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Because of the varied topographic and climatic situations in which they occur, there is no single explanation which accounts for all glacier-dammed lakes. It is more useful as an introduction therefore, to cite some specific examples which illustrate the range of characteristics which these lakes exhibit.

Perhaps the most studied glacier-dammed lake is one located at Vatnajökull, Iceland. This subglacial lake is filled with water melted by geothermal heat, which is held in a subglacial caldron. As the caldron fills, the overhanging ice roof is lifted and the water drains out through a tunnel. This occurred at 10 year intervals initially, but now occurs every 5 to 6 years (Nye, 1976; Björnsson, 1974).

A recently created lake occurs at Steele Glacier, Yukon (Map 1). Here, a surge of the glacier blocked drainage from a tributary valley and formed Hazard Lake. The lake filled to a surficial outlet and drained from it for several years. During the eighth year it drained suddenly through a subglacial tunnel (Collins and Clarke, 1977), and this has been repeated annually. Relic shorelines indicate that Hazard Lake is not the first to occur at this site (Sharp, 1947).

A lake at Tulsequah Glacier, B.C., also drained subglacially. Here, a tributary glacier receded upvalley

HISTORY OF A GLACIER-DAMMED LAKE
ON DONJER RIVER, YUKON

BY

(C) Max S. Perchanok

A Thesis Submitted to the
Faculty of Graduate Studies
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Department of Geography
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1980

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ON DONJEK RIVER, YUKON"

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ABSTRACT

Landforms in upper Donjek River valley, southwest Yukon, indicate the former presence of a glacier-dammed lake here. The lake was filled on at least four separate occasions since the Pleistocene glaciations.

"Lake Donjek" first filled between 1270 and 1430 AD, when Donjek Glacier advanced strongly and dammed Donjek River. This lake may have lasted for 200 years. It drained and refilled repeatedly during this time. The age and duration of the second and third periods in which the lake filled are unknown. The latest active period began sometime after 1622, and ended by 1840 AD. Flood deposits downstream from the lake basin suggest that it drained by glacier outburst.

Donjek Glacier has experienced long-term fluctuations and seasonal oscillations in historical times. If these continue at past rates, Lake Donjek will be filled again in the near future.

PREFACE

*
"I'm a jökulhlaup and I'm all right.
I fill all year
And I drain one night."

heard on the trail at Lake Donjek.

* a jökulhlaup is a glacier outburst

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Max Perchanok
Ottawa
March, 1980

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CHAPTER 1

GLACIER-DAMMED LAKES

1.1 Introduction

The St. Elias, Wrangell and Chugach Mountain ranges of the North American cordillera are one of the world's major supporters of glacier-dammed lakes today, having an estimated 750 lake basins (Post and Mayo, 1971). Most basins occur high in the relatively inaccessible and untravelled mountains, but still have importance for man and for the natural environment around them. When filled, the larger of the basins completely inundate river valleys, affecting human travel, communications and settlement, as well as biota, local climate and geomorphic processes.

Some lakes affect their surroundings more adversely when they drain than when they are filled, because they drain very suddenly and cause catastrophic floods downstream (Post and Mayo, 1971). A lake of this type on upper Donjek River (Map 1), is particularly problematic in this regard. Although it has never been observed in a filled state, geomorphologic evidence indicates that it was filled in the recent past, and that it could be filled again in the near future. If this were to occur, a potential flood

hazard would be created at the Alaska Highway and Pipeline crossing, 50 kilometres downstream (Canada, 1979, 1977).

This work examines the cause and history of a lake formerly dammed by Donjek Glacier, and presents a Holocene chronology of the lake. The possibility of similar events occurring in the future is also examined. A geomorphological approach is taken, in which landforms at Lake Donjek are interpreted in light of known events in the regional earth history, and of the physical principles which govern glacier-dammed lakes.

Glacier-dammed lakes are not a well-known phenomenon. In Chapter One, the cause, location and unusual temporal characteristics of the lakes are introduced. The physical principles which cause an ice-dam to be formed and to fail are also introduced.

The existence and characteristics of a glacier-dammed lake on the long term are governed by the advance or recession of one or more glaciers. Glaciers in southwest Yukon have undergone numerous periods of advance and of recession, and these would cause Lake Donjek to alternately fill and empty. Chapter Two describes the glacial history of southwest Yukon which would affect Lake Donjek.

Evidence for various events at the site of Lake Donjek is presented and interpreted in Chapter Three.

The evidence consists of landforms, sedimentary and alluvial deposits, and vegetation patterns. Chronologic data associated with the various events is also described.

In the concluding chapter, the history of Lake Donjek is presented chronologically, and compared with events in the regional earth history. Finally, the possibility of future fillings of Lake Donjek is considered.

1.2 The Occurrence of Glacier-Dammed Lakes

Glacier-dammed lakes occur where surficial or subglacial drainage is blocked by glacier ice. They form a continuum with glacier-marginal lakes where drainage is along a glacier, but can also block drainage from intersecting valleys. Blachut and Ballantyne (1976) summarize the topographical situations in which glacier-dammed lakes occur by classifying them according to location (Fig. 1).

Glacier-dammed lakes have a restricted size and geographical distribution in the present non-glacial climatic period. They are limited to relatively small basins in polar and alpine regions today, but in the past have occupied basins of thousands of square kilometres between ice masses of continental scale. Concentrations of glacier-dammed lakes today occur in the northern cordillera of North America, in Iceland and in Norway (Canada, 1977; Post and Mayo, 1971; Liestol, 1956; Thorarinsson, 1939).

Figure 1. CLASSIFICATION OF GLACIER-DAMMED LAKES BY LOCATION

after: Blachut and Ballantyne, 1976.

Because of the varied topographic and climatic situations in which they occur, there is no single explanation which accounts for all glacier-dammed lakes. It is more useful as an introduction therefore, to cite some specific examples which illustrate the range of characteristics which these lakes exhibit.

Perhaps the most studied glacier-dammed lake is one located at Vatnajökull, Iceland. This subglacial lake is filled with water melted by geothermal heat, which is held in a subglacial caldron. As the caldron fills, the overhanging ice roof is lifted and the water drains out through a tunnel. This occurred at 10 year intervals initially, but now occurs every 5 to 6 years (Nye, 1976; Björnsson, 1974).

A recently created lake occurs at Steele Glacier, Yukon (Map 1). Here, a surge of the glacier blocked drainage from a tributary valley and formed Hazard Lake. The lake filled to a surficial outlet and drained from it for several years. During the eighth year it drained suddenly through a subglacial tunnel (Collins and Clarke, 1977), and this has been repeated annually. Relic shorelines indicate that Hazard Lake is not the first to occur at this site (Sharp, 1947).

A lake at Tulsequah Glacier, B.C., also drained subglacially. Here, a tributary glacier receded upvalley

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while Tulsequah Glacier did not. The closed basin which appeared between the tributary and the trunk valley glacier filled with water and became Tulsequah Lake (Marcus, 1960).

Not all such lakes drain subglacially. Between Lake which occurs at the coalescence of Thompson and White Glaciers on Axel Heiberg Island, drains annually by cutting a gorge in the ice dam (Maag, 1969). Lake George, dammed by a glacier on Knik River, Alaska, drained by a combination of means. It was dammed when Knik Glacier advanced across an intersecting river valley, and drained annually from 1918 to 1966. As reported by Stone (1963), Lake George drained subglacially for a short period until the ice dam collapsed on the tunnel. Then, drainage continued through a gorge which was cut in the collapsed dam.

Glacier-dammed lakes are characterized by their variability. They occur in association with glacial advance, recession and equilibrium. Most lakes overflow surficially for some period, and some drain subglacially, some supraglacially, and some not at all.

1.3 Temporal Characteristics

Because they are created and controlled by glaciers, glacier-dammed lakes are a dynamic landscape feature. On the long term they appear or disappear, fill or drain according to the activity of the damming glacier.

On the short term, a lake which is caused by a singular glacial advance or recession can also have repeated periods of filling and draining, such as those reported at Vatnajokull, Hazard Lake, Lake George, etc. These cycles occur irrespective of climatic or glacial fluctuations and are self-generated. They may however be affected by climatic changes. Maag (1969) notes that lakes on Axel Heiberg Island do not drain during years of low runoff in which the lakes are not completely filled. Changes in a previously constant cycle are also reported at Lake George, Vatnajokull, and elsewhere.

The temporal characteristics of a glacier-dammed lake are an important aspect of the lake when it is considered as an environmental problem. The recurrence interval of lake fillings and drainings are important factors in planning and engineering design, for instance (Williams, 1979; Canada, 1977). For this reason Post and Mayo (1971) developed a physical-temporal classification for ice-dammed lakes (Table 1). It is an innovative scheme in that it recognizes the temporal variability of glacier-dammed lakes, and the possibility of future occurrence of a lake where no evidence exists for occurrence in the past.

The scheme is ambiguous however. The distinction between potential future lakes and former or temporary lakes is often arbitrary and unnecessary. Recent Lake

TABLE 1

COMPARISON OF CLASSIFICATION SCHEMES FOR GLACIER-DAMMED LAKES
ALONG SHAKWAK VALLEY, YUKON

<u>Reference</u>	<u>Location</u>	<u>Temporal Classification</u>	<u>Blachut and Ballantyne</u>	<u>Post and Mayo</u>
Collins and Clarke, 1977	Steele Glacier	active	D	temporary
Denton and Stuiver, 1969a	Donjek Glacier	dormant	G	former
Canada, 1977	Kluane Gl.	dormant	D	former, temporary
Canada, 1977	Klutlan Gl. St. Clare Ck.	dormant	D	former
Canada, 1977	Klutlan Gl. Harris Ck.	dormant	D	former
Capps, 1910	Russell Gl.	dormant	D	former
Kindle, 1952	Lowell Gl.	dormant	G	former
Kindle, 1952	Dezadeash R. L. Champagne	relic	H	former
Kindle, 1952	Bates R. L. Fisher	relic	H	former

KEY

Temporal Classification: see text

Blachut and Ballantyne (1976): see Fig. 2

Post and Mayo (1971):

1. lakes for which flood histories are available
2. former lakes dammed by glaciers
3. temporary lakes caused by periodically surging glaciers
4. other potential future lakes
5. river icings
6. glaciers on volcanoes

Alsek in southwest Yukon (Map 1), for instance is used by them to illustrate a former lake basin, but it was dammed by a glacier which is thought to surge, and it is being studied now as a potential future hazard (Clague, 1979; Canada, 1977; Kindle, 1952).

1.3.1 A New Temporal Classification

The author proposes a less ambiguous classification scheme which includes active, dormant and relic glacier-dammed lakes. These categories are based only on the likelihood of occurrence of a lake. Because the categories are more general than those of Post and Mayo (1971), they can be used with a minimum of information, yet describe the characteristic of glacier-dammed lakes which is most important in the context of man's activities. The classification answers the question: what is the likelihood of this lake forming in the future? It is not concerned with the cause of formation because each lake must be considered individually in that respect.

Active Lake: An active lake is one which is known to be filled, or to be in the low-water period of a regular filling-draining cycle. Hazard Lake at Steele Glacier is an example of this type, and has been since it formed in 1966.

Dormant Lake: A dormant lake is one which has not been observed full and does not have a regular

filling-draining cycle, but which either has done so or could. It includes dry, marginal basins which could be blocked by a glacial advance such as those included in recent reports on glacier-dammed lakes (Canada, 1977; Post and Mayo, 1971), and basins for which there is firm evidence of having been dammed and filled in the recent geologic past. Examples of the latter include Recent Lake Alsek (Clague, 1979; Kindle, 1952), and an older lake at Steele Glacier (Sharp, 1947), where shorelines and other geomorphologic evidence indicate the former presence of lakes.

Relic Lake: Relic glacier-dammed lakes are those which last existed during the Pleistocene, and which could not be refilled under present climatic conditions. This category includes the large, late-Pleistocene lakes of North America, such as Lake Agassiz, Lake Missoula, (Embleton and King, 1968, p.268), and Lake Champagne (Kindle, 1952). The continental ice sheets which dammed them no longer exist and their former presence can be determined only from landforms which they created. Their future existence is such a remote possibility as to pose no problem for man's activities.

This proposed classification, and those of Post and Mayo, and Blachut and Ballantyne, are compared in Table 1, for some large glacier-dammed lakes along the Alaska Highway.

1.4 The Physics of an Ice Dam

The study of glacier-dammed lakes has two important aspects; lake filling and lake draining. Hypotheses for lake draining are presented in most accounts of glacier-dammed lakes because it is usually lake draining which affects man's activities. The physical principles which allow a glacier to cross and impound a flowing river are not discussed separately in the literature, but they should be as they are different from those which control drainage. In order to forecast possible future activity of a dormant lake, the conditions which allow it to fill are as important as those which trigger the lake to drain.

1.4.1 Principles of Glacier Outburst

Many hypotheses have been proposed to explain the sequence of events which cause the rapid draining of a glacier-dammed lake through or under an ice dam. They should account for a standard series of events including:

1. initial ability of the glacier to impound drainage
2. a trigger to release the water
3. complete lake discharge
4. reclosing of the drainage route

5. a cyclic or variable drainage chronology

Some theories are reviewed here in order to illustrate the variables which may control lake activity, and thus help in interpretation of landscape evidence at Lake Donjek.

1.4.1-A Flotation Hypothesis

Thorarinsson (1939) proposed a simple model to explain self-generated drainings of a glacier-dammed lake at Vatnajökull, Iceland, based on flotation of the dam. Because of the difference in density of ice and water, an impounded lake will float its ice dam when lake depth reaches 9/10 the thickness of the dam, so long as water is able to penetrate beneath the dam. A constant was added to account for the loss of mass to crevasses in the critical dam zone, and Nye (1976) added a further correction for the cantilever effect of that part of the dam which overhangs the lake.

Flotation provides an explanation for the cyclicity of drainings; they would occur each year when meltwater refilled the lake to the level required to float the dam. However, the dam would reform as soon as the lake had drained below the critical flotation depth, and the lake would never drain completely.

1.4.1-B Deformation Hypothesis

Glen (1954) showed that plastic deformation of the ice dam could be a trigger for drainage. He calculated that

hydrostatic pressure in a hole or lake 200 metres in depth will exceed glaciostatic pressure at that depth, and thus will open a hole through the glacier. While this is possible in theory, most ice-dammed lakes are not this deep. Marcus (1960) proposed a similar mechanism but also that flotation could act as the initial trigger. If the ice initially floated, then the force of the water rushing into the hole could exceed glaciostatic pressure in a lake of less than 200 metres depth.

Like the flotation hypothesis however, plastic deformation of the ice and maintenance of a tunnel would become ineffective as the lake drained, and the tunnel would close. Marcus did not calculate the hydrodynamic force involved, and the theory has not been examined quantitatively.

1.4.1-C Melting Hypothesis

Marcus (1960), Gilbert (1972), and Mathews (1973) tested the hypothesis that subglacial tunnels can be enlarged by melting once they are opened by some other means. Mathews calculated that 25 to 50 percent of the energy required to melt a tunnel could be supplied from energy released in descending through the tunnel, and Gilbert found that heat stored in the water of Summit Lake, B.C., could provide enough energy for the tunnel to be melted during lake drainage. Marcus found that up to 75 percent of the tunnel volume required to accomodate drainage

from Tulsequah Lake could be opened by melting. Melting also provides a positive feedback, since the volume of water passing through the tunnel increases as it is melted. This could explain the typically rapid increase in discharge observed during lake draining.

1.4.1-D Drainage Capture Hypothesis

Whalley (1971) and Fisher (1973) proposed that drainage capture is responsible for the initiation of lake drainage. It would account for both a trigger and for maintenance of lake drainage through a tunnel. Fisher showed that a slow, subglacial leak preceded rapid drainage of Summit Lake, and proposed that outburst follows pre-existing passageways through the ice dam. Annual drainage would be initiated when seasonal inflow to the lake caused hydrostatic pressure at the lake bottom to exceed that of the englacial drainage system. Whalley conjectured that rapid drainage begins when seasonal, up-glacier growth of the englacial drainage system reaches and captures down-glacier drainage from the lake. Observations of basal and englacial water pressure made elsewhere (Hodge, 1976; Mathews, 1964) support the hypothesis of seasonally fluctuating pressure and an interconnected englacial drainage.

1.4.1-E Synthesis of Hypotheses; Theory of Outbursts

Nye (1976) combined the hypotheses of flotation, deformation and melting to model outbursts from the subglacial lake at Vatnajökull, Iceland. His hypothesis can

be summarized as follows:

Drainage of the lake begins when the depth of lake water behind the dam reaches approximately 9/10 depth of adjacent ice. This could occur either by dam flotation or by tapping of englacial drainage passages. As water begins to flow, the tunnel walls are melted by sensible heat and by frictional heat generated in passing through the tunnel. This provides a positive feedback; as more water passes through the tunnel it is melted and widened.

At the same time, the tunnel tends to close by plastic deformation of ice surrounding its walls. When the lake is full and hydrostatic pressure is at a maximum, the rate of tunnel enlargement by melting exceeds the rate of closure by deformation. As the lake is drained the latter becomes predominant. The tunnel closes and outburst ends abruptly because plastic deformation of the tunnel walls increases as,

$$(G-H)^3,$$

where (G) is glaciostatic pressure, and (H) is hydrostatic pressure (Nye, 1976). As the lake level falls, plastic deformation increases exponentially.

This theory improves on previous ones because it explains continued drainage even after lake level falls below the critical level for flotation, and because it explains the very rapid increase in discharge and subsequent, abrupt tunnel closure.

1.4.2 Application of Outburst Theory to Lake Drainage

The theory of outbursts as developed by Nye, can be used to predict the type of drainage which will occur from a glacier-dammed lake in a particular topographical situation. In general, subglacial outburst will occur when hydrostatic pressure at the lake bottom exceeds either glaciostatic pressure at the bottom of the ice dam or hydrostatic pressure in subglacial water passages which are connected to the lake.

In the situation of a glacier having a stationary terminal position and constant rate of forward flow, drainage is controlled by the level to which the lake fills, as determined by topography. If there is an available overflow below the critical depth (approximately 9/10 ice depth), outburst will not occur. If there is no outlet below the critical depth, an outburst will occur when the lake fills to that depth. If the supply of water to the lake is constant this will be repeated cyclically.

If the glacier with no outlet has an advancing and thickening terminus, the lake will take longer to fill to the critical depth. When it does reach the critical depth, the outburst will be of greater magnitude than that described above.

If the same glacier has a downwasting terminus, the lake will outburst more frequently and with less magnitude

than that described above. Eventually in this case, the drainage tunnel will not be reclosed and the lake will become dormant.

1.4.3 Corollary of Outburst Theory; Principles of Dam Formation

A glacier-dammed lake drains when hydrostatic pressure at its bed exceeds glaciostatic or hydrostatic pressure at the adjacent glacier bed. When drainage begins, the pressure difference is augmented by thermal erosion of the tunnel. A corollary to this is that a lake will form when glaciostatic pressure exceeds hydraulic pressure in a flowing water course, and when the rate of erosion of the damming glacier is exceeded by the rate of forward movement of the glacier front.

During the formative stages of an ice dam, the pressure difference or buoyancy factor may favour the glacier, since water level will be minimal. Thermal and mechanical erosion are maximized at this time, since the advancing glacier is exposed to erosion both at the dam site and along the ice front downstream from the dam. This implies that the formation of a dam requires a stronger glacial advance than does its maintenance. Conversely, a dam can be maintained even after cessation of the glacial advance which initially created it, since forces acting to breach the dam are minimized between the time that it is initially formed and when it is first breached.

1.4.4 Conclusions

Variables which control lake formation and drainage are dynamic and result in a continually changing balance between lake filling and draining. Because of this, glacier-dammed lakes have an unusual temporal nature; a series of ephemeral lakes can be impounded and released cyclically by a dam which is apparently in a state of equilibrium. Fluctuations in lake level alone can cause it to achieve thresholds of drainage. Likewise changes in the damming, glacier can cause filling and draining without a preceeding hydrologic change.

CHAPTER 2

GLACIERS AND GLACIAL HISTORY OF THE ST. ELIAS MOUNTAINS

2.1 Physiography

The geologic history of the area is described by Muller (1967), and Denton and Armstrong (1969). The St. Elias is part of a physiographic unit dating to late Cretaceous times, when sedimentary and volcanic rocks were uplifted along fault zones. The resulting mountain chain including the St. Elias, Chugach and Wrangell Mountains, rises to over 5000 metres in elevation and stretches for 500 kilometres along the Gulf of Alaska (Map 1).

2.2 Early Glaciations

The St. Elias has been subject to many glaciations. Evidence for early glaciations is reported by Denton and Armstrong (1969). They describe 12 tillites in upper White River valley (Map 1), which were deposited from 10 to 2.7 million years ago.

Krinsley (1965), and Bostock (reported in Hughes et al, 1969) report evidence for 4 Pleistocene glaciations in Yukon Territory (Fig. 2), based on drift morphology and

level, and stratigraphic sections.

Numerous radiocarbon dates from material in sections studied more recently provide ages for only 3 major glaciations (Fig. 2). The oldest of these is recognized in the north of the field area by drift of subdued morphology which extends beyond boundaries of more modern drift, and by stratigraphic sections at which two till units underlie the more modern drift (Denton, 1974). In the south of the field area, stratigraphic sections display the older tills (Denton and Stuiver, 1969). On the basis of stratigraphic position Denton (1974) tentatively correlates the oldest tills at White River and south of Kluane Lake. This early episode is termed the Shakwak Glaciation. Denton and Stuiver (1969 b) theorize a non-glacial interval following the Shakwak glaciation (Fig. 2). This is based on the occurrence of outwash and organic beds, and intensely weathered outwash which overlies Shakwak drift south of Kluane Lake.

Material incorporated in till which stratigraphically overlies non-glacial deposits near Kluane Lake, yields a radiocarbon date of 49,000 BP. Denton and Stuiver (1969 b) call the glaciation associated with this till, the Icefield (Fig. 2). Deposits overlying the till indicate that recession was complete here by 37,000 BP. Organic material overlying moraines at Snag to the north, provides

dates that indicate deglaciation there had occurred by 30,000 BP. Deposits from the end of these glaciations, termed respectively the Icefield and Mirror Creek, are considered to be rock-stratigraphic although the tills have not been physically traced together.

A distinct boundary of hummocky topography which fringes the St. Elias near White River, marks the eastern extent of the most recent glaciation. Material overlying drift here provides a radiocarbon date for the maximum of this episode, of 13,660 BP. This episode is referred to as the Macauley glaciation. The hummocky topography is traceable to Kluane Lake, and is assumed to be contemporaneous with glacial deposits there (Denton, 1974). Material underlying outwash near Kluane Lake provides a maximum date of 29,600 BP for the beginning of the Kluane glaciation.

Till fabric, large scale fluting, and topographic boundaries indicate that ice of the Macauley-Kluane glaciation flowed north from Shaskwak valley and east from White River, to coalesce as a piedmont glacier west of Snag (Denton, 1974). Recession of Kluane ice was complete by 9780 BP, and recession at White River was complete by 9360 BP (Fig. 2).

2.3 Holocene Glaciations

Denton and Stuiver (1969 a) and Börs and Goldthwait

(1969) describe a stratigraphic sequence in Slims and Donjek valleys from which they construct a Holocene glacial chronology for the southeastern St. Elias Mountains. The sequence consists of loess over Kluane-age drift, a buried soil, and modern loess.

They hypothesize that the lower, older loess is derived from active outwash of late Kluane-age glaciers. The buried soil which overlies this loess provides a radiocarbon date of 9780 BP for the end of the Kluane glaciation (Denton and Stuiver, 1969).

The presence of the buried soil is interpreted as an indication that glaciers nearby had receded sufficiently to allow vegetation of outwash deposits. The extent of recession is indicated in the south of the field area by the presence of buried soil up to 27 kilometres upvalley from the present terminus of Kaskawulsh glacier, and of large spruce trees incorporated in its terminal moraine.

Material at the top of this soil provides a date of 2640 $\pm$ 80 BP (Denton and Stuiver, 1969a) for the end of this period of glacial recession in the southeastern St. Elias Mountains. The early Holocene period of glacial recession and tree-line elevation has been termed the Hypsithermal (Flint, 1971, p.124).

Renewed glacial activity following deposition of the soil is indicated by an overlying loess deposit in Slims and Donjek valleys. The loess is believed to indicate an increased supply of fine sediments resulting from renewed

glacial activity (Denton and Stuiver, 1969a; Borns and Goldthwait, 1969). A bed of volcanic ash near the base of this loess provides a minimum age for renewed glacial activity of 1250 BP, although tree stumps incorporated in moraines fronting Kaskawulsh and Donjek glaciers give firm dates for glacial advances of 500 and 440 BP respectively..

The ash mentioned above is one of two pyroclastic deposits originating in a vent on upper White River, Alaska (Lerbekmo et al, 1975). An eastern lobe blankets the St. Elias Mountains and southwest Yukon with up to 15 centimetres of tephra, providing a time-stratigraphic horizon which has been dated at 1250 BP. A northern lobe covers the White River area and lowlands in northern Shakwak valley but is absent in upper Donjek valley and areas to the south. The northern lobe is dated at 1487 BP.

In the northeastern St. Elias Mountains, Denton and Karlen (1977) and Rampton (1970) report evidence for several glacial advances from about 3000 BP to 300 BP (Fig. 3). The age of trees incorporated in moraines of Natashat and Giffin glaciers and buried by White River ash indicate that a glacial re-advance began here by about 3000 BP and ended by 1650 BP. An advance of Klutlan Glacier and an additional re-advance of Natashat and other glaciers began about 1250 BP, and culminated by 800 to 560 BP. Another advance

Figure 3. HOLOCENE END MORaine CONSTRUCTION, EASTERN ST. ELIAS MOUNTAINS

3.a. BRACKETED DATES OF CONSTRUCTION

[beginning of moraine construction
] end of moraine construction

sources: 1. Lowell - Kindle, 1952

2. Kaskawulsh - Denton and Stuiver, 1969
Borns and Goldthwait, 1969

3. Donjek - Denton and Stuiver, 1969

4. Hazard-Rusty - Denton and Karlen, 1977

5. Klutlan - Rampton, 1970

3.b. HISTOGRAM OF MORaine CONSTRUCTION

(Moraines for which only one end bracket is available are assumed to be constructed during the period in which that bracket falls only)

6. Natazhah - Denton and Karlen, 1977

7. Guerin - Denton and Karlen, 1977

8. Giffin - Denton and Karlen, 1977

9. Russell - Denton and Karlen, 1977

occurred at several glaciers beginning about 500 BP (Denton and Karlen, 1977; Rampton, 1970; Fig. 3).

This late Holocene period of glacial advance was widespread in the Northern Hemisphere, and is called the Neoglacial (Flint, 1971, p.524). Holocene glacial advances in southwestern Yukon began about 3000 BP and peaked in the last 500 years. Several glacial advances occurred in the northeastern St. Elias Mountains but firm evidence for only one advance is found at glaciers in the southeast.

2.4 Modern Glaciation

Until the end of the Neoglacial, the Holocene history of glaciers in the St. Elias is in accord with the climatic history of the Northern Hemisphere. Several major glaciations occurred during the Pleistocene, with the most recent one ending by about 9000 BP. After an intervening Hypsithermal episode, a Neoglaciation occurred and peaked within the last 500 years.

Since systematic observations began in the last century, most St. Elias glaciers have been receding and now terminate upvalley from their Neoglacial moraines. The recessions have been punctuated in many cases by short-term advances and by surges (Fig. 4; Post, 1969). These were most widely reported in the periods 1925-30 and 1965-75.

Figure 4. GLACIAL ADVANCES, ST. ELIAS MOUNTAINS, 1880-1980

sources: Collins and Clarke, 1977

Rampton, 1970

Denton and Karlen, 1977

Denton and Stuiver, 1969

Field, 1975

Sharp, 1947

Johnson, 1972

NOTE: A glacier surge is a rapid advance of short duration.

Advances and surges are distinguished here as reported in the literature cited.

2.5 Upper Donjek Valley

The upper reaches of Donjek River flow in a deep, U-shaped valley which heads at Kluane Glacier. Muller (1967), ascribes the deepening of the valley to post-Nisling, fluvial and glacial action. Krinsley (1965), however states that ice of the Nisling flowed east from Donjek valley. No depositional evidence of early glaciations has been found here, and the age of Donjek valley is unknown.

As outlined above, Donjek Glacier advanced and became a tributary to a north-flowing ice stream in Shakwak valley during the Kluane glaciation. Deposits of loess, buried soil and ash near the terminus of the Donjek indicate that the late Quaternary chronology used by Denton and Stuiver (1969 b), is applicable here.

A till-covered bedrock knoll in Donjek River near Bighorn Creek (Map 2), gives evidence that the valley was once floored with till to a level 10 metres or more above the modern alluvial valley floor. Paleochannels on Kluane-age till which have been covered with a sequence of loess, woody soil and White River ash, occur along the east side of the valley 40 metres above the modern river (Map 2).

The inclusion of Hypsithermal soil along with volcanic ash and spruce logs in the outermost end moraine, indicate that Donjek Glacier had a Hypsithermal recession and subsequent Neoglacial advance similar to that of Kaskawulsh Glacier, 40 kilometres to the south (Denton and Stuiver, 1969 a).

Stumps in the moraine provide a date for the beginning of the maximum advance of 520 to 210 BP, and trees growing on the moraine date subsequent recession of the glacier from its outermost moraine at 1825 AD.

CHAPTER 3

THE LANDFORMS OF LAKE DONJEK

3.1 Methodology

Lake Donjek is a dormant lake; it is not filled at the present time. Neither the cause nor the frequency of filling and draining can be determined by direct observation. Landforms resulting from the lake are therefore interpreted in light of physical and temporal characteristics of glacier-dammed lakes elsewhere and in light of the theory of outbursts discussed above.

This study is an historical one relying on many lines of evidence, each of which elucidates a small part of the story. Methods used to collect evidence in the field included sketching, photographing and surveying landforms and vegetation, tree increment boring, topographic and stratigraphic mapping. Samples of surficial material were taken for grain size analysis and radiocarbon dating.

All levels in the surveying program are tied to a bench mark located above the highest landform created by the lake. The bench mark lies approximately on the 1128 metre (3700 foot) contour of NTS sheet 115G/3 (provisional), and so is assigned this absolute elevation.

Sites referred to in the following discussions are shown on Map 2. Only Donjek River, Bighorn Creek, Donjek and Kluane Glaciers appear on NTS maps of the area. All other place names are unofficial and are used here to facilitate descriptions.

3.2 Geographical Summary of Landforms

The spatial and stratigraphic/temporal relationships among the various types of geomorphological evidence for Lake Donjek are complex. As shown on Map 2, landforms associated with Lake Donjek occur from the north end of Donjek Glacier terminus to Mullet Creek, 16 kilometres to the south. Donjek River flows along the terminus in a channel which is frequently constricted by glacial deposits or ice. Large and unusual flood deposits are found along the channel.

Near the south (upstream) end of the terminus is the relatively deep tributary valley occupied by Banana Creek. Relic shorelines, overflow channels, other paleochannels, and incised valley-fill deposits are found here. The deposits contain beds of alluvial and lacustrine material.

A large moraine borders the extreme south end of the glacier terminus. It is a very striking feature in the landscape and constricts Donjek River at Kluane Rapids. Shorelines are found on this moraine and also encircling that part of the former lake basin which lies upstream.

The main part of the basin upstream from this moraine is floored with gravel originating from alluvial fans of several tributaries to Donjek River. The mouths of these tributaries are protected from the main flow of Donjek River, and contain sedimentary deposits morphologically similar to those at Banana Creek. These include alluvium, particularly at Bighorn and Mud Creeks, and lacustrine material at Mullet, Bighorn and Mud Creeks.

3.3 Shorelines

A series of horizontal, gravel benches occupy the lower slopes of Donjek River valley for a distance of 10 kilometres upstream from Donjek Glacier terminus (Map 2). The highest occurs at the base of an unvegetated scarp, at a level of 1127 metres. The second is a similar bench at 1121.5 metres. These will be referred to as A and B, respectively. Less distinct benches occur at 1114, 1110 and 1102 metres (Figs. 5 and 6).

3.3.1 Classification of Shoreline Types

Gravel benches are frequently referred to in the literature on glacial lakes. Because of their form and location they are interpreted as shoreline features. Two types can be distinguished on the basis of morphology.

Large, beach-like terraces or benches are commonly associated with glacial and glacier-dammed lakes. Like other shorelines, they consist of gently dipping surfaces

Figure 5. SHORELINE PROFILES

location: see Map 2, site c and d

source: field survey and notes, 1978

Figure 6. SHORELINES OF LAKE DONJEK

location: Donjek River at Kluane Rapids; see Map 2, site c

bounded on one side by a steeply dipping or concave, ascending slope and a steep, descending slope on the other. This classification includes the wide, Pleistocene benches cut in bedrock or large calibre material at high elevations in southwest Yukon (Kindle, 1952), and well-developed shorelines of glacier-dammed lakes at Steele Glacier (Sharp, 1947) and Recent Lake Alsek (Clague, 1979; Kindle, 1952; Fig. 7). The size of these features implies that they represent long-term lake levels. They are frequently marked by driftwood concentrations. To distinguish them from terraces caused by fluvial or periglacial action, they will be referred to here as shoreline terraces.

The second type are similar to shoreline terraces in form, but are smaller. They are developed only in gravel and soft sediments, frequently superimposed on larger shoreline terraces. They also occur in series, with approximately equal vertical spacing (Fig. 7). A series of diminutive terraces at Lake George, Alaska is referred to by Stone (1963) as "terraces", while Maag (1966) terms similar features at Crusoe-Baby Lake on Axel Heiberg Island, "micro-shorelines". They will be referred to here as shoreline terraces.

The origin of shoreline terraces is not so clear as that of terraces. They are much smaller in both the vertical and horizontal dimensions than terraces and so

Figure 7. SHORELINES OF RECENT LAKE ALSEK

location: see Map 1

are probably formed in a shorter period of time. This implies that they represent lake levels occupied for a short time. They also occur in vertical series. Maag (1969) observed cyclic stillstands during the draining of Crusoe-Baby Lake, which resulted from the interaction of a constant rate of outflow and a diurnally fluctuating inflow. They could also be caused by frequent, possibly diurnal glacier movement which cyclically open and close the drainage route, or from diurnal wind patterns which would cause shoreline formation for only a part of each day. At present no general explanation can be put forward for the origin of vertical series of shoreline terracettes. It can be accepted however, that they represent water levels which were maintained for a brief period during the draining of a glacier-dammed lake.

3.3.2 Shoreline Features of Lake Donjek

Gravel benches A and B at Lake Donjek are shoreline terraces. Composition of terrace A varies around the basin; at Klwane Rapids, George's Gorge and Banana Creek it is of angular gravel, similar in texture and colour to nearby outcrops. Where it overlies till it is of rounded cobbles. It also occurs on the south side of the end moraine of Donjek Glacier. The width of the terrace varies from about 2 to 30 metres.

Terrace B is found at most locations upstream from

Kluane Rapids, but is absent between Kluane Rapids and the mouth of Banana Creek. This might be because B was obliterated by the glacial advance which caused the lake associated with A, and implies that A is the younger.

Upstream from Kluane Rapids the composition of terrace B is similar to that of terrace A. At Banana Creek terrace B has a clay surface which forms a morphologic unit with lacustrine material here (Map 2). The lacustrine material dates from the most recent lake, which is associated with the higher shoreline terrace. This implies that the lower shoreline B predates A.

The less distinct, lower shorelines at Lake Donjek resemble poorly developed terracettes. Their limited geographic distribution in the basin suggests that they were formed in a relatively short period of time, possibly by wave action directed by prevailing downvalley winds at the northeast side of the basin. They might represent a step-like lowering of the lake as suggested by Maag (1969) or simply discrete periods of wave action during an uninterrupted lake draining.

3.3.3 Conclusions

Shoreline terraces indicate that Lake Donjek has been filled at least twice, and that the most recent lake filled to the highest level. The absence of a shoreline on the west side of the valley between Kluane Rapids and Banana Creek, suggests that glacier ice formed the western lake

shore here, and the absence of terrace B on the east side suggests that it was obliterated by the glacial advance that caused the higher shore. Shoreline terrace B therefore dates from an older lake episode than does shoreline terrace A. Terracettes at Kluane Rapids may indicate that the most recent lake drained in a step-like manner.

3.4 Overflow Channels

Donjek River flows in a broad, gravel channel upstream and downstream from Donjek Glacier terminus. Along the terminus it is constricted between recent moraines and a wall of ice to the west, and vertical cliffs of Kluane-age till to the east. Paleochannels far above the level of the modern river indicate former drainage routes in Donjek valley (Map 2).

3.4.1 Stratigraphy and Chronology

Three dry channels and a deep gorge occur in a granodiorite knoll at the mouth of Banana Creek, at the downstream limit of the shorelines (Map 2; Fig. 5). The channels are referred to as overflows a, b and c. Channel A is at an elevation of 1128 metres above sea level, and is at a higher elevation than any other feature associated with Lake Donjek. It leads downstream over a rock lip to a gravel floored basin carved in the downstream side of the knoll. The basin has a vegetation cover of grass and birch shrubs similar to that of nearby valley slopes. Test pits

Figure 8. OVERFLOW CHANNELS

location: Donjek River at Banana Creek; see Map 2

view: looking upstream

a,b,c, see text

Figure 9. VEGETATION ZONES, WEST SIDE OF VALLEY

view: see Map 2; looking upstream from moraine at Phantom Creek, to alluvial fan of Grandent Creek

partially rooted but at various angles (Fig. 11).

3.5.1 Dendrochronology

A spruce tree at the erosional scarp near Grandant Creek provides a maximum date for occupation of the highest shoreline by the waters of Lake Donjek. The downslope part of the tree's root system is exposed approximately one metre above the ground surface, while the upslope portion is buried in the soil; it appears that the soil was washed from the roots by Lake Donjek. Fallen trees at the same level nearby give credence to this hypothesis (Fig. 11). The tree must have been growing before the lake reached this level, so its age is a maximum for the highest water level. When cut down by a survey party in 1952 (J. Muller, pers. com.), it had approximately 330 annual growth rings. The highest level of Lake Donjek was therefore reached, after 1622 AD (332 BP).

Living trees above the shorelines today exceed 300 years of age. The oldest tree below the shorelines was 138 years in 1978. This gives a minimum date of 1840 AD (110 BP), for the most recent draining of Lake Donjek. A more realistic date is obtained by adding a recolonization period to the tree age. Denton and Stuiver (1969 a) derive a period of 53 years from spruce tree ages on moraines of known age at the north end of Donjek Glacier terminus. It is likely that revegetation would be more rapid in the former

Lake Donjek overflowed through Channel b for perhaps several tens of years.

Channel c coincides in elevation with the second gravel terrace (Map 2; Fig. 8). It occurs as a rounded trough aligned in a cross-valley direction similar to striations on adjacent granodiorite surfaces. Its shape and alignment suggest that it was eroded by an advance of Donjek Glacier across the river and onto the knoll. It would have been subsequently occupied by overflow from the lake.

Channel c is truncated by a gorge leading from channel b. This indicates that b is the younger of these features. This implies that the highest lake level -which is associated with channel b- is the youngest and corroborates the conclusion drawn from the shoreline stratigraphy, about relative shoreline ages.

3.4.2 Paleohydrology

Deductions can be made about the drainage history of Lake Donjek, using data from channel b. Assuming that the present lake level of Donjek River near the former ice dam site (1088 m.a.s.l) is similar to that during the last lake episode, the maximum lake depth here was 39 metres. The ice thickness at the same location is not known, but glacial deposits occur 45 metres above the river, on a knoll between

channel b and the present glacier terminus. This is probably a close estimate of the maximum glacier thickness at that time, as no modern glacial deposits in the vicinity are higher.

These figures indicate that the level of the most recent lake was approximately 9/10 thickness of the ice dam. This implies that the lake would have overflowed through the channel at the time of maximum glacial advance and thickness, but would have drained by outburst as the dam downwasted slightly.

If the glacier had a similar thickness when channel c was occupied, the overflow level was slightly less than 9/10 dam thickness. Overflow from the channel was preferred over outburst at that time.

3.4.3. Conclusions

These overflow channels indicate that Lake Donjek was filled to at least two different levels and overflowed from these levels for tens of years or more. The most recent lake overflowed from the highest level through a pre-existing channel of Pleistocene age, while an older lake overflowed through a trough which was carved in the rock knoll by a cross-valley advance of Donjek Glacier. The channel elevations imply that an early episode of Lake Donjek drained primarily through an overflow channel while a later episode alternated between overflow and outburst drainage.

3.5 Vegetation

Vegetation in Donjek River valley is characterized by an open spruce forest, which extends from the edges of the very wide river floodplain to the base of the steep rock walls of the Donjek Range. In general, the forest is more dense on the west, and open on the east side of the valley. This pattern is interrupted upstream from Donjek Glacier terminus. Here, the floodplain is separated from the forested valley slopes by a zone of younger vegetation (Figs. 9 and 10).

The broad alluvial fans which cover much of the western side of the former lake basin have a very sparse vegetation of grasses and fireweed (Fig. 9). Stands of alder grow on higher, sandy areas of the floodplain near Phantom Creek.

Above the floodplain is a zone of alder thicket. On the west side of the basin, this is interspersed with young spruce trees while on the east are poplar groves (Figs. 9 and 10). Clay and silt lake-bottom remnants which occur at the mouths of tributary streams on the east side of the valley (Map 2), are very sparsely vegetated.

The boundary between the forested valley slopes and the intermediate alder zone is sharply demarcated by the erosional scarp at the highest shoreline. Dead trees occur along this scarp. Some occur as driftwood along the shoreline bench. Others are found along the top of the scarp,

Figure 9. VEGETATION ZONES, WEST SIDE OF VALLEY

view: see Map 2; looking upstream from moraine at Phantom Creek, to alluvial fan of Grandant Creek

Figurs 10. VEGETATION ZONES, EAST SIDE OF VALLEY

view: see Map 2; looking upstream from moraine at Phantom Creek, to alluvial fans of Fanny and Bighorn Creeks.
also shows lacustrine sediments at Mud Creek

partially rooted but at various angles (Fig. 11).

3.5.1 Dendrochronology

A spruce tree at the erosional scarp near Grandant Creek provides a maximum date for occupation of the highest shoreline by the waters of Lake Donjek. The downslope part of the tree's root system is exposed approximately one metre above the ground surface, while the upslope portion is buried in the soil; it appears that the soil was washed from the roots by Lake Donjek. Fallen trees at the same level nearby give credence to this hypothesis (Fig. 11). The tree must have been growing before the lake reached this level, so its age is a maximum for the highest water level. When cut down by a survey party in 1952 (J. Muller, pers. com.), it had approximately 330 annual growth rings. The highest level of Lake Donjek was therefore reached, after 1622 AD (332 BP).

Living trees above the shorelines today exceed 300 years of age. The oldest tree below the shorelines was 138 years in 1978. This gives a minimum date of 1840 AD (110 BP), for the most recent draining of Lake Donjek. A more realistic date is obtained by adding a recolonization period to the tree age. Denton and Stuiver (1969 a) derive a period of 53 years from spruce tree ages on moraines of known age at the north end of Donjek Glacier terminus. It is likely that revegetation would be more rapid in the former

Figure 11. DEAD TREES ALONG HIGHEST SHORELINE

location: see Map 2, site e

view: looking south across alluvial fan of Grandant Creek

lake basin than on a moraine, since a mature forest remained immediately above the unvegetated shore. The moraines would have been isolated from surrounding vegetation by active outwash, and in addition would have had a more hostile climate and unstable surface because of nearby and underlying ice. A period of 30 years is adopted here as the interval between lake draining and growth of the first spruce tree in the basin. This places the latest draining of Lake Donjek at 1810 AD (140 BP).

Tree ages within the basin increase with elevation in a step-like manner, with a large increase coinciding in level with a shoreline terracette (Fig. 12). This could indicate the level of a major stillstand during the draining of Lake Donjek, approximately 126 years ago. The absence of evidence for an overflow and evidence provided by other types of vegetation however, suggest that this is not the case. It is also refuted by the presence of driftwood along the highest bench, but not on the lower ones.

3.5.2 Soil Development

On the east side of the basin a thin, dark crust of moss covers the parent material of silt or gravel. The thickness and distribution of the crust is consistent from river level up to the highest gravel shoreline benches. On the west side of the basin peat covers a sandy parent material except on the surface of the gravel benches. While there is a much thicker and more highly developed organic

Figure 12. SPRUCE TREE AGE

source: field survey 1978

layer on the west side of the basin, here too there is no marked vertical difference at a site.

Lichens (Xanthoria elegans) occur on exposed rocks within and surrounding the basin, but are not useful as a dating tool. At some locations they are so large as to coalesce, virtually covering host rocks and forming indistinguishable masses. At other locations they are overgrown by grass and shrubs. As a general illustration, maximum lichen diameters of up to 65 millimetres were measured within the lake basin. Using a growth curve derived for the Canadian Rockies, this gives an age of approximately 170 years (Osbourne and Taylor, 1974). A growth curve could not be constructed at Lake Donjek because lichen diameters here are unrelated to the age of adjacent trees.

The uniformity of soil development on the basin slopes suggests that the most recent episode of Lake Donjek filled to the maximum level. This corroborates other evidence that the highest shoreline is the younger one and that no long-term stillstands occurred during the last draining of the lake.

3.5.3 Conclusions.

Vegetation and soil development indicate that the active episode which last filled Lake Donjek began after 1622 AD (232 BP) and ended about 1810 AD (140 BP). Lake

Donjek filled to its highest level during this episode, and when it drained it did so with no long-term stillstands.

3.6 Fluvial Sediments

Four major types of sediment occur in the former lake basin. In order of increasing age these are: modern alluvial gravels, aeolian sands and silt, relic alluvial gravels, and relic lacustrine clay (Map 2).

Modern alluvial deposits occur as cobbles and gravel on the floor of the main valley and in alluvial fans, and as streambank silt. The modern valley floor consists mainly of gravel outwash carried by Donjek River from its source at Kluane Glacier, and from glaciers in the headwaters of Bighorn, Grandant, Phantom and Banana Creeks. The alluvial fans of Bighorn, Fanny and Grandant Creeks are particularly large and extend far into the former lake basin, constricting the channel of Donjek River. Deposits of silt occur along the banks of the river and in embayments at the glacier front. Modern tributary streams and their alluvial fans have incised through and extend to lower levels than relic deposits which are described below.

Inactive alluvial fans and incised deposits at creek mouths indicate past changes in grade of most streams draining into the lake basin. These changes could result from changes in local base level to which the streams flow, in stream discharge, or in stream load. They reflect the environmental history of upper Donjek valley.

3.6.1 Banana Creek

At Banana Creek, an exposure of lacustrine sediments (see below, and Map 2, Fig. 13,14), is capped by a convex, lobate gravel deposit which terminates at approximately the level of the highest shoreline. The surface of the gravel is gullied (Fig. 13).

Gravel deposits of similar calibre and thickness are interbedded with lacustrine and deltaic sediments elsewhere in this exposure (Fig. 14). Because of the calibre of the material, the form of the deposit, its level straddling that of nearby shorelines, and its location in a modern creek valley, the gravel is interpreted as a relic alluvial fan which post-dates deposition of underlying lacustrine beds, and predates incision of Banana Creek through the lacustrine, deltaic and fluvial beds exposed here.

The four relic gravel deposits represent four periods in which the streambed was not innundated by waters of Lake Donjek. As no evidence would remain of other beds which may have been removed before deposition of those underlying them, this should be interpreted as a minimum number of subaerial episodes here. The succession of alluvial and lacustrine beds implies that aggradation of the alluvial fan at the creek mouth occurred during successive episodes until the present.

The modern fan of Banana Creek lies 4 metres below the uppermost relic alluvial deposit, indicating that the

Figure 13. FLUVIAL AND LACUSTRINE SEDIMENTS AT BANANA CREEK

location: see Map 2; Banana Creek at Donjek River

view: looking down Banana Creek at the mouth

Figure 14. STRATIGRAPHIC EXPOSURE AT BANANA CREEK

modern stream is incising its bed. This could be a result of a change in discharge of Banana Creek, in bed-load supply or in base level.

3.6.1-A Changes in Stream Discharge

Banana Creek is a glacial stream which flows from two small, alpine glaciers in the Donjek Range. It has a strongly diurnal flow regime, peaking in late afternoon and drying up completely overnight. This indicates that it is almost entirely glacier-fed, and that long-term changes in glacier-mass balance would be reflected in its flow pattern and in its ability to do geomorphological work. Increased glacial ablation would increase streamflow and cause channel incision, while decreased ablation would reduce the supply of meltwater and the stream's ability to move debris.

Deposits in the headwaters of Banana Creek suggest that variations in meltwater supply have occurred. Barren moraines of very large and angular rock occur in the bottom of the valley of Banana Creek headwaters, 400 metres downstream from the glacier termini. The moraines are lichenized but otherwise unvegetated. This is in contrast with surrounding grassy, alpine slopes.

By comparison, moraines in Donjek valley which are similarly located in the bottom of the Kluane-age valley and downvalley from Donjek Glacier, are of Neoglacial age.

This is a common phenomenon in the St. Elias Mountains, and suggests that the Banana Creek moraines are also of Neoglacial age. Evidence indicates therefore that the Banana Creek glaciers have a history similar to that of most glaciers in the St. Elias; they expanded during the Neoglacial and have now retreated considerably from their Neoglacial terminal positions. This supports the hypothesis that recent incision of the channel of Banana Creek is a result of increased stream discharge. Borns and Goldthwait (1969) suggest a similar origin for incised alluvial fans along Slims River (Map 1).

3.6.1-B Changes in Bed-load Supply

The change in grade of Banana Creek could also be caused by a change in supply of material transported by the stream. Denton and Stuiver (1969 a) suggest that Neoglacial expansion of Kaskawulsh, Donjek and Kluane glaciers (Map 1), "reactivated valley trains", and made fresh, unstabilized debris available for transport by meltwater streams. This hypothesis could also explain events on Banana Creek; they had an oversupply of debris during the Neoglacial, and are now readjusting to decreased debris supply.

Glacial advance would not likely affect stream load to the same degree at Banana Creek as in Slims and Donjek River valleys, however. Kluane, Kaskawulsh and Donjek glaciers advanced during the Neoglacial in valleys which were floored with unconsolidated outwash and moraine deposits.

The Banana Creek glaciers advanced in bedrock-floored valleys, where relatively less debris would be made available for transport by meltwater.

On the other hand, the Neoglacial climate would have increased the rate of periglacial weathering processes, and this could have increased the debris supply to Banana Creek. Much of the bed-load presently originating in the headwaters appears to be derived from debris-slides and talus cones. The supply from these sources would have increased during the Neoglacial, and coupled with a decreased meltwater supply, would have resulted in aggradation in the lower reaches of Banana Creek at that time. In the present non-glacial regime, it could be expected that relatively less debris would be made available. This would result in erosion of the Neoglacial valley-fill deposits.

3.6.1-C. Changes in Local Base Level

Changes in the local base level to which the grade of Banana Creek is adjusted could also cause alternation of channel filling and incision. The local base level would have changed as Lake Donjek filled and drained during the active part of its history and since its last drainage.

The base level at creek mouths fluctuated as the water level in Lake Donjek rose and fell. It is unlikely that this type of fluctuation in base level is responsible for the present incision of stream channels, however, as

the succession of fluvial and lacustrine beds indicates an aggrading streambed both during and between former lacustrine episodes.

A non-cyclic change in base level may have been caused by erosion of lake bottom sediments adjacent to the ice dam. This would have occurred after the most recent withdrawal of Donjek Glacier from the dam site. Observations do not support this theory however. Withdrawal of ice here would have affected the grade adjustment of streams in the former lake basin only. Observations along Donjek Glacier terminus indicate that streams tributary to Donjek River downstream from the ice dam site are also incising in their lower reaches, similar to streams flowing to the lake basin.

3.6.1-D Conclusions

The present condition of stream channel incision at Banana Creek probably results from changes in the supply of meltwater and bed-load debris. Evidence suggests that during the Neoglacial period, meltwater supply to Banana Creek was decreased and bed-load supply increased, resulting in aggradation at the creek mouth. In the present non-glacial period meltwater supply is greater and bed-load supply decreased, causing the creek to cut through the material formerly deposited in its mouth.

3.6.2 Mud Creek and Fanny Creek

Vegetated and inactive alluvial fans which overlie

lake shorelines also occur at Mud and Fanny Creeks (Map 2), and the modern flow of Mud Creek has incised through underlying lacustrine deposits in a manner similar to Banana Creek. Although underlying gravel is not exposed at Mud Creek, numerous springs at the base of the lacustrine terrace suggest that an older, underlying gravel deposit occurs here.

3.6.3 Bighorn Creek

Stratigraphic and topographic evidence suggests that the environmental history of Bighorn Creek is similar to that of Banana and Mud creeks. The stratigraphic evidence occurs at a streambank exposure located 1 kilometre upstream from the modern alluvial fan (Map 2, site f). The exposure, adjacent to the active stream, exhibits three beds of gravel separated by beds of loess. The top bed of loess has a vegetation cover of grass and spruce trees.

The topographic evidence is in the form of an "island" which protrudes 2.5 metres above the surrounding alluvial fan, approximately 1.5 kilometres downstream from the streambank described above (Map 2, site g). The steep, north face of the island reveals about 2 metres of gravel capped with 10 centimetres of loess. The island is covered with alders and grass in contrast with the unvegetated alluvial fan which surrounds it.

The similarity in calibre and location of the gravel beds here with those already described at Banana Creek, suggest that the Bighorn deposits are remnants of a former valley-fill, and that the environmental history of Bighorn Creek is like that of Banana Creek. The presence of loess beds in these exposures supports this hypothesis. Following the explanation of Denton and Stuiver (1969 a) and Borns and Goldthwait (1969) the loess was derived from reactivated glacial and outwash deposits in Neoglacial times. Loess which is interbedded with gravel at the streambank exposure and covers the gravel island, indicates that the gravel beds are of Neoglacial age. The conclusion can therefore be drawn that Bighorn Creek, like Banana Creek, aggraded the alluvial fan at its mouth during active periods of Lake Donjek, in the Neoglacial.

The end of the valley-fill period at Bighorn Creek can be dated from the age of spruce trees presently growing on top of the streambank here. Many are larger in diameter than one in which 150 annual growth rings were counted. This implies that both loess and gravel deposition here were sufficiently reduced to allow revegetation by at least 1828 AD. If the 30 year revegetation period adopted for the lake basin is used here, then the end of Neoglacial conditions occurred by about 1800 AD. This is also a maximum date for the beginning of the removal of the valley-fill, brought on by an increase in streamflow and decrease in bed-load supply.

3.6.4 Phantom Creek

The inactive fan of Phantom Creek lies at a level several metres lower than immediately adjacent shorelines (Map 2). It probably eroded through the shorelines and deposited its large fan immediately following the last active period of Lake Donjek. The fan was completely dry during June and July 1978, but has a few unvegetated channels which may be active at some time during the year. An elevated channel bar supports a spruce tree which was 29 years old in 1978. Parts of the fan have been buried by debris flows from the adjacent moraine (Map 2). Phantom Creek issues from a ravine beside the right lateral moraine of Donjek Glacier and likely dried up as the glacier receded from this moraine.

3.6.5 Conclusions

Alluvial sediments provide evidence which supports the conclusions of Denton and Stuiver (1969 a) and Borns and Goldthwait (1969) about environmental history in the area. The evidence indicates the former presence of Lake Donjek. Interbedded gravel and clay beds at Banana Creek and Mud Creek indicate that periods of lacustrine sedimentation have alternated with periods of fluvial deposition here.

Loess interbedded with gravel deposits indicates that streambed aggradation occurred in the lower reaches of Bighorn Creek during the Neoglacial, ending in about 1800 AD. Deposits

in the headwaters and near the mouth of Banana Creek suggest that streambed aggradation occurred as a result of decreased meltwater flow and increased debris supply during the Neoglacial. Since approximately 1800 AD, these streams have been eroding deposits at their mouths.

3.7 Lacustrine Sediments

Exposures in the lower reaches of some creek valleys tributary to Donjek River exhibit beds of fine sediments. At Banana and Mud creeks fine sediment is interbedded with fluvial deposits which are described above. The fines occur as incised plains (Figs. 10 and 13). At Bighorn and Mullet creeks they occur as plain remnants at the creek mouths. Material of similar texture occurs beneath a silt terrace on the west side of Donjek River, near Phantom Creek (Map 2).

3.7.1 Banana Creek Sediments

The lower reaches of Banana Creek contain valley-fill deposits which occur as a flat, clay plain (Fig. 13). The creek has incised a channel 80 metres wide and 4 metres deep through the plain to expose a succession of gravel, sand and clay beds (Fig. 14). The gravel beds represent periods of fluvial activity as described above.

3.7.1-A Sand Beds

The sand beds occur near the upstream end of the Banana Creek exposure, at elevations of 1118 and 1119 metres (Fig. 14). The lower of the beds overlies a clay

bed from which it is separated by a pebbly contact zone. The sand exhibits horizontal and inclined strata and current ripples in a few layers (Fig. 15). The bed outcrops downstream as a thin, structureless bed of fine sand containing detached and twisted sections of clay laminae (Fig. 14). A gravel unit separates the lower sand bed from an upper bed of similarly horizontal and dipping sands (Fig. 15). Contacts between the sand, gravel and clay are all sharp.

The location of the sand beds at the mouth of a stream and below the level of shorelines, and the succession of horizontal and dipping beds, indicate that they were deposited as deltas of Banana Creek in Lake Donjek.

The elevation of delta surfaces is sometimes assumed to mark former lake levels (Gustavson and Ashley, 1975). The deltas at Banana Creek probably do not represent former water levels however. A partially exposed sand bed upstream from the deltas may be a remnant of delta sediments which overlay the beds described above (Fig. 14).

3.7.1-B Clay Beds

Three complete clay beds and fragments of a fourth are exhibited in the right bank exposure at Banana Creek. Two clay beds occur in the left bank exposure (Fig. 14).

To facilitate discussion, clay beds in the right bank exposure are labelled A, B, C and D (Fig. 14). All

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Figure 15. SAND BEDS AT BANANA CREEK

location: see Figure 14

scale: survey rod is 4 metres long

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the beds have sharp, non-gradational contacts with adjacent gravel and sand beds. This is an indication that the clay beds and gravel beds were deposited under different hydrologic conditions as has been emphasized in the discussion of fluvial sediments.

Some general conclusions about the clay beds can be derived from a description of their appearance in the field:

Bed A: Bed A has a very finely laminated structure of clay layers with silt partings. It forms the gently sloping, gullied surface of most of the Banana Creek valley-fill deposit.

Bed B: Bed B has more than 200 laminae, some of which exhibit colour banding. Couplets are characterized by an apparently ungraded, relatively thick clay member with a very thin, intervening silt member. A parting usually occurs at the silt. Depressions in the upper surface of bed B are similar to gullies in the upper surface of bed A (Fig. 14,16).

Bed C: The poor exposure of bed C precludes detailed description of its properties.

Bed D: The internal characteristics of bed D vary laterally and vertically. At the upstream end of the exposure it includes 20 horizontally bedded, reverse-graded couplets of very heavy clay and silt. At the downstream end it contains about 200 laminae which display tonal banding (Fig. 16).

Figure 16. CLAY BEDS AT BANANA CREEK

location: see Figure 14

The texture of the beds and their location below the elevation of nearby shorelines suggests that they are lacustrine deposits from Lake Donjek. The interbedding of lacustrine and fluvial deposits indicates that four successive periods of fluvial and lacustrine conditions occurred here.

The textural variation within clay laminae is similar to that observed in glaciolacustrine deposits at many other locations which have been interpreted as annual rhythmites called varves (Embleton and King, 1968, p.436). If the clay beds at Banana Creek are varved they indicate that bed D was deposited in glacier-dammed lakes which lasted about 200 years. Bed B exhibits laminae which may be varves, while beds A and C are almost certainly not varved.

3.7.1-C Varves

Analyses were performed on samples taken from bed D at Banana Creek, to determine whether they exhibit the textural characteristics of varves (Appendix C).

The diagnostic characteristics of varves have been under discussion for many decades. There is general agreement that they exhibit textural fining upwards within a couplet, with a sharp boundary occurring at the base of the silt member. This is the result of an annual cycle of sediment transport and deposition in the lake. Random and cyclic, sub-annual variations in sediment supply which are sometimes erroneously interpreted as an annual cycle, also cause vertical changes in varve texture (Shaw, Gilbert

and Archer, 1978; Peach and Perrie, 1975; Fig. 17 a,b).

Further complications are added if the lake drains cyclically, as do many glacier-dammed lakes. In this case the end-of-summer reservoir of fine sediments is lost. This would result in a missing winter, clay layer and a thin varve (Fig. 17 c). This situation is reported at annually draining Between Lake, on Axel Heiberg Island (Maag, 1969). Annual layers could not be distinguished in samples taken from the bottom of Between Lake, and both normal and reverse-graded laminae occur there.

A monolith containing lacustrine sediments was obtained from Bed D at Banana Creek, in order to determine whether the sediments exhibit the textural characteristics of varves. The monolith consists of a series of clay blocks containing fine partings. The blocks are separated by layers of fine sand (Fig. 18). The thickness of the clay and sand layers varies markedly; the lower section of the monolith is predominantly clay with thin partings, while the mid and upper section have thicker sand layers. A roll-up structure and current bedding occur in sand layers.

The alternation of clay blocks with layers of sand is consistent with models of glaciolacustrine sedimentation. The irregular thickness of the layers however, is unlike the simple varve model presented in Fig. 17a.

The variations in thickness may be caused by fluctuations in sediment supply (Fig. 17b) and in drainage characteristics

Figure 17. HYPOTHETICAL TEXTURAL MODELS OF VARVED SEDIMENTS

Figure 17a. Effect of sub-annual variations in sediment supply during summer.
after: Peach and Perrie, 1975

Figure 17b. Effect of sub-annual variations in sediment supply during summer and winter.
after: Shaw, Gilbert and Archer, 1978

Figure 17c. Effect of sub-annual variations in sediment supply during summer and winter, and of glacier outburst which drains lake in late summer.

Figure 18 MONOLITH CONTAINING LAMINATED SEDIMENTS FROM BED D

(Fig. 17c). In a glacier-dammed lake which does not drain by outburst, a regular series of laminae as occurs in the lower part of bed D, is to be expected. When drainage by outburst occurs the coarse, summer sediment predominates. This is the case in the upper section of bed D. This would indicate that few outbursts occurred during the early history of bed D, and that outbursts became more frequent later on.

A more detailed textural analysis was performed on samples from within a clay block near the top and near the bottom of bed D (Fig. 19 and Appendix C). The former exhibits a regular variation in texture with depth. The sand fraction particularly appears to vary cyclically and resembles the hypothetical model for varved sediments affected by glacier outburst. The latter more closely resembles the summer to spring textural variation in Fig. 17b. This is consistent with the suggested history of bed D, in which outbursts would be recorded in the upper part (Fig. 17a) but not in the lower part (Fig. 17b). It should be borne in mind that these two sets of samples are from within clay layers and do not include the thicker sand layers which would be interpreted as spring or summer deposits. The structure and textural variations of sediments in bed D conform to hypothetical models of varve sedimentation.

Figure 19. TEXTURAL VARIATION OF CLAY LAMINAE FROM BED D

Figure 19b. Textural variation in samples 9-20 from bottom of Bed D at Banana Creek

Figure 19a. Textural variation in samples 21-37 from top of Bed D at Banana Creek

location of samples: see Figure 18

3.7.1-D Organic Material

Organic material occurs as thin layers in bed D on the right cutbank of Banana Creek and also in a clay bed on the left streambank (Fig. 14,18). A radiocarbon age was obtained from material in the left cutbank. This exposure is separated from the right bank by 80 metres of incised streambed. The left bank is poorly exposed and exhibits only 2 clay beds, interbedded with gravel (Fig. 14). The upper bed is similar in tone, texture and structure to bed A on the right bank. It is underlain by gravel, and the gravel in turn is underlain by a 2 metre vertical section which is obscured and therefore unknown. A basal bed consists of clay laminae with numerous layers of sand and silt, and 7 thin, sandy layers containing black organic material. A date of 500 ± 80 BP (GSC-2791) was obtained on a sample from an organic layer near the middle of the bed (Fig. 14).

Clay facies on the right and left banks are believed to be time-stratigraphic units. Although part of the overlying section on the left bank is obscured, material exposed at the top is identical in thickness, texture and structure with that on the opposite bank (Fig. 13), and the laminated clay is overlain with the same thickness of valley-fill sediments. The lower clay beds also exhibit similar textural banding) unlike any of the other beds.

Finally, only the bottom clay beds contain organic layers.

Plant macrofossils in the organic material which was radiocarbon dated are from species present around the basin today (Appendix B). Although similar organic layers are not uncommon in glacial lake deposits, their origin in the present case is a problem. The sampled layer includes well-preserved plant and insect fossils mixed with sand, silt and clay. It is unlikely the fossils are in situ as they are not rooted, nor do any soil horizons occur in underlying laminae.

If not in situ, the organic material must have been redeposited on the lake floor. This could occur by slowly settling from the lake surface, by transport in an inflowing current, or from a debris slide from the lake shore. All of these processes are likely to have occurred at Lake Donjek, so each will be examined in more detail.

Sedimentation Hypothesis:

If the material had been deposited by settling from the lake surface, some degree of sorting according to particle density would have occurred, as it did in the clay beds discussed above. Sorting was not observed in the field exposures, so this hypothesis can be eliminated.

Debris-Slide Hypothesis:

Evidence for debris slides occurs at several locations along the lake shorelines (Map 2, site b).

The deposit resulting from such an event would likely contain a heterogeneous mixture of organic material from above the water level, as well as shoreline sand and gravel. Beds underlying the debris flow would be contorted or otherwise disturbed. The organic deposits at Banana Creek do indeed contain a mixture of organic material which would have been available above the shoreline, and occur at the base of a cusate scarp which resembles the head of a debris slide. However, they do not contain any gravel, of which there is an abundance at the above shoreline, nor is there evidence for disturbance of underlying clay laminae. The debris-slide hypothesis is neither proved nor disproved, but is retained as a working hypothesis.

Inflow Current Hypothesis:

Deltas in the Banana Creek exposure indicate that inflow currents were active during lacustrine periods here. The deltas contain no organic layers however, and the organic layers are not current bedded or size sorted. The organic material was therefore not likely redeposited by inflowing currents.

Periodic Drainage Hypothesis:

Another hypothesis is suggested on the basis of

the temporal nature of glacier-dammed lakes, the Holocene glacial history of Donjek River valley, and present-day vegetation here. The organic layers may be a deposit resulting from periodic drainage during an early, active period at Lake Donjek.

While some glaciers in the northeastern St. Elias Mountains advanced early in the Neoglacial period, no firm evidence is reported for an early Neoglacial advance of Donjek Glacier. This suggests that the oldest known lake deposits - from which organic material is dated at 500 ± 80 BP-- are probably from the earliest active phase of Lake Donjek in Holocene times. If so, the lake from which the organic material is derived would have inundated vegetated valley slopes like those presently above the level of lake shorelines.

During this time, plant needles and seeds and other material washed from the forest soil would have been carried in the lake, and washed along the shore. When the lake drained periodically as many glacier-dammed lakes do, this material would be deposited as a layer on the lake bottom. Similar material would not be deposited by more recent lake drainings because subsequent lakes inundated basin slopes from which vegetation had already been washed or buried.

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If this hypothesis is accepted, the organic layers indicate a minimum of 8 filling-draining events during the earliest lake episode. Any of these hypotheses is consistent with an age for the earliest known lake of 500[±]80 BP, derived from organic material in the bottom clay bed at Banana Creek.

3.7.2 Other Lacustrine Deposits

Remnants of fine-textured "plains" like that at Banana Creek are also found at Mud, Bighorn and Mullet creeks (Map 2 and Fig. 10). The material at Mud Creek is believed to overlies an older gravel deposit because vegetated gravel occurs on slopes above it, and because springs issue from its base. Numerous ice lenses are exposed in the streamcut at Mud Creek, and thermokarst hollows occur on the surface of the plain.

The plain at Mullet Creek also contains ice lenses, and an organic layer similar to that at Banana Creek. The deposit at Bighorn Creek is poorly exposed but is morphologically like those elsewhere. Clay layers underlying sand and silt on the left bank of Donjek River near Phantom Creek, suggest that the fine-textured plains are parts of a lacustrine deposit which once covered most of the valley floor.

3.7.3 Conclusions

The deposits of lacustrine sediments at various locations

in Donjek River valley upstream from Donjek Glacier indicate that it was formerly inundated by a glacier-dammed lake. Successive beds of lacustrine material indicate that this occurred at least 4 times.

The age and duration of the periods of lake activity is indicated by vegetation and by characteristics of some sediments. Organic material in the lowest exposed bed of lacustrine sediments provides a radiocarbon age of 500 ± 80 BP. (GSC-2791) for the earliest known lacustrine episode. The organic layers, laminated structure and graded texture of this bed suggest that this lake episode lasted approximately 200 years, and that drainage by glacier outburst was rare at first but became more frequent as the lake grew older.

3.8 Moraines and Glacier Fluctuations

Donjek Glacier terminus is bordered with moraines. These can be divided into three zones. At the north end of the terminus is a series of nested, arcuate moraine ridges. Denton and Stuiver (1969 a), subdivide this into an older, stable and vegetated Drift A, and a younger, unstable Drift B. Both are ice-cored and contain numerous kettle lakes and outwash channels. Tree stumps in the outermost moraine here provide a maximum date for the earliest Neoglacial advance of Donjek Glacier of 520 to 210 BP (Radiocarbon correction of Stuiver, 1966). Recession from, and revegetation of this moraine occurred before 1825 AD,

as indicated by the age of trees growing on the moraine (Denton and Stuiver, 1969 a). Since that time there has been net retreat, with minor readvances prior to 1947, 1961, 1965 and 1979 (Johnson, 1972; Denton and Stuiver, 1969a; W.A. Wood, V. Schilder and J. Jacquot, pers. com.).

A massive end moraine borders the south end of the glacier terminus, extending from the right lateral moraine to the ice front at Donjek River (Map 2). The distal side of this moraine has willow and grass vegetation, and two well-preserved shoreline terraces. The proximal side is unstable and exhibits an ice core. Numerous channels cut through the moraine and the shorelines on it, having drained moraine lakes sometime after the last draining of Lake Donjek (Map 2).

There is no direct means of dating the south moraine, but two lines of evidence suggest that it is similar in age with the moraine at the north end of the terminus. Firstly, both are the outermost moraines of Donjek Glacier and are bordered by outwash sediments. Secondly, the two shorelines on the upstream moraine are at similar levels with the prominent shorelines elsewhere in the basin. Since the lower shoreline is older, the moraine must have stabilized before an early lake drained. The moraine and shoreline were not subsequently disturbed during a later advance which again dammed Donjek River. This suggests that the lower shoreline was constructed during the early Donjek Neoglacial advance of 520 to 210 BP. Glacial advances which caused later lakes must

have been of smaller magnitude than the one which created the lake associated with the lower shoreline terrace, since the moraine was not disturbed.

The third zone of moraine is a ridge which occupies the valley floor between Kluane Rapids and Banana Creek (Map 2). The relative location of the ridge, the glacier front, Donjek River, and high level paleochannels here, suggest that the ridge marks a former, advanced position of the ice front. Although at lower levels than lake shorelines, the ridge shows no sign of having been inundated. The paleochannels head at the highest shoreline at Kluane Rapids, and extend downstream as a boulder-bedded chute between the moraine ridges and the eastern shore of the lake basin.

Three conclusions can be drawn from the form and location of the ridges and the channel. Firstly, the advanced glacier front must have confined the river against the east side of the basin at Kluane Rapids. Secondly, the river channel at one time flowed over a ridge of moraine here at the level of shoreline A. These conclusions imply that the single, gravel terrace between Kluane Rapids and Banana Creek was a narrow neck of water connecting an upper basin dammed by the glacier and moraine at Kluane Rapids, and a downstream basin dammed at Banana Creek. The third conclusion is that during or soon after the release of the

$$Q = \frac{1.55 D^{2/3} w}{s^{7/6}}$$

where Q is instantaneous peak discharge, D is clast b-axis diameter, s is water surface slope and w is channel width. Units are given in Table 4, and the derivation and assumptions of the equation are given in Appendix D.

Estimates of outburst discharge derived from this equation are given in Table 4. For comparison an estimate derived from an empirical equation relating lake volume to outburst discharge (Clague and Mathews, 1973) is also given. This equation is derived from outbursts in a variety of situations and has $r^2 = .96$.

The new estimates in Table 4 exceed the measured 1978 peak flow for Donjek River (Canada, 1978a) by up to 20 times, and the suggested 100-year design flood (Canada, 1978b) by up to 16 times. The difference in peak discharge derived from the upstream and downstream current ripples suggests that two outburst events may be recorded in the deposits.

Figure 20. PROFILE OF FLOOD DEPOSITS

source: field survey 1978

location: see Map 2, site h

it nears the end of the constriction along the glacier terminus. These wave forms are both larger and more widely distributed than those at the upstream site. Unlike the upstream forms, they have a gentle stoss and steep lee slope and are convex upstream in plan view (Map 2 site i).

Comparison of these features with bedforms found in glaciofluvial and glaciolacustrine environments (Table 3), indicates that they are most similar to giant dunes and ripples described by Clague (1979), Pardee (1942), and Thiel (1932). The features described by Thiel were formed by water flowing at very high velocity when a moraine-dammed lake was suddenly drained. The landforms described by Clague and Pardee are believed to have a similar origin; they were formed by strong currents during the catastrophic draining of glacier-dammed lakes. The restricted location of these features on Donjek River just downstream from the site of a former ice dam, suggests that they were formed by a flood originating at Donjek Glacier terminus; a glacier outburst which drained Lake Donjek.

3.9.1 Discharge During Outburst

The maximum discharge resulting from glacier outburst can be estimated using hydraulic relationships between clast size and stream velocity, and channel geometry at the site of the unusual bedforms. Clague (1975) used an equation applicable to wide, outwash channels such that,

Table 3. Glacio-fluvial and Glacio-lacustrine Bedforms

DESCRIPTION	WAVELENGTH or REFERENCE SPACING (m)		AMPLITUDE CLAST * (m)		PROFILE	PLAN	LOCATION	STRUCTURE
	REFERENCE SPACING (m)	AMPLITUDE CLAST * (m)	SIZE (m)	PROFILE				
diamond bar	a. 20-50	0.3	.10-.35	low relief	diamond	outwash		
transverse rib	a. .05-2.0	clast	.01-.45+	step-like	rib	gravel stream	overlie fines	
transverse rib	b. .05-2.2	clast	.47	step-like	rib	gravel stream	overlie fines	
ripple	b. 1.8		.002	current ripple		stream	bedded	
giant current ripple	c. 15		.80	dune		gravel stream	sorted surface	
giant ripple marks	d. 2-150	.3-15	.008-.02	current ripple	convex	downstream lake bottom	bedded	
giant dunes	e. 17	3	.04	dune	convex	downstream lake bottom	sorted	
Donjek, primary	f. 60-110	.8-1.6	.04-.35	antidune	convex	downstream gravel stream	imbricate, sorted	
Donjek, secondary	g. 2-26.5	.1-2.2	.04-.35	?	?	gravel stream	sorted	
Donjek, downstream	h. 25	1-2	.1-1	dune	convex	upstream gravel stream	crudely sorted?	

*mean or b-axis diameter of clasts

References a. Boothroyd and Ashley, 1975
b. Church and Gilbert, 1975
c. Thiel, 1932

d. Pardee, 1942
e. Clague, 1979 and field obs.
f. Upstream site, field obs.

g. upstream site, field obs.
h. downstream site, field obs. and photos

$$Q = \frac{1.55 D^{2/3} w}{s^{7/6}}$$

where Q is instantaneous peak discharge, D is clast b-axis diameter, s is water surface slope and w is channel width. Units are given in Table 4, and the derivation and assumptions of the equation are given in Appendix D.

Estimates of outburst discharge derived from this equation are given in Table 4. For comparison an estimate derived from an empirical equation relating lake volume to outburst discharge (Clague and Mathews, 1973) is also given. This equation is derived from outbursts in a variety of situations and has $r^2 = .96$.

The new estimates in Table 4 exceed the measured 1978 peak flow for Donjek River (Canada, 1978a) by up to 20 times, and the suggested 100-year design flood (Canada, 1978b) by up to 16 times. The difference in peak discharge derived from the upstream and downstream current ripples suggests that two outburst events may be recorded in the deposits.

TABLE 4

ESTIMATES OF DISCHARGE FROM LAKE DONJEK

Q Peak	Volume	D	s	w	Comments
13300(m ³ /s)	-----	.184*(m)	.005 ^a	225(m)	upstream site, valley width
8866	-----	.184*	.005 ^a	150	upstream site, width of gravel bar with ripples
6270	-----	.567+	.03 ^b	190	downstream site, width of gravel bar with ripples
10890	-----	.567+	.03 ^b	330	downstream site, valley width
2268	162x10 ^{6.3} m ³	----	-----	----	Q = 75V ^{.67} (Canada, 1977) ^c max max

* mean of largest measured b-axis at 14 locations along a traverse
+ estimated mean of largest b-axis at 5 locations
a surveyed slope of gravel bar, 1978
b slope of gravel bar measured from air photos
c Q = instantaneous peak discharge during outburst
max

V = maximum lake volume before outburst
max

CHAPTER 4

SUMMARY AND CONCLUSIONS

The environmental history of Lake Donjek is reconstructed by interpreting landforms, vegetation and observed glacial fluctuations. It can be compared with events elsewhere and provides a useful addition to the regional earth history. A practical application of the study is a forecast of possible future active phases at Lake Donjek. Finally, a basis is provided for further work in southwest Yukon.

4.1 Geochronology of Lake Donjek

Lake Donjek has a varied history. It is a dormant lake at the present time but has had both active and dormant episodes in the past. The active periods are referred to here as the Lake Donjek I, II, III, and IV.

Prior to about 1270 to 1430 AD (680-520 BP), upper Donjek River valley was probably very similar to today. Tree stumps incorporated in the Donjek moraine indicate that the pre-Lake Donjek period was one of glacial recession, and the earliest lake sediments contain organic material like that which would be found on the modern valley slopes. Alluvial deposits underlying lacustrine sediments from the earliest known lake are at an elevation close to that of

the modern streambed, implying that stream runoff and debris load were similar to the present. It is unlikely Lake Donjek existed during the Hypsithermal.

4.1.1 Lake Donjek I

The earliest known active episode at Lake Donjek began between 1270 and 1430 AD (680-520 BP), when Donjek Glacier advanced strongly across Donjek River valley and dammed Donjek River at Banana Creek. The glacier also advanced far downvalley and achieved its greatest extent in Neoglacial times. Moraines formed during this advance are beyond the limit of any succeeding glacial advance.

Varve-like sediments at Banana Creek indicate that this episode may have lasted for 200 years. Organic material in the same sedimentary deposit suggest that Lake Donjek I inundated a formerly vegetated and forested valley floor and that the lake filled and drained at least eight times. Textural variations in the deposit suggest that the drainings were caused by glacier outbursts.

The uppermost beds of the Lake Donjek I deposit at Banana Creek are highly contorted, suggesting that they were disturbed at the beginning of the subaerial episode which followed. This may have occurred as the lake drained or when the overlying gravel was deposited on the saturated, exposed lake sediments. The episode ended between 1470 and 1630 AD (480-320 BP). A period of alluvial deposition followed the final draining of Lake Donjek I.

4.1.2 Lake Donjek II and III

Beds of lacustrine sediments at Banana Creek indicate two subsequent episodes of Lake Donjek. Lake Donjek II is known only from one exposure of sediments and was presumably of short duration. It was followed by a period of alluvial deposition. Lake Donjek III is known from laminated lacustrine beds. If the laminae are varves they indicate a duration of 200 years for this episode, but the temporal character of the deposit is not known from available evidence. Alluvial gravel overlies sediments from Lake Donjek III.

4.1.3 Lake Donjek IV

Donjek Glacier advanced once more and impounded Donjek River sometime after 1622 AD (328 BP). Although this advance dammed the river to a level exceeding that of former lakes, it was of smaller magnitude than earlier advances. The southern end moraine has undisturbed shorelines from both lakes on its distal side, and moraines at the north end of the glacier terminus date to the time of Lake Donjek I.

The lake overflowed through a rock channel at Banana Creek for several tens of years or more, as indicated by the depth of channel incision. At one point the basin at Banana Creek was nearly isolated from the larger, upstream lake by the advancing ice and large end moraine of the glacier. A narrow neck of water was maintained however, and was bounded to the west by glacier ice.

Lake Donjek drained completely between 1810 and 1840 AD (140-110 BP). The nature of channel deposits downstream from the lake and estimates of the flood which created them, suggest that drainage last occurred as a glacier outburst. No other evidence for cyclic, self-draining during Lake Donjek IV remains; but evidence from Lake Donjek I and theoretical deductions suggest that it did occur.

4.2 Correlations and Climatic Implications

Evidence from Lake Donjek indicates that the Neoglacial maximum occurred at Donjek Glacier between 1270 and 1430 AD (680-520 BP). The period between and immediately following active episodes of the lake saw alluvial deposition and channel aggradation. This suggests that these subaerial or inter-lacustrine periods were not associated with significant climatic warming.

Lake Donjek had drained by 1840 AD (110 BP). After this time the supply of meltwater to streams tributary to Donjek River was increased and the supply of bed-load debris was decreased. As a result they began to incise their former alluvial fans and other valley-fill deposits.

The dates derived from evidence obtained at Lake Donjek are in general agreement with the age of fluctuations of Donjek Glacier obtained by other means. Denton and Stuiver (1969 a) conclude that the maximum Neoglacial advance occurred between 1430 and 1740 AD (520-210 BP) and that recession from the outermost moraine had occurred

by 1825 AD (125 BP). The occurrence of 4 active episodes at Lake Donjek suggest that there were at least 4 discrete glacier fluctuations during this time.

The only other glacier-dammed lakes in the St. Elias with a known history are Hazard Lake at Steele Glacier, and Recent Lake Alsek on Alsek River. Shoreline evidence suggests that Hazard Lake was dammed for an unknown period during the Neoglacial, again prior to 1930, and again from 1966 to the present (Collins and Clarke, 1977, Sharp, 1947). The present lake was dammed by a very strong surge so its modern history is not necessarily related to widespread climatic conditions.

Recent Lake Alsek is believed to have had active periods ending about 1400 to 1600 AD (550-350 BP), 1725 AD (225 BP), and 1850 AD (100 BP), (Clague 1979). These dates fall within the period of activity of Lake Donjek and lend credence to the hypothesis that it had multiple active phases during the Neoglacial. This conclusion can reasonably be applied to all lakes in the St. Elias and adjacent mountain ranges, formerly or presently created by glacial advances.

4.3 A Projection to the Future: Forecast of a New Active Episode

In historical times, Donjek Glacier has experienced net recession from its Neoglacial maximum position, with periodic readvances of generally decreasing magnitude (Fig. 21).

Figure 21. FLUCTUATIONS OF DONJEK GLACIER TERMINUS

Figure 21 a SEASONAL OSCILLATIONS AT ICE-DAM SITE, 1978-79

Figure 21 b HISTORICAL FLUCTUATION AT ICE-DAM SITE, 1941-79

If it continues to advance with the frequency which has occurred since 1929, a maximum should be expected at the ice-dam site in 1980.

Repeated observations of the terminus during 1978 and 1979 indicate that a seasonal oscillation is superimposed on the long-term fluctuations (Fig. 21). This could result from seasonal changes in the rate of glacier advance, from seasonal changes in river discharge, or from the combined effect of both factors. The oscillation was particularly dramatic in 1979. In April of that year the glacier had completely overridden Donjek River, causing the River to flow beneath it at the ice-dam site. By July however, the ice front had retreated by tens of metres and no longer constricted the river.

If the long-term fluctuation peaks in 1980 as expected, the seasonally advanced terminal position is likely to be maintained throughout the summer of 1980 and dam Donjek River again.

4.4 Recommendations For Further Work

This study provides a basis for further work in fields related to glacial geomorphology. Further studies at Lake Donjek could contribute to knowledge of geochronology, paleoclimatology, paleohydrology and geomorphic processes in southwest Yukon.

4.4.1 Geochronology

Additions have been made to the known Holocene chronology of Donjek valley and Yukon Territory. The amount of detail added is limited by the techniques and evidence available during the field program. Further historical evidence could be obtained by repeated observation of actively eroding cutbanks and by subsurface stratigraphic techniques.

Lichens in the area studied are not suitable for dating Lake Donjek. They may, however, provide suitable chronometric data for fluctuation of the small glaciers in Banana Creek headwaters. This data would add to the knowledge of glacier and climatic fluctuations in southwest Yukon, and would also add support to the hypothesis presented here about changes in the grade of Banana Creek.

4.4.2 Paleoclimatology

Inferences as to the climatic changes which have affected Lake Donjek and surroundings have been made. More detailed and concrete evidence for climatic fluctuations might be obtained by detailed palynologic and dendrochronologic studies. Sites suitable for such work occur downstream from Lake Donjek, along the margin of Donjek Glacier terminus.

4.4.3 Paleohydrology

Estimates of the magnitude of flood resulting from the

98

draining of Lake Donjek have been derived from channel deposits along Donjek River. Accurate measurement of these deposits was possible only in a restricted area. A larger number of accurate measurements would give a more representative flood estimate.

4.4.4 Geomorphic Processes

This study presents evidence which suggests that sedimentation in Lake Donjek followed the varve model. This conclusion is based on the structure and texture of sedimentary deposits. A palynological study of the varved sediments would add further support to this hypothesis.

A forecast of a new episode of Lake Donjek is presented. The forecast is based on observed rates of advance of Donjek Glacier terminus and on seasonal fluctuations in discharge of Donjek River. This theory could be tested by comparing the rate of cross-valley advance of Donjek Glacier and changes in the rate of flow of Donjek River to the degree of channel constriction at the ice-dam site.

APPENDIX A. STRATIGRAPHIC PROFILES ADJACENT TO CHANNEL A

APPENDIX B. PLANT MACROFOSSIL REPORT No. 79-3

Sample No.: 7-7-1

Locality: East side of Dónjek R., 55km S. of Alaska Hwy, Y. T.

Lat.: 61° 10' N Long.: 139° 25.5' W

Collected by: M. Perchanok

Submitted by: R. Richardson (picked from sample submitted for ¹⁴C date)

FOSSILS:

Pinaceae--pine family

Picea sp. - needles and seeds

Betulaceae--birch family

Betula sp.--dwarf type samara (B. nana or B. glandulosa)

Cyperaceae--sedge family

Carex sp.--achene

DISCUSSION:

1. In addition to the above mentioned plants the sample picked by Richardson included one weevil leg (Curculionidae)--probably from Lepidophorus lineaticollis Kirby, a pronotal fragment of an elaterid beetle, and the head of a heteropteran bug.

2. The fossils are too few and too nonspecific in their environmental implications to allow a detailed paleoenvironmental conclusion; however the occurrence in the same assemblage of Picea needles and shrub birch seeds probably indicates at least an open forest.

Identification and Discussion by:

J. V. Matthews, Jr.
July 4, 1979

APPENDIX C

SIZE ANALYSIS OF SEDIMENTS AT BANANA CREEK

- Purpose:** To determine whether textural variations in sediments from Lake Donjek conform with the varve model for glaciolacustrine sedimentation.
- Field Samples:** Soil monoliths including clay, silt and sand layers were removed from a fresh cutbank on the north side of Banana Creek. The procedure was to drive steel plates behind and on either side of an exposed section (see Fig. 16). Monoliths were wrapped in plastic and stored in boxes. Macroscopic characteristics were recorded photographically and by tracing onto acetate overlays (Fig. 18).
- Lab Samples:** Three sets of samples were obtained from the monolith shown in Fig. 16. The first set was taken from clay sections within the monolith (Fig. A-1), in order to investigate general characteristics of the monolith. The second set was taken from a clay section near the top of the monolith, and the third set from a clay section near the bottom of the monolith (Fig. 18, 9-20 and 21-37). The first set was obtained by breaking small blocks from the clay sections, with a knife. The second and third sample sets were obtained by wetting the monolith and slicing off samples at 2 millimetre intervals using a bevelled, tin plate.
- Size Analysis:** Preparation of Samples 1 to 8
- Oven dry bulk sample and weigh
 - Liquify with water, burn off organic material with hydrogen peroxide
 - Oven dry, weigh
 - Liquify with water, centrifuge and decant, repeat
 - Oven dry, weigh

The % by weight of organics was obtained from step c, and of soluble salts from step c (Fig. A-1)..

Size Analysis: Preparation of Samples 9 to 37

- a. Liquify with water, burn off organic material with hydrogen peroxide
- b. Liquify with water, centrifuge and decant, repeat

Size Analysis: Wet Sieving

- a. Liquify with water and add 2 ml of 50 mg/l Calgon to disperse
- b. Wash through 300 mesh (5.2 ϕ) sieve
- c. Oven dry and weigh material retained on sieve
- d. Catch washings in 100 ml flask, add distilled water as necessary

Size Analysis: Falling Drop (after Nickling, 1972)

- a. Shake flask to disperse sediment thoroughly, and pour into testube
- b. At preselected times for 4, 5, 6, 7, 8, 9, 10 ϕ withdraw a sample using micropipette
- c. Release sample from micropipette into tube of anisole, and measure falling time between reference marks on tube
- d. Calibrate falling time to gm/l using prepared solutions of Na Cl
- e. Compute concentration, correction for Calgon, total sediment weight in sample, and % weight in size classes (Fig. A-2)

Figure A-1. Characteristics of Sediments from Lake Donjek

sample locations: clay laminae from Bed D, on north bank
of Banana Creek (see Figures 14 and 16)

FALLING DROP LAB.										SAMPLE DEPTH & CON.										20°C										Depth Dilution Factor = 0.10 (wind)																																												
4.00 ft					4.50 ft					5.00 ft					5.50 ft					6.00 ft					6.50 ft					7.00 ft					7.50 ft					8.00 ft					8.50 ft					9.00 ft					9.50 ft					10.00 ft														
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APPENDIX D

ESTIMATION OF DISCHARGE DURING GLACIER OUTBURST, AFTER CIAGUF (1975)

Stream discharge (Q) is the product of channel width (w), depth (d), and water velocity (v). Discharge during past, unobserved flood events can be estimated where these variables can be determined from relic geomorphological features.

Channel width can be determined from river terraces, flood deposits, or vegetation scars.

Velocity is estimated using the Manning flow resistance equation,

$$(1) \quad v = \frac{R^{2/3} s^{1/2}}{n},$$

where (R) is hydraulic radius, (s) is slope of the energy gradient (water surface), and (n) is the channel resistance coefficient. Hydraulic radius cannot be measured directly but is assumed equal to flow depth (d) for wide channels (Leopold, Wolman and Miller, 1964, p. 222).

Flow depth cannot be measured directly but can be estimated using the Shields equation,

$$(2) \quad t_c = 890D,$$

and the formula,

$$(3) \quad t_c = pg_s d,$$

where (t_c) is the critical tractive force for entrainment of clasts of b-axis diameter (D), and (p) is fluid density, (g) is gravitational acceleration, and (s) and (d) are as defined above.

Church (1970), found that a more suitable constant of Shields relationship for imbricate, gravel floored channels is 1800. Using Church's constant and combining equations (2) and (3),

$$(4) \quad d = .184 D/s$$

Substituting (4) in (1), gives

$$(5) \quad V = \frac{.323 D^2}{n s^{1/6}}$$

The channel resistance coefficient (n) is estimated from the Strickler equation (Chow, 1959, p. 205), where,

$$(6) \quad n = .038 D^{1/6}$$

Substituting (4) and (6) in (5), gives velocity in terms of water surface slope and maximum clast size on the channel bed. Finally, (4) is substituted for the depth term in the discharge equation, and paleodischarge is expressed as,

$$(7) \quad Q = \frac{1.55 D^3}{s^{7/6}}$$

Clague's model makes the following assumptions:

- a. Resistance coefficient is dependent mainly on bed roughness and not on form roughness
- b. B-axis diameter of the largest moving clasts is representative of the critical tractive force acting on the streambed
- c. Clast packing is similar to that on the Baffin Island sandar. studied by Church (1970)
- d. Flow is in an open channel, not a tunnel

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Map 2.

LANDFORMS OF LAKE DONJEK

surficial materials

landforms

special sites

- a sand dunes
- b slumped sediments
- c shoreline profile
- d shoreline profile
- e location of dead trees
- f location of loess overlying relic alluvium
- g alluvial fan remnant
- h location of flood deposits
- i location of flood deposits
- j location of stratigraphic exposure

sources NAPL A15434 178
A24952-21-27
field observations 1978

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km

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