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ON THE NATURE AND ORIGIN OF MUCK DEPOSITS, KLONDIKE
DISTRICT, YUKON TERRITORY

by
TIFFANI FRASER, B.A. (Hons)

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Master of Arts
Department of Geography

Carleton University
Ottawa, Ontario
17 September 1995

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DISTRICT, YUKON TERRITORY"

submitted by Tiffani Fraser, B.A. Honours,
in partial fulfilment of the requirements for the degree of
Master of Arts.

A handwritten signature in cursive script, appearing to read 'CH. Gunn', is written over a horizontal line.

Thesis Supervisor

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Chair, Department of Geography

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Abstract

The nature, origin, and geocryological characteristics of muck deposits have been studied in the Klondike District, Yukon Territory. Klondike mucks comprise two units: Pleistocene silt overlain by Holocene peat. Both units are perennially frozen and contain bodies of massive ice, namely segregated and intrusive ice and ice wedges. The Silt unit comprises primary and redeposited McConnell-aged loess, which began accumulating between 26,240 and 24,025 ^{14}C years BP, and declined during later stages of the McConnell glaciation. The Organic unit comprises in situ and colluvial material which began to accumulate as early as 9,945 ^{14}C years BP. Permafrost aggraded through the mucks syngenetically. Massive icy bodies in the Silt unit are mostly late-McConnell phenomena, while those in the Organic unit are smaller, Holocene features. The study sheds new light on eolian and slope processes occurring in eastern Beringia during the Late Wisconsinan glaciation.

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Chapter 1: INTRODUCTION

This thesis discusses the nature, origin, age, and periglacial development of Pleistocene 'muck' deposits in the Klondike District, central Yukon Territory. The study contributes sedimentological and chronological information towards an understanding of late Quaternary valley evolution in an unglaciated environment.

In the Klondike District, organic, silty sediments, known as 'black muck', are the most recent deposits, and are found on top of older, gold-bearing sediments. The mucks are classified into two major units: a lower Pleistocene silt; overlain by organic-rich Holocene deposits (Figure 1.1). The silt is commonly tan, grey or brown, and contains Pleistocene mammal bones and some of the largest ground ice masses in central Yukon. The upper unit is often black, and contains in situ and colluvial peat, plant macrofossils, silt, sand and gravel. Both units are perennially frozen. In its undisturbed state, muck can be several metres thick. When muck is disturbed, it thaws and emits a repulsive odour which has been aptly compared to that of a charnel house (Richardson 1861).

1.1 Study Area and Background

The study is focussed on the Klondike District, west-central Yukon Territory (NTS map sheet 115 N/O) (Figure

Figure 1.1

Photograph of a typical muck section in the Klondike District, portraying a silt unit overlain by an organic-rich unit. Auriferous valley-bottom gravels can be seen at the base of the measuring tape.

1.2). The district is bounded by Indian River to the south, Klondike River to the north, Flat Creek to the east and Yukon River to the west (Figure 1.3). The area lies between $63^{\circ}30'$ and $64^{\circ}10'$ N and $138^{\circ}30'$ and $139^{\circ}30'$ W. The area formed a part of the eastern Beringian refugium, a portion of northeastern North America and northeast Russia which remained unglaciated during the Quaternary (e.g., Hopkins et al. 1982).

The Klondike is famous for its placer gold deposits. Gold was discovered on Bonanza Creek in summer 1896, precipitating the Klondike Gold Rush of 1898. Since the discovery, the Klondike goldfields have consistently been the major producer of gold in the Yukon (Morison 1985).

Muck deposits have traditionally been considered a hindrance to gold-mining, since the gold is in gravels, located in valley bottoms or on benches, overlain by several metres of frozen muck. In order to reach the gold, miners must strip away the frozen muck, a laborious and expensive process.

The muck, however, is of value to the academic field of Quaternary research. Muck deposits contain fossilized information about the nature of the Beringian ecosystem and information about late Quaternary depositional processes in unglaciated terrain. Since mining in the area began, fossilized remains of terrestrial mammals, many which are now extinct, have been recovered from the muck deposits.

Figure 1.2

Location of the Klondike Placer Mining District, west-central Yukon Territory.

Figure 1.3

The Klondike Placer Mining District showing major rivers and creeks, and all minor creeks, gulches and pups mentioned in the text (after Morison 1985).

Remains of woolly mammoth, steppe bison, and small horse are common in the Klondike (e.g., Harington 1987). The muck also contains important stratigraphic information which can be used to define late Pleistocene depositional and erosional processes. Finally, the muck is perennially frozen and contains massive icy bodies of various forms and origins. The fossils, stratigraphy and periglacial characteristics of the muck provide valuable paleoenvironmental information on Beringia, from which climatic associations and other paleogeographical information can be drawn.

1.2 Origin and Nature of Klondike Muck

This study builds upon the work of Tyrrell (1917), Campbell (1952), Harington and Clulow (1973), Milner (1976), Naldrett (1982), and French and Pollard (1985) who have studied one or several aspects of the Klondike muck deposits, and have offered suggestions surrounding their nature, origin, age, and/or periglacial characteristics. It also draws upon the work of Wilkerson (1932), Tuck (1940), Black (1953), Péwé (1955; 1968; 1975a; 1975b), Péwé and Journaux (1983), Hamilton *et al.* (1988), and Guthrie (1990) who have studied muck deposits in Alaska, particularly in the vicinity of Fairbanks.

Research conducted on muck deposits in Alaska predates that in the Klondike District. Alaskan models suggest that

in the Fairbanks area, resedimented windblown material, from more than one Pleistocene glaciation, has led to the massive silty deposits seen in valley bottoms. These models attribute the origin of more organic-rich units to both in situ and colluvial vegetation that collected during warmer and wetter interstadial periods. Because these deposits contain material from several glacial periods, evidence of several cycles of permafrost aggradation and degradation are represented in exposures. Degradation has resulted in the melting of massive icy bodies, the formation of relict features such as ice-wedge casts, and deepening of the active layer or the elimination of frozen ground.

There is little information surrounding the origin, age and periglacial characteristics of muck deposits in the Klondike. Muck in the Klondike has often been characterized as windblown silt overlain by partly in situ, and partly transported, organic material (e.g., Milner 1976, Naldrett 1981). As very little scientific evidence exists for these hypotheses, statements surrounding the origin of muck in the Klondike appear to be based upon Alaskan research (e.g., Péwé 1955, 1975a). In addition, there is little dated material from in situ organic horizons in the muck. This lack of chronological control has made it difficult to determine where the muck accumulation period fits in both the Quaternary history of central Yukon, and evolution of valleys in the Klondike District.

1.3 Objectives and Methodology

To enhance understanding of the nature, origin, age, and periglacial characteristics of muck deposits, the objectives of this study are to:

- (1) describe the nature and distribution of the muck deposits;
- (2) determine the origin of the muck deposits;
- (3) provide an age for the muck accumulation event(s), and to define a place for this (these) event(s) in the late Quaternary history of central Yukon Territory, and the Klondike District;
- (4) comment on geocryological characteristics and periglacial history of the muck deposits;
- (5) provide a model summarizing the environmental history of the muck deposits.

This study involved both field and laboratory components. Field work was conducted between June 1st and September 10th, 1994. Twenty-three different exposures, from six major drainages: Hunker, Bonanza, Bear, Dominion, Quartz and Sulphur Creeks were visited. At each exposure, beds were described and measured, and sedimentological columns were constructed depicting major units identified. Samples were taken at each exposure for subsequent particle-size distribution, mineralogy, organic content, grain shape and surface texture, radiocarbon dating and pollen analysis. Ground ice and permafrost characteristics were described and sampled at each site as well. The data collected in the

field and derived in the lab have been assembled to contribute towards the following working hypotheses:

- (1) muck deposits in the Klondike District, which are found in the bottoms and lower-reach of valleys, are most often comprised of two main units: a Pleistocene silt (the Silt unit), unconformably overlain by a Holocene peat (the Organic unit);
- (2) the Silt unit is comprised of both primary and redeposited loess, and the Organic unit consists of both in situ and colluvial organic material;
- (3) the Silt unit was transported to the Klondike District as loess during the McConnell (Late Wisconsin) glacial period;
- (4) Holocene peat accumulation in the Klondike District began as early as 9,945 ^{14}C years BP;
- (5) muck deposits in the Klondike were permanently frozen shortly following their accumulation in valley bottoms;
- (6) massive icy bodies in the Silt unit are mostly late McConnell phenomena which have derived their water source from both ground and surface waters, while icy bodies in the Organic unit are Holocene in age, some being modern features;
- (7) during the early Holocene, a post-glacial warming period was responsible for truncating ice wedges below the surface and the transport of large volumes of silt from the district.

1.4 Outline of Chapters

The next chapter discusses the theories of muck accumulation in the Klondike District, as well as in other areas of unglaciated North America, particularly Alaska. Chapter three discusses the regional physiography and geology of the Klondike District, the glacial history of

central Yukon, and the modern Klondike environment. Chapter four describes the methodology of this research project. Results of field and laboratory analyses are offered in chapter five, as well as a discussion of their significance. Chapter six concludes the study and offers suggestions for further topics of research.

Chapter 2: THE DEVELOPMENT OF THE KLONDIKE MUCK DEPOSITS

The Klondike muck deposits are of considerable interest because of their location above auriferous gravels, and the potential paleoenvironmental information contained within them. Various authors have commented upon muck deposits in the Klondike, but little is known about their origin, geocryology, or the timing of their development. Substantiated hypotheses, however, do exist about muck development in other parts of eastern Beringia, such as Alaska, and similarities between those deposits and the Klondike mucks have been noted.

The purposes of this chapter are to: (1) provide a modern, working definition of the term 'muck' for the Klondike District; (2) describe the general nature of the deposits, based upon historical and modern research; (3) show the geographical distribution of muck deposits in Beringia; (4) comment on research conducted on the muck deposits in Alaska; and, (5) discuss the literature surrounding the origin, geocryology and chronology of muck deposits in the Klondike.

2.1 Definition of Muck

Previous researchers have used the term muck to describe various deposits. To avoid confusion, a working

definition for 'muck' in the Klondike District was developed during summer field investigations in 1994. In this thesis, 'muck' refers to silt, and other organic-rich materials that overlie valley-bottom gravels.

2.2 Description of Muck

Historically, the term 'muck' has been used to describe various deposits. Prindle (1913) and Tuck (1940) describe 'muck' as a black, organic-rich deposit, derived from the decomposition of moss and other vegetation. Tyrrell (1917) considers 'muck' to be derived from vegetation which is partly in situ, such as peat, and partly transported. The definition of 'muck' has also included a silt component. This silt is light-coloured and fine-grained, containing little or no organic material (Tuck 1940), and comprises "predominantly...very fine, partly rounded angular grains of quartz, with grains of other minerals resistant to decomposition" (Prindle 1913: 93). In one instance 'muck' has been used to define all creek bottom deposits, including angular, cross-bedded gravels, which lie below the silt, on bedrock (Campbell 1952). Since the 1970s, the term 'muck' has been used to describe a frozen, organic-rich silt, which overlies gold-bearing gravels (Harrington and Clulow 1973; Naldrett 1981; Harrington 1989; Vongpaisal et al. 1993). The diversity of definitions of 'muck' suggest the variety of

deposits that have been studied.

Detailed descriptions of Klondike muck deposits were made in summer 1994 (see Chapter 5). The deposits are located in valley bottoms and are most often comprised of two distinct units: a lower, well-sorted silt; overlain by an organic-rich peat (Figure 1.1). When frozen, muck deposits form stable exposures which can be several metres thick. In summer 1994, maximum thicknesses were slightly greater than 25 metres. When muck thaws, it loses its stability and will flow away like a thick slurry. Historically, Klondike miners have used this property to their advantage. Monitors, or pressurized water jets, have often been used to thaw and strip the muck away from the underlying gravels (Figure 2.1). After monitoring, the thawed silt and organic material is then carried downstream, in suspension, to a settling pond.

2.3 Location of Muck

Portions of Canada, Alaska and western Siberia which remained unglaciated during Quaternary glaciations are referred to as Beringia (Hopkins 1967; Figure 2.2). Muck deposits have been recorded from various locations throughout the region. The area is renowned for its periglacial environment which provided refugia for a large diversity of plants and animals during the Pleistocene

Figure 2.1

Photograph of a placer mining operation on Sulphur Creek using a 'monitor' to strip muck from the gravels.

Figure 2.2

Map of northwestern North America and northeast Russia (after Hopkins, 1982: Fig.1). Unglaciated portions of this area constituted the Beringian refugium. Beringia also included portions of the Bering Shelf which were exposed when sea-levels were lower during Quaternary glaciations.

glacial periods. Due to cold and arid full-glacial conditions, the vegetation of Beringia was treeless and open, displaying both tundra and steppe-like characteristics (Schweger 1990). The fauna of Beringia is believed to have been more abundant and diverse than at present. It included many large animals such as the woolly mammoth, steppe bison, small horse, and camel (Guthrie 1982). In addition, portions of the Bering Land Bridge, including exposed Bering and coastal shelves, may have served as migration routes for animals, plants and humans migrating from Asia to North America (Matthews 1976; Harington 1978).

In eastern Beringia, muck is found in Alaska in the Fairbanks area (Prindle 1913; Tuck 1940; Black 1951; Taber 1953; Péwé 1975b; Hamilton et al. 1988), Seward Peninsula (Porsild 1938), Colorado Creek (Thorson and Guthrie 1992) and at Lost Chicken Creek in the Fortymile District (Porter 1988). Muck deposits in the Yukon Territory are found in the Klondike (e.g., Tyrrell 1917; Campbell 1953; Milner 1976; Naldrett 1981), and Sixtymile Districts. In western Beringia, muck is reported in Mamontova Gora, central Yakutia (Péwé 1977).

Common among the various muck deposits is that they are most often exposed and studied in placer mining areas. Placer mines are favourable locations to study muck, as activities involved, such as 'monitoring', provide accessible, clean, and vertical exposures available for

study (Figure 2.3).

2.4 Muck Research in Alaska

Muck studies from Alaska are mentioned for three reasons: (1) the studies in Alaska, for the most part, pre-date the research done in the Klondike; (2) the research from Alaska is comprehensive and the theories are well substantiated by field and laboratory results; and (3) similarities surrounding the nature and origin of muck deposits in the Klondike and in Alaska have been noted.

2.4.1 Origin

In the first half of this century, the origin of the massive silt deposits in Alaska was a matter of controversy (Péwé 1968). Researchers argued that the silts were fluvial, lacustrine, marine or estuarine in origin, or were the result of in situ bedrock disintegration (Prindle 1913; Harrington 1918; Wilkerson 1932; Taber 1943, 1953). An eolian (wind-blown) origin was first proposed from field observations that the silt was "uniformly fine-grained" (Tuck 1940: 1304). Later, following extensive field and laboratory work, and a systematic elimination of other hypotheses, the eolian hypothesis was accepted (Péwé 1968).

Silty deposits in interior Alaska are now considered to

Figure 2.3 **Photograph of a muck section on Sulphur Creek**
immediately following monitoring.

be derived from loess of glacial outwash (Guthrie 1990: 53; Figure 2.4). Loess originates from the glacial grinding of rock into tiny particles. These particles are then deposited beyond the glacier terminus by outwash streams. Strong katabatic winds blowing off the glacier, lift the glacial dust from stream bars and carry it across the unglaciated landscape, where it accumulates, often as thick deposits. While loess deposition is active in the Fairbanks area today (Guthrie 1990: 56), it was much more extensive during glacial periods. During Pleistocene glaciations, when Beringia was bounded by extensive glaciers and glacial outwash streams, the area became mantled with thick loess deposits, many which are still visible (Péwé 1975a, 1975b).

Less controversial than the debate regarding origin, is the notion that following silt deposition, portions of the silt were eroded and redeposited into valley bottoms. Slopewash, gullying, solifluction, sheetwash, fluvial and thawing of ground ice are identified as processes involved in silt retransportation (Wilkerson 1932; Taber 1943; Péwé 1955; Hamilton et al. 1988; Guthrie 1990: 55; Thorson and Guthrie 1992). The timing of silt redeposition, however, remains unresolved. While some research favours the timing of silt redeposition as occurring during warmer and wetter interstadials (e.g., Hamilton et al. 1988), others include the reworking of silt by rain and snowmelt during glacial periods (Guthrie 1990).

Figure 2.4 **Origin of modern loess in interior Alaska**
 (Guthrie 1990: Fig. 2.9).

Warmer and moister conditions in the history of muck development are represented by in situ organic horizons, as during these periods, soils are able to form, and climatic conditions are favourable for vegetation growth. The Eva Formation, for example, is a paleosol found in muck deposits in the Fairbanks area. This paleosol contains rooted tree stumps suggesting the presence of a buried forest (Péwé 1975a). In addition, the Ready Bullion Formation, a Holocene loess deposit in the same area, contains rooted stumps of birch and spruce, plant fragments, peat lenses, sticks and logs (Taber 1943; Péwé 1975a). Often these organic horizons contain colluvial organic and inorganic material as well. Accumulations of tree trunks, branches and bones are noted as having been "washed in" to the valleys (Tuck 1940: 1300), along with retransported loess, bedrock fragments, and gravel lenses (Tuck 1940, 1943; Péwé 1975).

2.4.2 Geocryological Characteristics

The types of ground ice identified in muck deposits include pore ice, segregated ice, wedge ice, and buried ice, such as a buried thaw pond (Tuck 1940; Taber 1943; Hamilton et al. 1988; Thorson and Guthrie 1992). Porsild (1938) observed mounds formed by hydraulic pressure, or intrusive ice, in muck deposits in the Seward Peninsula.

Pore ice is "ice that fills or partly fills pore space

in the ground" (Péwé 1975b: 48). It forms by the in situ freezing of pore water and involves no addition of water. Segregated ice is described as ice seams, lenses or layers that grow in the ground by the migration of water to the freezing front as the ground freezes (Taber 1943). Foliated ground ice or ice wedges, are large masses of ice which grow in thermal contraction cracks in permafrost (Péwé 1975b). The theory of thermal contraction is described by Leffingwell (1915, 1919) and is developed by Lachenbruch (1962). Buried ice includes sea, lake, river, and glacial ice, recrystallized snow and/or aufeis (accumulations of ice formed by spring floods), which have been buried and preserved in sediments. Because of its geographical position, buried sea or glacial ice would not likely be found in muck deposits in central Alaska. Pingo ice is "clear or relatively clear ice that occurs in permafrost in nearly horizontal or lens-shaped masses 3 - 15 m in diameter" (Péwé 1975b: 49).

Ice wedges and ice-wedge casts can be observed in Alaskan mucks. Ice wedges observed in Alaska include only those that have formed during, or since the last (Wisconsin) glaciation (Péwé 1975b). Ice-wedge casts of earlier glacial periods (Illinoian and pre-Illinoian) are present in muck deposits in the Fairbanks district (Péwé 1975b). These casts indicate former periods of periglacial activity which were followed by warmer periods when the ground was able to thaw.

2.4.3 Chronology of Muck Development

Muck deposits near Fairbanks often represent deposits which discontinuously span most of the Pleistocene and Holocene periods (Hamilton and Brigham-Grette 1991). Deposits from full-glacial conditions have been interpreted as mostly redeposited loess, while interglacial deposits contain more organic material, especially plant macrofossils, and are colluvial and in situ in nature. Interglacial periods were also times of significant erosion. Surficial deposits in the Fairbanks area are shown schematically in Figure 2.5, and are described below.

In the Fairbanks area, redeposited loess deposits of full-glacial eras are the Gold Hill Loess and the Goldstream Formation (Péwé 1975a). The Gold Hill Loess (GHL) consists of loess derived from early Pleistocene glaciations, including the Illinoian (Péwé 1975a), and possibly earlier one(s) (Péwé 1989). The GHL is a well-sorted silt unit, up to 55 m thick, representing a long interval of rigorous periglacial climate when the treeline was 450 - 600 m lower than today. Ice-wedge casts are seen in this unit, but not ice wedges (Péwé 1975a, 1975b).

The Goldstream Formation consists of retransported valley silts of Wisconsin age (Péwé 1975a). This formation contains an abundance of vertebrate and plant fossils, including partial carcasses of vertebrates which were

Figure 2.5 **Quaternary surficial deposits of the Fairbanks area (after Pewe 1977).**

- Rb Ready Bullion Formation
- GsF Goldstream Formation
- Ev Eva Formation
- GHL Gold Hill Loess
- Gt Terrace gravels (known locally as Cripple Gravel)
- Gc Creek-bottom gravels (known locally as Fox Gravel)

entombed in the silt and permanently frozen. Large ice wedges are present in this unit, representing a time of rigorous periglacial conditions (Péwé 1975b).

Interglacial episodes represented in Fairbanks muck deposits include the Dawson Cut Formation, the Eva Formation, and the Ready Bullion Formation (Péwé 1975a). The Dawson Cut Formation is the oldest deposit overlying valley bottom gravels. It is a silt unit, 1-3 m thick, that contains peat lenses, logs and forest beds. The deposit was formerly believed to represent a pre-Illinoian interglacial period, possibly the Yarmouthian (Péwé 1975a). As the deposit underlies the Old Crow tephra, recently dated to 1.89 ± 0.20 Ma (Westgate *et al.* 1990), the Dawson Cut Formation is likely much older than Yarmouthian.

The Eva Formation is a paleosol representing a warm period following the Illinoian glaciation (Péwé 1975a). It is a forest bed 1 m thick, containing roots and logs of white spruce, and birch up to 25 cm in diameter and 3 m long. Radiocarbon ages show that this forest bed represents a warm interval occurring before 57,000 years BP, and it is presumed to be of Sangamon age (Péwé 1975a, 1975b). Other evidence in the Fairbanks area suggests that this peaty horizon could be mid-Wisconsin ($\approx 30 - 60$ ka BP) in age (Hamilton and Brigham-Grette 1991). During this interglacial period, loess from the Illinoian glaciation was deeply gullied and removed, and permafrost thawed, and may have

completely disappeared (Péwé 1975a).

Following the Wisconsin glaciation, approximately 10,000 years ago, a warming interval occurred which caused the permafrost table to be lowered by 2 - 3 m, and the top of the ice wedges located in the Goldstream Formation to melt down 0.3 - 3m (Péwé 1975b). Since the warming, the permafrost table has risen. Loess and retransported silt that have been deposited since, and during the warming, are known as the Ready Bullion Formation (Péwé 1975a). This formation is 0.3 - 8 m thick, and, in valley bottoms and on lower slopes, forms the substrate for the modern soil. The unit, except for the upper 1.5 m, is permanently frozen, and contains active ice wedges (Hamilton et al. 1988). The unit does not contain bones of extinct animals (Péwé 1975a).

2.5 Muck Research in the Klondike

Although Klondike muck deposits have received considerably less attention than those from Alaska, there are several reports on their development.

2.5.1 Origin

As in Alaska, the silty unit in the Klondike valleys is often characterized as resedimented windblown material (Campbell 1952; Harington and Clulow 1973; Milner 1976;

Naldrett 1981). Unlike Alaska, however, little sedimentological evidence (e.g., particle-size analysis) exists to support a windblown theory. Upper slope frost weathering is postulated as an additional source for the silt (Milner 1976). From field observations, solifluction, meltwater rill erosion, slopewash, earthflows, rockslides, gelefluction, low energy streams and local ponding are all considered responsible for the resedimentation of the silt into valley bottoms (Campbell 1952; Harington and Clulow 1973; Milner 1976; Vongpaisal et al. 1993).

Both in situ and colluvial origins are postulated for the organic unit. Campbell (1953) observes traceable beds of peat along lower Hunker Creek, where the horizons were less than 1 m thick and contained tree trunks up to 25 cm in diameter. Milner (1976) includes a peat and a woody peat facies in his model of valley-bottom deposits. Naldrett (1981) notes traceable beds of peat which he interpreted as relatively long periods of stability, during which organic deposits could develop in place. Tyrrell (1917) considers a partly in-place and partly transported origin for organic material in the muck. In-place materials are described as growing peat bogs that were able to form on frozen gravel deposits during the Glacial Epoch. Transported material accumulated during floods, when torrential waters were able to cover the banks, breaking down trees, shrubs and sticks.

The waters then carried the organic debris to bog flats where they were distributed, along with sand and clay.

2.5.2 Geocryology

The literature contains brief discussions concerning the nature and origin of massive icy bodies in Klondike muck. Tyrrell (1917: 41) observes that the muck contains a "large quantity of water in the form of ice, the percentage by weight being on average about 44%". He notes that throughout the muck, layers of clear ice can be found. These clear layers are thought to have formed from spring water rising from the gravels beneath, and freezing before reaching the surface. Campbell (1952) comments upon the frozen nature of the muck, and observes that water contained within the deposits is in the form of ice. He draws upon the work of Taber (1943) and Tyrrell (1917) and claims that clear, or almost clear ice, is formed in all fine-grained sediments that are well supplied with groundwater.

The most comprehensive work conducted on massive ground ice in the Klondike is by French and Pollard (1986). Their study involved a stratigraphic and petrofabric investigation of ground ice exposed by a mining operation on lower Hunker Creek, in order to define an origin for the massive ice seen in the exposures. They were unable to determine the origin of the ice with certainty, but suggested that buried surface

ice, such as a buried snowbank, or segregation ice, were probable explanations. The buried snowbank hypothesis was substantiated, in part, by the small and uniform crystal sizes of the ice, suggestive of snow crystals, and by the orientation of bubble inclusions at an angle possibly parallel to the layering of a snowbank. Two lines of evidence were used to support a segregated origin for the ice: first, the occurrence of massive ice over sands and gravels is typical of massive segregated ice described from the Mackenzie Delta (e.g., Mackay 1971, 1973); and, second, the small crystal sizes in the ice could be equated with other genuine segregated ice bodies. Pore ice, wedge ice, tension crack ice, open or closed cavity ice, and intrusive ice were systematically discounted as origins for the icy bodies.

2.5.3 Chronology of Muck Development

The chronology of muck development in the Klondike is not as well-defined as in Alaska, as there are relatively few radiocarbon dates available from in situ organic horizons. Despite the lack of temporal control, chronological hypotheses based upon stratigraphic observations, however, do exist. While ideas differ on the precise timing of these events, most authors would agree that the muck deposits record changing climatic conditions

during the Pleistocene. Although a full discussion of Pleistocene glacial history in central Yukon is presented in Chapter 3, the terminology and chronology for the glacial periods is now introduced (Table 2.1).

Four Pleistocene advances of the Cordilleran ice sheet have been inferred from geomorphological evidence in central Yukon (Bostock 1966). These glaciations, from oldest to youngest, are known as the Nansen, Klaza, Reid and McConnell. The Nansen and Klaza, often referred to as Pre-Reid glaciations, are pre-Illinoian in age. The Reid glaciation is thought to be Illinoian in age, although an Early Wisconsin age has not been discounted. The McConnell is the classical Late Wisconsin glaciation. Glacial advances from the Southern Ogilvie Mountains have been correlated to the Pre-Reid, Reid and McConnell events. These advances are known as the 'old', 'intermediate', and 'last' glaciations.

There are different opinions regarding the time of Klondike muck accumulation. In a general account, Tyrrell (1917: 42) presumes that the muck accumulated during the Glacial Epoch (Pleistocene), a time when "the mean annual temperature of that country was considerably lower than it is at present". Following accumulation, the muck froze, and has been frozen ever since. Tyrrell (1917: 44) argues that the muck has remained frozen since the "beginning of refrigeration", because the gravels from the valley sides have not given way and been incorporated into the muck.

Table 2.1 Stratigraphic nomenclature of the Pleistocene glacial sequence in the Yukon Cordillera and Southern Ogilvie Range (from Heginbottom and Vincent 1986 and Hughes *et al.* 1989, after Bostock 1966, Vernon and Hughes 1966, and Hughes *et al.* 1969).

General Chronostratigraphy			Cordilleran Ice Sheet	Glaciation in Southern Ogilvie Range
Holocene			Non-Glacial Interval	Non-Glacial Interval
Pleistocene	Late	Wisconsin	McConnell Glaciation	"Last" Glaciation
		Sangamon	Reid -McConnell Non-Glacial Interval	Non-Glacial Interval
	Middle	Illinoian	Reid Glaciation	"Intermediate" Glaciation
			Klaza-Reid Non-Glacial	Non-Glacial Interval
	Early	Pre-Illinoian	Klaza Glaciation	"Old" Glaciation
			Nansen Klaza Non-Glacial	
			Nansen Glaciation	"Old" Glaciation?

Gravels in the muck would suggest that from time to time, the climate was warm enough to thaw the permanently frozen ground.

Campbell (1952) estimates that muck has been accumulating since the beginning of the Wisconsin glaciation. During the onset of the Wisconsin, a cold climate regime was responsible for what he referred to as 'muck below grade': angular, cross-bedded gravels which originated from frost-fractured bedrock subject to fluvial transport and deposition. He proposes that following the severe cold conditions, climatic conditions ameliorated. His speculations are based upon observations of the decrease in particle-size of the material above the gravels, and the observation that towards the tops of the exposures, there are "several prominent organic layers which contain good-sized stumps of trees in position of growth" (Campbell 1952: 98).

Milner (1976) suggests that his different muck facies represent the equilibrium between erosion, deposition of colluvium, and soil development during climatic changes following Reid and McConnell glaciations. He postulates that loess began accumulating in the Klondike during the Reid glaciation. During Reid-McConnell interglacial period, colluvial processes retransported loess, fine-grained material produced by frost weathering, and shattered bedrock, to valley bottoms. Following retransportation, the

sediments became permanently frozen. He proposes that loess accumulation occurred again during the McConnell glaciation. At the end of the McConnell, loess was retransported during a period of significant erosion. Following erosion, early Holocene conditions prevailed. He suggests that early Holocene sediments are represented by organic soil with calcareous pond deposits, wood dated at 9,520 ^{14}C years BP (GSC-73; Dyck and Fyles 1963), buried grassland deposits, silty soils and spruce sphagnum forest soils. In contrast, he suggests that Late Holocene sediments are represented, in part, by charcoal and fire-induced solifluction scrolls (sic), showing that the climate was dry enough to burn vegetated slopes.

Naldrett (1981) proposes that Pre-Reid glaciations were the probable source of wind-blown silt which was later incorporated into ice-rich muck deposits. During the Reid or McConnell glaciations, permafrost and ice wedges formed in the creek gravels and muck. He describes warmer periods in the Pleistocene as times when main valleys in the Klondike experienced repeated infilling by clastic sediments. During colder conditions, permafrost aggraded into these sediments and massive icy bodies were formed.

Several researchers have commented upon a period of permafrost degradation in the muck deposits, represented by a thaw unconformity (Campbell 1952; Milner 1976; Naldrett 1981). The unconformity exists within a few metres of the

present surface of the muck and can be recognized from the occurrence of truncated ice wedges. This unconformity is believed to correlate with the period of warmest climate during the early Holocene (Campbell 1953; Milner 1976; Naldrett 1982). Campbell (1953) states that this warm period occurred approximately 4,000 years BP, however the post-glacial climatic optimum is now recognized as having occurred in the central Yukon at an earlier date, between approximately 10,000 and 7,000 years BP (Burn et al. 1986). Harington and Clulow (1973) recognize a period of exceedingly rapid, heavy erosion at approximately 11,000 years BP, which may correlate with this thawing period. The thaw unconformity has been correlated to a similar unconformity seen in deposits in the Fairbanks area (e.g. Péwé 1975b), at Mayo (Burn et al. 1986; Burn 1990), and in the western Arctic (e.g., Mackay 1983).

Radiocarbon dating of in situ organic horizons has provided a distinct chronology of muck accumulation in the Fairbanks region of Alaska. In the Klondike, however, radiocarbon dating has been used primarily to date fossil vertebrate remains, and, occasionally, organic material. The determination of ages for bone specimens is an important tool in defining paleofaunal characteristics in eastern Beringia. Many of the dated fossils found in muck deposits, however, are colluvial in nature (Harington 1978), and therefore, do not provide chronological information

pertaining to the accumulation of muck. Dated material from in situ horizons, such as peat or grass beds, can provide accurate chronological information for particular surfaces that existed in the past.

There are a few dates available for organic material in Klondike muck deposits (Table 2.2). On the right bank of Hunker Creek at the mouth of Last Chance Creek (see Figure 1.2), a date of $30,800 \pm 1,600$ ^{14}C years BP (GSC-88; Dyck and Fyles 1964) was determined for fine plant detritus located in the silt unit. The sample was taken from 0.6 m above the creek level, and 1.2 m below the top of the silt. The silt unit at this location was overlain by 6.1 m of peat. At the same location, a wood sample from the base of the peat unit, overlying the silt, was dated at $9,520 \pm 130$ ^{14}C years BP (GSC-73; Dyck and Fyles 1963). Another date of $8,660 \pm 140$ ^{14}C years BP (GSC-57; Dyck and Fyles 1963) was determined for wood 1.2 m above the basal contact of the peat unit. The range in dates have been used to infer a major stratigraphic break between the organic unit and the silt unit (Dyck and Fyles 1964). It is unknown if these organic samples were derived from in situ horizons.

A date of $>53,900$ ^{14}C years BP (GSC-527; Lowdon and Blake 1968), was determined for spruce wood from Hunker Creek between 'Too Much Gold' and 'Gold Bottom' Creeks. The wood specimen was taken from organic silt overlying auriferous gravels and underlying silty gravel with mammoth,

Table 2.2 Existing dates for organic material located in Klondike Muck Deposits

Date (YBP)	Material	Location	Position in Section	Reference
> 35,000 (1/GSC/181)	spruce wood	Left limit of Hunker Creek between Too Much Gold and Gold Bottom Creeks	From organic silt overlying auriferous gravels. Silt was overlain, successively, by silty gravel with mammoth, horse, and bison remains, organic silt, and peat.	Dyck and Fyles (1962)
> 53,900 (GSC-527) (supersedes 1/GSC/181)	spruce wood	Left limit of Hunker Creek between Too Much Gold and Gold Bottom Creeks	From organic silt overlying auriferous gravels. Silt was overlain, successively, by silty gravel with mammoth, horse, and bison remains, organic silt, and peat.	Lowdon and Blake (1968)
30,800 $\pm$ 1,600 (GSC-88)	fine plant detritus	Right bank of Hunker Creek at mouth of Last Chance Creek	In frozen silt unit, 0.6 m above creek and 1.2 m below top of silt. Silt overlain by 6.1 m of peat.	Dyck and Fyles (1964)
9,520 $\pm$ 130 (GSC-73)	wood	Right bank of Hunker Creek at mouth of Last Chance Creek	Base of peat unit which overlies silt	Dyck and Fyles (1963)
8,660 $\pm$ 140 (GSC-57)	wood	Right bank of Hunker Creek at mouth of Last Chance Creek	1.2 m above basal contact of peat unit	Dyck and Fyles (1963)

horse, and bison remains, organic silt, and peat. This date has been interpreted by others as a maximum age for muck accumulation on the floor of Hunker Creek, correlating with either the Reid glacial or post-Reid interglacial period (Hughes et al. 1972; Naesar et al. 1982). This date superseded one of >35,000 ^{14}C years BP (I/GSC/181; Dyck and Fyles 1962) determined for the same wood specimen. Again, it is unknown if this sample was taken from an in situ organic horizon.

Several radiocarbon dates are available for fossil bones exposed in the Klondike mucks. There is an abundance of information about vertebrate remains in the Klondike, as the Dawson area is regarded as one of the richest Pleistocene mammalian sites in Canada (Harington 1985). Since 1966, hundreds of Pleistocene mammal bones have been collected from over sixty-five placer mines in the Klondike District alone (Harington and Morlan 1992).

The bones in the Klondike are mainly exposed by placer mining operations. The majority of bones are found within the basal 1.5 m of the silty unit, just above the contact with the underlying gravels (Harington 1987; Figure 2.6). While many of the bones have a fresh appearance because of their preservation in frozen ground, they are mostly incomplete, and are rarely found in their original state of deposition (Harington 1978).

The most common remains uncovered in the Klondike, and

Figure 2.6

Mammal bones located at the contact between gravels and overlying silt in Skookum Gulch, July 1994.

in most other muck localities in Beringia, are small horse (Equus lambei), mammoth (Mammuthus primigenius), and steppe bison (Bison priscus) (Harington 1978). Remains of dall sheep (Ovis dalli), caribou (Rangifer tarandus), moose (Alces alces), American lion (Panthera leo atrox), short-faced bear (Arctodus simus), and arctic ground squirrel (Spermophilus parryi), to name a few, have also been found (Harington 1978). The dominance of bison, mammoth and horse remains have led some paleontologists to believe that Beringia was characterized by an extensive grassland environment during the Pleistocene glaciations (e.g., Harington 1977, 1978; Guthrie 1985, 1990).

The majority of bone specimens collected from the Klondike area during the 1970s and 1980s are Late Wisconsin in age, particularly in the 15,000 - 30,000 ^{14}C years BP range (Harington 1989). Within the last few years, AMS techniques have revealed older dates, specifically between 35,000 and 50,000 years BP (C.R. Harington, personal communication, 1995). It is interesting to note that even though the majority of bones found in situ are located in the same stratigraphic position, i.e., close to the gravel/silt contact, there is a distinct range in age of specimens of up to several thousand years.

One of the most interesting finds in the Klondike District was a partial carcass of Equus lambei in September 1993, on Last Chance Creek. The carcass consisted of

"...most of the right foreleg with dried flesh, skin and hair on the lower parts" (Harington et al. 1993). The carcass had been found in situ in frozen silt, along with a large part of the hide with a long, blondish tail, and portions of the gut and stomach contents. AMS dating yielded an age of $26,280 \pm 210$ B.P. (Beta 67407), indicating "...that the horse died during a relatively warm interval (interstadial) before the peak of the last glaciation about 20,000 to 18,000 years ago" (Harington et al. 1993).

2.5 Summary of Chapter

In the past, the term 'muck' has been used most commonly to describe silty and organic deposits which are located in Beringia, portions of unglaciated Canada, Alaska and western Siberia. In Alaska, studies have shown that valley-bottom silt deposits are glacially-derived eolian material which has been retransported by a variety of slope and alluvial processes. Organic materials represent interstadial periods and are both in situ and colluvial in origin. Muck deposits in Alaska contain a variety of ice types, such as pore, segregated, wedge and buried ice. Extensive dating of organic material and tephras suggest that muck in the Fairbanks area represents deposits which discontinuously span most of the Pleistocene and Holocene.

As in Alaska, muck deposits in the Klondike District

are considered to be resedimented loess, but little scientific evidence exists to support this hypothesis. The organic unit is considered to be in situ and colluvial in nature. There are several reports on the presence of ground ice in the Klondike mucks, but only one detailed geocryological study has been conducted. The study by Pollard and French (1986) determined either a buried snowbank or segregated origin for a body of ice located in frozen muck on Hunker Creek. Various opinions exist regarding the age of the muck deposits. Some suggest that the muck deposits are Pre-Reid materials, while others suggest that they are Reid and/or McConnell. The lack of radiocarbon dates from in situ organic horizons located in the muck, has made it difficult to determine the age of the deposits with certainty.

Chapter 3: STUDY AREA

This chapter considers the physiographical, geological, and modern environmental setting of the Klondike District. Special emphasis is placed upon the Quaternary evolution of the landscape, including glaciation in central Yukon, and sedimentation in Klondike valleys. The chapter concludes with descriptions of the modern climate, vegetation, drainage and periglacial characteristics of the study area.

3.1 Physiographic and Geologic Setting

3.1.1 Physiography

The Klondike District is part of the Klondike Plateau, a topographic subdivision of the Yukon Plateaus (Bostock 1948, Mathews 1986; Figure 3.1). The plateau is an uplifted erosional surface of Tertiary age, characterized by dissected, rolling terrain of accordant ridges (Bostock 1948, 1970; Tempelman-Kluit 1981). During the late Tertiary, extensive subaerial erosion resulted in a mature landscape of smooth, rounded summits and valleys and a well-developed system of streams which may have drained in south-westerly direction to the Gulf of Alaska (Tempelman-Kluit 1980). During the late Miocene or Pliocene, the erosional surface began to be uplifted (Tempelman-Kluit 1980), causing stream

Figure 3.1 Map of the physiographic regions in the Yukon (in Oswald and Senyk 1977: Fig. 4; after Bostock 1948).

rejuvenation and downcutting into the plateau. Early Pleistocene glaciation in the St. Elias Mountains may have blocked southwest drainage to the coast, rerouting the Yukon River to the northwest (Tempelman-Kluit 1980). This northwest route defines drainage in the Yukon today, although it is considered unstable (Tempelman-Kluit 1980).

Several cycles of uplift and stream dissection have produced the modern Klondike landscape of round-topped hills and ridges (Gleeson 1970). The ridges are long with steep sides, and culminate in summits known locally as domes (Gleeson 1970). King Solomon Dome, the largest hill in the area (1229 m), is the source area for many major gold-bearing creeks, including Hunker, Bonanza, Quartz, and Dominion. The ridges are dissected by V-shaped valleys (Gleeson 1970). These valleys are flat and wide in their lower reaches, but gradually narrow toward their heads into steep-sided, narrow gulches (McConnell 1903). At various elevations, gravel benches, indicative of several cycles of erosion, have been incised into the bedrock of the valley walls (Gleeson 1970).

3.1.2 Geology

i) Regional

The Klondike District is situated within the Yukon

Cataclastic Complex (YCC) (Tempelman-Kluit 1981). The YCC is comprised of highly sheared and metamorphosed rocks which have been accreted to the western margin of the North American continent (Tempelman-Kluit 1981 - Figure 3.2). Northeast of the YCC is the Tintina Trench, a narrow graben occurring along the Tintina fault: a northwest-trending strike-slip fault which experienced 450 km of dextral offset during the Tertiary (Tempelman-Kluit 1980).

ii) Local

The Klondike District is underlain by a stack of structural panels, Assemblages I, II and III, which are separated by regional-scale thrust faults (Mortensen 1990). Assemblage I, the uppermost unit, crops out over most of the central and southern Klondike District. It consists largely of metamorphosed mid-Permian felsic plutonic, subvolcanic and tuffaceous rocks, including chloritic schist, felsic schist, quartz +/- feldspar augen-schist and orthogneiss. Assemblage II underlies Assemblage I, and is exposed over much of the eastern Klondike District. It consists of mid-Paleozoic or older metasedimentary and mafic and felsic metavolcanic rocks, the bulk of which are fine-grained micaceous quartzite and feldspathic quartzite, with lesser amounts of chloritic schist and amphibolite. Assemblage II rocks have been intruded by a large body of latest Devonian

Figure 3.2

Map showing the tectonic subdivisions of the North American margin on the northeast (brick pattern), and elements of the accreted portion on the southwest (shaded) (Tempelman-Kluit 1981). The Klondike District is located in the Yukon Cataclastic Complex, southwest of the Tintina fault and east of the Yukon/Alaska border.

to Early Mississippian granitic augen-orthogneiss. Assemblage III underlies I and II in the northern, western, and southern parts of the district. It consists mostly of medium to dark grey carbonaceous phyllite, schist and quartzite (Mortensen 1990).

3.2 Quaternary Geology of the Klondike

3.2.1 Glaciation in the Central Yukon

Although the Klondike District remained unglaciated during the Quaternary, glacial products and periglacial activity affected this area.

i) The Cordilleran Ice Sheet

From geomorphological evidence, four glacial advances of the Cordilleran ice sheet have been recognized in central Yukon (Bostock 1966; see Figure 3.3). From oldest to youngest these advances include the Nansen, Klaza, Reid and McConnell. Each of these glaciations was less extensive than its predecessor. The ice marginal features of the Klaza and Nansen advances are poorly preserved, while those of the McConnell are the best preserved. Because it is often difficult to delineate whether old glacial remnants are Nansen or Klaza, or even older, advances that pre-date the Reid are referred to as Pre-Reid (Hughes et al. 1989).

Figure 3.3

Maximum extent of glaciers in Yukon Territory and western District of Mackenzie during various Pleistocene glaciations (Hughes *et al.* 1989; after Bostock 1966; Rampton 1971; Hughes *et al.* 1983).

The Nansen glaciation was inferred from till seen on tributaries of Nansen and Victoria Creeks, and the Klaza glaciation from a major glacial diversion of the Klaza River caused by ice blocking Lonely Creek (Bostock 1966). Paleomagnetic evidence suggests that the Nansen glacial advance is older than 1.87 Ma, and the Klaza glaciation occurred between 0.79 - 1.67 Ma (Jackson et al. 1990).

The Reid glaciation is named after a well-defined terminal moraine in the valley of Stewart River near Reid Lakes (Bostock 1966). The timing of the Reid glacial period is equivocally defined. There are no dates relevant to the beginning of the Reid, however it is believed that Reid ice began to retreat before 42,900 ^{14}C years BP (GSC-524; Lowdon and Blake 1968) and probably before 80,000 years BP (Hughes et al. 1989). The younger date comes from wood found in Sheep Creek tephra which was cut into the surface of Reid outwash. The older date is from U-Th and U-Pa dates of bones associated with the tephra (Hamilton and Bischoff 1984). The Reid glaciation is often presumed to be Illinoian in age, although due to the variation in dates, an Early Wisconsin age has not been completely ruled out (Hughes et al. 1989; Jackson et al. 1990).

The McConnell glacial limit is marked by fresh glacial landforms in central Yukon (Tarnocai et al. 1985). The limit of this glaciation, a moraine crossing the Stewart River approximately 18 km west of Mayo, was first recognized by

McConnell (1903). The McConnell glaciation is Late Wisconsin in age (Klassen 1987; Matthews et al. 1990; Jackson and Harington 1991). The oldest evidence for what might have been the onset of McConnell glaciation in the Selwyn Mountains comes from Mayo. An age of $38,100 \text{ ka} \pm 1330$ ^{14}C years BP (GSC-4554; Matthews et al. 1990), has been determined for an in situ stump in an exposure along the Stewart River. Following this period, the record in Mayo shows climate deterioration. By $29,600 \pm 300$ BP ^{14}C years BP (TO-292), trees had disappeared from the area, a periglacial climate was well-established, and conditions were conducive to glaciation in the Selwyn Mountains to the east (Matthews et al. 1990). No dates exist for the end of the McConnell glaciation in the central Yukon, however retreat of Late Wisconsin ice occurred in the area of the St. Elias Mountains, west-central Yukon, by $13,660 \pm 180$ ^{14}C years BP (GSC-1110; Rampton 1971), and a correlative glacial advance in the Southern Ogilvie Mountains probably retreated before $13,740 \pm 190$ ^{14}C years BP (GSC-515; Lowdon and Blake 1968). Radiocarbon ages from the continental divide of the Selwyn Mountains indicate that ice had disappeared from that area by 9,000 years BP (Jonasson et al. 1983; MacDonald 1983).

ii) Interglacial Periods

Interglacial periods following the Pre-Reid, Reid and

McConnell glaciations in the central Yukon, are represented by paleosols which have developed upon glacial deposits. Wounded Moose soils are developed upon Pre-Reid glacial deposits, and are believed to have formed during a warm and subhumid climate, followed by a more temperate and humid one during a Pre-Illinoian interglacial. Diversion Creek soils are developed upon Reid glacial deposits. These soils are thought to have formed during a cool and humid climate region during the Sangamon interglacial period (Tarnocai 1989). The Wounded Moose and Diversion Creek paleosols have not been reported from the Klondike District, although paleosols on Pre-Reid surfaces have been observed approximately 35 km southeast of the Klondike District (Rutter et al. 1978).

The Holocene has produced a number of relict soil features which can be found in modern Canadian soils (Tarnocai 1990). The presence of relict earth hummocks, buried forests and peat, for example, have been used to reconstruct a Holocene climatic regime suggesting a number of climatic fluctuations. Radiocarbon dates of basal peat materials, for example, show that the majority of peat began to develop between 4 - 6 ka in continental North America (Tarnocai 1978). This lag in peat development has been used as evidence to support the post-glacial climatic optimum (Tarnocai 1990), a relatively warm and dry period which lasted several thousand years following the retreat of

glacial ice from the North American continent (Ritchie and Hare 1971; Terasmae 1972; Delorme et al. 1977). In addition, dates obtained from cryoturbated organic materials from soils associated with earth hummocks suggest "...increased cryogenic activity and hummock formation about 3.5 ka BP as a result of climatic cooling" (Tarnocai 1990: 373).

iii) Glaciation in the Southern Ogilvie Mountains

Evidence of at least three Pleistocene montane glaciations have been recognized in the Southern Ogilvie Mountains (Vernon and Hughes 1966). These glacial advances are referred to as the 'old', 'intermediate', and 'last' glaciations, and, based upon pedological evidence, have been correlated with the Pre-Reid, Reid, and McConnell glaciations respectively (Tarnocai et al. 1985; Smith et al. 1986 - Figure 3.3). These glaciers flowed from the mountains north towards the Taiga valley and south towards the Tintina Trench (Vernon and Hughes 1966).

One or more 'old' glaciations are believed to have deposited the Flat Creek Gravels (McConnell 1905) and the Klondike Gravels (McConnell 1907). The former is a deposit of more than 200 m of glacial lacustrine sediments, outwash gravel, and till, in the Tintina Trench. The latter is a glaciofluvial deposit which lies upon late Tertiary, non-glacial, White Channel Gravels, along the lower reaches of

the Klondike River. A fission-track date of 1.22 ± 0.49 Ma for the Mosquito Gulch tephra, a tephra which is cut into a terrace of White Channel Gravels and is, in part, correlative with Klondike Gravel depositions, provides a minimum date for the 'old' glaciation (Naesar et al. 1982).

The 'old' glaciations were followed by a lengthy period of time during which the Klondike River and its tributaries were greatly incised (Hughes et al. 1972). During this period, two major incisions resulted in terrace, and valley bottom gravel deposits in the Klondike District respectively. Organic material in silt on the floor of Hunker Creek has been dated at $>53,900$ ^{14}C years BP (GSC-527; Lowdon and Blake 1968) and has been used to provide a minimum age for the incision of the Klondike River and its valleys preceding the 'intermediate' glaciation. It is unknown if this organic material dated was in situ or colluvial in nature.

The 'intermediate' glaciation in the South Ogilvie Mountains was similar to, although less extensive than, the 'old' glaciations, and the 'last' glaciation was even less extensive than the 'intermediate'. Glaciers of the 'last' glaciation were restricted to valleys near the crest of the range. The onset of the 'last' glaciation is unknown, but it probably retreated before $13,740 \pm 190$ ^{14}C years BP (GSC-515; Lowdon and Blake 1968; Hughes et al. 1989).

3.2.2 Surficial Deposits in the Klondike

Surficial deposits in the Klondike include gravels and muck. While muck characteristics are discussed thoroughly in Chapter 5, mention of surficial gravels is presented in this section.

McConnell (1905; 1907) divided auriferous gravel deposits in the Klondike into stream gravels, terrace gravels, White Channel Gravels, and Klondike Gravels (Figure 3.4). This classification was modified by Gleeson (1970) and included:

- a) high-level gravels;
- b) terrace gravels; and
- c) valley and creek gravels.

High-level gravels consist of White Channel Gravels and the overlying Klondike gravels. Due to differential uplift of the Klondike Plateau, these terraces extend up to 200 m above present stream levels (Hughes et al. 1993). White Channel Gravels form terraces approximately 50 - 100 m above the present day stream levels (Morison 1985). They are a non-glacial, gravelly sequence, which was deposited during uplift of the Klondike Plateau in the Pliocene, and ended with the deposition of Pre-Reid glaciofluvial sediments (Klondike Gravels; Morison 1985).

Figure 3.4 **Generalized valley profile across lower part of Bonanza Valley showing the gravel deposits and muck (in Morison 1985; after McConnell 1905, 1907).**

- a. MUCK.
- b. STREAM GRAVELS.
- c. TERRACE GRAVELS.
- d. WHITE CHANNEL GRAVELS.
- e. HIGH LEVEE RIVER GRAVELS. (KLONDIKE GRAVELS).
- f. KLONDIKE SCHISTS.

As mentioned, the Klondike Gravels represent glaciofluvial sedimentation during a Pre-Reid advance from the Southern Ogilvie Mountains (Hughes et al. 1972), and lie stratigraphically on top of the White Channel Gravels. At the mouth of Bonanza Creek, White Channel facies and Klondike Gravels are interbedded, demonstrating contemporaneous deposition of these gravels during the Pre-Reid glacial interval (Hughes et al. 1972).

Terrace gravels are divided into intermediate and low-level terrace gravels (Gleeson 1970). Intermediate-level terrace gravels occur along Bonanza and Hunker Creeks and are remnants of former valley bottoms. They are irregular in distribution, and occur at various elevations on the valley walls. Low-level terrace gravels are best developed on Dominion Creek near its source, on Quartz Creek from its source to below Calder Creek and at the mouth of Gold Bottom Creek. Terrace gravels are deposits resulting from the first major incision of the Klondike Plateau following the Pre-Reid glacial periods (Gleeson 1970).

Creek gravels cover the valley bottoms and are usually 4 - 10' (122 - 305 cm) deep (Gleeson 1970). In the gulches and near the heads of creeks, the gravels are angular to subangular, while in the lower portions of the creeks, the gravels are rounded to subrounded. Creek gravels are deposits resulting from the second major incision of the Klondike Plateau following the Pre-Reid glacial period

(Hughes et al. 1972). Gravels of the Yukon and Klondike Rivers are well-rounded, and the primary source for the material is from the western slopes of the Ogilvie Mountains (Gleeson 1970).

3.3 Modern Environmental Conditions

3.3.1 Climate

The climate of the Klondike area is subarctic continental, with short summers, long winters, with periods of intense cold, infrequent winds, and light snowfall and rain (French and Heginbottom 1983). The mean annual air temperature in Dawson City between 1951 and 1980 was -5.1°C , and mean annual total precipitation 306.1 mm, of which an average of 123.4 mm (water equivalent) fell as snow (Atmospheric Environment Service 1982). Since the Dawson weather station, like most in Yukon, is situated in a valley bottom, the climatic data for Dawson City are not necessarily representative of the whole Klondike area (French and Heginbottom 1983).

3.3.2 Vegetation

The Klondike District is in the northern boreal forest (Pettapiece et al. 1978). White and black spruce (Picea

mariana and Picea glauca) are found in pure stands, or are mixed with trembling aspen (Populus tremuloides), balsam poplar (Populus balsamerifera) and white birch (Betula papyrifera). North-facing slopes, or areas of permafrost, are often dominated by black spruce, accompanied by a shrub layer and ground cover of lichen, feather mosses, sphagnum, and/or Dwarf birch (Betula glandulosa) and tamarack (Larix laricina) (Naldrett 1981). Warmer south-facing slopes, or areas of little or no permafrost, are characterized by white birch, aspen, poplar, alder (Alnus rubra) and/or white spruce (Naldrett 1981).

Modern vegetation in the Klondike is a result of regrowth since the gold rush (Naldrett 1981). "During the period 1896 - 1903, nearly all of the Klondike area was cut for lumber, and while the species distribution was not significantly affected, a stable community has still not developed" (Naldrett 1981: 32). Vegetation distribution has also been influenced by fire (Naldrett 1981; Tarnocai et al. 1993). Besides destroying trees, fire changes the composition of vegetation, for example, from black spruce to aspen, birch, or poplar (Oswald and Senyk 1977).

3.3.3 Permafrost

Permafrost is "[g]round (soil or rock) that remains at or below 0°C for at least two years" (Associate Committee on

Geotechnical Research 1988: 63). Permafrost terrain is comprised of perennially-frozen ground overlain by an active layer which thaws each summer. Permafrost distribution is broadly controlled by climate, but regionally controlled by factors such as aspect, slope configuration, host materials and vegetation (Naldrett 1981). The depth of permafrost depends upon the present surface temperature regime and former fluctuations in ground surface temperature (e.g., Lachenbruch et al. 1982).

The Klondike District is in the zone of widespread permafrost (Figure 3.5). The thickest permafrost in the region is found under cooler north-facing slopes, and is frequently absent from the opposite slopes (French and Heginbottom 1983). The persistence of frozen ground in central Yukon, where summers are warm, has been attributed to extremely low winter temperatures which are "...brought about by topographic enhancement of atmospheric inversions" (Burn 1993: 18). McConnell (1905), Brown (1967) and EBA (1977, 1978) report permafrost depths of roughly 60 m in the Dawson area. Milner (1976) reports thicknesses of 60 m and 70 m in White Channel Gravel deposits at Lovett Hill, and below Eldorado Creek respectively.

Massive ground ice bodies in the Klondike are reported as relict, or paleo-features (Naldrett 1981).

Figure 3.5 **Permafrost regions of the Yukon and adjacent Northwest Territories (in Burn 1990: Fig. 1; after Brown 1978).**

3.3.4 Drainage

i) Surficial hydrology

The drainage of the Klondike District is dendritic (French and Heginbottom 1983: see Figure 1.3). Major creeks flow from King Solomon Dome, the regional topographic high (1229 m), and from ridges extending northwest. Hunker, Bonanza, and Eldorado Creeks drain northward into the Klondike River, and Quartz, Dominion and Sulphur Creeks drain southward into the Indian River. Bear Creek, a small tributary of the Klondike River, originates from a smaller dome (1040 m) in the northern part of the region. Both Klondike and Indian Rivers flow west into Yukon River.

ii) Groundwater

Discontinuous permafrost in the Klondike creates a complicated groundwater flow regime (Naldrett 1981). Because permafrost presents a relatively impermeable barrier, ground-water flow is restricted to unfrozen zones or taliks (Naldrett 1981). Groundwater flow in permafrost terrain is demonstrated in the Klondike by active formation of icy bodies such as open-system pingos and icings (Naldrett 1981; French and Heginbottom 1983). Open-system pingos form where substantial hydrostatic heads develop from topographic

gradients (French and Heginbottom 1983). Icings are sheetlike masses of layered ice formed on the ground surface or on river or lake ice, by freezing of successive flows of water that may seep from the ground, flow from a spring, or emerge from below river ice through fractures (Associate Committee on Geotechnical Research 1988).

The presence of water below permafrost is documented as well. Tyrrell (1903: 188), for example, describes a 'peculiar artesian well' which had formed when a shaft had been sunk to 221' below the surface on Eldorado Creek. Above this depth, frozen materials, including bedrock, appeared to have formed an impermeable barrier to water flow. Below this depth, the bottom of the frozen layer had been penetrated as "water began to rise...and rose rapidly to the surface, since which time it has been discharging about...1,000 imperial gallons a minute".

Chapter 4 METHODS

Data collection for the study involved field and laboratory work. Field work was conducted in the Klondike District during summer 1994, and work in the laboratory was conducted in fall 1994 at Carleton University.

4.1 Field Procedures

4.1.1 Site Selection

Accessibility and freshness of exposures were major factors in site selection. The best exposures were ones which had been recently uncovered by placer miners, particularly where monitors had been used to strip muck from gravels. The best time to study these exposures was immediately after they had been stripped, before the sediments thawed and slumping occurred.

Twenty-three muck sections, from 18 different exposures, were selected from all major drainage basins in the Klondike. The spatial distribution of sites throughout the study area is given in Figure 4.1. Site names, coordinates and elevations are given in Table 4.1. From the Hunker Creek watershed, muck exposures were studied at placer mine sites at: Hester Creek, Hunker Creek near Mint Gulch, No Bottom Gulch, 15 Pup (a small tributary of Last Chance Creek), and Hunker Creek approximately 1.5 km from

Figure 4.1 Distribution of study sites throughout the study area. For this map, 'BR' denotes Bear, 'S' denotes Sulphur, 'H' denotes Hunker, 'B' denotes Bonanza, 'D' denotes Dominion, and 'Q' denotes Quartz. Site numbers are listed in Table 4.1. For precise creek names, see Figure 1.2.

Table 4.1 Exposure names, locations, co-ordinates and elevations.

Section Number	Creek Name	Drainage Basin	Longitude and Latitude	Creek Elevation (m asl)
Quartz-1	Quartz Creek (Large Exposure)	Quartz Creek	63°48'55"N; 139°02'45"W	550
Quartz-2	Quartz Creek	Quartz Creek	63°48'55"N; 139°02'45"W	550
Quartz-3	Quartz Creek (Small Exposure)	Quartz Creek	63°48'47"N; 139°04'00"W	540
Quartz-4	Upper Quartz Creek	Quartz Creek	63°49'50"N; 139°01'00"W	600
Quartz-5	Mack Fork	Quartz Creek	63°48'34"N; 139°02'41"W	545
Sulphur-1	Sulphur Creek near Quinn Gulch	Sulphur Creek	63°47'15"N; 139°55'04"W	580
Dominion-1	Unnamed creek south of Rob Roy	Dominion Creek	63°48'34"N; 139°55'04"W	555
Hunker-1	Hester Creek	Hunker Creek	63°59'02"N; 139°02'56"W	470
Hunker-2	Hunker Creek near Mint Gulch	Hunker Creek	63°56'13"N; 138°53'19"W	560
Hunker-3	Hunker Creek across from Mint Gulch	Hunker Creek	63°56'10"N; 138°53'15"W	560
Hunker-4	24 Pup	Hunker Creek	63°54'49"N; 138°54'53"W	740
Hunker-5	15 Pup	Hunker Creek	63°58'44"N; 139°02'56"W	535
Hunker-6	Lower Hunker Creek	Hunker Creek	64°00'57"N; 139°09'15"W	400
Bonanza-1	Upper Bonanza	Bonanza Creek	63°54'44"N; 139°14'15"W	535
Bonanza-2	Homestake Gulch	Bonanza Creek	63°56'10"N; 139°13'34"W	770
Bonanza-3	Gauvin Gulch	Bonanza Creek	56°63'13"N; 139°14'08"W	840
Bonanza-4	Skookum Gulch	Bonanza Creek	63°55'11"N; 139°20'08"W	560
Bonanza-5	Trail Gulch	Bonanza Creek	64°00'44"N; 139°21'23"W	420
Bonanza-6	Bonanza Creek	Bonanza Creek	63°55'40"N; 139°20'23"W	430
Bear-1	Bear Creek	Bear Creek	64°00'44"N; 139°14'49"W	370

the Klondike highway (formerly known as the Mayes' site). From the Bonanza Creek watershed, sites were studied at: Trail Gulch, Bonanza Creek across from Claim 49, Upper Bonanza near O'Neil Gulch, Homestake Gulch, and a ridge between Gauvin and Homestakes Gulches. One exposure was chosen from Bear Creek, and one from Skookum Gulch was studied in the Eldorado Creek watershed. Eldorado Creek is a tributary of Bonanza Creek, and the exposure name from Skookum Gulch is identified as such (i.e., Bonanza-4). In the southern portion of the Klondike, sites were visited at Sulphur Creek near Quinn Gulch, and on an unnamed creek immediately south of Rob Roy Creek in the Dominion Creek watershed. A large muck exposure (approximately 20 - 30 m by 250 m) was studied at Ken Tatlow's mine on Quartz Creek, just upstream from Mack Fork. A smaller exposure was described immediately downstream from Mack Fork. Natural muck exposures were visited on Quartz Creek upstream from the mine, and at Mack Fork.

4.1.2 Data Collection

i) Muck Characteristics

At each exposure, creek elevation and aspect were recorded, and sedimentary units were described. Unit descriptions included: sedimentary structures; texture;

colour; thickness; type of grading; nature of the basal contact; organic constituents; and cryogenic characteristics. Samples were collected at approximately 50 cm intervals for subsequent analyses including: particle-size distribution; grain morphology and surface texture; mineralogy; organic content; and pollen. Samples of in situ organic material were also taken for radiocarbon dating.

ii) Distribution of Muck

The distribution of muck was determined to enhance the spatial understanding of muck deposits in the Klondike. Muck deposits were recorded on a topographic map of the study area to determine their distribution throughout the study area. In addition, muck limits within several valleys were determined. Pits were dug along transects perpendicular to the valley-floor. The presence of shattered bedrock immediately below the organic mat, combined with the absence of silt, were used as elevation limits for the muck. Where possible, elevations were recorded for either side of the valley, and cross-valley profiles were then drawn.

4.2 Laboratory Procedures

i) Particle-Size Analysis

Particle-size analysis is an important sedimentological tool, as it aids in understanding modes of sediment transport and deposition (Folk and Ward 1957). Particle-size analysis measures the distribution of individual inorganic particles in a sample (Lowe and Walker 1984: 91). The major features of particle-size analysis are the dispersion of soil aggregates by chemical, mechanical or ultrasonic means, and the separation of particles according to size, by sieving and sedimentation (Gee and Bauder 1982).

The particle size of 81 Silt unit samples, from various locations throughout the study area, were determined by sedimentation. The method is a revision of Gee and Bauder (1982). The samples were dispersed using ultrasonic means. Size fractions determined were: clay ($<2\mu$); fine silt (2 - 5μ); medium silt (5 - 20μ); coarse silt (20 - 50μ); fine sand (0.05 - 0.25 mm); medium sand (0.25 - 0.5 mm); and coarse sand and greater (>0.5 mm). The size fractions are based upon those of the Canadian System of Soil Classification (1987).

ii) Organic matter content: loss on ignition

The determination of organic matter content in a sample provides a measurement of biological productivity (Lowe and Walker 1984: 93). Organic matter content (%) for 131 silt samples was determined by loss-on-ignition (LOI) (Nelson and Sommers 1982). The samples were selected from various locations throughout the study area. The LOI method involves heating a sample to a temperature where carbon ignites. Organic content in the samples is then indicated by the weight loss following combustion. For this study, samples were not pre-treated, and were heated to 400°C for eight hours as recommended by J.K. Torrance, Carleton University.

iii) Mineralogy

The mineralogy of a sample can provide information on the origin of material (Lowe and Walker 1984: 94). Mineralogy is often determined by X-ray diffraction (XRD). XRD is a method in which an X-ray beam of known wavelength is directed at a crystal. After entering the crystal, the beam is diffracted by reflecting off atom planes in the structure. By recording the angular positions of diffracted beams, the spacing between atomic planes can be determined, and the internal structure of a crystal may be established, allowing for identification of the mineral (Allaby and

Allaby 1991).

Fifteen silt samples, from six exposures, were prepared for XRD analysis. The bulk fraction, consisting of grains <1.0 mm, were analyzed without pretreatment. The samples were slightly ground with a mortar and pestle, as recommended by Ron Conlon, Department of Earth Sciences, Carleton University.

iv) Grain Shape and Surface Texture

The shape and surface textures of sand grains can be used to distinguish between sediments which have accumulated in different depositional environments (Lowe and Walker 1984: 92). The characteristic shape and surface texture of six silt samples were determined using a Scanning Electron Microscope (SEM), in the Department of Earth Sciences, Carleton University. The samples were pre-treated with hydrogen peroxide to remove organic material, and were washed with distilled water to clean grain surfaces. Fine sand and medium to coarse silt were separated from the bulk samples for analysis. The surface features and shapes of common minerals were the focus of analysis. Photographs of particles at various magnifications were taken for reference.

v) Radiocarbon Dating

Eleven organic samples were submitted to the Brock University Radiocarbon Dating Laboratory. Most of the samples were collected from organic horizons at the lower contacts of both the Silt and Organic units, in order to provide boundary dates for the Silt unit, and to date the onset of Holocene conditions in the study area. One sample was taken from within the Silt unit. The samples were collected from Quartz Creek (Quartz-1; Quartz-2), 24 Pup (Hunker-4), 15 Pup (Hunker-5), Lower Hunker Creek (Hunker-6), Bear Creek (Bear-1) and Skookum Gulch (Bonanza-4). Precise locations of samples within each exposure are presented in the next chapter.

vi) Pollen analysis

Palynology, the study of fossil pollen and spores, is often used to reconstruct vegetation patterns at local and regional scales, and to deduce climate changes over time (Lowe and Walker 1984 : 156). Pollen analysis consists of two major components: a preparation stage, where pollen grains are extracted from the sediment; and a counting stage, where pollen assemblages are determined.

Pollen was extracted from four silt samples using the method of Frenzel (1964), modified by Dr Marie-Anne Geurts,

Department of Geography, University of Ottawa. The method was designed specifically for separating pollen from loess. Samples were selected at 5 m intervals from exposure Quartz-2. Grain counting was attempted, but the data obtained were insufficient for use in this thesis, due to difficulty in species identification. Most of the pollen grains were damaged, some severely. Although the silty material does contain pollen and spore grains, their state of preservation made palynology impractical for this study.

Chapter 5: RESULTS AND DISCUSSION

This chapter presents results and discussion of field and laboratory observations conducted on Klondike muck deposits. Section 5.1 describes the general nature of the deposits, and characteristics of the Silt and Organic units. Section 5.2 describes the distribution of mucks, both within the Klondike District and within individual valleys. Based upon these observations, the origin of muck deposits in the Klondike is discussed in Section 5.3. Section 5.4 reveals the age of the muck deposits, and interprets these dates with reference to both the late Quaternary history of central Yukon, and valley evolution in the Klondike. The geocryological history of the deposits is also inferred in this section. Section 5.5 concludes the chapter by presenting a depositional model for the muck deposits.

5.1 The Nature of the Klondike Muck Deposits

5.1.1 General Characteristics

In summer 1994, 23 muck sections, from 18 different exposures were studied. The state of exposures varied from valley to valley. In some, complete vertical muck sections were available for study, but in the majority, only partial exposures existed. From site descriptions, a general and

consistent pattern about the nature of muck deposits emerged.

Muck deposits are located in valley bottoms and most often comprise two units: a lower, well-sorted silt; overlain by an organic-rich peat (Figure 1.1). The Silt unit is a thick (maximum 23.7 m), homogenous silt deposit, which is perennially frozen, and often dark brown, grey or tan. The unit unconformably overlies auriferous valley-bottom gravels, but it is also found overlying angular, weathered bedrock. The lower contact is usually distinct, although in two cases, it was interstratified with gravels and sand. The unit is thickest in the central portions of the paleovalleys, and thins upslope. It may be absent in modern valleys where the creeks have eroded through the sediments to bedrock. The unit contains abundant rootlets, occasional twigs and ground squirrel nests at various elevations. It also contains occasional continuous sand/pebble layers and pockets, many of which are iron-stained. In the lower portions of the silt, particularly within the first 50 cm, in situ organic beds are sometimes seen. These organic beds have a very strong odour and often contain grass macrofossils, and bones of a variety of Pleistocene mammals, such as mammoth, horse and steppe bison. In the upper portions of the unit, there are often large bodies of massive ice, including ice wedges and intrusive ice. Unless the deposit has been thawed, small ice lenses (0.1 - 0.5 mm

thick) are seen throughout the entire unit.

The Organic unit is a thinner deposit (maximum 13.5 m), consisting of perennially frozen silt, sand, gravel, and an abundance of plant macrofossils such as peat lenses, stumps, roots and sticks. It is black, and mostly disorganized, although continuous organic beds may be seen. The unit often unconformably overlies the Silt unit, however, sometimes it directly overlies creek gravels where the Silt unit is absent. The lower contact is distinct, and sometimes scoured. The unit is thickest in the centre of the modern valleys, and thins upslope on either side. Massive icy bodies are seen throughout the unit, such as ice wedges, intrusive and aggradational ice. Ice wedges in this unit are vertically less extensive than those seen in the Silt unit. Intrusive and aggradational ice have also been observed. Small ice lenses occur throughout the unit. Mammal fossils are normally not seen in this unit, but, bones were seen at the lower contact in Hester Creek, where the unit overlay creek gravels.

Figures 5.1 - 5.3 show characteristic schematic muck sections from 24 Pup (Hunker-4), Bear Creek (Bear-1), and Quartz Creek (Quartz-1). The sections from 24 Pup and Bear Creek are representative of sections that do not contain bodies of massive ice. From bottom to top, the section at 24 Pup shows; (1) weathered bedrock; (2) creek bottom gravels; (3) the Silt unit (subdivided into different sedimentary

Figure 5.1 Schematic representation of a muck exposure from 24-Pup. A photograph of the exposure is on page 2, Fig. 1.1. From bottom to top, the section shows weathered bedrock (1), creek gravels (2), the Silt unit (3), and the Organic unit (4).

Figure 5.2 Schematic representation of a muck exposure from Bear Creek. From bottom to top, this section shows creek gravels (1), the Silt unit (2,3,4,5), and the Organic unit (6). The top of this section was disturbed.

Figure 5.3 Schematic representation of a muck exposure from Quartz Creek. Common to exposures containing massive ice were slumped features which obscured gravels and lower portions of the Silt unit. This section shows the Silt unit (2,3) which contains a massive ice wedge (1: stippled pattern), and the Organic unit (4).

units); and (4) the overlying Organic unit. From bottom to top, the section at Bear Creek shows. (1) creek bottom gravels; (2) the Silt unit (subdivided into different sedimentary units); and (3) the overlying Organic unit. The section from Quartz Creek is representative of exposures containing massive ice. This section contains: (1) slump material at the base which obscures view of gravels and the lower portions of the Silt unit; (2) the Silt unit (subdivided into different sedimentary units) and the locations of massive ice wedges; and (3) the overlying Organic unit. The sedimentary units and secondary features of the sections are described in sections 5.1.2 and 5.1.3.

5.1.2 The Silt Unit

The Silt unit was seen at 19 of 23 exposures. Characteristics of the unit described in this section include: (i) texture; (ii) mineralogy; (iii) grain shape and surface texture; (iv) total organic content; (v) sedimentary structures; and (vi) secondary or additional features.

i) Texture

The particle-size distributions (defined on p. 68) of 74 samples from the Silt unit were determined. The samples were taken from each location where a Silt unit existed.

Samples were chosen at various heights within the section. For larger sections (>10 m in height), samples were chosen at approximately 2 m intervals. For the smaller sections (<10 m in height) samples were chosen at approximately 50 cm intervals.

The results show that the samples are very well sorted (Table 5.1), dominated by particles in the coarse silt fraction (mean = 50.7%), with lesser, but significant amounts, in the medium silt (mean = 23.9%) and fine sand (mean = 12.8%) fractions. Fine silt and clay fractions were minimally present (means = 4.6% and 5.3% respectively), along with negligible portions of medium and coarse sand and greater (means = 0.6% and 1.1% respectively). Table 5.1 shows the particle size analysis of 74 Silt unit samples collected from the entire study area. Tables 5.2a to 5.2e present the particle-size distribution averaged for (a) each exposure, and, (b), each major drainage. Tables show that and medium silt, coarse silt, and fine sand comprise the bulk fraction of the samples (mean = 87.5%), and that mean values calculated for separate exposures, and separate drainages, are comparable. The high percentage of silt and fine sand, as well as the spatial and temporal uniformity in particle-size distribution of the samples are characteristic features of loess (Pye 1987: 198,199).

**Table 5.1 Mean Textural Characteristics of the Silt Unit for
74 Samples from 19 Exposures in the Study Area**

Particle Size	Mean (%)	Maximum (%)	Minimum (%)	Standard Deviation
Clay	5.3	14.3	0.0	2.4
Fine Silt	4.6	10.6	0.0	2.6
Medium Silt	23.9	36.2	3.6	7.3
Coarse Silt	50.7	77.0	31.5	7.7
Fine Sand	12.8	34.8	4.6	6.9
Medium Sand	0.6	3.7	0.0	0.6
Coarse Sand and greater	0.9	7.0	0.0	1.3

Table 5.2a Particle-size distributions for Quartz Creek drainage

Exposure	n	Clay (%)	Fine Silt (%)	Medium Silt (%)	Coarse Silt (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)
Quartz-1	22	6.9	5.8	26.0	45.2	14.6	0.67	2.8
Quartz-2	14	5.0	5.6	21.2	52.1	14.7	0.3	0.8
Quartz-3	7	6.1	4.2	20.0	47.9	18.3	0.9	2.0
Quartz-4	2	5.5	1.3	12.9	58.3	21.0	0.4	0.4
Total Average	31	5.7 %	5.0 %	21.6 %	49.8 %	15.8 %	0.6 %	1.7 %

Table 5.2b Particle-size Distributions for Sulphur Creek drainage

Exposure	n	Clay (%)	Fine Silt (%)	Medium Silt (%)	Coarse Silt (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)
Sulphur-1	2	3.6	1.9	16.1	56.9	26.5	0.5	0.3
Total Average	2	3.6 %	1.9 %	16.1 %	56.9 %	26.5 %	0.5 %	0.3 %

Table 5.2c Particle-size distributions for Hunker Creek drainage

Exposure	n	Clay (%)	Fine Silt (%)	Medium Silt (%)	Coarse Silt (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)
Hunker-3	4	3.5	4.9	26.0	45.1	17.5	1.4	1.7
Hunker-4	3	4.9	7.9	33.2	40.3	10.5	0.9	2.1
Hunker-5	6	5.7	4.5	30.1	46.9	10.8	0.5	1.5
Hunker-6	4	6.5	0.67	26.0	52.7	13.7	0.4	0.2
Total Average	17	5.2 %	4.1 %	28.7 %	46.7 %	13.0 %	0.8 %	1.3 %

Table 5.2d Particle-Size Distributions for Bonanza Creek Drainage

Exposure	n	Clay (%)	Fine Silt (%)	Medium Silt (%)	Coarse Silt (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)
Bonanza-1	1	4.6	2.6	3.6	77.0	11.6	0.2	0.0
Bonanza-2	4	5.7	4.1	18.9	49.0	20.5	1.1	0.4
Bonanza-3	1	3.1	2.2	23.4	61.2	7.5	1.3	0.7
Bonanza-4	4	9.9	3.5	27.1	49.6	8.8	0.4	0.2
Bonanza-5	6	3.2	4.1	28.0	56.2	8.4	0.1	0.1
Bonanza-6	2	3.1	8.3	32.0	44.1	10.2	0.5	0.7
Total Average	18	5.3 %	4.3 %	24.6 %	53.2 %	12.1 %	0.6 %	0.4 %

Table 5.2e Particle-Size Distributions for Bear Creek Drainage

Exposure	n	Clay (%)	Fine Silt (%)	Medium Silt (%)	Coarse Silt (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)
Bear-1	6	3.8	4.8	22.8	57.4	10.36	0.14	0.22
Total Average	6	3.8 %	4.8 %	22.8 %	57.4 %	10.36 %	0.14 %	0.22 %

ii) Mineralogy

Fifteen Silt unit samples were analyzed by X-ray diffraction for bulk mineral content. Samples were chosen from: Quartz-2 (19, 762, 1502, and 2290 cm above lower contact); Hunker-4 (50, 198, and 340 cm above lower contact); Hunker-6 (approximately 150 cm above base of exposure: lower contact was not visible); Bonanza-2 (150, 310, and 420 cm above lower contact); Bear-1 (10, 350, and 700 cm above lower contact); and Bonanza-6 (approximately 100 cm from base of exposure: lower contact was not visible). The samples analyzed were selected to provide a diverse spatial representation of material throughout the study area, as well as a temporal one within selected valleys.

Results of XRD analyses showed that although variations in peak intensities of minerals exist among samples, the bulk mineralogy of silty material from Klondike muck deposits displays a consistent pattern. The minerals identified in all samples include: chlorite; mica; quartz; and plagioclase feldspar. In addition to the common minerals, small traces of amphibole were present in five samples, and in five others, orthoclase feldspar was identified as a constituent mineral.

XRD peak identification was based upon Brindley and Brown (1984; see Table 5.3). Figures 5.4a, 5.4b and 5.4c display representative XRD plots for samples from sites

Table 5.3 **XRD peaks identified from diffractometer traces of Silt unit samples. Adapted from Brindley and Brown (1984).**

Basal Spacings (rounded average, in Å)	Possible Mineral Species (untreated) (001) = order of reflection
14.0 - 14.3	chlorite (001)
9.9 - 10.1	micas (001)
8.2 - 8.5	amphiboles
7.1 - 7.2	chlorite (002)
4.95 - 5.05	micas (002)
4.73 - 4.74	chlorite (003)
4.26	quartz
3.66 - 4.04	plagioclase feldspar (several low-order reflections)
3.50 - 3.60	chlorite (004)
3.34 - 3.35	mica (003), quartz (low-order reflection)
3.23 - 3.26	orthoclase feldspar (2 lines)
3.15 - 3.21	plagioclase feldspar (2 or 3 lines)
2.89 - 3.04	plagioclase feldspar (2,3, or 4 lines)

Figure 5.4a XRD plots for a silt sample collected at the top of the Silt unit from Quartz-2. This plot shows the lowest mineral peak intensities for all 15 samples analyzed.

Figure 5.4b XRD plot for a silt sample collected from Hunker-4. This sample had the strongest chlorite peaks of all 15 samples analyzed.

Figure 5.4c XRD plot for a silt sample collected from Bonanza-2. This sample displayed the strongest quartz, plagioclase feldspar, and mica peaks of all 15 samples analyzed from the Silt unit.

Quartz-2, Hunker-4, and Bonanza-2. Figure 5.4a shows XRD results for a silt sample from Quartz-2 (2290 cm above lower contact), which displays the smallest intensity peaks for the suite of minerals identified from all samples. Figure 5.4b shows the XRD results for a silt sample from Hunker-4 (292 cm above lower contact), which displays the strongest chlorite peaks of all samples analyzed. Figure 5.4c shows the XRD results for a silt sample from Bonanza-2 (435 cm above lower contact), which displays the strongest quartz, plagioclase feldspar, and mica peaks. Peaks of identified minerals from all other samples (n=12), lie between the extreme peak intensities shown in Figures 5.4a, 5.4b and 5.4c. The consistency in XRD results shows the uniformity of samples both spatially and temporally within the study area. The types of minerals present in the samples are similar to those identified in loess deposits globally (Pye 1987: 229).

iii) Grain Surface Morphology and Surface Texture

The shape and surface texture of grains from 6 Silt unit samples were observed by SEM. Samples chosen for analysis included ones from Quartz-2, Quartz-3, Hunker-4, Bonanza-2, Bonanza-3, and Hunker-6. Sample selection was designed to provide representation from different drainages, as well as different sedimentary units. Samples were taken from: horizontally bedded silt, 3.6 m above the contact with

underlying gravels (Quartz-3); a disorganized silt unit containing organic and sand pockets, 1.0 m above the underlying gravels (Quartz-2); massive silt, 0.5 m above the lower contact with gravels (Hunker-4); a wavy laminated silt unit, 3.1 m above the contact with underlying weathered bedrock (Bonanza-2); massive silt, approximately 1.0 m below the surface organic mat (Bonanza-2); and massive silt, approximately 9.0 m below the organic mat (Bonanza-6).

There were no distinct differences in grain shapes between the samples. The shapes of grains in all samples ranged from angular to rounded, with sub-angular and sub-rounded grains the most common. Figure 5.5a shows an angular quartz grain from Quartz-2. Figure 5.5b shows a rounded to sub-rounded clay mineral grain from the same sample. Figure 5.5c shows the range of particle shapes from a sample collected from Bonanza-2. The presence of both angular and rounded grains suggest the presence of both mechanically fractured particles such as loess, and ones which may have been subject to weathering and/or redeposition.

In general, a range in surface textures between smooth and severely pitted was observed (Figures 5.5b and 5.6); and the adherence of smaller particles to the larger particle surfaces, despite numerous pre-washings (Figure 5.5a). These surface characteristics have been observed on glacially-derived loess particles, as well as on particles derived from a variety of other periglacial and non-periglacial

Figure 5.5a SEM photograph of an angular quartz grain from a Silt unit sample collected at Quartz-2. Scale-bar is 10 μm .

Figure 5.5b SEM photograph of a rounded to subrounded clay mineral grain from a Silt unit sample collected at Quartz-2. The grains shown in Figures 5.5a and 5.5b are from the same sample. Scale-bar is 10 μm .

Figure 5.5c SEM photograph of the range in particle shapes in a Silt unit sample from Bonanza-2. Scale bar is 100 μm .

Figure 5.6 SEM photograph of the pitted-nature of a silt grain collected from the silt unit at Bonanza-2. Scale bar is 10 μm .

sources (Pye 1987: 215).

iv) Total Organic Content

The total organic contents of 131 silt samples were determined by LOI. Samples were chosen from each location where a Silt unit existed. At larger exposures (>10 m), samples were chosen at approximately 5 m intervals, while at smaller exposures (<10 m), samples were chosen at approximately 2 m intervals. For exposures with complete, or intact Silt units, samples were analyzed for organic content at approximately 50 cm intervals.

For the entire study area, the organic content of the Silt unit was high. The mean organic content was 6.3%, with a standard deviation of 3.5. Maximum and minimum values were 20.0% and 1.4% respectively.

Organic content curves were produced for sections with intact or complete Silt units, including Quartz-2, Quartz-3, Hunker-3, Hunker-4, Hunker-5, Bonanza-2, and Bear-1 (see Figures 5.7 and 5.8 for examples from Quartz-2 and Bear-1). Common to these sites were high organic contents within the first 100 cm of the basal contact with gravels or bedrock. These high values ranged from 7.0% at Quartz-3 (0 cm above basal contact), to 12.2% at Hunker-3 (95 cm above basal contact). Values remained high at Quartz-3 to a level of 370 cm above the lower contact. The organic content measured at

Figure 5.7

Organic content curve for the Silt unit at Quartz-2. The curve represents the organic content pattern observed at exposures with thick Silt units (> 8 m).

Figure 5.8

Organic content curve for the Silt unit at Bear-1. This curve represents the organic content observed at exposures with smaller silt units (< 8 m), where the organic content: (1) is high at the base; (2) is slightly lower in the centre portions of the unit; and (3) increases towards the upper contact of the unit.

the base of the sections provided the highest organic contents of all Silt units in the study area, and are associated with a paleosol at this position.

Above the basal organic-rich zone, organic content patterns differed from site to site. For the two large sections (Silt units >8 m thick), i.e., Quartz-2 and Quartz-3, organic content declined throughout the mid-portions of the unit, and remained at lower, and consistent values up to the upper contact. Mean values for Quartz-2 and Quartz-3 were 5.5% and 4.4% respectively.

For the smaller sections (Silt units <8 m thick), i.e. Hunker-3, Hunker-4, Hunker-5, Bonanza-2, and Bear-1, organic content values were generally much higher, with mean values ranging between 10.6% and 4.8%. Above the basal organic-rich zones, the organic content values either remained as high as at the base with minor exceptions (Hunker-4; Bonanza-2), or decreased slightly and then increased towards the upper contact of the unit (Hunker-3, Hunker-5 and Bear-1).

The high organic contents of the Silt samples, particularly in the temporal sequences, suggest the existence of a unit which likely aggraded slowly over time, allowing for vegetation growth throughout the period of its accumulation.

v) Sedimentary Structures

Six major sedimentary sub-units were identified within the Silt unit. These sub-units are: (i) massive silt; (ii) horizontally-bedded silt; (iii) wavy planar-stratified silt; (iv) disorganized to crudely stratified silt, organics, sand and/or gravel; (v) silt with angular bedrock clasts; and (vi) tephra. The presence of these sub-units suggest that the Silt unit consists of both primary and redeposited eolian materials.

a) Horizontally-Bedded Silt

Horizontally-bedded silt defines the most common sedimentary structure of the Silt unit in the study area (Figures 2.3 and 5.9). This sub-unit is comprised of thick, horizontally-bedded, well-sorted silt. The beds range in thickness from 0.5 to 5 cm. All of the beds dip approximately 10° - 15° towards the centre of the valley. The bedding is very difficult to see, but is emphasized by: ice seams and lenses; colour variations between beds or groups of beds; thin, continuous organic laminae, particularly grassy material; and continuous layers of sand, and/or pebbles. The sand and pebble lenses are often oxidized. The sub-unit also contains occasional small sand and organic pockets (few being larger than 10 cm in

Figure 5.9

Photograph of an exposure of horizontally-bedded silt (Hunker-5). The bottom of a large ice wedge is located at the left of the picture.

diameter), twigs, and abundant rootlets.

This sub-unit was seen at Quartz-1, Quartz-2, Quartz-3, Sulphur-1, Hunker-5, Hunker-6, Bonanza-5, and Bonanza-6. It is a slope deposit which likely accumulated seasonally by slopewash/sheetwash processes caused by spring snowmelt and storm events.

b) Massive Silt

This sub-unit consists of well-sorted silt with no visible sedimentary structures (Figure 5.10). In most respects, it is similar to horizontally bedded silt, only with a lack of clearly-defined horizontal beds.

Massive silt defines sub-units that are sedimentologically structureless, and ones which appear structureless because of the frozen state of the exposure. The former case was best observed on thawed, dry exposures. Often it was seen grading into horizontally-bedded silt. It was observed at Quartz-1, Bonanza-2, Bonanza-3, Bonanza-4, Bonanza-5 and Bear-1. The deposit is likely eolian in origin, indicated by the lack of bedding and, as mentioned previously, the characteristic particle-size distribution of the samples.

A significant section of massive silt was seen at Bonanza-3. Here, approximately 1.75 m of silt was exposed in a roadside cut on a ridge between Homestake and Gauvin

Figure 5.10 **Close-up photograph of a bed of massive silt (Quartz-1).**

Gulches. The silt here was located at 840 m asl, the only silt observed in the study area above valley floors. It is possible that this exposure may be a deposit of material, perhaps loess, which may have escaped redeposition into valley bottoms. As will be discussed in Section 5.2, the muck deposits are almost always found in valley bottoms and not on ridges or hilltops.

Melted silt often obscured visible sedimentary structures on small, thawing exposures along Quartz, Hunker and Eldorado Creeks. It is possible that these sections contain some sedimentary structures, but none were obvious in the field.

c) Wavy Planar-Stratified Silt

This sub-unit consists of crude to distinctly wavy, planar, stratified silt (Figure 5.11). The silt beds are thin, ranging from 0.5 to 3 cm thick, and they may be either continuous or discontinuous. The sub-unit also contains thin organic layers and sand laminations interstratified with the silt. Stratification in this sub-unit is emphasized by colour variations between the silt, organic material, and sand. The silt is mostly dark or light brown, the sand is often iron-stained, and organic lenses are black. Sometimes occasional organic pockets or lenses may be found, none of which were larger than 10 cm in

Figure 5.11 **Close-up photograph of a unit of wavy, planar, stratified silt (Bonanza-2).**

diameter. These pockets often contain small plant macrofossils such as grass or peat.

This sub-unit is not widespread in the study area, and was best observed in thawed, dry exposures as either a thin unit, or as a lens within either a massive or horizontally-stratified sub-unit. It was located at Sulphur-1, Quartz-2, Hunker-3, Hunker-4, Bonanza-2, Bonanza-5, and Bear-1, at various positions in the sections. While wavy planar bedding defines the major sedimentary structure of this sub-unit, channel-shaped zones containing small cross-bedded ripples were occasionally seen, cross-cutting this, or other sub-units (Figure 5.12). The sub-unit exhibits bedding characteristics of material that has been deposited by fluvial processes. The size of the sub-units and the relative underrepresentation of the sub-unit throughout the study area suggest that water reworking of the sediments was likely ephemeral.

d) Disorganized to Crudely Stratified Silt, with Organics, Sand and/or Gravel

This sub-unit consists of disorganized to crudely stratified silt, with organic material, sand, and sometimes gravel. Most often, the organic material, sand, and gravel were found in small pockets and/or lenses, within a well-sorted silt matrix (Figure 5.13). Sometimes well-defined

Figure 5.12 **Photograph of a channel-shaped structure
containing cross-bedded ripples (Bonanza-2).**

Figure 5.13 **Photograph of disorganized silt with sand and tephra pockets, and wood, overlying iron-stained gravels (Bear-1).**

beds were observed (Figure 5.14).

This sub-unit was often found at the base of the Silt unit, immediately overlying the auriferous gravels. It was seen at Dominion-1, Quartz-1, Quartz-2, Hunker-3, Hunker-5, Bonanza-2, Bonanza-4, and Bear-1. In some places, (Quartz-2 and Dominion-1), crude, horizontal stratification of silt, sand and organic material (mostly grass), and/or gravel was seen at the base of the Silt unit, giving the unit a gradational, rather than a distinct, lower contact. Where bones were found, they were most often associated with this basal, disorganized sub-unit. In only one instance was the sub-unit observed within the Silt unit, rather than at the base. At Quartz-4, the sub-unit was found overlying massive silt, approximately 111 - 268 cm from the base of the exposure.

There are several interpretations of this sub-unit. First, the unit could represent the beginning stages of the most recent silt accumulation event in the Klondike valleys, with contemporaneous soil formation. In the early stages of deposition, the freshly deposited silt could have been reworked by valley streams, becoming stratified with existing gravels and sands (e.g., Dominion-1 and Quartz-2), and, in places, forming the substrate for the organic material growing in the valleys before the bulk of the silt was deposited there. Second, it is also possible that this sub-unit represents an entity which is stratigraphically

Figure 5.14 Photograph of disorganized to crudely stratified silt, with organic material and sand lenses (upper right). This unit increases in stratification up-section. In situ organic horizons may be seen by the handle of the trowel. The unit overlies creek gravels (Hunker-3).

distinct from the majority of the Silt unit. This basal sub-unit may represent remnant material from an earlier depositional episode, on which a paleosol was formed. Third, this sub-unit may represent post-depositional reworking of the basal silt sediments by groundwater and/or cryogenic processes. Finally, it is possible that several of these interpretations are responsible for the presence of this sub-unit at the base of the Silt unit.

e) Silt with Angular Bedrock Clasts

This sub-unit consists of a matrix of well-sorted silt with angular bedrock clasts (Figure 5.15). The clasts range in size from pebbles to boulders and their orientation within the silt matrix is random. The amount of clasts varies at each site, but the unit is always matrix-supported. Sometimes pockets of organic material can be found in the unit as well.

This sub-unit was found in areas where extensive mining activity had almost completely removed muck from the valleys. In these valleys, silt was in close contact with underlying bedrock, and in some cases, bedrock was already exposed. This sub-unit was seen at Sulphur-1, Hunker-3, Hunker-6, Bonanza-1, and Bonanza-6. The sub-unit displays characteristics of a slope deposit of mass-wasted silt which has incorporated fractured bedrock into its matrix during

Figure 5.15 Photograph of a thick unit of silt with angular bedrock clasts. Massive icy bodies have intruded the sediments at this exposure (Hunker-6). The measuring stick is 1.75 m tall.

deposition into valley-bottoms.

f) Tephra

Seven tephra beds were found in muck exposures in the study area, at five separate locations. Thick, reworked tephra beds were seen at Quartz-2 and Quartz-3. These tephras were continuous, ranged from 10 - 90 cm thick, and were located within horizontally-bedded silt, 365 and 562 cm above the gravels respectively. Ripple and planar-bedded structures were seen within the beds (Figure 5.16). Due to the position of the tephras within the exposure, and the proximity of exposures within the same drainage area, the tephras at Quartz-2 and Quartz-3 are likely correlative.

Thin, in situ tephra beds were seen at exposures Quartz-1, Hunker-5, and Bear-1. These tephras were thin, ranging from 5 - 30 cm in thickness, and were continuous and often cryoturbated (Figure 5.17). Tephras at Quartz-1, Hunker-5, and Hunker-6 were in similar stratigraphic positions, within horizontally-stratified silt units, between 3 - 5 m below the organic mat. A second, similar tephra was seen at Hunker-5, approximately 75 cm below the upper one. The tephra at Bear-1 was located in a disorganized silt, sand and organic unit, approximately 1 - 30 cm above the underlying iron-stained gravels (Figure 5.13).

Figure 5.16 **Photograph of a redeposited tephra bed at**
Quartz-3.

Figure 5.17 **Photograph of a thin, in situ tephra bed in horizontally-stratified silt (Hunker-5). Ice wedges are present to the bottom-left and right of the tephra.**

vi) Secondary and Additional Features

Secondary and additional features of the Silt unit are ground ice, fossil animal remains, paleosols, and cryoturbated silt with plant macrofossils.

a) Ground Ice

Ground ice bodies observed in the Silt unit were: small segregated ice lenses; massive ice including ice wedges and intrusive ice; and pool ice. Small segregated ice lenses were observed throughout the entire Silt unit at exposures which were permanently frozen. The lenses were normally 0.1 - 0.5 cm thick, however lenses up to 2 cm in thickness were also seen. The lenses were always horizontal in orientation.

Large ice wedges were seen in the Silt unit at exposures Quartz-1, Sulphur-1, Hunker-2, Hunker-5, and Hunker-6 (Figure 5.18). They were identified by: (i) their characteristic V-shape; (ii) vertical foliation of ice seams; and (iii) upturned bedding adjacent to the wedge. The upper position of the ice wedges at all sections was approximately 50 - 100 cm below the upper contact of the Silt unit. The tops of the wedges were flat, and were variable in width (ranged between 1.5 m and 4.0 m). The flat tops of the wedges at regular distances below the surface

Figure 5.18 **Photograph of a massive ice wedges at Hunker-5.**

and below the line of annual thaw, are evidence of the thaw unconformity recognized by others. It is likely that most of the wedges seen in the mucks were viewed obliquely, however, it is possible that complete ice wedges were seen at Hunker-5 in true cross-section. At this section, measured heights of wedges were similar (between 5.0 and 7.0m), and widths at the tops were as much as 2.0 m across. The similar position and size of the wedges suggest that they are syngenetic: ones which grew in an area where the grounds surface was neither aggrading nor degrading. The majority of wedges seen in the Silt unit in the study area: were distorted and had coalesced; were located at the same position within the Silt unit; and were not active as they were located below the depth of annual seasonal thaw.

Fossil ice wedge features, or ice wedge casts, were seen at Hunker-2 and Hunker-3 (Figure 5.19). The features were highly distorted, and contained a disorganized mixture of silt, sand, pebbles and cobble-sized clasts.

Intrusive ice was seen at exposures Quartz-1, Hunker-5, and Hunker-6. It was identified by: (1) dykes or sills of ice which extended horizontally along an entire exposure, cutting bedding structures in enclosing sediments; and (2) color gradation from clear to yellow-colored ice: evidence of solute expulsion which occurs as the freezing plane advances through a chamber of water (Pollard and French 1984 - Figure 5.20a and 5.20b).

Figure 5.19 **Photograph of a distorted ice-wedge cast at Hunker-3. A small bird bone was found in the hole which had been excavated at the bottom right of the cast.**

Figure 5.20a **Photograph of a body of intrusive ice (Hunker-5). Notice the colour variation from grey on right to yellow on left - evidence of solute expulsion.**

Figure 5.20b Close-up photograph of an intrusive ice body showing clear ice on left grading into yellow ice on right (Hunker-5).

Pool ice was also seen in the muck deposits, often as a result of shafts dug by miners. Pool ice is formed from water that has filled a large cavity in permafrost. Often stratified layers of ice could be seen in cross section. Pool ice was seen at Bonanza-4, Hunker-4, and Bonanza-2. Often old mining tools such as ladders, shovels, and lanterns were found frozen in these ice bodies (Figure 5.21).

The presence of ice wedges, segregated ice lenses and intrusive ice suggest that both surficial run-off and groundwater were active in the study area during aggradation of the Silt unit.

b) Fossil Animal Remains

Fossil animal bones were found in most valleys where muck was studied. In the majority of cases, bones were found in slump material; however, several (14) were found in situ. In situ bones were found in muck deposits at Sulphur-1 (1), Dominion-1 (1), Hunker-2 (1), Hunker-5 (1), Bonanza-2 (3), Bonanza-4 (6), and Bear-1 (1).

Most of the bones found in the Silt unit (9) were located either at, or near, the contact with underlying gravels. Some bones (3) were found within the gravels themselves, but just below the contact with the overlying silt. Exceptions to this observation were bones found at

Figure 5.21 **Photograph of an old timer's ladder which was exposed following the melting of pool ice at Bonanza-2 (photograph courtesy of A. and M. Roberts).**

Hunker-2 and Bear-1. At the first location, a small bird bone was found in the bottom of a distorted ice-wedge cast located in wavy, planar-stratified silt, approximately 300 cm above the underlying contact with gravels (Figure 5.19). At the second location, a bone was found in a paleosol formed in massive silt, approximately 194 cm above the silt/gravel contact.

Fossil ground squirrel nests were seen at four locations: Quartz-1; Quartz-3; Sulphur-1; and Bonanza-4 (Figure 5.22). The nests consisted of pockets of grassy material, approximately 10 - 20 cm in diameter, and they sometimes contained fossil bones and droppings. The nests were usually connected to tunnels which were also preserved in frozen silt. Most nests were found in the lower portions of the unit. A nest with a fossil jawbone and vertebrae was preserved near section Quartz-1, in a mound of frozen, horizontally bedded silt, approximately 3 m above creek gravels. A nest with visible tunnels was seen in horizontally-bedded silt at Quartz-3 approximately 150 - 175 cm above the silt/gravel contact, and at Sulphur-1, approximately 150 cm above the silt/bedrock interface. A nest was also observed in massive silt at Bonanza-4, approximately 50 cm above the gravel/silt contact.

Figure 5.22 **Photograph of a squirrel's nest at Quarts-3. The nest was found in horizontally-stratified silt, approximately 150 - 175 cm above the silt/gravel contact.**

c) Paleosols

Four distinct paleosols were seen in the Silt unit. The first was observed at the base of the unit overlying either gravel or bedrock. The paleosol in these areas was evident from plant macrofossils, particularly continuous grass beds, and by significantly higher organic content percentages in the basal zone than in the rest of the unit. This paleosol was seen at Sulphur-1, Dominion-1, Quartz-1, Quartz-2, Hunker-3, Hunker-5, Bonanza-2, Bonanza-4 and Bear-1.

The second paleosol was seen within the Silt unit at Quartz-2. It was distinguished by a thin (5 cm), continuous grassy bed approximately 541 cm above the silt/gravel contact. The horizon had formed upon horizontally bedded silt, but was overlain, unconformably, by a thick tephra bed.

The third paleosol was observed at Bonanza-5, and the fourth from Bear-1. The paleosols were similar in appearance. Both were continuous, thick silt bands (31 cm and 44 cm respectively), which contained abundant rootlets, twigs, and were dark brown to purple in colour. The paleosol from Bonanza-5 had formed upon horizontally bedded silt, and was located 116 - 147 cm above the base of the section (the lower contact of the silt was not seen at this exposure). The paleosol from Bear-1 had formed on wavy planar

stratified silt, located 172 - 216 cm above the silt/gravel contact. Organic content for both paleosols was high: 8.9% for Bonanza-5; and 6.6% for Bear-1.

Paleosols observed within the Silt unit suggest periods when silt accumulation was either low, or at a temporary standstill. During these periods, weathering and vegetation growth were active.

d) Cryoturbated Silt with Plant Macrofossils

This feature consists of pockets of disorganized silt with organic material (often macrofossils), including peat and wood. It may also contain sand pockets, distorted tephra, and/or angular bedrock clasts (Figure 5.23). These pockets are located in exposures which contain large bodies of massive ice, particularly Quartz-1, Hunker-5, Hunker-6, and Bonanza-6. They are always found near the Organic/Silt unit contact, in pockets either completely surrounded by massive ice, or in proximal locations to massive ice bodies. The origin of these pockets is likely due to either the growth of ground ice in the organic layer distorting sediments and displacing them downwards, or due to involutions created by density differences between the Silt and Organic units. Involutions may be caused by differences in density of saturated soils during advancement of the freezing front which "may cause some bulbs [of material] to

Figure 5.23

Photograph of a large pocket of cryoturbated silt with organic material and a distorted tephra (white) (Quartz-1). The unit is bounded on the bottom and left by an ice wedge, and the body of ice in the upper right corner is likely intrusive.

sink and form nearly spherical, isolated masses, or connected pods of displaced material" (Selby 1984: 402).

5.1.3 The Organic Unit

The Organic unit was seen at 15 of 23 sections, but it is likely that it had been present in each of the valleys prior to commencement of mining activities. This section describes the sedimentary structures and additional features of the Organic unit.

i) Sedimentary Structures

The Organic unit is predominantly organic material, but it also contains inorganic materials. Two major sedimentary sub-units were identified in the Organic unit: (i) stratified organic beds and silt; and (ii) disorganized organic material and silt with sand and gravel pockets. These sub-units were often seen at the same exposure and contacts between the two were indeterminate. The sub-units suggest that the Organic unit developed by both in situ and colluvial processes.

a) Stratified organic beds and silt

This sub-unit consists of up to four continuous, in

situ organic horizons, which are interstratified with unsorted silt, and, to a lesser extent, sand and gravel (Figure 5.24). In situ peat is the dominant organic material located in the organic horizons. In some cases, in situ peat and tree stumps were seen. At Hester Creek, the organic horizons were continuous, but contained broken-up plant fragments, as well as in situ material. Often the organic horizons were heavily cryoturbated, but continuity of horizons was maintained.

The sub-unit also contains abundant pockets and/or lenses of sand and gravel which cross-cut the stratification in the unit, and are likely secondary features. Some of these pockets are channel-shaped in nature, and contain well-sorted, stratified material. Others are unsorted and massive. Often the sand and gravel is iron-stained. In addition, occasional small pockets or lenses of well-sorted, stratified silt may be seen.

This sub-unit was seen at exposures studied at Sulphur-1, Quartz-4, Hunker-1, Hunker-2, Hunker-4, Hunker-6, Bonanza-1 and Bear-1. It represents individual, or a number of periods of stability during accumulation of the Organic unit (surface neither aggrading nor degrading), during which vegetated surfaces were able to develop.

Figure 5.24 **Photograph of a muck exposure at Hunker-6. Here the Silt unit at the base of the exposure is overlain by stratified organic beds (peat), and silt. The Organic unit here contains small ice wedges in the upper centre and centre-right portions of the photograph.**

b) Disorganized Organic Material and silt, with sand and gravel pockets

This sub-unit consists primarily of disorganized organic material, particularly macrofossils of peat and wood, mixed with silt (Figure 5.25). The sub-unit is similar to the 'stratified organic beds and silt' sub-unit described above, however, in this case, there are few recognizable in situ organic horizons. Occasionally, the lower contact of this sub-unit consists of a fairly continuous, in situ peat bed, although, above this bed, the rest of the unit was disorganized (e.g., Quartz-1).

This sub-unit was the most widespread Organic sub-unit seen in the valleys. It is located at all sections where the natural organic mat had been undisturbed, specifically Quartz-1, Quartz-3, Quartz-5, Hunker-5, Bonanza-4, and Bonanza-6. It represents mass wasting processes such as active-layer glides or debris flows which may have been induced by a number of processes, including fire and a supersaturated active layer following spring melt.

ii) Additional Features

Both ground ice and fossil animal remains were also noticed in the Organic unit.

Figure 5.25 **Photograph of disorganized organic material and silt, with sand and gravel pockets (Sulphur Creek).**

a) Ground Ice

Ground ice in the Organic unit is similar to that in the Silt unit. Ground ice types observed in the Organic unit were: (1) small, segregated ice lenses; and (2) massive ice bodies such as ice wedges, intrusive ice, and aggradational ice bands.

The Organic unit is permanently frozen and contains, particularly in areas which are silt-rich, small, segregated ice lenses. The lenses are 0.1 - 0.5 cm thick, and are horizontally oriented.

Ice wedges observed in the Organic unit were shorter than those observed in the Silt unit (Figure 5.26). These ice wedges also appeared to be thinner than those in the Silt unit, but, as mentioned previously, it is difficult to know if ice wedges are being observed in true cross-section. The ice wedges in the Organic unit were located at various distances below the organic mat, and were various sizes. Some of the wedges were located at the base of the active layer, and are, perhaps, active. Many of the wedges were distorted in appearance, and some extended down into the Silt unit, often coming into contact with older ice-wedges, or bodies of intrusive ice. Distorted wedges may be the result of slow-moving hillslope processes such as frost creep and/or gelifluction.

Intrusive ice was observed in the Organic unit as well.

Figure 5.26 **Photograph of ice wedges in the Organic unit (Quartz-1). Ice wedges are smaller in the Organic unit than in the Silt unit.**

The bodies of the ice were similar in nature to those in the Silt unit, where ice dykes or sills cutting across bedding structures were observed, and evidence of solute expulsion was seen.

Aggradational ice was visible in the Organic unit as well. Aggradational ice "is formed near the surface of permafrost, usually by segregation at the end of the thaw season, which has become incorporated into permafrost by addition of material to the ground surface, causing the base of the active layer to rise" (Burn 1993: 5). Bands or discontinuous lenses of aggradational ice were observed primarily at the base of the Organic unit, and were approximately 15 cm in thickness.

Like the Silt unit, the segregated ice lenses, ice wedges and intrusive ice suggest that the water source for ice in the Organic unit was both surficial runoff and groundwater.

b) Fossil Animal Remains

Few visible fossil animal remains were seen in the Organic unit. Large mammal bones, including the horn of a steppe bison, were seen in the gravels immediately underlying the Organic unit at Hunker-1. Small shells were seen in a well-preserved, frozen peat lens within a disorganized organic material and silt sub-unit at Hunker-2,

approximately 50 cm above the base of the section (lower contact of unit was not seen, but was likely within a metre of the base of the exposure). The shells are similar to photographs of Succinea, a freshwater mollusc, observed in Clarke and Harington (1978: Fig. 2.g).

5.2 The Distribution of Klondike Muck Deposits

5.2.1 Within the Study Area

Muck distribution in the study area was influenced by valley-size, aspect, and disturbance. In small, undisturbed valleys, muck could be found on both sides of the valley, as the smaller creeks had not eroded a valley wide enough to permit intensive daily sun exposure on frozen sections. When disturbed, muck was best preserved on slopes facing north, and thawed on slopes facing south. In recently disturbed, small valleys, muck exposures on either side of the valley often varied in thickness: north-facing exposures were always thicker.

In larger valleys, particularly Hunker, Quartz, Sulphur, and Bonanza, muck is either non-existent, or is found on north-facing slopes. Muck in larger valleys is only rarely found on south-facing slopes, as summer sun exposure on south-facing valley walls is intensive enough to have completely thawed the deposits. In rare instances, muck was

found on south-facing slopes in areas protected from the sun. These areas were often amphitheatre-shaped bends in the valley, likely created by a paleochannel (e.g., Bonanza-6).

Figure 5.27 shows the distribution of muck deposits observed in the Klondike District, based upon field observations made in summer 1994. It is important to note that this map is not meant to show the only locations that muck can be located in the study area. It is rather a schematic representation of the places muck was encountered during the field season. It is likely that more muck exposures exist than is suggested on the map.

5.2.2 Within the Valleys

Within the valleys, muck is found in the bottoms, and in the lower reaches. Although values differed for each valley, the extent of muck up the valley sides did not exceed 77 m above the natural creek level. In addition, muck was not normally found on ridges separating valleys, except at section Bonanza-3, or on domes from where the creeks originated. The location of muck in the bottoms, and in lower reaches of valleys indicates that muck has collected there, likely by a combination of slope processes. The sighting at Bonanza-3 suggests that in the past, muck occupied upland areas as well.

Figures 5.28a and 5.28b show cross-valley profiles of

Figure 5.27 Map of the distribution of muck deposits observed in the Klondike District, based upon field observations made in summer 1994. Black circles denote muck localities.

greatest in arid and semi-arid areas of the world which receive less than 1,000 mm of precipitation per year, and have sparse vegetation (Carson and Kirby 1972: 219).

Sheetwash is mostly responsible for the horizontal stratification of beds commonly seen in the Silt Unit, as "[i]t is believed that slopewash and intense freeze-thaw activity during the Pleistocene resulted in the deposition of rhythmically bedded slope deposits" (French 1976: 141, referencing Dylik 1960). The water available for surficial erosion came likely from snowmelt in the spring, suggesting that most erosion occurred during this period of the year. Vegetation must have been sparse in the valleys, limited only to grass beds observed regularly throughout the unit which grew during the summer periods.

Debris flows also played a role in retransporting silt to valley bottoms. Debris flows may occur when sediments become saturated enough to flow. Evidence for this type of mass movement are the massive silt beds containing clasts of angular bedrock. A property of loess is its variable stability. "When dry, loess has the ability to stand in vertical sections ... but when saturated with water the shear strength is greatly reduced and the material is subject to subsidence, flowage and sliding" (Pye 1987: 200). In the Klondike, saturated silt overlying bedrock incorporated weathered clasts into the matrix and flowed downslope where it was deposited as a massive unit. Guthrie

muck within: a) a large valley; and b) a smaller pup. The profile elevations are taken from topographic maps. The elevations of muck up the valley walls are taken from field measurements which were then converted to values relative to those taken from the maps. Because of the discrepancies involved with using field altimeters, it is important to note that the profiles are to show the relative, not absolute, location of muck within the valleys.

5.3 The Origin of the Klondike Muck Deposits

5.3.1 The Silt Unit

The physical characteristics of the Silt unit suggest that the material was transported to the Klondike District as loess. Bedding within the Silt unit suggests that the loess is: (1) primary eolian material; and (2) loess that has been reworked by both fluvial and colluvial processes. In addition, there is other evidence beyond sedimentary structure to suggest that the loess has been redeposited. Secondary and additional features of the Silt unit suggest that the unit accumulated incrementally over time.

5.3.1.1 Loessal Origin for the Silt Unit

The particle-size distribution, mineralogy, and grain

morphology and surface texture are strong evidence of a loessal origin for the Silt unit.

i) Particle-size distribution

The grain size distribution of 'typical' loess shows a pronounced mode in the range 20 - 40 μm ..., and is positively skewed (i.e., towards the finer sizes). Typical loess often contains up to 10% fine sand, but in cases where the sand content exceeds 20% the term 'sandy loess' is appropriate. Up to 20% clay is not unusual in typical loess; if the sediment contains more than 20% clay it can be described as clayey loess...Typical unweathered loess is composed mainly of particles between 10 and 50 μm in size, and usually has a prominent mode between 20 and 30 μm (Pye 1987: 199, 207-208).

Pye (1987: 208) compared loess samples from 10 different sites around the world, and reported a mean particle size between 20 and 30 μm . A continuum of aeolian sediments exists between dune sands, 'typical loess' and clayey loess.

The particle-size distribution of all the samples analyzed from the Silt unit conform to Pye's definition of a 'typical loess'. For the sample population, the grain-size distribution is uniform, composed mainly of coarse silt (20 - 50 μm ; mean = 50.7%), and the distribution is positively skewed. Coarse and medium silt (5-50 μm), comprise 74.6% of the mean grain-size distribution, and coarse and medium silt and fine sand (5 - 250 μm) comprise 87.4%. A mean of 12.8% fine sand is present in the sample

population, but, there is not enough to consider the unit as 'sandy loess'. Since the samples were selected from various drainages and elevations within exposures, the consistency of grain-sizes is strikingly uniform both spatially and temporally in the study area.

ii) Mineralogy

Pye (1987: 199,209) describes the mineralogy of loess as "consisting chiefly of quartz, feldspar, mica, clay minerals and carbonate grains in varying proportions [with] 50 - 70% quartz, 5-30% feldspar, 5-10% mica, 0-30% carbonate, and 10-15% clay minerals". He also mentions that while these numbers are averages, markedly different mineralogies are sometimes found.

The XRD analyses conducted on Silt unit samples, from various geographical and temporal locations within the study area, are characteristic of the mineralogy of 'typical' loess, as defined by Pye (1987: 229). While mineral quantities were not determined in this study, the XRD diffractometer traces showed, on average, the strongest peaks for quartz and plagioclase feldspar. Smaller, but recognizable peaks were observed for both mica and chlorite. As mentioned in Section 5.1.2. (b), the mineralogical suite was consistent both spatially and temporally for the study area, but peak intensities differed slightly from sample to

sample.

iii) Grain Shape and Surface Texture

The shape of grains in loess depends on their mineral compositions and crystallographic structure, the processes responsible for their formation, and the degree of pre- and post-depositional shape modification induced by weathering and diagenesis (Pye 1987: 214).

Mechanical weathering of rock is a primary factor in loess formation, for grains are produced by the sub-glacial crushing of rock. Generally speaking, loess particles derived from a strictly mechanical environment, i.e., no chemical weathering, will appear freshly broken. Freshly-crushed quartz silt grains are blocky and angular or sub-angular, and display conchoidal fracture. Feldspars grains are strongly influenced by cleavage, and grains are thus often equidimensional and blocky. Silt-sized grains of rhombohedral carbonates (calcite and dolomite) occur frequently as equidimensional rhombs bounded by flat crystal faces, and phyllosilicate minerals occur predominantly as platy grains (Pye 1987: 214-215).

Transport and post-depositional processes are likely to modify freshly-fractured particles. Cailleux (1942) states that blown sand grains are mainly rounded and possess a surface texture which has a matt or frosted appearance as a result of wind abrasion, by contrast with those which have

been deposited in water, which are usually more angular and shiny. Saltation may also play a role in the rounding of sand grains (Selby 1985: 329). In addition, grains which have undergone weathering, such as soil formation, will likely display shape differences, for example, quartz often shows edge rounding due to solution and reprecipitation (Pye 1987: 214-215).

The samples analyzed by SEM showed a range of particle shapes from angular to rounded, with a dominant portion in the sub-angular to sub-round category (Figures 5.4b and 5.4c). The result is that many of the grains had much rounder edges than one would expect to see from fresh, mechanically-broken rock. The fact that there are angular and sub-angular grains within the samples, however, suggests that these grains could have been glacially ground. The rounder grains have likely undergone shape modifications due to processes involved in wind transport, and/or post-depositional processes such as chemical weathering and redeposition (see next Section).

"The surfaces of loess grains are often covered by adhering clay-size particles and/or amorphous aluminosilicate coats" (Pye 1987: 215). The adhering clay-size particles were initially interpreted by Smalley and Cabrera (1970) as glacial comminution (minute fragment) debris. This interpretation, however, has been challenged, as similar particles have also been observed on grains from

a wide range of non-glacial environments (Warnke 1971; Whalley and Smith 1981), and have been produced by non-glacial processes in the lab (e.g., Pye and Sperling 1983). Pye (1983) found that many of the adhering particles on European loess grains consisted of a mixture of kaolinite, illite, clay-sized quartz and carbonate grains held in position by electrostatic charges or thin moisture films. Encrustations of amorphous silica or aluminosilicate material have been observed on loess particles as well, particularly if sampled from more weathered horizons (Pye 1987: 215-216).

The surface textures of the grains displayed both the adherence of smaller particles, and what were likely encrustations, as described in the literature, and as shown by the pitted nature of the particles (Figure 5.5). The mineralogical component of these encrustations, however, is unknown. While both particle adherence and the growth of encrustations are both features that may occur in a range of depositional environments, it is known with certainty that they occur on loess particles.

iv) Summary of Physical Characteristics

The grain-size distribution and mineralogy of the Silt unit suggests that the unit is composed of loess. The morphological and surface textural features of the grains,

while not indicative of loess on their own, when combined with the textural and mineralogical results, strongly suggest that the material of the Silt unit was once windblown into the Klondike District as loess.

5.3.1.2 Deposition of the Silt Unit

Sedimentological investigations of the Silt unit suggest that the unit is comprised of both primary and redeposited eolian materials (i.e., loess and tephra). There is also additional evidence to support the role of redeposition. Secondary and additional features suggest that the unit accumulated incrementally.

i) Primary Eolian Materials

Portions of the Silt unit contain primary eolian materials. Sedimentary units indicative of primary eolian material are: (1) massive silt; and (2) thin, in situ tephra beds.

Péwé (1955: 719) writes that "[a]bsence of definite stratification is characteristic of loess". Brodzikowski and van Loon (1991: 483) state that:

[m]ost extraglacial loesses...share a massive appearance, a yellow, brown or yellowish-grey (olive grey) colour and a high silt content....Sand grains in the loesses are usually randomly distributed, although thin laminae may

sometimes be found that are clearly enriched in sand... lamination [of sand] is usually discontinuous and irregular, and the thickness of the laminae varies from less than a millimetre to about one centimetre.

The 'massive silt' unit observed in Klondike mucks is primary loess. The continuous and discontinuous sand laminations located within the unit are likely the result of paleo-wind intensities which may have been strong enough to suspend, and then deposit coarser material at certain periods throughout accumulation of the unit. Thin organic laminae observed within the unit are likely horizons representing periods of limited loess accumulation, during which organic material was able to grow.

Thin (3 - 10 cm), continuous tephra horizons located at Quartz-1, Hunker-5, and Hunker-6 are airfall deposits which show no evidence of reworking. The preservation of the thin beds indicates deposition of material on a dry paleosurface.

ii) Retransported Eolian Materials

The Silt unit is also composed of redeposited eolian materials. Redeposition occurred by mass-wasting and, to a lesser extent, alluvial processes associated with a periglacial environment. Sedimentary units indicative of mass-wasting are: (1) horizontally-bedded silt; and (2) silt with angular bedrock clasts. Sedimentary units indicative of alluvial processes include: (1) wavy planar stratified silt;

and (2) redeposited tephra beds. Other evidence to support the notion that the unit contains redeposited materials are: (1) the location of deposits in the bottoms and lower-reaches of the valleys; (2) colluvial bones at the base of the unit and the mummified horse found at 15 Pup in summer 1993; and (3) poorly-preserved pollen extracted from the sediments.

a) Mass-Wasting Processes in a Periglacial Environment

Mass-wasting processes in a periglacial environment can be divided into four main types: (1) large-scale fast mass movements involving large quantities of saturated material such as debris flows and mudflows (internal deformation); (2) large-scale masses of material transported in the form of slumps or landslides (no internal deformation); (3) small-scale, usually surficial, fast mass movements connected with the presence of permafrost, such as skinflows, mudflows, local debris flows, active-layer gliding or slumping, and rockfall/blockfall; and (4) slow, surficial mass-transport processes connected with the presence of permafrost, such as creep and gelifluction (Brodzikowski and van Loon 1991: 449). Slopewash is also considered an important mechanism in sediment retransportation including both surface wash (sheetwash),

and subsurface wash (particles transported through soil pores) (Brodzikowski and van Loon 1991: 449).

Mass-wasting processes involved in retransporting loess to valley bottoms in the Klondike District are: (1) slopewash in the form of sheetwash; (2) debris flows; and (3) gelifluction. It is important to note that few mass-wasting processes occur as individual phenomena, but rather as a complex of processes acting upon slopes (French 1976: 134). The following interpretations have isolated single processes considered primarily responsible for the structures seen within the Silt, i.e. sheetwash, debris flows and gelifluction, but these are likely not exclusive to the bedforms seen in the field.

Sheetwash is a type of slope erosion in which particles are entrained by surficial water and are carried along in unconcentrated overland flow, or in small, discontinuous, ephemeral channels (French 1976: 141; referencing Carson and Kirkby 1972: 190). Sheetwash in high Arctic periglacial regions is considered equally as important as solifluction in transporting materials downslope (French 1976: 142). The major factor influencing the rate and amount of erosion is vegetation as it "intercepts precipitation, breaks the impact of raindrops, improves soils structure and infiltration around roots, binds the soil and subdivides overland flow around plant stems and litter" (French 1976: 141). Rates of surface soil transport are reported as

greatest in arid and semi-arid areas of the world which receive less than 1,000 mm of precipitation per year, and have sparse vegetation (Carson and Kirby 1972: 219).

Sheetwash is mostly responsible for the horizontal stratification of beds commonly seen in the Silt Unit, as "[i]t is believed that slopewash and intense freeze-thaw activity during the Pleistocene resulted in the deposition of rhythmically bedded slope deposits" (French 1976: 141, referencing Dylik 1960). The water available for surficial erosion came likely from snowmelt in the spring, suggesting that most erosion occurred during this period of the year. Vegetation must have been sparse in the valleys, limited only to grass beds observed regularly throughout the unit which grew during the summer periods.

Debris flows also played a role in retransporting silt to valley bottoms. Debris flows may occur when sediments become saturated enough to flow. Evidence for this type of mass movement are the massive silt beds containing clasts of angular bedrock. A property of loess is its variable stability. "When dry, loess has the ability to stand in vertical sections ... but when saturated with water the shear strength is greatly reduced and the material is subject to subsidence, flowage and sliding" (Pye 1987: 200). In the Klondike, saturated silt overlying bedrock incorporated weathered clasts into the matrix and flowed downslope where it was deposited as a massive unit. Guthrie

(1990: 55) writes that in central Alaska, "[c]ycles of silt deposition and stabilization probably occurred throughout the Pleistocene, but episodes of extreme silt erosion stripped loess deposits from valley bottoms as well as hillsides". These extreme episodes of erosion are likely the result of a supersaturated active layer which may be caused by a number of reasons, for example (1) an early, rapid snowmelt in spring; (2) an intense rainstorm; or (3) a hot summer which increased the depth of the active layer and thus melted ground ice. The debris flow deposits seen in the Klondike muck deposits represent these extreme episodes of erosion. It is important to mention debris flow deposits which do not contain weathered bedrock, may also be present in the muck deposits, simply, because bedrock was unavailable. In these cases, silt was likely deposited at the bottom of the slope downslope as a massive unit. Debris flows of this sort, characterized by a high proportion of fine particles, are called mudflows (Brodzikowski and van Loon 1991: 496).

Other mass wasting processes were likely active during aggradation of the silt, for example, slower-moving processes such as gelifluction and frost creep. Gelifluction is slow-flowing soil from high to low ground caused by a saturated active layer and high pore water pressures (Selby 1985: 405). It is greatest in early summer and declines towards autumn. Brodzikowski and van Loon (1991: 497) state

that "[l]oesses, with their typical grain-size distribution, seem exceptionally susceptible to this [gelifluction] process". Frost creep is "the ratchetlike downslope movement of particles as the result of frost heaving of the ground and subsequent settling upon thawing" (Washburn 1979: 198). The combination of gelifluction and frost creep processes were likely the cause of ice-wedge distortions. Due to the uniformity of grain sizes of the Silt unit, it is likely that many sedimentary structures which may have made these processes more recognizable in the sedimentary record were not observed.

b) Alluvial

Alluvial processes involved in retransporting the loess to valley bottoms in the Klondike District were small-scale ephemeral systems such as rills and gullies. Rills form where surface wash becomes concentrated as water is diverted around objects (Selby 1985: 217). Gullies are distinguished from rills mostly by size: gullies are more than about 0.5 m in depth and width, and may be more than 10 m across (Selby 1985: 217). Alluvial bedforms were identified in the Silt unit by 'wavy planar stratified silt' and from thick tephra beds showing planar and cross-bedded lamination. Rills were evident from occasional small (<50 cm wide) channel structures containing cross-bedded silt. Gully channel

boundaries were not visible, however, zones of wavy planar stratified silt were seen within the Silt unit, suggesting that water reworking of the sediments on a larger scale had occurred. Further evidence for alluvial activity are the thick tephra beds containing wavy planar and cross-bedded laminations. Often, the upper and lower contacts of the tephra units were interbedded with silt. Alluvial features were not well-represented within the Silt unit, and are thus considered to have played a smaller role than mass-wasting in redeposition of the unit to valley bottoms.

c) Other Evidence for Retransportation

Evidence to support the process of silt retransportation is not limited to sedimentary structures. (1) The location of silt in the bottoms and lower-reaches of valleys; (2) the presence of colluvial bones at the base of the Silt unit and the mummified horse recovered from muck in summer 1993; and (3) the state of pollen grains extracted from the silt; are further support for the retransportation hypothesis.

A significant observation supporting the role of redeposition is that today, muck is, with one exception, located in the bottoms and lower reaches of the valleys. Considering that a significant proportion of the muck deposits has been identified as loess, the position of the

muck in valley bottoms indicates reworking, for loess would originally have been deposited over the entire study area, not just in the valley bottoms.

A second point is the presence of colluvial bones at the base of the Silt unit, overlying creek gravels, and, the recovery of frozen horse carcass from 15 Pup in September 1993. As mentioned, Pleistocene mammal bones of a wide range in age are almost always found at the base of the Silt unit, overlying either gravels or bedrock. The concentration of bones at the base of a unit, which, as will be shown in a subsequent section, are sometimes younger than the sediments they occupy (see Section 5.4), can only be explained by extreme cases of concentrated slope run-off such as gullies, eroding through the silt to the gravel/bedrock lying below, and depositing bones located within the silt at the base of the section. If the sediments were in their original place of deposition, one would expect to find bones at various positions within the Silt unit, with older bones at the base, and younger ones near the top. Reworking of the sediments by gully erosion has concentrated bones of various ages at the base of the Silt unit. Guthrie (1990: 68-79) outlines a similar role of gully formation as an important process in the history of muck development in the Fairbanks area.

Guthrie (1991: 71) writes that "[m]ummification is not just a matter of freezing; carcasses must be buried by some

rapid process". In his research conducted on Blue Babe, a Pleistocene bison mummy found encased in Fairbanks muck deposits, he concludes that:

[a]t the close of winter, the bison carcass was buried by silt carried in rapidly moving snowmelt water...[t]he carcass probably thawed the first summer, but remained bedded on frozen ground and covered by cold silt. He was refrozen in subsequent winters and, as silt accumulated year after year, was gradually interred beneath the lower reaches of annual thaw within permafrost (Guthrie 1990: 113).

Hopkins (1982) suggests that environmental conditions favourable for burial, and thus rapid silt movement, such as snowy winters, heavy spring runoff, and very dry summers, prevailed during the last glaciation. Guthrie (1990: 74) states that:

[m]ost silt in the valley bottoms is finely bedded, indicating that the normal amount transported may have been rather modest. But during heavy rain or rapid snowmelt, enormous quantities could be moved over a short time...I can imagine silt washing downslope during the Pleistocene, varying from broad sheets to channelled streams flushing over their banks...The majority of Alaska Pleistocene fossils were buried by the kind of deposition just described.

The mummified horse recovered from 15 Pup in the summer of 1993 was enclosed in silt (R.M. Gotthard, personal

communication 1994). Sedimentological descriptions of the area in which the horse was likely found were made in 1994. Hunker-5 revealed the Silt Unit (2.39 m thick) overlain by the Organic unit (6.45 m thick) (exposure Hunker-5 - see Figure 5.29c). The bedding in the Silt unit at this site was obscured by melting silt, however, more bones (likely mammoth) were seen at the base of the unit in the approximate area in which the horse was found, within 1 m above the underlying gravel. The bones at the base of the unit suggest the presence of a paleo-gully in this location. While the exact cause of death of the horse has not been determined, based upon Guthrie's (1990) observations, and the bones found at Hunker-5, fast-flowing, mass-wasted silt may have buried, and preserved the horse, in a paleo-gully at 15 Pup for over 26,000 years.

A third point, is the state of the pollen grains extracted from the Silt unit. As mentioned, palynological work was too difficult to conduct for this thesis, as pollen grains were severely damaged, making identification practically impossible. Terasmae (1967: 4) noted that the "extensive recycling (deposition-erosion) of surficial deposits during the Quaternary makes the extraction of a long and legible fossil record very difficult". With reference to his attempt to examine plant bearing deposits near Dawson, he writes:

[in] palynological studies of valley bottom silts, which contain abundant finely divided plant detritus, the poor preservation or absence of pollen has been attributed to the large-scale movement and recycling of this deposit. Well preserved and abundant pollen is found occasionally in this stratigraphic unit and indicates that destruction of pollen has occurred during accumulation of this silt unit which originated when loess was redeposited in the valley bottoms from adjacent slopes (Terasmae 1967: 4).

Further, Edwards (1993: 4) writes that "to date there have been few attempts to isolate pollen from Alaskan loess. Because of the low concentration and poor preservation of pollen, extraction and analyses are laborious". With reference to a palynological study conducted at Birch Creek, on a mid- to late-Pleistocene loess exposure (Edwards and McDowell 1991), Edwards (1993) states that a large proportion of pollen grains were severely corroded, indicating a poor preservational environment. With these former attempts to produce pollen diagrams from redeposited or primary loess, along with the attempt made to identify pollen from the silt in the Klondike, it is likely that the redeposition of the silt, may have played a major role in damaging the pollen grains, in addition to the non-acidic environment the grains were found in.

iii) Incremental Accumulation

Additional and secondary features of the Silt unit suggest that the unit accumulated mostly slowly and steadily, rather than catastrophically. Evidence to support this theory comes from observations of the existence of paleo-surfaces which must have existed during accumulation of the Silt unit: (1) thin, distinct, continuous tephra beds which resulted from airfall on a dry surface; (2) paleosol formation and/or weathering zones seen in the silt; (3) ground squirrel nests; (4) in situ grassy beds and rootlets seen at regular intervals throughout the Silt unit; and (5) the high organic content for the entire unit, representing continual vegetation growth throughout accumulation of the unit.

Loess accumulation in the study area was likely the greatest in fall/winter, and redeposition into valley bottoms was likely greatest in the late winter/spring and summer. As loess would have been entrained by the wind from exposed river bars beyond the glacial terminus, lower river levels during the fall, following a dry summer, would have provided a great amount of dry material available for entrainment. As mentioned, Hopkins (1982) suggests that very dry summers occurred throughout the last glaciation. In addition, strong katabatic winds blowing off the glacier in winter, would have provided optimal conditions for loess

transport. Globally, it is estimated that loess accumulation was $0.5 - 3 \text{ mm yr}^{-1}$ around the time of the last glacial maximum.

In terms of silt redeposition, late winter/spring was likely a period of reasonable seasonal retransportation. As loess redeposition by mass movement and fluvial action rely primarily upon the amount of water in the active layer, snowmelt in late winter/early spring, may have provided conditions necessary for incremental redeposition. Summer storms would have provided optimal conditions for silt retransportation as well. Catastrophic events such as debris flows were likely initiated during summer storms, particularly during late summer when the active layer was completely unfrozen. During these periods, significant amounts of material would have been retransported, particularly if the active layer was completely thawed. Slower-moving processes of silt retransportation, such as gelifluction and frost creep, were year-round phenomena, but were likely enhanced when the active layer became saturated, such as in late winter/early spring, when snow melted and the active layer began to thaw, and in late summer/early fall, when the zone of seasonal frost began to freeze downwards, expelling water into the lower portions of the active layer.

5.3.2 The Organic Unit

Field observations during summer 1994 indicate that the Organic unit consists of both in situ and retransported organic material. Like the Silt unit, the Organic unit appears to have accumulated slowly, although, there is evidence for occasional catastrophic accumulation.

Evidence for in situ organic material are the numerous, continuous peat beds located in the Organic units of the muck exposures. In some of these cases, in situ tree stumps were seen, evidence of a former, forested surface (e.g., Hunker-4). As many as four continuous organic horizons existed at a single site (e.g., Hunker-4 and Hunker-6).

Retransportation of organic material is suggested by the disorganized nature of many portions of the Organic unit seen in the study area. Often organic material was twisted and broken, with a random orientation, or found in disorganized pockets. The presence of disorganized silt, sand and gravel pockets, and colluvial bedrock fragments scattered randomly throughout the unit supports this interpretation as well. It is likely that individual layers of the material were retransported catastrophically, as either debris flows, or active layer glides, caused by a variety of processes such as fire, rapid spring snowmelt, heavy rainstorms, or processes resulting from a deepening of the active layer such as the melting of ground ice.

Gelifluction and creep were likely involved in retransportation as well, when the active layer was more stable.

Incremental accumulation of the Organic unit is recognized by the presence of several paleosurfaces identified by in situ organic layers and ice wedges having formed at a various depths, evidence of an aggrading permafrost table induced by aggrading sediments. Debris flow events were most likely to have occurred during late summer/early fall, after the active layer had completely thawed and a layer of saturated soil was sandwiched between a growing layer of seasonal frost and the underlying permafrost. Fires may have induced catastrophic active-layer movement during the summer and fall as well.

5.4 The Age of the Klondike Muck Deposits

5.4.1 Radiocarbon Dates

This section presents ^{14}C dates for 11 organic samples collected from the Klondike muck deposits. Organic material was collected from two major locations within the muck: at the base of the Silt just above the lower contact with creek gravels or bedrock; and at the base of the Organic unit overlying the silt. In addition, one sample was collected from organic material underlying a thick tephra. Samples

from the base of the Silt unit were collected at Quartz-2 (BGS-1754); Hunker-5 (BGS-1758); Bonanza-4 (BGS-1768); and Bear-1 (BGS-1770). Samples from the base of the Organic unit were collected at Quartz-1 (BGS-1756), just downstream from Quartz-2; Hunker-4 (BGS-1757); Hunker-5 (BGS-1759); Hunker-6 (BGS-1772); Bonanza-4 (BGS-1769); and Bear-1 (BGS-1771). The sample underlying the tephra was taken from section Quartz-2 (BGS-1755). Sections and locations of sampled organic material are shown in Figures 5.29a - 5.29g.

The material collected at the base of the Silt unit included grass and wood sampled from disorganized to crudely stratified silt with organics, sand and/or gravel. Grass was collected from in situ beds, approximately 10 cm thick, at Quartz-2 and Bonanza-4. These beds contained well-preserved grass specimens which had a very distinct, strong odour. The beds were surrounded by, and infiltrated with, silt. Wood was collected at Hunker-5, and Bear-1. Wood from Hunker-5 was located in an organic horizon containing several wood fragments at the contact between creek gravels and silt. Wood from Bear-1 was located in a black, continuous, silty organic horizon, approximately 40 cm above creek gravels.

Organic material contained within the Silt unit was collected from beneath a tephra bed at Quartz-2, 562 cm above the grass specimen collected at the base of the same exposure. The grass bed was approximately 2 cm in thickness, and was continuous. The grass collected was well-preserved.

Figure 5.29a Schematic representation of Quartz-2 showing locations of samples BGS-1754 and BGS-1755.

Figure 5.29b Schematic representation of Quartz-1 showing location of sample BGS-1756. This section is slightly downstream of Quartz-2. The stippled pattern represents an ice wedge.

Figure 5.29c Schematic representation of Hunker-5 showing location of sample BGS-1758.

Figure 5.29d Schematic representation of Bonanza-4 (sections on both sides of valley) showing locations of samples BGS-1768 and BGS-1769.

Figure 5.29e Schematic representation of Bear-1 showing location of samples BGS-1770 and BGS-1771.

Figure 5.29f Schematic representation of Hunker-4 showing location of sample BGS-1757.

Figure 5.29g Schematic representation of Hunker-6 showing location of sample BGS-1772.

Organic material collected from the base of the Organic unit included wood and peat. Wood (twigs and roots), located in continuous peat horizons, was collected from Hunker-4, Hunker-5 and Hunker-6. The sample from Hunker-5 was collected at a section directly across from the location where wood had been collected at the base of the Silt unit, as frozen, better preserved samples were located there. The wood from Hunker-6 was collected from an organic horizon which had collected in a melted ice-wedge, forming a cast. In situ peat was collected for dating at Bonanza-4, immediately across the valley from the location where the grass at the base of the Silt unit had been collected, as the Organic unit at the first location had been removed. Both in situ peat and wood were dated from Bear-1.

The results of the ^{14}C dating are shown, according to position in section, in Tables 5.4a, 5.4b and 5.4c. The ^{14}C dates for organic material at the base of the Silt unit range from $26,240 \pm 500$ years BP (BGS 1758) at Hunker-5, to $31,000 \pm 1,400$ years BP (BGS 1770) at Bear-1. Organic material within the Silt unit, collected at Quartz-2, was ^{14}C dated at $24,025 \pm 550$ years BP (BGS 1755), thus confirming the older date of $27,150 \pm 660$ ^{14}C years BP (BGS 1754) at the base of the same section.

Material from the base of the Organic unit ranges in age from $3,060 \pm 80$ ^{14}C years BP (BGS 1759) at Hunker-5, to $9,945 \pm 150$ ^{14}C years BP (BGS 1772) at Hunker-6.

Table 5.4a ^{14}C Dates for Organic Material at the Base of the Silt Unit

Date (YBP)	Material	Location	Position in Exposure
26,240 $\pm$ 500 (BGS 1758)	wood	Hunker-5 15 Pup	at interface between gravels and silt unit
27,150 $\pm$ 660 (BGS 1754)	in situ grass	Quartz-2 Quartz Creek	continuous grass bed lying 0.5 cm on top of gravels, enclosed in silt
28,450 $\pm$ 1,250 (BGS 1768)	in situ grass	Bonanza-4 Skookum Gulch	continuous grass bed lying on top of auriferous gravel unit, enclosed in silt
31,000 $\pm$ 1,400 (BGS 1770)	wood	Bear-1 Bear Creek	a black, continuous organic-rich bed with wood fragments and tephra 40 cm above gravels

Table 5.4b ^{14}C Date for Organic Material Within the Silt Unit

Date (YBP)	Material	Location	Position in Exposure
24,025 $\pm$ 550 (BGS 1755)	grass	Quartz-2 Quartz Creek	grass bed underneath a thick tephra unit approximately 5.65 m above the creek gravels and 5.62 m above grass sample (BGS-1754) at base of same exposure

Table 5.4c ^{14}C Dates for Organic Material at the Base of the Organic Unit

Date (YBP)	Material	Location	Location in Exposure
3,060 $\pm$ 80 (BGS 1759)	wood in continuous peat horizon	Hunker-5 15 Pup	base of organic unit overlying silt unit
5,525 $\pm$ 200 (BGS 1757)	wood in continuous peat horizon	Hunker-4 24 Pup	base of organic unit overlying silt unit
6,450 $\pm$ 80 (BGS 1756)	tree root	Quartz-1 Quartz Creek	base of organic unit overlying silt unit
6,500 $\pm$ 80 (BGS 1769)	peat	Bonanza-4 Skookum Gulch	base of organic unit overlying weathered bedrock
8,215 $\pm$ 105 (BGS 1771)	peat and wood	Bear-1 Bear Creek	base of organic unit overlying silt unit
9,945 $\pm$ 150 (BGS 1772)	wood twigs in continuous peat layer	Hunker-6 Lower Hunker Creek	base of organic unit overlying silt unit

5.4.2 Interpretation of New Radiocarbon Dates

i) Late Quaternary History of Central Yukon

Dates from organic material of the base of the Silt unit suggest that the unit is a McConnell-aged (late Wisconsin) deposit. The dates suggest that between $31,000 \pm 1,400$ ^{14}C years BP and $26,240 \pm 500$ ^{14}C years BP, climatic conditions in the Klondike were conducive to the formation of grass beds. Shortly after this period, silt, derived from loess created by McConnell glaciers, began to accumulate in the study area. The date of $24,025 \pm 550$ ^{14}C years BP (BGS 1755), from organic material below the tephra at Quartz Creek, 562 cm above the basal organic material, confirms these older, basal dates and indicates that loess deposition was active in the Quartz Creek drainage between 27,150 (BGS 1754) and 24,025 (BGS 1755) ^{14}C years BP. This latter date also reveals a maximum age for the redeposited tephra which overlies the dated organic bed.

Dates from the organic material at the base of the Organic unit suggest that the unit is Holocene in age. The ages suggest that peat development in the Klondike District began as early as $9,945 \pm 150$ ^{14}C years BP (BGS 1772), and as late as $3,060 \pm 80$ ^{14}C years BP (BGS 1759). The older date is in the same range as the date of $9,520 \pm 130$ (GSC-73; Dyck and Fyles 1963) for wood collected at the base of

the peat overlying silt on Hunker Creek at the mouth of Last Chance Creek. The range in ages may be the result of post-depositional reworking, such as gelifluction or cryoturbation, for example, that may have resulted in younger organic material being displaced to lower positions in the section.

Tarnocai (1990: 369) states that:

[r]adiocarbon dates of basal peat materials indicate that peat deposition in continental Canada did not begin until several thousand years after the continental ice sheet melted. A comparison of all of the radiocarbon dates available from the continent indicates that the majority of peat deposits began to develop between 4 and 6 ka BP.

Tarnocai (1978) suggests that during the early Holocene (the climatic optimum), the climate was perhaps too warm and dry for optimum peat development. As the climate cooled, the boreal and subarctic regions became established as areas of optimum peat development. The older dates from the base of the Organic unit in the Klondike district seem to suggest that the Klondike area had favourable conditions for peat development, as early as $9,945 \pm 150$ (BGS 1772) ^{14}C years B.P. Moist conditions favorable for peat growth in the Klondike at 9,945 years BP may have arisen from the location of the beds in the bottom of valleys receiving any available run-off, and/or from the melting of ground ice which seems to have occurred during the post-glacial climatic optimum.

ii) Valley Evolution in the Klondike District

Valleys in the Klondike District have undergone several cycles of erosion and deposition of clastic sediments, spanning a time interval from the late Tertiary, to the Holocene. The muck deposits represent the latest cycle of deposition in the area, on which modern soil is developed. Presently, the muck deposits are being eroded, assisted by miners, during this warmer, climatic interval.

Other deposits in the Klondike include White Channel Gravels, Klondike Gravels, terrace, and creek gravels. The White Channel Gravels are non-glacial sequence which was deposited during uplift of the Klondike Plateau in the Pliocene, and ended with deposition of the Klondike Gravels (Morison 1985). Klondike Gravels are Pre-Reid outwash deposits. Terrace and creek gravels are deposits representing downcutting phases between the Pre-Reid and Reid glacial intervals. Because the radiocarbon dates presented earlier show that the muck deposits are McConnell-aged and Holocene deposits, the Reid glaciation is apparently not represented in the Klondike District. It is likely that during the Reid glaciation, loess accumulated in the valleys as it did during the McConnell glaciation. Following the Reid, most, if not all of the loess from the area was likely eroded and carried out the district. This scenario seems likely if one considers the length of the

Reid-McConnell interglacial (~100 ka?, assuming that the Reid is Illinoian), and that for a portion of the time, the climate following the Illinoian was significantly warmer than it is at present (Tarnocai 1990).

It is also possible that Reid loess may be preserved on terraces, or remnants may be preserved, for example, as inclusions within creek gravels. The silt in which spruce wood dated at >53,900 ^{14}C years BP (GSC-527; Lowdon and Blake 1968), for example, could be remnant Reid loess on which vegetation had been growing. The dated wood was located in organic silt overlying auriferous gravels, and overlain by silty gravel with mammoth, horse, and bison remains, organic silt, and peat. The description of these sediments suggests that there are organic silt deposits below the zone in which the Pleistocene bones are normally observed (i.e. at the base of the Silt unit). These deeper silt beds or inclusions could be preserved Reid material. Another possibility is that the paleosol observed at the base of the Silt unit is formed upon remnant Reid loess, and that McConnell loess, comprising the bulk of the Silt unit, is actually sedimentologically distinct from the silt on which the paleosol was formed. This hypothesis would suggest that the Reid-McConnell interglacial period did not remove all of the Reid loess from the Klondike District, but that instead, a portion of it was preserved and used as a substrate for a pre-McConnell-aged soil.

iii) Periglacial and Geocryological History

In the early stages of muck accumulation in the Klondike District, silt deposits existed above the permafrost table, as demonstrated by the paleosol and associated ground squirrel nests located at the base of the Silt unit. Since saturated silt flows readily in a thawed state, the thickness of the Silt unit above the lower basal paleosol suggests that permafrost has played a role in its preservation. Permafrost appears to have aggraded throughout the Silt unit following this paleosol development, and throughout the period of silt accumulation during the McConnell glaciation. Permafrost must have existed continuously throughout the accumulation of the unit, as any significant period of thaw would have eroded the sediments, resulting in their removal from the study area.

Large ice wedges located in the upper portion of the Silt unit were likely formed after the McConnell glacial maximum, and before the post-glacial climatic optimum. The reasons for this time period are: (1) the position of wedges in the upper portions of the Silt unit; and (2) the significant length of the wedges. As ice wedges form at the base of the active layer, the position of the wedges in the Silt unit suggests that a stable ground surface and permafrost table existed for a significant period of time, allowing for their extensive growth. A stable ground surface

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PRECISIONSM RESOLUTION TARGETS

may have existed following the glacial maximum. During this period, it is likely that loess was still accumulating in the Klondike District, but as the glacier terminus moved further away, loess deposition was probably reduced. In addition, the liberation of water from melting glaciers could have provided an additional source of water for snow, and then snowmelt in spring, resulting in enhanced erosion of silt every year. As a result, loess deposition and erosion during this period could have been close to equal, which would have been a significant contrast to full-glacial conditions when loess production was closest to the Klondike, and snow accumulation and spring run-off were significantly reduced.

The significant length of the massive icy bodies also supports a post-maximum glacial/pre-Holocene age for the ice wedges. During the full glacial period, the Klondike District would have been dry, as the McConnell glaciers would have been storing available precipitation during their advance as ice. Snowfall in winter and runoff in spring would have been significantly reduced, and tension cracks in the ground may not have been filled with water to form ice wedges. In contrast, the Klondike District would have been more humid during McConnell deglaciation, as more precipitation would have been available. Increased snowfall in winter, and then snowmelt in spring, would have provided enough runoff to fill deep tension cracks in the ground,

forming ice wedges.

Intrusive ice may have formed at any period throughout accumulation of the Silt unit. A large number of the bodies, however, likely formed following the glacial maximum, rather than before or during. Reasons to suggest maximum intrusive ice formation during this time period are: (1) the location of the ice bodies near the upper contact of the Silt unit, implying that they are younger than the silt at the upper contact of the unit; and (2) increased water available for ice body formation during deglaciation. Intrusive ice bodies were observed in this study only near the upper contact of the Silt unit, however, it is possible that they exist throughout the Silt unit, having been covered by slump during field investigations during summer 1994. Groundwater flow in the Klondike today suggests that some of these intrusive ice bodies may be modern.

The post-glacial climatic optimum resulted in a period of thaw in the Klondike District. During this period, the active layer deepened, the tops of the ice wedges melted down, and silt thawed, eroded, and perhaps was removed from the study area. Evidence for this warming period are: (1) the observation that ice-wedges and intrusive ice bodies are truncated below the present active-layer table; (2) the flat, sometimes erosional, upper contact of the Silt unit; and (3) the presence of occasional ice-wedge casts in the upper portions of the Silt unit (e.g., Hunker-2 and Hunker-

6) .

The Organic unit likely became perennially frozen as it accumulated throughout the Holocene. Ice wedges have formed throughout the unit at various positions, suggesting that there have been several periods throughout the Holocene when the ground surface and the permafrost table were stable. The ice wedges are also variable in size, but they are always much shorter than those seen in the Silt unit. Smaller ice wedges in the Organic unit could be the result of a number of factors, such as: (1) aggradation of the unit before they were able to grow to extreme sizes; (2) reduced ground-cracking during the Holocene due to warmer ground/air temperatures; or (3) smaller cracks produced in the Organic unit than in the Silt unit as the result of different physical properties of the ground. Small modern ice wedges are seen in the unit as well, at the base of the active layer.

Aggradational and intrusive ice may have formed at any period throughout the accumulation of the Organic unit. Aggradational ice bodies formed when concentrations of water at the base of the active layer became permanently frozen during upward movement of the permafrost table as the unit aggraded (Mackay 1983). Holocene conditions were wetter and warmer in central Yukon compared to glacial ones. As result of these milder conditions, it is likely that aggradational ice and intrusive ice were actively forming. Intrusive ice

growth is probably still an active process in the Klondike District today. Pool ice in both the Organic and Silt units formed at the turn of the century, when shafts were dug by miners in search of gold, and throughout the accumulation of the muck deposits, in holes or pits created during slumping.

5.5 Environmental History

From the results presented in Sections 5.1 - 5.4, this section reconstructs the development of the Klondike muck deposits in chronological sequence.

i) Pre-McConnell interstadial: > 26,240 ± 500 years BP

Between approximately 26,240 and 31,000 years BP (^{14}C dates from wood at base of Silt units at Hunker-5 and Bear-1 respectively), the climate in the Klondike District supported the growth of grass, as indicated by the species of organic matter seen in the paleosol overlying creek gravels at the base of the Silt unit. This period is correlative with a treeless, low-arctic tundra 29.6 ka BP in the Mayo area (Matthews et al. 1990). There was fluvial activity during this late interstadial period, as water lain sediments are observed in the vicinity of the paleosol, perhaps representing small-scale, slow-moving meandering

channels.

Climatic conditions at a period prior to the formation of this paleosol appear to have been warmer, as creek-bottom gravels underlying the muck deposits are often heavily iron-stained, and bedrock, when observed was extremely weathered.

**ii) Beginning of McConnell Glacial Advance: between
26,240 and 24,025 years BP**

The beginning of the McConnell glaciation is represented in the Klondike District by the accumulation of loess which began sometime after 26,240 years BP (^{14}C date from wood at base of Silt unit at Hunker-5), and before 24,025 years BP (^{14}C date from grass bed below tephra at Quartz-2). At first, loess deposition into the District was minimal as the glaciers were small, and perhaps as far away as the Selwyn and St. Elias Mountains. Loess deposition was likely greatest in the fall and winter, when the braidplains draining the glaciers were exposed and dry, and when strong katabatic winds were blowing off the glaciers, allowing for maximum silt entrainment from the river bars. Loess was deposited over the entire Klondike area, forming a blanket-like deposit conforming to the topography. In late winter and early spring, snowmelt provided enough run-off to erode

the loess from the hillsides by slopewash into valley bottoms. This erosion was minimal every year, however, following winters of heavy snowfall, for example, more significant amounts of silt were likely transported. Summer storms likely resulted in enhanced erosion of silt from hillslopes due to mass-wasting. During the summer, the valley-bottoms, and perhaps the hillslopes, became vegetated by grasses. These grasses played a major role in trapping the loess when it accumulated in the fall.

The deposition of silt into the valley bottoms was quickly followed by permafrost aggradation through the sediments.

**iii) McConnell Glacial Maximum: between 22,000 and
18,000 years BP**

The McConnell glacial maximum was accompanied by maximum loess production and accumulation, minimum water availability, and cold climatic conditions. Loess deposition continued in the Klondike, and yearly erosion due to snowmelt was low. Minimal erosion continued throughout the glacial maximum. During years of increased snowfall and rapid snowmelt in spring, erosion of the silt was enhanced. There is no doubt that throughout the glacial period there were summers when temperatures were slightly warmer than average, when the permafrost table was lowered, ground ice

melted, and mass-wasting processes such as debris flows and gullies and rills formed in the deposits. Warmer periods are recognized in the deposits by occasional weathering zones or paleosols (e.g., Bear-1 and Bonanza-5). These warmer periods were likely the times during which Pleistocene bones were transported to lower depths within the Silt unit, and eventually to the base of the unit to rest upon the underlying gravels. Gelifluction and frost creep were also involved in silt retransportation during this time period.

iv) McConnell Deglaciation: after 18,000 years BP and before 9,945 years BP

Following the glacial maximum and before 9,945 years BP (^{14}C date for wood in peat at base of Organic unit at Hunker-6), loess accumulation declined in the Klondike, and the majority of massive icy bodies began to form. As the glaciers receded, the source of loess became further away, and it is likely that loess deposition declined. In addition, melting glaciers provided increased amounts of available water which may have resulted in increased erosion of the silt due to increases in yearly precipitation. In addition, an increase in available water likely replenished surface and groundwater sources responsible for the formation of massive icy bodies. During this period, deep ice wedges were able to form. The ice wedges suggest a

period of time when the ground surface and permafrost table were stable, and when there was sufficient surface water to fill tension cracks in the ground. Although it is difficult to say with certainty, speculation is that a stable ground surface may have existed in the study area as a result of a balance of loess deposition and erosion during this period. Replenished groundwater reserves provided the source for intrusive ice bodies.

As early as 9,945 years BP, climatic conditions in the Klondike were suitable for peat growth in some areas.

v) Post-Glacial Climatic Optimum: between 10,000 and 7,000 years BP

Sometime between 10,000 and 7,000 years BP, a post-glacial climatic optimum occurred in central Yukon (Burn et al. 1986). During this period the permafrost table was lowered, silt was eroded and removed from the district, and the tops of massive ice-wedges were truncated. The warming appears to have occurred after 9,945 years BP, as peat of this date was observed in the bottom of small ice-wedge casts at Hunker-6.

vi) The Holocene following the Climatic Optimum

The majority of the Organic unit developed after the

post-glacial climatic optimum. The unit accumulated by in situ organic processes, as well as by colluvial processes such as debris flows, and gelifluction interspersed with small-scale ephemeral fluvial activity. Mass-wasting throughout the Holocene may have been induced by several means such as fire (e.g., French 1976: 62), excessive snowfall resulting in enhanced snowmelt in spring, and/or a deepening of the active layer in summer, liberating water from icy bodies in permafrost. Permafrost aggraded through the unit as it developed. Ice wedges of various dimensions and at various positions within the unit suggest that the unit aggraded incrementally, and that there were periods when the ground surface and permafrost table were stable - i.e. neither aggrading nor degrading. Aggradational ice observed in the unit resulted from a rise in the permafrost table incorporating water which had collected at the base of the active layer.

Holocene conditions have resulted in erosion of the muck deposits, particularly from the southern faces in the larger valleys. In these valleys, muck remains preserved only on north-facing slopes, and in smaller pockets which have been protected from the sun. Muck is still present on both sides of the valley in smaller pups and gulches.

Chapter 6 CONCLUSIONS

This chapter offers a summary of the new information presented in this thesis surrounding the nature, origin, age and periglacial development of the Klondike muck deposits. The relevance of this information to the literature concerning the eastern Beringian ecosystem is then briefly considered. The chapter concludes by offering avenues for further research.

6.1 The Nature, Origin, Age, and Periglacial Development of the Klondike Muck Deposits

This study has determined that muck deposits in the Klondike District are located in the bottoms and lower reaches of valleys, and are comprised of two main units: a Pleistocene silt; overlain by a Holocene organic peat. The Silt unit lies unconformably upon auriferous valley bottom gravels and is primarily comprised of silt and fine sand (mean = 92%). In terms of texture, mineralogy, grain morphology and surface texture, the unit is temporally and spatially uniform throughout the area. The unit contains fossil mammal bones at its lower contact, fossil ground squirrel nests, paleosols, tephra beds, and massive icy bodies.

The origin of the Silt unit is eolian, which blew as loess into the study area during the McConnell glaciation.

Since its original deposition, much of the loess has been retransported to valley bottoms by mass-wasting processes such as slopewash and debris flows, and by alluvial erosion in rills and gullies. Gelifluction and frost creep were also involved in retransportation. Redeposition into valley bottoms was mostly incremental, however during certain periods, catastrophic redeposition may have occurred.

Permafrost aggraded through the Silt unit during deposition throughout McConnell glaciation, the result of which are small, segregated ice lenses observed throughout the unit. The origin of massive icy bodies is from both surface and groundwater sources which were likely most active during McConnell deglaciation. Ice wedges located at the top of the unit were truncated during the post-glacial climatic optimum which occurred in the central Yukon between 7,000 and 10,000 years BP (Burn et al. 1986). During this period, the permafrost table was lowered, and silt was eroded and transported from the area.

The Organic unit lies unconformably upon the Silt unit, and is comprised of both in situ and colluvial organic, and to a lesser extent, inorganic materials. In situ horizons are composed primarily of peat, but tree fragments are also commonly seen. Colluvial deposits resulted from mass-wasting processes such as debris flows and gelifluction, as well as small-scale ephemeral fluvial channels. The unit is Holocene in age, where the lower contact of the unit ranges in age

from 9,945 to 3,060 ^{14}C years. The unit is permanently frozen and contains massive icy bodies. Ice wedges in this unit are vertically less extensive than those in the Silt unit, and are located at various depths. The unit also contains bodies of aggradational ice.

6.2 Relevance of the new information to Beringian research

This study contributes several elements to the literature concerning eastern Beringia. First, the study offers a detailed analysis of glacial-aged processes in unglaciated terrain in the central Yukon. It is the first detailed investigation of the physical properties and sedimentology of muck deposits in the Klondike District. From this study, it is determined that large-scale aggradation of loess was occurring in eastern Beringia during the McConnell glaciation, and the beginning of this event was between 26,040 and 24,025 ^{14}C years BP. In addition, the study determines that colluvial, as well as eolian processes were active in the Klondike District during the glacial period, and that retransportation of silty material was not solely an interglacial phenomenon.

Second, this study compliments the literature concerning valley evolution in the Klondike District. Before this study, muck deposits were considered the youngest deposits in the area, but their age, and correlation to late

Quaternary events, had not been scientifically determined. From the radiocarbon dates presented in this thesis, the age of the deposits was confirmed as younger than 26,040 ^{14}C years BP, correlating to the McConnell glacial event. This new information allows for the reconstruction of Klondike valleys from the late Tertiary to the Holocene. Contrary to suggestions by others, this study suggests that muck deposits contain very little Reid loess, if at all.

Third, the thesis has shown that the processes contributing to the formation of muck deposits in the Klondike District are similar to those in Alaska, but the stratigraphic record is different. Muck deposits in the Klondike District are younger than those in Alaska, recording a shorter period of geologic history. The Silt unit in the Klondike may be correlated to the Wisconsin Goldstream Formation in Fairbanks, and the Organic unit to the Ready Bullion Formation. If the Eva Formation in Fairbanks is mid-Wisconsin in age, as suggested by Hamilton and Brigham-Grette (1991), the paleosol at the base of the Silt unit in the Klondike would be correlative. Gold Hill Loess and the Dawson Formation are not represented in the Klondike District. Because the stratigraphic record is shorter in muck deposits in the Klondike, the permafrost and geocryological history is also different. In Fairbanks, the Sangamon interglacial period is represented in deposits, a period of time during which silt was deeply gullied, and

ice-wedge casts were formed in Illinoian and earlier silt deposits. Except for the post-glacial climatic optimum which lowered the permafrost table for a period of time following the McConnell, the muck deposits in the Klondike have not undergone any major period of thaw.

6.3 Opportunities for Further Research

The current study has offered a preliminary discussion surrounding the nature, origin, age, and geocryology of the Klondike muck deposits. The objectives of research were broadly designed, in order to give an overview of the subject matter and to provide baseline data on a subject which had formerly attracted little attention. As a result, the research conclusions have touched upon several aspects of Quaternary research, including sedimentology, geocryology, and geomorphology. This project, in addition to the conclusions presented, has shown that the Klondike muck deposits require much more attention than was presented here.

Further research is proposed into several aspects of this thesis. First, an investigation into the source of the loess may be useful in identifying paleo-wind directions during the McConnell glaciation. Heavy mineral analyses conducted on the samples from the Silt unit may provide point-source origins for the material. Second, an analysis

of the numerous tephras observed in the Silt unit would provide excellent stratigraphic markers which may be used to correlate the muck deposits with other deposits in Beringia. Third, the pollen and spores contained within the Silt unit deserve special attention. Although the deposits contained damaged grains, pollen and spores were abundant in the deposits, and with the proper skills and training, reliable pollen counts may be obtainable. Fourth, the paleosol at the base of the Silt unit contains bones, plant macrofossils and pollen which may provide information about the Reid-McConnell interstadial in the west-central Yukon. A fifth area of research is the geocryology of the muck deposits. Petrofabric, dissolved ionic composition, and isotopic analysis of the massive icy bodies may provide clues surrounding their origin and age. Related to ice origin is an area of research concerning the role of groundwater in the Klondike District, and its relation to the source of gold in the creeks. While the source of gold in the Klondike remains a mystery, there has been some suggestion that precipitation of gold from groundwater is not unlikely. A final contribution to the current research would be a study conducted on muck deposits in other areas of eastern Beringia, particularly in the Sixty Mile and Fortymile placer mining areas. Studies in these neighbouring localities may shed some new light on the nature, origin, and geocryology of muck deposits in eastern Beringia.

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