Aggregate resource exploration using a process-depositional model of meltwater channel development in the Eagle Plains area, northern Yukon

Kristen Kennedy and Duane Froese[1]
University of Alberta, Edmonton, Alberta

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ABSTRACT

Yukon's northern oil and gas basins remained unglaciated during the Pleistocene. The absence of coarse aggregate material generated by glaciation, coupled with continuous permafrost, has required expensive programs of crushing and hauling bedrock for road and infrastructure development. This study examines fluvial deposits associated with the late-Pleistocene Eagle River meltwater channel as potential sources of aggregate for regional development. In particular, it applies a process-depositional model of meltwater channel development to understand the distribution and potential quality of aggregate resources in the area. We identify three zones with meltwater channel development: (i) an upper erosional zone (~ 50 km) of scoured bedrock associated with initial development of the channel; (ii) a middle zone (~ 35 km) of coarse deposition on high terraces associated with initial channel incision; and (iii) a lower zone (~ 75 km) dominated by fine lacustrine and deltaic deposits that likely overlie coarse fluvial deposits with up to 30 m of clay, silt and sand.

RÉSUMÉ

Les bassins pétrolifères et gazifères du nord du Yukon sont restés en grande partie non glaciés pendant le Quaternaire. L'absence de granulats grossiers engendrés par les glaciations associée à la présence de pergélisol continu ont exigé de coûteux programmes de concassage et de transport de matériaux du substratum rocheux pour l'aménagement des routes et de l'infrastructure. Dans le cadre de cette étude on examine les dépôts fluviaux associés au chenal d'eau de fonte de la rivière Eagle au Pléistocène tardif comme sources potentielles de granulats pour le développement régional.

Les résultats préliminaires indiquent que le déversoir d'une longueur de 160 km s'est formé lors d'une débâcle glaciaire d'eau de fonte retenue par un barrage glaciaire qui a causé une incision rapide et une importante érosion. On identifie trois zones de développement du chenal : (i) une zone d'érosion en amont (~ 50 km) de substratum rocheux affouillé associée au développement précoce du chenal ; (ii) une zone centrale (~ 35 km) de dépôts grossiers sur les hautes terrasses associées à l'incision initiale du chenal ; et (iii) une zone en aval (~ 75 km) dominée par des dépôts lacustres et deltaïques fins — limon, argile et sable fin qui atteignent jusqu'à 30 m d'épaisseur — qui recouvrent vraisemblablement des dépôts fluviaux grossiers.

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[1] *duane.froese@ualberta.ca*

INTRODUCTION

The Eagle River lies on the former 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 (Figs. 1 and 2).

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 (Fig. 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 (Fig. 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 westerly drainage of the Porcupine River into central Alaska and draining the glacial lake system in the Old Crow, Bluefish and Bell basins (Thorson and Dixon 1983; Duk-Rodkin *et al.*, 2004).

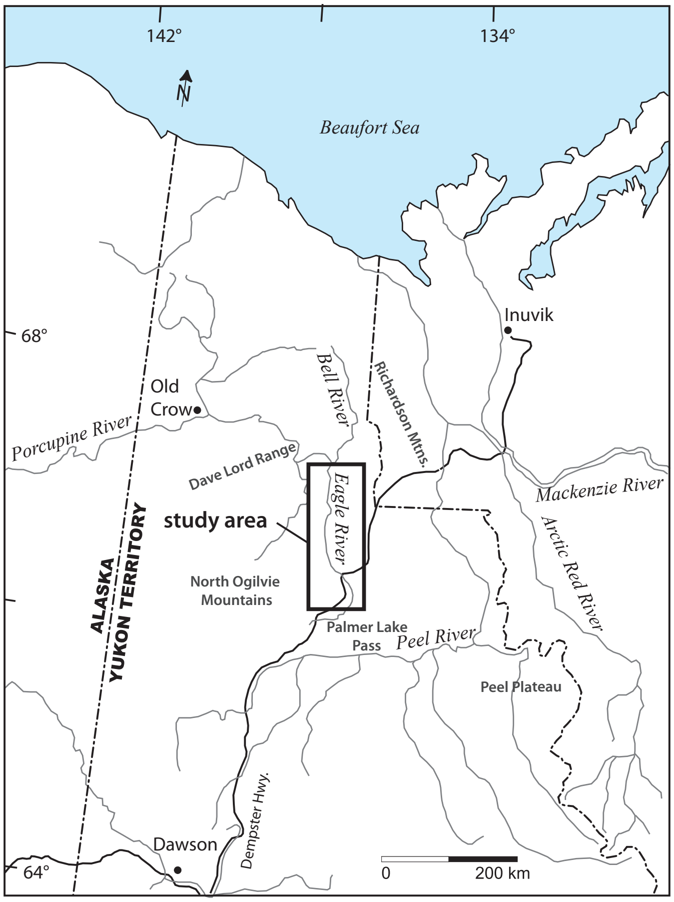

Figure 1. *Location of study area.*

PLEISTOCENE CHRONOLOGY

Flooding of the Eagle River meltwater channel was intimately connected with extensive continental ice in the western Mackenzie basin blocking drainage from the

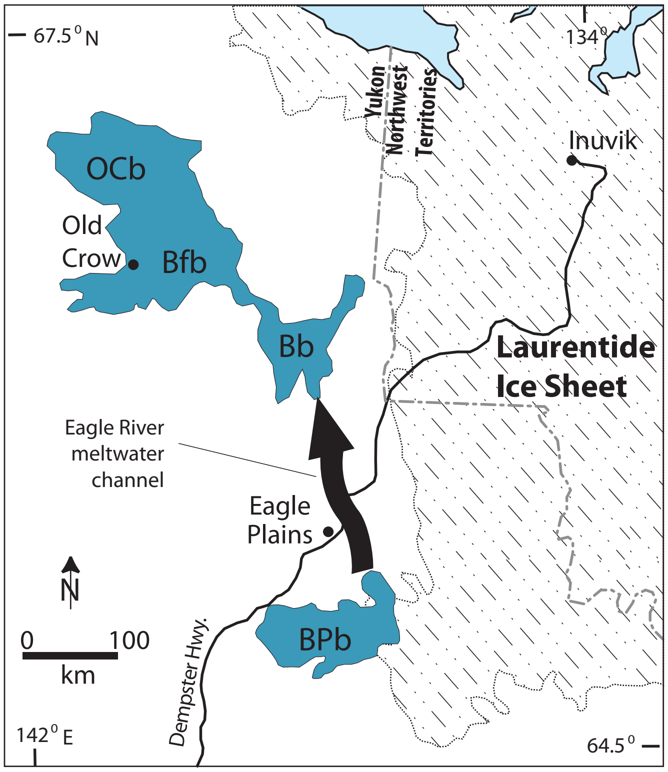

Figure 2. *Glacial lakes (shaded areas) formed by the impoundment of east-flowing drainages by the Laurentide Ice Sheet. The Eagle River meltwater channel linked a lake in Bonnet Plume basin (BPb) with a continuous lake in Bell (Bb), Bluefish (Bfb) and Old Crow (OCb) basins.*

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 (30 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 suggest that lake sediments in Old Crow basin, originally thought to represent the maximum advance of the Laurentide Ice Sheet at *ca.* 30 ka BP, are more than 40 ka BP and 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).

REGIONAL SETTING

The Eagle Plains ecoregion is a rolling lowland between the Richardson, North Ogilvie and Dave Lord Mountain ranges (Figs. 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).

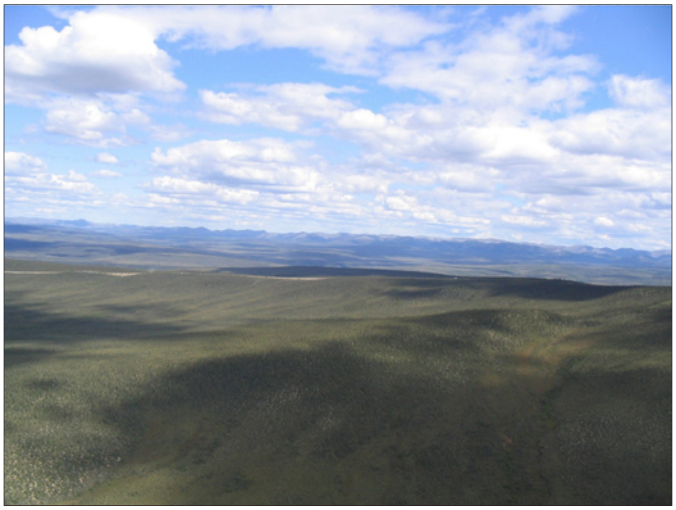

Figure 3. *Easterly view of the Eagle Plains area toward the Richardson Mountains. The Dempster Highway is visible in the middle of the photo.*

PROCESS-DEPOSITIONAL MODELS

Process-depositional models have been developed to understand the formative 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 occurs; 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, channelized flow develops; this is 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 thickness and bedrock composition and resistance to erosion, surficial geology of cover materials, 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 identified 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 (Fig. 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 (Fig. 5). The flood channel begins ~60 km upstream of the Dempster Highway bridge near the drainage divide at Palmer Lake (Fig. 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 (Fig. 6). Pediment surfaces are well

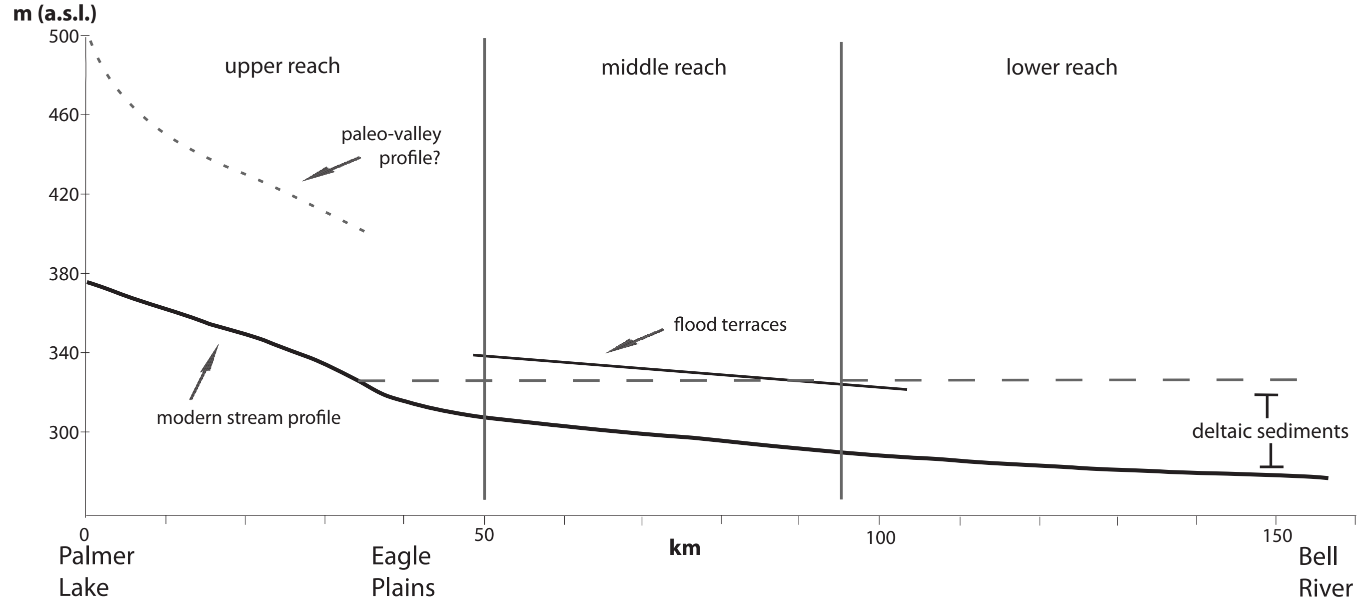

Figure 4. *Longitudinal cross-section of the modern Eagle River stream profile and the hypothesized paleo-Eagle River profile with locations of flood terraces and the area of deltaic sedimentation. The distribution of erosion and deposition along the channel results in three distinct (upper, middle and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

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

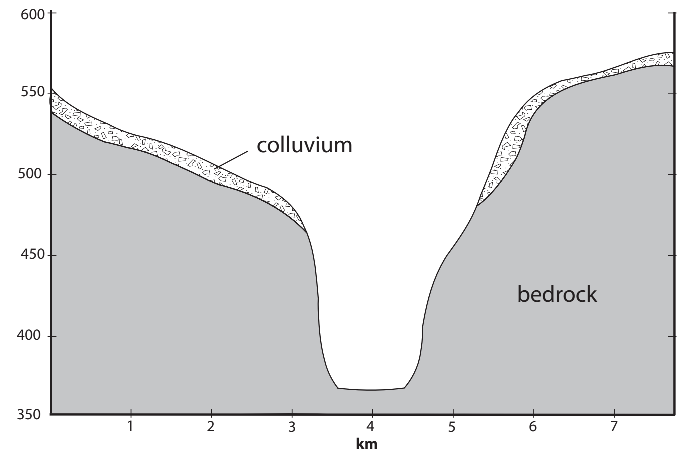

Figure 6. *Schematic cross-section of the upper reach of the Eagle meltwater channel. Steep bedrock on the valley sides is blanketed by colluvial deposits that have likely been formed over long periods of periglacial weathering. (VE = 20x)*

Figure 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.*

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 rerouting. The upper reach has the highest topographic relief in the study area.

MIDDLE REACH (~45 KM)

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 commonly overlain with flood-deposited gravel and sand (Figs. 7 and 8). Terraces are located at elevations of 340-360 m above sea level (a.s.l.) (20-30 m above the modern alluvial plain) and are well developed on the outside bends of the channel and

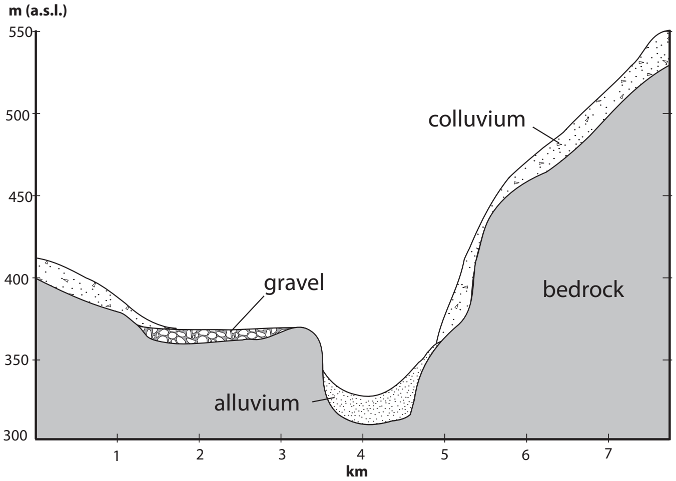

Figure 8. *Schematic cross-section of the middle reach of the Eagle meltwater channel. The broader channel in this reach allows for coarse gravel deposits to be preserved above bedrock terraces. (VE = 20x)*

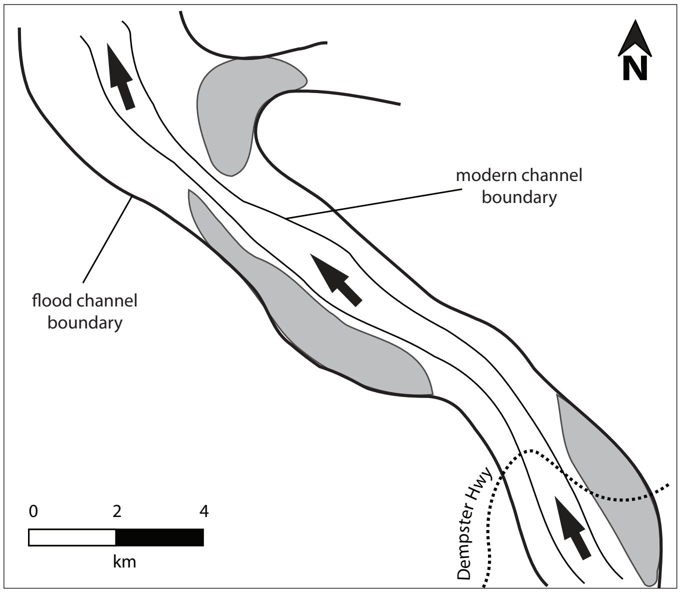

Figure 9. *Schematic view of the middle reach of the Eagle meltwater channel with shaded areas outlining coarse gravel deposits on the outside bends and at tributary junctions of the channel.*

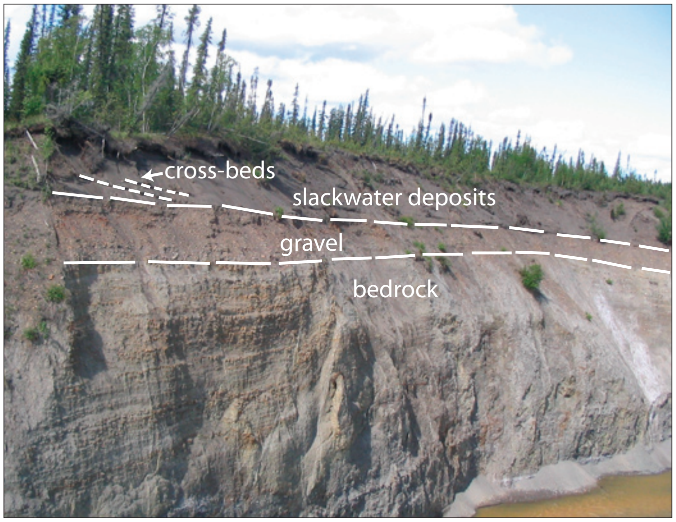

Figure 10. *Upstream-trending slackwater deposits above an erosional bedrock contact on a tributary to the Eagle River. Tributary flow is toward the left, and steep cross-beds in sandy slackwater deposits indicate flow was to the right (upstream) when they were deposited. Section is approximately 30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

at the junctions of tributary valleys (Fig. 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 moderately to well sorted. Field observations of clast lithology indicate about 90% of deposits are composed of locally derived sandstone, with about 10% of clasts being shale and 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 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. (Fig. 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.

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

	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%

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 armoured 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 (Fig. 11). Beginning ~25 km downstream of the Dempster Highway bridge, the increasing thicknesses of fine sand, silt and clay obscure underlying deposits of flood material.

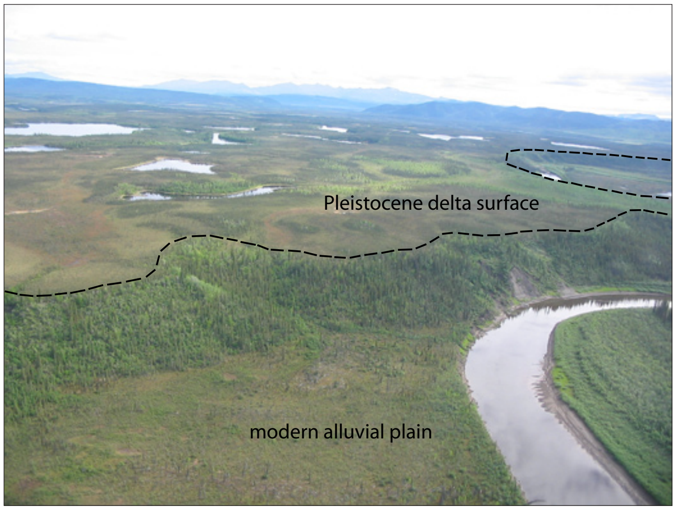

Figure 11. *View of deltaic sediments blanketing the lower reach of the Eagle River. Flow of the river is toward the bottom of the photo, and the delta top is ~20 m above the river surface.*

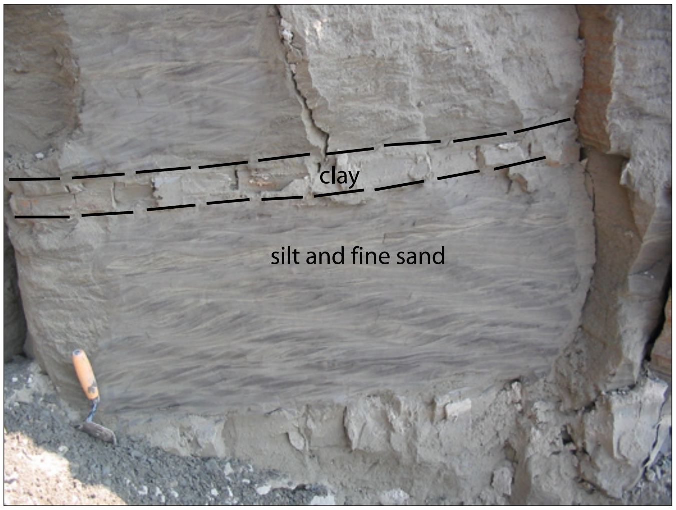

Figure 12. *Stratified deltaic/lacustrine deposits within the lower reach. Massive clay alternating with ripple cross-laminated silt and fine sand.*

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 (Fig. 12). Massive clay beds have thicknesses up to 2 m near the base of exposures and thin upward as coarser grained ripple cross-beds become thicker and more frequent. The top of the sediments display evidence of subaerial 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 (Fig. 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 commonly, but not always, overlain by significant gravel deposits and are concentrated along outside bends of the meltwater channel reflecting expansion of flow onto these surfaces. Eddy or alcove bars were probably formed in tributary mouths as the result of deposition from back-flooding into valleys (Baker, 1973; O'Connor, 1993) (Fig. 13). Upstream-trending cross-beds in slackwater sediments of tributary valleys (Fig. 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 was 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 alluvial plain are concentrated at tributary junctions, and decrease in concentration downstream from the tributary, producing small fans of coarse deposition in the modern valley. Development on the tributary alluvial plains may be preferred due to the low water levels present in the summer months.

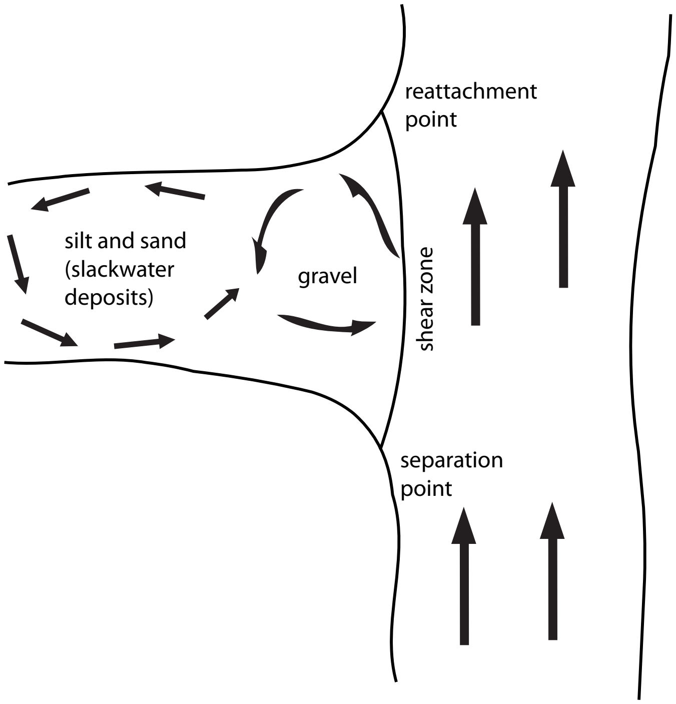

Figure 13. *Flow conditions associated with the formation of slackwater deposits. Flood water in the main channel inundates tributary valleys with turbulent flow that deposits coarse materials near the point of separation (at tributary junction) and finer material further up-valley in the tributary.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

LOWER REACH

Thick occurrences of horizontally stratified sand with interbedded silt up to 20 m thick occur 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 (typically, boulders are common in 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 glacial material transported into the Bonnet Plume basin by the Laurentide Ice Sheet. 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 (J. 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 the 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 and 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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