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The Last Cordilleran Ice Sheet in Southern Yukon Territory
Le dernier inlandsis de la Cordillère dans le sud du Yukon
Die Kordilleren-Eisdecke im Gebietdes südlichen Yukon

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L'Inlandis de la Cordillère
The Cordilleran Ice Sheet

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Article abstract

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THE LAST CORDILLERAN ICE SHEET IN SOUTHERN YUKON TERRITORY*

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ABSTRACT The Cordilleran Ice Sheet in Yukon radiated from ice-divides in the Selwyn, Pelly, Cassiar, and eastern Coast Mountains and was contiguous with a piedmond glacier complex from the St. Elias Mountains. Expansion of glaciers in divide areas could have been underway by 29 ka BP but these did not merge to form the ice sheet until after 24 ka BP. The firn line fell to approximately 1500 m at the climax of McConnell Glaciation. Flow within the ice sheet was more analogous to a complex of merged valley glaciers than to that of extant ice sheets: topographic relief was typically equal to or exceeded ice thickness, and strongly influenced ice flow. Surface gradients on the ice sheet were fractions of a degree. Steeper ice-surface gradients occurred locally along the digitate ice margin. Retreat from the terminal moraine was initially gradual as indicated by recessional moraines within a few tens of kilometres of the terminal moraine. Small magnitude readvances occurred locally. The ice sheet eventually disappeared through regional stagnation and downwasting in response to a rise in the firn line to above the surface of the ice sheet. Regional deglaciation was complete prior to approximately 10 ka BP.

RÉSUMÉ *Le dernier inlandsis de la Cordillère dans le sud du Yukon*. L'Inlandsis de la Cordillère a progressé dans le Yukon à partir des lignes de partage des glaces des monts Selwyn, Pelly et Cassiar et de l'est de la chaîne Côtière; il était contigu à un glacier de piémont complexe en provenance des monts St. Élias. Les glaciers ont pu se développer dans les régions de partage des glaces à partir de 29 ka BP, mais ils ne se sont fusionnés pour former un inlandsis qu'à partir de 24 ka BP. À l'optimum de la Glaciation de McConnell, la ligne de névé s'est abaissée à environ 1500 m. L'écoulement à l'intérieur de l'inlandsis ressemblait davantage à celui d'un complexe de glaciers de vallées coalescents qu'à celui des inlandsis actuels: le relief rejoignait l'épaisseur de glace ou la dépassait et influençait grandement l'écoulement glaciaire. Sur l'inlandsis, les gradients du profil topographique se mesuraient en fractions de degrés, mais le long de la marge digitée, les gradients étaient par endroits plus prononcés. Le retrait à partir de la moraine frontale a au départ été graduel comme l'indiquent les moraines de retrait à quelques dizaines de kilomètres de la moraine frontale. Il y eut localement quelques récurrences mineures. L'inlandsis disparut avec le temps par stagnation à une échelle régionale et fonte en réponse à une hausse de la ligne de névé au-dessus de la surface de l'inlandsis. À l'échelle régionale, la déglaciation était terminée avant 10 ka BP environ.

ZUSAMMENFASSUNG *Die Kordilleren-Eisdecke im Gebiet des südlichen Yukon*. Die Kordilleren-Eisdecke in Yukon breitete sich strahlenförmig von den Eisscheiden der Seywyn-, Pelley- und Cassiar-Berge und den östlichen Küstenbergen aus und grenzte an einen Vorlandgletscher von den St. Elias-Bergen. Die Ausdehnung der Gletscher in den Eisscheiden-Gebieten könnte schon um 29 ka v.u.Z. eingesetzt haben; doch sind sie erst nach 24 ka v.u.Z. zu der Eisdecke verschmolzen. Die Firn-Linie sank auf etwa 1500m während des Höhepunkts der McConnell-Vereisung. Das Fliessen innerhalb der Eisdecke entsprach mehr einer Einheit verschmolzener Talgletscher als dem der noch vorhandenen Eisdecke: das topographische relief stimmt in beispielhafter Weise mit der Dicke des Eises überein, oder übertraf diese und beeinflusste sehr stark die Eisströmung. Auf der Oberfläche der Eisdecke betrug das Gefälle nur Bruchteile eines Grads. Steilere Eisoberflächengefälle gab es örtlich entlang des fingerförmigen Eisrands. Der Rückzug von der Endmoräne geschah anfangs graduell, was aus den einige 10 km von der Endmoräne entfernten Rückzugsmoränen hervogeht. Örtlich gab es einige kleinere Rückvorstösse. Die Eisdecke verschwand schliesslich durch regionale Stagnation und Abzehrung infolge eines Anhubs der Firnlinie über die Oberfläche der Eisdecke hinaus. Die regionale Enteisung war vor etwa 10 ka v.u.Z. vollendet.

* Geological Survey of Canada Contribution No. 57790

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INTRODUCTION

This paper is concerned primarily with the portions of the last Cordilleran Ice Sheet[1] that covered the Selwyn Mountains and contiguous areas of the Yukon Plateaus and parts of the Cassiar and eastern Coast Mountains in adjacent northern British Columbia (Fig. 1). This region is, with the exception of scattered cirque glaciers and local ice fields in the Itsi and Ragged Ranges of the Selwyn Mountains, essentially unglacierized and, assuming the present interglaciation is analogous to milder phases of the last (Reid/McConnell) one, it can be assumed that the last Cordilleran Ice Sheet developed following largely unglacierized conditions. This is in contrast to the portion of the ice sheet which can be better thought of as a piedmont lobe complex fed from expanded versions of ice caps in the St. Elias Mountains (Hughes, 1987) and similar high coastal ranges to the northwest in Alaska such as the Chugach and Wrangell Mountains and the Alaska Range (Hamilton and Thorson, 1983).

PHYSIOGRAPHY

The physiographic divisions of the southern Yukon are shown in Figure 1 after Mathews (1986). This area is dominated by the Yukon Plateaus, rolling upland surfaces ranging between 1000 and 2000 m in elevation. This surface ranges from partly dissected to extensively dissected by anastomosed valley systems eroded during preglacial and glacial times (Jackson, 1989). Valleys incised 500 m or more below the plateau surface are common. Yukon Plateaus are traversed by two large northwest-southeast valleys, Tintina Trench and Shakwak Trench. These two features are structurally controlled by the Tintina and Denali faults, respectively, and their secondary parallel splinter faults. Yukon Plateaus are flanked to the west by the glacierized St. Elias Mountains with peaks rising to 5900 m and to the east, south, and southwest by the Selwyn, Kaska, and eastern Coast Mountains, respectively. The Pelly and Cassiar mountains are the primary subdivisions of the Kaska Mountains in southern Yukon. The summits of the Selwyn, Cassiar and Pelly Mountains, locally rising to 2500 m, have been intensely glacially eroded and sculpted into classical alpine cirque, arête, and horn topography. The Selwyn and Kaska Mountains are separated from the northern Rocky Mountains by Liard Lowland, a broad apparently structurally controlled intermontane lowland. The Coast and St. Elias Mountains separate Pacific drainage from the Yukon River system, which flows to Bering Sea. The Kaska and Selwyn Mountains separate Yukon River drainage from tributaries to the Mackenzie River system which empties into the Arctic Ocean.

CLIMATE

The climate of Yukon is sub-Arctic continental (Wahl and Goos, 1987). Winters are long and bitterly cold and summers, at lower elevations, are short and mild. Mean annual temperatures range from −2°C in the south to −10°C in the far north. The mean monthly temperature of January, the coldest month is −25° to −35°C whereas July, the warmest month, ranges from 13° to 16°C along valley floors. However, snow can fall at any time during the year in alpine areas. Permafrost is widespread in the area. The Pacific Ocean is the primary source of moisture for Yukon. Two wet zones exist: one coincident with the St. Elias Mountains with total annual precipitation exceeding 2000 mm in divide areas, and a second interior wet zone coincident with divides in the Cassiar, Pelly and Selwyn Mountains where summits over 1900 m are widespread and total annual precipitation may exceed 700 mm (Fig. 2 A). The few locally extensive cirque glacier complexes and ice fields in the Selwyn Mountains occur above 1900 m in the Itsi and Ragged Ranges. Valley glaciers descending from these source areas reach elevations as low as 1500 m. Elsewhere, extant glacial ice is confined to small cirque and niche glaciers above 1900 m.

REGIONAL AND MULTIPLE GLACIATION IN YUKON

Current stratigraphic evidence (Table I) suggests that the last Cordilleran Ice Sheet is the latest of at least six that have periodically covered southern and central Yukon during the Pleistocene. The latest mantling of much of southern Yukon with glacial ice was well documented by the early 1890's through the efforts of geologist/explorers of the Geological Survey of Canada and the United States Geological Survey (Dawson, 1889; McConnell, 1890; Russell, 1890; Hayes, 1891). Evidence of multiple glaciation in central Yukon in the form of till beyond the limits of the last ice sheet was observed, but not correctly interpreted, at the turn of the century (McConnell, 1903). Four glaciations of central and southern Yukon were recognized by Bostock (1966) based upon morphostratigraphic, stratigraphic, and geomorphic evidence. These were named Nansen (oldest), Klaza, Reid, and McConnell (youngest). Although glacial landforms related to the two oldest and most extensive glaciations are everywhere subdued, deposits are locally extensive, notably in the Stewart River valley and Tintina Trench between the Stewart and Klondike rivers. However, discrimination between deposits of these glaciations is not usually possible. Their distributions are combined together as pre-Reid glaciation in Figure 3. In southwestern and west-central Yukon, Denton and Stuiver (1967) and Rampton (1971a) constructed glacial stratigraphies based upon lithostratigraphic and morphostratigraphic units respectively. A stratigraphy of multiple tills of Early to Middle Pleistocene age was constructed by Klassen (1987) in the Liard Lowland near the town of Watson Lake.

CHRONOLOGY AND MAGNITUDE OF PRE-McCONNELL GLACIATIONS

Deposits of the two pre-Reid glaciations are overlain or interfinger with basalts and hyaloclastites of the Selkirk Volcanics in the Fort Selkirk area (Table I). Paleomagnetic investigations and radiometric dating indicate that the two pre-Reid glaciations occurred more that 790 ka. The older of the two occurred more than 1.08 Ma (Naeser *et al.*, 1982; Jackson *et al.*, 1990). It is

1. The term "ice sheet" is used here because "Cordilleran Ice Sheet" is solidly established in the geologic literature. It will be shown in this paper that much of this ice sheet was a complex of merged valley glaciers strongly controlled by topography. Consequently, ice sheet is used in its broadest sense as a glacier that forms a continuous cover over a large area of the earth's surface.

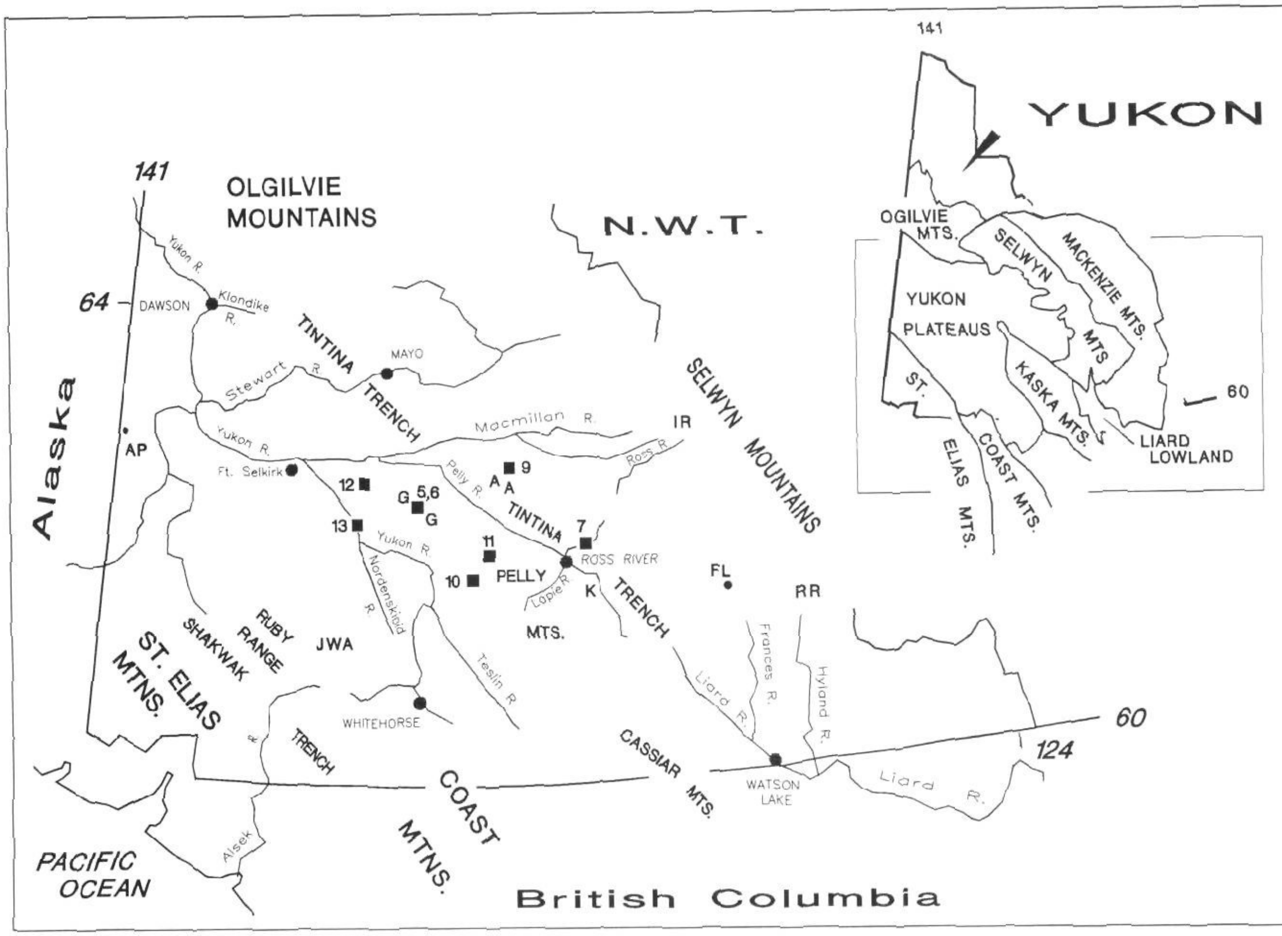

FIGURE 1. Physiography of southern Yukon and northernmost British Columbia. G. Glenlyon Range; JWA. Jarvis and Aishihik and West Aishihik valleys; FL, Finlayson Lake; RR. Ragged Range; IR. Itsi Range; K. Ketza River Fossil site. Small boxes and adjacent numbers indicate location and numbers of photographic figures.

Physiographie du sud du Yukon et de l'extrémité septentrionale de la Colombie-Britannique. G. Glenlyon Range; JWA. vallées des rivières Jarvis, Aishihik et West Aishihik; FL, Finlayson Lake; RR. Ragged Range; IR. Itsi Range; K. site fossilifère de Ketza River. Les carrés pleins et les numéros attenants donnent l'emplacement et les numéros des photographies.

not known if either of the pre-Reid glaciations correlate with the Shakwak Glaciation (southwestern Yukon) which lacks any absolute dating control.

On the other side of the Continental Divide, Klassen used K-Ar dating of interstratified basalts for constraining the ages of tills in Liard Lowland. These tills, with the exception of the Late Pleistocene (McConnell equivalent) till, were deposited during regional glaciations that apparently occurred during the time interval separating the Reid and the pre-Reid glaciations discussed above (Table I). The extent of glacial ice cover during these glaciations, compared to that of the McConnell Glaciation in the Liard Lowland, region is not known. However, the glacial cover west of the Continental Divide in central Yukon must have been less extensive than that of the subsequent Reid Glaciation as no traces of these glaciations survive.

Reid Glaciation and equivalent Icefield and Mirror Creek glaciations occurred prior to 80 ka BP ago on the basis of minimum ages of tephras that overlie deposits of these glaciations (Hughes *et al.*, 1989). However, the fresh nature of Reid deposits indicates that the Reid Glaciation is likely Illinoian in age although an Early Wisconsinan age cannot be completely ruled out (Hughes *et al.*, 1989; Jackson *et al.*, 1990). The Reid ice sheet had an extent intermediate between those of the pre-Reid and McConnell glaciations in central Yukon. The equivalent advance in the Snag-Klutlan area was the most extensive known[2].

McCONNELL GLACIATION

The latest (McConnell) glaciation was Late Wisconsinan in age (Klassen, 1987; Matthews *et al.*, 1990; Jackson and

2. The lack of glacial drift equivalent in age to the pre-Reid drift beyond the Mirror Creek limit and the significantly greater extent of pre-Reid drift compared to the Reid and McConnell drift in central Yukon may be linked. The St. Elias Mountains, with summit elevations exceeding 5000 m, have experienced considerable uplift during the late Tertiary and Quaternary. For example, tillites deposited in intermontane and marine environments during the Miocene and Pliocene crop out to elevations of 2000 m in the St. Elias Mountains (Denton and Armstrong, 1969). Consequently, St. Elias Mountains could have been significantly lower during the late Pliocene/early Pleistocene pre-Reid glaciations. If this was the case, lower elevation might be expected to have had the combined effect of trapping less moisture within the St. Elias Mountains resulting in smaller ice sheets there and larger ice sheets in the interior of the Yukon as compared to the later Reid and McConnell glaciations.

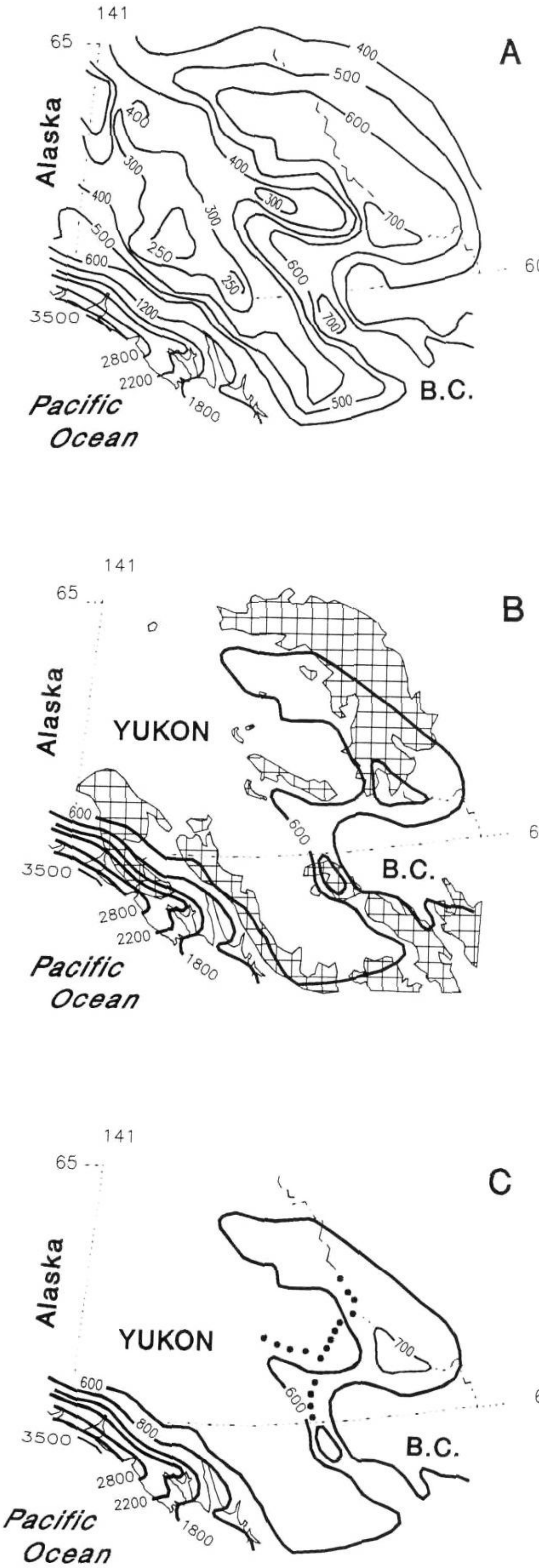

FIGURE 2. A. Isohyet map (mm) of southern Yukon and northern British Columbia; B) ≥ 600 mm isohyets superimposed on areas containing summits with elevations ≥ 1900 m (cross-hatched pattern); C) Contemporary ≥ 600 mm isohyets superimposed upon the generalized divide (dotted line) separating the Selwyn and Cassiar lobes, which advanced into the Yukon River basin, from the Liard lobe and other glaciers which advanced into the Mackenzie River basin (contemporary climatic data from Wahl and Goos, 1987).

A. Cartes des isohyètes (mm) dans le sud du Yukon et dans le nord de la Colombie-Britannique. B) Isohyètes de ≥ 600 mm superposées aux régions dont certains sommets sont à des altitudes ≥ 1900 m (quadrillage); C) Isohyètes contemporaines de ≥ 600 mm superposées à la région de l'interfluve séparant les lobes de Selwyn et de Cassiar, qui ont progressé vers le bassin du Yukon, du lobe de Liard et d'autres glaciers qui eux progressaient vers le bassin du Mackenzie (données climatiques de Wahl et Goos (1987).

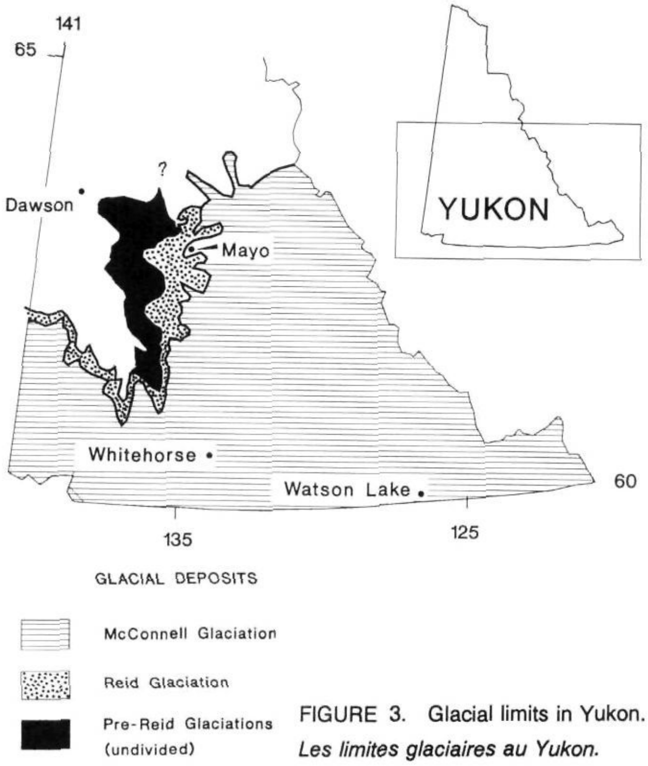

FIGURE 3. Glacial limits in Yukon.

Les limites glaciaires au Yukon.

Harington, 1991). This last Cordilleran Ice Sheet was the least extensive of known Yukon regional glaciations (Fig. 3). Further comments on the chronology of the ice sheet growth and decay will be made later in this paper.

CLIMATIC CONTROLS ON ICE SHEET GROWTH

The climatic factors that controlled the seeding and growth of the Cordilleran Ice Sheet in southern Yukon can be deduced through reconstruction of flow patterns and divides within it and comparison of the reconstructed ice sheet with contemporary climatic variables. The main controls that influence Yukon's present climate include latitudinal effects, proximity to the Pacific Ocean and topography (Wahl and Goos, 1987). Yearly solar insolation patterns vary markedly with latitude. Nearly continual darkness persists over much of the winter north of the Arctic Circle whereas continuous daylight characterizes the summer months. The contrast between these extremes

TABLE I

Glacial stratigraphy of southern Yukon (modified from Hughes et al., *1989)*

Age	Yukon Plateau	Snag-Klutlan Area	Shakwak Trench (Silver Creek)	Southern Olgivie Mountains	Liard Lowland
	(Bostock 1966; Hughes *et al.* 1989; Jackson *et al.* 1990; Jackson and Harington in press)	(Rampton 1971)	(Denton and Stuiver 1967)	(Vernon and Hughes 1966)	(Klassen 1987)
HOLOCENE	Postglacial (Stewart soil)	Neoglaciation Slims Nonglacial Interval	Neoglaciation		
		13.7 ka BP	12.5 ka BP		
PLEISTOCENE	McConnell Glaciation	Macauley Glaciation	Kluane Glaciation	Last glaciation	Glaciation
	Diversion Creek soil Sheep Creek Tephra (*ca.* 80 ka)	Old Crow Tephra (80-130 ka)	Boutellier nonglacial interval		Non glacial
	Reid Glaciation	Mirror Creek Glaciation	Icefield Glaciation	Intermediate glaciation	Glaciation
	Wounded Moose soil		Silver nonglacial interval		Non glacial 232 ± 21 Glaciation 545 ± 46 Glaciation
	790 ka				
	Klaza Glaciation		Shakwak Glaciation?		
	Nonglacial (Fort Selkirk Tephra > 1 Ma)				
	Nansen Glaciation		Shakwak Glaciation?		

decreases southward. The wettest zones correspond to the highest mountain elevations along major drainage divides and proximity to the Pacific Ocean. The Arctic Ocean is essentially ice-covered all year and contributes little moisture. The northern and western limits of glaciation portrayed in Figure 3 reflect progressive decreases in precipitation due to the synergetic effects of increasing aridity with increasing distance from the Pacific Ocean and rain shadow effects and progressively decreasing elevation.

Figure 4 is a reconstruction of features of the Cordilleran Ice Sheet in southern Yukon south of latitude 63° and east of the piedmont lobe complex derived from the St. Elias Mountains. It shows ice-flow directions, nunataks, and cirque complexes. The paleo-firn line fell as low as 1500 m based upon the elevations of the floors of the lowest cirques that supported cirque glaciers during McConnell Glaciation in the Ruby Range (Denton and Stuiver, 1967, p. 488-490), Ogilvie Mountains (Vernon and Hughes, 1966, and maps therein) and Glenlyon Range (Fig. 5 and 6; Campbell, 1967, and map GSC 1222A therein).

Although the paleo-firn line determined the minimum elevation of glacier formation, the seeding and growth of the ice

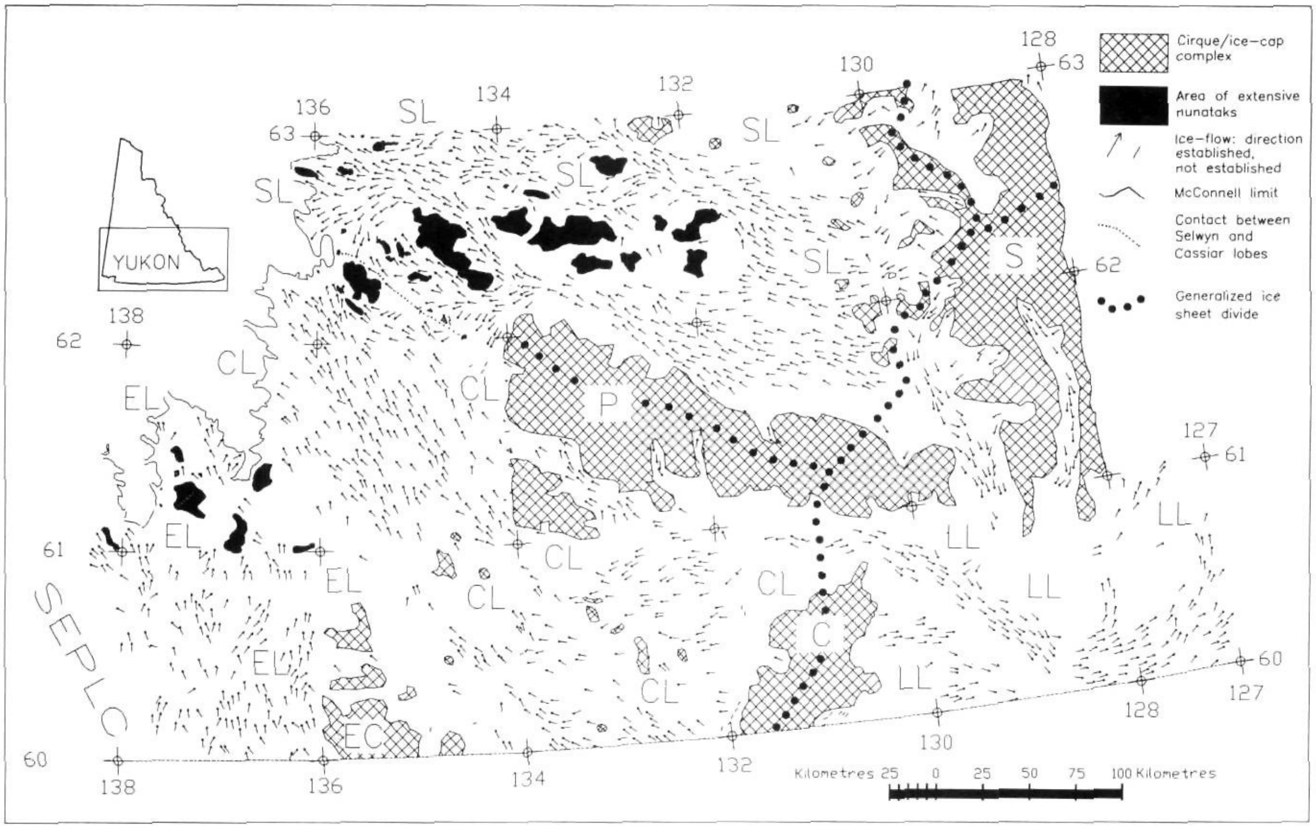

FIGURE 4. Ice-flow directions and ice-limits of the Cordilleran Ice Sheet in southern Yukon (generalized from Jackson and Mackay, 1991). SPELC. St. Elias piedmont lobe complex; EL. Eastern Coast Ranges Lobe; EC. Eastern Coast Ranges; CL. Cassiar Lobe; C. Cassiar Mountains; P. Pelly Mountains; SL. Selwyn Lobe; S. Selwyn Mountains; LL. Liard Lobe. The boundaries between the Eastern Coast Mountain Lobe and the Cassiar Lobe and St. Elias piedmont lobe complex have not been defined.

Directions de l'écoulement glaciaire et limites glaciaires de l'Inlandsis de la Cordillère dans le sud du Yukon (généralisées à partir de Jackson et Mackay, 1991). SPELC. complexe du lobe de piémont St. Elias; EL. lobe de l'est de la chaîne Côtière; EC. est de la chaîne Côtière; CL. lobe de Cassiar; C. monts Cassiar; P. monts Pelly; SL. lobe de Selwyn; S. monts Selwyn; LL. lobe de Liard. Les limites entre les différents lobes n'ont pas été définies.

FIGURE 5. Glenlyon Range, a former nunatak which protuded through the Selwyn Lobe (looking north). Black lines mark the former upper limit of the Selwyn Lobe at approximately 1500 m. The range was free of ice except for scattered cirque glaciers and protuberances of the Selwyn Lobe into valleys (See Fig. 6). NAPL T7-132L.

Glenlyon Range, un nutatak qui perçait le lobe de Selwyn (vue vers le nord). Les traits noirs montrent la limite supérieure du lobe de Selwyn, à environ 1500 m. La chaîne n'était pas englacée sauf pour quelques glaciers de cirque épars et des segments du lobe de Selwyn dans les vallées (voir fig. 6). PNA T7-132L.

sheet appear to have been controlled by precipitation patterns very close to those of today (Fig. 2C). The contemporary 600 mm isohyet (Fig. 2) outlines the major north-south trending divides in the ice sheet shown in Figure 4.

PALEOGLACIOLOGY OF THE CORDILLERAN ICE SHEET IN THE STUDY AREA DURING McCONNELL GLACIATION

Hughes *et al.* (1969) assigned names to semiautonomous sectors of the Cordilleran Ice Sheet in southern Yukon. These sectors (eastern Coast Mountains, Selwyn, Cassiar and Liard lobes) are shown in Figure 4. The Selwyn lobe flowed west from Selwyn Mountains and shared a common ice divide with the Liard lobe in the area of Finlayson Lake. The Cassiar lobe flowed west and northwest from the Cassiar Mountains. It was separated from the Selwyn lobe by the Pelly Mountains. The Liard lobe flowed south from the Selwyn Mountains and southeast and east, respectively, from the Pelly and Cassiar Mountains. The Pelly Mountains supported complexes of ice caps which shed ice to the Cassiar and Selwyn lobes as well. The eastern Coast Mountains lobe, which flowed northwestward from the summits of the Eastern Coast Mountains in northwestern British Columbia, was mid-way between the pied-

FIGURE 6. Cirque moraine in the Glenlyon Range. Arête ridges and cirque rims are denoted by toothed lines; ice-limits during the last glaciation (McConnell Glaciation) are denoted by lines ornamented by dots. Pre-McConnell glaciation ice limits are denoted by ornamented lines. Cirques 1 and 2 (floor elevations approximately 1680 and 1540 m, respectively) contained a small glacier which reached limit A (elevation 1460 m) at the climax of the last glaciation. Ice apparently did not advance from adjacent cirque 3. B marks the limit of a small tongue of the Selwyn Lobe which advances into the Glenlyon Range (arrows indicated the direction of advance). C marks the limit of an older, probably Reid-age cirque advance; partial stereogram, NAPL T10-122C).

Moraine de cirque dans Glenlyon Range. Les crêtes d'arête et les rebords des cirques sont identifiés par des barbules. Les limites glaciaires de la dernière glaciation (Glaciation de McConnell) sont données par les traits à points. Les limites de la glaciation de pré-McConnell sont indiquées par les courbes. Les cirques nos 1 et 2 (altitudes des fonds à 1680 et à 1540 m) renfermait un petit glacier qui a atteint la limite A (altitude de 1460 m) à l'optimum de la dernière glaciation. Il semble qu'il n'y ait pas eu d'avancée glaciaire à partir du cirque n° 3. B donne les limites d'une petite langue glaciaire du lobe de Selwyn qui a progressé vers le Glenlyon Range (la flèche donne la direction). C. donne la limite d'une avancée d'un cirque plus ancien probablement pre-Reed (stéréogramme partiel, PNA T10-122C).

mont lobe complex originating in the St. Elias Mountains and the Cassiar lobe.

ICE FLOW DURING ONSET OF McCONNELL GLACIATION

Little is known about the pattern of ice flow during the initial stages of McConnell Glaciation. What is known has been gleaned from sediments in Tintina Trench where extensive natural exposures occur. Plouffe (1989) determined fabrics and clast compositions through vertical profiles of McConnell till in Tintina Trench at the mouth of the Lapie River valley near the village of Ross River (Fig. 1). He noted changes in fabrics and pebble contents compatible with an initial north-directed advance of a valley glacier from Pelly Mountains, followed by flow to the northwest parallel to Tintina Trench as valley glaciers merged to form the Selwyn lobe. This pattern likely was repeated throughout the study area with glacial onset along the lines of the model for Cordilleran glaciation documented by Kerr (1934) and Davis and Mathews (1944): glaciers formed and expanded in upland areas such as the Pelly, Selwyn and Cassiar Mountains, with descent of the firn line to approximately 1500 m. Valley glaciers expanded beyond the mountains into lower lying areas thickening and merging in the process to form an ice sheet.

Striated gravel and bedrock below McConnell till documents basal sliding of wet-based glacial ice throughout the southern Yukon. However, scattered evidence exists to suggest cold-based conditions existed locally; folded and thrust-faulted gravels and sheared and drag folded glaciolacustrine sediments are common below the McConnell till (McConnell, 1906, p. 59; Klassen, 1989, p. 147-189; Fig. 7). Such structures have been investigated elsewhere (Moran *et al.*, 1980; Thomas, 1984) and the conditions favourable to their formation have been attributed to pore pressures sufficiently large to reduce effective normal stress in sediments below the glacial sole to values less than glacially induced shear stress (approximately 1 bar; Eyles, 1983a, p. 39-41). Models for the generation of these high pore pressures involve restricting subglacial drainage through the freezing of the glacial sole to its substrate in advance of wet-based ice flow (Moran *et al.*, 1980; Mooers, 1990) or freezing of the glacier sole to its bed due to ice accumulation and flow dynamics (Eyles, 1983a, p. 20-23). The former conditions would be expected during glacial onset as the relatively thin and easily chilled margins of glacial ice advanced over permafrost terrain (Eyles, 1983a, p. 21).

ICE-FLOW AT THE CLIMAX OF McCONNELL GLACIATION

The maximum McConnell terminus of the Cordilleran Ice Sheet in southern Yukon is marked by well preserved moraines and sharply incised ice-marginal channels (Bostock, 1966; Campbell, 1967 Hughes; *et al.*, 1968). Nunataks were particularly abundant in the Selwyn lobe and were distributed from the margin to approximately two thirds of the way to the glacial divide in the Selwyn Mountains, a distance of approximately 200 km from the ice terminus (Figs. 4, 8 and 9; Duk-Rodkin *et al.*, 1986; Jackson, 1989; Jackson and Mackay, 1991). Upper ice limits on these nunataks are defined by moraines, ice-marginal meltwater channels, and the lower limits of craggy periglacial landforms (McConnell, 1906; Hughes, 1990, p. 6). These well defined terminal and nunatak ice limits were used to construct a generalized profile of the maximum limits of the former ice sheet over a distance of 114 km from the ice front using the elevations of the locally highest ice-marginal features

FIGURE 7. Thrusted and folded gravels beneath McConnell Glaciation till. Some bedding planes have been accentuated by lines in order to better delineate deformed beds.

Lits de graviers faillés et pliés sous-jacents au till de la Glaciation de McConnell. On accentué certains plans de stratification afin de souligner les couches déformées.

(Fig. 8)[3]. The generalized ice surface profile has an average slope of 0.5° over the outermost 50 km, 0.3° over the next 52.5 km and 0.05° farther east. Slopes in the profile have not been corrected for isostatic rebound. This generalized profile is most representative of actual ice surface gradients over the outer (westernmost) 50 km where the profile lines are roughly parallel to flow directions. Farther east, the profile lines intersect flow lines at about 30° and tend to indicate lower gradients than actually existed. For example, ice limits descend from approximately 1890 m to 1550 m parallel to the ice-flow direction between nunataks 115 km and 200 km inboard from the ice-terminus[4]. This yields an overall gradient of 4 m/km or 0.2° over this distance. Former nunataks were not recognized farther inboard. However, cirque and arête landforms are nonexistent below 1980 m elevation in the area of the divide of the Selwyn lobe with ice draining toward the Mackenzie Valley in the Selwyn Mountains (Jackson, 1987). This probably approximates the elevation of the ice sheet at the divide.

The flow of the ice sheet was controlled strongly by topography: ice flowed along major valleys, bifurcated around nunatak areas, rejoined and finally divided into a digitate terminal zone[5]. This topographically directed, merging ice flow is documented by flow indicators such as whale-backs and crag-and-tails which provided most of the flow directional data displayed in Figure 4. They indicate that flow occurred as merging ice streams which followed major valleys such as Tintina Trench, and the South MacMillan, Big Salmon, Little Salmon, Frances, Hyland, Teslin/Yukon, and Nordenskiold river valleys. Extensively streamlined topography is infrequent outside of these valleys. The absence of these streamlined landforms indicates that ice flow may have been comparatively sluggish in secondary valleys, especially in those located in ranges which were transverse to the regional ice-flow direction.

The areas of most complicated ice flow were likely in divide areas of the Pelly, Cassiar and Selwyn Mountains. Numerous divides likely existed between ice caps in these rugged mountains (Jackson, 1987). However, ice directional features are not well preserved and distinctive rock types with small aerial extents, which might be used as trace indicators, are not common (Jackson, in press).

Away from divide areas, ice-flow gradients varied due to flow bifurcation and reunion. Notable differences in ice elevations Lacross nunataks (Fig. 9) likely reflect superelevation of the ice surface due to compressive flow on the stoss side of nunataks and relative depression on their lee side.

COMPARISON WITH EXTANT ICE SHEETS

The overall profile of the Selwyn lobe and, by inference, the rest of the Cordilleran Ice Sheet in Yukon[6] excluding the St. Elias Mountains and adjacent areas of its piedmont lobe complex, was flatter than profiles of the contemporary Greenland and Antarctic ice sheets (Paterson, 1969, p. 145-162; Duk-Rodkin *et al.*, 1986). The best numerical approximation to the measured profile is the curvilinear profile of a valley glacier modelled by Shilling and Hollin (1981), after Nye (1952a, 1952b). This finding is not surprising since flow in the Selwyn lobe was similar to flow in a valley glacier: shear stress not only occurred along the sole of the ice sheet but also along the sides of high relief roughness elements, *i.e.* valley and mountain sides (Eyles, 1983b, p. 91-96).

Ice flow was channelled entirely by underlying topography rather than predominantly independent of it, as is largely the case in the contemporary ice sheets of Greenland (Flint, 1971, p. 51-54; Reeh, 1989) and Antarctica (Denton *et al.*, 1971). Consequently, the Cordilleran Ice Sheet within the southern Yukon never exceeded phase 3 of the Cordilleran glaciation model of Davis and Mathews (1944).

3. The data shown in Figure 8 have a vertical scatter, particularly near the terminus of the ice sheet. The scatter corresponds to distortion in the distribution of the data points caused by the manner of plotting, in which points within a north-south belt, 100 km wide, were projected onto a single east-west plane. Within the belt, the flow direction varied as much as 50° from the generalized westward flow (Campbell, 1967) and represents several merging flows.

4. The locations of the nunataks are 62.7°N, 134°W and 62.3°N, 132°W.

5. This merging valley glacier model is not new. It was first suggested by Johnston (1926) for the Cordilleran Ice Sheet in northern British Columbia.

6. Observations from the area of the Selwyn lobe apply to the areas of the Liard and Cassiar lobes where similar sharply defined ice limits on former nunataks are not abundant; both lobes descended from and traversed common and comparable terrain.

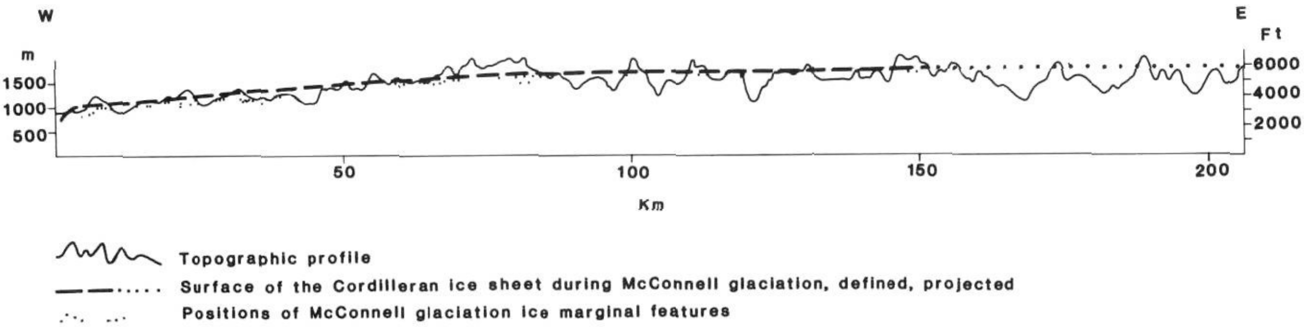

FIGURE 8. Generalized topographic profile oriented east-west showing the upper limit of Selwyn Lobe. The profile was constructed by projecting eight separate east-west profiles onto a single plane between latitudes 62° and 63° N and longitudes 137° and 132° W (vertical exaggeration × 6). The fine dots on the section are positions of ice marginal features used to construct the section (modified from Duk-Rodkin *et al.*, 1986).

Profil topographique généralisée est-ouest montrant la limite supérieure du lobe de Selwyn. La reconstitution du profil a été faite par la projection de huit différents profils est-ouest sur un seul plan entre 62 et 63° de latitude N et 137 et 132° de longitude W (exagération verticale × 6). Les points sur le profil donnent l'emplacement des formes de marge glaciaire qui ont servi à reconstituer le profil (modifié à partir de Duk-Rodkin et al., *1986).*

FIGURE 9. View north of a former nunatak (summit elevation 1800 m) in the Anvil Range defined by moraine ridges (marked by dashed lines). The moraine on the north (stoss) side of the nunatak is 30 m higher than the moraine on the south side, likely due to compressive flow. Arrows indicate high elevation, ice stagnation landforms similar to those seen in Figure 10. The distinctive dentritic drainage patterns have developed in the deposits of a former ice-dammed lake formed during the downwasting of the Selwyn Lobe (NAPL T10 140L).

Vue vers le nord d'un nunatak (altitude de 1800 m) dans le Anvil Range délimité par des crêtes morainiques (tirets). La moraine sur le côté nord (en pente douce) du nunatak est de 30 m plus élevée que la moraine du côté sud, probablement en raison d'un écoulement en compression. Les flèches montrent des formes de stagnation glaciaire de haute altitude comme celles de la figure 10. Le réseau de drainage dendritique dans le fond de la vallée s'est formé dans les dépôts d'un ancien lac de barrage glaciaire qui s'est formé durant la fonte du lobe de Selwyn (PNA T10 140L).

DISAPPEARANCE OF THE CORDILLERAN ICE SHEET

The Cordilleran Ice Sheet disappeared rapidly at the close of McConnell Glaciation through a combination of downwasting and stagnation. Many cirques in Selwyn and Pelly Mountains have ice stagnation landforms on their floors which are continuous with similar features in adjacent valleys (Fig. 10; Jackson, 1987). It can be concluded from these relationships that ice stagnated in these cirques during or prior to stagnation in adjacent valleys. These stagnation features occur up to 1830 m elevation in the Pelly and Selwyn Mountains. Consequently, it appears that early in the deglaciation of the Selwyn lobe and by inference, the Cordilleran Ice Sheet in southern Yukon, the firn line rose significantly above 1830 m elevation and remained above 1830 m until the present day. This rise in the firn line resulted in the wholesale starvation of the ice sheet. The resulting thinning of the ice sheet is documented by flights of former ice-walled channels along many valley sides (Fig. 11).

Recessional moraines occur only within a few kilometres of the McConnell limits in the Yukon drainage basin and are usually only apparent where the ice margin was pressing

FIGURE 10. Crevasse fillings and small eskers (unornamented solid lines), Pelly Mountains. These features are distributed from cirques floors (*ca.* 1370-1520 m) to the floors of adjacent valleys (elevations *ca.* 1310-1370 m). Flights of former ice-walled channels are denoted by dotted lines. Cirque rims and arête ridges are denoted by toothed lines (partial stereogram).

Remblais de crevasses et petits eskers (soulignés par les traits fins) dans les monts Pelly. Ces formes de stagnation glaciaire sont réparties sur les fonds des cirques (environ 1370 à 1520 m) et des vallées adjacentes (altitudes entre 1310 et 1370 m). Une série de paléochenaux glaciaires est soulignée par les pointillés. Les rebords des cirques et les crêtes d'arête sont délimités par des barbules.

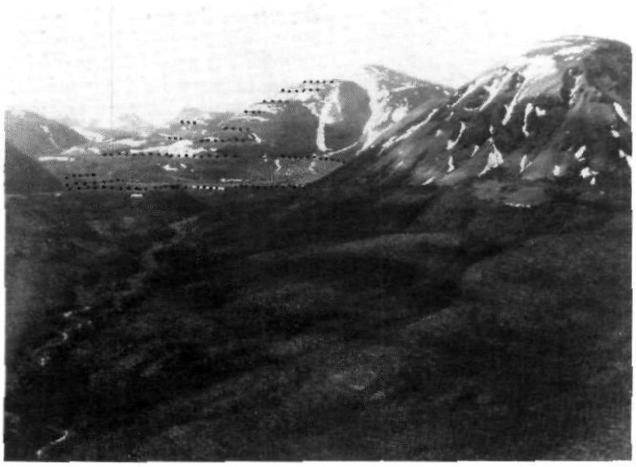

FIGURE 11. Flights of former ice marginal channels descending from 1670 to 1220 m in the headwaters of Magundy River, Pelly Mountains. The channels have been accentuated with dotted lines.

Séries d'anciens chenaux (pointillés) de marge glaciaire passant de 1670 à 1220 m à la source de la Magundy River, dans les monts Pelly.

against an upland (Fig. 12). Stratigraphic evidence for an apparently local readvance of unknown extent has been noted in the Yukon valley directly below Five Finger Rapids, 15 km inboard of the McConnell limit (Fig. 13). Here, in a 60 m exposure, till ascends over and pinches out into massive outwash gravels. The till/gravel contact is striated and the gravels underlying the till in the area of pinchout have been deformed into thrust-faulted and overturned folds presumably by the readvance. The till is, in turn, overlain by thick lacustrine sediments which can be traced up to five kilometres up adjacent valleys and locally exceed 50 m in thickness. The readvance apparently dammed this area of the Yukon River valley forming an extensive lake in the process.

Stratigraphic evidence for local readvance is also found in Jarvis, Aishihik, and West Aishihik valleys (Fig. 1; Hughes, 1990). In West Aishihik valley, the infered readvance was a minimum of 4 km. Ice in Aishihik and West Ashihik valleys was derived from the eastern Coast Mountains lobe; Jarvis valley is near the juncture of that lobe and the St. Elias Mountains piedmont lobe complex.

East of the Continental Divide, a more classical pattern of ice retreat has been documented during the last phase of the Liard lobe in the upper Frances and Hyland river basins (Dyke, 1990). Although the pattern of ice retreat was complicated, valley glaciers which headed in the Ragged Range and adjacent ranges retreated leaving conspicuous lateral and end moraines in their wake. This apparent persistence of active ice flow in this area until the last phase of deglaciation is attributable to the high elevations of the Ragged and adjacent ranges (2000-2500 m); these are among the highest range in the Selwyn Mountains, and receive attendant high precipitation (Fig. 2). As a result, the Ragged Range supports extensive contemporary icefields.

The style of deglaciation of the Liard lobe beyond these exceptional alpine areas is yet to be investigated in detail.

SUCCESSION OF ICE-DAMMED LAKES IN THE INTERIOR OF THE SELWYN LOBE

The succession of progressively lower and younger lakes ponded within the Pelly Mountains, Anvil and South Fork Ranges and Tintina Trench during downwasting (Jackson, 1989) is illustrated in Figure 14. The mechanisms by which some of these lakes were ponded is problematic if the ice sheet is viewed as downwasting in a uniform fashion, with the cirques free of ice before the valleys. Thicknesses of more than 50 m of thinly and rhythmically bedded glaciolacustrine fine sands and silts in many locations require that substantial ice dams be placed across valley mouths in order to produce depths of

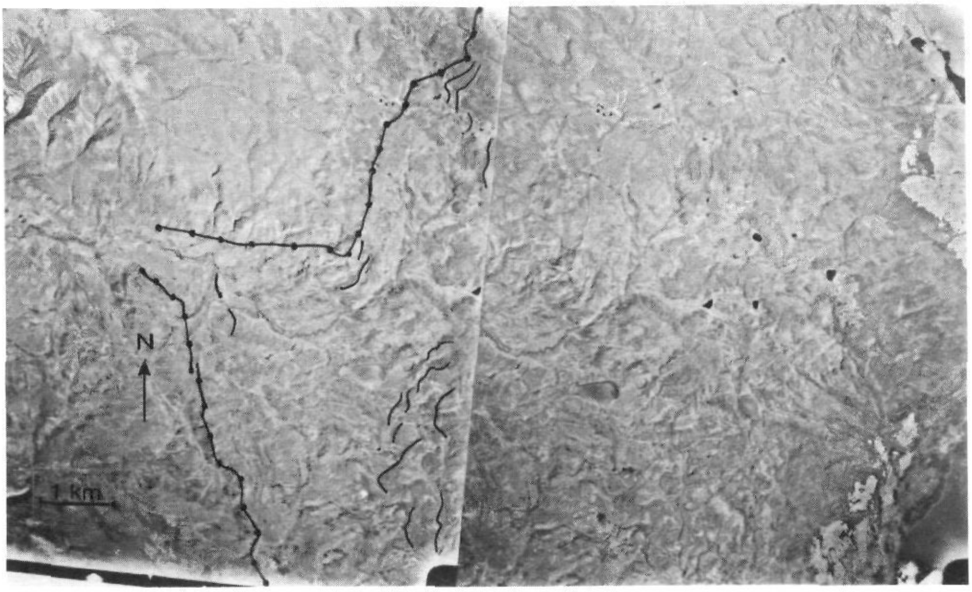

FIGURE 12. Part of the digitate terminal moraine of the Selwyn Lobe denoted by ornamented lines. The unornamented lines mark retreatal moraine ridges. These are found where the ice sheet impinged on uplands and within a few kilometers of the terminal moraine.

Partie de la moraine frontale digitée du lobe de Selwyn (trait à points). Les traits fins montrent les crêtes morainiques de retrait. On les trouve là où l'inlandsis a atteint les hautes terres et à quelques kilomètres de la moraine frontale.

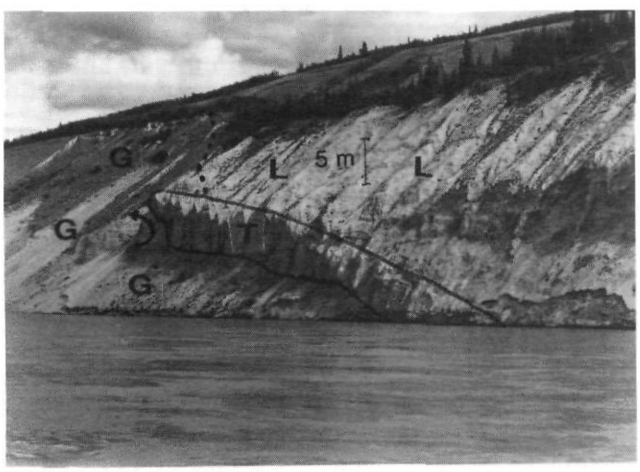

FIGURE 13. Till pinchout and tectonized subtill gravels, near Five Finger Rapids. Yukon River is in the foreground. L. Glaciolacustrine sediments; G. glaciofluvial gravels; T. till. Arrow indicates direction of overturning of gravel beds.

Lentille de till et graviers tectonisés sous-jacents au till, près de Five Finger Rapids. Au premier plan, le fleuve Yukon. L. Sédiments glaciolacustres; G. graviers fluvioglaciaires; T. till. La flèche donne la direction du renversement des couches de graviers.

closure sufficient to pond lakes more than 50 m deep. Periodic thickening of ice margins due to surging of trunk glaciers within major valleys such as Tintina Trench is one mechanism which could account for ponding of some of these lakes without requiring a readvance of the entire ice sheet during deglaciation.

The one locality where an ice-flow reversal has been documented is the Lapie River valley within the Pelly Mountains immediately adjacent to Tintina Trench. An extensive lake with a maximum surface level of between 1040 and 1080 m was ponded in this area. Plouffe (1989) found clasts of South Fork Volcanics crystal tuff 9 km upstream of Tintina Trench. The nearest outcrop of these rocks is tens of kilometres north of Tintina Trench. These clasts could only have been carried into the Lapie River valley by southward ice-flow into the Pelly Mountains from the lowlands of Tintina Trench.

Successions of formerly ice-dammed lake basins have been mapped only within the former limits of Selwyn and Cassiar lobes in the Pelly Mountains and adjacent areas of Yukon Plateaus. Further investigations in southern Yukon will be required in order to determine if these are local or regional phenomena.

CHRONOLOGY OF THE LAST CORDILLERAN ICE SHEET

Only a fragmental chronology can be assembled to document the growth of the Cordilleran Ice Sheet in Yukon. The oldest evidence for what might have been the onset of glaciation in Selwyn Mountains comes from the Mayo area. A radiocarbon age of 38,100 ± 1330 BP (GSC-4554; Matthews *et al.*, 1990) has been determined on a buried stump in growth position in an exposure along Stewart River[7]. The stump is rooted and buried within sands, silts and organic sediment reflecting a fluvial environment comparable with the contemporary meandering Stewart River. Analysis of pollen from these sediments indicates that an extensive forest cover existed in the area at that time (Matthews *et al.*, 1990). By 29,600 ± 300 BP (TO-292), trees had disappeared from the Mayo area and a periglacial climate was well established (Matthews *et al.*, 1990). This indicates a depression of the tree line by approximately 850 m and a mean July temperature at least 5°C colder than today (Matthews *et al.*, 1990). These climatic conditions are corroborated by a similar climatic record for the same period from Antifreeze Pond in west-central Yukon near the Alaska border (Rampton, 1971b). The unit at Mayo that yielded the 29.6 ka BP age is composed of dark organic silts, sands and organic detritus and is presumed to indicate an overbank depositional environment. It is overlain by gravels and trough cross-

7. Four other presently unpublished ages have been determined on wood from this stump by the Radiocarbon Dating Laboratory of the Geological Survey of Canada. They range between 33.7 and 36.8 ka BP (R. McNeely, personal communication, 1991).

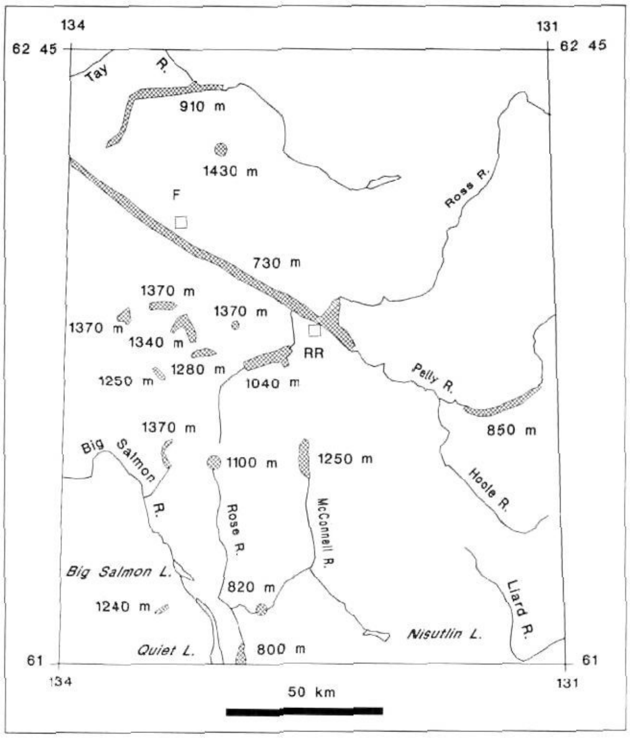

FIGURE 14. Elevations of ice dammed lakes, South Fork Range to Pelly Mountains. RR. village of Ross River; F. Town of Faro.

Altitudes des lacs de barrage glaciaire, du South Fork Range aux monts Pelly. RR. village de Ross River; F. ville de Faro.

bedded sands capped by till, reflecting proglacial and glacial sedimentation, respectively (Matthews *et al.*, 1990). Taken as a whole, the record in the Mayo area records climatic deterioration after 38.1 ka with climatic conditions conducive to or reflecting glaciation in the Selwyn Mountains to the east by 29.6 ka. The area was invaded by glacial ice sometime after this.

Bone-bearing gravels and colluvium beneath McConnell till immediately adjacent to the Pelly Mountains along Ketza River have been radiocarbon dated at 26,350 ± 280 BP (TO-393; Jackson and Harington, 1991). This age indicates that glacial ice had not expanded out of the Pelly Mountains, a centre of ice accumulation, by that time. At Tom Creek in the Watson Lake area, ice-free conditions persisted until at least 23,900 ± 1140 BP (GSC-2811; Klassen, 1987).

It can be inferred from the Mayo, Ketza and Tom Creek records that, whereas expansive glaciers may have existed in mountainous areas of eastern Yukon as early as 29 ka BP, montane valley glaciers did not advance into major valleys before *ca.* 26 ka BP and a full-bodied ice sheet did not come into being until after 23 ka BP.

Ages documenting the disappearance of the Cordilleran Ice Sheet in Yukon are also sparse. A radiocarbon age of 13,660 ± 180 (GSC-1110) was determined on organic-rich silt in lacustrine sediments in the terminus area of the St. Elias Mountains piedmont lobe complex in west-central Yukon by Rampton (1971a). This indicates that retreat from the terminal position had begun in this area before that time. Shell from marl 120 km inboard from the terminus of the Selwyn lobe in the Pelly River basin yielded an age of 12,590 ± 120 (TO-931; Ward, 1989) indicating extensive retreat by this time. This age must be regarded with caution since freshwater shells have been shown to provide unreliable radiocarbon ages (Clague, 1982). Radiocarbon ages from the Continental Divide area of Selwyn Mountains indicate that ice had disappeared from that area by 9 ka BP (Jonasson, *et al.*, 1983; MacDonald 1983).

SUMMARY AND CONCLUSIONS

Regional glaciation of Yukon Territory has occured at least six times during the Pleistocene. The last Cordilleran Ice Sheet advanced from the Selwyn, Pelly and Cassiar and eastern Coast Mountains in east-central and south-central Yukon. These uplands were likely free of glacier ice during the preceding interglaciation. In southwestern Yukon, the Cordilleran Ice Sheet coalesced with a piedmont lobe complex emanating from an ice cap covering the St. Elias Mountains. This ice cap likely persisted through the preceding interglaciation due to the greater altitude and precipitation levels of this mountain range compared to those farther east.

Ice-sheet growth was influenced by the same factors that govern contemporary precipitation patterns: principally topography and proximity to the Pacific Ocean. Former ice-sheet divides can be related to the contemporary 600 mm isohyet east of the St. Elias Mountains.

Ice sheet growth followed the stages described by Kerr (1934) and Davis and Mathews (1944): glaciers formed and expanded in upland areas such as the Pelly, Selwyn and Cassiar Mountains as the firn line descended to approximately 1500 m. Valley glaciers expanded beyond the mountains into low-lying areas, thickening and merging in the process to form an ice sheet. Ice flow was wet-based although some cold based flow did apparently occur locally, based upon the interpretation of glaciotectonic structures observed in the Pelly River basin.

Ice thickness was approximately equal to local topographic relief over most of the ice sheet. Consequently, nunataks were common and topography always controlled ice flow. This is in contrast to the contemporary ice sheets of Greenland and Antarctica where ice thickness exceeds greatly the underlying topographic relief. The ice sheet can best be conceptualized as a complex of merged valley glaciers.

The Cordilleran Ice Sheet disappeared rapidly at the close of McConnell Glaciation through a combination of downwasting and stagnation. Early in the deglaciation, the firn line rose significantly above 1830 m elevation and has remained above 1830 m until the present day. This rise in the firn line above ice sheet resulted in the wholesale starvation of the Cordilleran Ice Sheet exclusive of the ice cap in the St. Elias Mountains. Stagnation and downwasting is documented by flights of ice-walled channels and glacially dammed lakes. Small readvances have been documented only at the ice sheet terminus. Ice remained mobile longest in major valleys where it was initially thickest and flow locally reversed into upland valleys.

Only a fragmental chronology can be assembled to document the growth of the Cordilleran Ice Sheet in Yukon. Paleoclimatic evidence suggests that climatic conditions conducive to or reflecting glaciation existed by *ca.* 29.6 ka.

Glacial cover was confined to mountainous areas until after *ca.* 26 ka, and the full-bodied ice sheet developed only after *ca.* 24 ka.

Ice began to recede prior to *ca.* 13 ka and had disappeared from divide areas by *ca.* 9 ka.

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