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Fluvial Geomorphology of the Yukon River, Yukon Flats, Alaska

by

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Abstract

An anomalous assemblage of alluvial channel patterns exist on the Yukon River as it flows through the Yukon Flats depositional basin in East-central Alaska. The river braids as it emerges onto the Yukon Flats from a confined valley. 120 km downstream, at the confluence of the Porcupine River, rapid channelization occurs until the classification 'wandering gravel-bed' applies. Continued channelization results in an irregular meander pattern observed in the final 30 km before the river is abruptly confined within bedrock valley walls.

Downstream grain-size analysis of bed sediments shows that gravel dominates the composition of bed material despite extremely low slope measurements in the wandering reach (10 to 20 cm/km) and a complete lack of valley confinement for over 400km.

Landsat MSS imagery of a 21-year flood event reveals bankfull conditions to exist between 20,300 m^3/s and 23,390 m^3/s, placing the 'wandering-reach' bankfull re-occurrence interval between 17 and 21 years. Flood data indicates ice-jam flooding is responsible for 90% of all overbank events and thus both vertical floodplain aggradation and channel geometry are governed by these conditions, while only lateral migration and within-channel deposition result from summer flows.

Regional stratigraphy and radiocarbon dating suggest that the Yukon has not significantly changed its vertical position since 11, 500 BP, and possibly since well before 150,000 BP. A borehole in the center of the Flats and ground penetrating radar shot along the river, indicate that only 25m of gravel have accumulated since lake impoundment ended in the Late Pliocene (thinning to 14m upstream near Circle, AK). Field-work revealed that downstream of the borehole, scour-holes up to 25m deep are active today. This indicates that this system has likely remained 'in-grade' since the Pleistocene. This condition exists despite several glacial/inter-glacial cycles, the Late-Pleistocene capture of the northern Yukon Territory drainage by the Porcupine River, and the catastrophic flooding from the overflow of glacial lake Old Crow.

The anomaly of the multi-channeled morphology existing over such a long distance at such a low slope, may be explained by bank instability due to gravel comprising the lower 30-50% of bank facies. When this inherent instability is combined with a discontinuous distribution of permafrost, bank strength thus also becomes spatially heterogeneous, resulting in irregular patterns of bank erosion that are completely uninfluenced by valley confinement. Analysis of stream power relationships indicates channel changes are likely the result of decreasing slopes downstream. 30 years of change mapping reveal no avulsions and only a few neck cut-offs, indicating that the smaller side 'slough' channels evolve only from lateral erosion/deposition processes. Landsat MSS imagery supports the hypothesis that diversion of flow from ice-jamming during spring break-up also contributes to the maintenance of these channels and thus are fundamental factors to anabranching in this case.

Acknowledgements:

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Chapter 1: Introduction

1.1 The Problem

The middle reach of the Yukon River, as it flows through Yukon Flats depositional basin in east-central Alaska, displays channel patterns of which the shape, size and lateral extent are not seen on any other river in North America. Braiding occurs as the river emerges onto the Yukon Flats from a narrow confined valley. One hundred twenty kilometers downstream, at the confluence of the Porcupine River, the anomaly begins when this pattern shifts to one of more channelization with up to 5 individual, straight or sinuous, channels operating simultaneously. Continued channelization results in 1 or 2 of these channels becoming dominate with many sinuous 'slough' side channels branching off and rejoining the main flows. A short reach of meandering is present followed by renewed anabranching before the river is abruptly confined within bedrock valley walls. Because this has never been documented, no data exists that can shed light on the causes of the Yukon River's anomalous channel patterns.

Specifically, the following aspects of the nature of this fluvial system remain uninvestigated or unexplained.

1) It is unknown what causes the observed multiple channeled morphology, what processes operate within it and why such a low-gradient river maintains an anabranching pattern rather than reverting to a single channel form.

2) It is unknown what type or caliber of sediment this reach of the Yukon River is transporting or if there is any significant change as the river traverses the low-gradient Yukon Flats.

3) It is unknown if this multiple channel pattern is laterally active and if so, at what rate does channel shifting occurs.

4) It is unknown whether conventional channel geometry relationships can be used to model this type of system, or as a comparative tool when relating to other rivers.

5) The long-term history of the Yukon River remains poorly understood and uninvestigated using modern techniques, a factor which contributes to the difficulty in understanding modern processes and responses

1.2.1 Previous Work on the Yukon River

Only a small collection of scientific literature exists that specifically concerns the Yukon River. Most research has been exploratory or observational in approach, and none has undertaken a systematic study of the fluvial processes operating on the Yukon Flats. The Yukon Flats was not visited by European explorers until the late 1840's when Alexander Hunter Murray of the Hudson's Bay company reached the present site of Fort Yukon. He arrived by way of the Porcupine River, via the Rat Pass from the Mackenzie River system. It was then several years before it was found that the river flowing past the new Fort Yukon Trading Post was, in fact, the downstream portion of what Fort Selkirk had been built on 15 years earlier (Wright 1976). Needless to say, the progress of regional geographic knowledge has been slow due to the extremely remote nature of the area and difficult logistics. The following will document what has been done thus far.

The first truly scientific, rather than casual, observations of the Yukon River were made by Russell (1890). He described the surficial geology of Alaska and what is now the Yukon Territory as he traveled up the Yukon in a steam-powered 'sternwheeler'. He postulated that the Yukon River, 500 km downstream of the study area near Nulato, was migrating northward due to the Coriolis effect. He was the first to note that the "lowlands" (Yukon Flats) seemed to be a vast floodplain deposit. He also postulated that there may have been a lake in the basin at one time, although noted that no shorelines could be found to support this. Most importantly, he noted the role of river ice processes. Specifically, this role included: 1) the transport of large clasts by ice-drives; 2) the 'ploughing' of the gravel bed by ice-push during break-up; 3) the scratching, polishing, and even faceting of clasts by the motion of debris-laden ice grinding past; and 4) the importance of ice-jam flooding in causing overbank events which locals claimed to be more severe than summer flooding. For only having 3 months in the field, Russell's observations (far more numerous than noted) are a marvel, reflective of the keen observation abilities of so many of the early geographers and geologists.

Russell's work was built-upon by Eardly (1938) in the first attempt to understand the fluvial processes operating in the Yukon system. Although his work was carried-out between 80 to 800 km downstream of the study area, it remains the only fluvial-style research done on the middle and lower Yukon to date. Eardly's aim was to determine if the Yukon River was laterally migrating in the meander-belt between Nulato and Holy Cross. He used crude dendrochronology and historical evidence to estimate migration rates. He found that in a 10km wide floodplain (which can vary between 3 and 30 km wide along that reach), it would take 1000-2000 years to rework. He assumed that vertical degradation was occurring based on the fact that erosion seemed to be exceeding deposition. However, one should consider that fluvial processes and time-scales were, at the time, poorly understood and that many of the high 'banks' he was observing have since been found to be loessal in origin (i.e. the 'Palisades' section). Eardly also addressed the origin of 'slough' channels (small sinuous side anabranches). He postulated that they were formed from the deposition of sediment between the bank and the main channel, forming an active side channel. Normally, this channel would fill in, but if a clear-water tributary entered along its length, it remained open, the input-material mined out. With vegetation stabilization, the newly-formed bar becomes part of the bank and the side channel narrows to a sinuous form in equilibrium with flow inputs. The idea is not unsound although other processes may also be at work. Finally, he identified two forms of deposition occurring in the system: 1) lateral deposition on the inside of meander bends (point bars) and 2) overbank vertical aggradation from ice-jam induced flooding. The second process is worthy of note because he claimed that summer floods never increased stage more than 3m, never overtopping the banks, but localized ice-jam flooding could reach as high as 12m and last for a few days. He also found ice-jam flood beds of more than two feet thick for a single event. He couldn't have realized it at the time, but Eardly's (1938) Yukon River observations of this form of sedimentation style differ from almost all of the subsequent fluvial literature. He essentially stated, conventional (non-ice induced) bankfull discharge does not occur on that reach of the Yukon River.

Another worker, Williams (1955) documented ice processes on the Yukon River within the confines of the Yukon Flats. While spending an autumn and the following spring at the village of Beaver, he noted and measured the conditions of both freeze-up and break-up. Nothing anomalous was noted for the freeze-up conditions. However, during break-up he recorded a 3m increase of the ice-level before the ice cover broke up into 3-5m pans and began to move out. Shortly after the drive began, upstream and downstream jamming caused water level to rapidly rise and fall, although no true flood occurred at Beaver that season. He later noted that flooding at Beaver only occurs about once every 50 years (Williams 1962). As far as geomorphic processes, ice was observed "...ramming the banks with tremendous force"(Williams 1955). Other work done by this author at the village of Beaver concerned the verification of Russell's (1890) idea that the Yukon was migrating northward. In the case of the Yukon Flats, Williams (1952) found wind generated waves to be the main agent of preferential migration to the north. He also claimed that the north bank was significantly higher than the south due to the Yukon incising into the fan deposits of the Chandalar and Christian rivers. However, this observation was not made systematically and will later be refuted in this research. Even in his later work, Williams (1962) maps the Holocene flood deposits which show no clear indication that the Yukon prefers a northward course. One useful observation made from his 1952 study (Williams 1952) was that the bank strength of frozen silt was higher than sand or gravel and could thus be undercut further into the bank before collapsing in a large block. Although some points are criticized here, William's (1952, 1955, 1962) contribution to the knowledge of the Yukon Flats region is unparalleled by any subsequent research, particularly if one considers that most of his earlier work was completed without any topographic map coverage of the area.

Two other papers concerning the Quaternary history of the Yukon River well downstream of the study area are worthy of discussion. Knebel and Creager (1973) investigated the Holocene transgression migration of the Yukon through the delta region. This study used Bering Sea bathymetry, ocean cores, and deltaic sediments to find that most deltaic lobes south of the present mouth were abandoned before 11,000 BP. Using this study as a springboard, Mason and Beget (1988) attempted to quantify the Late Pleistocene discharge. Using some of the abandoned channels noted by Knebel and

Creager (1973) and others upstream, this study used channel sinuosity to estimate discharge. They found the Late Pleistocene discharge to represent only 45% of the modern discharge, likely due to a decrease in precipitation and glacier melt during the height of the last full-glacial cycle. This work is a good first step but caution must be used. Only 1 radiocarbon date of 8000 BP constrains the age of only 2 of the 10 paleo-meanders used in the study. The other 8 paleo-channels used occurred on abandoned sections of the delta and were only "roughly" dated to between 16-11 000 BP. No possibility was mentioned that these "paleo-meanders" could have represented only anabranches of the total flow (distributary channels being quite common on deltas and indeed all along the present middle and lower Yukon River) and would thus, underestimate the actual paleo-discharge. However, in theory, their idea is sound enough to warrant the consideration of their findings as a reasonable, albeit rough, estimate.

The above papers represent the total amount of work done that specifically pertains to the middle – lower Yukon River. The significance of more regional studies, or those that pertain to non-fluvial aspects of the Yukon Flats, will be discussed in Chapter 2. The lack of fluvial literature relating to a river as large and unique as the Yukon, and specifically to the Yukon Flats reach indeed needs to be rectified. Through a systematic approach, this study aims to help complete the picture of the Yukon River as a fluvial system.

1.2.2 The Concept of Grade

The 'graded river' concept has been defined differently by many workers over time. The idea has been present in the geomorphological literature since introduced by Gilbert (1877). Since then, two main approaches to the problem have developed, the long-term stability school, and the 'process' approach. A review the definition of the 'grade' concept is of value in understanding the context and implications of this research.

The definition of grade has taken on many forms. Gilbert's (1877) definition referred to a stream that maintains an equilibrium of mass balance, where the inputs into the system match the outputs. Davis (1902, p. 86) had a similar definition calling grade the "...balance between erosion and deposition attained by mature rivers". Although the concept that the properties of certain landform systems can be attributed to their 'maturity' or 'infancy' has fallen out of favor in the literature, the idea has recently begun to become popular again. Certainly, time is one of the overall ingredients in geomorphic processes, something particularly to keep in mind when referring to the Yukon River system.

Later thought on the subject lead to increasing detail in its definition. Mackin (1948, p. 471) defined the graded stream as:

> ...one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity for the transportation of the load supplied from the drainage basin. The graded system is in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change.

Leopold *et al.* (1964) criticized Mackin's emphasis on slope but supported his idea that equilibrium applies to rivers. They described the usefulness of the concept by both the implication that the channel can adjust to independent variables (sediment load, sediment caliber and discharge), and that there is stability in "form and profile". Thus, the distinction lies in the stability of a system, grade being the opposite of aggradation or degradation. This viewpoint is reflective of the long-term thinking (100's to 1000's of years) of a geologist but the definition of grade is different for those concerned with present processes and engineering problems.

Schumm and Lichty (1965) and Schumm (1977) argued that 'graded time' must represent the long-term in order to mask the effects of seasonal or anomalous changes to the regime of the system. Thus, 'progressive changes' are those that accumulate to affect changes to the overall stability of the system; i.e.: a climatic change induces more vegetative stabilization, limiting sediment supply over the long-term, leading to hydraulic changes in the system which produce the net product of incision (degradation of the floodplain). The time scale required to produce such a change is greater than that of human observation approaches that see only the noise of shorter-scale variability.

Knox (1976) argued that grade to be much more of a balance between short and long time-scale change. He defined graded streams as:

> ...[where] the relationship between process and form is stationary and the morphology of the system remains constant over time..[and that,] the ungraded should probably be defined as those undergoing relatively rapid morphologic changes involving properties of longitudinal profiles and/or cross-sections (Knox 1976, p. 179).

This interpretation suggests that systems experiencing change in hydraulic geometry are not in-grade and that overall mass-balance does not diagnose grade.

Leopold and Bull (1979, p.195) harmonize all of the above thinking into a reasonable working definition:

> A graded stream is one in which, over a period of years, slope, velocity, depth, width, roughness, pattern and channel morphology delicately and mutually adjust to provide the power and efficiency necessary to transport the load supplied by the drainage basin without aggradation or degradation of the channels. The threshold of critical power is passed and the stream is not graded when the volume of load supplied is insufficient or is too large to be transported and the channel bed degrades or aggrades.

This definition subtly refutes Knox (1976) by implying that long-term vertical stability is the only real test of grade and that either morphologic stability or instability can exist irrespectively.

So how can one tell if a system is in-grade? D. Smith and D. Froese (pers. comm., 1999) argue that the only real indicator of 'progressive change' is found in the geomorphologic and sedimentary record of the floodplain. Simply, if a system is lowering its floodplain (degrading), ^{14}C datable terraces should be found above the level that gets inundated by flood flows. If a system is aggrading, detection is more difficult, but coring, augering, or drilling should reveal buried terraces. Geophysical tools such as ground penetrating radar, shallow seismic, and electrical resistivity ground imaging may also be able to answer this question. However, determining if the depth of valley-fill exceeds the depth of maximum scour of the present channels is the most simple and cost-effective technique. One must acknowledge however, the possibility that hydraulic geometry changes over time, such as the transition from meandering to braiding, may affect the depth of scour in a system without causing elevation changes on the floodplain itself. Of course, if one applies caution and realism when interpreting the ratio between valley fill depth and modern scour depth, this technique is quite valid.

1.2.3 Large Rivers

The literature distinctively concerning large alluvial rivers is extremely sparse. Schumm and Winkley (1994) used a collection of case studies of large river research to illustrate that a high degree of variability is found in and between these systems. Kellerhalls and Church (1990) defined 'large' as those not likely to be affected locally by blockage resulting from landslides and fallen trees, with a discharge of greater than 20 m^3/s and a width of greater than 20m. Schumm and Winkley (1994) acknowledged this definition (because no other exists) and only poorly define 'large rivers' themselves, by saying that those described in their book are significantly larger than those specified in the above definition. The most important thing mentioned by Schumm and Winkley (1994) is that hydraulics and hydrology are not always the dominant controls on large rivers and that they can be quite sensitive to small influences. Conversely, they also illustrated examples were massive human modifications have caused no response at all (Stevens 1994). Specifically, Schumm and Winkley (1994) illustrated that geologic controls, sedimentologic controls, human impacts and spatial/ temporal influences all affect large river systems, and that each individual river will respond differently to each control depending on the history of its other controls. Essentially, this research is very reflective of the conclusions drawn by Schumm and Lichty (1965), only once applied to large rivers, the conclusions are substantially less conclusive. Thus, large alluvial rivers are complex, and variable/response relationships can be unpredictable. Attaining an understanding of these systems is compounded by the fact that almost all fluvial research has focused on small to medium sized rivers resulting in only a comparatively miniscule database. Before the nature of large river variability can be explained, more research must be carried out on large rivers.

1.3 Objectives

Fluvial channel patterns, anomalous in their shape, size and lateral extent, exist on the middle Yukon River in the Yukon Flats. The primary objective of this study is to make a first attempt at gaining an understanding into the cause of these channel patterns. This main problem can be broken down into component questions that must be answered. These questions progress from simple to complex and are as follows:

1) Can hydraulic geometry relationships be effectively used as a comparative tool on the multiple channeled Yukon River which has its flow divided by stable vegetated islands?
2) What size-range of bed-load sediment is being transported by this system? (e.g. sand rivers tend to behave very differently than gravel rivers) Does the caliber the of bed-load change significantly downstream? (i.e. does the system shift from gravel to sand, or do tributaries substantially alter the bed-load composition?) If these changes occur, are they coincident with channel pattern changes?
3) What causes the multiple channeled morphology and what maintains it at such low slopes?
    - 3a) do river ice processes play a role?
    - 3b) does bank composition act as a variable?
    - 3c) is hydrologic behavior a factor?
4) Where does the Yukon River fit in our understanding of fluvial processes specifically, where is its place in the continuum of river channel patterns?

Chapter 2: Regional Setting and History

2.1 Regional Physiography

The study area is located in the northeast interior of Alaska in a region known as the Yukon Flats (Figure 2.1.1) approximately 160km north of Fairbanks. The Yukon Flats is a Cenozoic depositional basin bordered by the Southern Foothills of the Brooks Range to the north, the Porcupine Plateau to the east, and the White and Crazy Mountains of the Yukon-Tanana Plateau to the south and west. Through it flows the Yukon River, joined by the Porcupine, Chandalar, and Christian rivers as well as some smaller tributaries. The Yukon Flats lies between 250 to 150 m in elevation. In this region, the Yukon River flows through a vast central lowland (alluvial-plain) bordered on the sides by a marginal escarpment (Figure 2.1.2). The spatial extent of the Yukon Flats lowland is worthy of special note. At it's widest, the Flats covers almost 100km north-to-south, tapering westward to approximately 35 km. The Yukon River runs in an arc from southeast to southwest through the center of the basin. It is approximately 250km long east-to-west making for a total land area of nearly 33, 000 km^2. The lowest "terraces" of this floodplain are utilized by the river during flood events with increasingly sparse reoccurrence intervals as one increases in elevation. These terraces often reflect the pattern of former river channel positions (Williams, 1962). Although there is only a minor elevation difference (less than 3m), there is a subtle physiographic difference between the "terraced" Holocene zone of lateral migration and the older more subdued looking Late-Pleistocene surface. This older surface is characterised by eolian infill of scroll patterns, sporadic dunes, the presence of thermokarst lakes, and is on-lapped by fine-grained alluvial fans which have built off of the marginal escarpment onto the vast

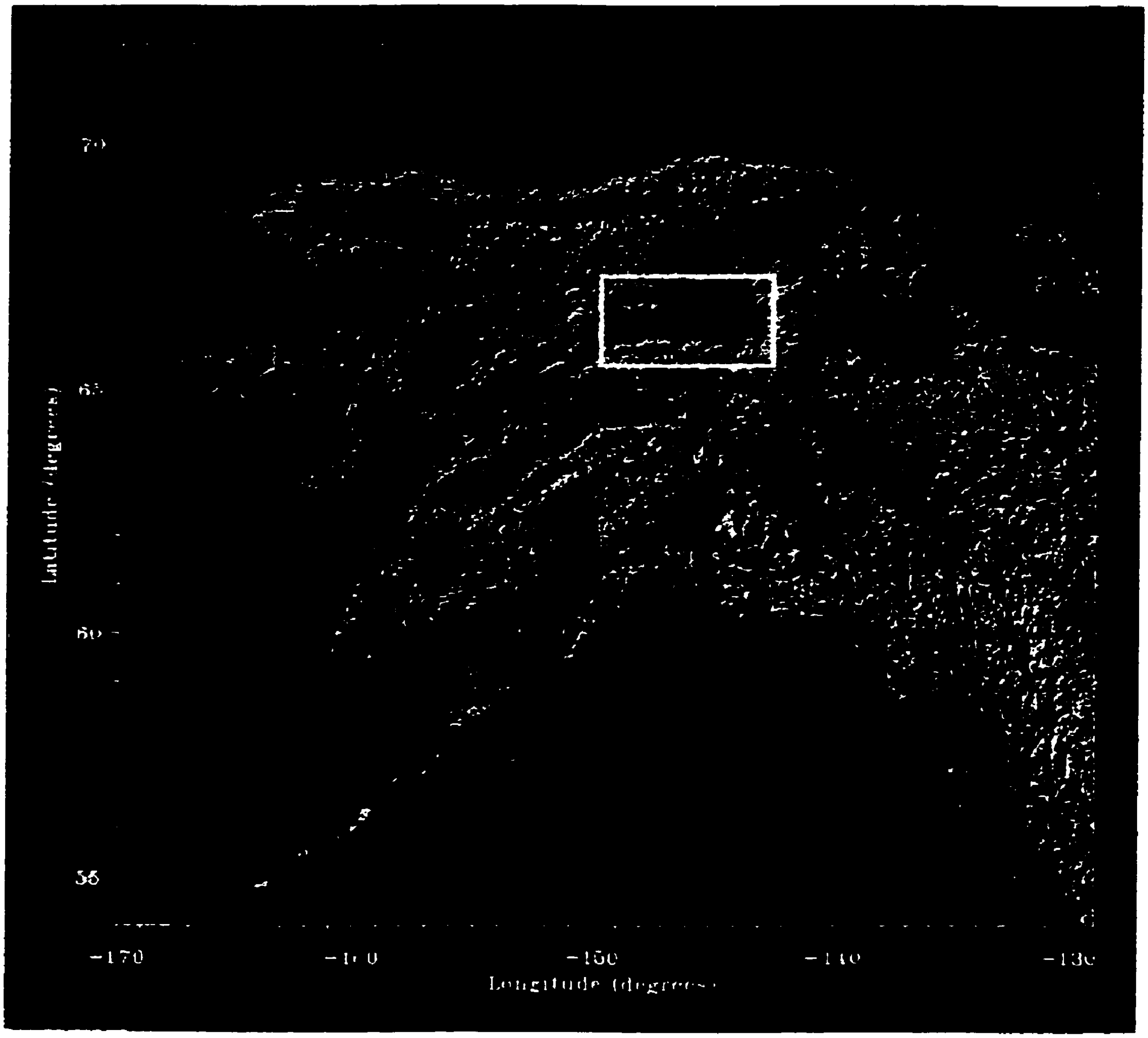


Figure 2.1.1. A digital elevation model of Alaska, showing the location and relative size of the Yukon Flats physiographic region (courtesy USGS).

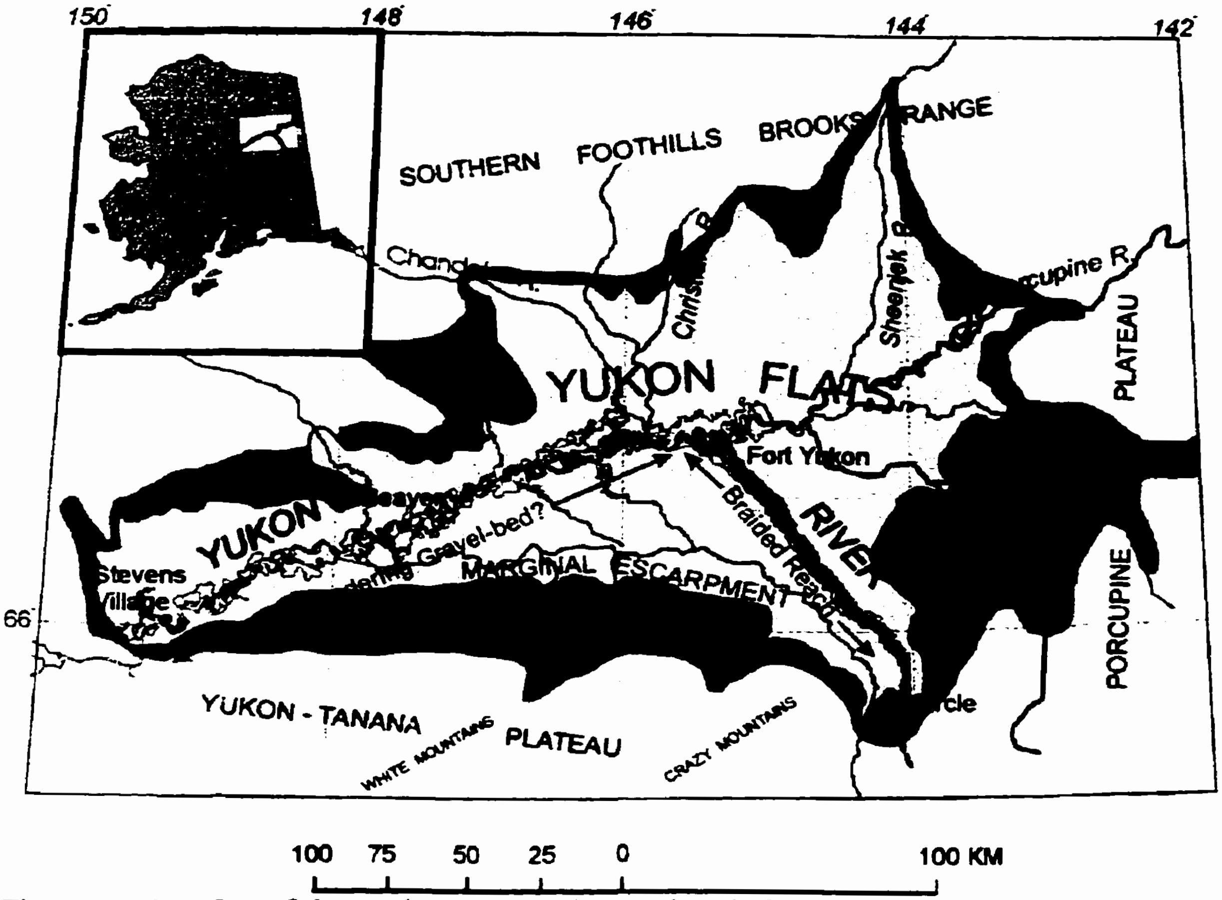


Figure 2.1.2. Map of the study area showing regional physiography

alluvial plain. A radiocarbon date from a cut-bank exposure, constrains the age of this older surface to 11,550 radiocarbon years B.P. (discussed in detail in Chapter 4). Discontinuous permafrost occurs throughout the Yukon Flats, although the thawed zones are most common and extensive on the active modern floodplain and beneath the numerous small lakes and oxbows (Williams, 1962). The escarpment can be more or less definable with the bluff ranging from 1 to 30 m in elevation (Williams, 1962). A marginal upland, delineated by the marginal escarpment and backed-up onto the White and Crazy Mountains to the south and the foothills of the southern Brooks Range to the north, exists up to 100 m higher than the floodplain and is extensively loess-mantled with depths of loess exceeding 35m. Figure 2.1.3 shows a cross-section through the Yukon Flats, illustrating the distribution of permafrost and the relative vertical position of the marginal escarpment. Figure 2.1.4 shows the spatial distribution of these topographic features. Williams (1962) suggested that the loess originated from the outwash floodplains of local rivers including the Yukon and the ancestors of the modern tributaries draining into the Flats. Similar eolian processes can still be seen operating in glacially-fed systems (Figure 2.1.5), implying that the existence of large braid-plains systems is synonymous with periods of rapid loess accumulation. Thus, it is likely that the majority of loess accumulation on the marginal upland and the Yukon Flats was also coincident with colder climate and the more glacial-proximal situation that existed on and off throughout the Pleistocene.

2.2 Tectonic Setting

Although it has been suggested that the Yukon Flats basin is a tectonic subsidence feature, the exact time-scale and nature of this subsidence is not well defined in the

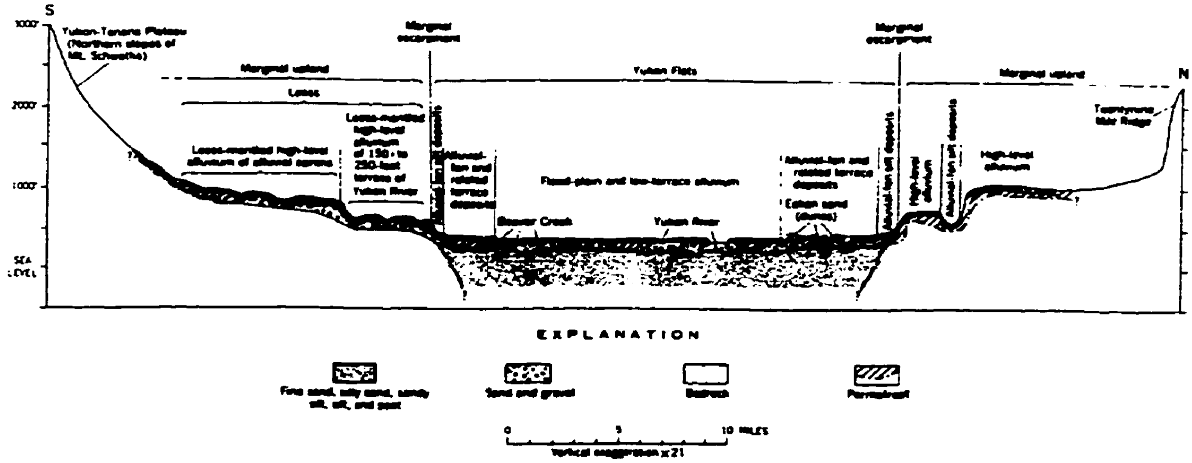


Figure 2.1.3. Cross-section through the Yukon Flats District between Twenty-mile Creek and Yukon-Tanana Plateau showing geologic units and permafrost (from Williams, 1962).

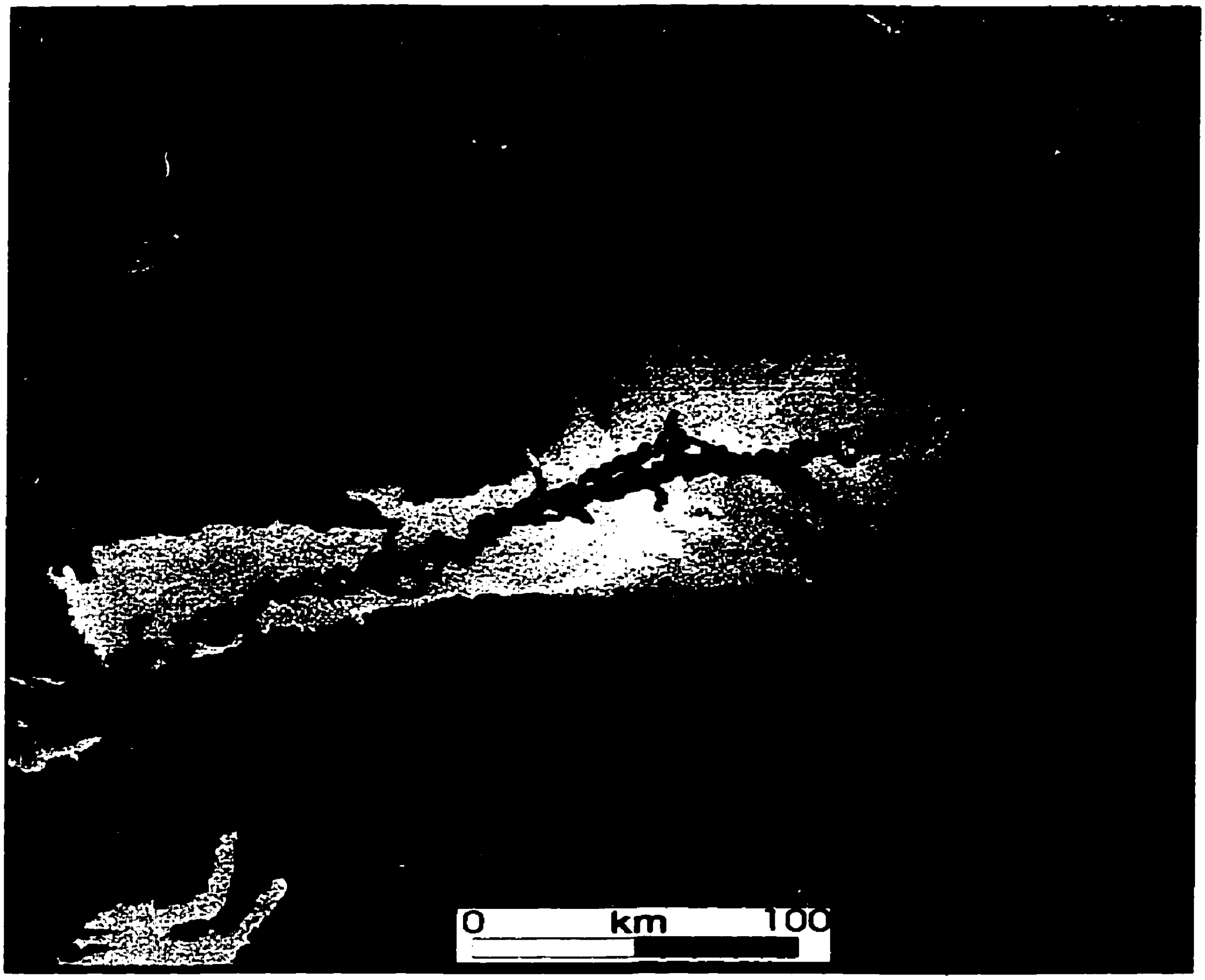


Figure 2.1.4. An IHS-shaded digital elevation model showing the relative relief of the Yukon Flats basin (courtesy USGS)..

Figure 2.1.5. The braid plain of the Delta River near Fairbanks as a source of loess (from Pewe, 1975).

literature. The Neotectonic Map of Alaska (Plafker, Gilpin and Lahr, 1986) shows two faults which may be of significance to origin of the Flats (Figure 2.2.1). The first is the 'Preacher Fault'. This fault is late Pleistocene in age with uplift occurring on the marginal upland. Continuing off of this fault is the 'Medicine Lake Lineament', a Holocene feature. Both of these features seem to be lateral extensions of the Tintina Fault system. As much as 50km of Late Tertiary or Quaternary right slip was postulated by Barker (1986) on the basis of geomorphic evidence. The Tozitna splay of the Tintina Trench, indicates 55km of right separation estimated (or from Circle to 147°15'). Gravity surveys reveal strong lows near the center of the Flats, suggesting that there may be over 3 km of fill in the center of the Yukon Flats basin (Figure 2.2.1). It has been suggested that the smaller grabens of the Tintina Fault may have over 5 km of Cenozoic fill. However, so little work has been done on the region whether the basin subsidence and lateral movement along splays were coincident events is just speculation. Dover (1994) implied that the Yukon Flats is part of a series of massive extensional-rotational basins that run north-south throughout Alaska (Figure 2.2.2). Williams (1962) postulated the majority of tectonic disturbance occurred during the Miocene tilting of basements rocks exposed in the "Fort Hamlin –Rampart" canyon (name no longer used locally) southwest of Steven's Village. This is supported by an incomplete borehole from Fort Yukon that revealed lake sediments to a depth of over 400m with a maximum of 16 Ma in the record (Ager, pers. comm., 1998). Thus, if lake impoundment was subsequent to the majority of subsidence, it likely began in the Early Miocene or earlier. Modern fault scarps south of the Crazy Mountains (Foster *et al.* 1983) indicate that the Tintina fault zone is still active.

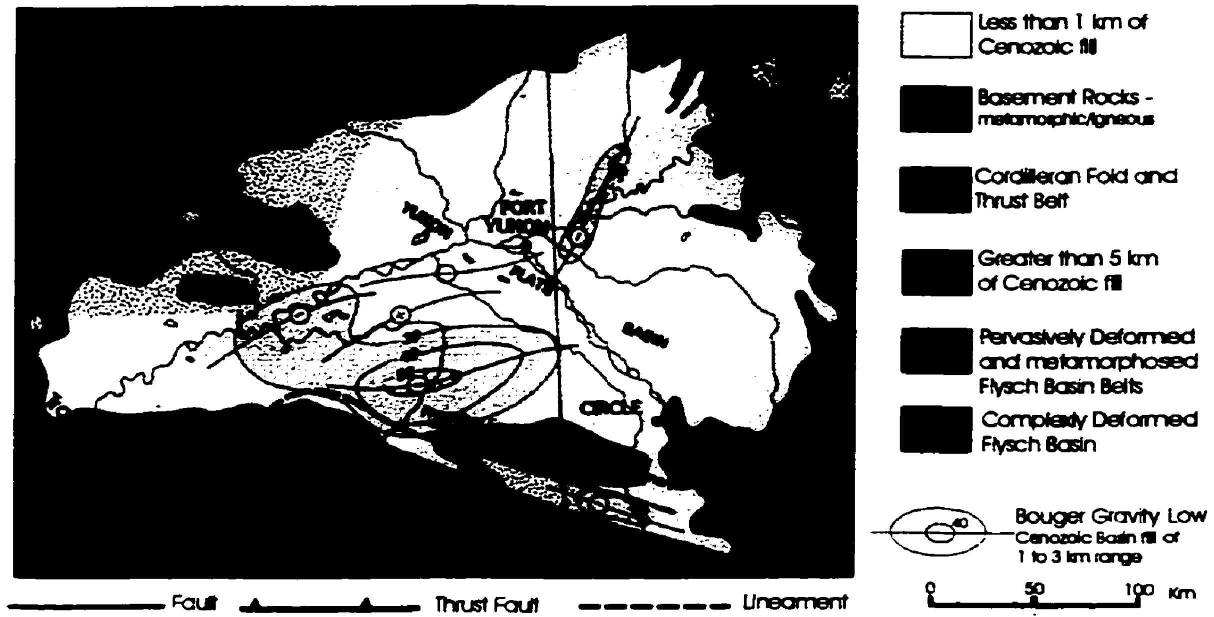


Figure 2.2.1. Neotectonic and Sedimentary Basin Map of the Yukon Flats, Alaska. Bouger gravity lows indicate areas of thick sedimentary fill (modified from Kirschner, 1986 with supplement from Plafker, Gilpin and Lahr, 1986).

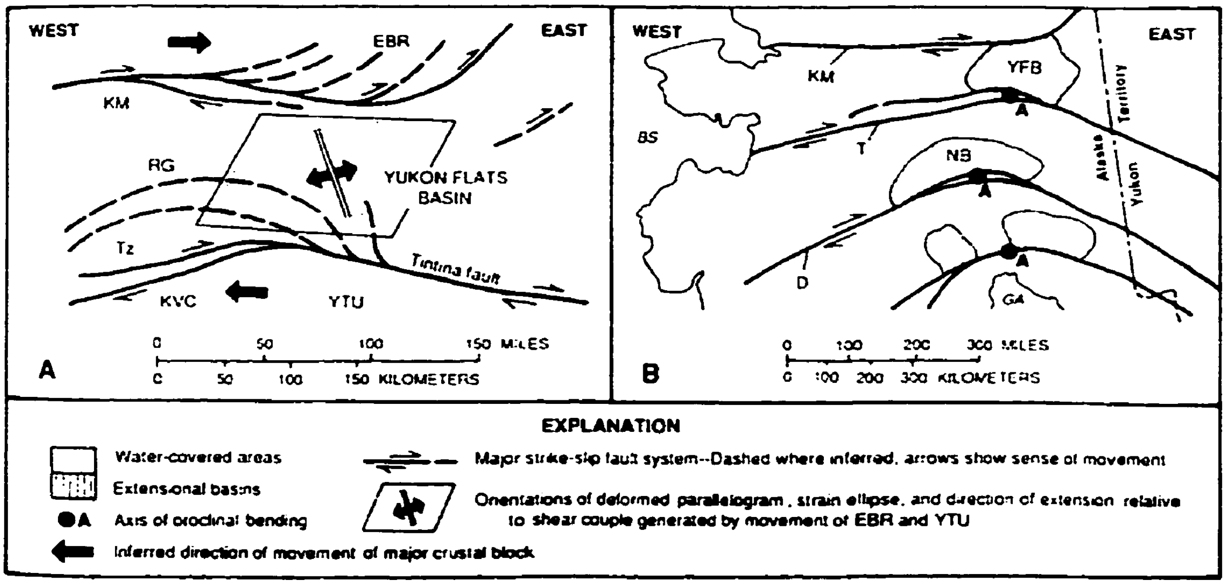


Figure 2.2.2. Possible origins of Alaskan extensional basins. A, extension by rotation between active strike-slip faults. B, Extension on convex sides oroclinally bent strike-slip faults. EBR, Brooks Range; KM, Kobuk-Malamute fault; RB, Ruby geanticline; TZ, Tozitna fault; KVC, Kaltag-Victoria Creek fault; YTU, Yukon-Tanana upland; YFB, Yukon Flats basin; BS, Bering Sea; GA, Gulf of Alaska; T, Tintina fault; NB, Nenana basin; D, Denali fault; A, axis of oroclinal bending (from Dover, 1994).

Williams (1962) noted deformation of pre-Cenozoic rocks exposed in the marginal escarpment (evidence pointing to genesis of this feature as erosional and tectonic rather than as a depositional terrace). These were thought to have deformed around Miocene time. However, he goes on to say that accumulation in the Yukon Flats basin could have been the result of more intense tilting of Eocene rocks in the Fort Hamlin – Rampart Canyon (where the Yukon is once again constricted into a single canyon channel) (Williams, 1962). These ideas are both concurrent with the observations of Ager and other workers in the recent drill-core taken from Fort Yukon. In this core, the deeper lake sediments are interpreted to be of Miocene-to-Pliocene origin (Ager, pers. comm., 1998).

Given this information, Williams' (1962, pg. 321) first interpretation (a) of regional geologic development seems appropriate for providing a basic framework for the Yukon Flat's geologic history:

> 1. Assuming the silt and silty sand are slightly older than or in part contemporaneous with the high-level gravel, two alternatives can be offered:
>
> a. During the Miocene disturbance, the Yukon Flats basin subsided with respect to the surrounding highlands sufficiently to impound the drainage and form a lake. At the same time, stream erosion of the uplifted highlands was accelerated and huge loads of gravelly sediments were deposited in the Yukon Flats basin. The deposits gradually encroached on the lake, partially or completely filling it. The lake outlet, probably a large river, sought a course across the lowest point in the highlands that rimmed the Yukon Flats basin. The course selected between Fort Hamlin and Rampart may have been a former route for waters draining the Yukon Flats basin or may have crossed one or more low divides separating the westward-flowing streams from the Yukon Flats drainage basin (Mertie, 1937). As time passed, the river cut down through the rocks of the highlands and formed a narrow valley in which it flowed in broad meanders. In the Yukon Flats the lake level was lowered with the fall in the level of the outlet, and the lake probably was largely filled with alluvium. By late Pliocene time, the highlands had been reduced to areas of mature dissection and moderate relief, and the lowlands had become flat plains with little relief (Mertie, 1937; Miller, Payne, and Gryc, 1959).
> At the end of Tertiary time, regional uplift, possibly accompanied by local

> warping or faulting, lowered the base level of erosion (Mertie, 1937). The broad, meandering channel of the Fort Hamlin-Rampart segment of the Yukon River began to be incised to form the present canyon, and a broad valley was excavated in the gravel fill and the lacustrine silt and silty sand of the Yukon Flats basin.

2.3 Glacial History of Alaska

Although glaciers once covered up to fifty percent of the entire landmass of Alaska, the Yukon Flats has remained unglaciated (Pewe, 1975). Figure 2.3.1 shows the known extent of glaciation in Alaska. Glaciations in the region began during a general cooling trend that started in the late-Tertiary as a result of regional orogeny and atmospheric cooling on a global scale (White *et al.*, 1997). A summary of the evidence concerning the nature and timing of glacial episodes in Alaska can be found in Hamilton (1989).

Due to a large proportion of alluvial landforms in the study area, it is apparent that glacial meltwater has played an important role in the development of the geomorphology of the Yukon Flats. The Chandalar, Sheenjek and Christian rivers, as well as other smaller tributaries flowing south from the Brooks Range, display extensive alluvial fans at their entrance into the Yukon Flats. Williams (1962) correlated the higher part of the Chandalar fan to early-to-mid Pleistocene morainal complexes found up-valley in the southern foothills of the Brooks Range. These moraines get to within 16km of the head of the fan. Although there is no evidence given to support it, he postulated that similar conditions existed for the Christian and Sheenjek valleys. The younger fans and terraces can be traced to younger moraines of mid-to-late Pleistocene (Pewe, 1975). The Yukon River has also formed a massive 100km long low-angle fan deposit (presumably gravel in composition) between Circle and Fort Yukon. Weber and Hamilton (1984) demonstrated that during the penultimate glaciation, Mt. Prindle in the

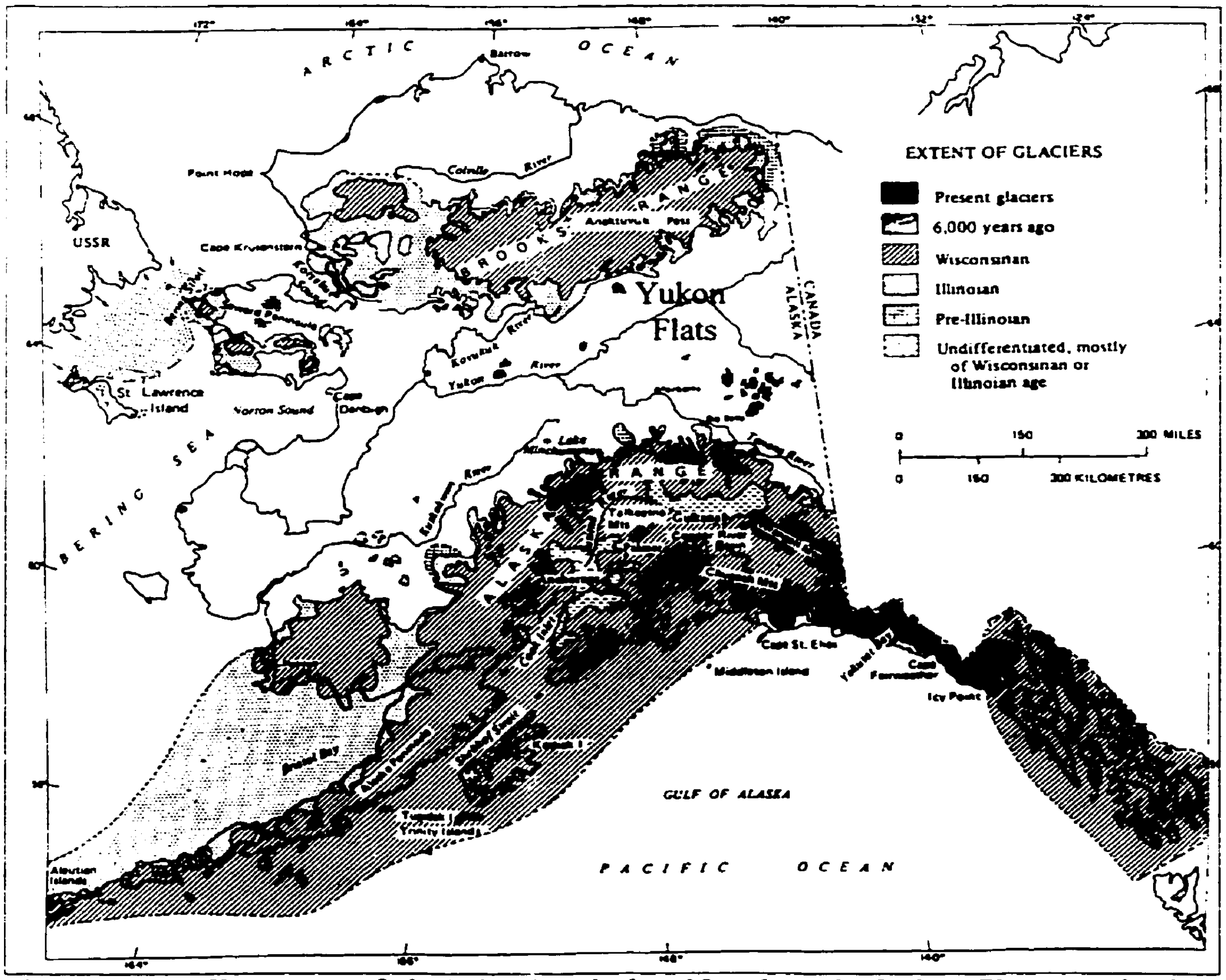


Figure 2.3.1. The extent of glaciation in Alaska. Note how the Yukon Flats remained unglaciated (from Pewe, 1975).

Crazy Mountains (SW of Circle) was capped with an ice sheet that was drained by small outlet glaciers. They also stated that most peaks over 900m would have shown similar conditions, placing outlet glaciers to the south of the Yukon Flats to within 20-30 km of the margins of the study area. These glaciations may have contributed to what Williams (1962) called the 'high terrace alluvium' on the Marginal Upland. These deposits are mantled by up to 35m of loess deposition, another product of glacial conditions. Therefore, although untouched by ice, the Yukon Flats was definitely affected by both climate fluctuations and glacial meltwater drainage.

2.4 The Porcupine Mega-floods

At least two catastrophic flood events entered the Yukon Flats during the Late-Pleistocene. Thorson and Dixon (1983) described intermittent impoundment and drainage of lakes in the Old Crow, Bell and Bluefish basins of the Yukon Territory by the Keewatin Sector of the Laurentide ice sheet. This impoundment eventually resulted in catastrophic floods moving through what is now the Porcupine River system (Figure 2.1.2).

According to these authors, Laurentide ice blocked McDougall Pass, forming glacial Lake Old Crow before 30, 600 B.P.. After initial damming, lake levels rose until reaching the lowest divide, overtopping and incising the height of land. Lowering of the divide continued until the lake sediments now laid in the Old Crow basin began to be incised. This flow flushed westward through the Porcupine, which had now captured the majority of the drainage in the northern Yukon Territory.

The list of evidence for these events is comprised mostly of erosional and depositional terraces. Thorson and Dixon (1983) were able to constrain the age of these sediments by radiocarbon dating organic materials and bone collagen. This dating shows that initial incision, based on a gravel terrace overlying scoured bedrock, began around 30, 600 BP. This fill was then scoured out by a second major incision event (age not constrained, thus may have been a pulse of the first event) which shows a coarse boulder lag at its base. A period of infilling occurred between 30.6 Ka BP and 26.6 Ka BP when yet another mega-flood coursed through the valley, this time affecting the lower Ramparts more than the now-graded upper Ramparts.

Thorson (1989), backed with more stratigraphic evidence than his earlier work, estimated that these discharges were comparable to the Lake Bonneville paleoflood. The author found geomorphic and stratigraphic features directly comparable to those reported by Bretz (1969) for the Channeled Scablands of Washington State (see also Baker and Nummendal, 1978). Using Baker's (1973) slope/area method for discharge estimation, Thorson (1989) suggested that discharge could have exceeded 134 000 m^3s^{-1}. This estimate was confirmed by Thorson (1989) using DuBoys equation for grain size on massive clasts found in the valley floor.

The exact impact of these floods on the Yukon Flats and thus, the Yukon River, is unclear. Thorson (1989) noted that deposition of the braid fan on the edge of the Flats at Herbert's Village, northeast of Fort Yukon, was a result of at least one of these floods. He also noted that temporary lacustrine slackwater sedimentation could have resulted from a backwater effect at the Rampart constriction west of Steven's Village. However, this could not have been the mechanism for deposition of the lake sediments found under

Fort Yukon because of their extreme thickness and pollen evidence indicating a Pliocene setting (Ager, pers. comm., 1998). The present study found no evidence on the Yukon Flats of these events in the field or on air photography. One possibility is that the uncomformable contact between the Pliocene lake sediments and the Pleistocene gravel in the Fort Yukon borehole, represents a scour and fill related to the Porcupine floods. It can definitely be concluded that there would have been a massive change in sediment influx into the Yukon River through the Yukon Flats, although the nature of this sedimentation remains unclear.

2.5 Yukon River Hydrology

The Yukon is one of the great river systems in the world. It is navigable from its mouth at the Bering Sea to Whitehorse in the Yukon Territory, 2900 km upstream. The discharge hydrograph is characterised by an extremely seasonal flow regime (Figure 2.5.1). The sub-arctic latitude of the Yukon's drainage area allows rapid, high-amplitude temperature shifts during seasonal change resulting rapid freezing and break-up (Williams, 1955). The Yukon's main tributaries are the White and the Donjek rivers. These rivers reside in heavily glacierized drainage basins, draining meltwater runoff from the icefields of the St. Elias Mountains. A third large tributary, the Porcupine, joins the Yukon in the middle of the Yukon Flats at Fort Yukon. The Porcupine has a short, rapid flow regime resulting from snowmelt draining from the Old Crow Basin. Often overlooked as a significant tributary, during flood this river can make up up-to 45% of the Yukon's flow at the confluence point (Figure 2.5.2). A northward flowing course, combined with rapid snowmelt from long spring days, results in ice break-ups, drives and jams which re-occur every 1.3 years (Figure 2.5.3). At the Steven's Village gauging station the drainage area equals 508,000 km^2 (Figure 2.5.4). A partial-duration reoccurrence interval plot shows the mean annual re-occurence discharge (Q_1) to be 10,300 cubic meters per second (CMS) (Figure 2.5.5). When compared to the mean *peak* discharge for the Bow River at Calgary of 230 m^3/s (Environment Canada, 1988) it is clear that the Yukon is a formidable flow.

Hydrology data coverage for this study is acceptable. The three main components of flow are accounted for. Eagle station (150km upstream of the study area) is assumed to represent the flow present in the braid reach due to a lack of significant tributaries entering between Eagle and Fort Yukon. The Steven's Village station is a good representative of the flow moving through the remainder of the Yukon Flats, including that which is picked up by the entrance of the Porcupine River into the system. Due to the fact that other tributaries downstream of the Porcupine represent less than 10 percent of the total flow at peak discharges, a subtraction of the Eagle flow from the Steven's flow provides a usable surrogate for the now defunct Porcupine station.

2.6 Effects of river ice and the behavior and characteristics of Northern Rivers

Circumpolar (Northern) rivers differ from those in the rest of the world in two distinct ways (Church, 1971). The first is a nival regimen characterized by major spring snowmelt floods. This phenomenon is compounded by the presence of river ice, often causing ice-jams. The second is permafrost. An overview of the specific processes affecting northern rivers is appropriate given the location of the study area.

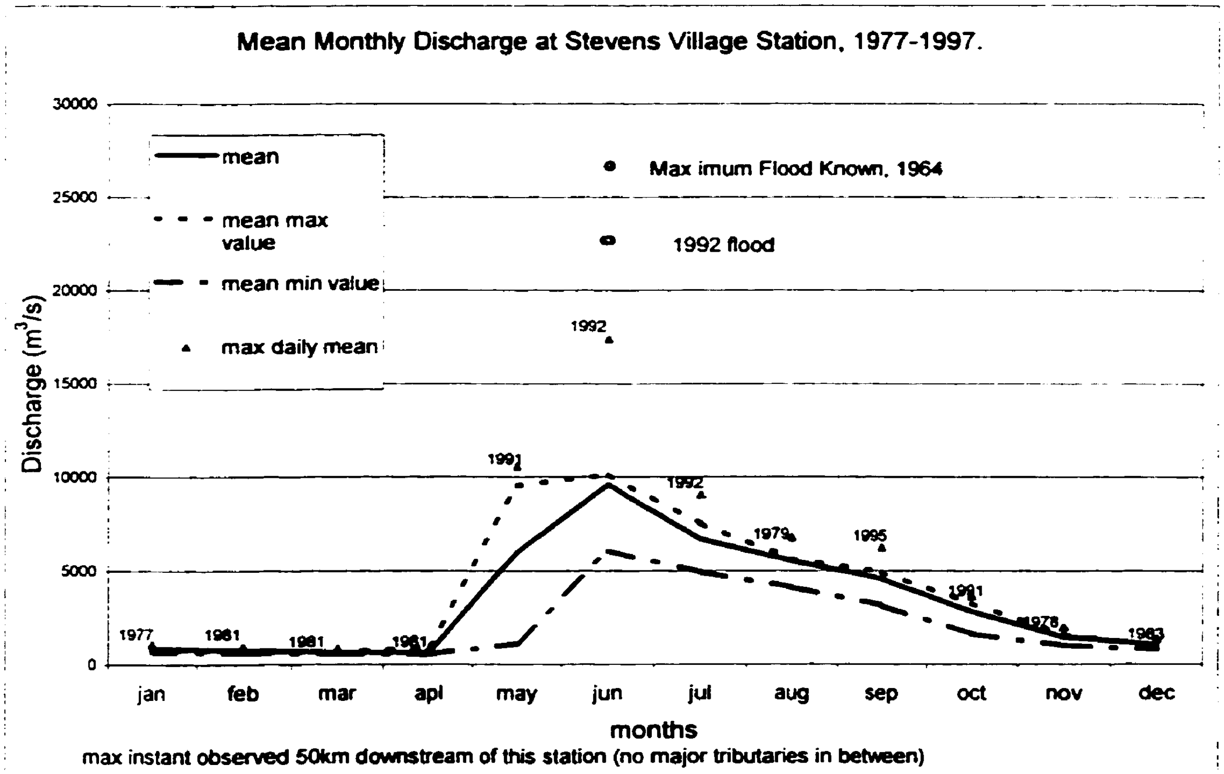


Figure 2.5.1. Mean monthly discharge hydrograph from the Yukon River at Steven's Village. This data is supplemented with known daily peak discharges. Note how the Yukon displays a highly seasonal, 'nival' flow regime. Mean peak summer discharge is close to 10, 000 m^3/s. The 1992 flood may have been ice-related (source USGS Alaska Water Survey Division).

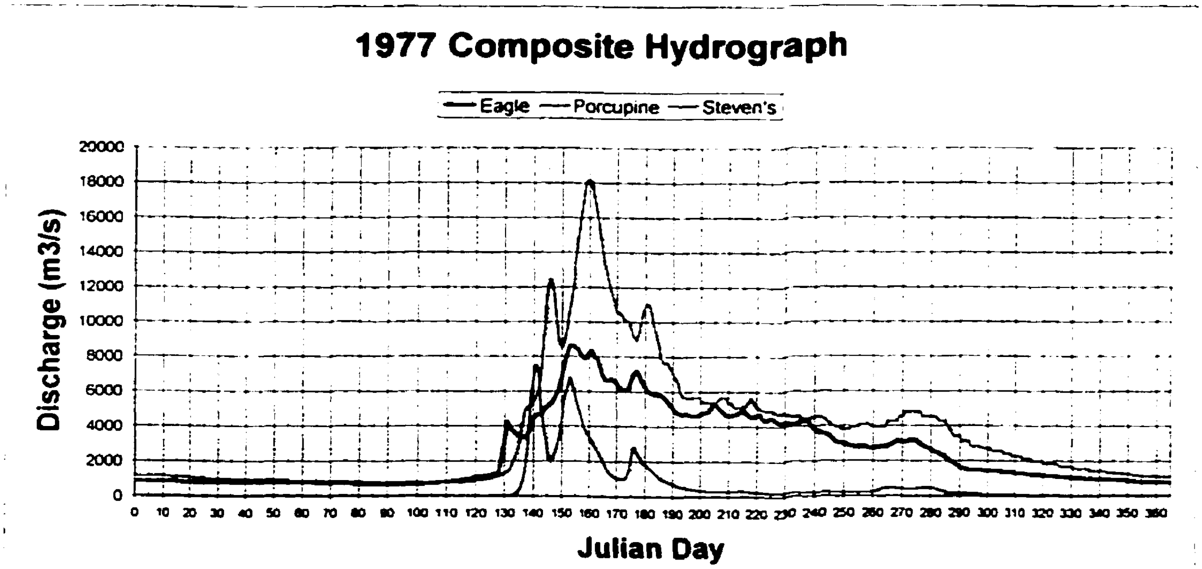


Figure 2.5.2. One of the only three years of overlapping discharge data for Eagle and Steven's Village stations on the Yukon River and the Fort Yukon Station on the Porcupine River. Note how much of the total downstream flow (Steven's) is made up by Porcupine discharge.

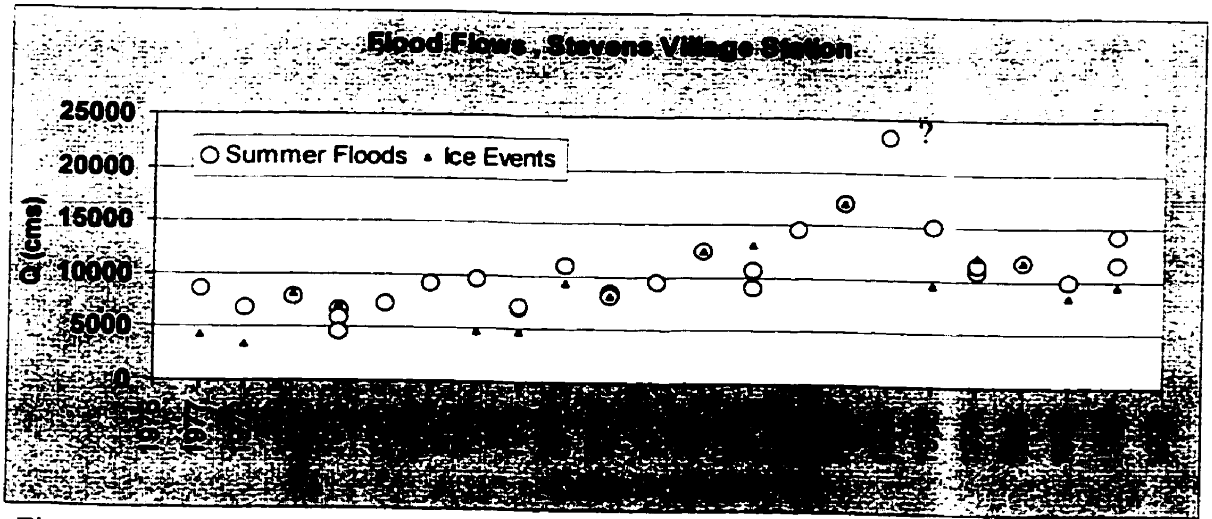


Figure 2.5.3. Yearly plot of the largest flood flows at Steven's Village station for a 20 year record. Ice discharges are corrected for artificial stage errors (source USGS, 1964).

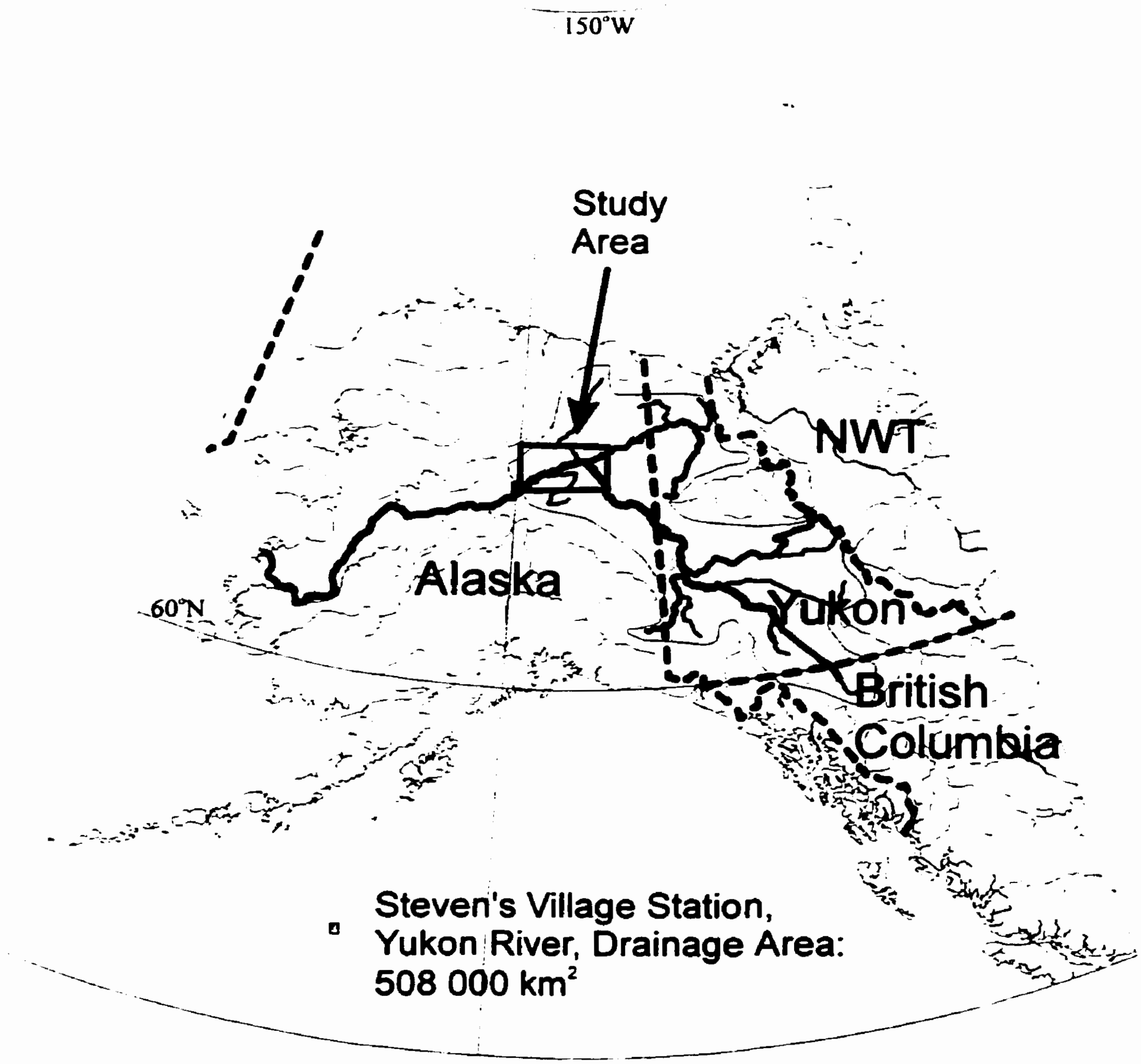


Figure 2.5.4. Drainage area of the Yukon River at Steven's Village Station (USGS # 1543500).

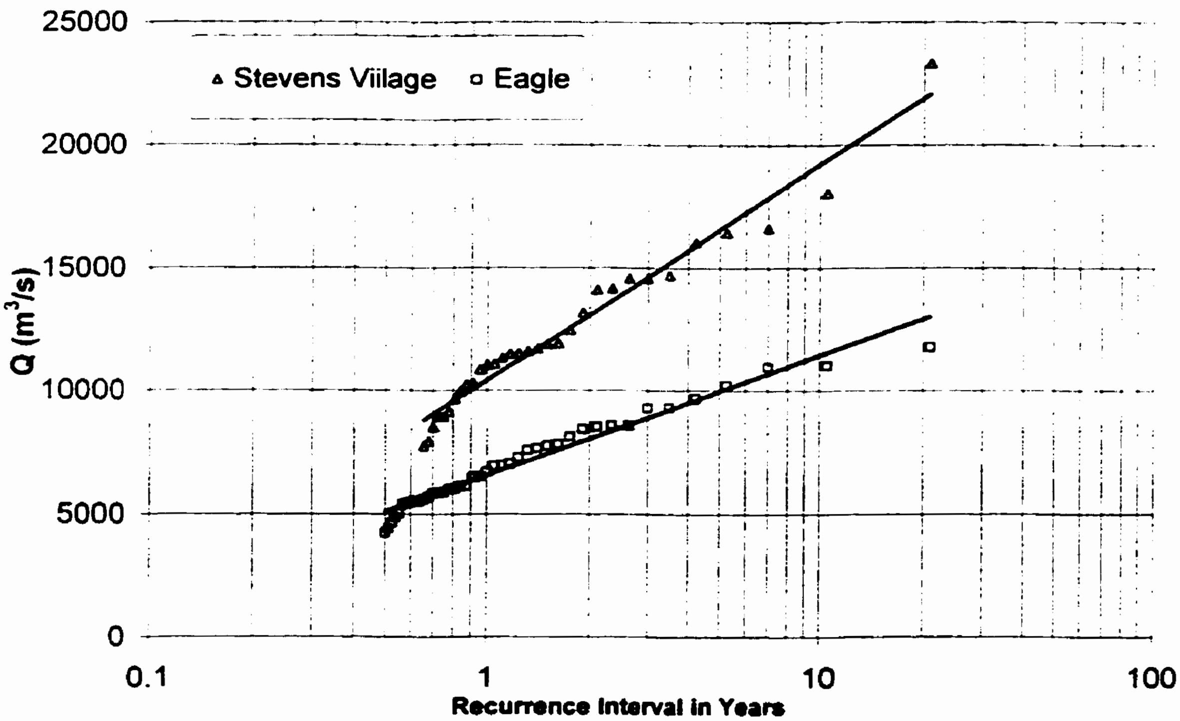


Figure 2.5.5 . Partial-duration recurrence plot based on all peak flood events at Eagle and Steven's Village stations. The Eagle data reflects the discharge of all reaches between Eagle and the confluence of the Porcupine River at Fort Yukon, at which point the Steven's Village data is indicative of flows within the remainder of the Yukon Flats. The steeper slope of the Steven's Village curve is the result of the short and rapid duration Porcupine River's flow.

High variability in discharge characterizes northern rivers. During the spring flood, 7 months of accumulated precipitation become available in only a few weeks. The result is two spring high water times; (1) when flow begins with ice present in the channels leading to ice jams (Eardly (1938) noted the Yukon could rise as much as 12m during one of these events), and (2) when the true spring peak discharge occurs. These two events can occur together (Church, 1971). On the Yukon River at Beaver, ice was observed to be 60 cm thick when break-up occurred in 1950 (Williams, 1955). Ice was also seen floating off of the bed studded with gravel and moving downstream with the surface ice. Williams (1955, pp. 493) witnessed an ice-jam at Beaver 900m long and 370m wide with blocks 10's of meters ramming the banks "...with tremendous force". The local residents of the area had seen ice rammed into bars and piled as high as 10m. Break-up on the Yukon that year took 1 day to move the 150 km from Fort Yukon to Beaver with rapid water level fluctuations throughout.

River ice and high stage fluctuations can play a important role in the morphology and sedimentology of the channel. Church (1971) noted that the Chandalar and Sheenjek rivers (both tributaries of the Yukon at the Yukon Flats) had major low water channels which were unusually sinuous. These channels were also armoured with coarse lag cobbles. Erosion on these rivers occurs as "irregular lateral activity" but is constrained where the channel abuts against a major terrace or bedrock (Church, 1971). Perhaps one of the most interesting effects of river ice happens at the bed. When ice freezes to the bed in a sub-surface icing fashion, heaving and derangement of the bed can result. Furthermore, extensive scour can occur do to diverted flows and increased pressure and velocity beneath the ice. The result can be streamflow redirection in summer, contributing to channel instability (Church, 1971).

Bank stability is another characteristic affected by ice in northern latitudes. The presence of ice wedges and pore-ice in permafrost can lead to unusual erosional phenomenon. In banks composed of sands and silts, undercutting and saturation contribute to block slumping. Ice wedges often provide the planes for melting and collapse after undercutting has occurred. Walker and Arnborg (1965), noted that on the Colville River, Alaska, this undercutting, termed the 'thermo-erosional niche' [from the Russian term, *termoerozionaja niza*], occurred during the spring flood at high stage. This niche can extend 8 m into the frozen bank sediments. An interesting result is the melt-out formation in the channel left by this process (Figure 2.6.1).

Usually this type of erosion only accounts for a few meters per year (Walker and Arnborg, 1965), but Eardly (1938) suggested that this type of process resulted in movement up to 30 m per year on the Yukon River, due primarily to large-scale slumping on high banks. With this said, it is apparent that discontinuous permafrost along the Yukon River could potentially play a significant role in the formation of the channel patterns found in the Yukon Flats.

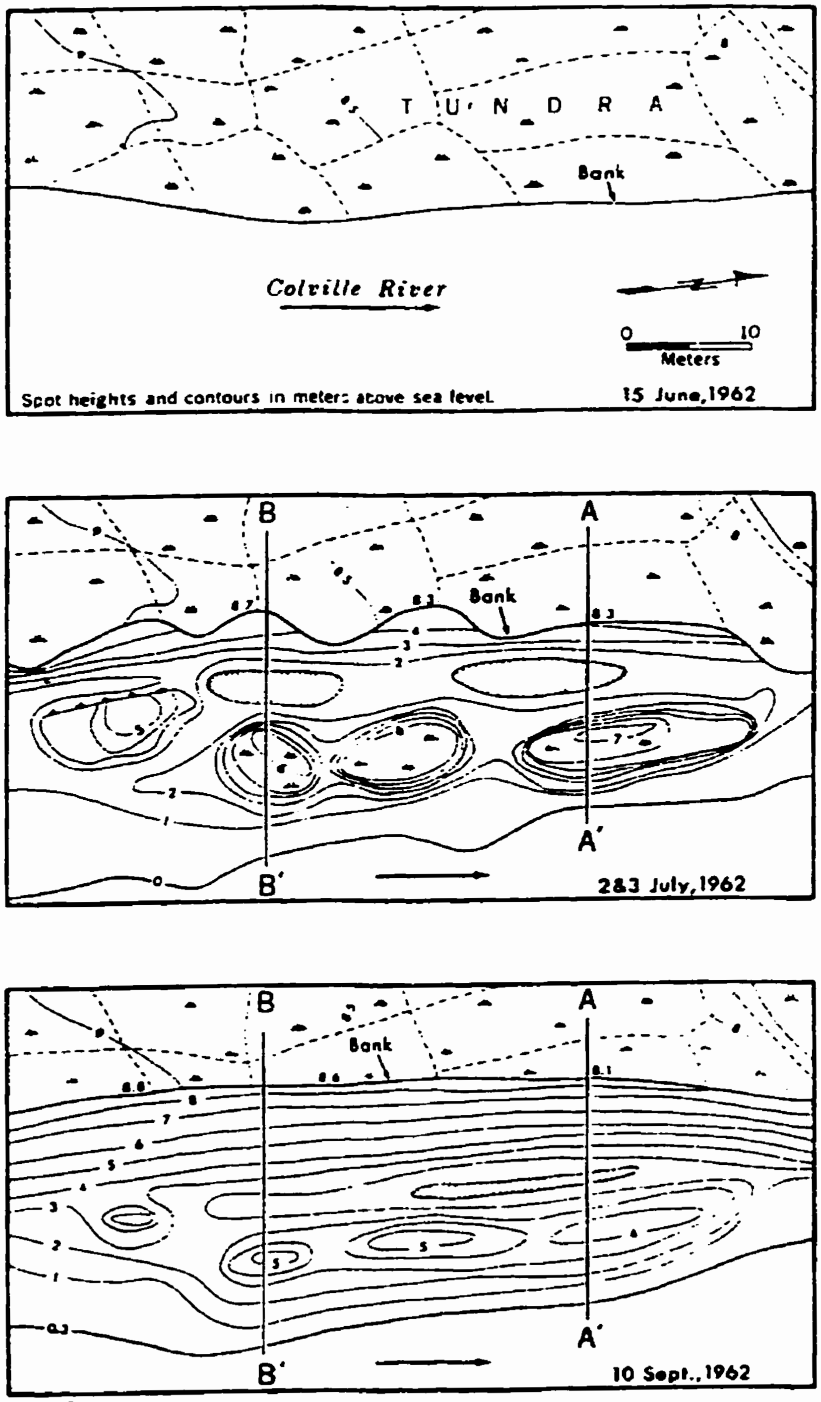


Figure 2.6.1. Block-slump melt-out from bank undercutting producing an erosional feature unique to northern rivers called **Thermo-erosional niche,** Colville River, Alaska. Contours represent resultant bathymetry (in feet). A similar process was observed operating on the Yukon River throughout the study area. However, ice-wedges (depicted here as dashed lines) were only found on the north bank of the braid reach and the gravel lower-banks of the Yukon also facilitated undercutting in non-frozen sediments (from Walker and Arnborg, 1965).

Chapter 3: Multiple Channel Systems: a review

3.1 Anabranching channel patterns

Although the Yukon does not rigidly adhere to any of the fluvial models, a review of systems with similar characteristics is appropriate. Since there have been virtually no fluvial studies attempted on this large section of the Yukon, a theoretical approach will be taken. Until relatively recently, early workers (e.g. Leopold and Wolman, 1957) lumped multi-channeled river patterns into the category of 'braided river'. However, it was later illustrated that this attempt to fundamentally classify rivers into three types, braided, meandering and straight, was oversimplifying what is actually a continuum of channel patterns. The 'anastomosed' river pattern has since been recognized as distinctive in form and process from the braided (Schumm, 1968, Smith 1976, 1983, Smith and Smith, 1980, Rust, 1978). Neill (1973) and Church (1983) have proposed another classification for high-energy, multi-channeled systems called 'wandering gravel-bed rivers'. Nanson and Knighton (1996) proposed that the variability seen in the systems classified under 'anastomosed' and 'wandering' is cause for a more detailed classification scheme. This idea is based on Schumm's (1985) term 'anabranching', into which he grouped all multi-channeled rivers. Using this classification scheme, elements of the study reach do approach specified models. Two of these will be discussed in the following section.

Nanson and Knighton (1996, pg. 218) define an 'anabranching' as "...a system of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull". The Yukon could be thus be classified as an anabranching river. The large islands that appear between the village of Fort Yukon and the Rampart constriction are vegetated and, although scroll bar patterns do indicate lateral migration, they appear to be relatively stable. According to Nanson and Knighton (1996), anabranching can occur concurrently with other types of channels and can be high or low energy. The specific requirements for anabranching are resistant banks, a flood-dominated or seasonal flow regime, and channel blockage or constriction mechanisms to trigger avulsion. The detailed classification system, developed by these workers, is divided into 6 categories, Type 1 through 6 (Figure 3.1.1). Although this classification seems arbitrary at first, the type number actually increases with the stream power of the channels. Thus, type 1 (a,b,c) are the low energy systems described in the literature as anastomosing, and types 4 through 6 are higher energy systems, 6 meeting Church's (1983) definition of a wandering gravel-bed river. On the Yukon, channel patterns in the study reach change downstream from braided to meandering. This transition, described in detail in the section on river morphology, demonstrates a range of multi-channeled patterns. Two of Nanson and Knighton's (1996) river types could apply to this transition, Type 3 and Type 5.

The Type 3 river pattern (Figure 3.1.1) is described as, "*...mixed-load, laterally active anabranching ...* " or as "...meandering multi-channeled rivers generally, they represent a diverse group...difficult to define as a single type, carrying a mixed load of sand and mud and, in some cases fine gravel" (Nanson and Knighton, 1996, pg. 225). Although only based on a small data set (only 3 rivers, each one quite different) the Yukon does conform to this description between Beaver and Stevens Village. In this type, it has been recognized that following channel avulsion directly associated with a major flood, a laterally active channel forms. This channel then atrophies to form a sinuous, less efficient channel and is then abandoned or avulses again to form a higher

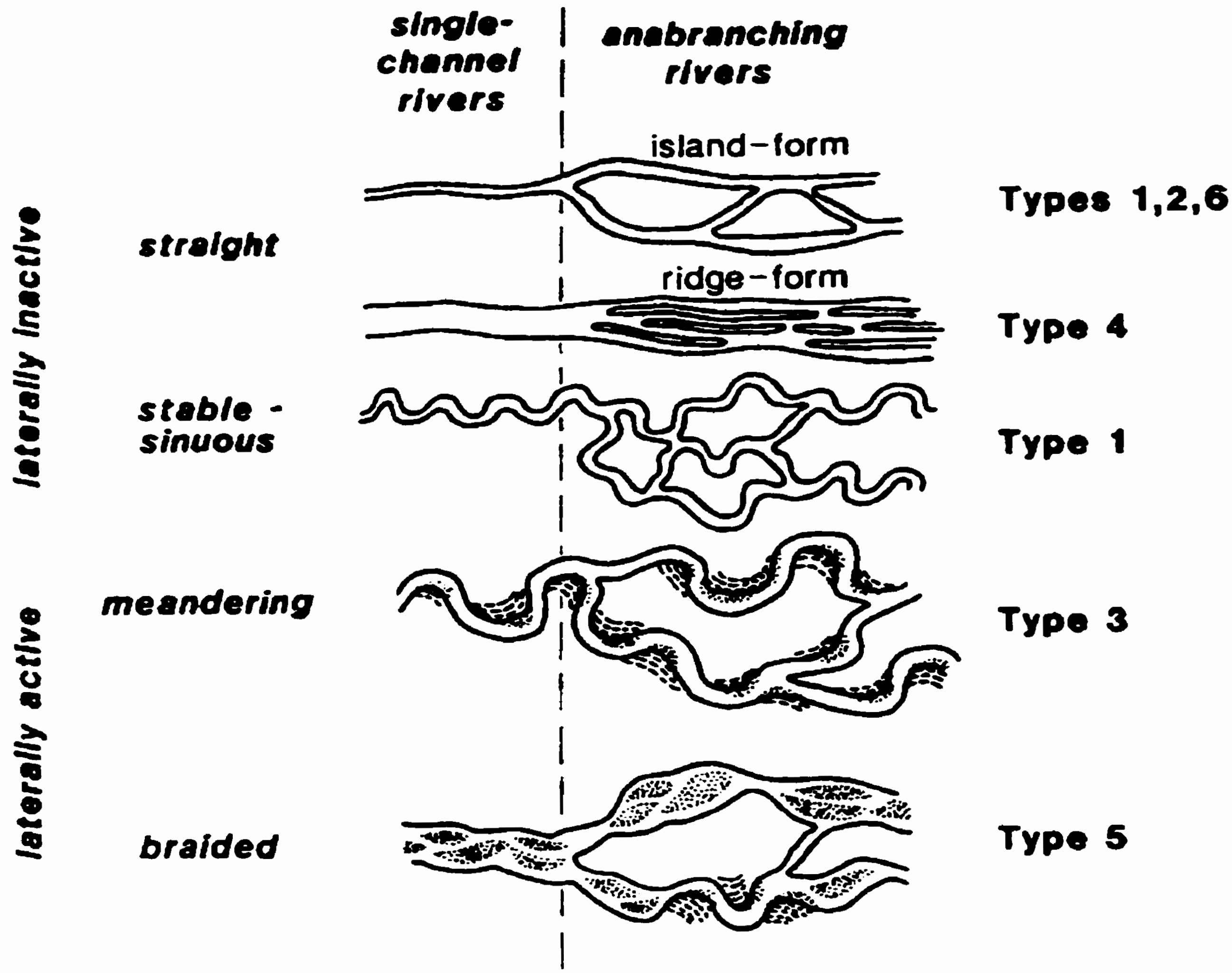


Figure 3.1.1. The classification system proposed for anabranching river patterns (from Nanson and Knighton, 1996).

energy channel. Type 3 rivers, described in the Knighton and Nanson (1996), are the Thompson R. and Murray R. in Australia and the Solimoes R. in Brazil. Although Type 3 rivers are associated with low energy environments, Britzga and Finlayson (1990) note that they can shift their position on a slope/discharge plot from low energy to high energy as they alternate from older, sinuous channels to recently avulsed, more energetic ones (Nanson and Knighton, 1996) (Figure 3.1.2). However, a complete examination of the source literature used to establish this classification category revealed very little similarity between the three systems and none of them matched Nanson and Knighton's (1996) sketch of the end-member in Figure 3.1.1.

Type 5 rivers are termed, "gravel-dominated, laterally active anabranching rivers". They are also described by Nanson and Knighton (1996, pg.229) as relatively energetic 'wandering gravel-bed rivers'. In Type 5 systems, the dominant channel commonly braids. This type is also vigorously laterally active. Desloges and Church (1987) found that the Bella Coola River in British Columbia has replaced the floodplain once every 300 years. One important feature of the Type 5 to note, is that: "the anabranching sections of these rivers appear to be initiated by enhanced bed-sediment input, displacing the flow into a series of anabranches, and the periodic formation of log or ice jams may augment this process. In this situation, it appears that anabranching is driven by the need to maintain the transport of bed material where this fraction of the load might otherwise accumulate" (Nanson and Knighton, 1996, p. 229). In the Yukon Flats basin, low slope and the accumulation of sediment may play a role. Because the channel is confined until its entrance onto the Flats, sediment which has been forced into transport through the long confinement could be deposited in the lesser-controlled

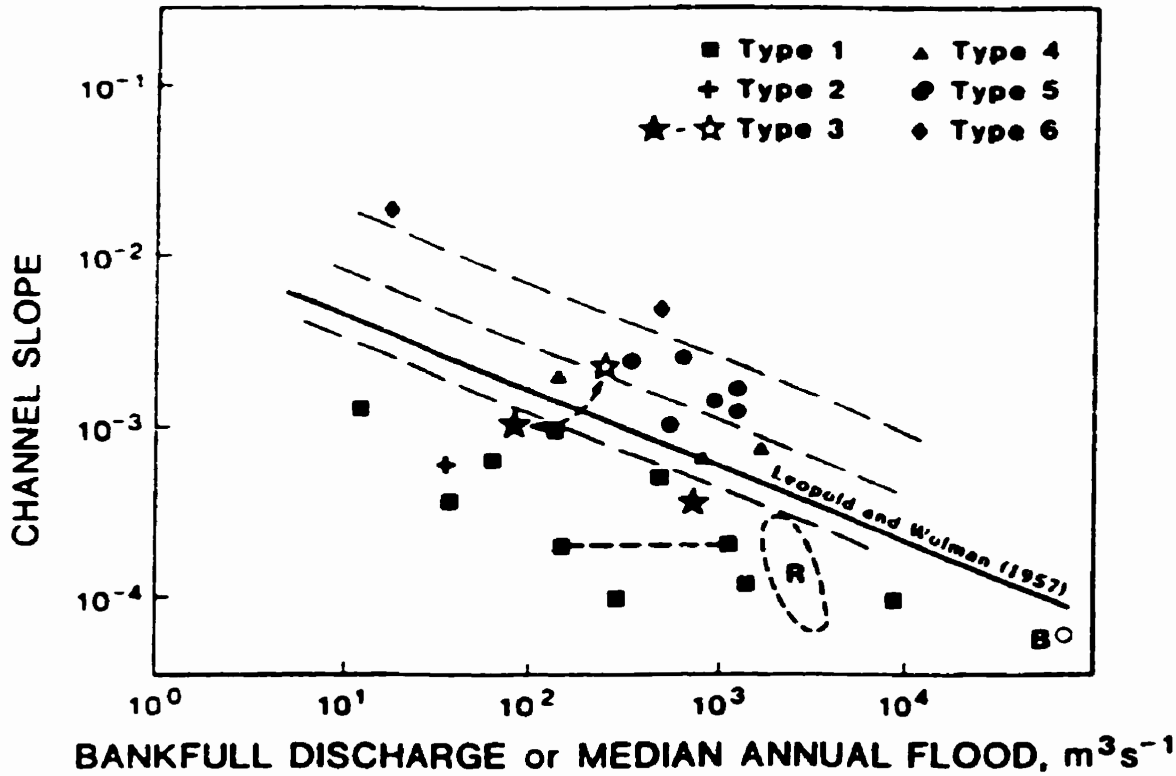


Figure 3.1.2. The slope-discharge relationships of the six types of anabranching rivers. Note the position of the Type 3 river which changes as channels avulse and fill (from Nanson and Knighton, 1996).

environment. Couple these factors with a seasonal meltwater flow regime and the occurrence of log and ice jams, and overall there is an ample supply of mechanisms to provide for a Type 5 process. A detailed examination of the literature regarding 'wandering gravel-bed' rivers will be carried out in the next section.

Nanson and Knighton (1996) segregate two main groups of processes required to produce a multi-channeled river pattern. First, **avulsion (erosion) -based processes**, refer to the scouring of new channels into the floodplain or the reoccupation of old channels. Second, **accretion – based processes** include channel extension into the depositional basin and the accretion of islands or within-channel bars that divide clearly separate channels. Popov (1962) argued that floodwaters can scour secondary channels in areas of low relief (Nanson and Knighton, 1996). In summary, the factors required for any multi-channeled system to develop are:

1) a flood-prone flow regime,
2) banks that are erosionally resistant relative to stream power (which lowers the channels ability to rapidly adjust to change and re-establish equilibrium geometry conditions), and
3) flow displacement caused by ice jam or vegetative blockage, or hydraulic damming due to the entry of a tributary.

Nanson and Knighton's (1996) attempt at examining and grouping anabranching river patterns is a good contribution to the fluvial geomorphology literature. However, their classification scheme will be compared with the forms and processes of the Yukon River and thus, may be subject to revision as another data set is added to our understanding.

3.2 Wandering Gravel-bed Rivers

Although it has been noted that the Yukon does not rigidly adhere to any one anabranching classification, the 'wandering gravel-bed' river seems to be the closest end-member analogy. The literature directly concerning this recently classified river-type is sparse, so this section will contain only a short review of previous work on these systems.

The term 'wandering' was first applied by Neill (1973) in reference to the behavior of the gravel-bed Athabasca River. Since then, Church (1983), Deloges and Church (1987) and Brierley and Hickin (1991) have focused attention on wandering rivers in western British Columbia. Consequently, much of the resulting literature defines wandering rivers based on comparative criteria with these studies. Miall (1996, pg. 212) briefly summarized this research, defining wandering rivers as "...an intermediate class between low-sinuosity, multiple channel rivers – the classic braided river – and high sinuosity, single channel rivers – the classic meandering river". He characterized them as having an intermediate sinuosity (1.2-1.5) and braiding parameter (1-3) at places having one channel and others displaying two or three. Desloges and Church (1987, pg. 99) described them as having "...an irregularity sinuous channel, sometimes split about channel islands and in some places braided; seasonal or perennial 'side' channels [sloughs] – subordinate anabranches of the river – are common". It was recognized by Desloges and Church (1987) that lateral accretion is the dominant mode of deposition. Church (1983) claimed that wandering rivers commonly occur in mountain valleys, particularly those which have experienced recent glaciation. In his study of the Bella Coola River, he noted there was no evidence for either aggradation or degradation and that there was a regular pattern to the occurrence of unstable reaches.

The sedimentology of wandering rivers is not very different from other gravel river types. Brierley (1989), Brierley and Hickin (1991), and Desloges and Church (1987) all described Gm or Gp (of Miall's classification) horizontally bedded to low-angle cross-bedded gravel sequences overlain by overbank sand and silt sequences or gravel to sand to silt channel fills. Desloges and Church (1987) distilled the model into a favored facies sequence of Gm/Sh/Fsc. However, Froese and Hein (1996) claim that preservation of overbank fines in the ancient record is rare, if not impossible due to they vertical stability inherent in wandering systems. The main distinction then between wandering gravel-bed facies and other gravel river facies, must be accomplished by careful attention to the lateral accretion trends in the gravel bedding that may be get preserved.

Chapter 4: Research Design and Methods

4.1 Large River Reconnaissance

Fieldwork was undertaken during June, July and early-August, 1998. Due to the extremely remote location of the study area and the size of the river being studied, a special style of fieldwork had to be adapted, a modernized version of that used by Leopold and Skibitzke (1967). After road access at the town of Circle, transportation for the entire fieldwork period was accomplished strictly through the use of a *Zodiac* MK IV inflatable boat with a 40 hp engine. In the 57 non-stop days spent on the water, the study reach was covered four times. The first two sweeps of the field area were essentially reconnaissance trips to scout for sample locations, stratigraphic exposures, and to observe the nature of the physiography and processes operating in the system. The Porcupine River was also explored from Fort Yukon to the Lower Ramparts near John Herbert's Village, 150 km upstream. The second two sweeps of the study reach, involved detailed survey along 31 cross-valley transects. These transects produced 87 individual channel cross-sections, a total of nearly 47 km of channel width and depth surveyed. Water-surface slope measurements were completed in conjunction with the channel surveys resulting in 79 individual measurements. A velocity sampling procedure was evaluated at four locations. Finally, 13 bed grain-size sites were sampled and analyzed in the field and numerous bank exposures were litho-stratigraphically logged. In all, nearly 3000 km of river travel was necessary to complete this study.

4.2 Air photo Analysis and Change Mapping

Aerial photography was widely used for this study. 1: 63 360 Orthophoto maps were used for locating sample sites and navigation in the field. 1: 130 000 and 1: 65 000 colour infrared (CIR) air photos were used for mapping channel changes and morphometric calculations.

To map channel changes over time, the remote-sensing package *PCI* was used. Three time slices were available for this project: 1953 USGS topographic map sheets, 1974 - 1:140 000 CIR photos, and 1982 - 1: 65 000 CIR photos. The following procedure was required to ensure that an accurate time-slice overlay could be created (given the variety of scales involved and the large amount of optical ground distortion that can result from high-altitude, small-scale aerial photography):

1) the maps and air photos were scanned in as .tiff files,
2) the map .tiffs for a given sample reach were imported into *PCI: GCP Works vers. 6.2* and converted to .pix files,
3) the map .pix flies were georeferenced to the Universal Transverse Mercator Zone 6 W projection (with NAD 27 – *Alaska ellipsoid* as a datum) using 'user entered' coordinates taken from the hard copy map sheets,
4) the air photo .tiffs were converted to .pix files and geocoded and rectified using image-to-image GCP (ground control points) from the geocoded map image. Ground control points common to both the maps and air photos had to be selected for this procedure. This proved somewhat difficult given the extremely remote location of the study area and the consequent lack of human infrastructure to provided stable ground control. However, many of the scroll patterns and thermokarst lakes are deep

and reasonably stable, and thus the residual values for the fit of the images were within acceptable error limits when these features were used. Usually second order transformations were used, higher orders were avoided to reduce overall individual pixel location inaccuracies,

5) for each sample reach, all three time-slices were entered as channels in the same image. This allowed for automatic common scaling and overlay to be achieved,
6) each coverage (actually 3 channels [24-bit] of 9) was then imported into *PCI: ACE Mapper* were they could be fitted with grids and plotted at the same scale,
7) using the output, Corel Draw 8 was used to map vegetated channel margins (not stage dependent) and overlay the time slice coverages (an easy, high-quality, low-tech solution that saved time and effort). During this process the 1974 coverages were abandoned due to massive and uncorrectable lens distortions, likely due to the fact that they were high altitude shots taken with only 3-inch negatives,
8) this map was used to quantify migration rates and the migration style of various channel types for 5, 15-20 km reaches between Circle and the Dalton Highway Bridge.

4.3 Channel Cross-sectional Geometry

4.3.1 Field Methods

To accomplish a reasonable amount of cross-sectional geometry measurements on a river where individual anabranches can reach 1700m in width, a new method had to be developed. The *Lasertech 100XL* laser ranging unit, which can measure distances of up to 2100m to within 1m accuracy, was used to partially solve this problem. Field trials on the Yukon River revealed that one could range a cutbank or treeline up to 1400m away using the unit in a hand-held configuration. This made it ideal for accurately gauging the position of the boat while ferrying a straight line across the channel. An *Eagle* sonar bottom profiler was used to map the depth of the channel bottom. This unit is accurate to within 10 cm and can be configured to range the bottom at various pulse intervals.

Used together, these two tools produce a detailed and accurate dataset of the individual channel geometry. Two people are required for this technique to succeed in the field. The first operates the boat and reads the bottom profiler whereas the second operates the laser range-finder and records the data in table format. The driver also uses a GPS unit in aid of this survey process. As the boat is ferried sideways across the channel (so that the angle of the craft equalizes the forward velocity vector with that of the river's speed) a predetermined heading is followed on the GPS compass-type display. This heading is established on shore at the left bank using a map and compass and some reference object on the far bank, which can be seen while ferrying. The start and end GPS lat/long or UTM positions also must be noted. Then, every 20-30m a laser-ranging of the left bank is shot and the surveyor calls out to the driver for the depth measurement. These distance and depth measurements can be recorded just in time for the next measurement. Orchestration of this technique is summarized in Figure 4.3.1.1. This type of transect method does not require a perfect horizontal interval distance, but as a result, does require some post-field interpolation processing. Thus, high-resolution data cross-sectional data, with starting and ending positions located in absolute space, can be generated using this methodology. The true advantage of this technique is that accurate data can now be acquired quickly for even the largest river channels, allowing for rapid

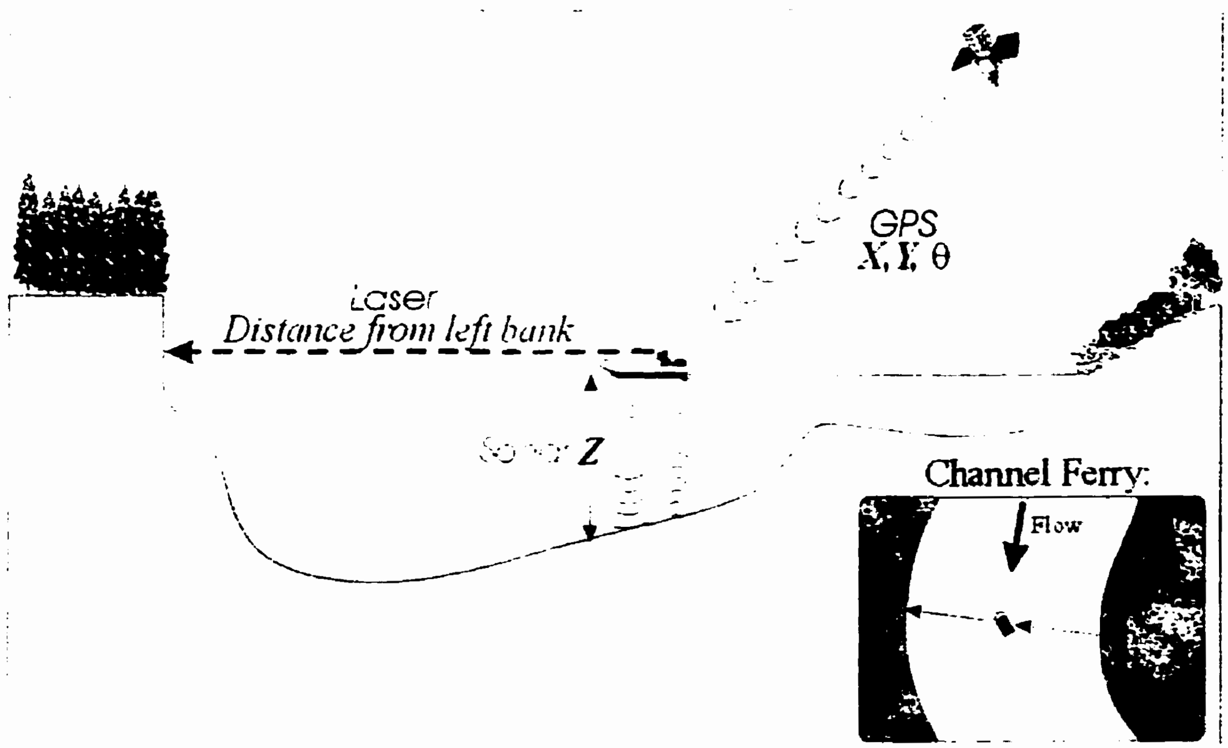


Figure 4.3.1.1. Summary of the laser/sonar channel survey technique designed for work on large rivers (> 100m wide, > 2m deep). The craft ferries the channel along a GPS-guided heading while distance from left bank and depth are recorded simultaneously.

collection of previously unattainable or costly results. In all, 31 cross-valley transects were recorded totaling more than 45km of detailed channel geometry measurement. Figure 4.3.1.2 shows the locations and spacing of these transects. The details concerning post-processing are provided in the next section.

4.3.2 Laboratory Processing

Once channel geometry data has been collected in the field, some processing is required to make the data useable in hydraulic calculations. This processing involves several steps:

1) The raw data must be entered into a spreadsheet (the following operations will hereby refer to *Microsoft Excel 98*®),
2) In this case, a USGS/US Army program called *CORPSCON* had to be run to convert all Lat./Long coordinates to UTM coordinates (figure 4.3.2.1),

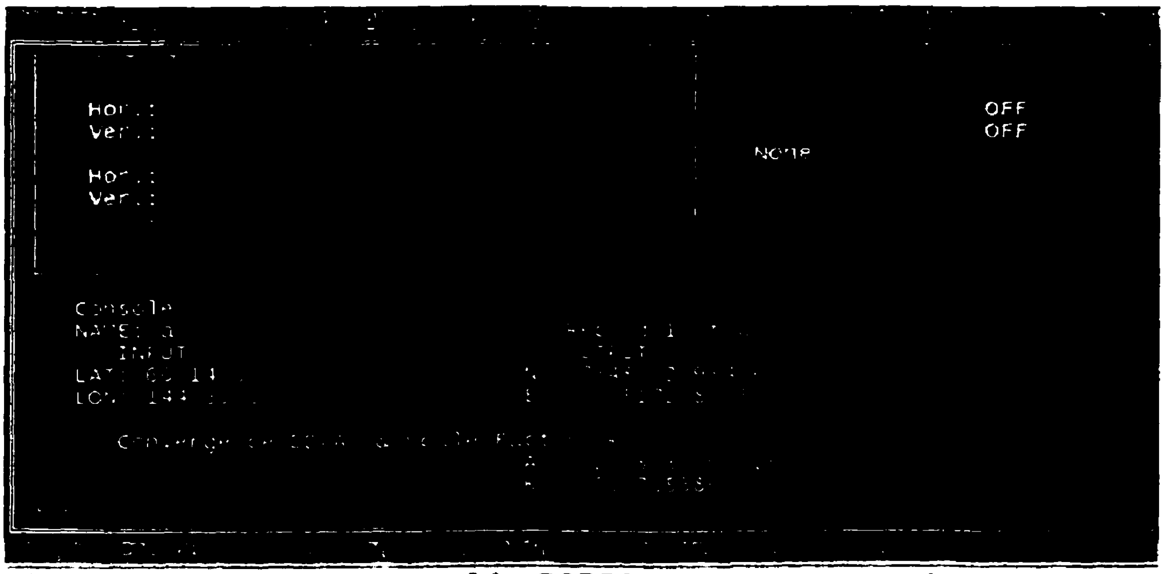


Figure 4.3.2.1. Screen-capture of the CORPSCON program console

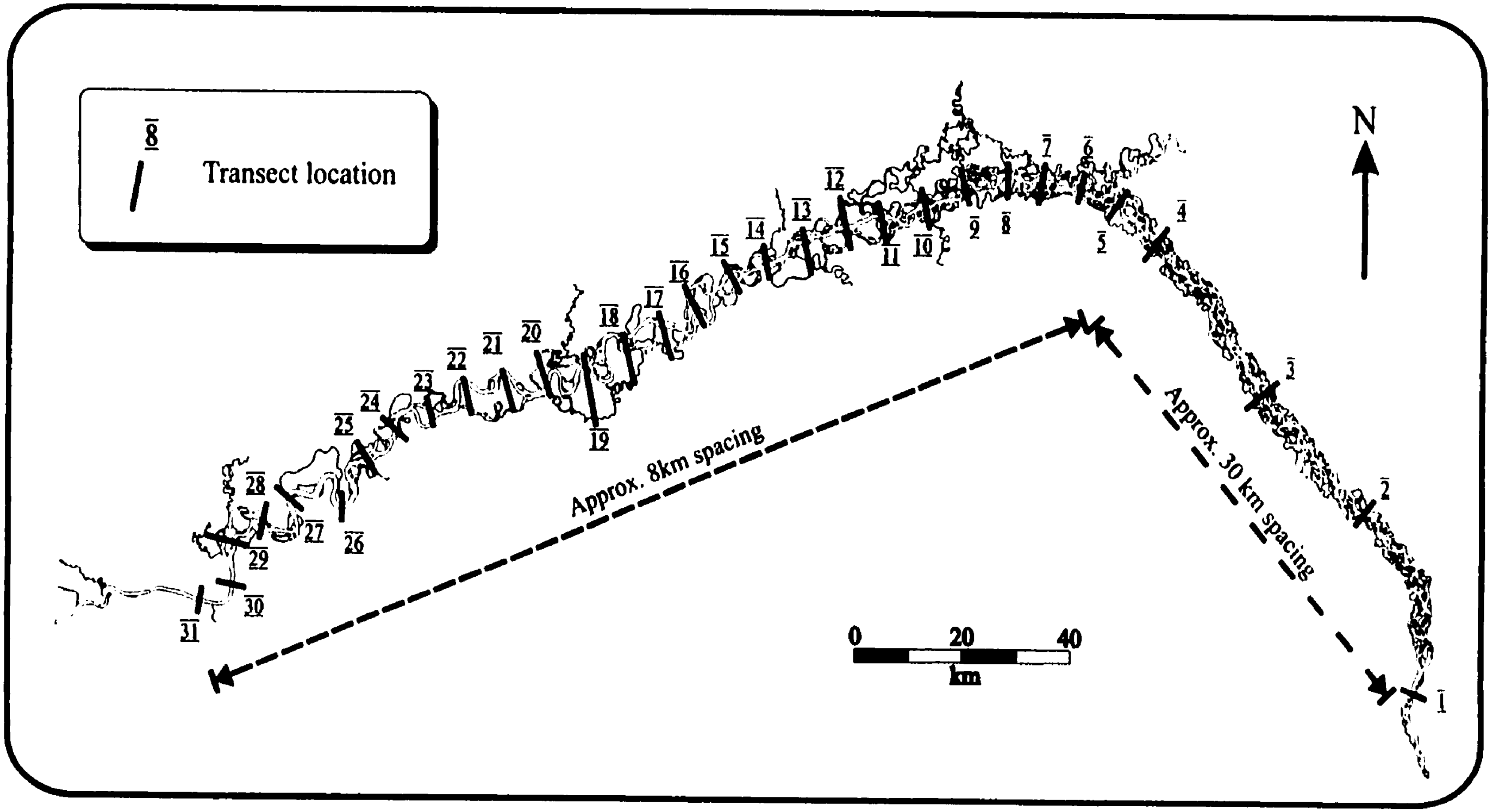


Figure 4.3.1.2. Location and spacing of all cross-valley transects surveyed in the field.

3) using the *Pythagorian Therom*, a short program had to be written to calculate the distances between specified UTM coordinates, specifically the beginning and end coordinates of each channel surveyed,

point 1		*point2*					
N	**E**	**N**	**E**	**deltaX**	**deltaY**	**c-squared**	**dist (m)**
7317962	396046.5	7318616	395122.9	923.50871	-653.6031	1280065.3	1131.4

Table 4.3.2.1. The program used to calculate distances between UTM coordinates

4) These distances, the distances between channels along islands, are then used to correct the individual; channel measurement so that their X-values read in 'distance from left bank' (this allows the worker to eventually generate a graph of the channel geometries),

5) The beginning and end Y-values were entered in as the measured bank heights (these must be entered as negative values because they are higher than water level).

6) For each valley transect, bankfull height must be established. This exercise proved to be quite challenging in that no rule or parameter had been set for estimating bankfull in a multiple channel system with mature vegetated islands. Several previous methods were evaluated but most dealt with single channel systems and those that didn't referred to 'classic' braid systems without stable islands (Johnson and Heil, 1996; Leopold and Skibitzke, 1967; Petit and Pauquet, 1997; Riley, 1972; Williams, 1978). It was decided that on an anabranching gravel-bed river, that the height of the highest active mid-channel bar on the largest channel along a transect was the best indicator of the mean high flow. If the largest channel was devoid of bars the height of

gravel and permanent vegetation (willows greater than 3m) on the point bar was used. Once bankfull is established, the depth measurements on the spreadsheet are corrected, creating a separate 'bankfull' geometry data set.

7) The geometries interpolated could then be graphed (figure 4.3.2.2).

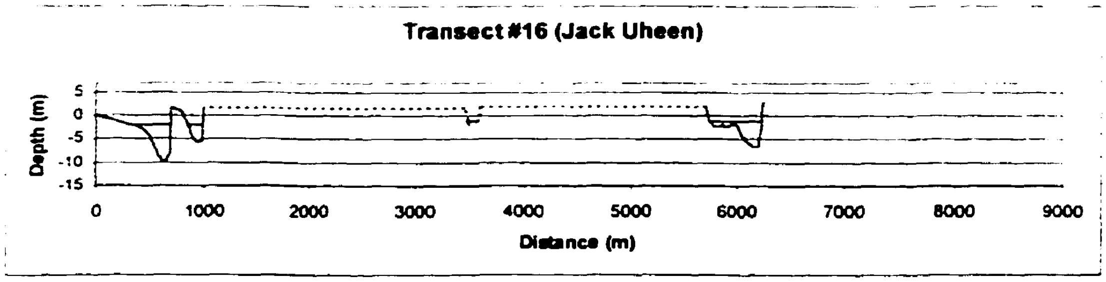


Figure 4.3.2.2. An example of a valley transect graphed for visualization

8) Because the X-axis interval in the raw data is variable, each data set was then linearly interpolated to 1m spacing using a FORTRAN 77 program. Linear interpolation was considered to be acceptable because of tight data spacing in the initial data set (the interval was usually less than 5% of the total width of an individual channel).

9) *Excel* was then used to calculate cross-sectional area (by summing the interpolated Y-values for each channel), mean depth, min depth, max depth, wetted perimeter, hydraulic radius, stream power, and unit area stream power for both the observed and bankfull channel geometries.

4.4 Grain-size Analysis

An approximation of bed grain-size was required to quantify the major shift in bed-load caliber that was expected to accompany channel morphology changes, and to act as a guideline for establishing Manning roughness coefficients in later formulae. In all, 13 bed samples were taken from recently active bar heads. Due to a limited time frame for completing fieldwork and the fact that the focus of the study was on morphology rather than downstream fining, only small representative samples were gathered and analyzed for each sample site. For each sample, 30kg (1 - 6 gallon pail) of gravel was taken from 10m behind the waterline at 5 separate spots. These individual ~6 kg samples, spaced 2m apart, were aligned transverse to the main axis of the bar. The top 15cm of alluvium was removed to ensure that larger 'lag clasts' would not skew the sample. Each 30kg sample was then wet-sieved into 1 *phi* categories from –5 *phi* to 1*phi*. These categories were then weighed to establish the relative percentage of the total sample weight made up by that sample. The finer-than 1 *phi* weight was derived by subtracting the total weight of all measured clast sizes from the original weight of the sample.

4.5 Slope Measurements

Water surface slope measurements were taken at each channel along each transect unless the situation made it impossible. Survey was completed using a 10X *Pentax* engineering auto-level, with a fluid-based auto-level stabilization feature. The stadia rod was placed directly at the water's surface using a piece of wood or a rock as a base. Measurements were taken over as long a distance as possible, usually 150-180m both upstream and downstream, allowing for over 300m surveyed (the limit of single point optical survey). Each upstream and downstream measurement was taken three times with the stadia rod moved 10m further away from the level with each measurement. The resulting three slope measurements were then averaged (and erred values discarded) to establish the slope of the specific channel being surveyed. This redundant technique was used to ensure rigor and accuracy in the data, reducing all possible variability in subsequent formulae.

4. 6 Stratigraphic Logging and Carbon Dating

At well-exposed cutbank sections along the river, detailed lithofacies logging was carried out to attain data on a few of the depositional settings present in the Yukon Flats system. Certain sections were also sampled for datable organics to help establish the Quaternary alluvial history of the system.

Chapter 5: Results

5.1 Introduction

As the Yukon River enters the Yukon Flats near Circle, it leaves a confined bedrock valley system (Figure 5.1.1) and instantly expands into a large braided pattern 4 to 6 km wide (Figure 5.1.2). At the confluence of the Porcupine River 115km downstream, the fluvial style begins to change to one of increased channelization, this reach has been termed the 'transitional reach' (Figure 5.1.3). Channelization continues until this reach can be described as 'wandering gravel-bed' although on a massive scale (Figure 5.1.4). This morphology is characterised by one or two main meandering channels with two or three high-sinuosity secondary 'slough' side-channels anabranching around and between them. Fewer channels are found downstream, eventually resulting in a meander pattern observed for a few wavelengths (Figure 5.1.5). However, just before the river is abruptly confined within bedrock valley walls, meandering decays into anabranching once again (Figure 5.1.5). It is the nature and cause of these transformations of alluvial styles that forms the focus of this research.

The following chapter will report the results of all data collected in the field and processed in the laboratory. The first section will focus on the measured characteristics of the different alluvial styles including the results of hydraulic geometry calculations, grain-size measurements and plan-form change detection. The second section will include descriptions and interpretations of the sedimentology of Quaternary sections that have relevance to the long-term history of the study area. Finally, a brief description of

Figure 5.1.1. **The Yukon River near the entrance to the Yukon Flats 8km upstream of Circle (photo from Heinsohn, Johnson, and Poulin, 1964)**

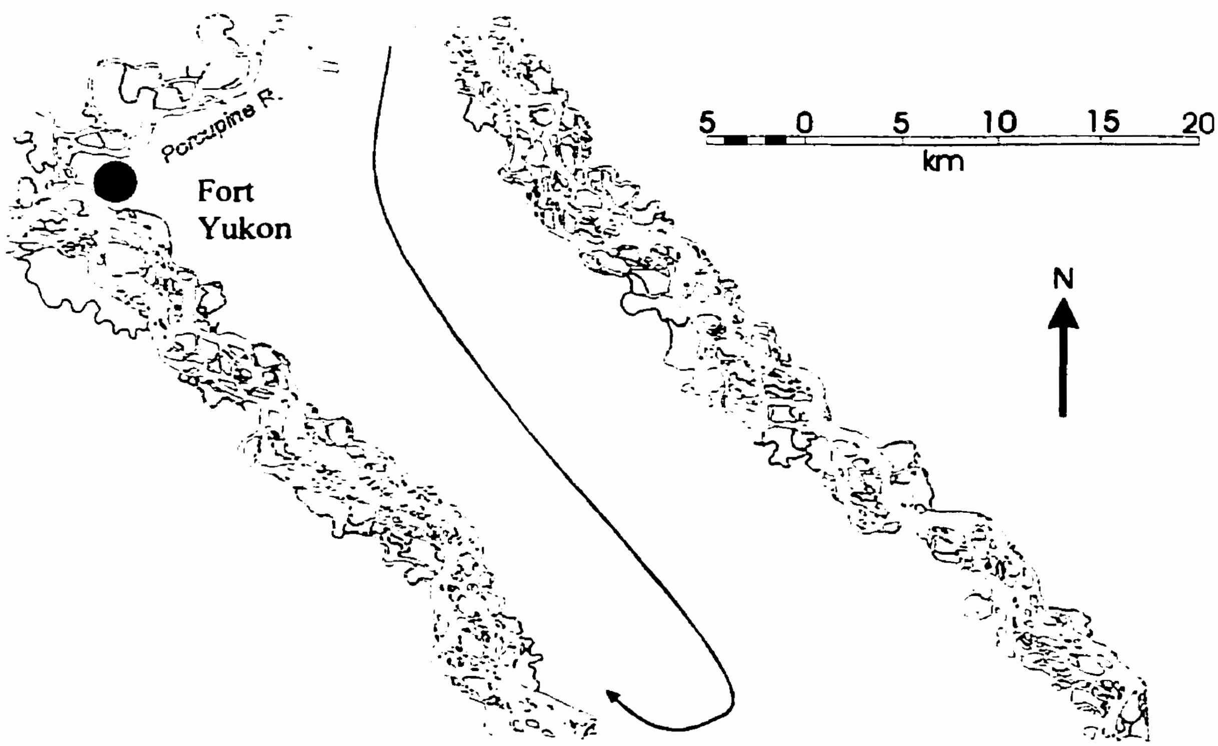


Figure 5.1.2. The braided reach of Yukon River between Circle and Fort Yukon. Note the presence of stable vegetated islands and complete absence of valley confinement. Flow is from bottom to top (photo from Heinsohn, Johnson, and Poulin, 1964).

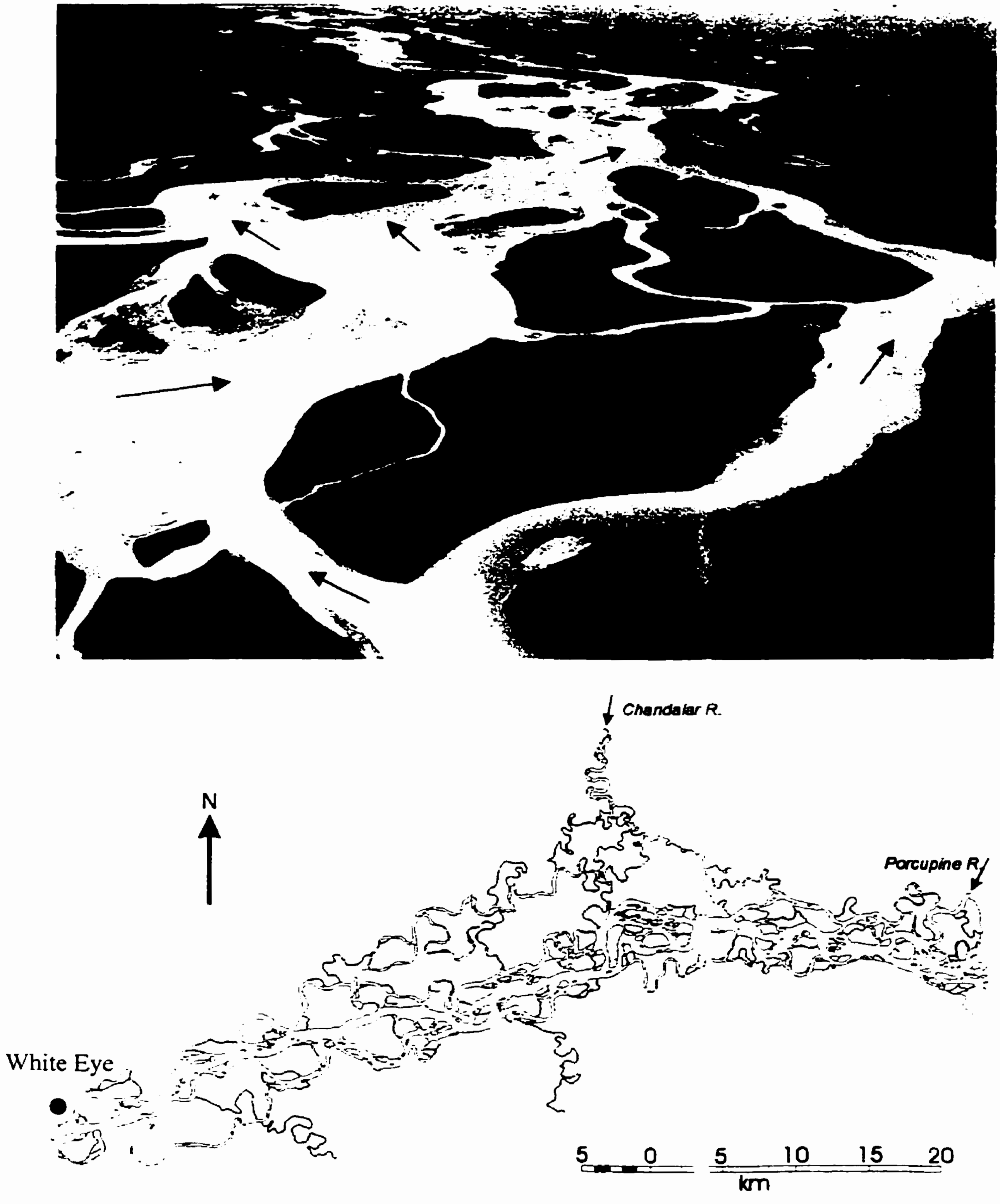


Figure 5.1.3. The transitional multi-channeled reach. Note the presence of mid-channel gravel bars <u>and</u> well-vegetated islands with scroll bars. Flow on the map is from right to left (photo from Heinsohn, Johnson, and Poulin, 1964)

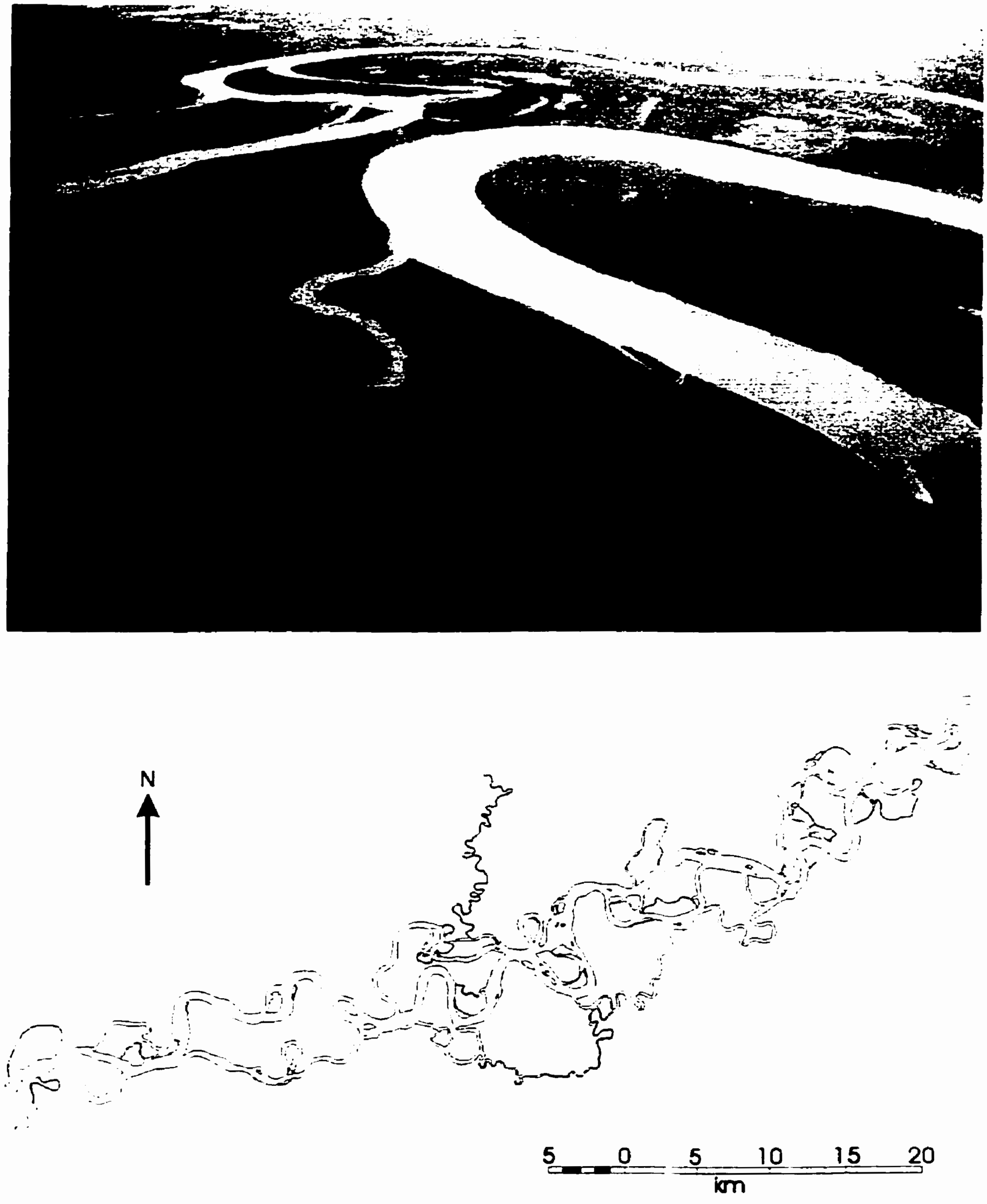


Figure 5.1.4. The anomalous multi-channeled pattern that is the focus of this study. The closest end-member classification is the 'wandering gravel-bed' river. Flow is from right to left (photo by author).

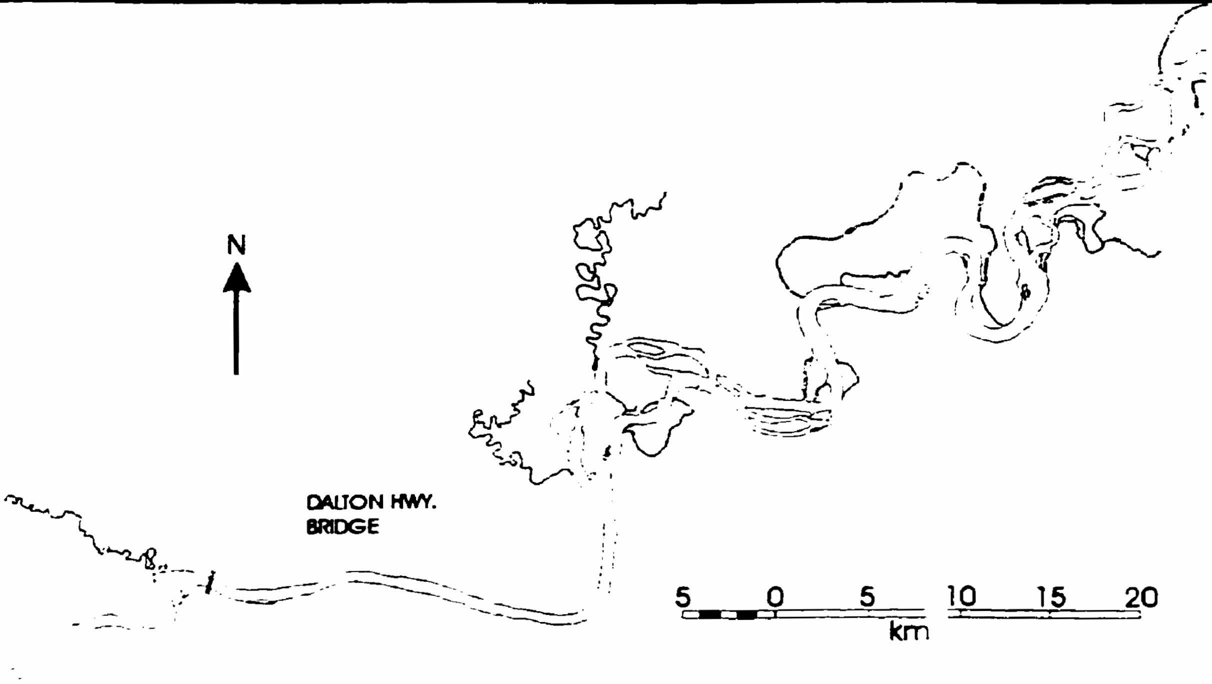


Figure 5.1.5. The meander and confined reaches. Note only 1.5 meander wavelengths occur before re-establishment of anabranching. The last anabranches may be due to underlying bedrock influence at the edge of the basin or a backwater effect created by the canyon. Flow is from right to left (confined reach photo from Heinsohn, Johnson, and Poulin, 1964).

the ground penetrating RADAR data collected, and interpretations of the RADARfacies will be included.

5.2 Geomorphology

5.2.1 Braided reach

Approximately one quarter of the Yukon River's channel pattern in the Yukon Flats can be called 'braided'. This reach begins 8km upstream of Circle to the town site of Fort Yukon, stretching for a total distance of 115km. The braid plain is most typically 5km wide, but ranges from 3km to 6km (Figure 5.1.2). The Yukon River's braid plain is not typical however, like those observed by Church, 1972; Smith 1973; Smith and Smith 1984; where high flows occupy the entire plain from valley side to valley side and little vegetation can be found on the temporary bar structures that divide flow. Rather, stable, vegetated islands of all sizes exist among the more temporary bar structures (Figure 5.1.2). Many of these islands must be quite old, supporting Black or White Spruce populations and not appearing to be inundated by flood flows with much frequency (likely less than once in twenty years (C. Pearce, pers. comm., 1998)). With portions of the braid plain occupied by islands, the true width of flow must be attained from totaling that found in the active channels. Figure 5.2.1.1 shows the actual width of flow during the annual flood (Q_I) which is 1100 to 1400m. This flow can be carried by anywhere from 2 to 8 channels (Figure 5.2.1.2) with the average being 4.96 for the entire 115km reach. Depths along the braid reach are anywhere from 2.1 to 3.5m on average (Figure 5.2.1.3) although the author commonly observed localized scour holes up to 11.5m deep at channel confluences and rapid changes in flow direction. Width-to-depth

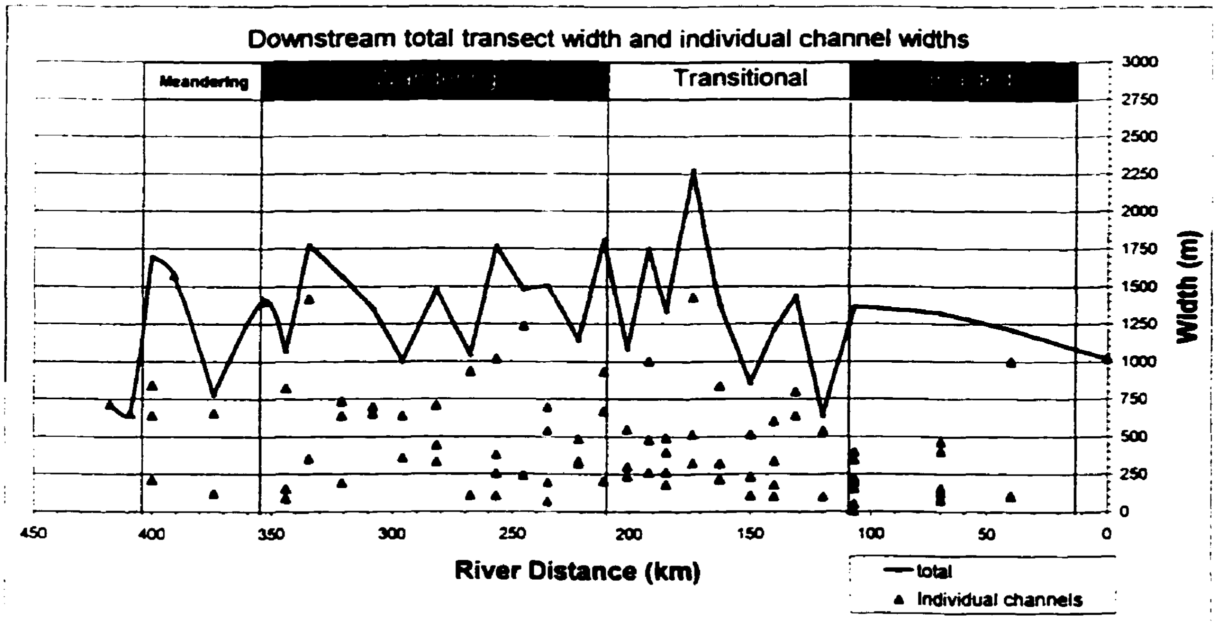


Figure 5.2.1.1. Downstream plot of both the widths of individual channels along a transect and the total of all active channel widths not including stable, vegetated islands.

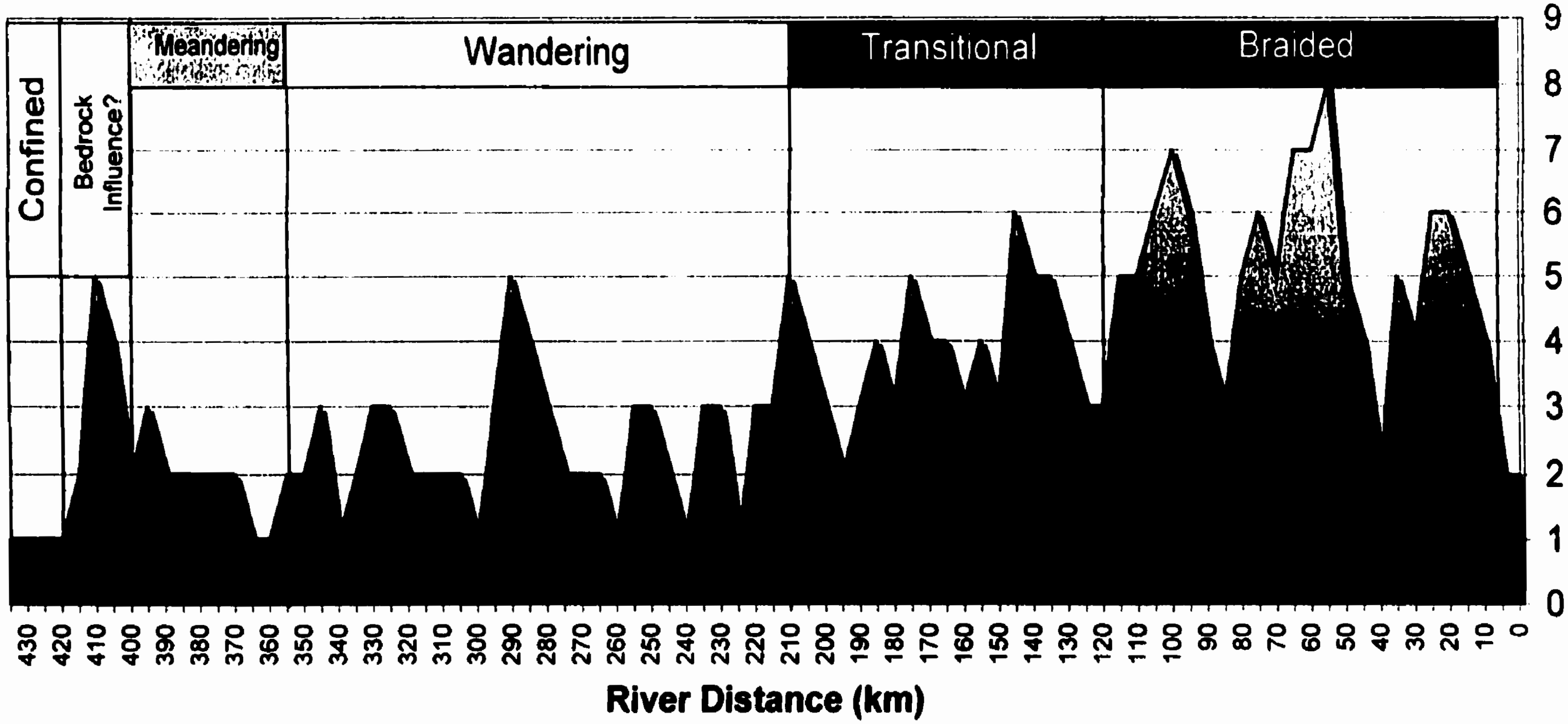


Figure 5.2.1.2. Downstream plot (from right to left) of the number of channels dividing flow along a cross-sectional transect.

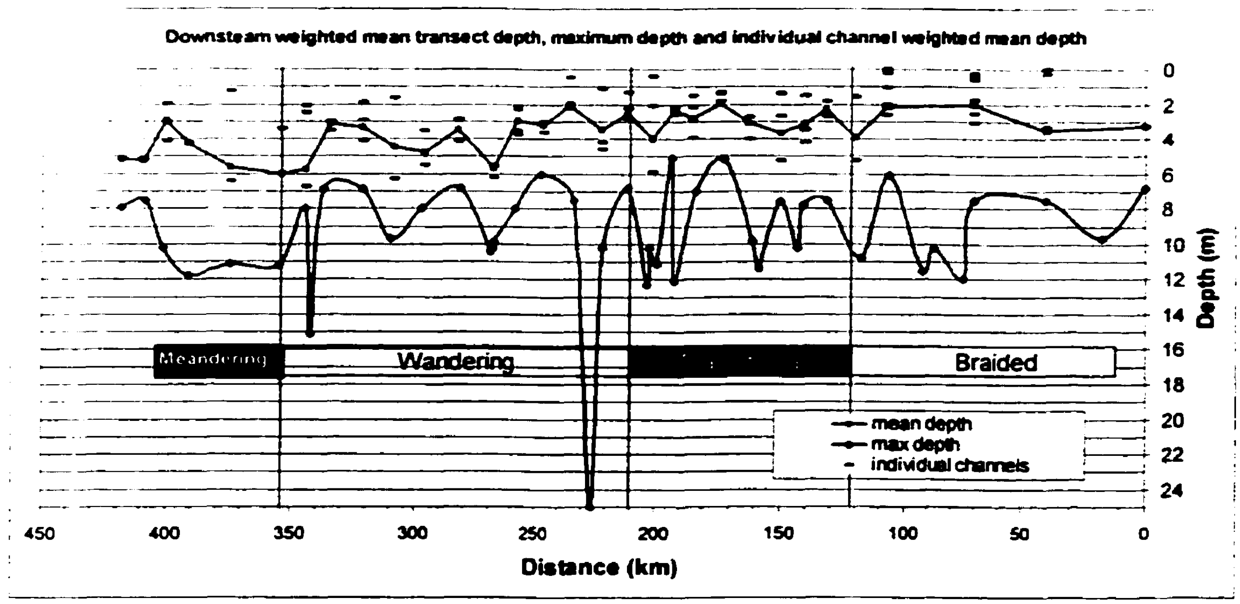


Figure 5.2.1.3. Downstream plot of both the weighted mean depths of individual channels and of all channels in a transect as well as the maximum depths observed in a transect.

relationships are noted in Figure 5.2.1.4 and Figure 5.2.1.5. There is a moderately poor relationship between width and depth in the braid reach. A linear expression of this relationship is $d = 0.0031w + 0.6127$. The R^2 value for this equation is 0.5903, meaning only 59% of the observed cases can be explained by this relationship. With only small changes in the Yukon's linear course along the braid reach the ratio between the distance covered by the channel and the straight-line distance, or sinuosity, is between 1 and 1.15 (Figure 5.2.1.6). Field data concerning the height of bankfull flow above the 1-year flood level (observation flow) was collected. For this study, bankfull flow was estimated as the elevation of the surface of the highest active bars within the channel or the height of permanent vegetation if the latter was not available. Figure 5.2.1.7 summarizes this data. Along the braid reach bankfull height was .8 to 1.4 meters above the Q_1 (partial-duration derived annual flood) stage. It should be noted that the majority of the aforementioned islands occupy much higher elevations, up to 4m above water level but usually around 2m (Figure 5.2.1.8).

5.2.2 **Transitional Reach**

The 'transitional reach' occupies the gap-length where braided turns to wandering. This reach is approximately 90km long, beginning at Fort Yukon (km 120) and terminating at White Eye (km 210) (Figure 5.1.3). The total widths occupied by all channels in a transect become erratic in this reach, as low a 600m in one location but as high as almost 2300m in another (km 170, Figure 5.2.1.1). 2300m is the greatest total channel width recorded on the Yukon Flats. Unlike the braid reach, individual channel widths are found displaying a greater range, from 100m to over 1400m with the average

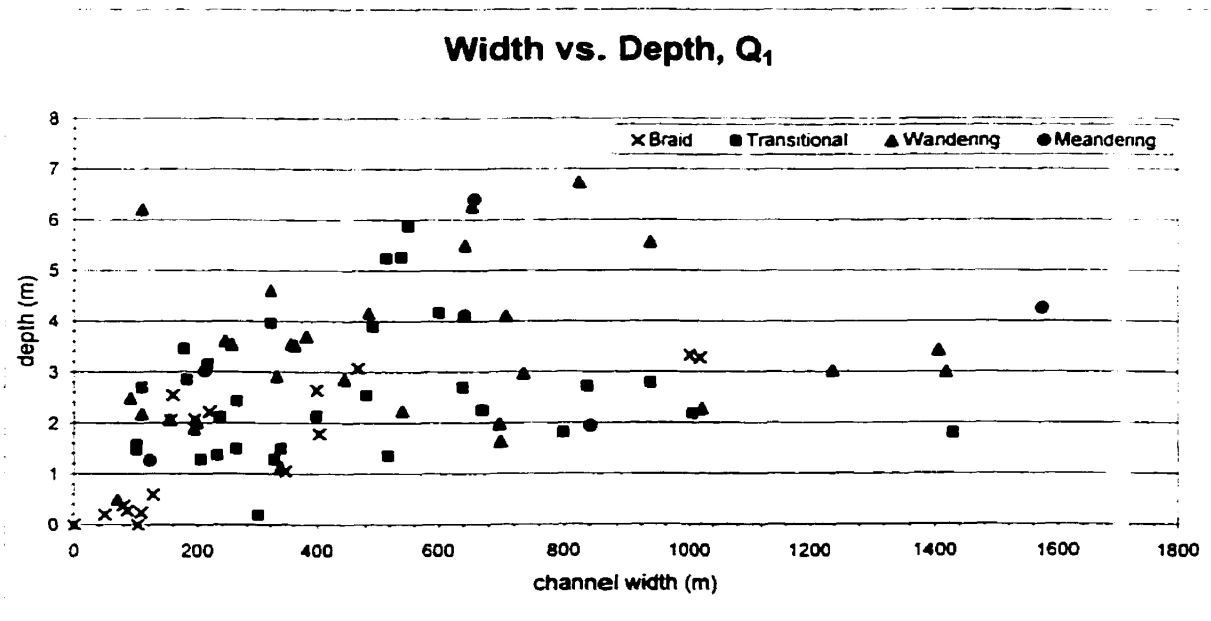


Figure 5.2.1.4. Channel width plotted against depth for the annual flood stage (Q_1).

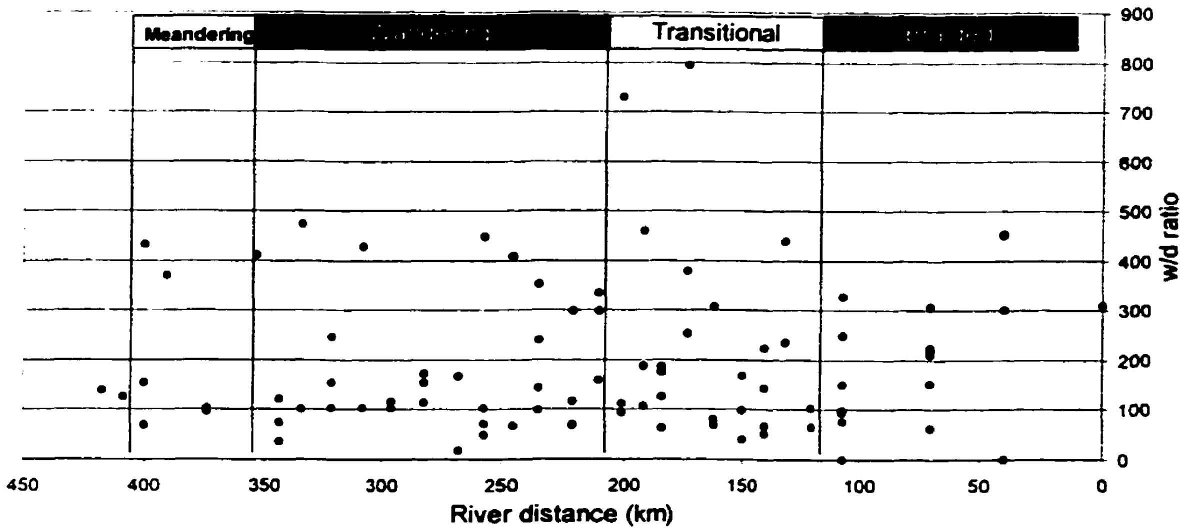


Figure 5.2.1.5. Plot of the downstream distribution of channel width/depth ratios.

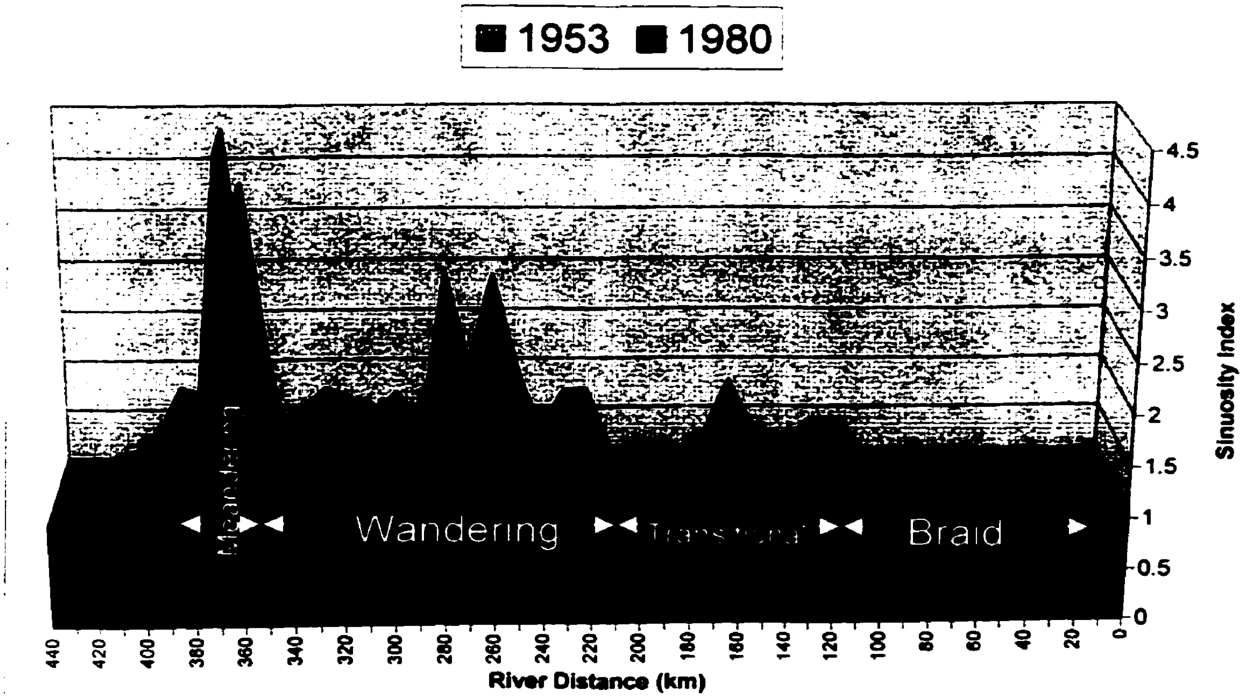


Figure 5.2.1.6. Sinuosity of the dominant (main) channel as seen in two different time periods. The notable change is primarily due to the neck cut-off of a large meander lobe.

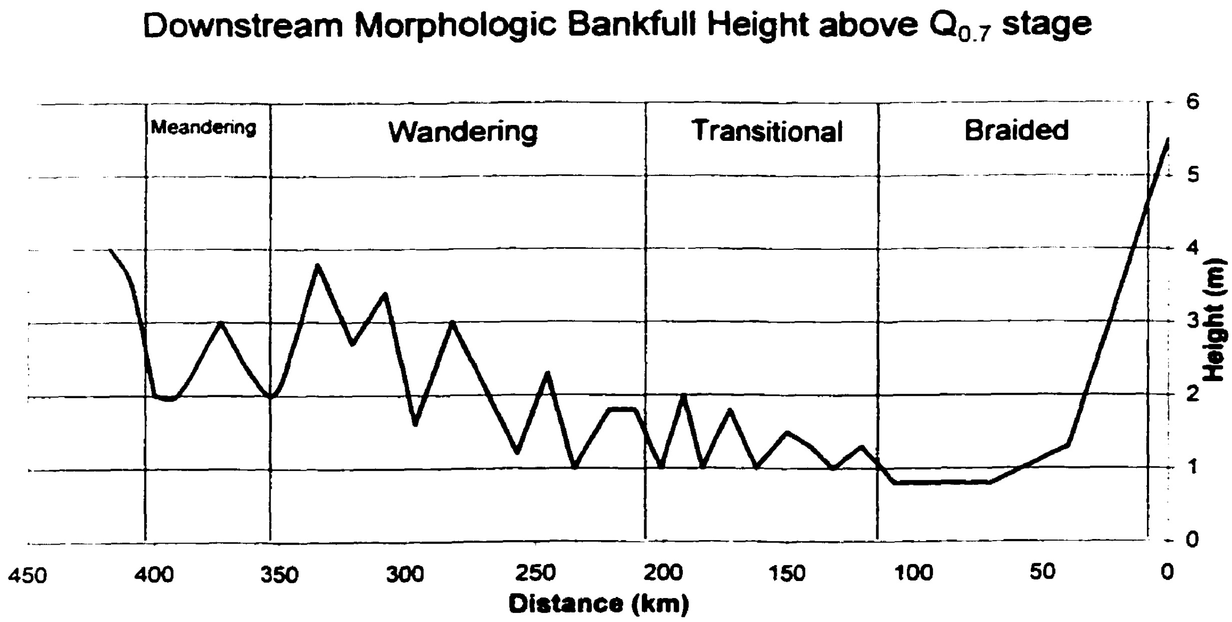


Figure 5.2.1.7. The height above water level (observed flow) of morphologic bankfull height (depending on the situation, this was decided by the height of the highest active gravel bar or the level of stable vegetation along a transect). Note the apparent periodicity in the fluctuation of this parameter.

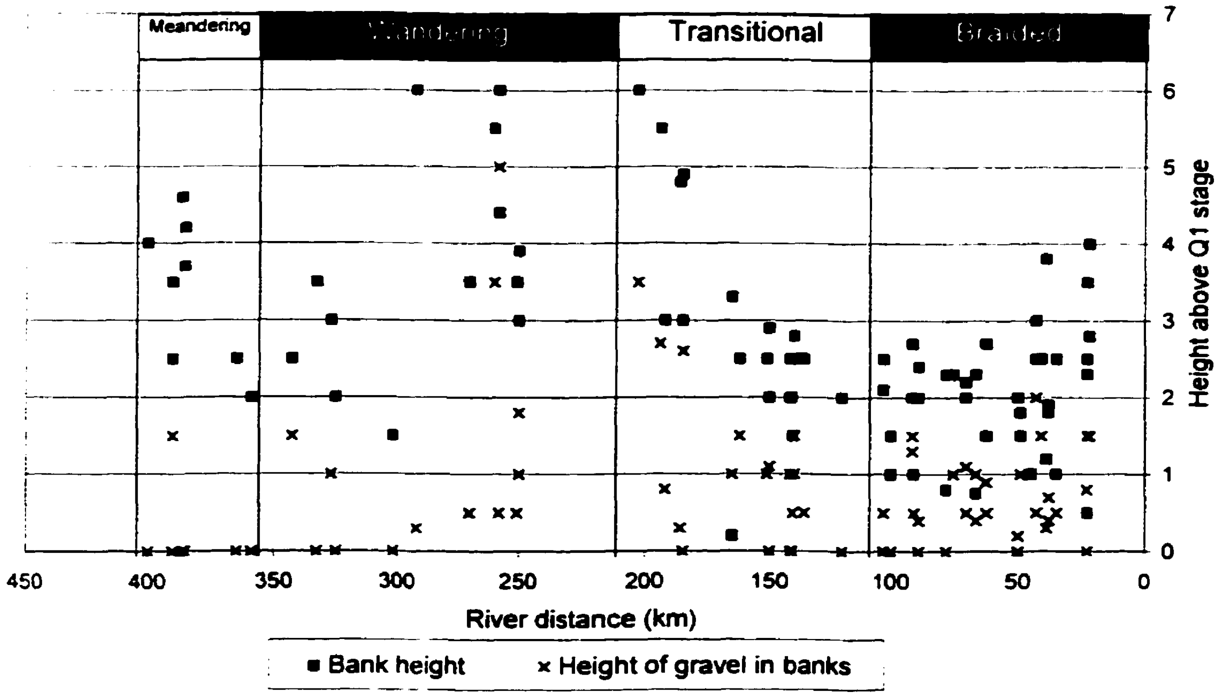


Figure 5.2.1.8. The downstream distribution of the bank heights and the maximum height of gravel observed in the banks. Above the gravel lies finer overbank sediments. Note the high degree of irregularity observed in this parameter. Ice-jamming may be playing a role. Also note almost the complete absence of gravel in the meandering reach.

channel being about 443m wide. In other words, the width of individual channels nearly doubles. The number of channels dividing flow, decreases to between 2 and 6 with the average being 3.84 (Figure 5.2.1.2). This quantity, combined with different channel behavior styles, separate the transitional reach as its own morphological entity. Due to too few data points in the braid reach, it is unclear if depths reflect an actual change or if the difference seen on Figure 5.2.1.3 is the result of a closer spaced sampling along the transitional reach revealing greater variability. However, overall depths do seem a bit deeper, approaching an average of 4m, though two 2m weighted mean transect depths were recorded. When widths and depth are compared the relation found in the braid reach decays and no correlation is evident (Figure 5.2.1.4). This may well be due to the relatively few data points collected in the braid reach which was logistically much more difficult to work in the field and does not form the focus of this study. There is definitely greater variability of width/depth ratios in the transitional reach values (Figure 5.2.1.5), ranging from 40 to nearly 800 with some clustering around 50-200. Sinuosity of the main channel thalweg increases to a range of 1.1 to 1.75 (Figure 5.2.1.6). Morphologic bankfull height also increases slightly, occupying values between 1 and 2 meters (Figure 5.2.1.7). Fluctuations between these heights seemingly occur at regular intervals that shorten downstream from 30km to 15km apart. It is in the transitional reach that the maximum heights of the banks increase significantly (Figure 5.2.1.8). At Fort Yukon (km 120), bank heights rise only 2m above mean annual water level. By White Eye (km 210), 6m banks can be found, with the height of gravel in the banks also rising from 0.5m to 3.5m respectively.

5.2.3 Wandering Reach

The wandering reach makes up the longest channel morphology found on the Yukon Flats. Unlike the clearly visible change from braiding at Fort Yukon, the boundary between the transitional reach and the wandering reach is much more subtle. Thus, it can be said that wandering begins is in the vicinity of White Eye ($\pm$ 10km) then splays across the lowlands for a distance of 145 'river' kilometers (Figure 5.1.4). However, although extensive, there is nothing constant about this channel pattern. Total transect channel widths continue to fluctuate though not as much as found in the transitional reach, occupying the range between 1000 and 1760m (Figure 5.2.1.1). Individual channels not only decrease substantially in number from an average of 3.8 to 2.4, but tend to be slightly wider individually, averaging 541m up from 442m. Thus, smaller channels are rarer but do exist and the larger channels become more common due to there being fewer channels overall. Depths continue to be slightly erratic throughout the wandering channel pattern length, though the transect mean depths show a trend of increasing downstream from 2-3.5m to 6m (Figure 5.2.1.3). The maximum scour depths recorded are remarkable. At one channel confluence near the beginning of the wandering reach a 25m (82ft) scour was recorded (km 226, Figure 5.2.1.3). This is the deepest individual scour found on the Yukon Flats and possibly on the entire Yukon River (at least between Dawson, YT and the Dalton Hwy Bridge. The wandering reach shows the lowest correlation between width and depth (Figure 5.2.1.4), an unexpected phenomenon giving channelization increases and that individual channels meander (meandering channels generally have lower and more predictable w/d ratios). Width/depth ratios do decrease in range however, slightly clustering around 100 but occupying values from 20 to 480 (Figure 5.2.1.5). The sinuosity of the wandering reach increases significantly averaging 1.5, but reaching as high as 2.9. This high sinuosity lowered to 1.9 sometime after 1953 when a neck cut-off downstream of Beaver straightened the main channel when a large meander was abandoned. Bankfull heights along this reach take on a dramatic change. Near White Eye, bankfull conditions are similar to those of the transitional reach, 1-2m. But near the end of the wandering reach, bankfull conditions can be found as high as 3.8m above the mean annual flood stage (Figure 5.2.1.7). Fluctuation of this parameter continues and the amplitude of this flux actually becomes greater, almost 2m from one survey point to the next. Maximum bank height does the opposite. It decreases downstream of 'km 300' from 6m to 3.5 to 2.5 entering the meandering reach. The elevation of gravel in the banks also drops, although it first reaches its highest point of 5m before lowering to between 1m and 1.5m (Figure 5.2.1.8).

5.2.4 Meandering Morphology

The meandering reach is the final morphologic unit investigated in this study. For much of the 53km meandering reach, 'meandering' may in fact be a misnomer. After only 1.5 meander wavelengths, flow once again breaks into multiple channels, although it seems clear that given the space, the Yukon River would be reverting to a meandering end-member morphology. The possible reasons for why anabranching resumes will be examined in the discussion (Chapter 6). The majority of this reach flows in one dominant, sinuous channel with only 1 or 2 'slough' channels in existence simultaneously (Figure 5.2.1.2). The average number of channels is 1.9. Correspondingly, total-transect channel widths closely or exactly match the width of the main channel and there is an overall drop to 800m. This is the narrowest total channel width is encountered after the confluence of the Porcupine River at Fort Yukon. However, as anabranching resumes, channel widths climb back up, nearly doubling to 1700m. Depths along the meandering reach are at their greatest, with mean depths of 5-6m. Depths also nearly drop in half as anabranching resumes (Figure 5.2.1.3). Once again, there is no correlation between width and depth values (Figure 5.2.1.4). Width/depth ratios exhibit values of 100 for the meanders but range from 70 to 440 for the downstream anabranches (Figure 5.2.1.5). Although there are only two data points along the 1.5 meanders, the field sites selected were reliable. Despite this, values of 100 for meandering channels are abnormal, with meandering rivers usually plotting at less than 40 (Smith, pers. comm.,1998). Sinuosity increases substantially along this reach to between 3.8 and 4.25, depending on the upstream thalweg position which shifted after 1953 (Figure 5.2.1.6). Morphologic bankfull stage indicators were found much lower in the meandering reach than the wandering reach. Bankfull height dropping down to between 2 and 3m above Q_1 stage. Contrary to that, maximum bank height increased rapidly back up to 4.7m. Gravel was only found in the banks in one locality where it made up the lower 1.5m of the bank. Five other observations along this reach showed no gravel in the banks.

5.2.5 **Slope**

The Yukon Flats, as its name suggests, is an area of extremely low slope. Slope data has been acquired in two ways: 1) field measurements of water surface slope and 2) elevations derived from the 1:63 360 USGS topographic maps.

Water surface slope measurements were collected for each channel at every transect location where possible. The majority of measurements were taken downstream of Fort Yukon (km 120). Due to only 8 measurements possible in the braid reach, data for this section will serve only as a guideline. In the remaining reaches, over 70 measurements exist, providing good overall coverage. The braid reach data suggests the average slope of this section could be approximately 30 cm/km (Figure 5.2.5.1). The highest individual water surface slope measured is found in the transitional reach, though overall slopes in this section are lower and some of the higher sinuosity channels can have very low slopes. The range of values is from 3.5 to 57 cm/km, averaging 20 cm/km. As flow enters the wandering reach, slopes continue to drop to an average of 11-14 cm per km (11 if an anomalous data point measured at a recent neck-cut off is ignored). The range of values is also lower in this reach, from less than 1 to 32 cm/km (some of the side 'slough' channels had undetectable water surface slopes in their lower reaches at $Q_{0.7}$ stage). Finally, in the meandering reach the lowest slopes were observed, ranging from less than 1 to 26 cm/km and averaging only 10.6 cm/km.

Slope data derived from map sources closely matches the above data. For most fluvial geomorphology studies, topographic maps of this scale would be of no use due to errors caused by mapping inaccuracy. However, the large scale of this study allows this technique to be useful with the error filtered out by both long distances and relatively

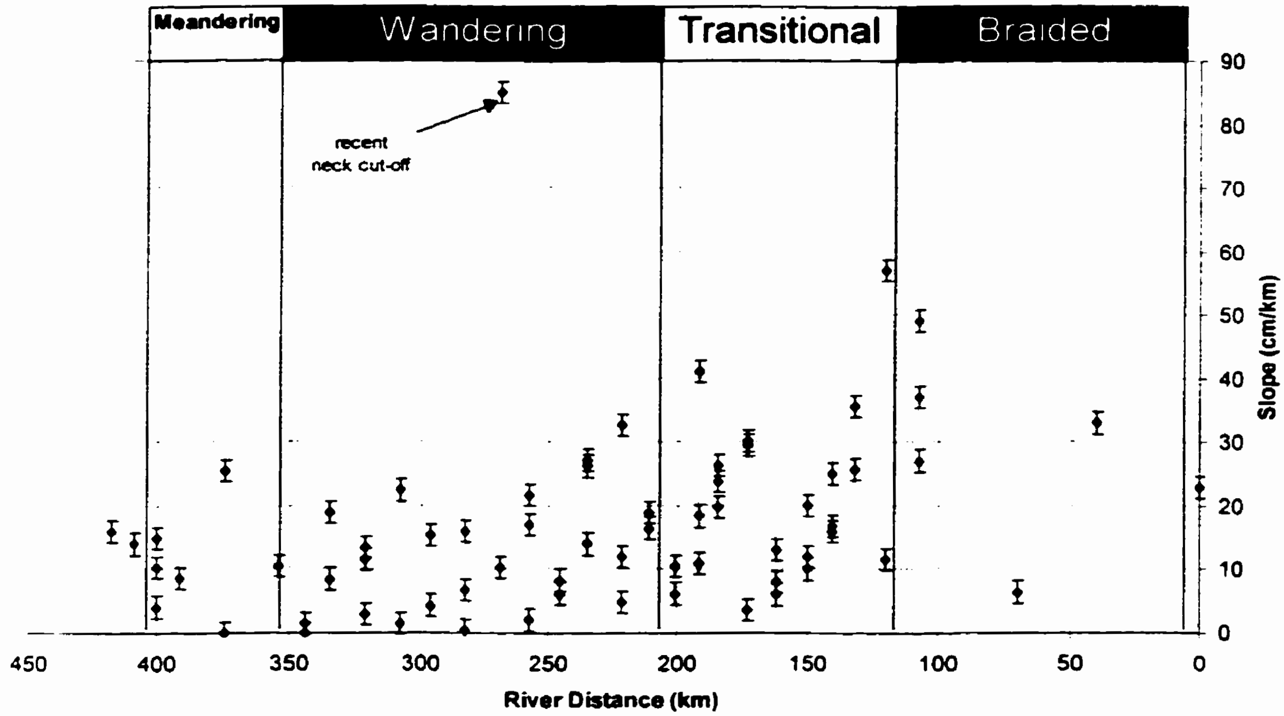


Figure 5.2.5.1. Field measured water-surface slope. Error bars represent one standard error. Note how low the slopes are for all channels on the Yukon Flats and the clear trend of decreasing downstream.

large elevation changes. In other words, even an error of 2m in elevation at a given contour becomes negligible over distances of 300 to 400 km. Figure 5.2.5.2 presents the elevation of the river surface in a downstream direction. A map has been added to illustrate where in space major breaks in slope occur. The two most prominent breaks in valley slope appear to coincide with channel pattern changes, both occurring just downstream of the delineated boundaries between channel patterns. Figure 5.2.5.2 uses 'valley distance' on the x-axis to attain valley slope, considered to be a more reliable indicator because it exists independently of channel pattern (Schumm and Lichty, 1965). As a result of the influence of channel sinuosity, valley slopes tend to be slightly higher than the average water surface slopes, although the two are invariably close. In the braid reach, valley slopes are approximately 40 cm/km. As with the water surface slopes, valley slopes decrease in a downstream direction to 30 cm/km in the transitional reach and 16 cm/km in the wandering reach. The meandering reach has the lowest valley slope at 13 cm/km. All average slope results are summarized by reach in Table 5.2.5.1.

braided	***transitional***	***wandering***	***meandering***
Average Field-measured Water Surface Slope			
30.462	20.056	13.706	10.583
Map derived valley slope			
40	30	16	13

Table 5.2.5.1. Summary of field measured water surface slopes (all values in cm/km)

5.2.6 Grain-size

Bed grain size data was collected at 13 sites along the Yukon River's 408km traverse of the Yukon Flats. Surprisingly, this data revealed that the bed of the river is gravel in composition from canyon to canyon and that no major or abrupt grain size transition occurs as is present on many of the rivers traversing the Canadian Great Plains

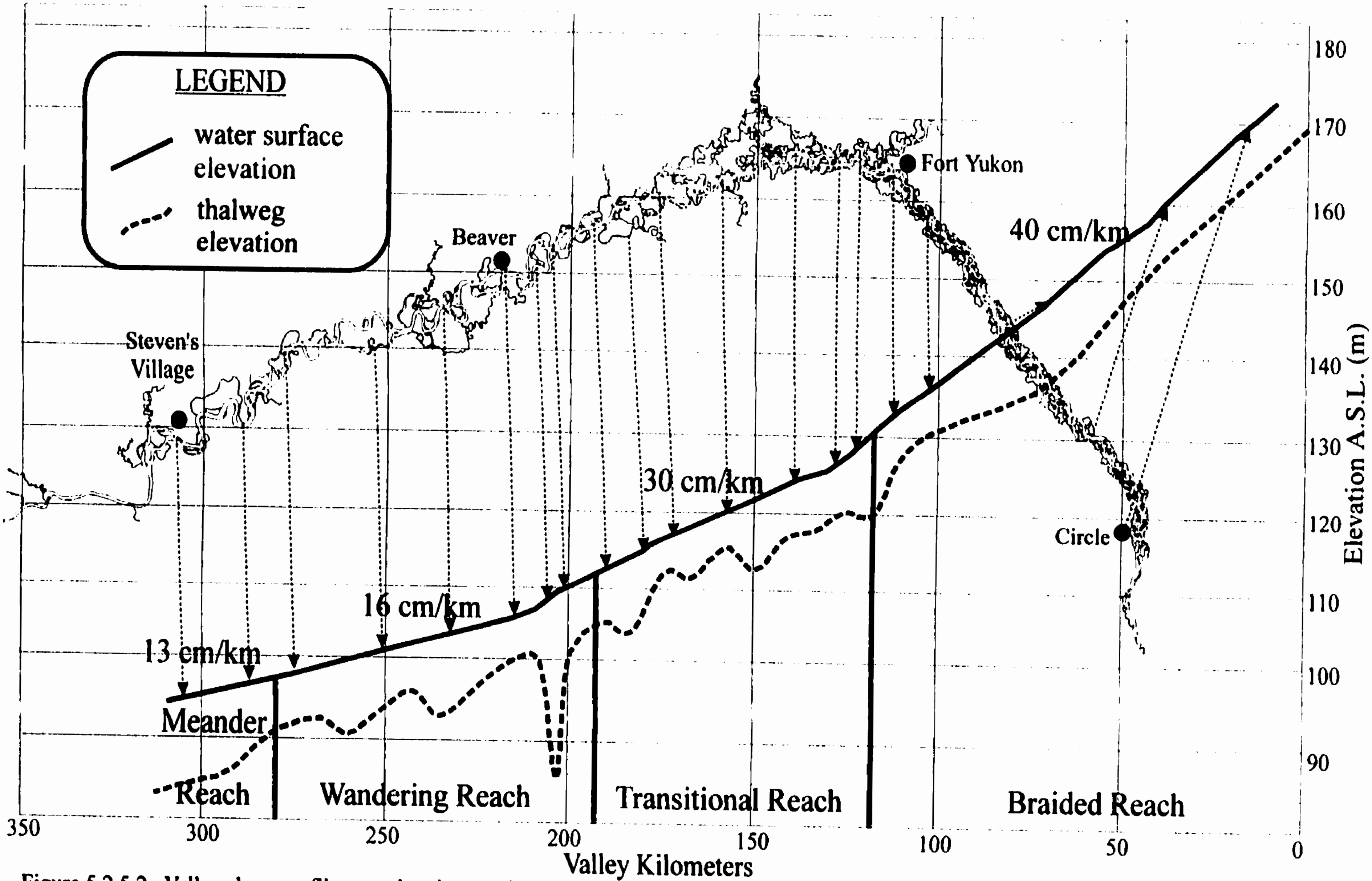


Figure 5.2.5.2. Valley slope profile map showing reach averages. Note how major breaks in slope occur very close to channel pattern changes.

(Shaw and Kellerhals 1982). To gain a better understanding of bed sediment characteristics, statistical analysis and downstream comparisons have been performed on the data. Despite the small sample sizes (30kg) limited by a short amount of time and finite logistical measures in the field, the data collected reveals itself to be quite robust and useful as an observation tool.

Data collection involved the wet-sieve method where samples were washed through a sieve array by pouring water over them. This technique, although the only practical field sieving technique available for fine gravel sediments in remote areas, produces data limited by the fact that 'finer than' sediments get washed though and lost in the process. Thus, the percent of the sample weight of this fraction (in this case finer than 1 phi) must be calculated as the remaining sample weight once all other size fractions are accounted for. All efforts were made to ensure that this process was carefully carried out to avoid erroneous, highly variable results (see Research Design and Methods).

When categorized and plotted against distance (Figure 5.2.6.1), it is very clear that the Yukon's bed-load is dominated by gravel grain sizes. 'Pebbles +' (-2Ø to-6Ø, 4 to 64mm (less than 2 clasts per sample in only 3 samples were greater than 64mm, none were found in samples taken downstream of Fort Yukon)) make up 60 to 80 percent of all samples. This curve shows a tendency to decrease downstream, displaying an R-squared value of 0.6095. In other words, 60 percent of the variability in between all 13 locations is explained by a downstream trend in pebbles comprising lower percentages of the entire sample weight. Although granules show a slight increase trend downstream, the majority of variability in the samples must be due to other factors than distance alone.

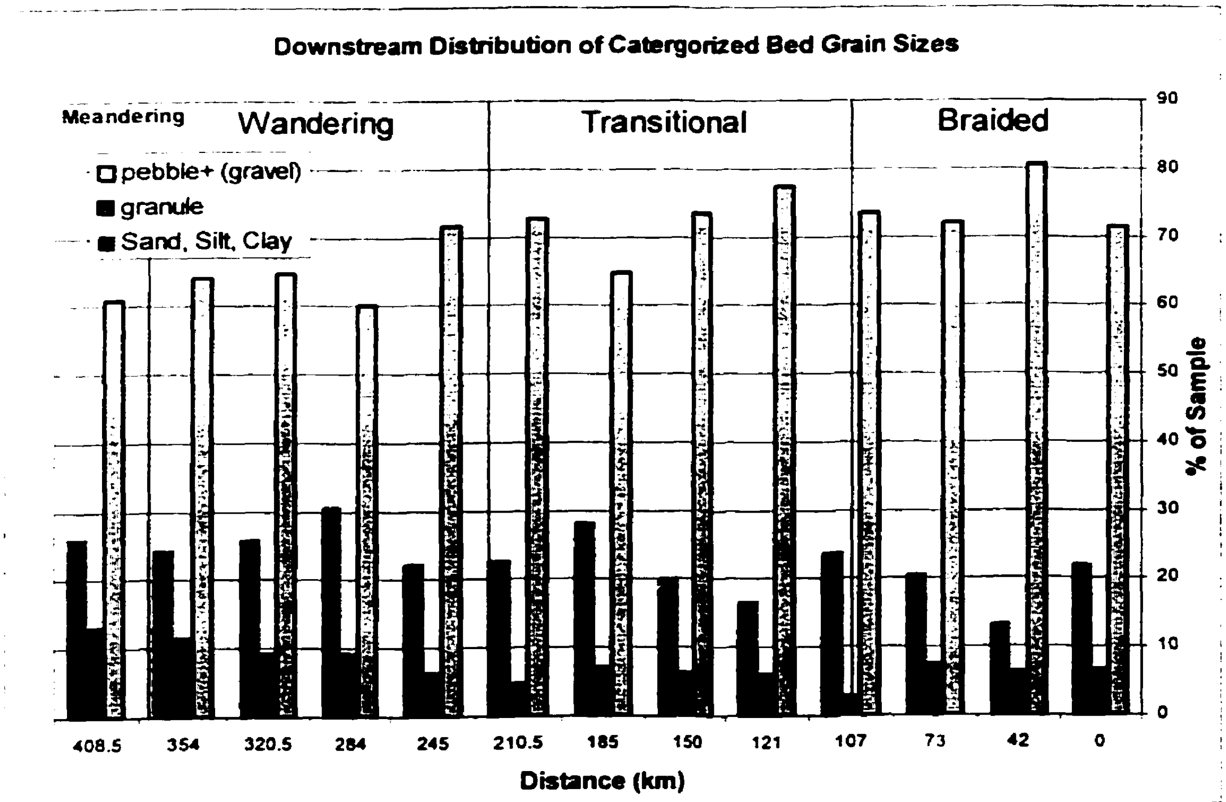


Figure 5.2.6.1. Downstream distribution of categorized bed grain sizes. Note how gravel dominates the composition of the bed material. A slight fining trend is evident in the decrease in the percentage of gravel and the increases in both granules and fines. However, this change is much lower than what would be expected over such a long distance.

The fine fraction, sand silt and clay, also appears to increase in a downstream direction, with a linear trendline increasing from 4.5% to 11% of the sample weight explaining 54% (r-squared .54) of the observed phenomenon. It should be noted that variability in any of the grain size categories will have a corresponding effect on the distribution of all other categories. Thus, although low, the r-squared values for the pebble and fine-fraction trends are reflective of geographic patterns. This is because the data is filtered by the interdependency of the populations regressed and only strong trends would appear at all due to the dampening effect of noise. Thus, the overall trend in the data points to a downstream decrease in pebbles, compensated by the shared response of increases in both the granule and sand, silt, clay fractions. Whether this could at all relate to channel pattern changes will be examined in the interpretations section of this chapter (5.2.8).

The above trends can also be observed when the grain size data is subjected to other statistical methods. Folk (1980) described in detail how these methods should be carried out when dealing with sediment grain size data and the following analyses conform to his recommended procedures. Figure 5.2.6.2 illustrates the cumulative percent curves for every sample. It should be noted that to attain the 100% intercept of the coarser than –5 *phi* fraction, the b-axis of each clast in this fraction was measured and the results averaged to attain a diameter in millimeters. Using the curves in Figure 5.2.6.2 to obtain specific percentile values (i.e. Ø95, Ø84, Ø75, Ø50, Ø25, and Ø16), the median, mean, sorting and skewness of the grain size distributions were calculated. Figure 5.2.6.3 shows the downstream distribution of the median (D_{50}) and D_{95} values. A linear curve fit to the median values matches the observed data remarkably well. An R-

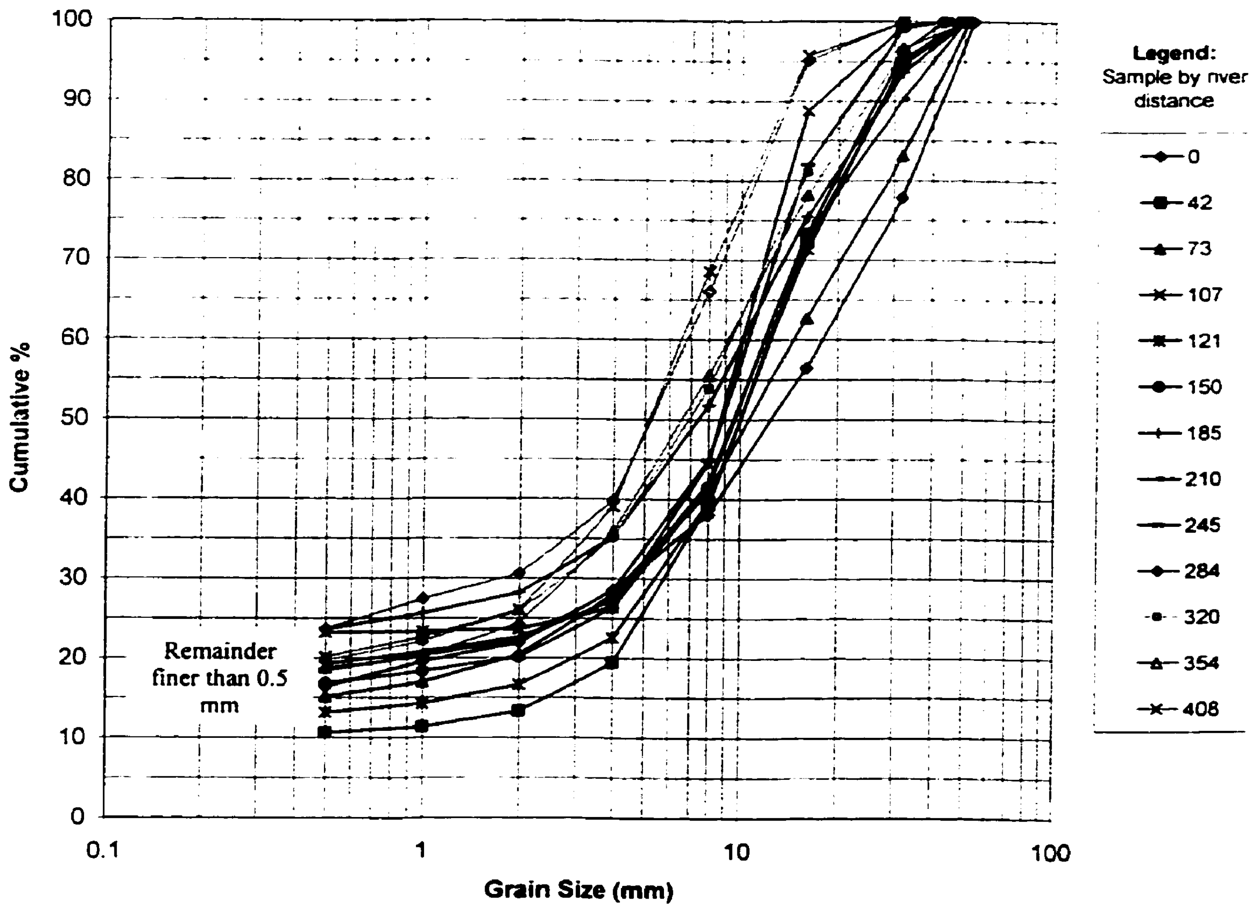


Figure 5.2.6.2. Cumulative percent plot of all measured grain size distributions.

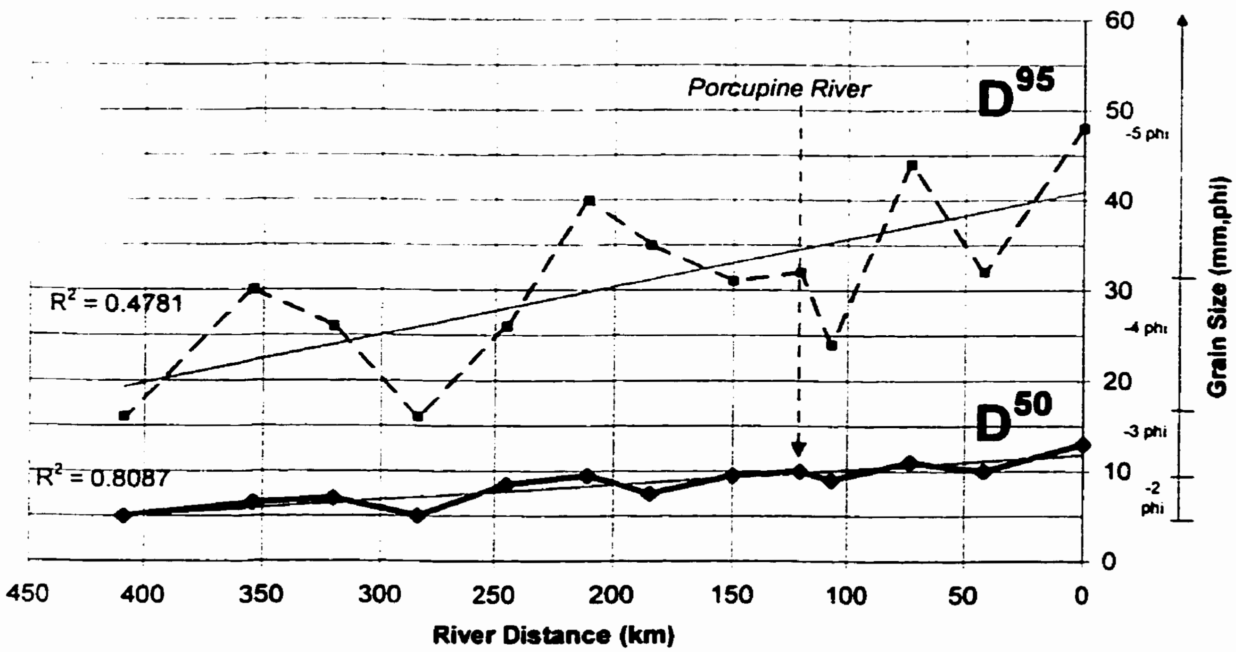


Figure 5.2.6.3. Downstream distribution of D_{50} and D_{95} grain sizes.

squared value of .81 shows that there is a trend of the median grain sizes becoming smaller in a downstream direction, from approximately 14mm to 5mm. The D_{95} plot shows a greater degree of variability (which is likely a product of the small sample size and must be interpreted with appropriate care), but is also decreasing downstream. Figure 5.2.6.4 summarizes the distribution of the remaining statistical parameters. Here, the sorting index curve (synonymous with 1 standard deviation) shows initial variability then flattens out downstream of the transitional reach, which ends at approximately km 210. This set of indices was calculated using the 'graphic standard deviation' formula described by Folk, 1980, pg. 44). In this work Folk (1980, pg. 46) refers to the 'inclusive graphic standard deviation' as a better measure, but it requires the Ø05 value, which in the case of this study is incalculable due to the nature of wet sieving. Graphic skewness, in sedimentology, refers to the offset of the majority of the distribution from normal or, how coarser or finer the sample is from being evenly distributed over all grain sizes. Figure 5.2.6.4 shows that all but one sample site are skewed to the coarser end of the distribution. In fact, examination of the histograms of these distributions (Appendix A) indicates that all are bimodal (example Figure 5.2.6.5). Thus, any skewness value is in realty, describing which mode of the distribution is dominant. Bimodality in fluvial gravels is common, caused by the so-called 'missing sand fraction' (*phi* 0 and 1 in Figure 5.2.6.5) (Smith, pers. comm., 1998). The graphic mean is affected both by skewness and bimodality and in Figure 5.2.6.4 can be observed slightly mimicking the sorting index curve. The graphic mean grain size variability decreases downstream, but is so high that it is not clear if any 'significant' fining trend exists. Generally though, the mean grain size of the Yukon River seems to decrease from –2 *phi* to just under –1 *phi*, and

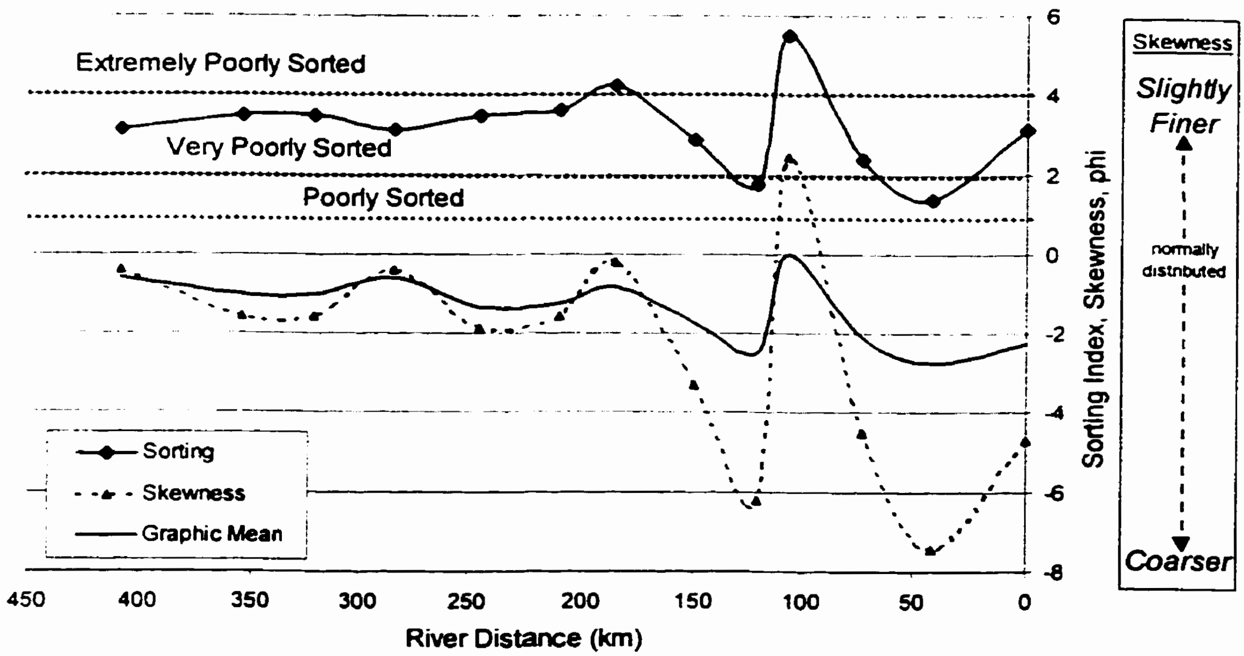


Figure 5.2.6.4. Sorting (standard deviation), Skewness, and Graphic Mean of bed sediments plotted against river distance. The graphic mean plots low because of the bimodal distribution of the bed material (the missing sand fraction).

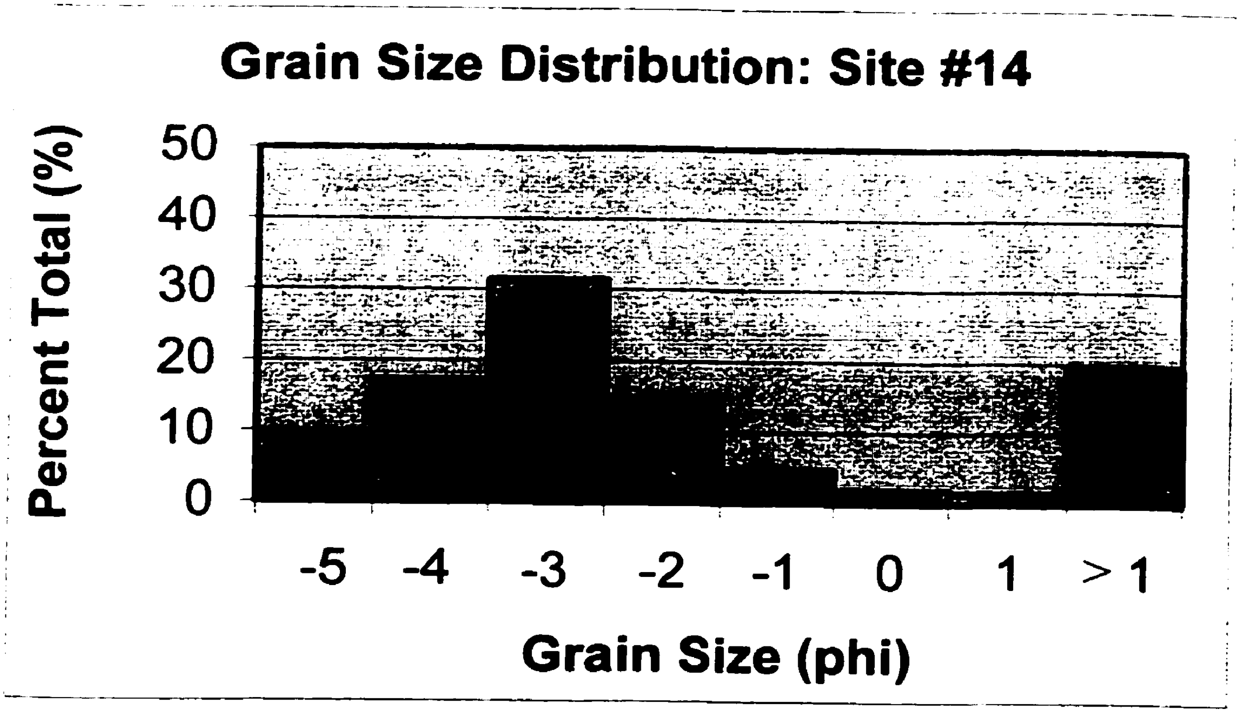


Figure 5.2.6.5. An example of a typical Yukon River bed gravel histogram. Note the bimodality of the sample.

remains very poorly sorted over the entire 408km distance it travels across the Yukon Flats.

5.2.7 Hydraulics

In order to investigate the energy distributions found between channel morphologies, discharge for each channel in each transect had to be estimated. In Chapter 2 it was established that reliable discharge data was available for the Yukon River in the Yukon Flats. However, the task of using this data to understand energy distributions and flow characteristics in a multi-channeled system is not simple. The following section will deal with the development of a methodology to estimate how much of the total flow value is carried by each channel in this anabranching system.

Given the type of data collected in the field and the success of previous researchers in estimating discharge from morphologic parameters, the 'hydraulic geometry' approach was adopted. Many workers have used the channel properties of width and depth to estimate the discharges carried by rivers. All except Bray (1973; 1975) and Drage and Carlson 1977 used single channel rivers in their attempts and all authors looked at medium to small rivers. Bray looked at rivers in Alberta which are typically gravel and may occasionally anabranch. Drage and Carlson (1977) applied this technique to braided rivers in Alaska. The morphology-discharge relationships found by these authors were deemed an appropriate first start due to the similarities in their study river to the Yukon River.

The principal of this technique is simple, attach coefficients to the independent variable until it regresses well with the dependent variable. In the case of Bray (1973; 1975) the equations produced were:

$$w = 4.29Q^{0.54}$$

and

$$d = 0.191Q^{0.38}$$

When the appropriate parameters from the Yukon River were plotted, mixed results were obtained (Figure 5.2.7.1). Given that the width discharge predictions for single channels should total to the actual discharge recorded at the gauging station, the estimates were moderately good, although in a few cases were up to 8000 m^3/s too high. In braid rivers the approach is to estimate the total width of flow so that bars would not factor. This was attempted for the Yukon by eliminating the separations of flow by islands and using the total width of all of the active channels in the equation. As observed in Figure 5.2.7.1, this approach failed also. When the depth relationships were explored (Figure 5.2.7.2), the result was generally under-prediction although close to the actual values in many examples.

Drage and Carlson's (1977) coefficients produce opposite, but also inaccurate results. When their relationships:

$$w = 4.66Q^{0.47}$$

and

$$d = 0.13Q^{0.38}$$

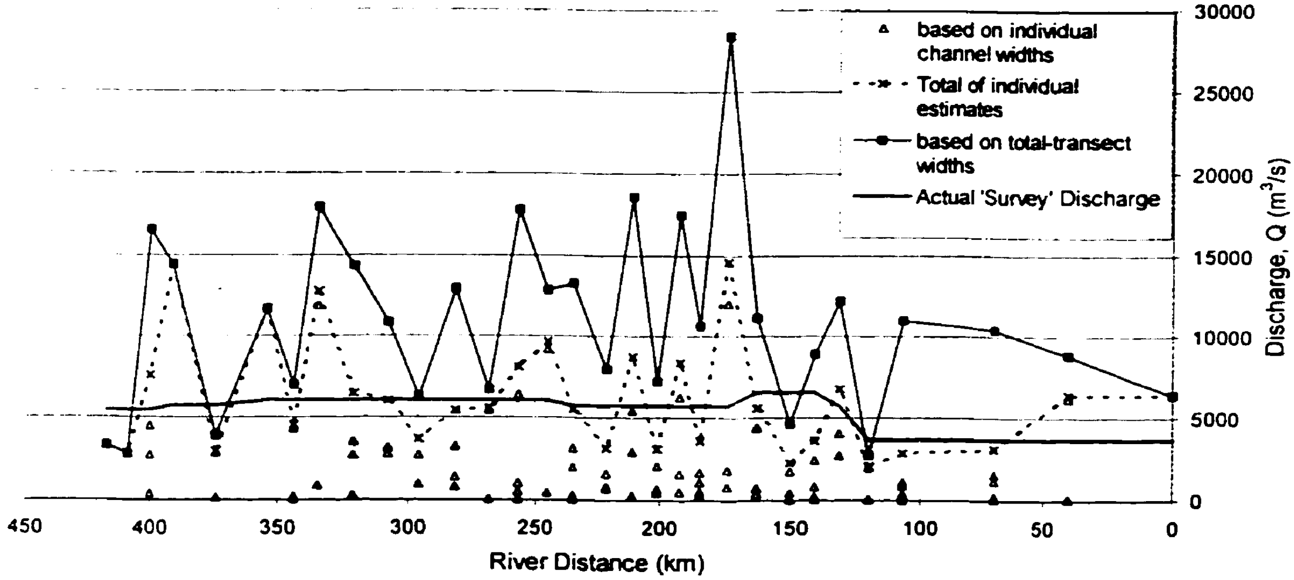


Figure 5.2.7.1. Hydraulic geometry method of estimating discharge using Bray's (1973) coefficients: $w=4.29Q^{0.54}$.

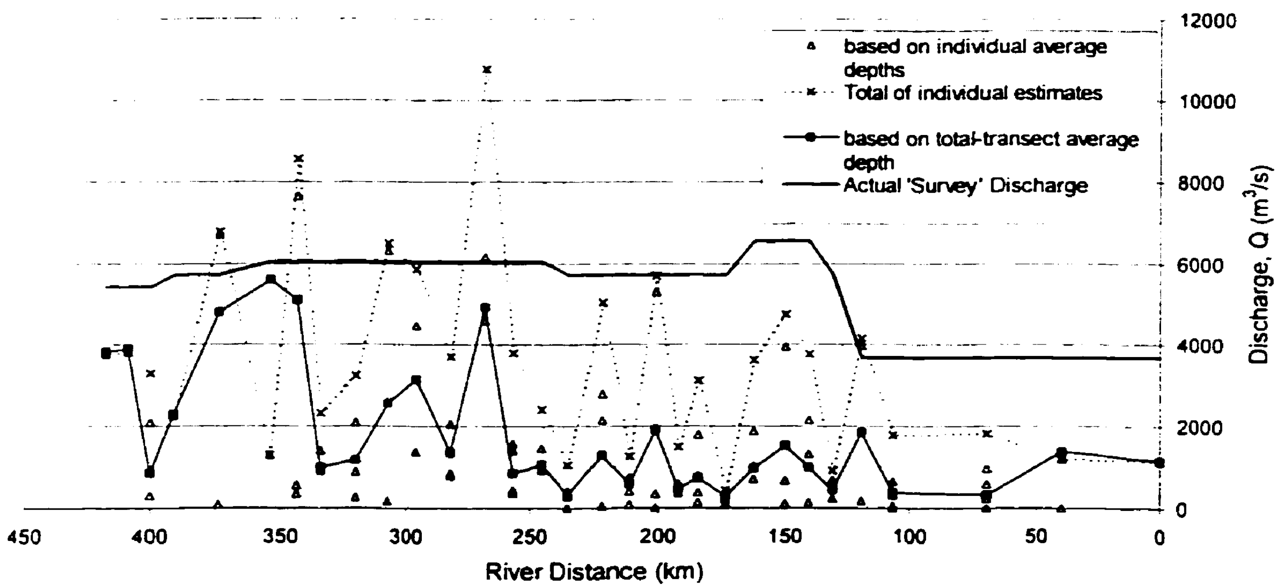


Figure 5.2.7.2. Hydraulic geometry method of estimating discharge using Bray's (1973) coefficients: $d=0.191Q^{0.38}$.

were plotted, width estimates grossly over-predicted by several orders of magnitude, over 120,000 m^3/s in one case (Figure 5.2.7.3 and Figure 5.2.7.4). Depth predictions were better, but not as good as Bray's relations. This time, depths tended to over-predict individual channel discharges, and under-predict the transect averages. So what does this mean? In fact, this exercise demonstrates that for the anabranching sections of the Yukon River the traditional hydraulic geometry relationships do not apply and can not be used to estimate discharge.

The solution to the above problem was to adopt an equation that could use more physical properties as input. The Manning's equation, a derivative of the continuity equation for rivers was selected as one with enough control by real-world parameters.

Continuity Equation

$$Q = wdv$$

where: Q = discharge
w = width
d = depth
v = velocity

Manning Equation:

$$Q = k\ \frac{R^{2/3} S^{1/2} A}{n}$$

where: k = constant (omitted when working in metric)
R = hydraulic radius Area/P where: P = 2d*w
S = slope (m/m)
A = cross sectional area of channel
n = Manning roughness coefficient

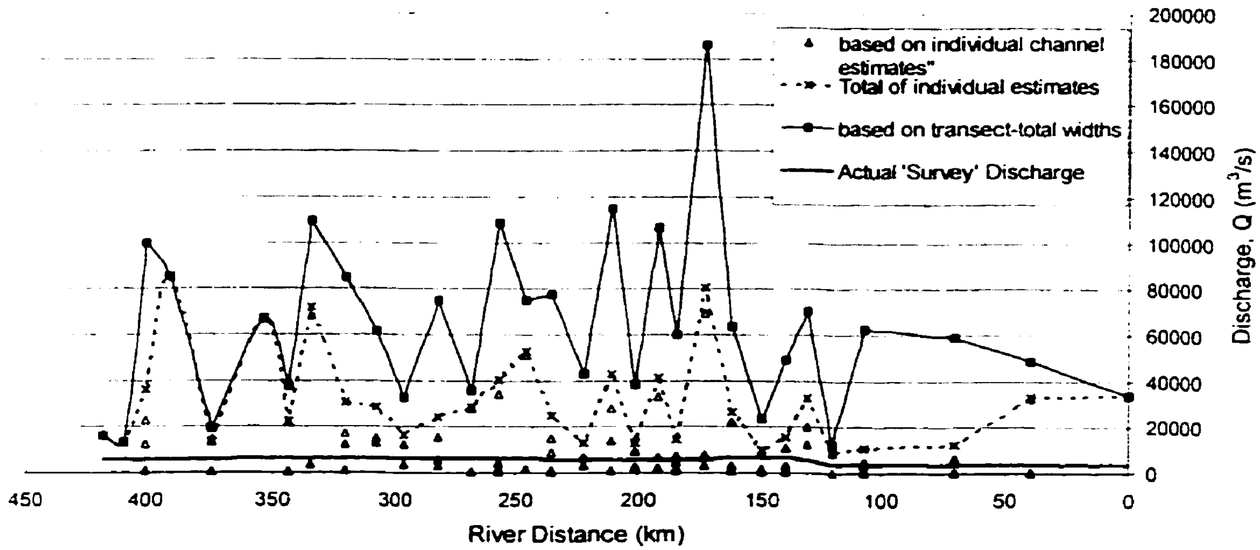


Figure 5.2.7.3. Hydraulic geometry method of estimating discharge using Drage and Carlson's (1977) coefficients: $w=4.66Q^{0.47}$.

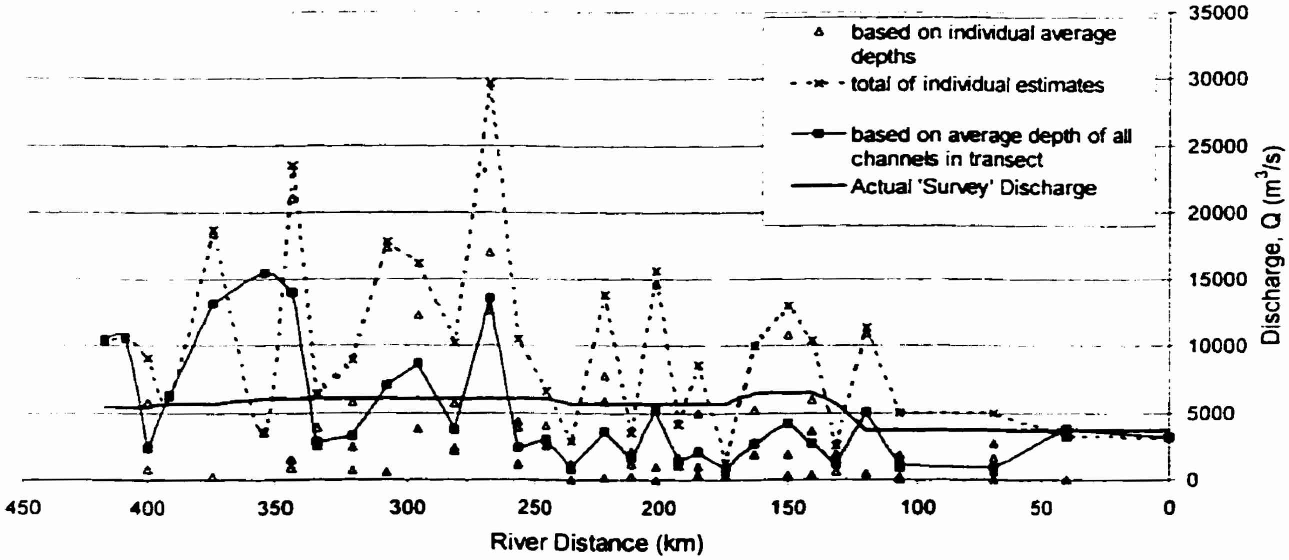


Figure 5.2.7.4. Hydraulic geometry method of estimating discharge using Drage and Carlson's (1977) coefficients: $d=0.13Q^{0.38}$.

The continuity equation itself could not be used because accurate velocity measurements, though attempted, were found to be impossible on a river of this size, particularly given the limited logistical resources of this study due to the remoteness of the region. The results of the Manning equation's discharge predictions are found in Figure 5.2.7.5. These predictions were considerably more accurate than the above, although not perfect. Only two problematic outliers were considerably inaccurate and one was due to a high slope value caused by a recent neck cut-off. Although not a fully accurate estimate of the flows carried by all channels, it was decided that they were accurate enough for assigning the *proportion* of flow moved by each channel in a transect. Since the true total discharge was known, the individual channel flows for each transect were totaled and that value divided by the individual channel flow to attain a number that represented the proportion carried by a given channel along a transect. For each channel, this proportion was then extracted from the known total discharge to establish a reasonable real-world estimate of the flow carried in each channel of each transect. An example of this procedure is shown in Table 5.2.7.1. The discharge for each channel is shown in Figure 5.2.7.6. As flow becomes more channelized downstream, the overall number of channels diminishes. Thus, individual channels in every reach carry more flow as one moves downstream. Figure 5.2.7.7 shows the average amount of flow carried by a single channel for each morphology type. Each morphology shows a step up from the previous until when the meandering reach is compared with the braided, each channel is carrying approximately 600% more flow. In conclusion, the above procedure using the Manning equation is the only known way to attain the discharge carried by anabranches unless the velocity of each and every channel is known.

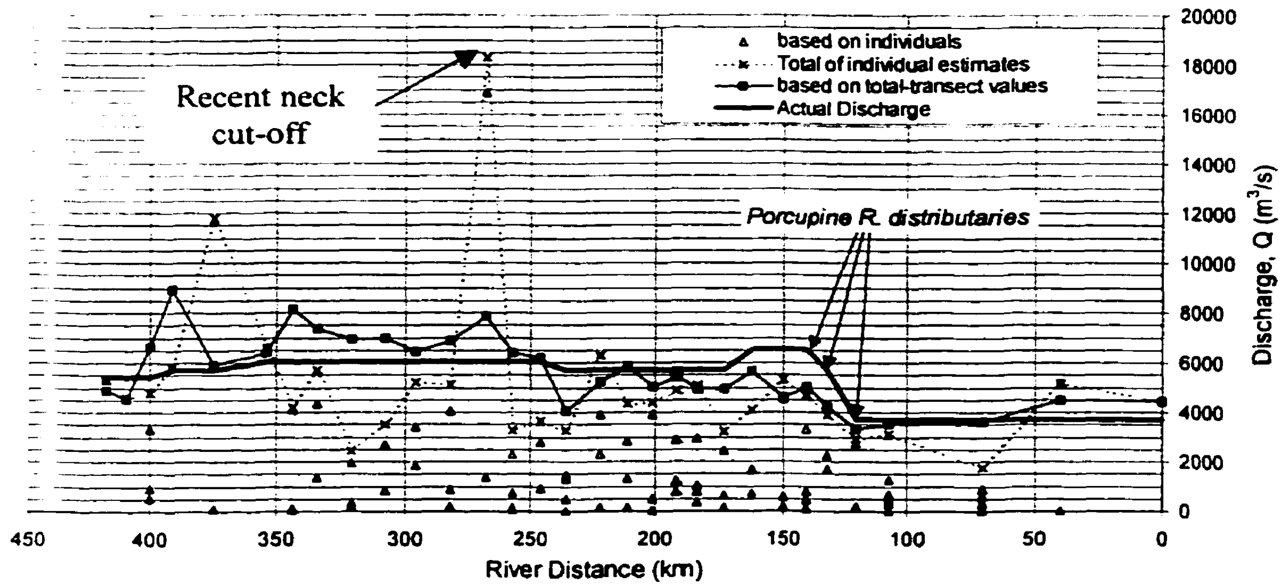


Figure 5.2.7.5. Raw flow estimates for 'survey discharge' based on the Manning slope/area equation. Note how this estimate is the closest of all presented.

Transect	w	mean d	CSA (actual)	slope (m/m)	Manning estimate	Total Estimated flow	Portion of Total est. flow	Actual Total Q	Individual channel flow
10a	517	1.36	713	0.000295	657.39	3240.296	0.2029	5720	1160.579
10b	1429	1.8	2568.96	0.0003	2432.48	3240.296	0.7508	5720	4294.395
10c	326	1.29	427	0.000035	150.42	3240.296	0.0464	5720	265.549

Table 5.2.7.1. An example of the steps required to attain a discharge estimate for individual channels in an anabranching system (proceeds from left to right). 'Actual' CSA (cross-sectional area) refers to that derived from the total of all 1x1 meter cells interpolated for the channels surveyed. This method provides a small degree of improvement in accuracy and facilitates calculations when working with the product of the laser-transect method.

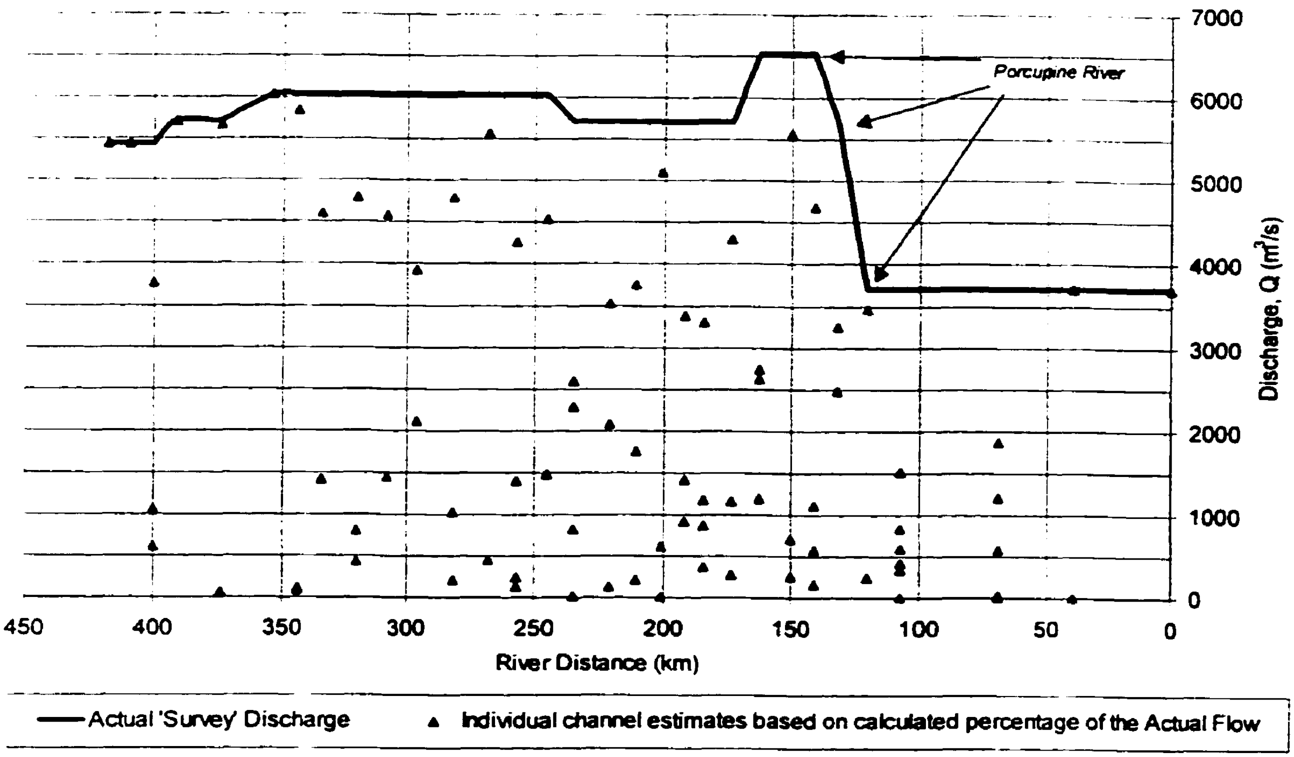


Figure 5.2.7.6. The resultant estimates for individual channel discharges plotted in a downstream direction. Fluctuations in 'actual survey discharge' are the result of corrections for differences in time and space.

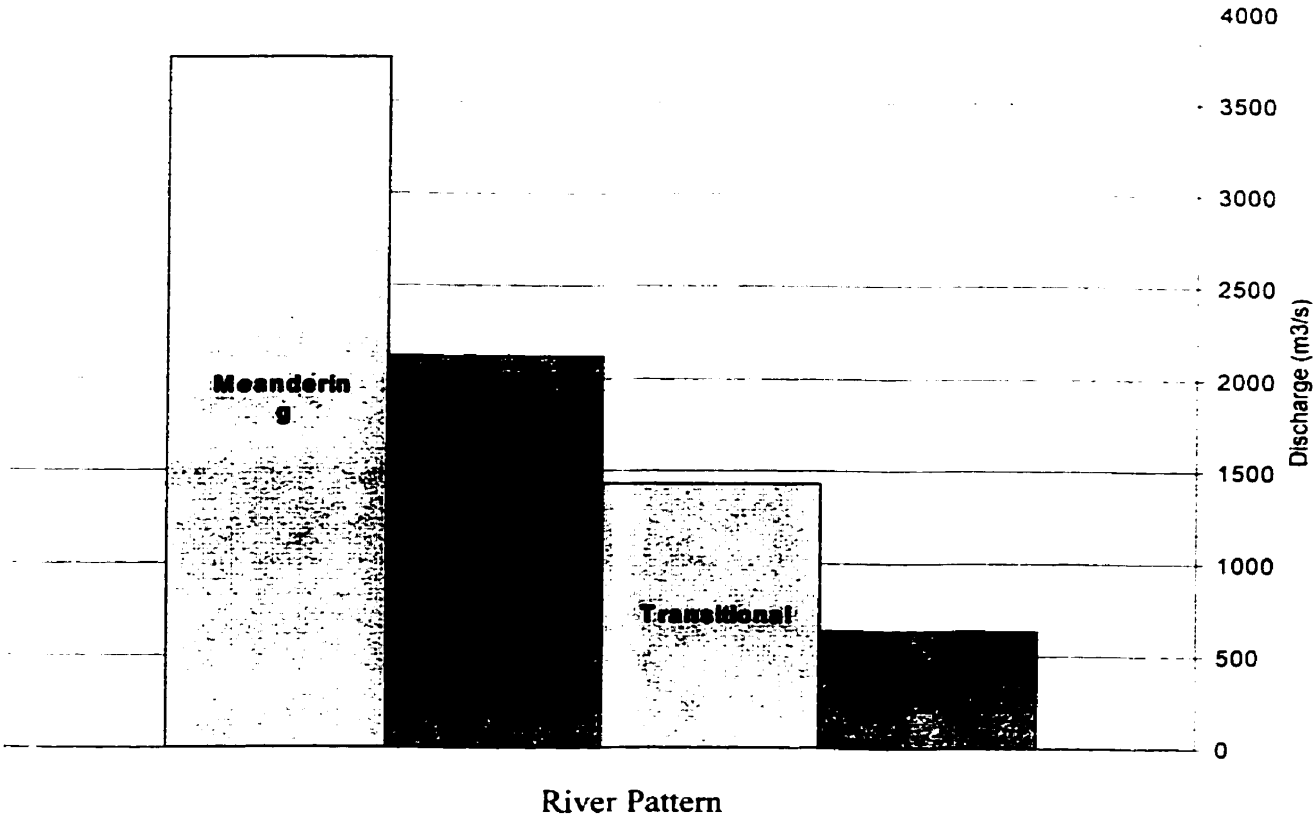


Figure 5.2.7.7. Average flow carried by a single channel in each morphology at 'survey' stage ($Q_{0.8}$).

The product of the above exercise is an ability to estimate the way energy is distributed in the fluvial system. Shear stress and stream power are the two ways of quantifying the energy exerted in channelized flows. Shear stress is an expression of the force that flow exerts on the bed. It is found using the following equation:

$$\tau_0 = \gamma R s$$

where: γ is the specific weight of water.
R is the hydraulic radius
s is the tan slope

Shear stress calculations for the study area are summarized in Figure 5.2.7.8. There does not appear to be any clear downstream trend in shear stress. If one were to remove the outlier data point caused by the recent neck cut-off, it may be possible to describe a general trend of decreasing shear stress downstream, until at the meandering reach, values increase again. Unit area stream power is a measure of the energy being expended by the system. Thus, low stream power values are a manifestation of the system minimizing the rate of energy expenditure (Yang and Song, 1979). The unit area stream power equation is:

$$\Omega = \frac{\gamma Q s}{w}$$

where Ω = stream power
Q = discharge
s = tan slope
w = width

When the unit area stream power valuc for the Yukon River are plotted, a downstream trend of lower values (when ignoring the outlier) is clear in the transitional reach and the wandering reach (Figure 5.2.7.9). As with shear stress values, the meandering reach

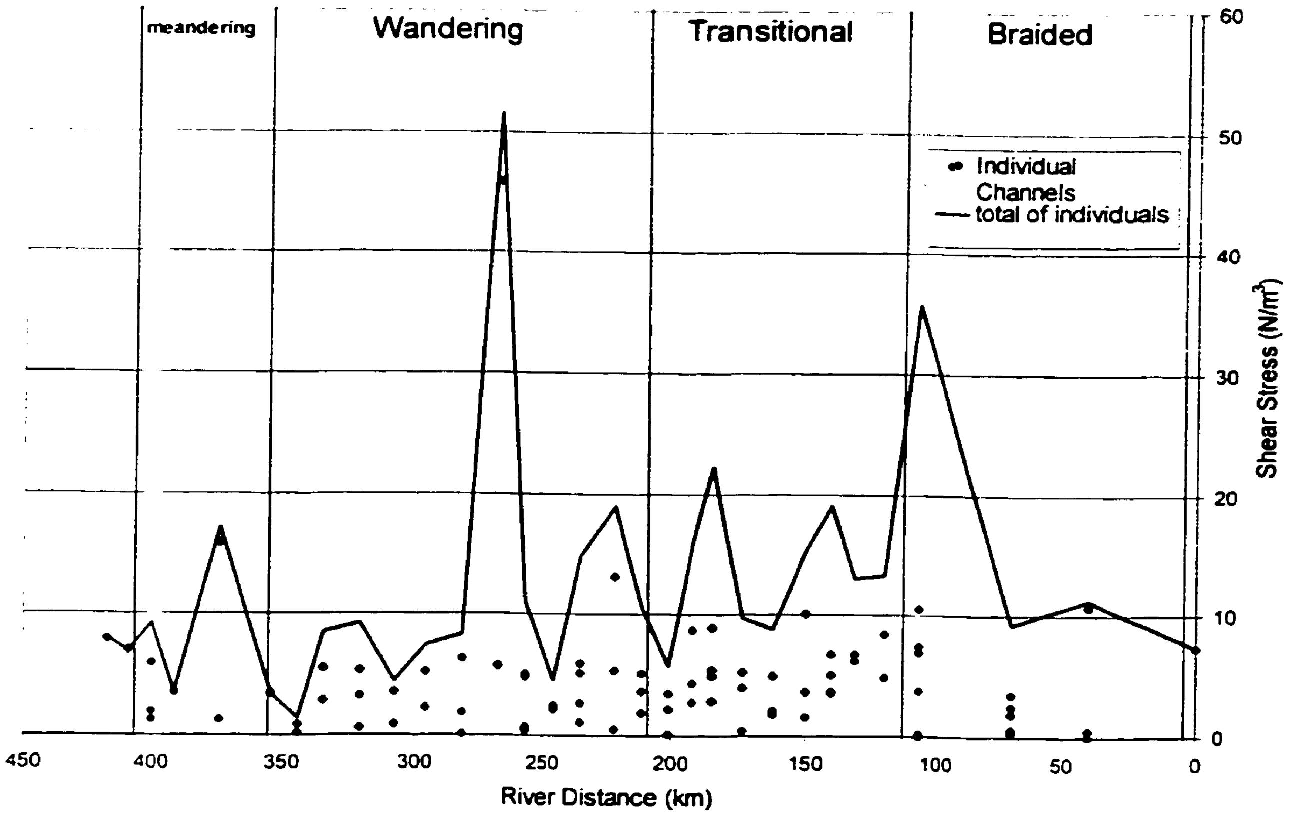


Figure 5.2.7.8. Downstream distribution of bed shear stress.

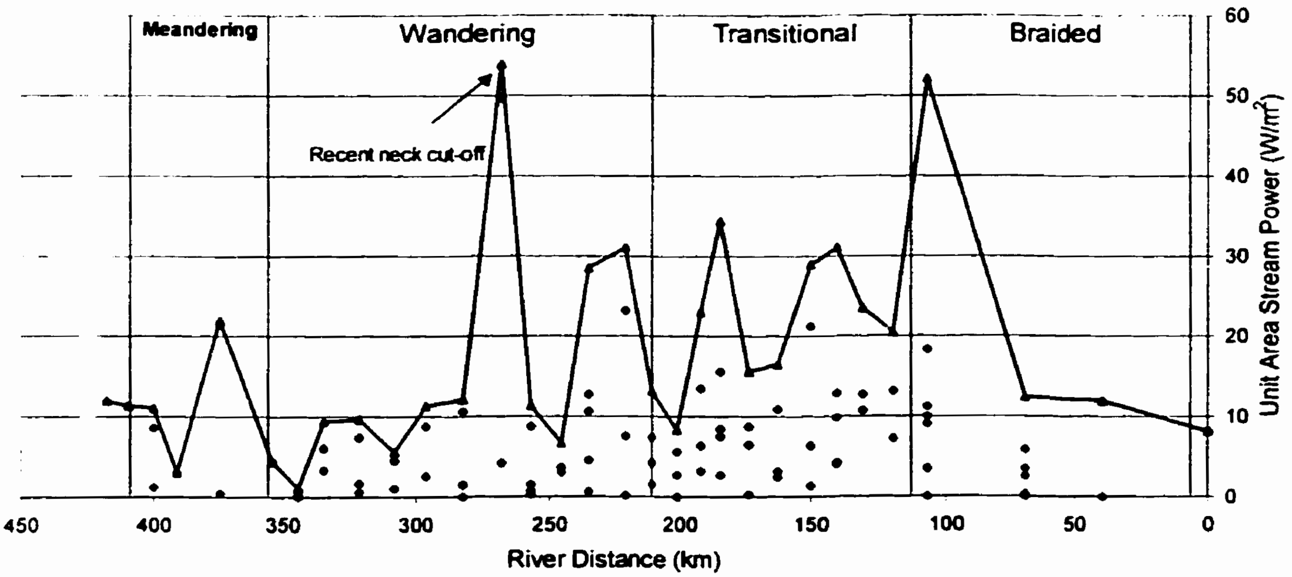


Figure 5.2.7.9. Downstream distribution of calculated unit area stream power. Points represent individual channel values while the line represent the total of those values along a transect.

displays an increase in values while the braided demonstrates to much variability to really comment on. The response of the stream power equation to the anomalous slope caused by the recent neck cut-off at km 268 illustrated a need to test how much of the stream power equation was influenced by slope. Figure 5.2.7.10 shows unit area stream power plotted as a dependent variable against the field measured slope values. For each successive downstream channel pattern the R-squared values are better. In fact, for the meandering and wandering reaches, respective R-squared values of .896 and .863 indicate that most of the stream power function for these reaches is dependent on the slope values. For the transitional reach the value is .705, leaving 29.5 % of the variability to be explained by other variables. In the braid reach, most of the variability in stream power must be due to factors other than slope. Thus, it would seem that as reaches display lower and lower slopes (Figure 5.2.5.2), their corresponding shear stress values become more dependent on slope than any other factor or combination of factors.

5.2.8 Migration Rates and Lateral Migration Styles

Using maps generated by the time-slice aerial photography and maps, observations concerning the rate of lateral channel shifting can now be documented. In all, five maps were created to show the Yukon River's channel changes between 1953 and 1982. Generally, each map was produced as a sample of the activity in each reach, although the last 60km of the river was thoroughly mapped due to the reverse trend in the number of channels observed there. As samples, the maps produced are good. The shortest sample, the braid reach, covers approximately 17km of the entire channel pattern

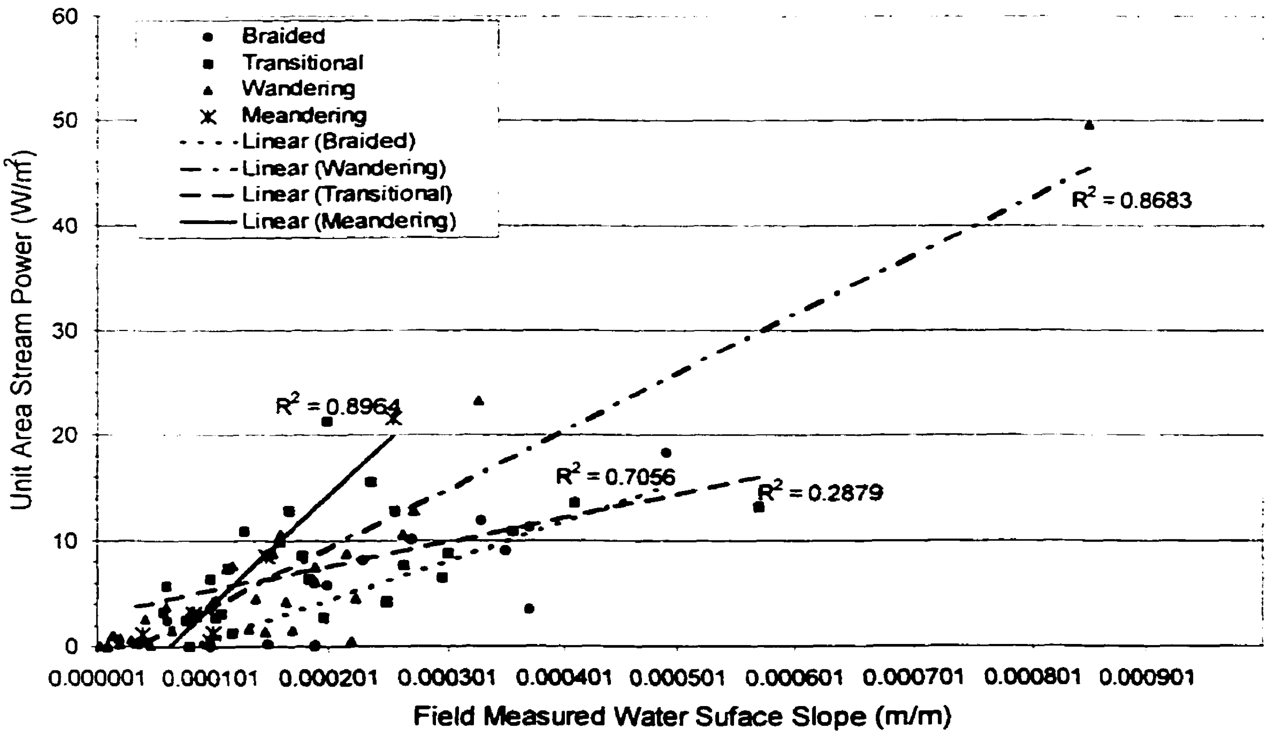


Figure 5.2.7.10. Reach-by-reach plot of unit area stream power versus water surface slope. Note the high correlations between the variables in the meandering and wandering reaches.

phenomenon. There is 35km of coverage for the transitional reach, 32km for the wandering reach, and full coverage of the meandering reach.

Typically in single-channel systems, migration rates are measured along the axis of movement of each meander bend (Smith pers. comm., 1999). Due to the multiple channeled nature of the Yukon River, another technique had to be developed. In order to sample the overall migration rates of the braid and transitional reaches, the mapped areas were measured along ten cross-sections at regular intervals. Then, the total distance eroded along each transect line was recorded. This quantity was then averaged with the total distance deposited to establish the amount of lateral migration along a particular transect. Finally, the values for each transect were averaged producing an average distance of erosion found in each channel pattern type. When this value is divided by time (29 years in this case), a rate in meters per year is produced. The wandering and meandering reaches had few channels, so the conventional technique mentioned above was used. Only in this case, every individual meander of each channel was measured for the distances eroded and deposited. These two values were then averaged together and the products of each averaged to establish a quantity for the reach. Once again, this was divided by time to establish a rate. It is hereby acknowledged that gravel rivers do not migrate at a constant rate each year rather, this quantity is useful for understanding the overall behavior of each channel pattern.

There are distinct changes in the migration rates between channel patterns. Table 5.2.8.1 shows the results of the above measurements. The clear difference in the rate of lateral movement between the transitional and wandering channel patterns is quite surprising. With the increased channelization found in the wandering reach. the rate of lateral movement drops to approximately 50% of that in the transitional reach.

Braided	Transitional	Wandering	Meandering
11.6 m/y	11.7 m/y	5.3 m/y	4.6 m/y

Table 5.2.8.1. Average migration rates calculated for each channel pattern type.

The braid and transitional reaches are nearly identical and the wandering and meandering reaches are similar. Initially this was thought to be an artifact of the measurement procedure, but when reviewed this was found not to be true. The higher rates can be determined visually as well. Figures 5.2.8.1 through 5.2.8.5 show that overall, migration is both greater in quantity and occurs more frequently in the upper reaches. Downstream, the only rapid migration documented is related to a major slough neck cut-off (Figure 5.2.8.3). This cut-off allowed the main channel to occupy a shorter course downstream, abandoning the largest meander in the wandering reach and consequently shortening the course of the river by over 10km. At this location major erosion seems to have ceased and deposition is the dominant process. Another observation worthy of note is that outer-bank cutting in the braid and transitional reaches is relatively low, especially if one considers the overall migration rates that occur in-between. Outer bank cutting is more dominant in the wandering and meandering reaches although it occurs at an overall slower rate. The resultant effect appears to be a potential for a wider active flood plain in the lower reaches of the study area than in the upper reaches. Thus, over the long term, braid reach migration occurs at a faster rate. but generally confines itself to within the same active channel margins. Actual shifts in the rivers position would thus take a lot longer than downstream.

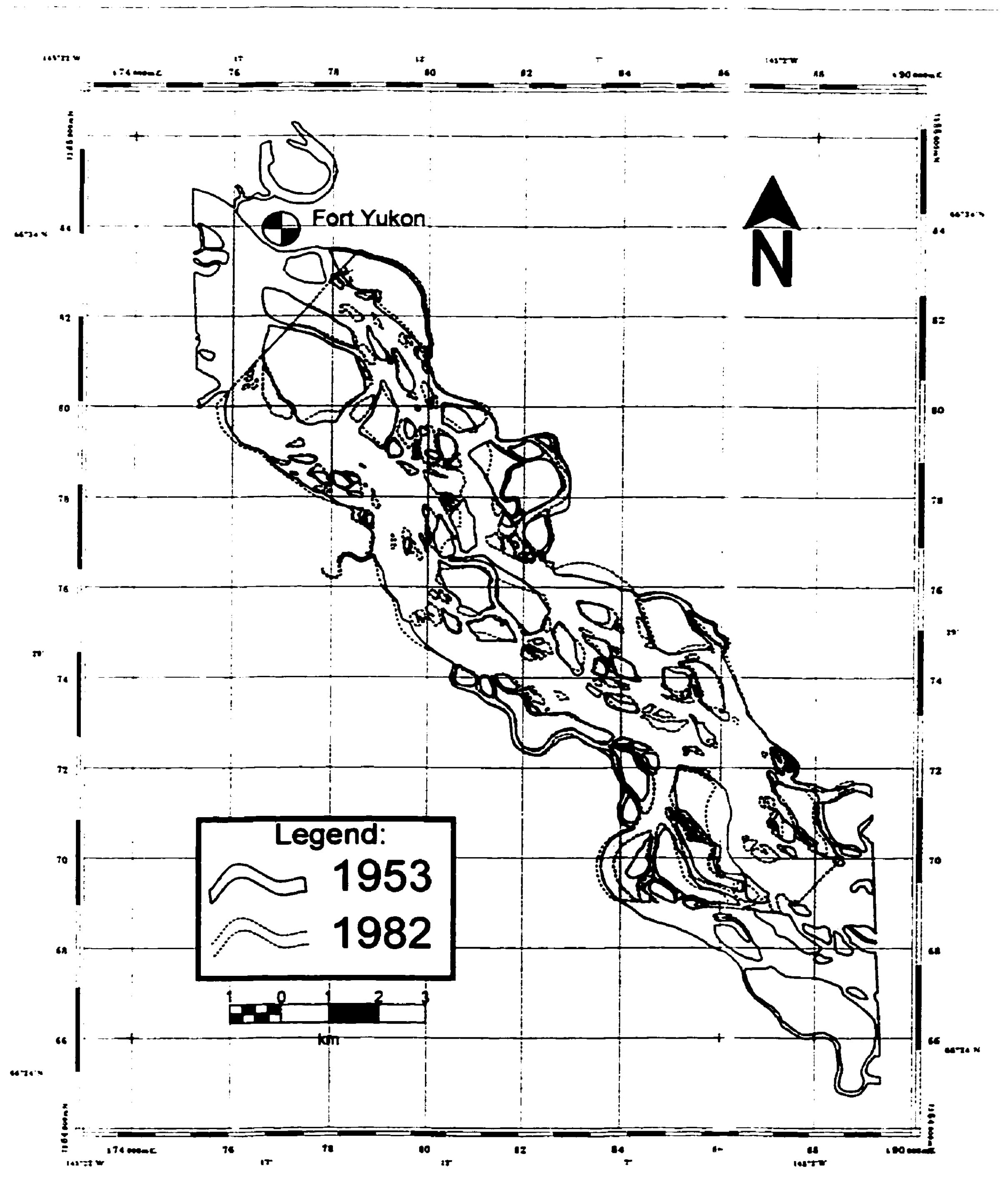


Figure 5.2.8.1. Braid reach time-slice map.

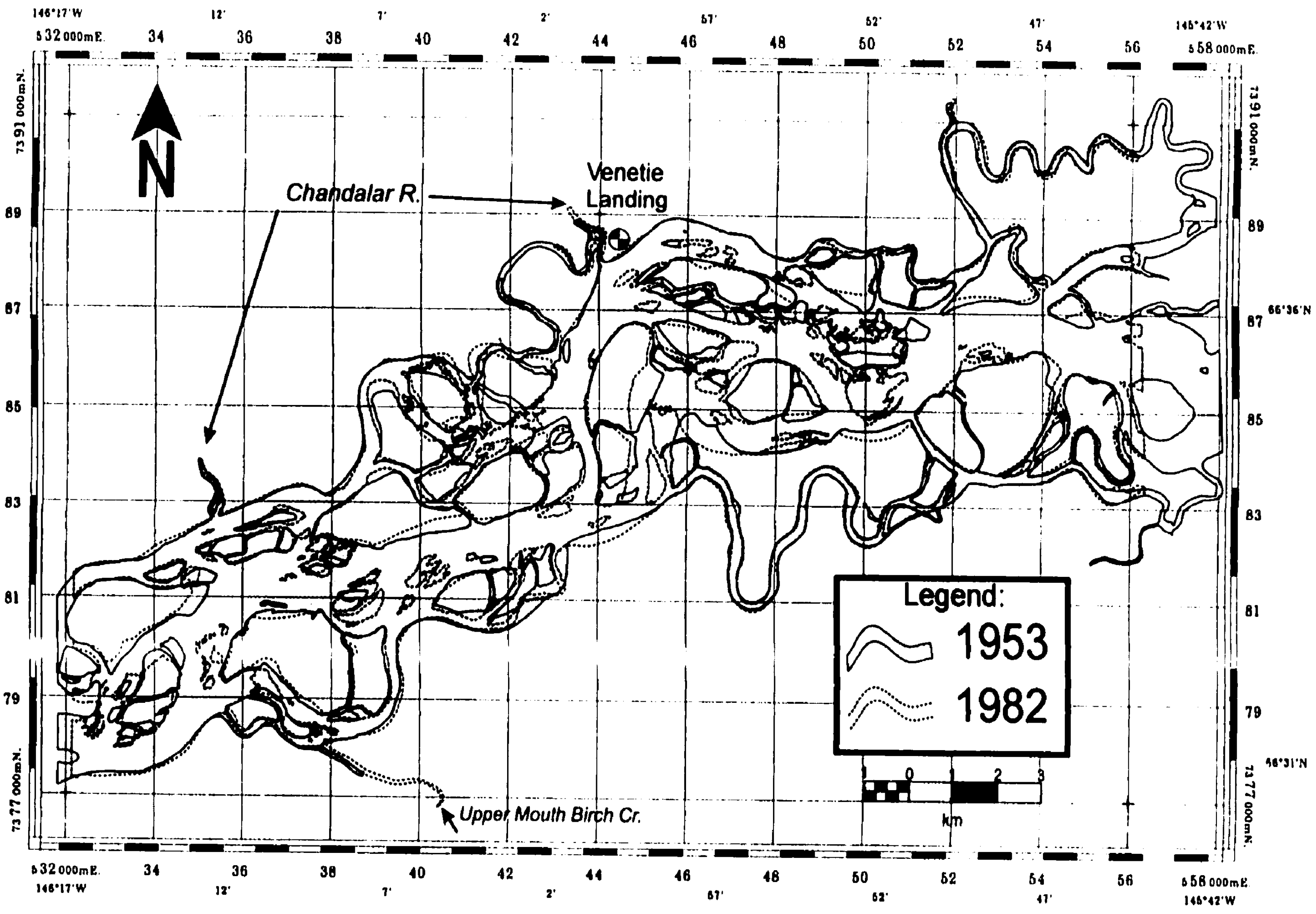


Figure 5.2.8.2. Transitional reach time-slice map.

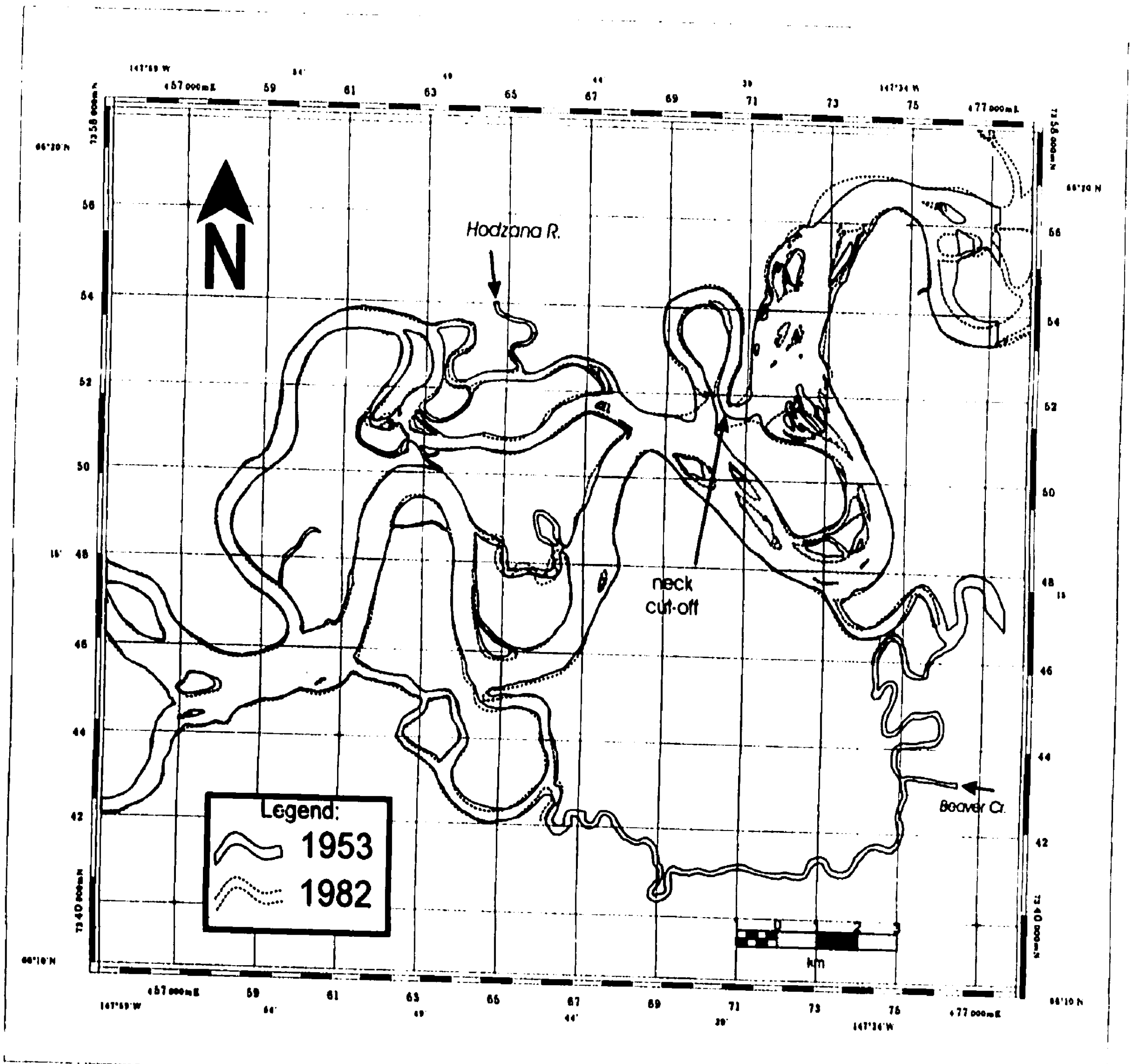


Figure 5.2.8.3. Wandering reach time-slice map.

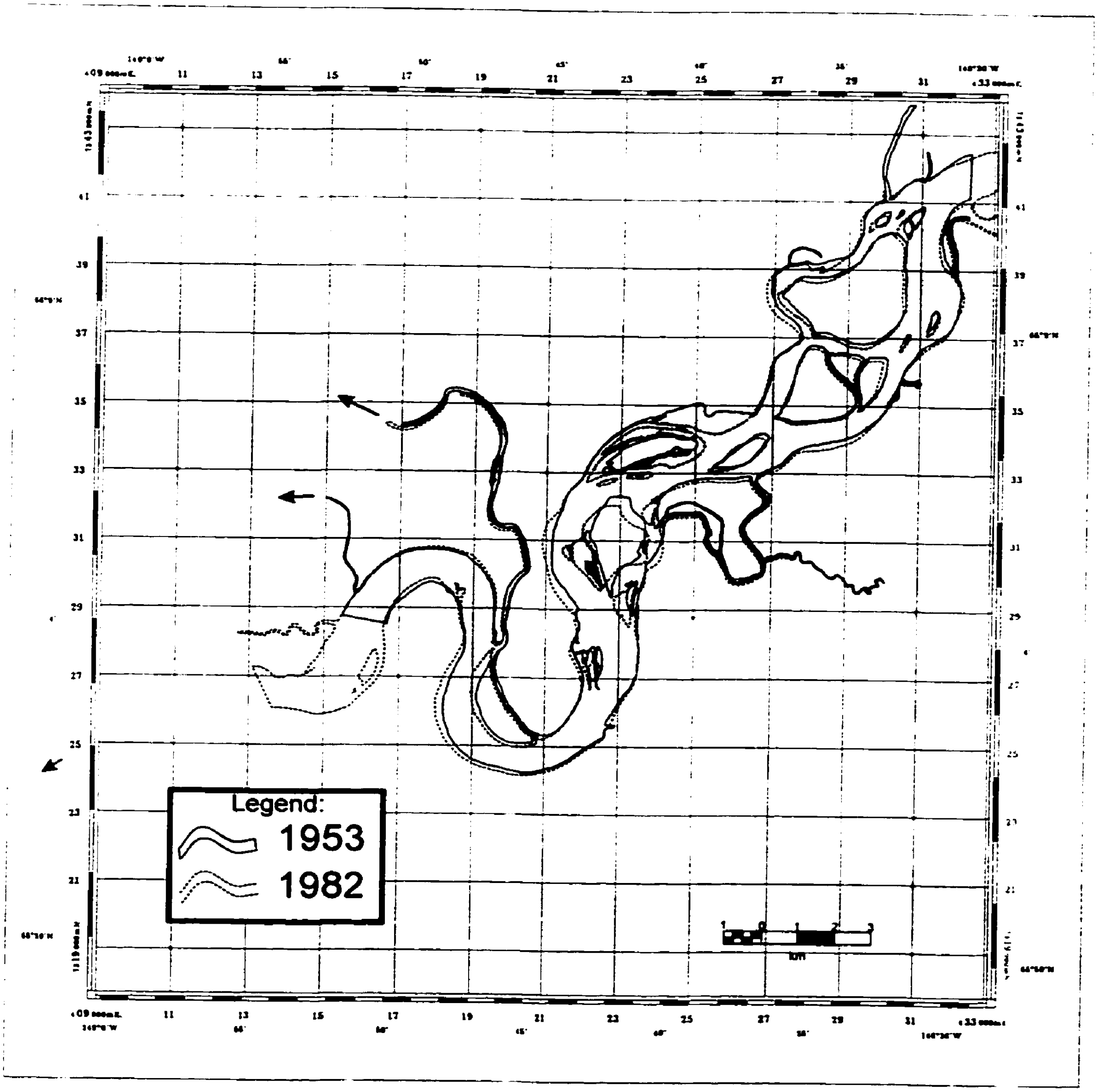


Figure 5.2.8.4.. Wandering to meandering transition time slice map.

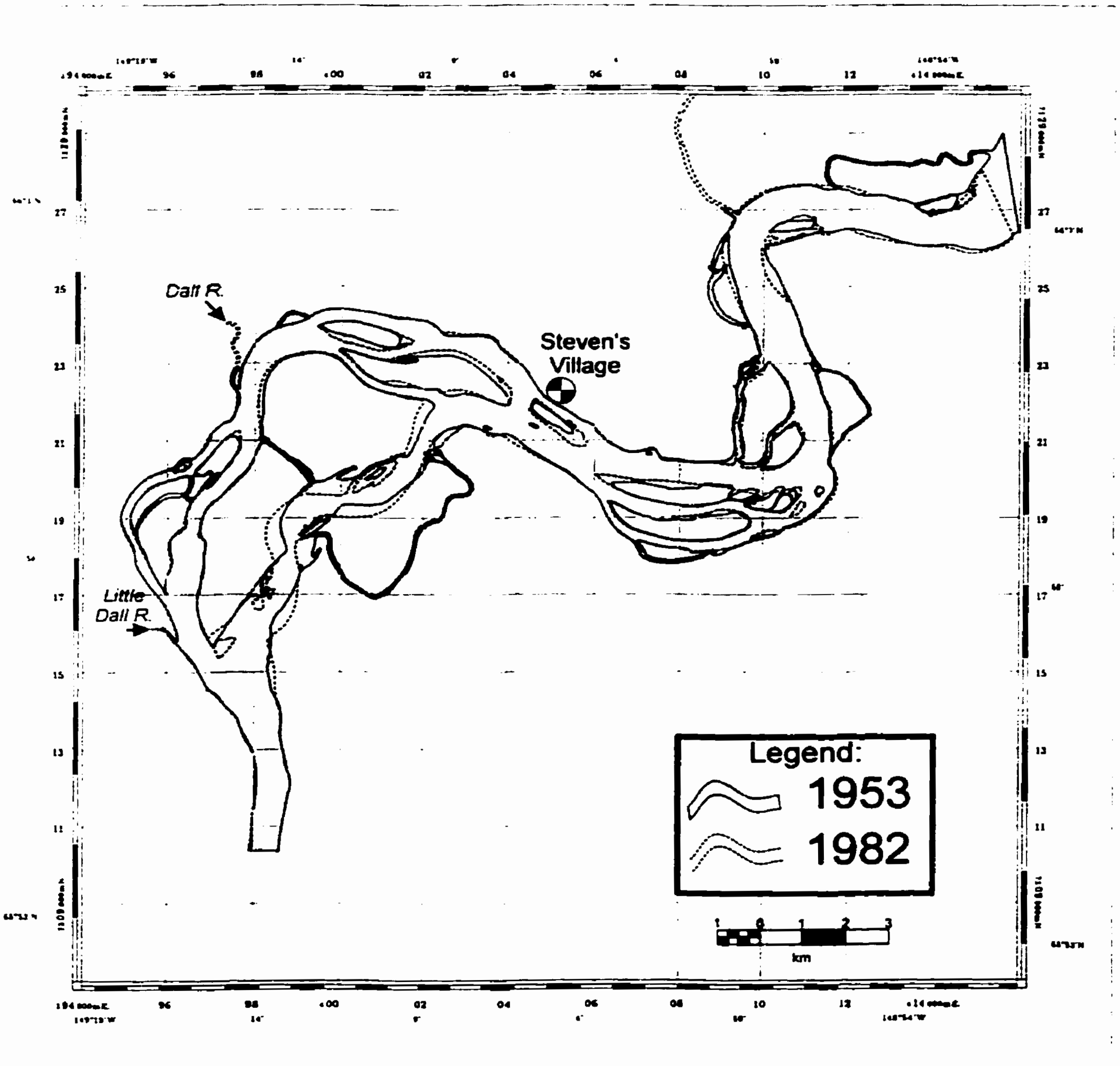


Figure 5.2.8.5. Remainder of the meandering reach before it enters the canyon, Note how anabranching resumes just above Steven's Village.

5.2.9 Summary

The analysis of all data collected has revealed several quantifiable trends that describe the morphologic differences between the study reaches of the Yukon River. These trends are not only useful in creating an understanding what exactly is changing but will also serve to provide a basis for explaining the causes of such changes. A brief summary of the data presented in section 5.2 will allow for a synthesis of the important results.

The majority of the relevant data is condensed into table 5.2.9.1. In that it would be redundant to go back into detail at this point, this table will serve as the body of the summary and only the direction of trends will be described.

All trends will be summarized in a downstream direction. Individual channel widths increase regularly downstream. This increase is primarily due to increased channelization with fewer anabranches carrying the same amount of discharge. Thus, discharge becomes more concentrated and less dispersed downstream, so that channels in the meandering reach carry 2.6 times more than those in the transitional reach. Synchronous with channel pattern changes, stepped decreases in both water-surface and valley slope occur. The slope of the meandering reach is three times lower than in the braid reach, which was already extremely low. Individually, channels become deeper from reach-to-reach, with the majority of change occurring between the braid and wandering reaches. The caliber of the Yukon's gravel bedload also decreases downstream, with the D_{50} and D_{95} sizes decreasing by 50% over the entire length of the study area. The ratio of overbank deposits to gravel in the banks is roughly the same along the anabranching sections of the river at 3:1, but bank gravel almost disappears in the meandering reach.

Channel Pattern Type	Average individual channel Width (m)	Average individual channel depth (m)	# of channels dividing flow	Avg. Field-measured Slope (cm/km)	Map Slope (valley slope) (cm/km)	Avg. D50 (mm)	Avg. D95 (mm)
Braid	289	1.5	5	30.5	40	10.8	37
Transitional	443	2.6	3.8	20.1	30	9.1	34.5
Wandering	541	3.2	2.4	13.7	16	6.8	27.6
Meandering	675	3.5	1.9	10.5	13	5	16
Trend	increase	increase	decrease	decrease	decrease	decrs.	decrs.

Channel Pattern Type	Avg. Bank Height (m)	Avg. Height of Gravel/ over-bank contact	Avg. % of bank made up of gravel	Avg. flow carried by each individual channel (m^3/s)	Avg. Unit Area Stream Power (W/m^2)	Migration Rates (m/y)
Braid	2.1	0.7	33.4	628.9	5.3	11.6
Transitional	2.9	1.0	32.8	1426.5	7.5	11.7
Wandering	3.5	1.1	31.0	2115.2	5.8	5.3
Meandering	3.3	0.2	5.6	3739.3	6.0	4.6
Trend	increase	_	decrease	increase	_	decrease

Table 5.2.9.1. Summary of the results described in section 5.2 indicating either an increasing or decreasing trend in a parameter.

The rate of lateral migration also decreases downstream, though the same in the braid and transitional reaches, it is only half as fast in the wandering and meandering reaches. In conclusion, it has been demonstrated that quantifiable variables accompany changes in channel morphology, these variables will be examined in the discussion in a first attempt at explaining pattern transitions and the causes of anabranching on the Yukon Flats.

5.3 Quaternary Sedimentary Evidence

5.3.1 Introduction

Among the other data collected in the field, several sedimentary sections were litho-stratigraphically logged. Two of these sections will be reported on due to their significance to the long-term history of the Yukon River and to the regional landscape evolution. The first is the 'Purgatory' section, a cut-bank exposure 60km downstream of Beaver (km 310). The second has been termed the 'Dalton' section because of its location 1.6km downstream of the Dalton Highway Bridge that crosses the Yukon River in the canyon downstream of the Yukon Flats. Both sections have yielded interesting radiocarbon dates and both contain a series of sedimentary environments. The following descriptions of these sections will also contain facies interpretations. The significance of the depositional environments will be examined in the discussion.

5.3.2 The Purgatory Section

The Purgatory section is a well-exposed river cut-bank on the northernmost left bank of the Yukon River. The surrounding geomorphology interpreted from aerial photography, consists of ridge-and-swale scrolled floodplain to the southwest (just downstream) and higher stabilized dunes and blow-out ridges to the northeast (Figure 5.3.2.1). The contact between the scrolled topography and the dune-covered surface was mapped by Williams (1962) as a Quaternary alluvial terrace escarpment, although there is little actual elevation difference between the geologic units unless a dune structure rests on the border. When logged, the exposure had been recently eroded by the spring high water.

The Purgatory section has four main stratigraphic units. The first and lowermost unit (unit A in Figure 5.3.2.2) is comprised almost entirely of fluvial gravel with one lens of fine sand is also contained within it (unit B). The fabric of the gravel is primarily massive pebble clast-supported with a fine sandy matrix although some occasional horizontal structure is detectable (Gcm and Gh under Miall's (1978) facies coding). This type of gravel is typical of fluvial bedload deposits such as longitudinal bars. Identical deposits can be seen forming by active mid-channel bars in both the wandering and braid reach of the present Yukon River system. Thus, they are not necessarily characteristic of a braided river, though it can be concluded that they are definitely laid by fluvial deposition.

The second main straigraphic unit lies above the gravels from 3.2 to 4m up-section, or above the $Q_{0.6}$ water-level (unit C Figure 5.3.2.2). This unit is composed of horizontally laminated silty fine sand with scattered lenses of massive fine sand. The entire unit is lightly iron-stained and contains large wood fragments, some of which were at least 1m in length with branch forks intact. The wood was extremely well preserved and showed signs of only slight reworking, presumably by fluvial transport. A large sample was extracted and radiocarbon dated. The age of the deposition of unit C 11,550 $\pm$ 70 radiocarbon years BP is (Lab #: **WAT- 4100**). The law of superposition, which states that if one deposit overlies another, the lower must be older than upper indicates the gravels are older. Given that the horizontal laminae of unit C are most likely representative of sub-critical or critical plane-bed flow conditions and that there is a thin silt drape covering the gravels, it is probable that unit C represents over-bank or abandoned channel deposits of the Yukon River. Again, identical contacts between gravel

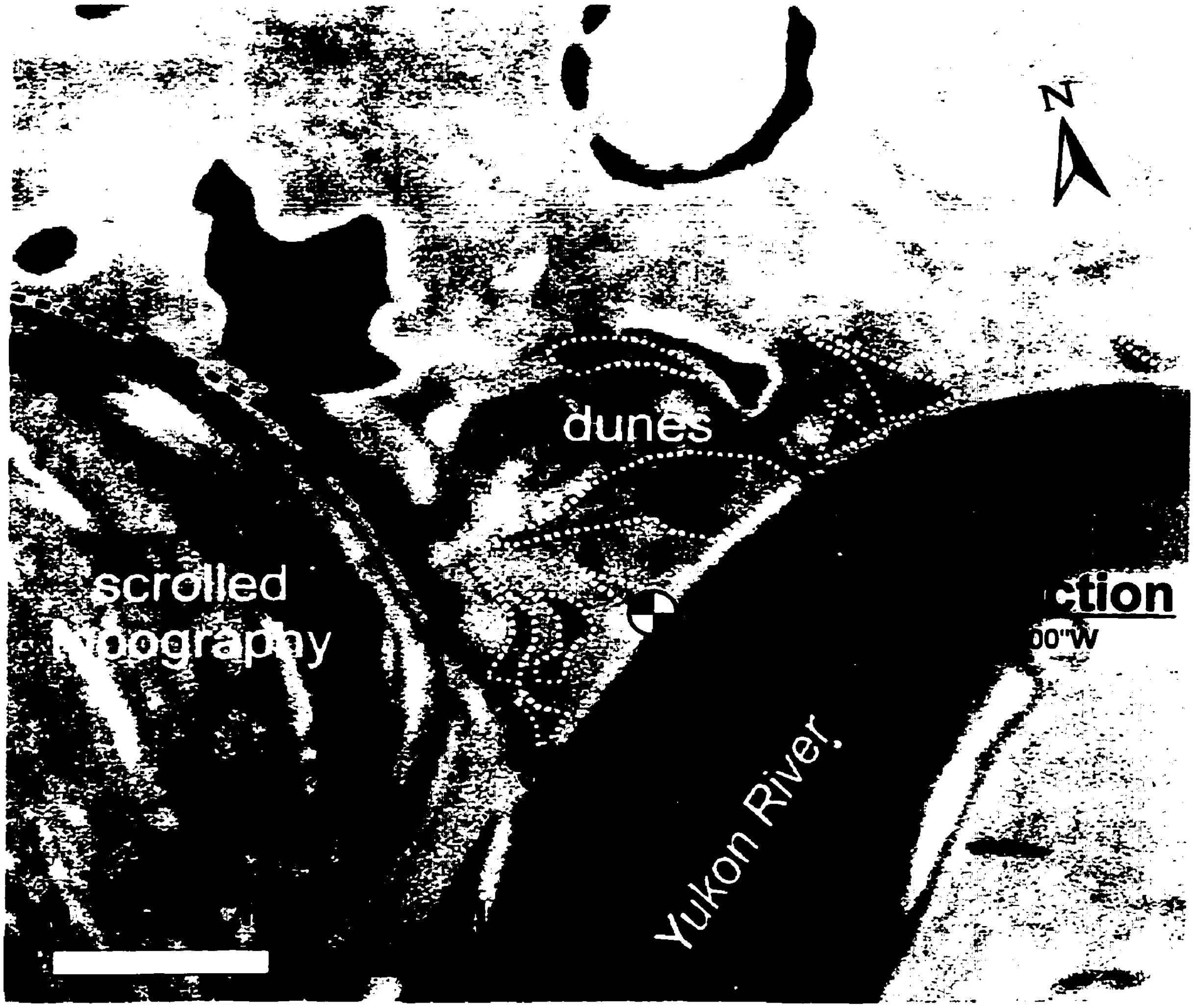


Figure 5.3.2.1. The location and local terrain of the Purgatory Section.

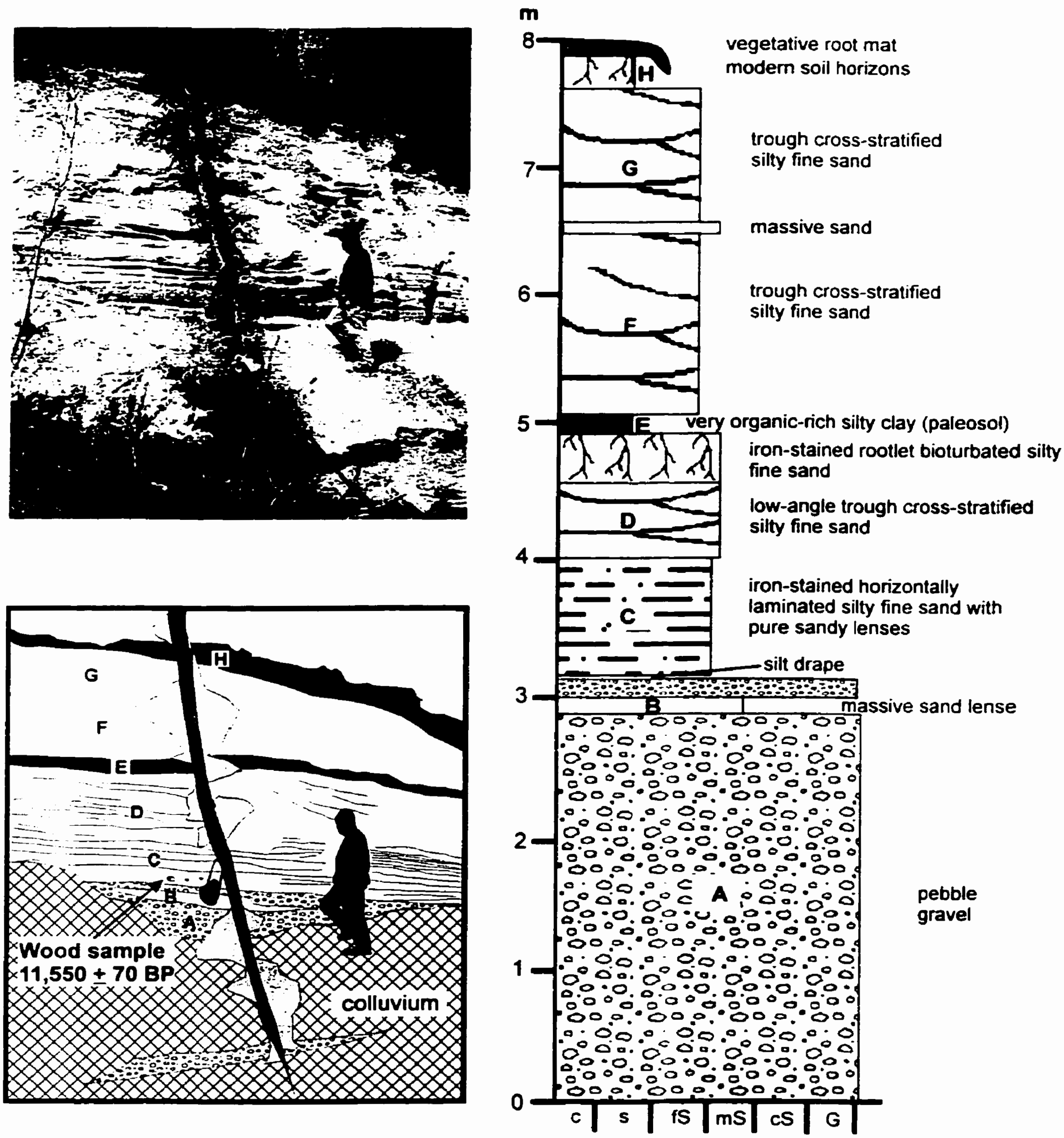


Figure 5.3.2.2. The Purgatory section shown in both photography and lithostratigraphic log. Letter indicators on the log match those on the photo key and those found in the text.

and over-bank-fines can be observed along every section of the active Yukon River in the Yukon Flats. The deposition of fines typically occurs as a point-bar or mid-channel bar build up high enough so that vegetative stabilization occurs. Once the initial wave of Horse-tail and Willows take root, bars begin to rapidly vertically accrete fine sands and silts, flows slowed and stabilized by the stalks and foliage of the *flora*. It is reasonable to suggest that 11,550 BP similar tenacious vegetation types lived on the Yukon Flats. In comparison, the present climate is likely almost as harsh and the location of the Purgatory section would have placed it hundreds of kilometers from the nearest glacier (Figure 2.3.1). However, the most convincing evidence to suggest vegetation was alive and well on the Yukon Flats is the wood found in the section.

Above the over-bank deposits of unit C a dramatic change in the depositional environment occurs. Although the grain-size of unit D is very similar to that of unit C, trough cross-stratification reveals a higher energy mode of deposition. This sedimentary structure is indicative of large-scale dune bedforms. The fact that the troughs in unit D occur at low angles, and the thickness of the unit suggest that transport and deposition were the result of eolian processes. Although active eolian dunes are not found on the Yukon Flats today, Williams (1962) mapped extensive eolian deposits outside the portion of the flood plain characterized by scroll-bar patterns, including eolian dunes in the vincinity of the Purgatory section. The increased sediment delivery, sparser vegetation and katabatic winds present that would have been present during the Late Pleistocene provide an ample mechanism for a stronger presence of eolian activity (Pewe, 1975). The upper half of unit D shows more iron staining and rootlet bioturbation. This indicates that this portion was subjected to a change in setting, likely one where vegetation was once again allowed to take root and stabilize the active wind-blown surface.

Unit E is particularly interesting in the context of the rest of the Purgatory section. It is a laterally continuous, thin (15cm), dark, organically rich, blocky, massive clayey silt. The contact with unit D is gradational, but a sharp contact occurs with the overlying unit F. Given the fact that unit D showed rootlet bioturbation, this unit could represent an incipient soil, or proto-paleosol. Thus the implication is that an extended period of stability is represented here, likely due to climatic forcing. This adds further credibility to the accuracy of the radiocarbon date, inferring that the deposition of the wood was not far in time or space from its point of entrainment.

Unit F and G are very identical to unit D and thus it is concluded that they are of the same origin. However, the fact that these units are separated by an incipient soil, it can be assumed a significant period of time separates them. Separating unit F and G is a thin, laterally continuous, massive sand lens. The possible origin for this deposit is unknown, athough it is likely strongly related to the eolian environments found directly above and below it. In speculation, it could be a result of rain-wash into a trough between dune forms or be the result of localized slope failure.

Finally, the uppermost unit, H, is composed of the modern soil horizons of the present surface. It is approximately 30-35cm thick, overlain by a 15-20cm thick vegetative root mat. The thickness and development of this soil suggests that this surface is quite old and represents long term stability. This observation again lends further credibility to the accuracy of the radiocarbon date and rules out the possibility that that wood has been eroded from storage in another section, re-transported, and deposited in the Purgatory section.

To summarize the above interpretations, the Purgatory section shows four main periods of deposition by three different processes. At the earliest time recorded in these sediments an active channel of the ancient Yukon River deposits the gravel as a mid-channel or lateral bar. This bar stabilizes and over-bank fines accumulate as vegetation establishes. During this time, 11,550 radiocarbon years BP, a piece of wood delivered from a short distance upstream comes to rest on the bar during the waning stages of a high flow event and is buried. Sands and silts, of fluvial origin are re-transported and deposited on the bar by eolian processes. This continues until vegetation re-establishes itself on the surface of dune topography and an incipient soil has the time and stability to develop. Renewed eolian activity overruns the vegetation, depositing nearly 2m of fine sands and silts before once again the surface is stabilized. This time stability persists forming the soil that rests on the present surface.

5.3.3 The Dalton Section

The Dalton section is a 50m (164ft) high river-cut section found on the inside of a sharp bend in the confined reach of the Yukon River 42km downstream of the Yukon Flats (1.6km below the Dalton Hwy. Bridge across from the confluence of the Ray and Yukon rivers). It is reasonably well exposed, displaying a continuous record for 42m vertically and approximately 60m laterally. It is a complex sedimentary assemblage and only a short amount of time could be committed to working it in the field. However, the information gathered from this exposure is valuable to the goals of this research.

Seven major sedimentary units divided by several thinner units make up multiple depositional environments in this section. The lowermost unit, A (Figure 5.3.3.1), ranges from 8.2m to 14m above the Yukon River. Although obstructed by colluvium at the location of the major exposure, another section 50m NE shows fluvial gravel at its base from 15 to 13m. On the other side, 20m to the SW, another small exposure shows gravel to a height of 7.8m. The approximate level of the gravel in the Dalton section has been interpolated in Figure 5.3.3.1. It is concluded that it was just beneath the colluvium, which was too soft to excavate without collapse. The sediments found in unit A were however, not gravel but fine sands and silts. These were laid in horizontally bedded packages at semi-regular intervals of 20-40cm. Lenses of massive fine sand were also present. Separating these packages were thin, (2-5 cm) dark organic-rich silty sands, some of the thickest (approx. 15cm) looked like paleosols. Though also heavily cryoturbated, these beds were reminiscent of the over-bank deposits noted in both the Purgatory section and along the modern riverbanks and thus, are interpreted as such.

Unit B shows a facies change to a more massive structure. Iron staining is heavier and the organic content is not detectable in this unit. The fine grain size, combined with a lack of structure suggests that the material is loessal in origin. Loess has been noted by Williams (1962) as occurring of the marginal upland to thicknesses of over 30m and his description bears resemblance to what is found in this unit.

Covering unit B is a thinner bed of complex origin. Unit C can be seen in Figure 5.3.3.1 both thickening and increasing in elevation to the right of the section. At its thickest, 2m of silt composed of 50-60% woody detritus can be found (Figure 5.3.3.2). In the lower, thinner sections of this bed the silts are lower in wood though still very dark

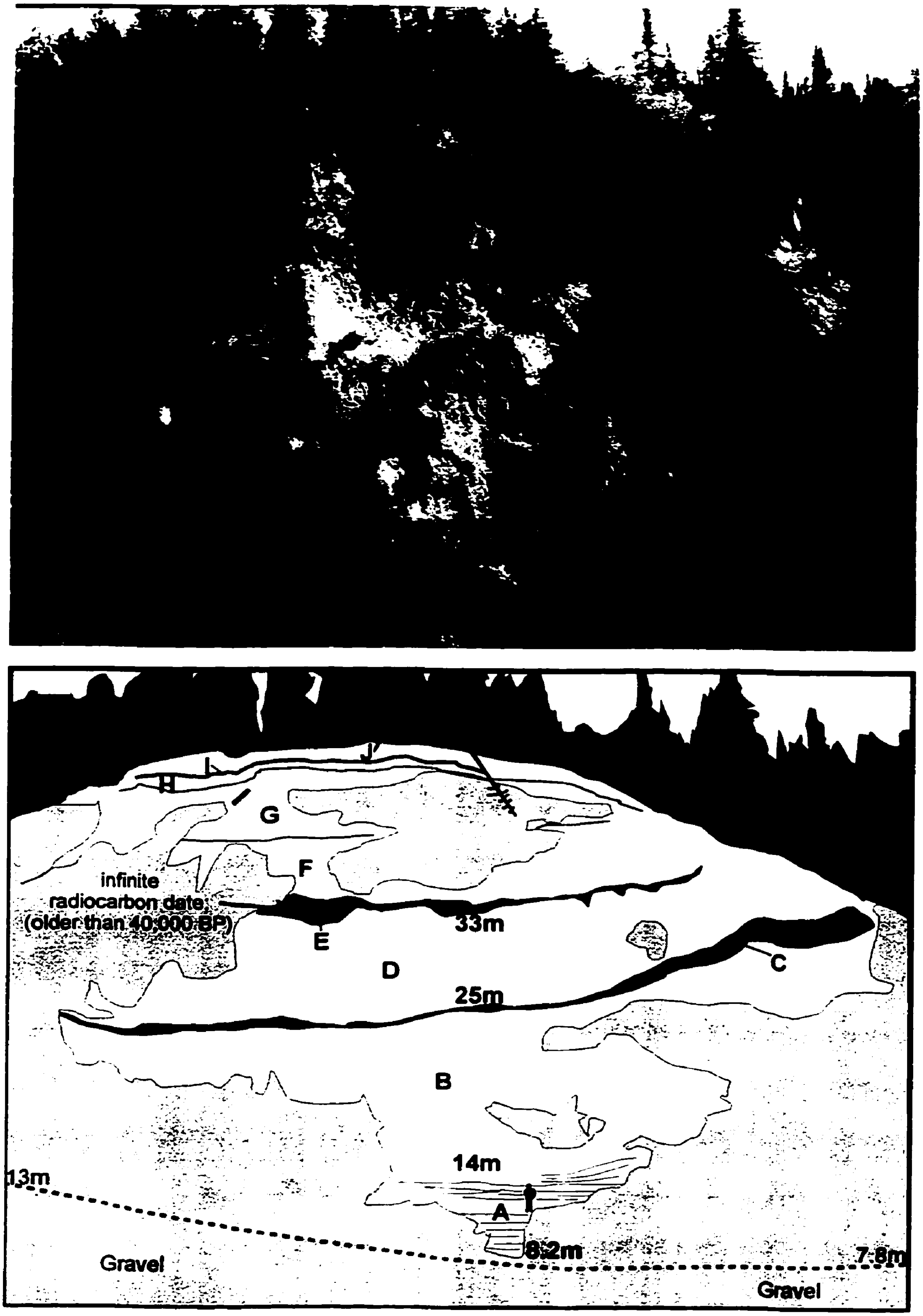


Figure 5.3.3.1. Photo and key of the Dalton Bridge Section. Note the figure in the lower levels of the section for scale.

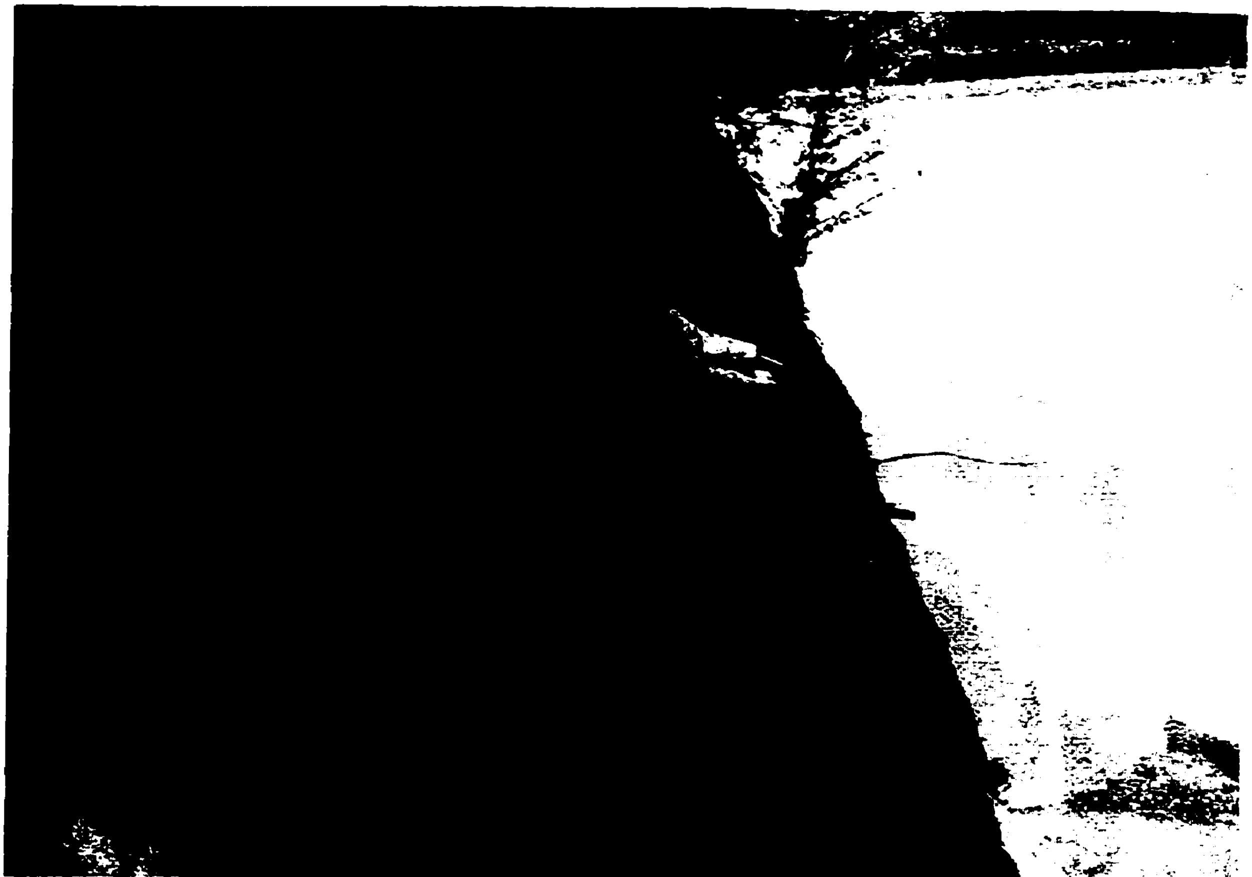


Figure 5.3.3.2. Close-up of unit E, 33m up in the Dalton Section. Note the high concentration of wood detritus. An organic-loess matrix has preserved this deposit which is substantially older than 40,000 years BP. The section lies on the inside of a sharp bedrock-controlled bend in the Yukon River (in the background).

and rich in organics.

The 20-30cm thickness strongly suggests that this unit represents a stable, non-erosional surface where a soil was allowed to develop over time. The origin of the large amount of wood is a mystery, though Froese (pers. comm., 1999) has since found pieces of it that appear to be beaver-chewed. Some of the pieces of wood also appear to be slightly burned and one can find small pieces of charcoal inter-bedded with the organic-rich silts. . It is thus possible that the detritus and massive silty matrix was deposited on top of a mat of organic material following the slope destabilization that resulted from a forest fire. Finally, what appears to be thin, discontinuous lenses of tephra are also found in this unit, although at this time the fission-track dating is incomplete. However, Froese (pers. comm., 1998) has indicated that this tephra does not match those on record for Alaska.

Unit D is identical in composition to unit B (In the photo of Figure 5.3.3.1 one can see both units show the same bird-holed appearance) and thus, is interpreted to be of the same origin.

Unit E, approximately 33m up-section, is another organic-rich bed with large amounts of woody material found within it. More homogenous in character but thinner than Unit C, this unit also has a lower concentration of wood material, about 10 – 40%. It tends to be more compact very fine sand and silt with wavy lamination. Iron-staining is prevalent throughout the gray to dark-brown massive structure. This unit is likely representative of a stable surface where vegetation had time to establish. The thichness of this unit and the accompanying organic material suggest that it is a paleosol. A piece of wood found within it was submitted for radiocarbon dating. The analysis produced only a background count of 14C, determining that the wood was of 'infinite' age beyond the 40 000-year limit of the dating technique. This means that unit E and everything below it is significantly older than 40 000 years, and suggests the possibility that at least a portion of the overlying 20m in the section may be as well.

Unit F is similar to the eolian units B and D, but contains woody material and leaf litter. Oxidization is present and the fine sand and silt is laid in a massive structure. Unfortunately, due to limited exposure and a lack of the appropriate mountaineering equipment to access the portion of the face containing this unit, little else is known about it. The depositional environment was likely a gradual accumulation of loess on a surface that was at least sparsely vegetated if not forested.

Unit G is like F in grain-size and structure but contains much lower concentrations of organics which are limited to dispersed leaf litter/root-mat type material. The same depositional environment as unit F is interpreted, though the subtle facies change could be possibly due to vegetation changes responding to climate alterations.

Above unit G is a more tan-coloured massive bed that shows no iron-staining. Separating unit G from H is a thin (2cm) bed of organic litter, though no evidence of a paleosol exists. The complete lack of oxidization in this case infers that unit H is younger than the one below it. This unit is also much thinner than loessal units G,F,D and B, possibly suggesting a shift to either less intensely cold and dry conditions to a more moderate climatic event. It is also possible that just a shorter period of time is represented.

Between the accumulations of units H and J is a very-well preserved vegetative root mat, unit I. This unit, virtually identical to the modern root-mat at the surface is undeniable proof of stable, vegetated conditions. Initially thought to be quite young, regrettably no organic materials were sampled from this unit for radiometric analysis. However, in retrospect, given the infinite date from unit E 12m below, it is possible that this bed is still quite old, even Late-Pleistocene. This idea does not seem unreasonable when one considers that successive Pleistocene glaciations were becoming less intense into this period (Pewe 1975) and that less loess deposition would occur overall as observed in unit H. Unit J shows the same trend, only 1.3m thick above the buried root mat. This interpretation is also supported by the work done by Edwards and McDowell (1991) and Ager *et al.* (1994) near Circle where the Late-Pleistocene is represented by only a thin bed of loess in comparison to earlier periods.

Unit J grades into unit K, the active vegetative root mat. It is composed mostly of massive very fine sand. Units H and J both have small molluscs (presumably air-breathing) inter-bedded within them. A laterally continuous white silt stringer was found in this bed and initially confused as a tephra. Overall the lack of tephras in the Dalton section was unexpected given that several are found in other Alaskan loess sections like the Gold Hill loess near Fairbanks (Pewe 1975).

The detailed picture of the sequence of events recorded in the Dalton Section is beyond the scope of this thesis but definitely should be kept in consideration for future studies. It can be concluded from the brief work done on it that there is a succession from fluvial to eolian processes. The majority of the depositional periods found in the section are older-than 40 000 years and what appears to be multiple glacial/interglacial cycles are found in the extensive loess deposits and numerous paleosols. Thus, the height of the fluvial sediments represent a minimum water level for the flow that deposited them sometime in what is likely the Mid-Pleistocene although possibly even earlier.

5.3.4 Floodplain RADAR-facies

Four ground-penetrating RADAR (GPR) data sets were acquired on the Yukon Flats. The data was collected by Duane Froese in June of 1998, as part of another study. The GPR unit was deployed on longitudinal bar tops at two locations, km 14 and km 20, both near Circle, Alaska (km 12). The arrays used in data collection included the 12.5, 25 and 50 MHz antennae. The objective of this exercise was the attempt to find the contact between fluvial gravel and Late-Tertiary lake sediments found in boreholes taken at Fort Yukon by Williams (1962) and Ager (pers. comm.,1998) in 1994. The hypothesis was that the 25m contact that earlier workers revealed would also be found 100km upstream but would be a bit shallower. Another possibility included finding no lake sediments, and imaging the bedrock floor of the basin by attaining the characteristic 'boomer' reflector with refraction patterns of gravel-bedrock contacts. In either situation, the information is not only useful for understanding the Tertiary tectonism of that part of the basin, but also the valley-fill depth helps to define the fluvial history as well.

The best two of the four data sets are shown in Figure 5.3.4.1. The contact between the Yukon River's Quaternary gravels and the underlying bedrock is clear. Refraction patterns at 14-15m in the 'km 14' data set and just over 17m in the 'km 40' data set is the very-likely result of the energy wave encountering fine sediment. This is supported by the fact that all reflectors are strong until the zone of refraction at around

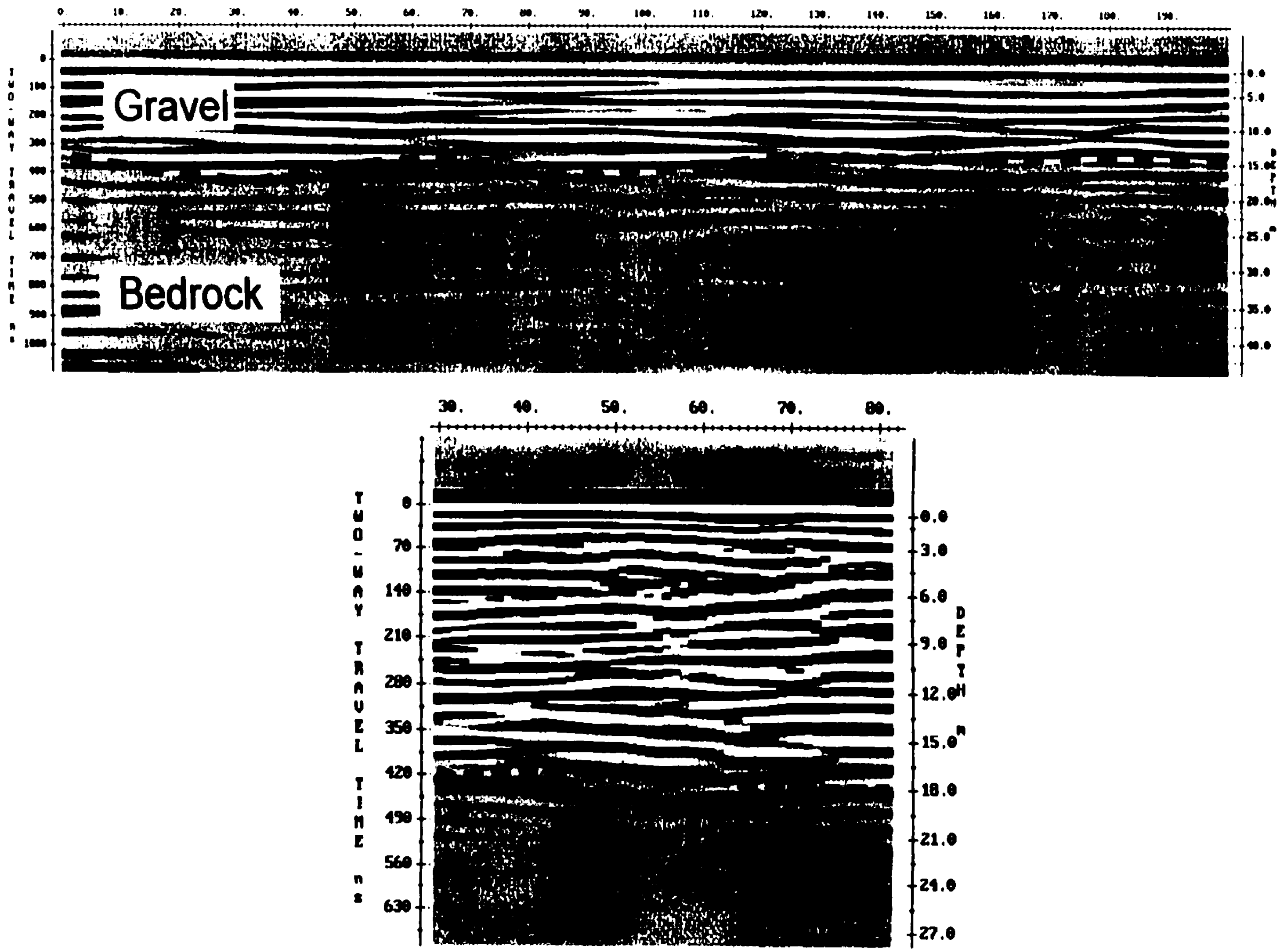


Figure 5.3.4.1. Ground Penetrating RADAR (GPR) facies of the Yukon River floodplain near Circle, Alaska. Note the refraction of the signal between 15-17m depth which delineates the Quaternary gravels from the underlying bedrock.

15m. If this phenomenon is the product of signal fade then a gradual weakening should be evident in the recorded reflections. The fact that both data sets demonstrate repeatable results at different locations in further proof of the usefulness of this technique. Finally, the contact deepens downstream at a rate that matches the surface slope (surface drops at 30-40cm/km, roughly 1.8-2.0m drop observed in 6km equaling a slope of 30-33cm/km) supporting the idea beyond a reasonable doubt. The implications of this finding, particularly in conjunction with other results, will be examined in the next chapter.

Chapter 6: Discussion

6.1 Introduction

Understanding the nature and causes of channel pattern changes is a fundamental theme in the study of fluvial geomorphology. In this chapter it is demonstrated why the Yukon Flats provides a good natural laboratory for studying this phenomenon. The long-term history of the Yukon is interpreted from the synthesis of known data, revealing a remarkable history of stability. Through the comparison of the characteristics of this river with other researched systems, it is noted that the behavior of the Yukon River may not support our previous knowledge of multi-channeled systems but rather, shows how little can actually be predicted about this river's behavior. This chapter will challenge the organization of the continuum of river channel patterns, shedding light on unexpected simultaneous occurrences of phenomena. Observations regarding the evolution of the characteristic side 'slough' channels is discussed as a contribution to our understanding of the overall function of the behavior of the Yukon Flats system, as well the driving forces behind anabranching are explored in the context of this study area.

6.2 Long-term History: at least 150 000 years of vertical stability

All rivers have histories. Thus, to understand them we must first understand what conditions existed in the past and what remains of the resultant products that could still be influencing the modern system. This is particularly true for large rivers because of the time-scale relationships governing their response times (Schumm and Lichty, 1965) and the potential for them to respond to even small pervasive disruptions (Schumm and

Winkley, 1994). The most obvious major events in the history of the Yukon River were the repeated Cenozoic climate fluctuations and subsequent glaciations that covered up to fifty-percent of the entire land-mass of Alaska.

As discussed in chapter 2, the Yukon Flats lies in an unglaciated zone of Alaska. But, ironically, it has been suggested that the Yukon River may owe the majority of its existence to one of the early (possibly Late Pliocene, Froese, pers. comm. 1998) glaciations of Northwestern North America. Templeman-Kluit (1980) postulated, based on Yukon River terraces, that a major drainage reversal resulted from the breach of an ancient divide close to the Canada/US border near Dawson, YT. Recently, the mechanism for this reversal has been attributed to Pre-Reid glacier ice damming and the formation of the newly mapped, massive, Glacial Lake Yukon (Duk-Rodkin and Froese, in-press). Similar in nature to the drainage capture by the Porcupine River, this lake overtopped the watershed boundary and flowed down the Yukon Valley into the Yukon Flats. The exact timing of the event if indeed it actually happened, is unclear, but is likely Late Pliocene (Froese, pers. comm., 1998).

The earliest regional glaciations in the vicinity of the study area are recorded as high gravel terraces that lay on the margin of the Yukon Flats near Circle. Yeend (1989) and Ager *et al.* (1994) identify an unconformity between Pliocene age ancestral Yukon River alluvium and 8 m of eastern-derived Plio-Pleistocene boulder-gravel, possibly marking increased coarse sediment supply from the onset of glaciation. The Pliocene age of these gravels is estimated from pollen and plant macrofossil remains found in the lower, older alluvial unit. *Pinus* (pine), *Picea* (spruce), and *Betula* (birch) are found, but so is *Tsuga* (hemlock), *Abies* (true fir), *Larix* (larch), *Corylus* (hazelnut), *Myrica* (bayberry) and *Viburnum* (high bush cranberry), representing a much warmer climatic period (Ager *et al.*, 1994). The authors caution that no date has been acquired for the coarse gravels and acknowledge that the loess cap that overlies them could be as old as Late Pliocene, a possibility demonstrated by the Gold Hill Loess near Fairbanks by Westgate *et al.* (1990). However, Ager *et al.* (1994) do constrain the maximum age of the deposits to be Pliocene by both the identification of *Polemonium*, which does not appear in the global fossil record until that time, and paleomagnetic evidence indicating that the sediments have a reversed polarity (indicating an age of at least 0.78 Ma). Thus this bed of boulder gravel may in fact, be a distal flood-bed from earlier stages of the initial drainage capture because as will be shown, the story after this time period is dominated by a period of incision.

The elevation of these gravels is conspicuously similar to that of the marginal upland (see Figure 6.2.1 and Figure 2.1.4). This prompts speculation that they both may be of the same age, formed by synchronous large gravel fans migrating into the lake that would have existed in the Yukon Flats basin at this time (Williams 1962; Ager pers. comm., 1998). Most of the southern Marginal Upland was likely formed by gravels washing out of the White and Crazy mountains through proto-versions of modern streams such as Beaver Creek. This accounts for what Williams (1962) called "high terrace alluvium" on the Marginal Upland which, it should be added, is mantled by up to 35m of loess. Other loess sections of this order of thickness in Alaska have proven to be very old, sometimes well back into the Pliocene (Westgate *et al.* 1990). However, Williams (1962) also mapped gravel outcropping on the Marginal Upland suggesting that it has a bedrock core and that at least some of the elevation difference between it and the

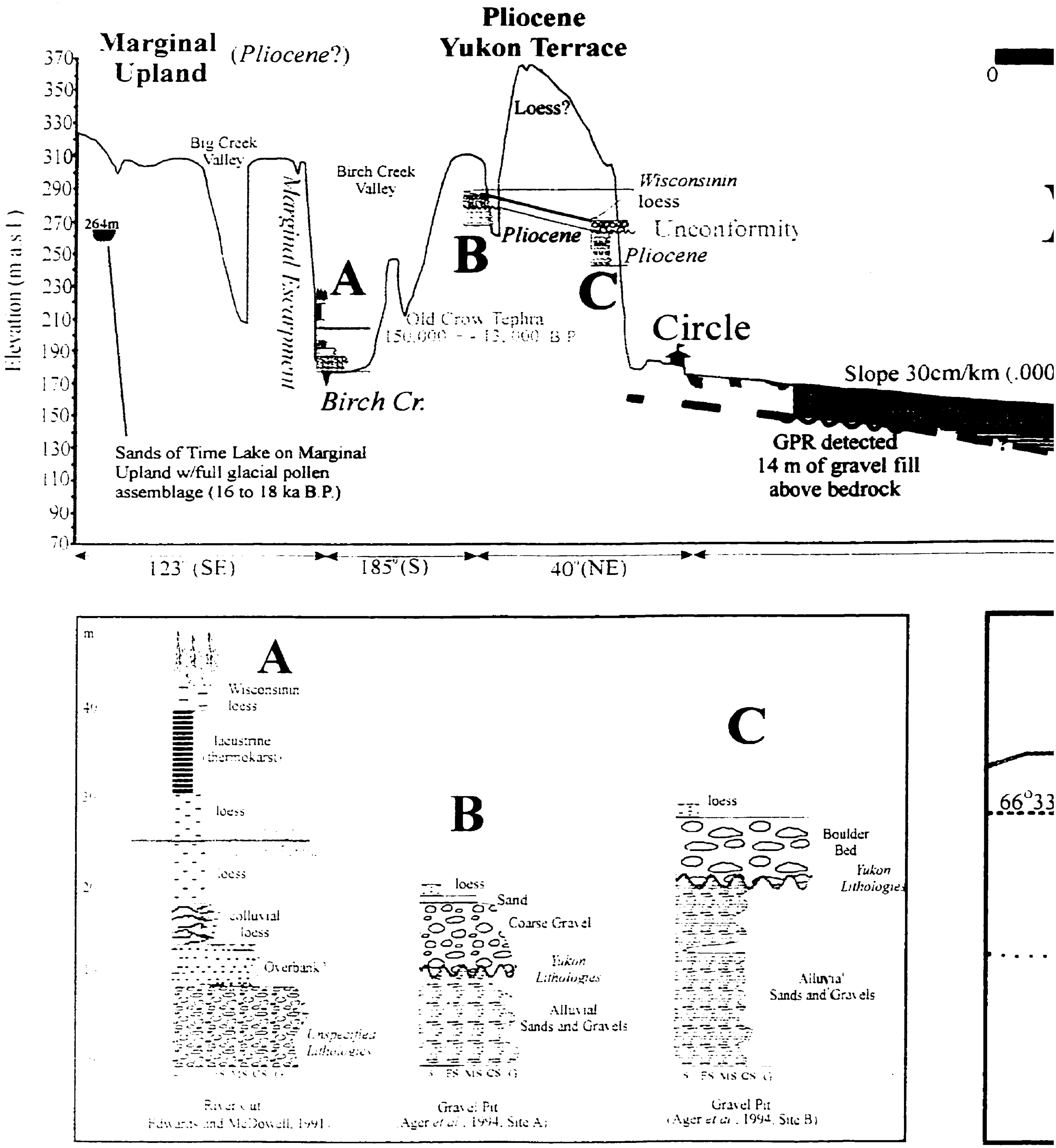
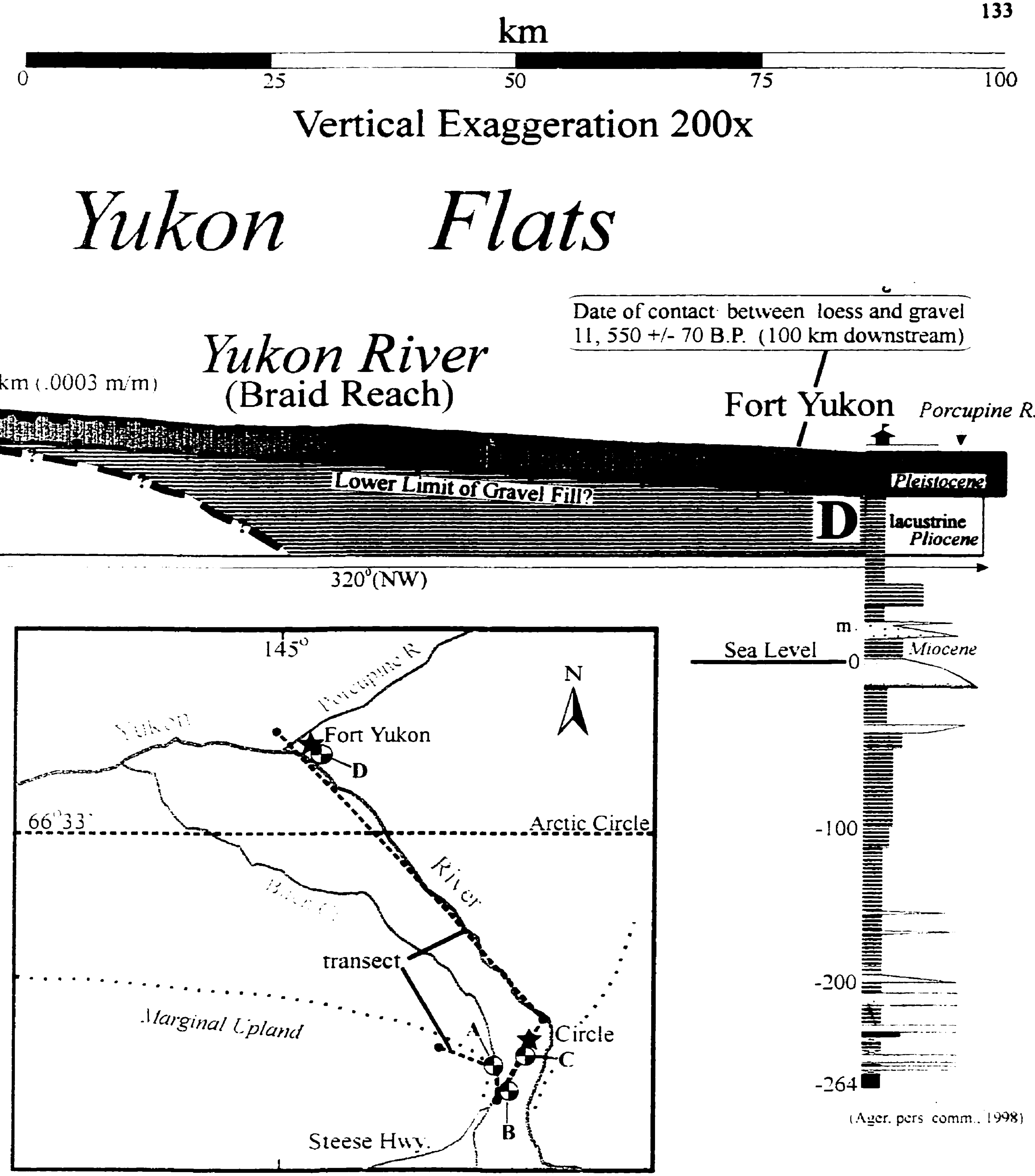


Figure 6.2.1. Topographic correlation of all known sedimentological data for the upper portion of the Yukon F



km
0
25
50
75
100
Vertical Exaggeration 200x
Yukon Flats
Date of contact between loess and gravel
11, 550 +/- 70 B.P. (100 km downstream)
Yukon River
(Braid Reach)
km (.0003 m/m)
Fort Yukon
Porcupine R.
Pleistocene
Lower Limit of Gravel Fill?
D
lacustrine
Pliocene
320°(NW)
m.
Sea Level
0
Miocene
-100
-200
-264
(Ager, pers. comm., 1998)
145°
Porcupine R.
Yukon
N
Fort Yukon
D
66°33'
Arctic Circle
River
transect
Marginal Upland
A
Circle
C
B
Steese Hwy.

Yukon Flats.

surface of the Yukon Flats may be due to tectonics. The sudden west-swinging dog-leg changes in stream course and the asymmetrical valley geometries of most of the rivers such as Beaver Creek that drain though Marginal Upland onto the Flats certainly suggest this could be true.

Thus, the majority of the fan(?)-terrace containing the gravels described by Yeend (1989) and Ager *et al.* (1994) may have been deposited well before the drainage capture by the comparative trickle the ancient Yukon River must have been and by sediments washed in by what would have been a coalescent Birch Creek fan. Yeend *et al.* (1989) concluded that even the most ancestral Yukon River entered the Yukon Flats at this point. This period is represented by the lower alluvial sands and gravels of sections B and C in Figure 6.2.1. The other possibility is that the unconformity between the two gravel facies and the boulder-beds in these sections is not the result of a flood catastrophe, but something else. This would mean that the entire Yukon fan was built quickly in response to the increased sediment load from both erosion of the former drainage divide and the new direct supply of glacio-fluvial sediment. The validity of this hypothesis will someday be revealed when the full story of the Yukon's reversal has been determined. However, if this were true, the streams on the southern Marginal Upland would have consequently also rapidly aggraded in response to the rise in base level.

The existence of a lake in the Yukon Flats basin at this time is supported by both William's (1960) and later, Ager's (pers. comm., 1998) boreholes at Fort Yukon showing an unconformity between Late-Pliocene age deep-water lacustrine sediments and 25 m of gravels overlain by eolian deposits. The majority of the gravels are thought to be of Pleistocene age although some 'chunks' of possible Late-Pliocene age *Pinus* were found at the base of the gravel unit. *Pinus* does not appear in the fossil record in Alaska until the Middle-Pliocene, and although the exact timing of its demise is unclear it is seen phasing out of other Yukon/Alaska floral records between 2 and 3 Ma (Ager, pers. comm., 1998).

If both the base of the Fort Yukon gravels and the Circle gravels are Late-Pliocene, then when was the marginal escarpment incised? Given the extent of the width of the Yukon Flats and the height of the steep slope of the Marginal Escarpment, it can reasonably be assumed that after initial incision, lateral-planation was the dominant mode of erosion. In a section cut into the marginal upland by Birch Creek near Circle, Edwards and McDowell (1991) find more sand and gravel with an age constrained by the presence of the Old Crow tephra (149,000 +/- 13, 000, see Westgate *et al.* (1990)) in an overlying loess unit (Figure 6.2.1). Palynology indicates that the period directly after the deposition of the Old Crow tephra was cold and dry, and likely represents the "penultimate glaciation" (isotope stage 6) followed by an interglacial episode (Edwards and McDowell, 1991, pg. 47). The correlation of the elevation of these sediments with those of Ager *et al.* (1994) in Figure 6.2.1, shows that the lower gravels probably represent Mid-to-Late Pleistocene Birch Creek (between 1.6Ma to 0.15Ma). This clearly constrains the vertical and lateral incision of the marginal escarpment by the Yukon River, to which Birch Creek is graded, to be older-than 150, 000 years (Figure 6.2.1). Astoundingly, this also indicates that the modern surface elevation of the Yukon Flats has consequently remained virtually unchanged since before deposition of the Old Crow Tephra and pre-dates the 'Penultimate Glaciation' in Alaska. The implications of this age constraint with regards to the present surface are profound. Sometime between the Late Pliocene and probably Mid Pleistocene, over 100 m of incision of the margin of the Flats has occurred. Because of the enormous size of the area excavated, a conservative estimate of the volume of sediment removed is 9×10^{11} m^3, or $900km^3$ (300km x 50km x 60m (averaged on the assumption of a V-shaped valley in the center of the flats before lateral planation)) from the Yukon Flats basin. Organics recovered from the overlying thermokarst lake sediments in Edwards and McDowell's (1991) section, were older than the range of ^{14}C dating and thus, the authors conclude the top unit of loess represents the Wisconsin Glaciation.

Other evidence indicates that the Yukon Flats and thus, the Yukon River have not changed in elevation for a long period of time. This evidence is composed of the two sedimentary sections and the GPR data presented in chapter 5. In order to discuss this material it seems logical to proceed in chronological order from oldest to youngest.

The Dalton Bridge Section effectively constrains the minimum age of the base-level elevation controlling fluvial deposition on the Yukon Flats. Finding a section like the one described in part 5.3.4 in a confined valley setting is rare. This setting simplifies the possibilities that could have been available to the Yukon River as conditions changed over time. The extensive loess record overlying the fluvial gravel in the section help confirm the idea that there has been fluvial vertical stability on the Yukon Flats with vertical accretion of eolian origin only. This confirmation has two pieces of reasoning. First, the infinite radiocarbon date from high-up (33m from waterline) in the section proves that everything below it is older-than 40 000 years. This age includes the gravels and overbank material at the base of the section. The thick loess units, organic units and paleosols that lay between the gravels and the radiocarbon date suggest that the gravels are on the order of many thousands of years older, possibly as old as Mid-Pleistocene. As a result, it can be surmised that any subsequent elevation of the bed was between the top of those gravels and the bedrock valley floor (actually the slope of the gravels from 13m to 7m could be representative of the slope of a channel margin or that found between a channel floor and the top of a bar, so this estimate is a maximum). Aggradation above this level can be ruled out because no terraces above them are found in the confined valley reach except for what appears to be highly denuded rock-cut terraces several hundred feet above the floor of the valley (Figure 6.2.2). The origin of these is unknown and they have never been documented before. However, their elevation is similar to that of the Marginal Upland and thus may be synchronous with the deposition of the 'high terrace alluvium' mapped by Williams (1962). The highest terraces may even represent an ancestral river that existed during or before the time of tectonic disturbance of the area, possibly an outlet or inlet to the Pliocene, or even Miocene, lake. The second reason ruling-out aggradation above the gravels is the fact that the primarily fine-grained section would not have survived in the canyon setting.

Incision far below the Dalton Bridge gravels is constrained by there being only a thin sheet of alluvial fill on the canyon floor. This was confirmed with boreholes drilled for the construction of the Trans-Alaska Pipeline bridge piers in the late 1960's (Alyeska Pipline Service Company, 1972). Figure 6.2.3 summarizes and correlates the findings of the ten boreholes. As can be seen, only 4 to 6m of gravel fill exists above bedrock. Thus, the Dalton Bridge gravels must represent a period of aggradation sometime after the deepest incision of the bedrock valley floor. This constrains the elevation of the downstream base-level controlling the Yukon Flats to between approximately 304 and

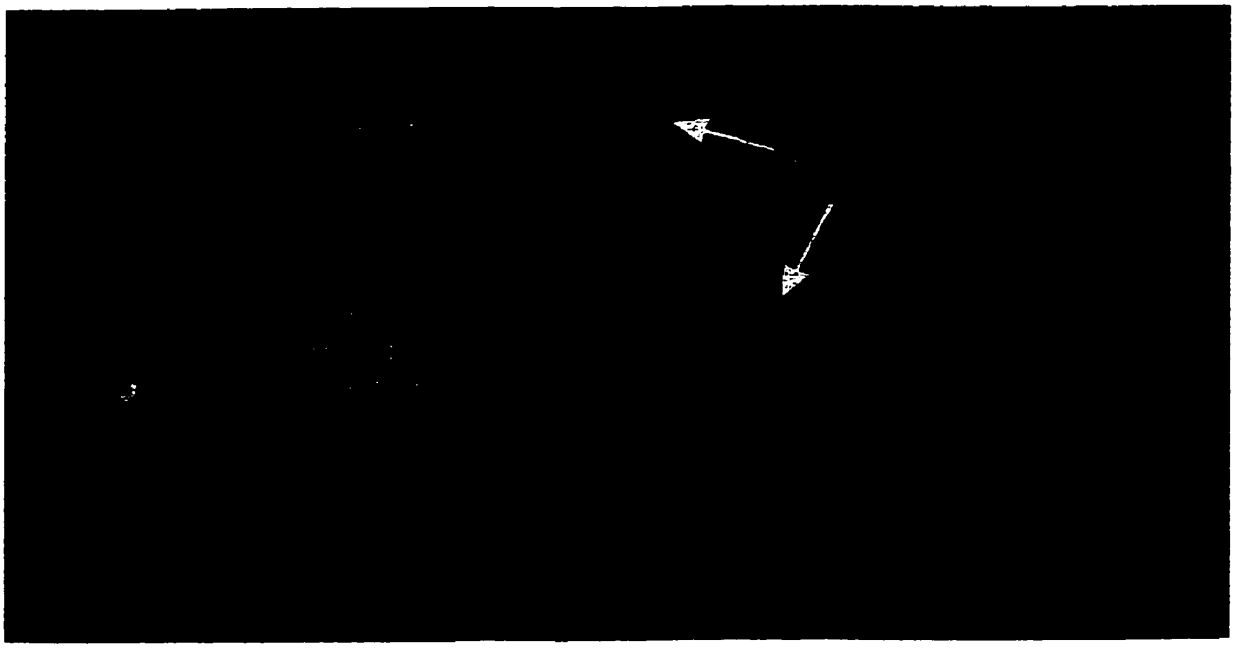


Figure 6.2.2. Oblique view of the location of the Dalton Bridge Section which constrains the age and elevation of downstream base-level control on the Yukon Flats.

(ft)

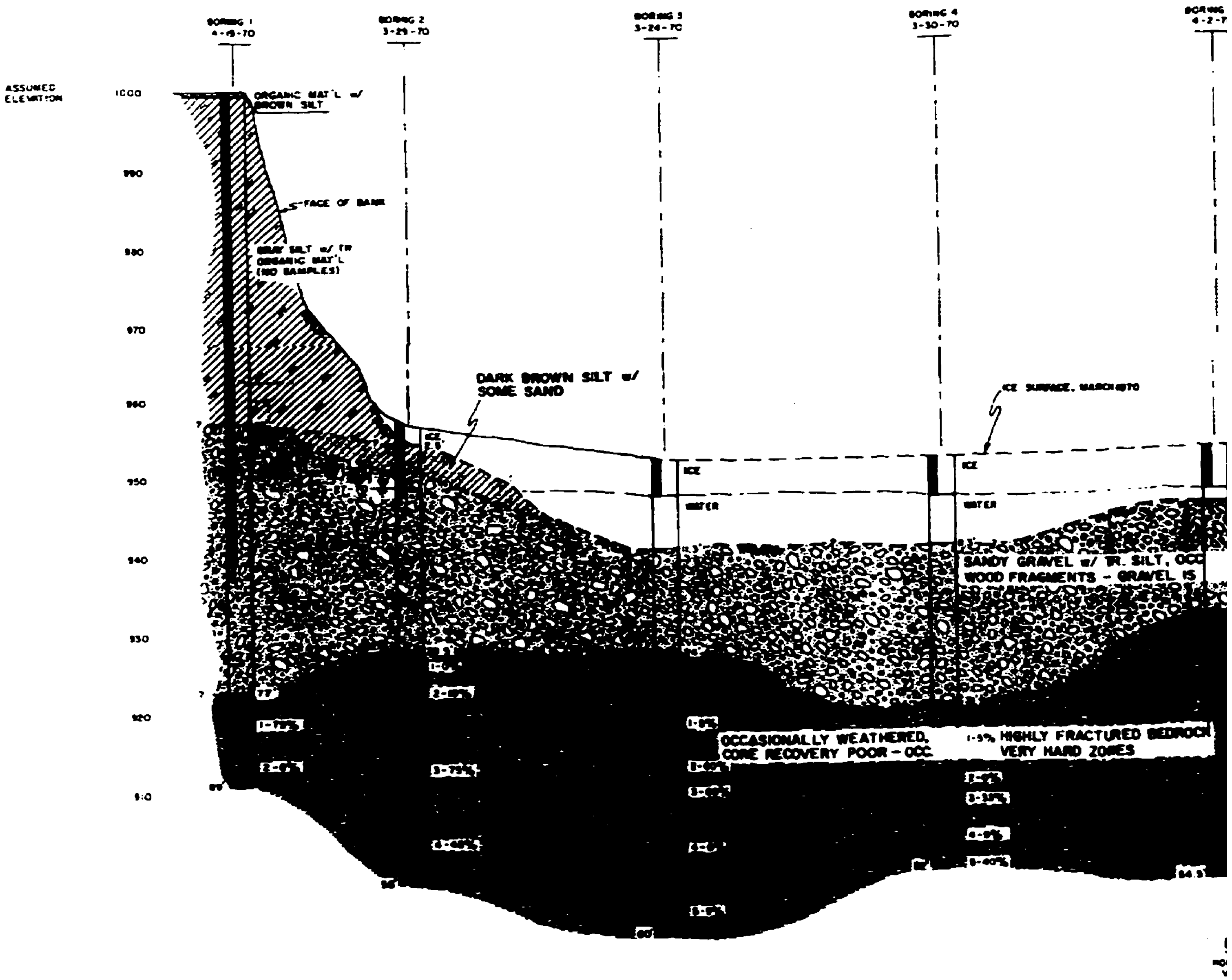
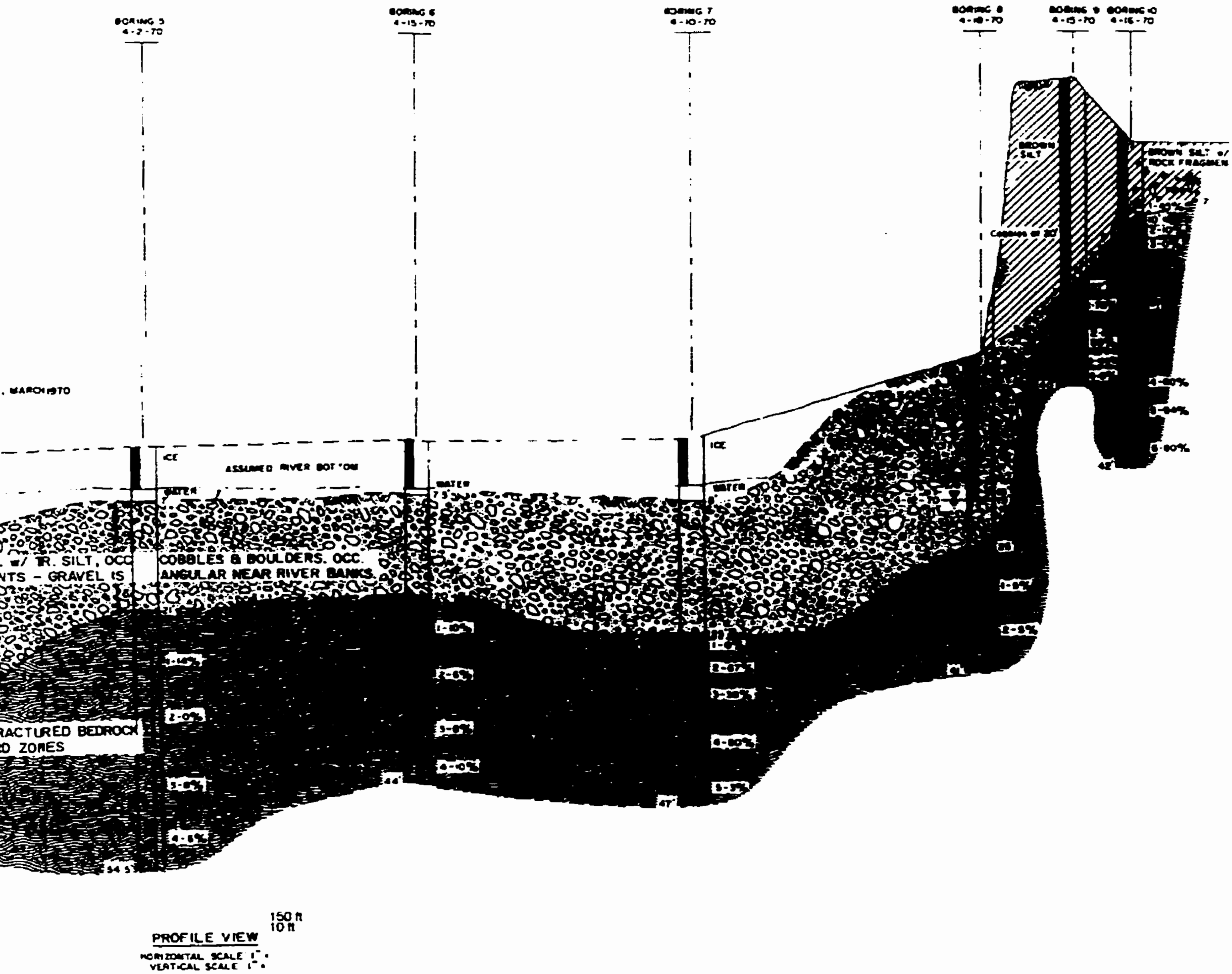


Figure 6.2.3. Correlation of the ten boreholes drilled along a transect across the Yukon River in the canyon downstream of



downstream of the Yukon Flats (from Alyeska Pipeline Service Company, 1972).

287m (based on core-datum elevations) meters above sea-level since sometime before 40 000 BP.

The Purgatory Section also reveals a theme of vertical channel stability. The radiocarbon date of 11,550 $\pm$ 70 BP at the contact between fluvial gravel and eolian sediments indicates that the height of gravel then, matched that of active bars found in the channels today. This date also puts the age of the topographically-subdued, eolian in-filled floodplain surface at Late-Pleistocene, leaving the scrolled-bar marked floodplain surface to have been formed in the Holocene. The lack of gravel terraces above this elevation rules out later aggradation and incision is impossible given the low slope of the basin and the fact that present base-level could only lower by a maximum of a couple of metres 200km downstream of this location.

Incision is also ruled out by both the Fort Yukon borehole data and the GPR data. The Fort Yukon core shows the maximum depth of gravel to be only 25m below mean water-level (the base of which may be Pliocene in age). With SONAR, the author has observed modern scour-holes up to exactly 25m depth not far downstream of Fort Yukon. Upstream, closer to Circle, ground penetrating RADAR shows the maximum depth of gravels to be shallower, 14 to 18m depth. With the depth of gravel and constrained for over half of the Yukon Flats basin and the maximum lowering of base-level constrained, it is safe to assume that incision has not occurred.

If the Yukon River has not significantly changed its vertical position by either aggrading or incising since at least the Late-Pleistocene, then it can be strongly argued that it is in-grade. This means that there has existed, an approximate equilibrium between the volume of sediment load input into the basin and the sediment transported out of it. That this situation has persisted for at least 150 000 years despite glacial and inter-glacial cycles bringing substantial changes in sediment yields and vegetation cover, is extraordinary. This is not the case in other glacier proximal systems. Church (1972) found that pro-glacial Baffin Island sandurs were aggrading. Smith (pers.comm.) found that the alpine braided sections of the North Saskatchewan River were aggradational over the the past 2400 years and braiding was caused by excessive gravel bedload. These are just two of the more important studies that form a trend in the literature that describes braid rivers as aggradtional over what Schumm and Lichty (1965) called, 'graded time'. "...[G]raded time refers to a short span of 'cyclic time' where a graded condition or dynamic equalibrium exists" (Schumm and Lichty, pg. 114). Only in the case of these braided rivers, graded time doesn't represent 'grade' but rather the opposite. Much of the newer, process-based literature does show that braid rivers can be 'in-grade', but to refer back to section 1.2.2., it was concluded that the process time-scale is too short to encompass the truest definition of grade (see Leopold and Bull 1979). In the case of the Yukon River, a braid river that <u>is</u> in-grade, graded time is temporally very-long. Schumm and Lichty (1965, pg. 114) also state: "As an erosion cycle progresses, more and more of the landscape may approach dynamic equilibrium. That is, the proportion of graded landforms may increase, and as it seems likely that temporary graded conditions become more frequent as time goes on". But how then can this 'frequency' have a period on the scale of what is seen on the Yukon Flats? A clue is revealed by Schumm and Lichty, (1965, pg. 114),

> ...it is apparent that during this time span a graded condition can apply only to components of the drainage basin. The entire system cannot be graded because of the progressive reduction of relief and volume of the system above base level, which occurs through export of sediment from the system.

•

Thus, the Yukon Flats represents a component of the Yukon River system that is graded. It would seem that its function then, is as a conduit for exporting sediment to the lower reaches of the system from the upper reaches. The amount of time required to establish this type of system certainly exists, as demonstrated, 2-3 million years. This period in the Earth's history has been dominated by climate fluctuation, and over time, the Yukon has reached an equilibrium with these conditions. One possibility that could play a factor in the attainment of grade is some form of proportionality between the size of a river and the time required to reach a balance between input and output. In other words, the length of graded time may be proportional to the size of a system.

The main feature that seems to allow vertical stability in this case could be the very terrain of the Yukon Flats itself. Located in the middle of the Yukon's course from headwater to delta, the Flats has escaped both the influences of sea-level changes downstream and of glacier-proximal disruption found in the higher, steeper regions of its headwaters. But the two key interrelated elements working on the side of grade are something the Yukon Flats has no shortage of, time and space. With no confines to the Yukon River within the Yukon Flats, the shock of disruptive events from upstream, like waves of sediment influx, catastrophic floods, and even climate-forced shifts in flow regime can be absorbed. In other words, sediment can be put aside in storage and energy can be dissipated until the system has <u>time</u> to deal with it. The Flats is so large, that even the impacts of the onset of a glacial cycle can be absorbed without changes in fluvial morphology (at least vertically). Just one meter of aggradation on the Yukon Flats represents the storage of roughly 3×10^{10} m^3 (thirty billion cubic meters or thirty <u>cubic</u> kilometers) of sediment.

The low slope of the region, combined with the lack of confinement, would allow massive energy absorption. An example of this can be found using the discharge and velocity estimated by Thorson (1989) for the Porcupine mega-floods, and extending the estimations into the Yukon Flats basin. Using the modified Manning slope-area equation (Baker 1973) with the appropriate roughness estimates, produces astounding results. Thorson (1989) estimated flow to be 134 000 m^3/s, at 8.7m/s velocity, with a depth of 26m in the Rampart Canyon reach. Working backward through the equation, the same discharge at Fort Yukon has a velocity of only around 1 m/s and the depth of flow has dropped to 3.8m. When these estimates are run through the Unit Area Stream Power equation (see part 5.2.4), the results are a drop from between 4000 and 11 000 W/m^2 in the canyon (depending on the concentration a particles in the flow) to approximately 11-17 W/m^2 at Fort Yukon. Despite the massive discharge, the low slope and 30km valley width of the Porcupine's course through the Yukon Flats produces stream power estimates at Fort Yukon that are comparable to that seen in many modern braided river systems (Chang 1979). And this estimate only covers 1/3 of the course of the flood-waters through the Yukon Flats. As stated by Thorson (1989) hydraulic ponding would have likely occurred as this discharge reached the canyon upon exiting the Flats. Ponding, at least inside the Flats, would have allowed for even more energy dissipation (and presumably slackwater sedimentation, though no evidence of flood beds have been found in two full seasons of fieldwork in the area. If they have been found they must have been relatively thin, and mistaken for the common ice-jam flood beds found throughout the Flats). This example provides insight into the 'cushioning-effect' that the Yukon Flats has on potentially disruptive events. It is this same effect, facilitated by large amounts of time and space, that as the evidence suggests, has likely allowed the maintenance of grade throughout the Late-Pleistocene, a situation that continues today.

6.3 Slough-channel Evolution

It is the side 'slough' channels that create the unique looking appearance of the Yukon's wandering through the Yukon Flats. The formation of these often long and highly sinuous anabranches has not been satisfactorily dealt with in the literature. This is likely due to the fact that they are not as extensive or predominant in other wandering systems (on the Flats they can reach 20km long and active slough branches have been noted covering 16km laterally from the leftmost channel to the rightmost). The literature which has dealt with the formation of multi-channeled systems has attributed their development to either lateral accretion processes or avulsion based processes (see chapter 3) (Nanson and Knighton 1996). "Anabranching behavior largely stems from avulsion channels incising into the existing floodplain, but in some cases islands grow vertically to floodplain height from large bars stabilized by vegetation within the channel" (Knighton 1998). Twenty-nine years of channel changes revealed through time-slice mapping provide a basis for examining the origins of these channels. This endeavor reveals that, on the Yukon Flats, avulsion-based processes do not seem to play a role and that 'slough' channels have their origins in lateral channel activity only.

The first way that sloughs can form is through an 'evolution' that begins with within channel deposition. This process happens gradually over time and the survivability of each step in the process becomes less likely from one to the next. The first step is the deposition of a mid-channel bar. This may happen in response to any number of reasons (see Ashmore 1991; or Ashworth 1996) but the most common seems to be a loss of flow competence due to channel over-widening. On the Yukon River channel over-widening is likely caused by the effects of ice-jamming although heterogeneity in bank-strength from the discontinuous distribution of permafrost may play a role (see next section). This condition can also be the result of simply a change in thalweg direction from upstream leaving a previous scour-zone to infill. The mid-channel bar then stabilizes into an island, a process facilitated by the influence of vegetation colonization (Knighton 1998). The vegetation succession on these features begins with Horsetail then, willows set in their roots. It is apparent from observation that willows have a high survivability, able to withstand the turbulence of high stage flows and rebound quickly after disruption by ice processes. They arrive on bars as floating detritus from upstream. Even large willows and balsam poplar have been observed establishing root systems and sprouting new shoots from their trunk after being beached on gravel bars. This allows for an increased rate of fine grained deposition on the lee side of the tree. Young willows and horsetail rapidly take advantage of the opportunity and occupy the space. This mini oasis quickly becomes a blockage to flow and grows as more material gets trapped in it from upstream. The result can be accelerated island formation often assisted by a log jam at the island head. However, this process can be reversed by extreme flood events and severe ice-driving. The uppermost example of Figure 6.3.1 shows the continuation of this process in action. The newly stabilized island, which now bifurcates flow in the channel, begins to laterally accrete towards the closest bank. It has been observed that there seems to be a critical distance between the island the closest bank in order for this step to result. That is, flow must be bifurcated unevenly, leaving bank-ward flow to be subordinate to that of the main

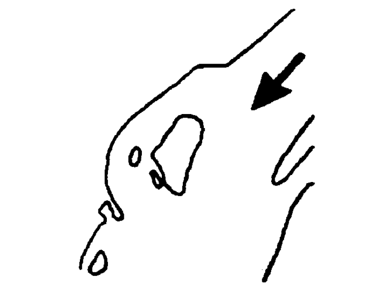
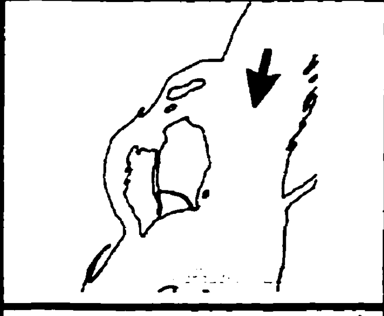
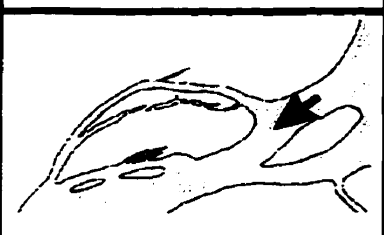
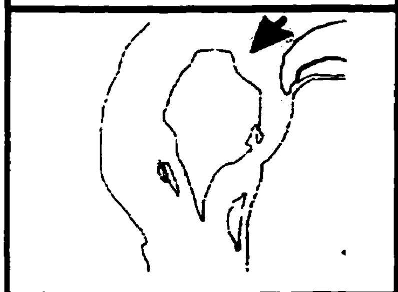
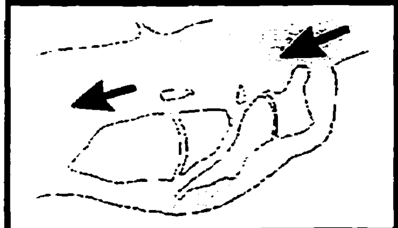
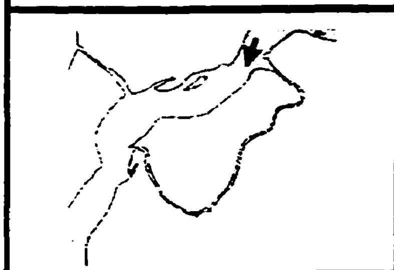
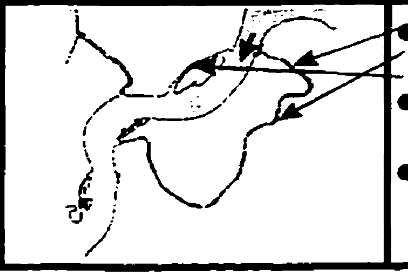
1953	1982	Processes
		• lateral growth of mid-channel island • island/bar consolidation • width decrease • sinuosity increase Cause: INPUT ANGLE CHANGE due to thalweg shift
		• width decrease • lateral island growth • lateral movement Cause: INPUT ANGLE CHANGE due to thalweg shift
		• sinuosity increase • lateral island growth • chute channel development on point Cause: INPUT ANGLE CHANGE due to thalweg shift
		• width decrease • sinuosity increase • island consolidation • lateral movement Cause: INPUT ANGLE CHANGE due to thalweg shift
		• width decrease (lateral accretion) • slight sinuosity increase • chute channel formation Cause: INPUT ANGLE CHANGE due to thalweg shift

Figure 6.3.1. 'Slough'-forming channel processes observed by time-slice mapping (individual examples not to scale).

channel, resulting in the bank-side of the island becoming a depositional environment. This most often produces more than one island forming in the leeward flow. Next, an important component in the formation of a slough begins, the islands consolidate themselves into one large mass, extending the overall length of the subordinate flow. (Other examples of island consolidation can be seen in Figure 6.3.2. This process seems to be the way that all of the large islands on the Yukon Flats have developed. Those in the upper two examples of Figure 6.3.2 are several kilometers across). As lateral migration of the island continues, so does scour on the outer bank, the result becoming the 'birth' of a separate laterally active channel. With flow conditions governed by the existence of a large stable island, the channels adjust their planforms (and presumably geometries) to ones more in-equilibrium with both sediment and water discharge. The consequence is often an overall width decrease and an increase in channel sinuosity (see the second example from the bottom Figure 6.3.1). As the angle between the main channel flow direction diverges from the orientation of the slough channel entrance, further adjustments occur. The result of this angle becoming too divergent is flow abandonment, a condition that leads to the inevitable infill of the slough first from lateral shrinking, then vertical accretion (channel fill). Also of note in Figure 6.3.1., is the formation of chute channels on some point bar type accretions. These chutes do not appear to have their origins in erosive avulsions but seem also to 'evolve' over time. This process, which is similar to that just described, is thus another possibility for the way at least some slough channels may have formed. The important aspect in both situations is that it is lateral activity that is the forming mechanism.

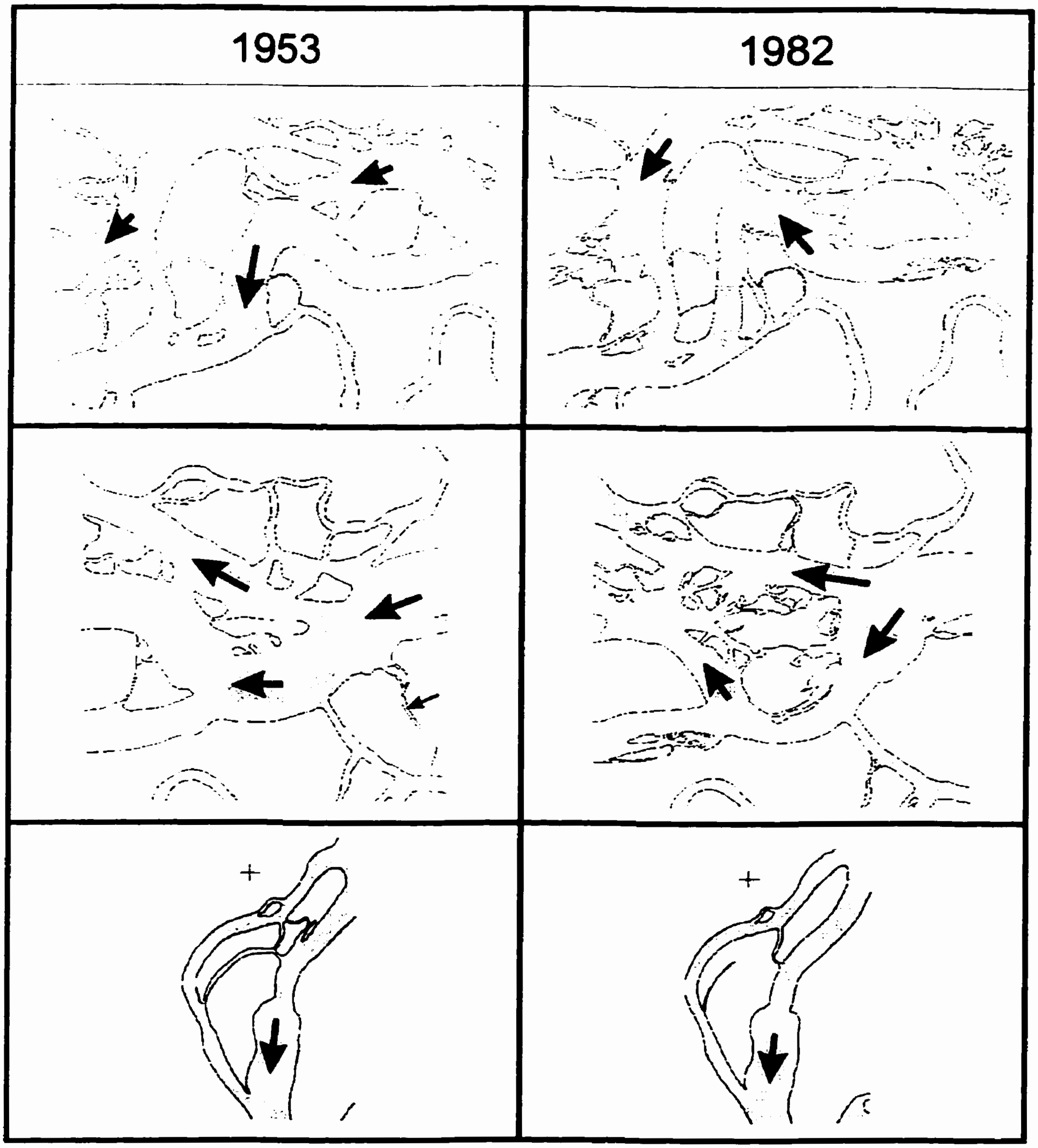


Figure 6.3.2. Three examples of island consolidation showing how the some of the many km large islands that bifurcate flow can form. Also note the complete infill of a small (50m wide in 1953) slough in the middle example.

The second slough channel forming mechanism also results from lateral activity, only in this instance, erosion is the driving force. Figure 6.3.3 shows the two significant results of lateral erosion in slough channels. The first result is the capture of flow by a channel when another has migrated into it (top example Figure 6.3.3). This event can isolate meander bends or whole sections of anabranches forcing them to adapt to a different set of flow conditions by altering channel geometry and sinuosity. Some of these portions may consequently infill while others may widen depending on the specific plan-form geometry of the situation. The second product of lateral migration, particularly on the most sinuous of channels, is meander neck cut-offs (shown in the lower two examples of Figure 6.3.3). This situation can also isolate meanders leaving them to evolve into slough-type channels if conditions are favorable for their survival. The center portion of Figure 6.3.3 shows a sinuous 'slough' channel that cut itself off. This provided a shorter route for the main channel flow and main channel switching resulted. This left the very large meander lobe of the main channel to become subordinate and infill, forming into a slough channel. By 1998, this former meander had dropped in width from nearly 1km to a few hundred meters (three hundred at the most) and sinuosity had increased substantially. The 'slough' meander loop had become completely inactive and the downstream end had completely filled in leaving an oxbow lake that was only really connected the river during high stage. To the right of this oxbow, in the main channel, the mid-channel proto-islands, observed in the 1982 portion of the time slice, had consolidated into a massive vegetated island that had a slough channel running between it and what was the right bank. So by its very nature of lateral migration, the slough channel in this time-slice cut itself off and captured and rerouted the main channel. This

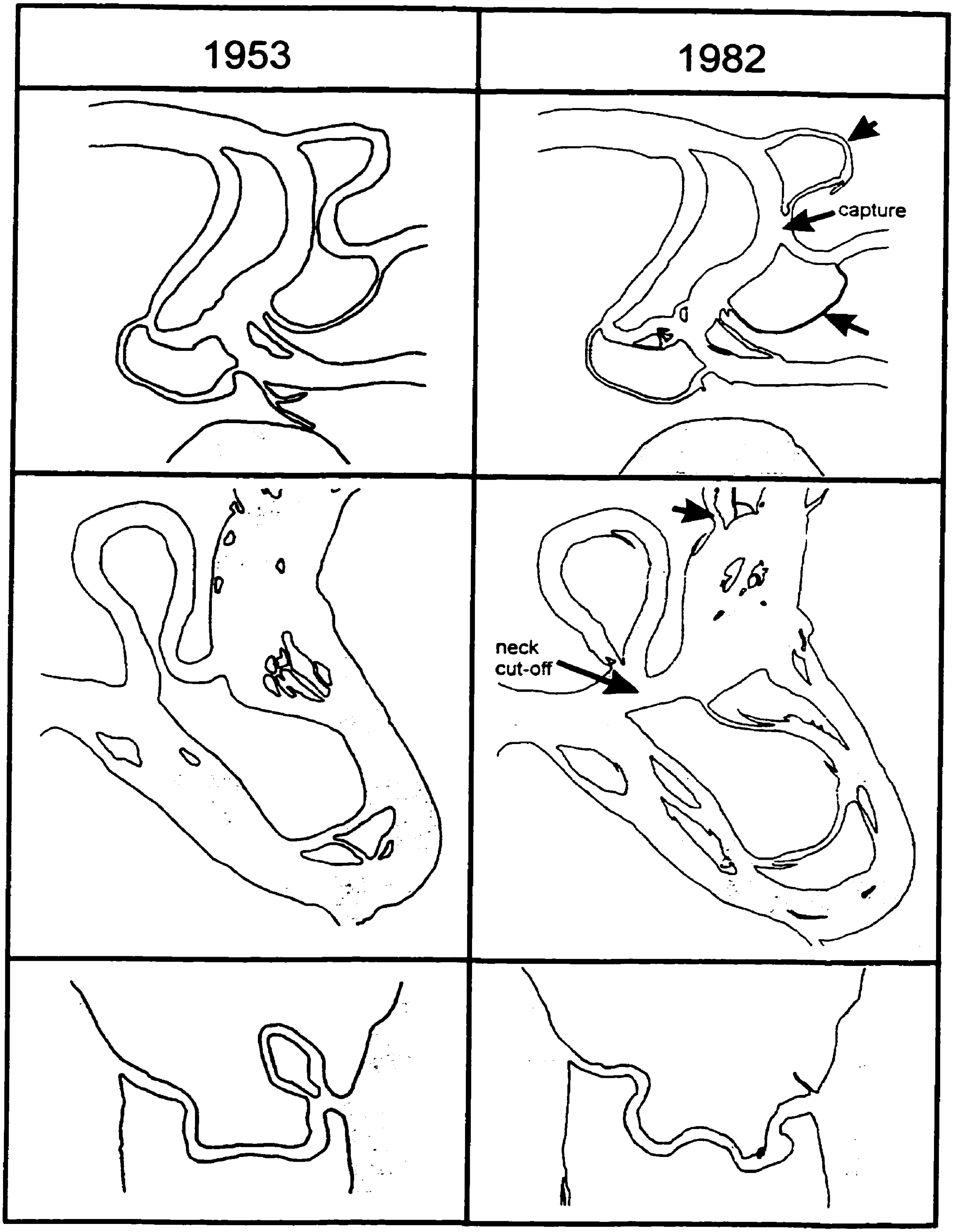


Figure. 6.3.3. Examples of cut-offs or captures occurring in slough channels. Note the nearly complete vertical accretion fill of the meander loop in the lower example and the shrinkage of sloughs in the upper. Cut-offs and captures from lateral migration both isolating and consolidating channels is another way that the multiple channel morphology stays predominant.

left the former main channel to become a slough and generated a new slough upstream by changing the position of the thalweg. So the channel pattern continuum continues on the Yukon Flats. Thus, it can be demonstrated that sloughs can also develop quite rapidly when erosion creates the appropriate conditions.

The other possibility formed by cut-offs is shown in the lower portion of Figure 6.3.3. This slough channel's lateral migration led to a neck cut off of one of its meander loops. Presuming this event occurred not long before 1953, the resultant oxbow was completely infilled and thickly vegetated within approximately 30 years. The result in this case was a sinuosity increase in the channel (likely to lower the increase in slope).

Nowhere in any of the thirty years of time slice coverage was a channel avulsion noted (see Figures 5.2.8.1-5.2.8.5). It can be concluded that the 'slough' side channels of the Yukon River result from lateral accretion and lateral erosion based processes. Sloughs can either 'evolve' from the deposition, stabilization, and bank-ward migration of mid-channel bars which consolidate to form large stable islands or form from the cutting-off of existing channels by either the meandering of a single channel or the migration of other anabranches.

6.3 On the River Pattern Continuum and the Causes of Anabranching

Many additions have been made to Leopold and Wolman's (1957) original division of rivers into three types of patterns, meandering, braided and straight. However, these authors recognized that the three simplistic divisions were actually only end-members of what is a continuum between these forms. Since, defining rivers by the criteria of their planform by attempting to place them along the continuum has sparked the recognition of new types of end-members (i.e. anastomosing and wandering). As discussed in chapter 3, the term anabranching applies to those rivers that do not display single-channel morphology. Single-channel meandering rivers usually make up to 90% of total valley lengths (Leopold 1994). Thus one of the true challenges in the science of fluvial geomorphology is finding anabranching rivers to add to the meager data set that exists (Nanson and Knighton 1996). The Yukon is a particularly good example of an anabranching river, only it does not fit well into the categories ascribed to explain the 'continuum of anabranching' due to a unique set of characteristics and behavior. Discussing the nature of these differences and examining what causes the Yukon River to anabranch is the focus of this section.

The first topic that needs to be addressed is the reason behind the failure of conventional channel geometry approaches when applied to the Yukon River. The application of the channel geometry-discharge relationships (see section 5.2.7) derived and modeled for other rivers, usually produces results that are at least within an order of magnitude. The complete lack of the Yukon's adherence to these relationships, using those derived for the most similar river styles in the most similar environments possible (Drage and Carlson 1977 and Bray 1973), prompted the investigation into why there existed such an anomaly. Attempts at estimating 'bankfull' flow from these equations, based on the addition of the morphologic bankfull heights to the surveyed transects, were such a failure they were not even included in the results section. This led to taking a closer look at the distribution of bankfull height (Figure 5.2.1.7) and the variation in all observed bank heights (Figure 5.2.1.8). While there was a trend of bankfull height increasing downstream, it was observed that a high amount of variation in this level existed, even between short distances. While in the field, anecdotal stories about flooding told by the local people usually included the mention of both rapidity, and ice damage to buildings. Photographs of the three worst floods at Circle all showed the presence of massive beached ice blocks. Thus, the hypothesis was developed that the majority of the flooding on the Yukon Flats was due to ice-jam floods. If the early work done on the Yukon River is read carefully, one will notice this idea mentioned (see section 1.2.1). Russell (1890) said that the local people on the Flats claimed that ice-jam flooding was more severe than summer flooding and Eardly (1938) found only ice-jam flooding significant to both high stage and the deposition of fines downstream. The hydrologic analysis that was a precursor to this research did show the regular occurrence of ice-drive floods, but no true corresponding stage data was available for the Yukon Flats to confirm the idea. However, to test this hypothesis, data was acquired from the Alaska Division of the U.S. Army Corps of Engineers. This data concerned the nature and stage of the worst flooding at Circle, Fort Yukon, Beaver, and Steven's Village and showed that only the very worst summer floods reach bankfull. It also showed that these are often not as severe as ice-jam flooding. Fort Yukon has a bankfull height of 432.2 feet and the worst ever flood witnessed since 1889 peaked at 435 feet. This 'worst ever' flood stage was less than 1 meter above bankfull. As well as this one, the other two worst floods were caused by ice-jams and they didn't even reach bankfull. However, although the stage was low, the velocity during the worst event was apparently very high and ice created the worst damage. Many lives were lost at Fort Yukon due to the ice-drive happening in the middle of the night. The worst summer flood at Beaver recorded by a gauging station was in 1992. This flood, 23 191 m^3/s (or the 21 year flood when calculated using partial duration series, Q_{21}, Figure 2.5.5) failed to reach even the elevation of the buildings located at the water's edge. Peaking on June 10, 1992, this flood was recorded as being caused by an ice-jam at Fort Yukon, although no cause was given in the reports of other villages, it is thus a possibility that even this flood was at least, ice-related. The beginning of the spring increase in flow, and presumably a 'thermal break-up' (where ice melts in the channel rather than an ice-drive, evident as a more gradual curve on the hydrograph) happened 12 days earlier with flow rising steadily until peak. The same flood, downstream at Steven's Village along the meandering reach, didn't even overtop the banks. Fortunately, affordable Landsat MSS satellite imagery that covered this event was available from the US Geological Survey. Figure 6.4.1 shows the lower portion of the study area on June 14th at 20 300 m^3/s, or the 17-year flood stage of the waning flow of the 1992 record discharge. The band used is near-infrared so water shows as dark patches. The Yukon's flow, laden with silt, shows as a gray but any standing or slow moving water shows darker (usually black). Only a small tributary can be noted overtopping its banks (Little Dall River), likely due to the 'backwater' effect caused by the Yukon's unusually high stage. Remarkably, the Yukon shows no signs of massive overbank flow other than wetted, low-lying, recent channel fills (not to be confused with the large recent burn patch or the numerous thaw lakes which are always present though likely slightly higher than normal due to snowmelt and rainfall). There is no question that some overbank had occurred here, but the scene should have looked more like images of the Red River flooding where hundreds or thousands of km^2 of floodplain would show signs of continuous ponded water up to kilometers from the edge the river's banks. Rather, channelized flow is maintained, even during an event of such magnitude.

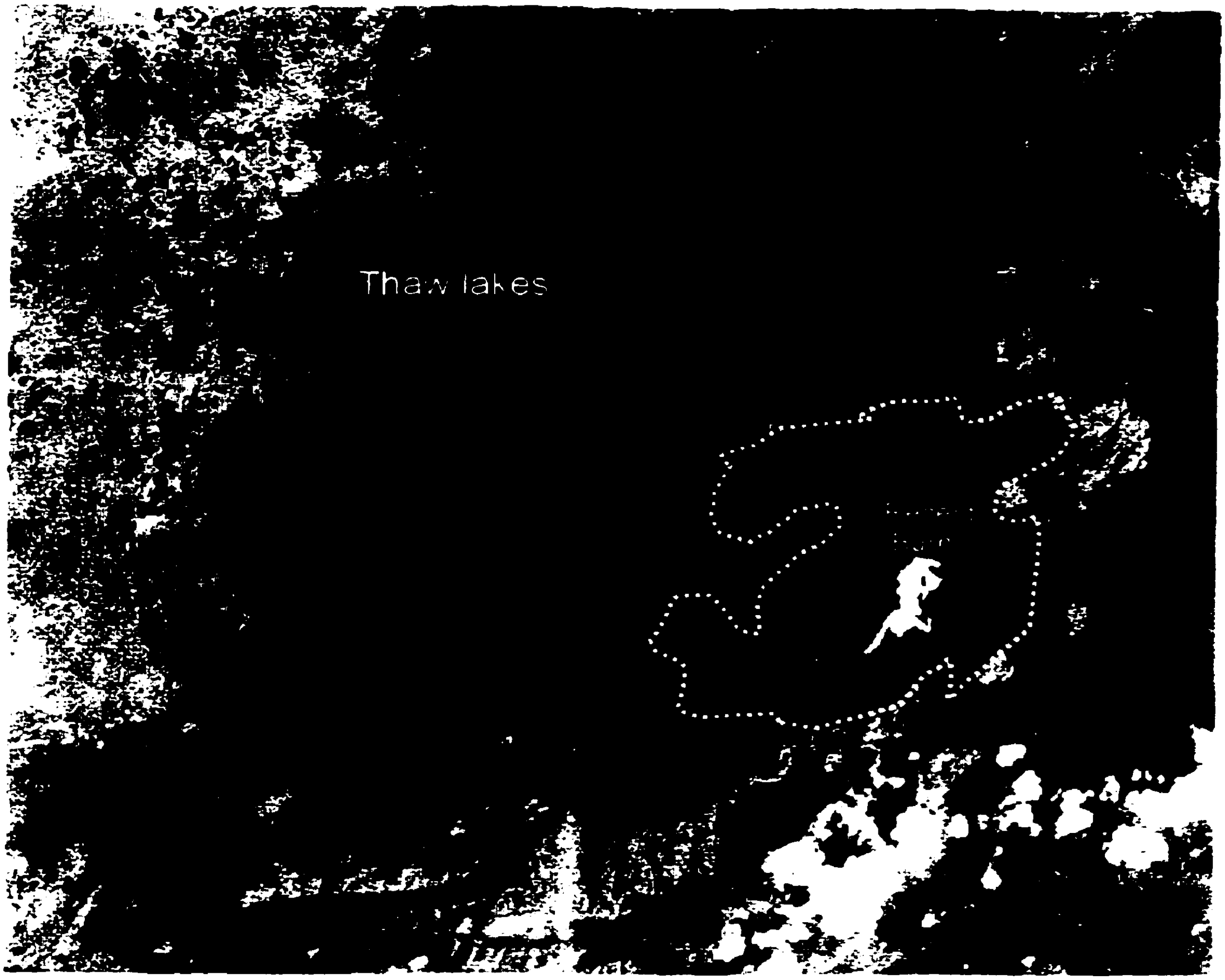


Figure 6.4.1. Landsat MSS imagery of the waning stage (Q17, 20 300 m3/s) of the largest flood event on record, 23, 330 m3/s (21-year flood). Note how only a tributary of the Yukon shows active overbank flooding and areas inundated by the Yukon are restricted to low-lying swales and abandon channel fills. Not the 'flood swath' one would expect from such a large event.

Other evidence of frequent high-stage from ice jamming exists. Figure 6.4.2 shows another Landsat MSS image of the 120km area between Fort Yukon and Beaver. In this scene, representing only a split second of time, no fewer than seven major ice jams are present, causing overbank flooding on their upstream ends. The majority of flow can be observed either bypassing the jams along the channel margins or rerouting through any upstream side 'slough' channels that are ice-free. Thus, a mechanism for the maintenance of these channels could be regular ice jam flood flushing of sediment. This type of process also provides a highly probable cause for the channel over-widening that can result in the mid-channel bar deposition that can lead to slough formation. This is not a new idea. Nanson and Knighton (1996) claimed that one of the causes of anabranching in "Type 5" (wandering) rivers, is obstruction of flow from log-jamming or ice-jamming leading to channel avulsion. However, this is most likely the first time that this processes has ever actually been documented happening and as it has been demonstrated, no avulsions are apparent on the Yukon Flats. The problem of irregular bank height is solved by this process as well. If the only high frequency overbank flow is caused by ice jams, then so must the majority of the overbank deposits that form the upper two thirds of the banks. The irregularity is caused by the nature of the distribution of ice jams. Higher banks then likely occur in areas of more frequent ice jamming (although it is clear that the amount of time a surface has had to accumulate overbank material also plays a factor in how high the banks will be). Therefore, the solution to the overall channel geometry problem is likely channel deformation and irregular floodplain deposition from the regular occurence of ice jams. Similar problems were discovered by Smith (1979) on 24 Alberta rivers that had regular ice-drives. He found that the 'bankfull' re-occurence

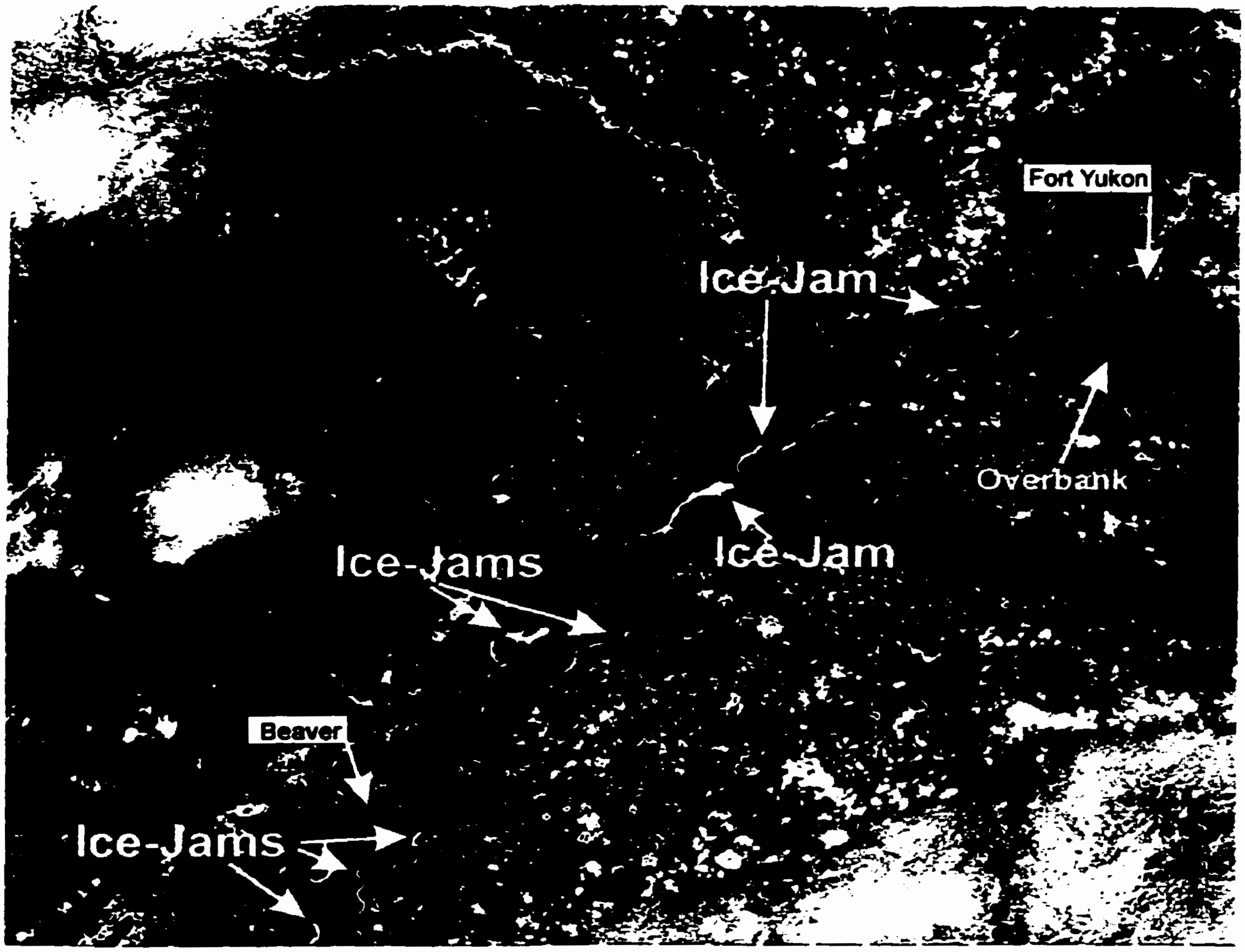


Figure 6.4.2. Landsat MSS image of the May 1989 break-up in progress on the Yukon Flats. Although this image shows only 1/3 of the study area, seven major ice jams are occurring at one moment.

interval had been pushed back to 16.7 years, nearly five times less frequent than on US rivers with no ice processes due to enlargement of the channel and higher banks. On the Yukon, this process must then also maintain a slight disturbance of the river's local equilibrium, no doubt helping to promote anabranching on the Yukon Flats. However, despite this disturbance, the river pattern overall must be in equilibrium with ice process in order to maintain grade. Other reasons for anabranching will be discussed below.

There has been much debate over which variables must combine in order to form a specific channel pattern. Initial emphasis was placed on the relationship between slope and discharge as an indicator (Leopold and Wolman 1957). As stream power is a product of those to variables, it too has been seen as a good discriminator between river types and works well with the continuum concept (Knighton 1998). Channel patterns are also governed by bank erodibility and thresholds dependant on the caliber of bed material. Thus, as one moves down the continuum, from braiding to meandering:

1) stream power decreases (decreasing slope at a constant discharge);
2) width to depth ratio decreases (increasing bank strength and/or decreasing bed load transport); and,
3) caliber of bed load decreases

(Knighton 1998)

Knighton (1998) also summarizes the four main factors that are thought to make a channel braid in the first place: abundant bed load, erodible banks, a highly variable discharge (though secondary to all other variables), and steep valley slopes.

The braid reach of the Yukon River displays some of these conditions. It has abundant gravel bedload, which is also found composing the lower 33% of bank deposits.

Steep valley slopes are definitely not an issue on the braid reach. This is likely an artifact of the Yukon's size because it has been recognized that braiding can occur at low slopes in large rivers (Smith pers. comm.; Knighton 1998). Also, discharge is variable due to the nature of the nival flow regime found on northern rivers.

In order to understand what is causing the channel change from braid to wandering to meandering on the Yukon Flats, we must look at it as a system. The first major change in river pattern happens at the confluence of the Porcupine River at Fort Yukon. Due to peak flow of the Porcupine bringing in as much as 40 % of the total discharge of the Yukon, stream power should increase and it does, but not much. Coincident with the flow increase is a 25% drop in valley slope (with a corresponding 34% decrease in water surface slope). Chang (1979) demonstrated that in braid rivers, the number of channels increases when stream power increases. However, only a small increase in stream power occurs due to the powerful control of slope in the stream power equation. The conflict between slope and discharge in the equation is visible in Figure 5.2.7.10 where specific stream power is regressed against slope. In the braid reach there is a 70% agreement between the variables. In the transitional reach, this agreement drops to 28%, illustrating the influence of the Porcupine's discharge on the hydraulics of the system. So if the slope decrease apparently explains so little of the phenomenon why then does this transition of pattern happen? The answer must then be, either a decrease in bed load size, an increase in bank strength, or the crossing of a geomorphic threshold. The caliber of bed load remains virtually the same in that no major jumps or changes occur, other than the slight decrease of sorting into the 'extremely poorly sorted' category. The effects of this on the character of the bed could play some role by making clasts more resistant to entrainment due to the infill of gaps and spaces between clasts by finer matrix (Andrews 1983; Brayshaw 1985). As for an increase in bank strength, this is unlikely due to the height of gravel in the banks increasing as much as 2m in some cases (Figure 5.2.1.8). However, when plotted on the slope/discharge graph of Leopold and Wolman (1957) (Figure 6.4.3), the drop in slope at Fort Yukon causes the Yukon River to cross the threshold between braided and meandering channels. When compared against another threshold, this time separating braided and anastomosing channels (Figure 6.4.4), it too is crossed by the drop in slope at Fort Yukon. A data set complied by Church (in Martin 1998) shows the slope discharge threshold dividing braided and wandering gravel rivers (Figure 6.4.5). The poor fit of the Yukon' s transition along this threshold is likely not due to a problem with the idea, rather is probably a result of too few data points for large rivers in the plot. If the slope of the line of the relationship were increased slightly, the Yukon would be crossing the threshold (and the outlying data points on the low end would fit in as well). Brierley (1989) and Brierley and Hicken (1991) found a slope decrease from 580 cm/km to 150 cm/km corresponded with the braid to wandering transition on the Squamish River in British Columbia. This transition also crosses the threshold boundary of Figure 6.4.5. The fact that two, and maybe all three, of these established geomorphic thresholds correlate with the Yukon's change in river pattern makes it very likely that at least the initial trend toward increasing channelization of flow is due to this threshold, something the stream power equation alone is insensitive to.

The river pattern change from the transitional reach to the wandering reach has no precedent. This division between the two patterns in this thesis was identified based on morphologic differences between them like the decrease in the number of active

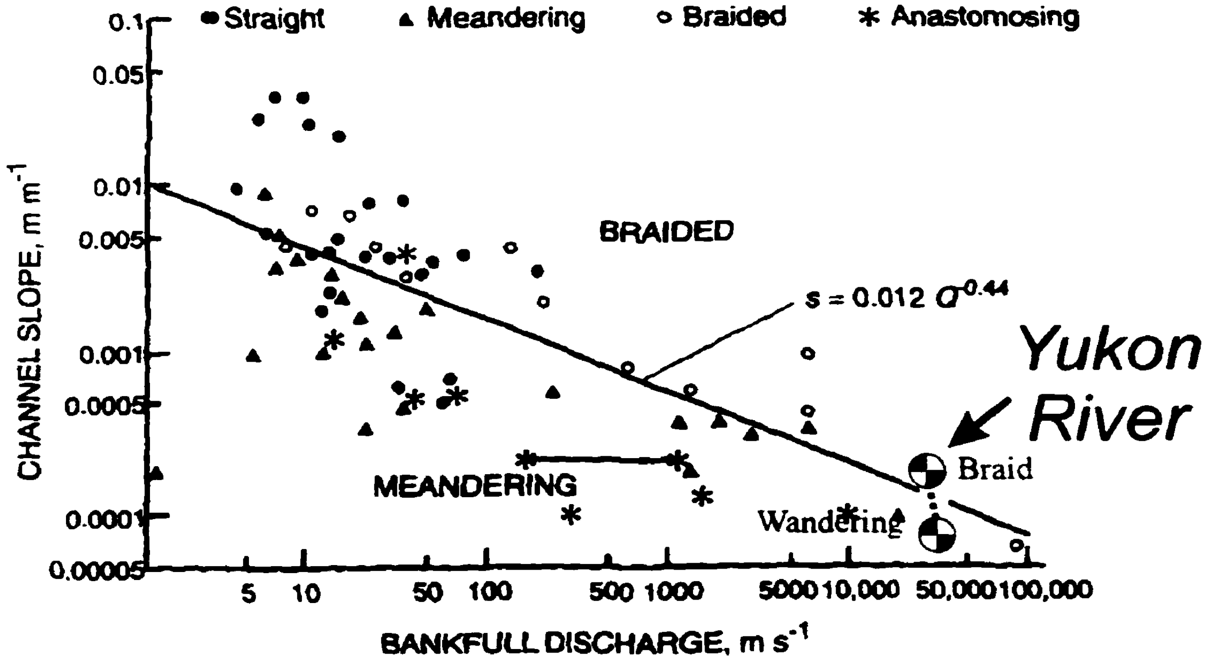


Figure 6.4.3. The Yukon River (study reach) plotted on the slope-discharge graph. The exact position of 'bankfull' discharge relates to the problems with this concept as it applies to the Yukon (see text) The line separating river types was derived by Leopold and Wolman (1957) (modified from Knighton, 1998, p. 209).

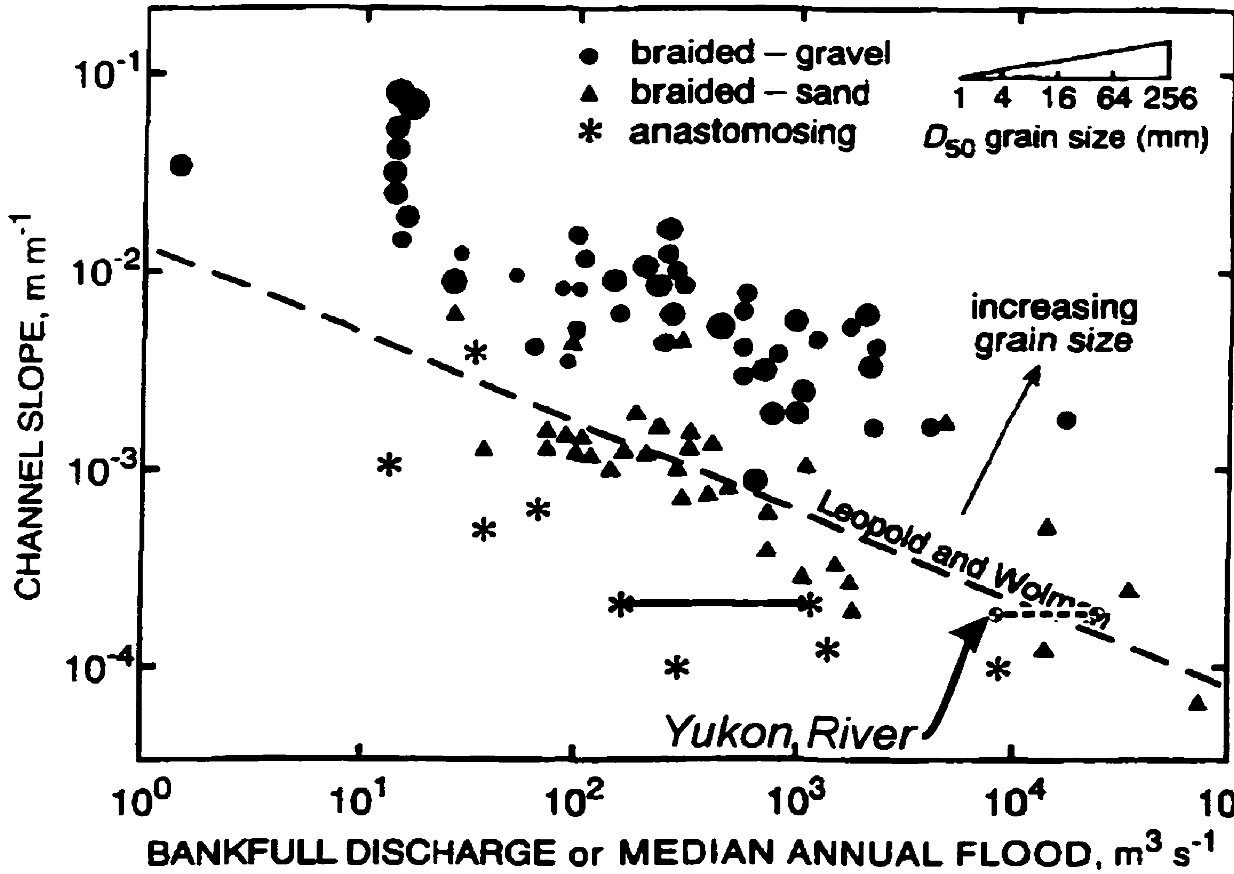


Figure 6.4.4. The Yukon plotted on a slope-discharge graph. On this plot the line distinguishes between braided and anastomosing rivers. Note how this threshold is crossed by the Yukon (when the 18-year 'bankfull' flood is plotted). Mean annual flood on the Yukon does not represent the 'channel shaping flow' due to the role of ice processes.

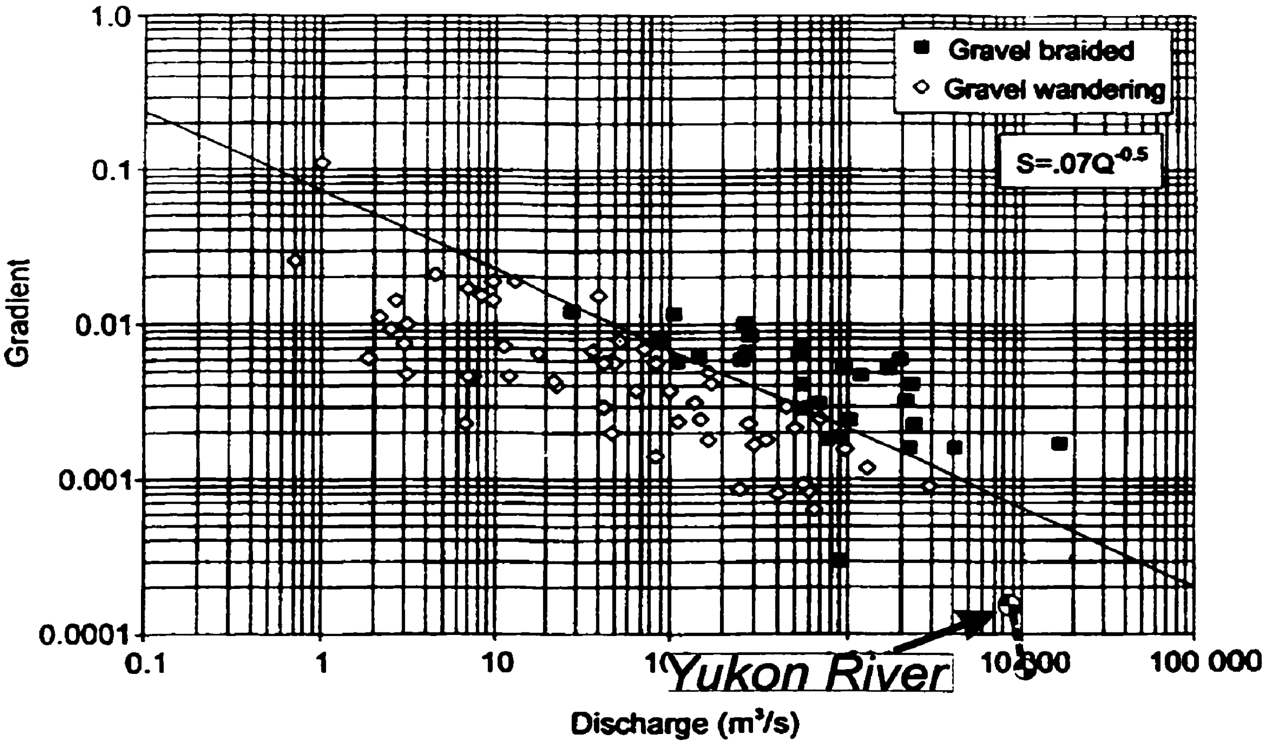


Figure 6.4.5. The slope-discharge threshold between gravel braiding and wandering determined by Martin (1996). Note how the Yukon just crosses this threshold. Perhaps as more large river data points are added to this plot the slope of the line may steepen. This would comfortable include the Yukon and some other marginal points.

channels, fewer mid-channel bars, increase in the size of individual channels, decrease in slope marked by a break and a significant reduction in lateral migration rates. With this said, the processes observed operating in them were very similar. Many of the trends in various data (i.e. specific stream power) display the same rates of change. And thus they may, in fact, be classifiable as the same river type with just the 'wandering' reach identifiable as the end-member pattern. This seems a bit ironic because wandering is considered to be a transitional form itself (Brierley 1989). However, at this point it should be re-stressed that the 'wandering' pattern is the dominant river type found on the Yukon Flats and that its 140kms (250 if one includes 'transitional'), which may be the longest ever researched, make it an end-member even by the most conservative of definitions.

The clues then to the cause of the remaining river pattern changes must be sought in the trends between the transitional and wandering reaches and the meandering reach. Nanson and Croke (1992) identify specific stream power ranges for specific river types. The lower boundary of this threshold is 10W/m^2, dividing meandering channels from straight or anastomosing lower energy ones. This threshold is crossed three-quarters of the way through the wandering reach and could be one impetus for the change in river form. The fact that the patterns marked by the threshold don't match the predicted outcome could be an effect of scale (the data sets for these types of studies rarely include rivers as large as the Yukon). However, the change in stream power is directly caused by the continual decrease in slope (R-squared of .89 in Figure 5.2.7.10). Migration rates also reach their lowest values, likely an artifact of the decrease in stream power. But the greatest change noted in any of the independent variables is in the bank composition.

The percent of gravel composing the lower component of the banks drops from about 30% to 5%. The 5% value is actually only the result of gravel being found in one bank, with all the others completely free of it. No gravel in the banks means that the entire composition is made up of the more cohesive fine sands and silts that normally comprise the overbank component of the Yukon River's banks. Couple this fact with the 3m+ height of these banks and suddenly a formidable barrier to erosion exists. The finer texture of the banks would also increase boundary resistance. As Knighton (1998, pg. 211) put it, "...as boundary resistance increases through either more cohesive banks or coarser bed material, a greater stream power is required for the onset of braiding". However, stream power is not higher in this reach and bed load is fining rather than coarsening (Figure 5.2.6.3), so the Yukon must channelize in order to maintain transport, particularly at an average slope as low as 10 cm/km. This phenomenon is very well summarized by Knighton (1998, pg. 211), "Meandering is assumed to occupy an intermediate position where erodibility and transportability are in approximate balance". Thus, the loss of gravel in the banks could be caused by its concentration in the lower regions of the channel, closer to the transport zone where it can be moved and not found higher due to the energy required to move it up in the channel. As already discussed, the fining of bed load is another potential cause for river pattern changes but it is clear that the hydraulics of flow, governed by the energy losses to slope and bank resistance, are the primary cause of the wandering to meandering transition.

The question can be asked: why doesn't the river just aggrade? The elevation of the meandering reach above sea level is just under 100m. The Yukon must continue its course for another 1290km before reaching the end of its delta. The product of this is an average slope of only 7cm/km after the Yukon leaves the meander reach. This can be compared to the 75m drop the river makes along the 350kms of the Yukon Flats. This makes the slope change found on the Yukon Flats the last major break in the Yukon River's slope profile. Changing this valley slope by aggradation would result if sediment were to allowed to accumulate. The fact that it doesn't must therefore mean that sediment is being transported out of the Yukon Flats. With the reductions in stream power noted above by the tendency of channel pattern to become more channelized, the ability to transport material decreases in a downstream direction. Therefore, theoretically there must be a reduction of the total volume of gravel to sand, silt and clay (not anywhere near as much of a burden to transport) over the distance of the Yukon Flats that equals the volume entering the basin near Circle. It was noted in chapter 5 that the median (D50) diameter of the bed load found on longitudinal bar heads decreases from 11mm to 5mm. This reduction, represents a 55% decrease. It has been argued that the 95th percentile size (D95) is more influential on the hydraulics of bed load transport (Brayshaw 1985). This shows a 58% reduction, from 45 to 19mm. These figures translate into grain size reduction rates of 0.01 mm/km based on D50 and 0.065 mm/km based on D95. The break in the classification between gravel and sand is 2mm. Therefore it is possible that enough material is reduced to the fines that wash out of the system as is equal to that which is brought in, maintaining grade. The adjustments in the system then must happen solely through channel pattern changes.

Where then does the Yukon River fit into the continuum of channel patterns? The laterally active gravel bed anabranches match most of the qualitative definitions examined in Chapter 3, but do the specific values of variables match the classification scheme for anabranching rivers? The scheme in question is that derived by Nanson and Knighton (1996) where stream power, bed material, bank material, lateral migration rate, vertical accretion rate and the ratio between island length and channel width are criteria. Figure 6.4.6 shows the Yukon's place in all of these criteria. Interestingly, the Yukon shares values of different criteria with all six of the anabranching river types. The vertical accretion rate (nil), bed material, and bank material are both on track with type 5 rivers (wandering). However, specific stream power puts the Yukon together with types 1 through 4 as if it were a sand bed anastomosing or mixed load laterally active river (type 3). If one recalls, Figure 3.1.1 shows type 3 rivers as looking very similar to most parts of the wandering reach. However, the examples given by Nanson and Knighton (1996) to support the separate classification were weakly related at best (see section 3.1) and in reality didn't match the Yukon. They have been characterised as having sand banks and bed load and only Austral-Asian examples have been documented. In these systems avulsion process were dominant and anabranches are considered to be short lived. Type 3 behavior is also seen in the ratio between island length and channel width (the exact position of this variable in unknown. For the figure it was quickly estimated plotting well within the range of both type 3 and type 5 rivers). However, its gravel nature makes the Yukon a type 5 river, despite its lower energies and longer more pervasive slough channels. Thus, the transition through the Yukon Flats consists of braided to type 5 anabranching ('wandering' (both the transitional and wandering reaches), to meandering and is primarily caused by low valley slopes that result in lower specific stream powers as one moves downstream.

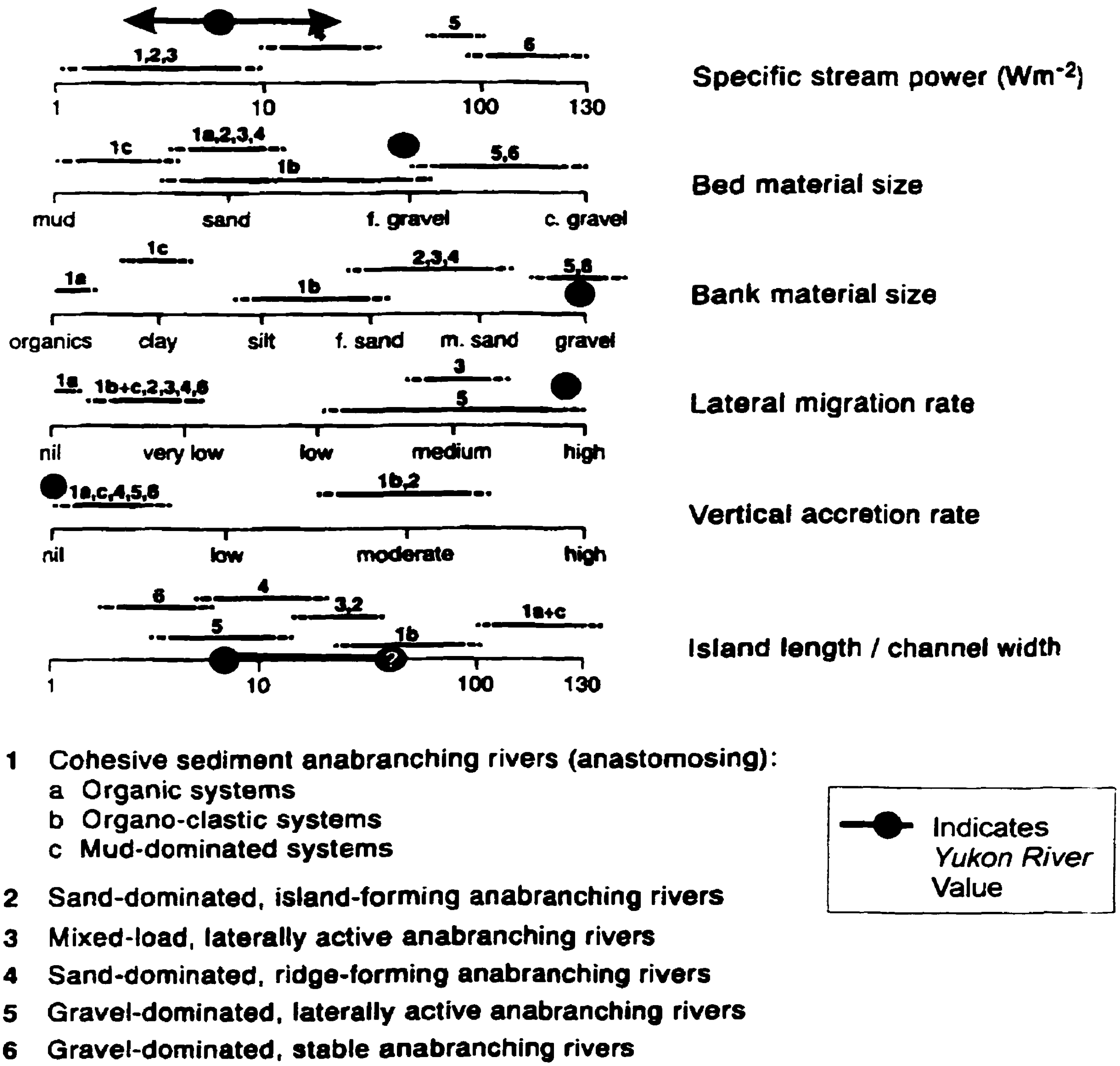


Figure 6.4.6. The classification scheme of Nason and Knighton (1996) for anabranching rivers Note how the Yukon doesn't adhere well to the scheme, particularly in the stream power category. This may be due to the Yukon's large size (modified from Nanson and Knighton, 1996).

6.5 Recommendations for future research.

This research has pointed out several ideas that require more testing. The situation of long term grade on the Yukon Flats has implications to sediment transport and storage relationships. It would be interesting to test whether shorter-term sediment transport into the Yukon Flats matched that exiting. It would also be useful to know if other sections of the Yukon River were in-grade and for how long. The Flats would be the perfect laboratory for the directed study of downstream reductions in clast sizes (downstream fining). This research should focus on the amount of sediment that is converted into suspended load. It is this reduction of material that likely helps maintain graded conditions by converting a significant portion of bed load into suspended load. This would thus allow the transport of this material out of the drainage area altogether. It would be interesting to know exactly what role, if any, the heavy suspended load concentration of the Yukon's flow played on sediment entrainment and transport. Another avenue of research related to bed sediments would be to see if the longer step-lengths (annual length of transport of within channel clasts, one point bar to the next) of wandering and gravel-meandering systems made the process of grain-size reduction more efficient. The further investigation of the sedimentary sections described in this work, with concentration on dating through paleo-magnetism, climate reconstruction through organic and plant macrofossil remains, vegetation history and paleosol chemistry investigation would provide a good opportunity to expand on similar work done around Alaska and the Yukon and contribute to the regional correlation of events. Answering why there were so few tephras found on the Yukon Flats when they exist in other parts of the region could shed light on former climate circulation and volcanic activity.

Investigating the sedimentology associated with ice-jam flooding on the Yukon River could shed light on the possibility of reconstructing such events on other rivers, also useful for establishing another form of climate proxy record. As it can be seen, there are many questions that should be answered. Part of this phenomenon is no doubt due to the fact that this research is the first of its kind done in the area. However, a word of caution should be expressed. The funding and logistics required to do research in the remotest parts of Alaska are intense. Careful planning is required to minimize risk and produce results.

Chapter 7: Conclusions

In chapter 1, several problems concerning our knowledge about the nature and history of the Yukon River as it flows through the Yukon Flats were outlined. The objectives of this research were to investigate and explain the following:

1) It is unknown what causes the observed multiple channeled morphology, what processes operate within it and why such a low-gradient river maintains an anabranching pattern rather than reverting to a single channel form.

2) It is unknown what type or caliber of sediment this reach of the Yukon River is transporting or if there is any significant change as the river traverses the low-gradient Yukon Flats.

3) It is unknown if this multiple channel pattern is laterally active and if so, at what rate channel shifting occurs.

4) It is unknown whether conventional channel geometry relationships can be used to model this type of system, or as a comparative tool when relating to other rivers.

5) The long-term history of the Yukon River remains poorly understood and uninvestigated using modern techniques, a factor which contributes to the difficulty in understanding modern processes and responses

The research presented and discussed in chapters 5 and 6 led to many important conclusions. Of most importance is that the Yukon River in the Yukon Flats reach, has remained vertically stable, or in-grade, for a extensive period of time surpassing a minimum of 150,000 years. Only 14-30m of gravel have accumulated on the floodplain since the Pleistocene. As a consequence, the surface of the Yukon Flats has also remained stable in its vertical position with only eolian processes accounting for localized vertical accretion. This situation has endured many glacial/ interglacial cycles and extreme events such as the repeated catastrophic flooding from the Porcupine River basin. Due to its low slope and large expanse, the Yukon Flats has the ability to absorb the impacts of energy and mass-balance disruptions.

As Yukon River flows through this expanse, it undergoes a braided to wandering to meandering transition. The initial river pattern transition from braided to wandering results from the slope/discharge relationship crossing a threshold boundary as slope decreases. Further transition is the result of continuously decreasing valley slope forcing channels to adapt to the resultant lower stream powers in order to maintain transport. Meandering occurs as the erodable, gravel lower-component of the banks suddenly disappears, increasing bank cohesiveness and stability. The reason for the disappearance of this gravel in the banks is unknown though is likely due to gravel occupying the lower regions of the channel where it can be transported more efficiently. Migration rates drop correspondingly from 11.6 m/y in the braid reach to 4.6 in the meandering reach.

The bed grain size of the Yukon is primarily fine gravel. This means that the hydraulics of this system must maintain the transport of this material because aggradation has not occurred. With the decrease in slope and stream power, the only possibility is that grain-size reduction from gravel to more easily transported fines allows volume to leave the system.

Traditional hydraulic geometry relationships cannot be used for predictions on the Yukon River. The only way the discharge of individual anabranches can be found is by dividing the known discharge of a single channel station by proportions determined by the Manning equation. The underlying reason for not being able to use known channel geometry relationships, related to highly fluctuating bankfull heights, is the result of the shape of Yukon channels being governed by regular mechanical river ice break-ups and ice-jamming (every 1.3 years). Flow is rerouted through the always available upstream side 'slough' channels helping to maintain them as flow relief channels. Ice-jamming can also reroute flow causing channel over-widening which can lead to bar deposition.

Sloughs form from the operation of lateral migration processes only. Avulsion processes were not found to occur on the Yukon Flats. These lateral migration mechanisms form sloughs in two ways. The first way is through an 'evolution' begun by bar deposition due to channel over-widening causing competence loss. Over-widening can be due to ice processes or upstream thalweg shifts. Bars vegetate and stabilize, vertically accreting to floodplain level while also growing laterally. Flow subordinate to that of the main channel allows lateral accretion away from the dominant channel. One island often consolidates with many isolating the subordinate flow into the resultant side channel. This channel then adjusts its plan-form sinuosity and geometry to reach equilibrium with flow conditions and continues to laterally migrate, often far from the center line of the main channel. The second way sloughs can form is from lateral erosion processes when sections of channel are cut-off by two channels migrating into each other. Meander neck cut-off on individual channels can also cause this result.

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