.*

**Depositional Environments**

Meltwater outburst channels are thought to develop in three distinct phases (Lord and Kehew, 1987; Fisher and Smith, 1993; O'Connor, 1993). First, incision, erosion, and channel expansion with minimal deposition will often dominate for significant distances beyond the drainage divide. Second, changes in paleo-topography or flood energy reduce erosive capability and result in deposition of coarse sediment and channelization of flow. Typical deposition during this phase includes pendant bars (channel-attached bars) and back-flooding of tributary junctions (slackwater sedimentation). The final phase in the development of meltwater channels is the deposition of suspended sediments. This final deposition may occur in the form of an extensive delta plain if the flows go into a proglacial lake; otherwise, slackwater sedimentation may occur where flow is impinged through a narrowing of the channel (Lord and Kehew, 1987; O'Connor, 1993). The three distinct phases of meltwater channel development as presented by Lord and Kehew (1987), Fisher and Smith (1993) and O'Connor (1993), are consistent with the erosional, depositional and morphological observations of the Eagle River meltwater channel (Kennedy and Froese, 2008). Here, we focus on the depositional environment of the Eagle River braid delta.

*Eagle River braid delta*

The Eagle River braid delta is the primary depositional feature of the Eagle River meltwater channel and preserves evidence to reconstruct the nature of meltwater drainage along the channel and in the Bell Basin. The sediments observed at the Bog Bluff section are used here to reconstruct the depositional history of the lower channel and basin. Unit 1 on the lower Eagle River is composed of flat-lying to gently dipping heterolithic facies of interbedded mud and ripple cross-stratified sand. This package is the dominant fine-grained deposit on the lower Eagle River and is overlain by a normally-graded downstream-decending wedge of coarse sand to silt in Units 2 and 3. The planar laminated sands and overlying waning-stage trough and planar cross-laminated sands are typical of low-density turbidity currents developed in deeper basins. Fine-grained deep basin lacustrine sediments are limited to the poorly preserved and variable deposits of massive clay in Unit 4, while the uppermost sediments (Unit 5) record post-drainage aeolian deposition.

Based on the facies associations observed at Bog Bluff, the fine-grained sediments of the lower reach of the Eagle River meltwater channel are interpreted as a progradational braid delta assemblage, followed by a transgression of the lake and ultimate drainage and base level lowering. Smith (1991) defines braid deltas as "… laterally extensive, sheet-like sand bodies dominated by trough and planar, tabular cross-bedding, underlain by lacustrine mud". Few Pleistocene braid deltas are known in Canada, with deltas more commonly being Gilbert-type deltas with well-developed foreset beds; however, Rhine and Smith (1988) interpreted the large (*ca.* 4000 $km^2$) sand sheet on the lower Athabasca River as a Pleistocene braid delta based on composition, form and regional setting.

Braided or fan-deltas are characterized by vertical facies transitions from basal muds into fluvial sands with transitional, heterolithic facies of interbedded mud and ripple cross-stratified sand (Wescott and Ethridge, 1980). The vertical facies association of the Athabasca braid delta comprises lacustrine muds and prodelta heterolithic sediments with lower delta-slope turbidite sands grading to upper delta slope sands and braided stream sands with overlying aeolian-dunes (Rhine and Smith, 1988). Similarly, the facies association of the Eagle River braid delta includes pro-delta heterolithic sediments (Unit 1), delta-slope turbidite sands (Units 2 and 3), lacustrine muds (Unit 4), and post-drainage aeolian deposits (Unit 5). The absence of deep basin lacustrine muds and delta-slope turbiditic sands lower in the stratigraphy could reflect a shallow receiving basin that inhibited development of a steep delta face slope or the absence of sufficiently deep water in the basin prior to the influx of meltwater. There is little evidence in the Eagle River area for an extended deep basin phase of the lake, and a late transgression may explain the absence of well-developed topset beds on the Eagle River delta.

Both the Athabasca and Eagle river braid deltas have a distinct fan shaped morphology that is largely unconstrained by topography (Rhine and Smith, 1988). Like the Eagle River delta, the Pleistocene Athabasca delta developed along the lower segment of a meltwater channel and was constructed during flood-sedimentation from the northwest outlet of glacial Lake Agassiz into the southern extension of glacial Lake McConnell (Fisher and Smith, 1993; Fisher et al., 2002). Braid delta deposits are typically associated with high sediment loads delivered over relatively short distances (Rhine and Smith, 1988). Smith and Fisher (1993) demonstrate the sediment source for the Athabasca braid delta was bedrock excavated from the meltwater channel itself. Similarly, the high sediment load of the lower Eagle River braid delta is likely derived predominantly from channel incision rather than glaciation in the Bonnet Plume Basin. An estimated 4.25 $km^3$ of soft shale was removed from the upper channel and used as a sediment source for fine grained deposits downstream (Zazula et al., 2004). While the Athabasca braid delta and associated Clearwater Spillway are an order of magnitude larger than the Eagle River meltwater channel and braid delta, the mechanisms of development and resultant landforms are similar.

Paleohydraulic calculations from the Clearwater Spillway indicate the initial meltwater flood likely lasted less than 150 days, and that deposition of the Athabasca delta may have been complete in a few hundred years or less (Smith and Fisher, 1993; Fisher et al., 2002). Based on the similarities between these deltas and the sedimentological evidence of rapid and continuous deposition on the lower Eagle River, it is likely the Eagle River braid delta complex has a similarly brief depositional history.

Previous authors have noted the cyclical nature of massive clay and ripple cross-stratified fine sand and silt that characterize Bell Basin deposits (Schweger, 1989; Duk-Rodkin and Hughes, 1995). Schweger (1989) suggested this repetition was caused by consecutive periods of basin filling and draining controlled by oscillations of an ice margin in McDougall Pass. Based on other slackwater sediments in adjacent Alaska, frost cracks and ice wedge casts would be expected if repetitive drainage events had occurred during deposition (Froese et al., 2003). We interpret the cyclically bedded sediments of the Bell Basin to represent rapid deposition related to the progradation of the braid-delta into a shallow receiving basin on the lower Eagle River. There is no compelling evidence to suggest multiple periods of subaerial exposure within the braid delta.

**Chronology**

Fifteen bulk sediment samples were collected at regular intervals through a 34 m thick vertical section of sediments on the lower Eagle River, and subsequently washed in a 0.425 mm sieve to remove fine sand, silt and clay. Eleven samples produced organic concentrate that was sorted using a binocular microscope to isolate and remove identifiable plant and insect macrofossils. Macrofossil abundance and preservation was greater at higher elevations in the exposure. Six bulk sediment samples (ranging in elevation from 301 to 328 m a.s.l) produced a total of 18 macrofossil sub-samples for AMS $^{14}C$ dating. Based on a successful method of $^{14}C$ dating in permafrost-affected areas demonstrated by Zazula et al. (2004; 2007), fragile macrofossils (flowers, seeds, leaves and seed capsules) representative of their depositional context (i.e. herbaceous xerophilic taxa from glacial environments) and formation of coherent ecological assemblages, were isolated and selected for the purposes of achieving duplication and assessing different types of material (needles, beetles and seeds).

Results of the dating are presented in Table 3-1. Finite ages from a variety of materials range from *ca.* 24,000-15,000 $^{14}C$ a BP. All woody materials (twig, bark and needles) have non-finite ages. All but one sample of the sedge *Carex* is non-finite, suggesting that samples of this taxon may be susceptible to prolonged preservation

| Material | Lab # | Elevation (a.s.l.) | Date | Sample # |
|---|---|---|---|---|
| *Picea sp. (needles)* | 40065 | 328 m | >34100 | 07KK31 |
| *Herbaceous Assemblage* | 40066 | 328 m | 15840 ± 90 | 07KK31 |
| | | | | |
| *Picea sp. (needles)* | 47252 | 325 m | >43300 | 07KK33 |
| *Carex sp. (seeds)* | 47254 | 325 m | 24250 ± 140 | 07KK33 |
| *Herbaceous Assemblage* | 47253 | 325 m | 17080 ± 90 | 07KK33 |
| *Morychus sp.* | 48838 | 325 m | 15640 ± 430 | 07KK33 |
| | | | | |
| *Carex sp. (seeds)* | 47257 | 318 m | >51400 | 07KK36 |
| *Picea sp. (needles)* | 47256 | 318 m | >49100 | 07KK36 |
| *Picea sp. (needles)* | 47255 | 318 m | >42200 | 07KK36 |
| *Morychus sp.* | 48839 | 318 m | 17280 ± 530 | 07KK36 |
| | | | | |
| *Carex sp. (seeds)* | 47259 | 316 m | >52400 | 07KK37 |
| *Picea sp. (needles)* | 47258 | 316 m | >44000 | 07KK37 |
| *Morychus sp.* | 48840 | 316 m | 17430 ± 200 | 07KK37 |
| | | | | |
| *Carex sp. (seeds)* | 47261 | 312 m | >49600 | 07KK38 |
| *Picea sp. (needles)* | 47260 | 312 m | >38400 | 07KK38 |
| *Morychus sp.* | 48841 | 312 m | 21600 ± 1300 | 07KK38 |
| | | | | |
| *Bark* | 40068 | 301 m | >42250 | 07KK41 |
| *Twig fragment* | 40067 | 301 m | >31600 | 07KK41 |

*Table 3-1: Results of AMS radiocarbon dates from a total of six bulk sediment samples collected at the Bog Bluff exposure. All samples were analysed at the University of California Irvine Keck Carbon Cycle AMS Facility (UCIAMS).*

similar to that of woody plant materials. The remaining ages (~21-15 $^{14}C$ ka BP) were derived entirely from macrofossils of herbaceous plant taxa with a "steppe-tundra" ecological affinity. Most macrofossils (seeds, fruits) from herbaceous taxa recovered from Pleistocene sediment samples are quite small, thus, in all cases, more than one macrofossil was required to achieve the minimum of ~0.019 mg of carbon required for AMS $^{14}C$ dating. Where possible, a single taxon or macrofossil type was used to make up individual samples, however, where taxon occurrences were limited, 'herbaceous assemblage' samples were selected to represent similar plant community types. Taxon compositions and abundances are presented in Table 3-2.

Specimens of the beetle (*Morychus* sp.) were selected for dating based on their steppe-tundra affinity and presence in most bulk sediment samples (S. Kuzmina, pers. Com. 2008). These four beetle samples returned finite ages; however, error ranges are large due to small sample sizes of the final carbon for analysis. Individual samples, and the section as a whole, show a large range in both finite and non-finite ages, underscoring the importance of reworking of older material in these sediments. These results demonstrate how bulk samples from the region could yield artificially old $^{14}C$ dates by containing any number of well-preserved macrofossils of varying age. The composite samples used in this study potentially contain macrofossils of differing ages that will produce a composite age older than the youngest component. We interpret all dates presented here as minimum ages of the deposition of the braid delta sediments. The youngest age from the section is 15,640 ± 430 $^{14}C$ yrs BP (*Morychus* sp.) and is consistent with a date of 15,840 ± 90 $^{14}C$ yrs BP (*Phlox* sp. fruit capsules fragments).

**Discussion**

The 'early' LIS model put forth by Duk-Rodkin et al. (2004) and Zazula et al. (2004) suggests the northwest Laurentide margin attained its maximum position up to 30,000 $^{14}C$ years BP and persisted there until ~16,000 $^{14}C$ years BP. This early maximum extent was suggested to be recorded by incision of the Eagle River meltwater channel and

*Table 3-2: Taxon compositions and abundances of bulk samples collected from the Bog Bluff exposure. Individual 14C sample compositions and resulting ages are presented along top. Macrofossil frequencies are represented by * = rare, ** = moderate, and *** = abundant.*

| **Samples** | **07KK31** | **07KK32** | **07KK33** | **07KK35** | **07KK36** | **07KK37** | **07KK38** | **07KK39** | **07KK40** | **07KK41** | **07KK44** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | Eagle River | Eagle River | Eagle River | Eagle River | Eagle River | Eagle River | Eagle River | Eagle River | Eagle River | Eagle River | Eagle River |
| **Type** | deltaic silt/ sand | deltaic silt/ sand | deltaic silt/ sand | deltaic silt/ sand | deltaic silt/sand | deltaic silt/sand | deltaic silt/ sand | deltaic silt/sand | deltaic silt/sand | deltaic silt/ sand | deltaic silt/ sand |
| **14C age** | *A: UCIAMS 40065: >34100 (picea needle); B: UCIAMS 40066: 15,840 ± 90 (phlox capsules)* | *no sample submitted* | *A: UCIAMS 47252: >43300 (picea needle); B: UCIAMS 47253: 17,080 ± 90 (potentilla, poa, phlox capsules); C: UCIAMS 47254: 24,250 ± 140 (carex sp.)* | *A: destroyed in pre-processing (poa, draba, potentilla, artemisia leaf, androsase, bastuca, papaver, cerastium)* | *A: UCIAMS 47255: >42200 (picea needle); A2: UCIAMS 47256: >49100 (picea needle); B: destroyed in pre-processing (phlox, potentilla, poa, cerastium, renunculous, empitrium); C: UCIAMS 47257: >51400 (carex sp.)* | *A: UCIAMS 47258: >44000 (picea needle); B: UCIAMS 47259: >52400 (carex sp.)* | *A:UCIAMS 47260: >38400 (picea needle); B:destroyed in pre-processing (phlox, potentilla, chenopodia, kobrasia); C:UCIAMS 47261: >49600 (carex sp.)* | *no sample submitted* | *no sample submitted* | *A: UCIAMS 40067: >31600 (twig fragement); B: UCIAMS 40068: >42250 (bark)* | *A: destroyed in pre-processing (mixed terrestrial seeds, macros)* |
| **Sample size** | *ca.1.5 L* | *ca. 1.5 L* | *ca. 1.5 L* | *ca. 1.5 L* | *ca. 1.5 L* | *ca. 1.5 L* | *ca. 1.5 L* | *ca. 1.5 L* | *ca. 1.5 L* | *ca. 1.5 L* | *ca. 1.5 L* |
| **Notes** | *abundant plant macros, insects, moss, some wood to 3 cm in length* | *fairly organic rich, not too many identifiable macros* | *organic rich with wood fragments and coarser clastic material* | *fine grained, grassy, organic poor* | *organic rich with lots of woody fragments and coarser clastics* | *organic rich* | *organic rich* | *organic poor* | *organic poor* | *not much organic or identifiable macros, a few large wood fragments* | *organic poor, grassy, fine grained* |
| **Bryophytes** | *** | * | ** | *** | * | ** | ** | * | * | * | ** |
| **Insects** | *** | ** | *** | * | *** | | ** | * | * | * | * |
| **Taxon** | | | | | | | | | | | |
| **Equisetaceae** | | | | | | | | | | | |
| *Equisetum* sp. (stems) | | | | | | | | | | | |
| **Pinaceae** | | | | | | | | | | | |
| *Picea* sp. (needle fragments) | *** | ** | * | * | *** | * | *** | * | | | * |
| **Potamogetonaceae** | | | | | | | | | | | |
| *Potamogeton* sp. (nutlets) | * | ** | * | | * | * | | | | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|
| **Najaceae** | | | | | | | | | | | |
| *Najas flexilis* (seed) | | * | * | | | | * | | | | |
| **Scheuchzeriaceae** | | | | | | | | | | | |
| *Scheuchzeria palustris* (seed) ? | | | | | | | | | | | |
| **Poaceae** | | | | | | | | | | | |
| Poaceae undet floret | | | | * | | | | | | | * |
| *Elymus* sp. (florets) | * | * | | | | | | | | | |
| *Festuca* sp. (florets) | | | * | * | * | | | | | | |
| *Alopecurus* sp. (florets) | | | | | | | | | | | |
| *Poa* sp. (florets) | ** | ** | ** | ** | ** | * | | * | | | * |
| **Cyperaceae** | | | | | | | | | | | |
| *Carex* sp. (trigonous achenes) | ** | ** | * | * | * | * | ** | | | | |
| *Carex* sp. (lenticular achenes) | *** | *** | *** | ** | * | * | *** | * | * | | * |
| *Eleocharis palustris-uniglumis* type (achene) | * | | | | | | * | | | | |
| *Kobresia myosuroides* (achene) | * | * | | | | | * | | | | |
| *Scirpus* sp. (achene) | | | | | | | | | | | |
| **Juncaceae** | | | | | | | | | | | |
| *Juncus* sp. (seeds, capsules) | | | | | | | | | | | |
| **Liliacea** | | | | | | | | | | | |
| *Llodia serotina* (seed) | | | | | | | | | | | |
| **Salicaceae** | | | | | | | | | | | |
| *Salix* sp. (twigs, buds, capsules) | * | * | * | | * | | * | | | | |
| **Betulaceae** | | | | | | | | | | | |
| *Alnus* sp. (nutlet) | | | | * | | | | | | | |
| *Alnus* sp. (cone fragment) | * | | | | | | | | | | |
| *Betula* sp. (bract) | | | | | | | | | | | |
| *Betula sp.* (tree type nutlet) | | * | | | | | * | | | | |
| *Betula* cf. *nana* | * | | * | * | | | | | | | |
| **Polygonaceae** | | | | | | | | | | | |

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| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Rumex* cp. (achenes) | * | | | | | | | | | | |
| **Chenopodiaceae** | | | | | | | | | | | |
| *Chenopodium* sp. (seeds) | * | | ** | * | | | ** | | | | |
| **Caryophyllaceae** | | | | | | | | | | | |
| cf. Caryophyllaceae undet. vegetative | | | | | | | | | | | |
| Caryophyllaceae undet. (seed) | | | | | | | | | | | |
| *Cerastium* sp. (seed) | * | * | ** | * | | | | | | | |
| *Silene involucrata* (seeds) | | | | | | | | | | | |
| *Silene taimyrensis* (seeds) | * | | | | | | | | | | |
| cf. *Silene* sp. (capsule fragment) | * | | | | | | | | | | |
| *Minuartia* type (seed) | * | * | * | * | | | | | | | |
| **Nyphaeaceae** | | | | | | | | | | | |
| *Nuphar* sp. (seed) | | | | | | | | | | | |
| **Ranunculaceae** | | | | | | | | | | | |
| *Ranunculus* sp. (small achene) | ** | ** | * | | * | | * | | | * | |
| *Ranunculus* cf. *sceleratus (ribbed)* | | | | | | | | | | | |
| **Papaveraceae** | | | | | | | | | | | |
| *Papaver* sp. (seed) | * | | * | * | | | | | | | |
| **Brassicaceae** | | | | | | | | | | | |
| Brassicaceae undet (large seed) | | | * | * | | | | | | | |
| *Draba* sp. (seeds) | ** | * | ** | ** | | | * | * | * | * | * |
| *Rorripa palustris* (seeds) | | | | | | | | | | | |
| **Saxifragaceae** | | | | | | | | | | | |
| *Parnassia cf. kotzebuei* (seed) | | | | | | | | | | | |
| *Saxifraga oppositifolia* (leaves) | | * | * | | | | | | | | |
| **Rosaceae** | | | | | | | | | | | |
| *Potentilla* sp. (achenes) | ** | ** | ** | ** | | * | * | * | | | |
| *Potentilla cf. palustris* (achene) | | | | | | * | * | | | | |

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| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Rubus idaeus* (achene) | * | | * | | | * | * | | | | |
| **Linaceae** | | | | | | | | | | | |
| *Linum lewisii* (seed) | * | | | | | | | | | | |
| **Empetraceae** | | | | | | | | | | | |
| *Empetrum nigrum* (seed) | | * | | | * | | | | | | |
| **Hippuridaceae** | | | | | | | | | | | |
| *Hippuris* sp. (nutlet) | * | * | * | | | | | | | | |
| **Haloragaceae** | | | | | | | | | | | |
| *Myriophyllum* sp. (nutlet) | * | * | * | | | | | | | | |
| **Apiaceae** | | | | | | | | | | | |
| Apiaceae undet. | | | | | | | | | | | |
| *Bupleurum americanum* (fruit) | | | | | | | | | | | |
| *Cicuta* sp. (fruit) | | | | | | | | | | | |
| **Ericaceae** | | | | | | | | | | | |
| Ericaceae undet leaves | | | | | | | | | | | |
| *Andromeda glaucophylla* (seed) | * | | | * | | | | | | | |
| *Chamaedaphne calyculata* (seed) | | | | | | | | | | | |
| **Primulaceae** | | | | | | | | | | | |
| *Androsace septentrionalis* (seed) | * | * | * | * | | | | | | | |
| **Menyanthaceae** | | | | | | | | | | | |
| *Menyanthes trifoliata* (seed) | * | * | * | | * | | | | | | |
| **Polemoniaceae** | | | | | | | | | | | |
| *Polemonium* sp. (seed, capsules) | | | | | | | | | | | |
| *Phlox* sp. (capsules) | ** | ** | ** | | ** | * | * | | | * | |
| **Scrophulariaceae** | | | | | | | | | | | |
| *Pedicularis* sp. (capsule) | | | | | | | | | | | |
| **Plantaginaceae** | | | | | | | | | | | |
| *Plantago* cp. (capsule) | | | | | | | | | | | |
| **Asteraceae** | | | | | | | | | | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|
| *Artemisia* sp. (flowers) | | | | * | | | | | | | |
| *Artemisia sp.* (leaf) | | | | * | | | | | | | |
| *Taraxacum* sp. (achenes) | * | | | | | | | | | | |
| **Violaceae** | | | | | | | | | | | |
| *Viola* ? (seed) | * | | | | | | | | | | |
| | | | | | | | | | | | |
| **Other Macros** | | | | | | | | | | | |
| *Daphnia* ephippium | ** | | * | | | | | | * | * | *** |
| *Limocephalus* ephippium | | | | | | | | | | | |
| *Nitella* oospores | | | | | | | | | | | |
| *Cristatella mucedo* statoblasts | * | * | * | * | * | | | * | | | |
| *Plumatella* statoblast | | | | | | | | | | | |
| *Cenococcum* sclerotia | *** | ** | | | | | | | | | |
| microtine pellets, bones | * | * | * | | | | | | | | |
| fish scale | | | | | | | | | | | |
| shell | | | | | | | | | | | |
| | | | | | | | | | | | |

deposition of associated fine-grained sediments in the lower Bell Basin (Schweger, 1989; Duk-Rodkin et al., 2004; Zazula et al., 2004). Similar to a suggested prolonged maximum from ~25 $^{14}$C ka BP (Dyke et al., 2002), a maximum at *ca.* 30 $^{14}$C ka BP requires the northwest margin to advance asynchronously with adjacent margins and retain a position near its maximum for more than 10,000 years.

While all three unglaciated basins were arguably influenced by proglacial drainage from the Laurentide Ice Sheet, the Eagle River meltwater channel provides the clearest connection between the Laurentide Ice Sheet and these basins; requiring a maximum, or near-maximum, advance of the Laurentide Ice Sheet in both the Richardson Mountains and Bonnet Plume Basin to initiate flooding of the Bell, Bluefish and Old Crow basins. Fine-grained sediments along the lower Eagle River meltwater channel are characterized by high-energy, rapidly aggrading bedforms and a crudely coarsening-upward sequence indicative of rapid deposition in a shallow braid delta environment. Radiocarbon dating of macrofossils from the delta provides a series of maximum ages ranging from ~21-15,000 $^{14}$C years BP. Combined, this evidence suggests that meltwater flooding of the Eagle channel, and associated deposition of the braid delta, was relatively short and culminated after ~16,000 $^{14}$C a BP. The new dates presented here are part of a larger series of maximum ages used to constrain the timing of meltwater diversion into the unglaciated basins (Table 3-3). The length of this record is useful in demonstrating the degree of recycling and prolonged preservation in these environments.

At ~330 m a.s.l., the top of the Eagle River braid delta is ~30 metres below the elevation required to breach the Ramparts divide and establish the modern westward drainage of the Porcupine River into the Yukon River watershed (Thorson and Dixon, 1983). This suggests that deposition of the braid delta occurred prior to the high stand of glacial Lake Old Crow, and that a subsequent transgression (potentially represented by Units 2 and 3 at Bog Bluff) occurred prior to final drainage of the basin after 16,000 $^{14}$C a BP.

In the Bluefish Basin, a series of AMS $^{14}C$ ages between 18,490 ± 160 $^{14}C$ yrs BP and 16,440 ± 100 $^{14}C$ yrs BP derived from macrofossils in alluvial, or perhaps deltaic, sediments, underlying glaciolacustrine clay have been suggested to represent a late-stage filling of the basin during the high stand of glacial Lake Old Crow (Zazula, et al., 2004). Based on the Eagle River braid delta chronology, these ages likely represent an earlier stage of aggradation of the Bluefish Basin, or the earliest stages of activation of the Eagle River meltwater channel. At ~300 m a.s.l., the Bluefish Basin sediments are significantly below the water levels required for ultimate drainage, but clearly record transgression and aggradation broadly during the Last Glacial Maximum. A minimum age for final drainage of glacial Lake Old Crow is indicated by the reappearance of large mammal fossils in the central Old Crow Basin at ~13,500 $^{14}C$ a BP (Table 3-3; Harington, 2003).

The earlier stages of a lake, or lakes, in the Old Crow basin are not immediately tractable with the observations from the Eagle River meltwater channel presented in this paper. Walde (1985) and Zazula et al. (2004) argue for the significance of a Paleozoic spore assemblage associated with stratified sands and silts of Unit 2b in the Old Crow Flats as recording the appearance of meltwater and associated pre-Quaternary palynomorphs derived from the Ford Lake Formation of the upper Eagle River meltwater channel. Meanwhile, Froese et al. (2007) report a series of AMS ages on discrete terrestrial plant macrofossils from the stratified sands and silts (ie. Unit 2b of Morlan, 1996) that range from ca. 40-44,000 yrs, indicating a lake existed in the area prior to any supporting evidence for Laurentide Ice Sheet influence. If these ages are accurate, it is unlikely the Paleozoic spore assemblage in Unit 2b is associated with glacially-induced flooding if the Eagle River meltwater channel. The sediments of Unit 2b may be comparable to earlier, tectonically-controlled lakes associated with uplift of the Richardson Mountains, and raise the significant possibility of non-glacial lakes extending in the area during the late Pleistocene. If this is correct, it would indicate the western Laurentide margin maximum extent is in fact quite late and may be after 16,000 $^{14}C$ a BP.

Previous authors argue for a sustained (*ca.* 10-15 ka) maximum of the northwest Laurentide Ice Sheet with multiple or prolonged glacial lakes forming in the adjacent unglaciated basins beginning as early as 30,000 $^{14}$C yrs BP (Zazula et al., 2004; Duk-Rodkin et al., 2004). The sedimentological observations and chronology presented here suggest that the available evidence can be explained with pro-glacial drainage of meltwater through the Eagle River channel persisting for a few thousand years or, likely, less. Transgression of the Bell, Bluefish and Old Crow basins likely began *ca.* 18 $^{14}$C ka BP as recorded in the Bluefish Basin. Rapid inundation caused by activation of the Eagle River meltwater channel probably occurred after ~18 $^{14}$C ka BP and was ongoing at ~15 $^{14}$C ka BP. A subsequent transgression of the lake initiated incision of the Porcupine River Ramparts and established westward drainage of the basins prior to ~13,500 $^{14}$C a BP This alternate interpretation of a broadly Last Glacial Maximum timing of the northwest LIS fits well with regional direct dating of the former ice margin in areas to the north and south of the study region.

At the present day headwaters of the Rat River, Catto (1986) dated water-washed wood found in glaciolacustrine sediments overlain by Laurentide till. The resulting radiometric ages of 21,200 ± 240 and 21,300 ± 270 $^{14}$C yrs BP (GSC-3813; GSC-3371), while likely over-estimating the true timing of the advance, place the maximum advance of the NW Laurentide Ice Sheet into the late Wisconsin (MIS 2) in the Richardson Mountains.

Chlorine-36 ages of ~20-28 $^{36}$Cl ka BP from cosmogenic nuclide exposure dating in the Canyon Ranges of Mackenzie Mountains, interpreted by Duk-Rodkin et al. (1996) to represent a pre-LGM maximum at *ca.* 30 $^{14}$C ka BP, likely represent LGM deposition at *ca* ~17-22 $^{14}$C ka BP, assuming $^{36}$Cl and calendar year ages are approximately equal (Dyke et al., 2002). The interpretation of a maximum Laurentide Ice Sheet extent after 22 $^{14}$C ka BP is consistent with a Laurentide advance after 21 $^{14}$C ka BP (AECV-1664c) and retreat before 11.6 $^{14}$C ka BP (AECV-1203c) from central Alberta (Burns, 1996).

*Table 3-3: Summary of new and previously published dates of the glacial lake chronology from the Bell, Bluefish, and Old Crow basins.*

| Age | Lab. No. | Reference | Locality | Material | Stratigraphy | Lat. (N) | Long. (W) | m a.s.l. | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 13,250 +/-70 | Beta-79853 | Harington, 2003 | Old Crow: CRH-149 | bison bone | bank of Old Crow River | | | ca. 275 | minimum age of drainage of glacial lakes in Old Crow flats |
| 13,415 +/- 390 | CRNL-1218 | Morlan et al., 1990 | Old Crow: CRH-87 | mammoth bone | bank of Old Crow River | | | ca. 275 | minimum age of drainage of glacial lakes in Old Crow flats |
| 13,900 +/- 340 | Beta-13867 | Harington, 2003 | Old Crow: CRH-92 | mammoth bone | bank of Old Crow River | | | ca. 275 | minimum age of drainage of glacial lakes in Old Crow flats |
| 14,860 +/-120 | Beta-88793 | Lauriol et al., 2002 | Jackson Rock Falls | wood fragment | aeolian silt above fluvial sand and gravel | 67° 25’ | 140° 52’ | 350 | age of loess deposition after drainage of glacial-lakes |
| 15,000 +/-10% | IRSL | Lauriol et al., 2002 | Jackson Rock Falls | aeolian silt | aeolian silt above fluvial sand and gravel | 67° 25’ | 140° 52’ | 350 | age of loess deposition after drainage of glacial-lakes |
| 15640 +/- 430 | UCI-48838 | this study | Eagle River | *Morychus* sp. | Cross-laminated fine sand and silt | 67° 05’ | 137° 06’ | 325 | maximum age for deposition of the Eagle River braid delta |
| 15840 +/- 90 | UCI-40066 | this study | Eagle River | *Phlox* capsules | Cross-laminated fine sand and silt | 67° 05’ | 137° 06’ | 328 | maximum age for deposition of the Eagle River braid delta |
| 16,440 +/-110 | AA-45510 | Zazula et al., 2004 | Bluefish River | *Carex* sp. achenes | Massive silty clay | 67° 23’ | 140° 22’ | 301 | maximum age for final drainage of Glacial Lake Old Crow, highest datable organic remains in sequence |
| 17080 +/- 90 | UCI-47253 | this study | Eagle River | *Potentilla, poa,* and *phlox* capsules | Cross-laminated fine sand and silt | 67° 05’ | 137° 06’ | 325 | maximum age for deposition of the Eagle River braid delta |
| 17280 +/- 530 | UCI-48839 | this study | Eagle River | *Morychus* sp. | Cross-laminated fine sand and silt | 67° 05’ | 137° 06’ | 318 | maximum age for deposition of the Eagle River braid delta |
| 17,400 +/- 120 | AA-42629 | Zazula et al., 2004 | Bluefish River | *Poaceae, caryopses, Artemisia* flowers | Planar, cross and trough laminated silt | 67° 23’ | 140° 22’ | 300 | dates glacial lake transgression to SW edge of Bluefish Basin |
| 17430 +/- 200 | UCI-48840 | this study | Eagle River | *Morychus* sp. | Cross-laminated fine sand and silt | 67° 05’ | 137° 06’ | 316 | maximum age for deposition of the Eagle River braid delta |
| 17,570 +/-140 | AA-45506 | Zazula et al., 2004 | Bluefish River | *Luzula/Juncus* siliques | Planar, cross and trough laminated silt | 67° 23’ | 140° 22’ | 299 | dates glacial lake transgression to SW edge of Bluefish Basin |
| 17,710 +/-840 | AA-45507 | Zazula et al., 2004 | Bluefish River | *Taraxacum* achenes | Planar, cross and trough laminated silt | 67° 23’ | 140° 22’ | 299 | dates glacial lake transgression to SW edge of Bluefish Basin |

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| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 18,030 +/- 250 | AA-45505 | Zazula et al., 2004 | Bluefish River | *Poaceae, caryopses* | Planar, cross and trough laminated silt | 67° 23’ | 140° 22’ | 300 | dates glacial lake transgression to SW edge of Bluefish Basin |
| 18,490 +/- 160 | AA-42631 | Zazula et al., 2004 | Bluefish River | *Poaceae caryopses, Artemisia* flowers | Planar, cross and trough laminated silt | 67° 23’ | 140° 22’ | 299 | dates glacial lake transgression to SW edge of Bluefish Basin |
| 18,700 +/- 130 | AA-42630 | Zazula et al., 2004 | Bluefish River | *Poaceae caryopses, Artemisia* flowers | Planar, cross and trough laminated silt | 67° 23’ | 140° 22’ | 299 | dates glacial lake transgression to SW edge of Bluefish Basin |
| 18,880 +/-210 | AA-45509 | Zazula et al., 2004 | Bluefish River | *Poaceae, caryopses* | Planar, cross and trough laminated silt | 67° 23’ | 140° 22’ | 299 | dates glacial lake transgression to SW edge of Bluefish Basin |
| 21,200 +/-240 | GSC-3813: radio. | Catto, 1986 | Upper Rat River | organic detritus | lacustrine silt | 67° 43’ | 135° 51’ | 220 | maximum date on establishment of glacial lake in Upper Rat River valley following glacial retreat from all-time limit |
| 21,300 +/-270 | GSC-3371: radio. | Catto, 1986 | Upper Rat River | organic detritus | lacustrine silt | 67° 43’ | 135° 51’ | 220 | maximum date on establishment of glacial lake in Upper Rat River valley following glacial retreat from all-time limit |
| 21600 +/- 1300 | UCI-48841 | this study | Eagle River | *Morychus* sp. | Cross-laminated fine sand and silt | 67° 05’ | 137° 06’ | 312 | maximum age for deposition of the Eagle River braid delta |
| 24,700 +/-250 | RIDL-229 | Morlan et al., 1990 | Cadzow Bluff | mammoth tusk | fluvial silt, sand underneath upper glaciolacustrine unit | 67° 34’ | 138° 54’ | 300 | maximum age for formation of Unit 3 glacial Lake Old Crow sediments in the Old Crow Basin |
| 25,170 +/-630 | CRNL-1232 | Morlan et al., 1990 | Cadzow Bluff | mammoth tusk | as above | 67° 34’ | 138° 54’ | 300 | maximum age for formation of Unit 3 glacial Lake Old Crow sediments in the Old Crow Basin |
| 25,200 +/-400 | RIDL-191 | Morlan et al., 1990 | Old Crow: CRH-20 | bone | bank of Old Crow River | | | ca. 275 | maximum age for formation of Unit 3 glacial Lake Old Crow sediments in the Old Crow Basin |
| 34,220 +/-170 | TO-124 | Schweger & Matthews, 1991 | Rock River | rodent faecal pellets | 20 cm below glaciolacustrine clay | 67° 15’ | 137° 04’ | 295 | maximum age for onset of Peel River diversion and transgression of glacial lakes, likely an interglacial assemblage |
| 36,900 +/-600 | GSC-2422: radio. | Hughes et al., 1981 | Hungry Creek | *Picea* wood | alluvium underneath till | 65° 35’ | 135° 30’ | 350 | assemblage reinterpreted by Schweger and Matthes (1991) as interglacial |

Furthermore, optical luminescence dating on the Tuktoyaktuk Peninsula suggests the most recent advance of the northwestern lobe of the Laurentide Ice Sheet occurred during MIS 2. Luminescence dating of pre-Laurentide sands within the Wisconsin glacial limit in the Tuktoyaktuk Coastlands indicate a maximum that is broadly LGM at ~22-16 $^{14}C$ ka BP (Murton et al., 2007) and possibly as late as ~17-15 $^{14}C$ ka BP (Mackay and Dallimore, 1992).

**Conclusions**

The depositional and erosional characteristics of the Eagle River meltwater channel provide a record of overflow into the Bell Basin at the climax of the last glaciation. Following significant erosion in the first two stages, the third and final stage of meltwater channel development was responsible for deposition of a large braid delta on the lower Eagle River. The delta is characterized by evidence of rapid aggradation and lacks features indicative of intermittent drainage or significant hiatuses in deposition.

This braid-delta complex provides important information on the nature and timing of meltwater overflow from the glaciated Bonnet Plume Basin into the unglaciated Bell Basin. Geomorphology, stratigraphy and sedimentology indicate the Eagle River meltwater channel was incised and its braid delta deposited in a relatively short period of time. Radiocarbon dates from the braid delta place it firmly in MIS 2 and constrain this event to the late-Wisconsin, and potentially as late as *ca.* 15,000 $^{14}C$ a BP. An early (*ca.* 30 $^{14}C$ ka BP) advance of the LIS resulting in intermittent shallow lakes in the Old Crow Basin as suggested by Zazula et al. (2004) requires the presence of an ice dam in McDougall Pass and a contemporaneous lake occupying the Bell Basin. No evidence of this early lake phase was documented in the Bell Basin.

Radiocarbon ages from this study have demonstrated that coarse, woody materials consistently over-estimate the ages of the sediments they are used to date. While still valuable as minimum ages; these dates must be considered within the context for potential depositional histories including extensive preservation and reworking.

Reworking of older organic material is significant at high latitudes (Nelson et al., 1988; Oswald et al., 2005), and likely contributes to artificially old ages presented in previous discussions of the chronology of the area (i.e. Duk-Rodkin and Hughes, 1995; Zazula et al., 2004). Since the original chronology of the northwest Laurentide Ice Sheet margin was outlined (Rampton, 1982; Hughes et al., 1981; Catto, 1986; Duk-Rodkin et al., 1996), significant advances in Quaternary dating methods, and in particular the ability to date small masses of carbon (Jull, 2007), have dramatically improved our ability to constrain the timing of Quaternary events. In large part, the chronology presented in this study is only possible through these advances and only recently tractable with AMS radiocarbon dating. This new record brings the chronology of the NW margin into line with other North American chronologies for the most extensive Laurentide advance and presents a consistent view of the late-Pleistocene advance of the Laurentide Ice Sheet in western North America.

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## Chapter 4: General discussion and conclusions

The timing and genesis of the Eagle River meltwater channel play a critical role in determining the late-Pleistocene history of the northwest lobe of the Laurentide Ice Sheet. This thesis reports on characteristics of the Eagle River meltwater channel and attempts to resolve some of the outstanding issues surrounding the formation of the channel. The depositional and erosional characteristics of the Eagle River meltwater channel have demonstrated that meltwater overflow into Bell Basin at the climax of the last glaciation was responsible for incision of the channel and deposition of a large braid delta on the lower Eagle River.

Three zones are identified with regard to meltwater channel development: (i) an upper erosional zone of scoured bedrock associated with initial development of the channel; (ii) a middle zone of coarse deposition on high terraces associated with initial channel incision; and (iii) a lower zone dominated by fine lacustrine and deltaic deposits. Aggregate in the Eagle Plains region is found primarily on high terraces formed by late Pleistocene flooding along the Eagle River associated with rerouting of Peel River drainage by the Laurentide Ice Sheet. The distribution of erosional area, flood deposits, and deltaic sedimentation in the meltwater channel is consistent with existing models of flood channel evolution in a proglacial setting.

Process-depositional models have proven to be applicable to northern regions and a cost-effective model for developing aggregate resources. However, additional definition of aggregate quality and quantity would be useful for both government and private sector economic development on the Dempster Highway corridor. This could be accomplished with ground penetrating radar surveys, auger drilling, and additional textural analyses to define thicknesses, extents and materials available on different terraces or terrace levels in the area.

The Eagle River meltwater channel and braid-delta complex provide a record of the maximum extent of the NW Laurentide Ice Sheet and diversion of meltwater from the Bonnet Plume basin into the interior basins of unglaciated northern Yukon. Deltaic sedimentation within the meltwater channel is crudely-coarsening upward from alternating beds of massive clay and silt to ripple cross-bedded sand. All sediments occur in rapidly-aggrading forms with no evidence for a significant hiatus in deposition. Radiocarbon ages on woody plant macrofossils and spruce needles are invariably non-finite, while radiocarbon ages obtained on macrofossils from herbaceous plant taxa with 'steppe-tundra" ecological affinity from the upper part of the delta range between 15,640 ± 430 and 21,600 ± 1300 $^{14}C$ yr BP. These ages, coupled with the rapidly-aggrading nature of the braid-delta sediments and landform, suggest an age of ca. 15-16,000 $^{14}C$ yrs BP for flooding of the Eagle River meltwater channel. The high frequency of non-finite and mixed ages underscores the significant problem of reworked, well-preserved macrofossils in Arctic environments, and the need for careful selection of both fragile and ecologically-representative macrofossils to establish reliable chronologies.

While this thesis has answered questions about the nature and timing of meltwater events in the Eagle River meltwater channel, it has raised more concerning the Quaternary history of Yukon's northern basins. Specific unresolved questions surrounding the diversion of Laurentide meltwater into the Bell Basin relate to pre-flood drainage patterns and elevations; the timing of initial glacially-induced flooding; and importantly, potential drainage routes that may have persisted via McDougall Pass and the Rat River into the Mackenzie River drainage. While this study has provided important information about the nature of meltwater flowing into the basin, little is currently known about how long meltwater persisted, or how it eventually exited the basin.

More broadly, the published chronologies from McDougall Pass, the Bonnet Plume Basin, and the Old Crow Basin need to be revisited in light of the LGM age for Laurentide glaciation that has been obtained for the Eagle River meltwater channel. In particular, the record of detrital bones in the Old Crow Flats (Harington, 2003) indicates the region became uninhabitable to large mammals *ca.* 24 $^{14}C$ ka BP. Based on the chronologies for the Eagle River braid delta, this is significantly earlier than we would expect glacial meltwater to be affecting the basin. This is either an inconsistency between the histories of the basins, potential influence of a non-glacial lake, or the result of errors in the chronologies of one of the two records.

Interpretations that are reliant on radiocarbon dates (including those in this thesis) are subject to repeated revision as methods and technologies improve. It may be worthwhile, in a region plagued by error-laden radiocarbon ages such as this one, to explore new methods that can contribute and lend support to Quaternary histories. Some useful applications might include: provenance geochemistry; pre-Quaternary palynological analyses; and, accurate measurements of strandline and divide elevations. Finally, an under-explored aspect of northern Yukon's Quaternary history is the contribution of neo-tectonic activity to regional drainage interruptions and diversions.

Some specific suggestions for future work include:

1) Revisiting the Hungry Creek site in the Bonnet Plume Basin documented by Hughes et al. (1981). The sub-till date from this site proved to be from an inter-glacial assemblage; however, there is a high probability that younger material can be obtained and accurately dated using the latest AMS radiocarbon techniques.
2) Revisiting the pro-glacial lacustrine sequence documented in the upper Rat River (McDougall Pass) by Catto (1986). The published dates on water-worked wood are likely over-estimating the age of these sediments that directly underlie Laurentide till.
3) Use a combination of high resolution imagery (i.e. LiDAR) and differential Global Positioning Systems (dGPS) to accurately map strandlines, deltas, and drainage divides within and between the Bell, Bluefish and Old Crow basins. Potentially combine these results with updated mapping of bedrock faults.

4) Using geochemical provenance signatures, compare sediments throughout the stratigraphy of the Bell and Old Crow basins to each other and regional bedrock sources to determine drainage routes and basin interconnectivity through the Pleistocene.
5) Additional work in the Bell Basin should be focused on obtaining material appropriate for AMS $^{14}C$ dating from pre-flood, or very early-flood, deposits. This could include revisiting the Rock River site documented by Schweger and Matthews (1991); finding new sites on the Rock, Eagle or Porcupine rivers that might contain this sequence; or sieving larger bulk samples in the lower sediments of the braid delta with potential to recover more, larger macrofossils.

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