Géographie physique et Quaternaire

# The Cordilleran Ice Sheet: One Hundred and Fifty Years of Exploration and Discovery
# L'Inlandsis de la Cordillère : cent cinquante ans d'exploration et de découvertes
# Die Kordilleren-Eisdecke: 150 Jahre Erforschung und Entdeckung

Lionel E. Jackson,, Jr. and John J. Clague

Volume 45, Number 3, 1991

L'Inlandis de la Cordillère
The Cordilleran Ice Sheet

URI: https://id.erudit.org/iderudit/032874ar
DOI: https://doi.org/10.7202/032874ar

See table of contents

Publisher(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (print)
1492-143X (digital)

Explore this journal

Cite this article

Jackson,, L. E. & Clague, J. J. (1991). The Cordilleran Ice Sheet: One Hundred and Fifty Years of Exploration and Discovery. *Géographie physique et Quaternaire*, *45*(3), 269–280. https://doi.org/10.7202/032874ar

Article abstract

Present concepts about the Cordilleran Ice Sheet are the product of observations and ideas of several generations of earth scientists. The limits of glaciation in the Cordillera were established in the last half of the nineteenth century by explorers and naturalists, notably G. M. Dawson, R. G. McConnell, and T. C. Chamberlin. By the turn of the century, the gross configuration of the Cordilleran Ice Sheet had been determined, but the causes of glaciation and ice-sheet dynamics remained poorly understood. This early period of exploration and discovery was followed by a transitional period, from about 1900 to 1950, during which a variety of glacial landforms and deposits were explained (e.g., Channeled Scablands of Washington; "white silts" of southern British Columbia), and conceptual models of the growth and decay of the ice sheet were proposed. Shortly after World War II, there was a dramatic increase in research into all aspects of glaciation in the Canadian Cordillera which has continued unabated to the present. Part of the research effort during this period has been directed at resolving the Cordilleran Ice Sheet in both time and space. Local and regional fluctuations of the ice sheet have been reconstructed through stratigraphie and sedimentological studies, supported by radiocarbon and other dating techniques. Compilations of late Pleistocene ice-flow directions have shown that the Cordilleran Ice Sheet was a mass of coalescent glaciers flowing in a complex fashion from many montane source areas. During the postwar period, research has also begun or advanced significantly in several other disciplines, notably glaciology, process sedimen-tology, geomorphology, paleoecology, and marine geology. Attempts are now being made to quantitatively model the Cordilleran Ice Sheet using computers and the geological database assembled by past generations of earth scientists.

*Géographie physique et Quaternaire,* 1991, vol. 45, n° 3, p. 269-280, 6 fig., 1 tbl.

# THE CORDILLERAN ICE SHEET: ONE HUNDRED AND FIFTY YEARS OF EXPLORATION AND DISCOVERY*

Lionel E. JACKSON, Jr. and John J. CLAGUE, Geological Survey of Canada, 100 West Pender Street, Vancouver, British Columbia V6B 1R8.

ABSTRACT Present concepts about the Cordilleran Ice Sheet are the product of observations and ideas of several generations of earth scientists. The limits of glaciation in the Cordillera were established in the last half of the nineteenth century by explorers and naturalists, notably G. M. Dawson, R. G. McConnell, and T. C. Chamberlin. By the turn of the century, the gross configuration of the Cordilleran Ice Sheet had been determined, but the causes of glaciation and ice-sheet dynamics remained poorly understood. This early period of exploration and discovery was followed by a transitional period, from about 1900 to 1950, during which a variety of glacial landforms and deposits were explained (e.g., Channeled Scablands of Washington; "white silts" of southern British Columbia), and conceptual models of the growth and decay of the ice sheet were proposed. Shortly after World War II, there was a dramatic increase in research into all aspects of glaciation in the Canadian Cordillera which has continued unabated to the present. Part of the research effort during this period has been directed at resolving the Cordilleran Ice Sheet in both time and space. Local and regional fluctuations of the ice sheet have been reconstructed through stratigraphic and sedimentological studies, supported by radiocarbon and other dating techniques. Compilations of late Pleistocene ice-flow directions have shown that the Cordilleran Ice Sheet was a mass of coalescent glaciers flowing in a complex fashion from many montane source areas. During the postwar period, research has also begun or advanced significantly in several other disciplines, notably glaciology, process sedimentology, geomorphology, paleoecology, and marine geology. Attempts are now being made to quantitatively model the Cordilleran Ice Sheet using computers and the geological database assembled by past generations of earth scientists.

RÉSUMÉ *L'Inlandsis de la Cordillère: cent cinquante ans d'exploration et de découvertes.* Les conceptions actuelles sur l'Inlandsis de la Cordillère sont le résultat des observations et des conceptions de plusieurs générations de chercheurs en sciences de la Terre. Les limites glaciaires de la Cordillère ont été établies dès la deuxième moitié du XIXe siècle par les explorateurs et les naturalistes, notamment G. M. Dawson, R. G. McConnell et T. C. Chamberlin. Au tournant du siècle, on connaissait la configuration générale de l'Inlandsis de la Cordillère, mais les causes de la glaciation et la dynamique de l'inlandsis étaient mal connues. Cette première période d'exploration et de découvertes a été suivie par une période de transition, de 1900 à 1950 environ, durant laquelle on a pu expliquer une grande variété de formes et de dépôts glaciaires et élaborer des modèles du développement et de la disparition de l'Inlandsis. Peu après la Deuxième Guerre mondiale, les recherches sous tous les aspects de la glaciation dans la Cordillère ont connu un essor considérable et elles ont toujours maintenu leur rythme depuis. Une partie des recherches a été consacrée à la connaissance spatio-temporelle de l'Inlandsis. On a pu ainsi reconstituer les fluctuations locales et régionales grâce aux études stratigraphiques et sédimentologiques appuyées par différentes techniques de radiochronologie, notamment le radiocarbone. Par la compilation des différentes directions des écoulements glaciaires, on a démontré que l'Inlandsis constituait un amas de glaciers coalescents qui s'écoulaient en un réseau complexe à partir de nombreuses sources en montagne. Durant cette même période, les recherches en de nombreuses autres disciplines ont commencé ou progressé: glaciologie, sédimentologie des processus, géomorphologie, paléoécologie et géologie marine. Actuellement, avec l'aide des ordinateurs, on tente d'élaborer des modèles quantitatifs en se fondant sur les données géologiques accumulées par les générations précédentes de scientifiques.

ZUSAMMENFASSUNG *Die Kordilleren-Eisdecke: 150 Jahre Erforschung und Entdeckung.* Gegenwärtige Vorstellungen von der Kordilleren-Eisdecke sind das Ergebnis von Beobachtungen und Ideen mehrerer Generationen von Wissenschaftlern der Erde. Forscher und Naturforscher, insbesondere G. M. Dawson, R. G. McConnell und T. C. Chamberlin haben in der letzten Hälfte des 19. Jahrhunderts die Grenzen der Vereisung in den Kordilleren dargelegt. Um die Jahrhundertwende war die allgemeine Gestalt der Kordilleren-Eisdecke bestimmt, jedoch verstand man kaum die Gründe der Vereisung und die Dynamik der Eisdecke. Auf diese frühe Periode der Erforschung und Entdeckung folgte eine Übergangsperiode von etwa 1900 bis 1950, während der eine Vielfalt von glazialen Landformen und Ablagerungen erklärt (z. B. Channeled Scablands von Washington; "white silts" vom südlichen British Columbia) und Begriffsmodelle des Wachstums und des Verfalls der Eisdecke vorgeschlagen wurden. Kurz nach dem 2. Weltkrieg kam es zu einem dramatischen Aufschwung der Erforschung aller Aspekte der Vereisung in den kanadischen Kordilleren, welcher bis heute unvermindert angehalten hat. Ein Teil der Forschungsbemühung dieser Zeit war darauf gerichtet, die Kordilleren-Eisdecke sowohl in Zeit wie Raum zu verstehen. Kompilationen der Eisströmungsrichtungen im späten Pleistozän haben gezeigt, dass die Kordilleren-Eisdecke eine Masse verschmolzener Gletscher war, die in einer verwickelten Weise von vielen Bergquellgebieten abfloss. In der Nachkriegszeit hat die Forschung auch in einigen anderen Disziplinen begonnen oder bedeutende Fortschritte gemacht. Jetzt versucht man ein quantitatives Modell der Kordilleren-Eisdecke zu erstellen mit Hilfe von Computern und dem geologischen Datenmaterial, das von früheren Generationen von Erdwissenschaftlern gesammelt worden ist.

* Geological Survey of Canada Contribution No. 45190

Manuscrit reçu le 10 décembre 1990; manuscrit révisé accepté le 21 mars 1991

## INTRODUCTION

This paper traces the evolution of ideas about the last Cordilleran Ice Sheet and its glacial deposits and landforms from the middle 1800s to the present. It emphasizes seminal contributions that led to a better understanding of glaciation in the Canadian Cordillera, and also traces changes in thinking and research methodology through time.

Research on glaciation and glacial deposits in the Canadian Cordillera has passed through three phases:

1. Initial recognition of past glaciation in the Cordillera and definition of the limits of glaciation through observations made on marine, overland, and river traverses. This phase began around 1840 and was essentially complete by 1900.

2. A transitional period, from 1900 to 1950, featuring documentation of geologic events and processes along the margins of the Cordilleran Ice Sheet and better conceptual models of ice sheet form, growth, and decay. The packhorse was increasingly eclipsed by the automobile and floatplane during this period.

3. The present epoch, marked by an explosion of research into all aspects of glaciation in the Cordillera, using tools such as airphotos and satellite imagery, helicopters, and a variety of analytical techniques. This coincided with a dramatic increase in government and industry support for Quaternary studies in Canada and the training of Quaternary specialists in universities.

## 1840-1900, BEGINNINGS

The first suggestion that the Canadian Cordillera had once been more extensively covered by glaciers was made by J. D. Dana (1849: p. 677) based upon his observations while a member of the United States Naval Exploring Expedition between 1838 and 1842[1]. Dana put forward this hypothesis as an explanation for the contrasting morphologies of the linear coastline of what is now Oregon and Washington and the fiord-cut coast of British and Russian North America. He also proposed that the glaciation had occurred as a result of elevation of the Cordillera considerably above its present elevation and that this elevation was followed by subsidence which submerged the glaciated valleys creating fiords.

The notion that this largely unexplored region had been extensively glaciated was a bold suggestion at the time. The iceberg-origin of drift was widely accepted (Lyell, 1833) and Agassiz's glacial theory was still controversial. It was not until the 1850s that the glacial theory was widely accepted on both sides of the Atlantic (Imbrie and Imbrie, 1979) and the scientific climate was favourable for the corroboration of Dana's hypothesis.

During the late 1850s and 1860s, survey parties were sent to the Vancouver Island — Puget Sound region and along the 49th parallel by the British and American governments (Fig. 1). Evidence of glaciation, such as fluting, striations, and glacial erratics were noted by geologist-explorers H. Bauerman (British Northwest Boundary Commission Survey), R. Brown (First Vancouver Island Exploring Expedition and British Columbia Expedition), and G. Gibbs (Pacific Railway Survey) (Bauerman, 1860; Brown, 1870; Gibbs, 1874).

In 1867, W. H. Dall, a former student of Louis Agassiz and a member of the Collins Overland Telegraph Survey, documented a lack of any evidence of glaciation along the lower Yukon River in the interior of Alaska. He also described remains of an extinct vertebrate fauna in this region (Dall, 1868)[2].

In 1874, G. M. Dawson (Fig. 2), the man who named both the Laurentide and Cordilleran ice sheets, began his legendary exploration of the Canadian northwest as a member of the North American Boundary Survey and later as an officer and finally Director of the Geological Survey of Canada. By the end of the decade, Dawson, along with J. Richardson, had documented former glaciation along the coast of British Columbia and the Alaska panhandle and demonstrated that glaciers had once covered what is now the continental shelf (Richardson, 1876; Dawson, 1877, 1878a, 1879a, 1880, 1887).

Dawson extended his ideas about glaciation during systematic traverses across the Cordillera in the late 1870s and 1880s (Dawson 1878b, 1879b, 1880, 1881, 1886, 1888, 1890, 1891, 1895; Dawson and McConnell, 1885, 1895; Fig. 1). On these traverses, he described surficial deposits, measured the directions of striations, noted erratics and located their sources. In 1878, he announced that widespread glaciation had occurred in the interior of British Columbia. In his words: "In several cases, I have observed grooving at such heights and with such bearings as to preclude the possibility of its being attributed to glaciers moving from any of the present mountain-systems, and seeming to require for its explanation ice-action on a very much greater scale." (Dawson, 1878a, p. 100).

In his 1888 paper, Dawson first spoke of a "Cordilleran glacier", with a central divide and ice flow independent of topography. The following year, he reconstructed former ice sheet thicknesses and surface elevations for part of the Interior Plateau of British Columbia (Dawson, 1889).

While Dawson was exploring British Columbia, complementary evidence for ice sheet glaciation in southern and central Yukon Territory was being gathered by R. G. McConnell. He defined the northern limit of glaciation in the Yukon and documented deep weathering of bedrock beyond this limit (McConnell, 1891).

In 1885, T. C. Chamberlin (Fig. 2), the other great progenitor of the Cordilleran and Laurentide ice sheets, and R. D. Salisbury mapped the southern limits of glaciation across the

1. Dana also made the parallel observation that a similar transformation of coastal morphology occurs with increasing southerly latitude along the west coast of South America. It was on this expedition that Dana made his better known observations on coral atolls which corroborated Darwin's observations made during the voyage of the H. M. S. Beagle (1832-1836).

2. Although Dall is credited with the first description of an extinct vertebrate fauna in what is now known as Beringia, he was not the first to recognize these fossils. Robert Campbell, a Hudson Bay Company explorer and trader, collected vertebrate bones from gravels near Fort Selkirk, Yukon Territory, between 1848 and 1852. A single mammoth leg bone reached the British Museum from Campbell's collection (Dawson, 1894).

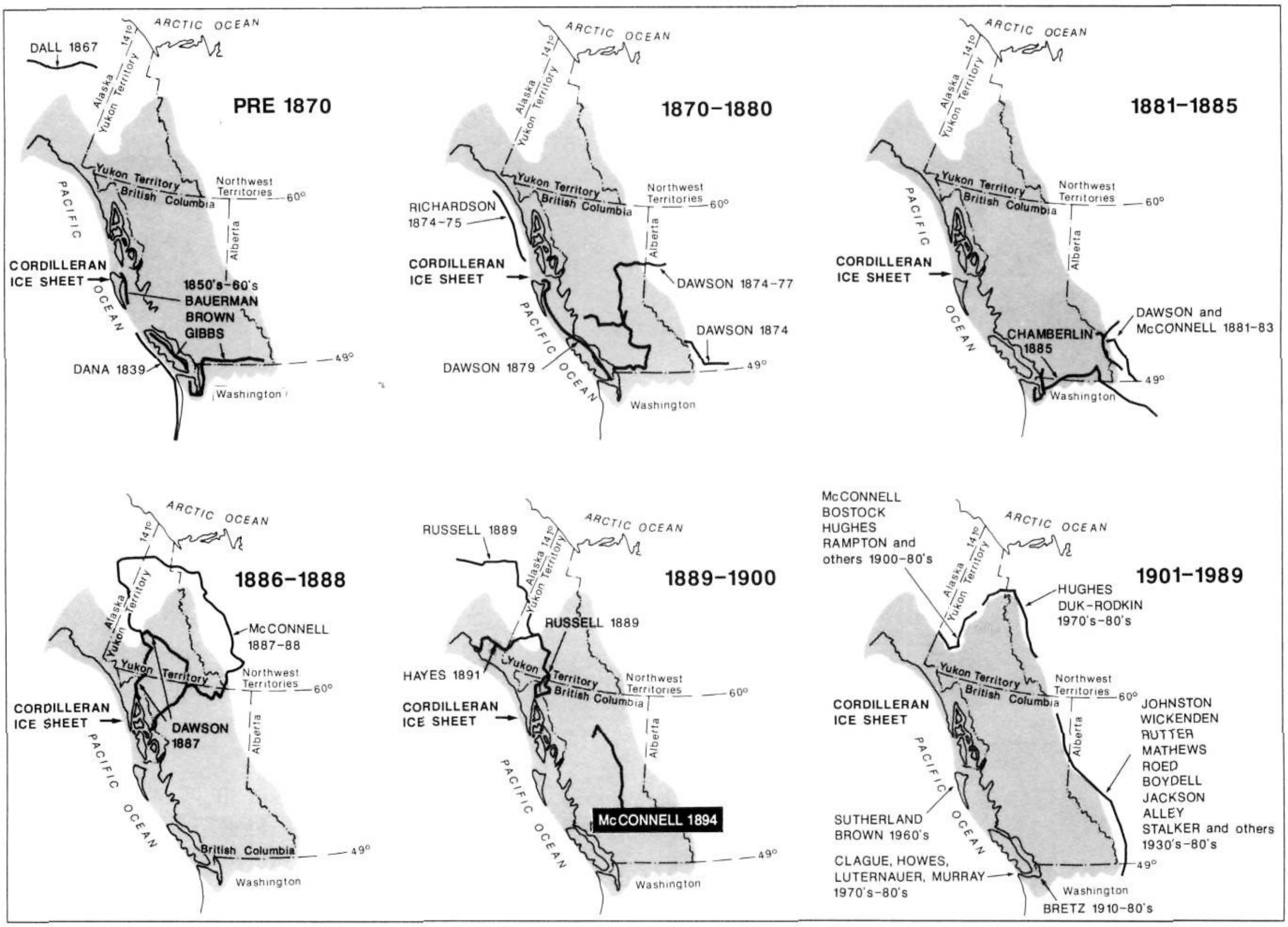


FIGURE 1. Traverses of early geologists/explorers who defined the extent of glaciation in the Canadian Cordillera.

*Circuits des premiers explorateurs géologues qui ont déterminé l'étendue des glaciations dans la Cordillère du Canada.*

northern United States on behalf of the United States Geological Survey (Chamberlin, 1886, 1888). In 1894, he produced his "Ideal map of North America during the Ice Age", showing a remarkably accurate reconstruction of the ice sheets that covered Canada and the northern United States during the late Pleistocene (Fig. 3),[3-4]. Although not the first map depicting the limits of past glaciation in North America (Plate XXV in Shaler and Davis, 1881), this and a more detailed colour map of "The Southern part of glacial deposits of the United States and Canada" (Plate XV in Geikie, 1894) were major contributions to knowledge at the time and strongly influenced subsequent thinking.

The last significant explorations of this period were carried out by I. C. Russell (1890) and C. H. Hayes (1892) of the United States Geological Survey in the Yukon River basin (Fig. 1). Hayes made the first traverse of the glacier-clad Saint Elias Mountains and documented Pleistocene glaciation in southwestern Yukon. Russell traversed the basin from central Alaska to the headwaters of Yukon River.

3. The term "Cordilleran Ice Sheet" first appeared on a map by Upham (1896, Plate 2).

4. The past existence of a Cordilleran ice sheet was not universally accepted. Tyrrell (1919) was still questioning the idea well into this century.

## CONCEPTUAL MODEL OF THE CORDILLERAN ICE SHEET

Although the general limits of the late Pleistocene ice sheet in western Canada had been documented by the end of the last century, the hows and whys of glaciation remained poorly understood and controversial. Knowledge of glacier flow and mass balance and contemporary glacial environments was almost totally lacking. Only a few glaciological studies were carried out prior to 1900, and the investigation of the sedimentology of present-day and Pleistocene glacial deposits was in its infancy (Jopling, 1975). Even the linkage between climate change and glaciation *e.g.*, Chamberlin, (1895) was not accepted universally. Dawson (1895; see also Johnston, 1932), for example, thought that it was just as likely that glaciation in the Cordillera had been caused by uplift of the land as a lowering of the firn line as had been proposed almost half a century before by Dana (1849).

Even with these limitations, Dawson's (1889) reconstruction of the "Cordilleran glacier" provided a reasonable basis for speculating on ice-sheet flow, growth, and decay. It featured radial outward flow from a central divide between 55° and 59°N latitude, at an elevation of about 3050 m. This ice sheet was similar in appearance to the present-day Greenland Ice Sheet. Dawson's view of the growth of the ice sheet has persisted essentially unchanged to the present and is the philosophical

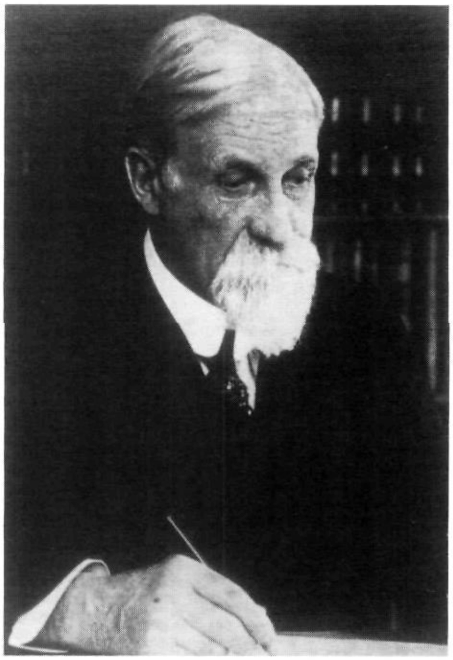

FIGURE 2. G. M. Dawson (left) and T. C. Chamberlin (right), the two geologists most responsible for developing the concept of the Cordilleran Ice Sheet.

*G. M. Dawson (à gauche) et T. C. Chamberlin (à droite) sont à l'origine du concept même de l'Inlandsis de la Cordillère.*


FIGURE 3. Chamberlin's representation of the vanished ice sheets of North America (Plate XIV *in* Geike, 1894).

*La répartition en Amérique du Nord des glaciers disparus, selon Chamberlin (planche XIV* in *Geike, 1894).*

underpining of recent conceptual and quantitative models of glaciation in this region: "It may be supposed that, under certain not improbable combinations of conditions, the mountainous country to the north... became preeminently the condensor of the Northern Pacific, and, from the mere accumulation of snow and ice, the focus of glacier-action and point of radiation of great glaciers. If the central plateau was ever filled thus by a great glacier-mass, the ice must have poured southward through the gaps on the 49th parallel, and westward across the Coast range, in a manner similar to that in which the ice supposed by Professor Geikie to have filled the Gulf of Bothnia must have crossed the Scandinavian peninsula." (Dawson, 1878a, p. 119).

## 1900-1950, TRANSITIONS

Science took a back seat to world events during much of this tumultuous period, which included two world wars and a great depression. Transportation technology, spurred in part by these wars, advanced rapidly, and airplanes and helicopters increasingly were used in support of field operations. Airphotos were first used during the latter part of this period. The automobile displaced the packhorse in areas with roads, and the outboard motor replaced the pole and paddle on lakes and rivers.

Between 1900 and 1950, relatively little additional information was gathered about glacial limits, except in central Yukon Territory (McConnell, 1903; Bostock, 1934, 1936) and in the Puget Sound-Juan de Fuca Strait area (Bretz, 1913, 1920). Observations related to the effects of glaciation and former ice flow directions, however, were routinely recorded by government geologists while mapping bedrock throughout the

Cordillera. These observations were subsequently synthesized by scientists with strong interests in Quaternary geology and glaciation, for example, Johnston (1926), Kerr (1934, 1936), Mathews (1944), and Armstrong and Tipper (1948) in northern and north-central British Columbia.

With the documentation of a former ice sheet in the Cordillera, previously mysterious geomorphic features and sediments could be explained. Implications of the Cordilleran Ice Sheet for other disciplines, such as glaciology and climatology, also became apparent. In the interior valleys of the Cordillera, extensive bedded silts, called "white silts" by Dawson (1888) and regarded by him to have been deposited during a postglacial marine incursion[5], were shown to be products of ice-marginal and proglacial lake ponding during deglaciation (Daly, 1912; Flint, 1935). A knowledge of glaciation was instrumental in explaining the geologic setting of placer gold deposits in central British Columbia (Johnston, 1926; Johnston and Uglow, 1926, 1933). The Channeled Scablands of eastern Washington were recognized as having formed during enormous floods from Glacial Lake Missoula, a large lake dammed by a lobe of the Cordilleran Ice Sheet (Wood, 1892; Pardee, 1910; Bretz, 1923a, 1923b, 1925, 1928a, 1928b, 1928c).

A controversy over the nature of the contact and interaction between the Cordilleran and Laurentide ice sheets began in the nineteenth century[6] but it was not until 1927, when artifacts were discovered in association with extinct ice age vertebrates at Folsom, New Mexico, that the issue generated widespread interest. Questions immediately arose as to whether or not humans could reach middle latitudes of North America during the late Pleistocene via an "ice-free corridor" between the two ice sheets[7,8]. W. A. Johnston (1933) was the first to suggest this possibility, based on his field investigations along the eastern side of the Rocky Mountain (Johnston and Wickenden, 1931), and arguments pro and con have raged ever since. Although still not resolved, this controversy has stimulated research on a variety of Quaternary topics along the eastern margin of the Cordillera in both Canada and the northern United States.

A better understanding of the Cordilleran Ice Sheet also stimulated interest in its effects on the crust and mantle. Johnston (1921) presented evidence for rapid sea-level change on the British Columbia coast during the Pleistocene, which he attributed to eustatic effects and to isostatic depression and rebound along the margin of the ice sheet. In 1934, R. A. Daly published his influential "The changing world of the ice ages", which included the first comprehensive synthesis of isostatic and eustatic effects of ice sheets, based in part on evidence from British Columbia. This work heralded recent research on this topic in Canada and elsewhere.

### ICE SHEET MODELLING DURING THE TRANSITIONAL YEARS

During the transitional period, more details were added to the picture of ice sheet morphology, flow, growth, and decay. Cross-sectional and conceptual reconstructions of the Cordilleran Ice Sheet grew in complexity. Daly (1912) constructed the first complete cross-section of the ice sheet along the International Boundary. Several depictions of the ice sheet from the early years of the twentieth century were based on the Greenland Ice Sheet analogue proposed by Dawson in the late 1880s (*e.g.*, Chamberlin, 1907, 1913).

In the 1920s, detailed study of ice-flow patterns in northern British Columbia led Johnston (1926) to abandon Dawson's Greenland Ice Sheet analogue. Instead, he suggested that the Cordillera was covered by a coalescent "system of intermontane, piedmont and valley glaciers" (a similar reconstruction for the Selwyn lobe in Yukon Territory has been made by L. E. Jackson *et al.* in this volume).

Analysis of ice-flow patterns and montane geomorphic features, such as rounded summits at high elevations, led Kerr (1934) and Davis and Mathews (1944) to formalize a four-phase model of glaciation in the Cordillera (Fig. 4). As climate deteriorated early during a glacial episode, small mountain ice fields grew and alpine glaciers advanced (alpine phase). With continued cooling and perhaps increased precipitation, glaciers expanded and coalesced to form a more extensive cover of ice in mountain areas (intense alpine phase). During long sustained cold periods, these glaciers advanced across plateaus and lowlands and eventually grew into large confluent masses of ice (mountain ice sheet phase). Throughout this period, the major mountain systems remained the principal sources of glaciers, and ice flow was controlled by topography. During the final phase, which was infrequently achieved, ice thickened to such an extent that domes with surface flow radially away from their centres became established over the interior of British Columbia and southern Yukon Territory (continental ice sheet phase).

## 1950-PRESENT, A NEW ERA OF EXPLORATION AND DISCOVERY

Governments, recognizing the importance of Quaternary deposits and processes for planning and development, initiated surficial geology mapping programs in the Canadian Cordillera after World War II. This coincided with the establishment of Quaternary geology courses in Canadian and United States universities. The result was a great increase in the number of Quaternary scientists and students working in the Cordillera, as well as an increase in the number and range of Quaternary

5. Traversing British Columbia from the Pacific coast, Dawson naturally thought that much of the silts and "boulder clays" were marine in origin. He attributed them to an incursion of the Arctic Ocean during a period of tectonic depression of the Cordillera following glaciation (Dawson, 1878a, 1888, 1891), an idea which apparently started with J. D. Dana (1849). Although, isostatic depression due to glacier loading was recognized as early as 1868 in Scotland (Jamieson, 1868), it was not until 1890 that I. C. Russell suggested that it may have played a role in ponding former glacial lakes in southern Yukon (Russell, 1890). The notion of a postglacial marine incursion into the centre of the Cordillera survived until the first decade of this century (Osborn, 1910, p. 442).
6. Chamberlain (1882) suggested that the two ice sheets had coalesced, whereas Dawson and McConnell (1895) placed the western limit of the Laurentide Ice Sheet hundreds of kilometres east of the Cordillera.
7. The coexistence of humans and late Pleistocene faunas in the New World was first suggested in the early nineteenth century (see Osborn (1910) for a discussion), but the Folsom discovery in 1927 was the first with incontrovertible evidence.
8. The term "ice-free corridor" was coined by Antevs (1937).

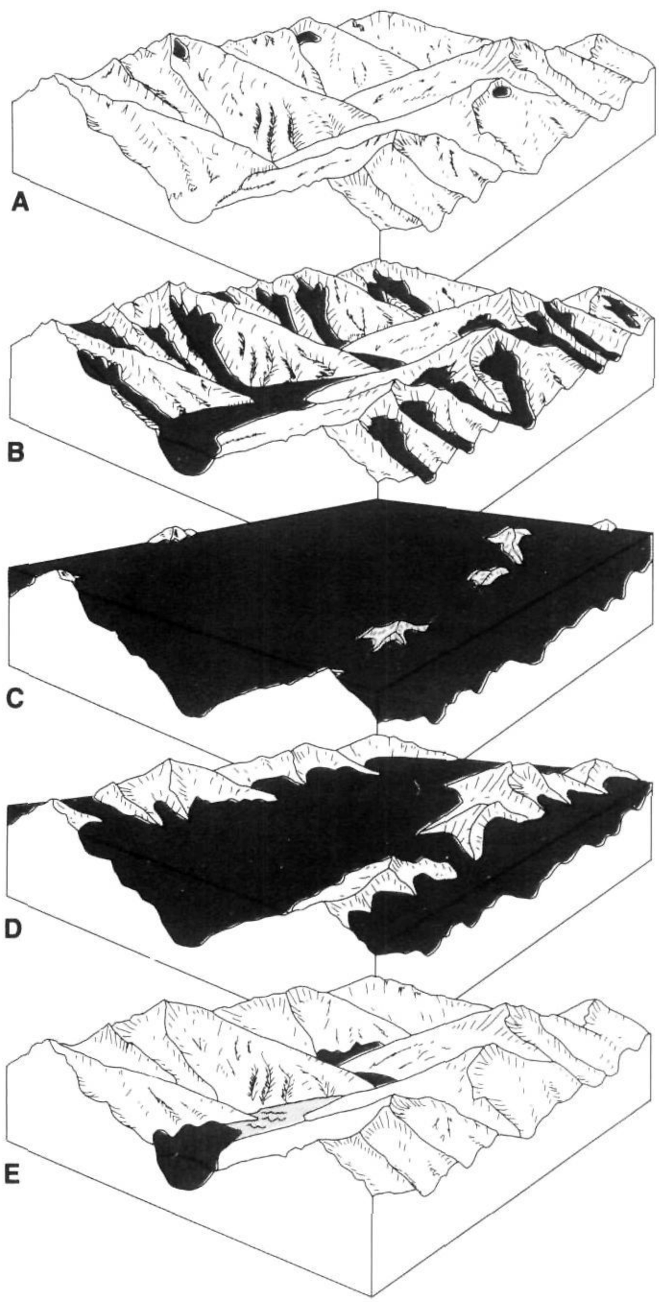


FIGURE 4. Conceptual model of growth and decay of the Cordilleran Ice Sheet (Clague, 1989, Fig. 1.13). A) Mountain area at the beginning of a glaciation. B) Development of a network of valley glaciers. C) Coalescence of valley and piedmont lobes to form an ice sheet. D) Decay of ice sheet by downwasting. E) Residual dead ice masses confined to valleys. Stages A-C follow the model of ice-sheet growth proposed by Kerr (1934) and Davis and Mathews (1944); stages D-E follow the ice-sheet model of Fulton (1967).

*Modèle conceptuel de développement et du retrait de l'Inlandsis de la Cordillère (Clague, 1989, fig. 1.13). A) Région montagneuse au début de la glaciation. B) Développement d'un réseau de glaciers de vallée. C) Coalescence de lobes de vallée et de piémont pour former un inlandsis. D) Retrait de l'inlandsis par fonte. E) Masses de glace résiduelles confinées aux vallées. Les stades A-C répondent au modèle proposé par Kerr (1934) et Davis et Mathews (1944); les stades D-E s'inspirent du modèle de Fulton (1967).*

studies. This began around 1950, accelerated markedly in the 1960s and 1970s, and continues today.

Part of this research effort has been directed at resolving the Cordilleran Ice Sheet in both space and time. Aerial photographs, satellite images, float planes, and helicopters have permitted the detailed mapping of formerly inaccessible areas in Yukon Territory and northern British Columbia. This, in turn, has provided a better understanding of the characteristics and history of the northern part of the Cordilleran Ice Sheet (Bostock, 1966; Hughes *et al.*, 1969; also see J. M. Ryder and D. Maynard in this volume).

Local and regional fluctuations of the ice sheet have been reconstructed by studying the stratigraphy and sedimentology of Quaternary deposits (Ryder and Clague, 1989; Jackson *et al.*, 1989), and radiocarbon dating has provided a chronological framework for these events (Fulton, 1971; Clague, 1980, 1981, 1989; Jackson and Pawson, 1984). Prior to 1950, detailed Pleistocene stratigraphic reconstructions had been attempted only for the Puget Lowland area of northwestern Washington (Willis, 1898; Bretz, 1913) and the Foothills of southwestern Alberta (Dawson and McConnell, 1895). Since 1950, two generations of Quaternary scientists have modified existing schemes and established new stratigraphies in many other areas (Table I).

TABLE I

*Examples of papers that established regional stratigraphic frameworks for areas covered by the Cordilleran Ice Sheet and satellite glaciers*

| Location | Reference |
|---|---|
| Central Yukon | Bostock, 1966, Hughes *et al.*, 1969 |
| Southwestern Yukon | Denton and Stuiver, 1967; Rampton, 1971 |
| Southeastern Yukon | Klassen, 1978, 1987 |
| Peace River basin, British Columbia | Rutter, 1976, 1977; Mathews, 1978 |
| Central British Columbia | Clague, 1987, 1988 |
| South-central British Columbia | Fulton and Smith, 1978 |
| Southern Rocky Mountain Trench, British Columbia | Clague, 1975 |
| Fraser Lowland, British Columbia | Armstrong *et al.*, 1965; Armstrong, 1981, 1984 |
| Puget Lowland, Washington | Willis, 1898, Armstrong *et al.*, 1965, Easterbrook, 1969, 1986 |
| Vancouver Island, British Columbia | Fyles, 1963; Howes, 1981a, 1981b, 1983 |
| Oldman River basin, Alberta | Dawson and McConnell, 1895; Alley, 1973; Alley and Harris, 1974; Stalker and Harrison, 1977 |
| Bow River basin, Alberta | Rutter, 1972; Jackson, 1980 |
| North Saskatchewan River basin, Alberta | Boydell, 1978 |
| Athabasca River basin, Alberta | Roed, 1975 |

A major contribution of this stratigraphic and sedimentological work has been the documentation of a lengthy interstadial period in the Canadian Cordillera during the Middle Wisconsinan. Nonglacial deposits of Middle Wisconsinan age are more extensive and better dated in the southern Cordillera than anywhere else in Canada (Fulton, 1968, 1971; Westgate and Fulton, 1975; Armstrong and Clague, 1977; Alley, 1979; Alley *et al.*, 1986; Clague *et al.*, 1990). The presence of these deposits near source areas of the Cordilleran Ice Sheet indicates that ice cover in western Canada was restricted during the Middle Wisconsinan. This has implications for Wisconsinan climatic reconstructions and ice sheet modelling.

Observations of sedimentological processes operating beneath and at the margins of extant glaciers (*e.g.*, Boulton, 1972, 1978; Church and Gilbert, 1975; Boulton and Eyles, 1979; Eyles and Miall, 1984) have been brought to bear in the study and interpretation of Quaternary sediments in the Cordillera (see N. Eyles and J. J. Clague in this volume). This has occurred in tandem with major advances in glaciology in the post-war era[9].

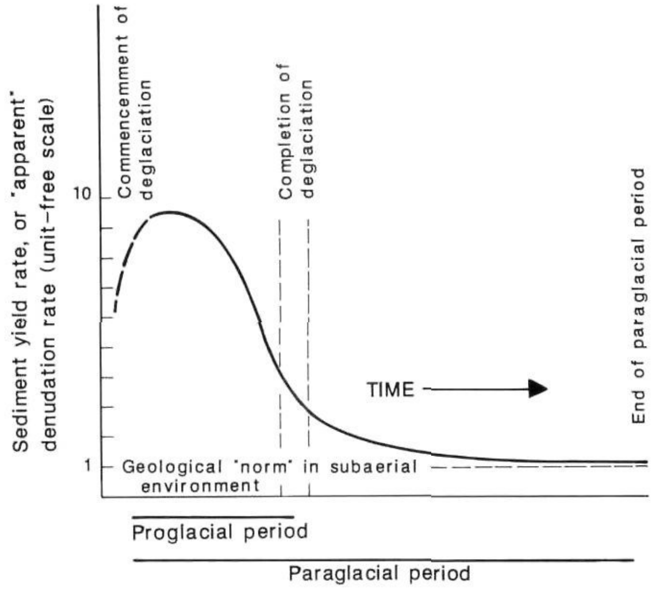


FIGURE 5. Schematic summary of the paraglacial sediment concept articulated by M. A. Church and J. M. Ryder (1972, Fig. 9).

*Schématisation du concept de sédimentation paraglaciaire tel que déterminé par M. A. Church et J. M. Ryder (1972, fig. 9).*

A few sedimentological studies in the Canadian Cordillera during the modern era can been considered benchmark contributions. An investigation of postglacial deposits in British Columbia valleys led Church and Ryder (1972) to document the role of glaciation in controlling patterns and rates of sedimentation during interglacial and postglacial periods (the concept of paraglacial sedimentation, Fig. 5). Other examples are the early studies of glaciomarine sediments near Vancouver by Armstrong and Brown (1954) and on Vancouver Island by Fyles (1956). These were perhaps the first detailed documentation in North America of marine sedimentation at the margin of a decaying ice sheet. They were necessary antecedents of, and set the stage for, later studies of transient crustal deformation and sea-level change induced by the growth and decay of the Cordilleran Ice Sheet (Mathews *et al.*, 1970; Clague *et al.*, 1982b; Clague, 1983).

Prior to 1950, relatively little was known about glaciation in the northern Cordillera. Important publications by H. S. Bostock in 1966 and O. L. Hughes and coworkers in 1969 and 1972 stimulated interest in the Quaternary geology of this region and triggered a recent major increase in research both inside and beyond the limits of glaciation. One of the most intensively studied areas in recent years has been the Old Crow area of northern Yukon Territory, which was inundated by a large proglacial lake during the last glaciation (Hughes, 1972; Thorson and Dixon, 1983). Stratigraphic, paleoecological, geochronological, and other studies of exposures along Old Crow and Porcupine River have revealed a complex history of sedimentation, erosion, and paleoenvironmental change in northern Yukon extending from the late Tertiary to the present (Hughes *et al.*, 1989, and references therein).

Compilations of late Pleistocene ice-flow directions in British Columbia and Yukon Territory (Wilson *et al.*, 1958; Prest *et al.*, 1968; Hughes *et al.*, 1969; Prest, 1984; Clague, 1989) have shown that the Cordilleran Ice Sheet was a mass of coalescent glaciers flowing from many montane source areas (Fig. 6). Flow was strongly controlled by topography in areas of high relief, but was largely independent of topography over the Interior and Yukon plateaus. Local, probably short-lived coalescence of Cordilleran and Laurentide ice masses occurred along the "ice-free corridor" at the eastern margin of the Cordillera adjacent to the Rocky and Mackenzie Mountains (Jackson *et al.*, 1989).

Research has also begun in several new areas during the current phase of exploration and discovery. For example, large areas of the British Columbia continental shelf have been surveyed from government-operated research ships during the last 30 years. Using methods such as seismic profiling and coring, marine geologists have provided information on the effects and extent of glaciation on the shelf (*e.g.*, Carter, 1973, 1974; Luternauer and Murray, 1983; Barrie and Bornhold, 1989). This work has been complemented by regional mapping and by geomorphic and stratigraphic studies on northern and western Vancouver Island and the Queen Charlotte Islands (Sutherland Brown, 1968; Howes, 1981a, 1981b, 1983; Clague *et al.*, 1982a). New dating and correlation techniques, including thermoluminescence and amino-acid dating, paleomagnetism, and tephra characterization, have also been extensively applied to Quaternary deposits in the Cordillera (Clague, 1989). Finally, studies of plant and animal fossils have provided important insights on past climates in this region (Clague and MacDonald, 1989; Mathewes, this volume). Some of the fossiliferous sediments were deposited at times of extensive ice cover, and the paleoclimatic inferences that can be drawn from them are important for modelling northern hemisphere ice sheets.

9. Although studies of glaciers date back more than a century and significant advances in glaciology were made during the first half of the twentieth century, a detailed understanding of the mechanism of glacier flow was achieved only after World War II (Paterson, 1969, p. 1).

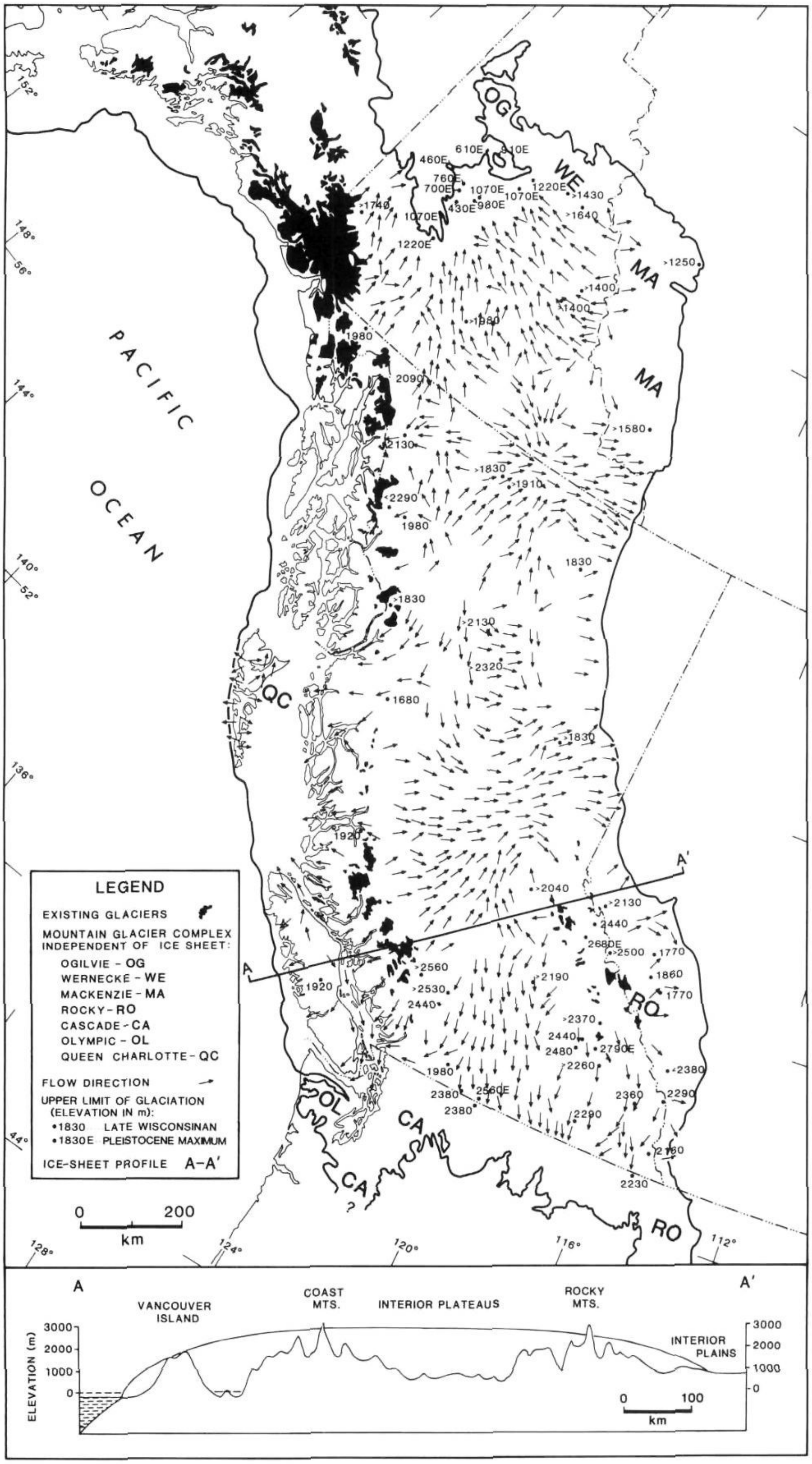


FIGURE 6. Maximum extent of Pleistocene glaciation in the Canadian Cordillera and adjacent areas, and ice flow pattern during the last glaciation (Late Wisconsinan) (modified from Claque, 1989, Fig. 1.12). The glacier complex shown in this figure includes the Cordilleran Ice Sheet and independent and nearly independent glacier systems in some peripheral mountain ranges. Nunataks were small in ice sheet areas at the climax of glaciation. In contrast, there were large ice free areas in some peripheral mountain ranges. Extent of glaciation, in part, from Crandell (1965), Lemke *et al.* (1965), Richmond *et al.* (1965), Prest *et al.* (1968), Hamilton and Thorson (1983), and Porter *et al.* (1983); ice flow pattern from Prest *et al.* (1969); data on upper limit of glaciation from Wilson *et al.* (1958).

*L'étendue maximale de la glaciation au Pléistocène dans la Cordillère du Canada et les régions avoisinantes et l'écoulement glaciaire au cours de la dernière glaciation (Wisconsinien supérieur) (d'après Claque, 1989, fig. 1.12), Le complexe glaciaire illustré comprend l'Inlandsis de la Cordillère et les systèmes glaciaires autonomes ou en partie autonomes de certaines chaînes de montagnes périphériques. À l'optimum glaciaire, les nunataks étaient petits dans la région de l'Inlandsis. Par contre, il y avait de vastes régions libres de glace dans les régions montagneuses périphériques. Données sur l'étendue glaciaire: Crandell (1965), Lemke* et al. *(1965), Richmond* et al. *(1965), Prest* et al. *(1968), Hamilton et Thorson (1983), et Porter* et al. *(1983): réseau d'écoulement glaciaire; Prest* et al. *(1969); données sur l'altitude limite des glaciations: Wilson* et al. *(1958).*

## ICE SHEET MODELLING

The four-phase model of glaciation proposed by Kerr (1934) and Davis and Mathews (1944) provides a useful framework for conceptualizing the growth of the Cordilleran Ice Sheet. Until the 1960s, it was assumed that the pattern of decay of the ice sheet was the exact opposite of this, *i.e.* plateaus and valleys became ice free before highlands. R. J. Fulton (1967), working in south-central British Columbia, was the first to suggest that this was not the case. He proposed that deglaciation of areas of low and moderate relief proceeded through four stages: (1) active ice phase — regional flow continued but diminished as ice thinned; (2) transitional upland phase — highest uplands appeared through the ice sheet, but regional flow continued in major valleys; (3) stagnant ice phase — ice was confined to valleys but was still thick enough to flow; and (4) dead ice phase — valley tongues thinned to the point where plasticity was lost. In such a model, highlands are the first areas to become deglaciated and valleys the last. This model has been applied with minor modifications to other parts of British Columbia and Yukon Territory (Tipper, 1971a, 1971b; Heginbottom, 1972; Ryder, 1976, 1981; Howes, 1977; also see L. E. Jackson *et al.*, and J. M. Ryder *et al.* in this volume). It laid the groundwork for our present understanding of the precarious nature of the mass balance of the Cordilleran Ice Sheet and the rapidity of its decay.

Attempts are now being made to model the Cordilleran Ice Sheet quantitatively, using computers and the database gathered by past generations of geologists and geomorphologists. Previous modelling was conceptual, by analogy, or relied on simple reconstructive techniques such as the construction of surface profiles or the use of contour maps where ice limits around nunataks could be established and linked with ice flow directions. The computer simulations that are now being made (Roberts, 1990, this volume) allow us to test our hypotheses about ice sheet growth and decay and climate change by growing and wasting ice sheets in compressed time.

## THE FUTURE

Over the past 150 years, it has been demonstrated that most of the Canadian Cordillera has been repeatedly glaciated. The limits of the most recent Cordilleran Ice Sheet have been established in both space and time, and local and regional patterns of ice flow have been documented. In addition, an understanding of how the ice sheet grew and decayed has been gained. We conclude with a few speculations about the directions that research into the Cordilleran Ice Sheet may take in coming decades.

Quaternary deposits and landforms have not been mapped for much of the area covered by the ice sheet. It is expected that significant efforts will be made by the Geological Survey of Canada and the British Columbia Geological Survey to map areas in central and northern British Columbia and Yukon Territory where little or no information is available and to upgrade existing surficial geology maps. Only when this task is well advanced or finished will a complete reconstruction of the last ice sheet be possible.

The use of computers to simulate the Cordilleran Ice Sheet, and as a tool in the analysis of various aspects of glaciation, will expand greatly over the next decade. This undoubtedly will facilitate research and hopefully will provide a more rigorous, quantitative foundation for models of ice-sheet evolution.

It is expected that much research will be devoted to refining existing absolute age dating methods and, perhaps, to developing new ones. Chronological control is crucial to many fields of earth science, but none more so than Quaternary geology. New developments in radiocarbon dating (*e.g.*, accelerator mass spectrometry method) will allow the chronology of the last Cordilleran Ice Sheet to be refined. Relatively new methods, such as amino acid and thermoluminescence dating, offer the promise that older glaciations may someday be as precisely dated as the last.

Lastly, much more effort will be devoted in coming years to three-dimensional analysis of sedimentary sequences ("basin analysis") in the Cordillera (Eyles *et al.*, 1985). This will require an interdisciplinary research effort, bringing together experts in geophysics, geomorphology, sedimentology, stratigraphy, paleontology, and other fields. Basin analysis holds the promise of not only expanding our understanding of the Cordilleran Ice Sheet, but also applying this understanding to practical issues such as land-use planning, groundwater supply, and foundation studies.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge assistance from Miss Mary Akehurst, Mrs. Fontane Hwang and Mr. Paul Nepote. Constructive and thoughtful reviews were provided by Drs. R. J. Fulton and M. C. Wilson.

## REFERENCES

Alley, N. F., 1973. Glacial stratigraphy and the limits of the Rocky Mountain and Laurentide ice sheets in southwestern Alberta, Canada. Bulletin of Canadian Petroleum Geology, 212: 153-177.

——— 1979. Middle Wisconsin stratigraphy and climatic reconstruction, southern Vancouver Island, British Columbia. Quaternary Research, 11: 213-237.

Alley, N. F. and Harris, S. A., 1974. Pleistocene glacial lake sequences in the Foothills, southwestern Alberta, Canada. Canadian Journal of Earth Sciences, 11: 1220-1235.

Alley, N. F., Valentine, K. W. G. and Fulton, R. J., 1986. Paleoclimatic implications of middle Wisconsinan pollen and a paleosol from the Purcell Trench, south central British Columbia. Canadian Journal of Earth Sciences, 23: 1156-1168.

Antevs, E. V., 1937. Climate and early man in North America, p. 125-132. *In* G. G. MacCurdy, Early man. J. D. Lippincott, Philadelphia and New York, 363 p.

Armstrong, J. E., 1981. Post-Vashon Wisconsin glaciation, Fraser Lowland, British Columbia. Geological Survey of Canada, Bulletin 322, 34 p.

——— 1984. Environmental and engineering applications of the surficial geology of the Fraser Lowland, British Columbia. Geological Survey of Canada, Paper 83-23, 54 p.

Armstrong, J. E. and Brown, W. L., 1954. Late Wisconsin marine drift and associated sediments of the Lower Fraser Valley, British Columbia, Canada. Geological Society of America Bulletin, 65: 349-363.

Armstrong, J. E. and Clague, J. J., 1977. Two major Wisconsin lithostratigraphic units in southwest British Columbia. Canadian Journal of Earth Sciences, 14: 1471-1480.

Armstrong, J. E. and Tipper, H. W., 1948. Glaciation in north central British Columbia. American Journal of Science, 246: 283-310.

Armstrong, J. E., Crandell, D. R., Easterbrook, D. J. and Noble, J. B., 1965. Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington. Geological Society of America Bulletin, 76: 321-330.

Barrie, J. V. and Bornhold, B. D., 1989. Surficial geology of Hecate Strait, British Columbia continental shelf. Canadian Journal of Earth Sciences, 26: 1241-1254.

Bauerman, H., 1860. On the geology of the southeastern part of Vancouver Island. Quarterly Journal of the Geological Society of London, 16: 198-202.

Bostock, H. S., 1934. The mining industry of Yukon, 1933, and notes on the geology of Carmacks map-area. Geological Survey of Canada, Summary Report 1933, Pt. A., p. 1A-8A.

——— 1936. Carmacks district, Yukon. Geological Survey of Canada, Memoir 189, 67 p.

——— 1966. Notes on glaciation in central Yukon Territory. Geological Survey of Canada, Paper 65-36, 18 p.

Boulton, G. S., 1972. Modern Arctic glaciers as depositional models for former ice sheets. Quaterly Journal of the Geological Society of London, 127: 361-393.

——— 1978. Boulder shapes and grain-size distributions of debris as indicators of transport paths through a glacier and till genesis. Sedimentology, 25: 773-799.

Boulton, G. S. and Eyles, N., 1979. Sedimentation by valley glaciers; a model and genetic classification, p. 11-23. *In* C. Schlüchter, ed., Moraines and varves; origin, genesis, classification. A. A. Balkema, Rotterdam, 441 p.

Boydell, A. N., 1978. Multiple glaciations in the Foothills, Rocky Mountain House area, Alberta. Alberta Research Council, Bulletin 36, 35 p.

Bretz, J. H. 1913. Glaciation of the Puget Sound region. Washington Geological Survey, Bulletin 8, 244 p.

——— 1920. The Juan de Fuca lobe of the Cordilleran ice sheet. Journal of Geology, 28: 333-339.

——— 1923a. Glacial drainage on the Columbia Plateau. Geological Society of America Bulletin, 34: 573-608.

——— 1923b. The channeled scablands of the Columbia Plateau. Journal of Geology, 31: 617-649.

——— 1925. The Spokane flood beyond the channeled scablands [2 pt.]. Journal of Geology, 33: 97-115, 236-259.

——— 1928a. Alternative hypotheses for channeled scabland [2 pt.]. Journal of Geology, 36: 193-223, 312-341.

——— 1928b. Bars of channeled scabland. Geological Society of America Bulletin, 39: 643-702.

——— 1928c. The channeled scabland of eastern Washington. Geographical Review, 18: 446-477.

Brown, R., 1870. On the supposed absence of the northern drift from the Pacific slope of the Rocky Mountains. American Journal of Science, 2nd ser., 50: 318-324.

Carter, L., 1973. Surficial sediments of Barkley Sound and the adjacent continental shelf, west coast Vancouver Island. Canadian Journal of Earth Sciences, 10: 441-459.

——— 1974. An evaluation of the provenance of terrigenous sediments from offshore Vancouver Island. Canadian Journal of Earth Sciences, 11: 664-677.

Chamberlin, T. C., 1882. Third annual report of the Director of the United States Geological Survey, 1881-1882. United States Geological Survey, p. 401-402.

——— 1886. Seventh annual report of the Director of the United States Geological Survey. United States Geological Survey, p. 76-85.

——— 1888. The rock-scourings of the great ice invasions. United States Geological Survey, 7th Annual Report, 1885-1886, p. 147-248.

——— 1895. Glacial phenomena of North America, p. 724-775. *In* J. Geikie, ed., The great ice age, 3rd edition. Edward Stanford, London, 850 p.

——— 1907. The Pleistocene or glacial period, Fig. 469 and 470, Chapter IX. *In* T. C. Chamberlin and R. D. Salisbury, ed., Earth history, vol. III, 2nd edition. American Science Series, Advanced Course, Henry Holt and Sons, 624 p.

——— 1913. Map of North America during the great ice age. Rand McNally, Chicago.

Church, M. and Gilbert, R., 1975. Proglacial fluvial and lacustrine environments, p. 22-100. *In* A. V. Jopling and B. C. McDonald, ed., Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Special Publication 23, 320 p.

Church, M. and Ryder, J. M., 1972. Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. Geological Society of America Bulletin, 83: 3059-3072.

Clague, J. J., 1975. Late Quaternary sediments and geomorphic history of the southern Rocky Mountain Trench, British Columbia. Canadian Journal of Earth Sciences, 12: 595-605.

——— 1980. Late Quaternary geology and geochronology of British Columbia. Part 1: radiocarbon dates. Geological Survey of Canada, Paper 80-13, 28 p.

——— 1981. Late Quaternary geology and geochronology of British Columbia. Part 2: summary and discussion of radiocarbon-dated Quaternary history. Geological Survey of Canada, Paper 80-35, 41 p.

——— 1983. Glacio-isostatic effects of the Cordilleran Ice Sheet, British Columbia, Canada, p. 321-343. *In* D. E. Smith and A. G. Dawson, ed., Shorelines and isostasy. Academic Press, London, 387 p.

——— 1987. Quaternary stratigraphy and history, Williams Lake, British Columbia. Canadian Journal of Earth Sciences, 24: 147-158.

——— 1988. Quaternary stratigraphy and history, Quesnel, British Columbia. Géographie physique et Quaternaire, 42: 279-288.

——— (compiler), 1989. Quaternary geology of the Canadian Cordillera, p. 15-96. *In* R. J. Fulton, ed., Quaternary geology of Canada and Greenland. Geological Survey of Canada, Geology of Canada, no. 1, 839 p. [also Geological Society of America, The Geology of North America, v. K-1].

Clague, J. J. and MacDonald, G. M., 1989. Paleoecology and paleoclimatology [Canadian Cordillera], p. 70-74. *In* R. J. Fulton, ed., Quaternary geology of Canada and Greenland. Geological Survey of Canada, Geology of Canada, no. 1, 839 p. [also Geological Society of America, The Geology of North America, v. K-1].

Clague, J. J., Hebda, R. J. and Mathewes, R. W., 1990. Stratigraphy and paleoecology of Pleistocene interstadial sediments, central British Columbia. Quaternary Research, 34: 208-226.

Clague, J. J., Mathewes, R. W. and Warner, B. G., 1982a. Late Quaternary geology of Graham Island, Queen Charlotte Islands, British Columbia. Canadian Journal of Earth Sciences, 19: 1786-1795.

Clague, J., Harper, J. R., Hebda, R. J. and Howes, D. E., 1982b. Late Quaternary sea levels and crustal movements, coastal British Columbia. Canadian Journal of Earth Sciences, 19: 597-618.

Crandell, D. R., 1965. The glacial history of western Washington and Oregon, p. 342-353. *In* H. E. Wright, Jr. and D. G. Frey, ed., The Quaternary of the United States. Princeton University Press, Princeton, 922 p.

Dall, W. H., 1868. Explorations in Russian America. American Journal of Science, 2nd ser., 45: 96-99.

Daly, R. A., 1912. Geology of the North American Cordillera at the forty-ninth parallel. Geological Survey of Canada, Memoir 38, 3 pt., 857 p.

——— 1934. The changing world of the ice age. Yale University Press, New Haven, Connecticut, 271 p.

Dana, J. D., 1849. Geology. United States Exploring Expedition, during the years 1838, 1839, 1840, 1841, 1842 under the command of Charles Wilkes U.S.N. Vol. X, printed by C. Sherman, Philadelphia, 756 p.

Davis, N. F. G. and Mathews, W. H., 1944. Four phases of glaciation with illustrations from southwestern British Columbia. Journal of Geology, 52: 403-413.

Dawson, G. M., 1877. Note on some of the more recent changes in level of the coast of British Columbia and adjacent regions. Canadian Naturalist, new ser., 8: 241-248.

——— 1878a. On the superficial geology of British Columbia. Quarterly Journal of the Geological Society of London, 34: 89-123.

——— 1878b. Report on explorations in British Columbia, chiefly in the basins of the Blackwater, Salmon and Nechacco Rivers and on François Lake. Geological Survey of Canada, Report of Progress 1876-1877, p. 17-94.

——— 1879a. Notes on the glaciation of British Columbia. Canadian Naturalist, new ser., 9: 32-39.

——— 1879b. Preliminary report on the physical and geological features of the southern portion of the interior of British Columbia. Geological Survey of Canada, Report of Progress 1877-1878, rept. B, 187 p.

——— 1880. Report on the Queen Charlotte Islands. Geological Survey of Canada, Report of Progress 1878-1879, rept. B, 239 p.

——— 1881. Report on an exploration from Port Simpson on the Pacific coast, to Edmonton on the Saskatchewan, embracing a portion of the northern part of British Columbia and the Peace River country. Geological Survey of Canada, Report of Progress 1879-1880, rept. B., 165 p.

——— 1886. Preliminary report on the physical and geological features of that portion of the Rocky Mountains between latitudes 49° and 50°30'. Geological Survey of Canada, Annual Report, new. ser., v. 1 (1885), rept. B., 169 p.

——— 1887. Report on a geological examination of the northern part of Vancouver Island and adjacent coasts. Geological Survey of Canada, Annual Report, new ser., v. 2 (1886), rept. B, 129 p.

——— 1888. Recent observations on the glaciation of British Columbia and adjacent regions. American Geologist, 3: 249-253 [also Geological Magazine, new ser., 5: 347-350].

——— 1889. Glaciation of high points in the southern interior of British Columbia. Geological Magazine, new ser., 6: 350-352.

——— 1890. On the glaciation of the northern part of the Cordillera, with an attempt to correlate the events of the glacial period in the Cordillera and Great Plains. American Geologist, 6: 153-162.

——— 1891. On the later physiographical geology of the Rocky Mountain region in Canada, with special reference to changes in elevation and to the history of the glacial period. Transactions of the Royal Society of Canada, 8(4): 3-74.

——— 1894. Notes on the occurrence of mammoth remains in the Yukon district of Canada and in Alaska. Quarterly Journal of the Geological Society of London, 50: 1-8.

——— 1895. Report on the area of the Kamloops map-sheet, British Columbia. Geological Survey of Canada, Annual Report, v. 7 (1894), rept. B, 427 p.

Dawson, G. M. and McConnell, R. G., 1885. Report on the region in the vicinity of the Bow and Belly rivers, North-West Territory. Geological Survey of Canada, Report of Progress, 1882-1884, rept. C, 169 p.

——— 1895. Glacial deposits of southwestern Alberta in the vicinity of the Rocky Mountains. Geological Society of America Bulletin, 7: 31-66.

Denton, G. H. and Stuiver, M., 1967. Late Pleistocene glacial stratigraphy and chronology, northeastern St. Elias Mountains, Yukon Territory, Canada. Geological Society of America Bulletin, 78: 485-510.

Easterbrook, D. J., 1969. Pleistocene chronology of the Puget Lowland and San Juan Islands, Washington. Geological Society of America Bulletin, 80: 2273-2286.

——— 1986. Stratigraphy and chronology of Quaternary deposits of the Puget Lowland and Olympic Mountains of Washington and Oregon. *In* V. Sibrava, D. Q. Bowen and G. M. Richmond, ed., Quaternary glaciations in the Northern Hemisphere. Quaternary Sciences Reviews, 5: 145-159.

Eyles, N. and Miall, A. D., 1984. Glacial facies, p. 15-38. *In* R. G. Walker, ed., Facies models, 2nd edition. Geoscience Canada, Reprint Series 1, 317 p.

Eyles, N., Clark, B. M., Kaye, B. G., Howard, K. W. F. and Eyles, C. H., 1985. The application of basin analysis techniques to glaciated terrains: an example from the Lake Ontario Basin, Canada. Geoscience Canada, 12: 22-32.

Flint, R. F., 1935. "White-silt" deposits in the Okanagan valley, British Columbia. Transactions of the Royal Society of Canada, ser. 3, 29(4): 107-114.

Fulton, R. J., 1967. Deglaciation studies in Kamloops region, an area of moderate relief, British Columbia. Geological Survey of Canada, Bulletin 154, 36 p.

——— 1968. Olympia Interglaciation, Purcell Trench, British Columbia. Geological Society of America Bulletin, 79: 1075-1080.

——— 1971. Radiocarbon geochronology of southern British Columbia. Geological Survey of Canada, Paper 71-37, 28 p.

Fulton, R. J. and Smith, G. W., 1978. Late Pleistocene stratigraphy of south-central British Columbia. Canadian Journal of Earth Sciences, 15: 971-980.

Fyles, J. G., 1956. Surficial geology of the Horne Lake and Parksville map-areas, Vancouver Island, British Columbia. Ph.D. thesis, Ohio State University, Columbus, 283 p.

——— 1963. Surficial geology of Horne Lake and Parksville map-areas, Vancouver Island, British Columbia. Geological Survey of Canada, Memoir 318, 142 p.

Geikie, J., 1894. The great ice age, 3rd edition. Edward Stanford, London, 850 p.

Gibbs, G., 1874. Physical geography of the northwestern boundary of the United States. American Geographical Society Journal, 4: 298-415.

Hamilton, T. D. and Thorson, R. M. 1983. The Cordilleran ice sheet in Alaska, p. 38-52. *In* S. C. Porter, ed., Late-Quaternary environments of the United States, Volume 1, The late Pleistocene. University of Minnesota Press, Minneapolis, 407 p.

Hayes, C. W., 1892. An expedition through the Yukon district. National Geographic Magazine, 4: 117-162.

Heginbottom, J. A., 1972. Surficial geology of Taseko Lakes map-area, British Columbia. Geological Survey of Canada, Paper 72-14, 9 p.

Howes, D. E., 1977. Terrain inventory and late Pleistocene history of the southern part of the Nechako Plateau. British Columbia Ministry of Environment, Resource Analysis Branch, Bulletin 1, 27 p.

——— 1981a. Late Quaternary sediments and geomorphic history of north-central Vancouver Island. Canadian Journal of Earth Sciences, 18: 1-12.

——— 1981b. Terrain inventory and geological hazards: northern Vancouver Island. British Columbia Ministry of the Environment, APD Bulletin 5, 105 p.

——— 1983. Late Quaternary sediments and geomorphic history of northern Vancouver Island. Canadian Journal of Earth Sciences, 20: 57-65.

Hughes, O. L., 1972. Surficial geology of northern Yukon Territory and northwestern District of Mackenzie, Northwest Territories. Geological Survey of Canada, Paper 69-36, 11 p.

Hughes, O. L., Campbell, R. B., Muller, J. E. and Wheeler, J. O., 1969. Glacial limits and flow patterns, Yukon Territory south of 65 degrees north latitude. Geological Survey of Canada, Paper 68-34, 9 p.

Hughes, O. L., Rutter, N. W., Matthews, J. V., Jr. and Clague, J. J., 1989. Unglaciated areas [Quaternary stratigraphy and history, Canadian Cordillera], p. 68-70. *In* R. J. Fulton, ed., Quaternary geology of Canada and Greenland. Geological Survey of Canada, Geology of Canada, no. 1, 839 p. [also Geological Society of America, The Geology of North America, v. K-1].

Imbrie, J. and Imbrie, K. P., 1979. Ice ages; solving the mystery. Enslow Publishers, Short Hills (Jew Jersey), 224 p.

Jackson, L. E., Jr., 1980. Glacial history and stratigraphy of the Alberta portion of the Kananaskis Lake map area. Canadian Journal of Earth Sciences, 17: 459-477.

Jackson, L. E., Jr. and Pawson, M., 1984. Alberta radiocarbon dates. Geological Survey of Canada, Paper 83-25, 27 p.

Jackson, L. E., Jr., Rutter, N. W., Hughes, O. L. and Clague, J. J., 1989. Glaciated fringe [Quaternary stratigraphy and history, Canadian Cordillera], p. 63-68. *In* R. J. Fulton, ed., Quaternary geology of Canada and Greenland. Geological Survey of Canada, Geology of Canada, no. 1, 839 p. [also Geological Society of America, The Geology of North America, v. K-1].

Jamieson, T. F., 1868. On the last geological changes in Scotland. Quarterly Journal of the Geological Society of London, 2: 161-195.

Johnston, W. A., 1921. Pleistocene oscillations of sea-level in the Vancouver region, British Columbia. Transactions of the Royal Society of Canada, ser. 3, 15 (4): 9-19.

——— 1926. The Pleistocene of Cariboo and Cassiar districts, British Columbia, Canada. Transactions of the Royal Society of Canada, ser. 3, 20 (4): 137-147.

——— 1932. Fifty years of Pleistocene geology in Canada. *In* Fifty years retrospect, p. 131-135. *In* Royal Society of Canada, Anniversary Volume, 1882-1932, 179 p.

——— 1933. Quaternary geology of North America in relation to the migration of man, p. 9-45. *In* D. Jenness, ed., The American aborigines, their origin and antiquity. University of Toronto Press.

Johnston, W. A. and Uglow, W. L., 1926. Placer and vein gold deposits of Barkerville, Cariboo district, British Columbia. Geological Survey of Canada, Memoir 149, 246 p.

——— 1933. Placer and vein gold deposits of Barkerville, Cariboo District, British Columbia. Geological Survey of Canada, Summary Report 1932, pt. AI, p. 1AI-75AI.

Johnston, W. A. and Wickenden, R. J. D., 1931. Moraines and glacial lakes in southern Saskatchewan and southern Alberta, Canada. Transactions of the Royal Society of Canada, ser. 3, 25 (4): 29-44.

Jopling, A. V., 1975. Early studies on stratified drift, p. 4-21. *In* A. V. Jopling and B. C. McDonald, ed., Glaciofluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists, Special Publication 23, 320 p.

Kerr, F. A., 1934. Glaciation in northern British Columbia. Transactions of the Royal Society of Canada, ser. 3, 28 (4): 17-31.

——— 1936. Quaternary glaciation in the Coast Range, northern British Columbia and Alaska. Journal of Geology, 44: 681-700.

Klassen, R. W., 1978. A unique stratigraphic record of late Tertiary-Quaternary events in southeastern Yukon. Canadian Journal of Earth Sciences, 15: 1885-1886.

——— 1987. The Tertiary-Quaternary stratigraphy of the Liard Plain, southeastern Yukon Territory. Geological Survey of Canada, Paper 86-17, 16 p.

Lemke, R. W., Laird, W. M., Tipton, M. J. and Lindvall, R. M., 1965. Quaternary geology of northern Great Plains, p. 15-27. *In* H. E. Wright, Jr. and D. G. Frey, ed., The Quaternary of the United States. Princeton University Press, 992 p.

Luternauer, J. L. and Murray, J. W., 1983. Late Quaternary morphologic development and sedimentation, central British Columbia continental shelf. Geological Survey of Canada, Paper 83-21, 38 p.

Lyell, C., 1833. Principles of geology [2 vol.]. J. Murray, London, 1099 p.

Mathews, W. H., 1944. Glacial lakes and ice retreat in south-central British Columbia. Transactions of the Royal Society of Canada, ser. 3, 38 (4): 39-57.

——— 1978. Quaternary stratigraphy and geomorphology of Charlie Lake (94A) map-area, British Columbia. Geological Survey of Canada, Paper 76-20, 25 p.

Mathews, W. H., Fyles, J. G. and Nasmith, H. W. 1970. Postglacial crustal movements in southwestern British Columbia and adjacent Washington state. Canadian Journal of Earth Sciences, 7: 690-702.

McConnell, R. G., 1891. Report on an exploration in the Yukon and Mackenzie basins, N.W.T. Geological Survey of Canada, Annual Report, new ser., v. 4 (1888-1889), rept. D, 163 p.

——— 1903. The Macmillan River, Yukon district. Geological Survey of Canada, Summary Report 1902, p. 20-36.

Osborn, H. F., 1910. The age of mammals in Europe, Asia, and North America. Macmillan Company, New York, 635 p.

Pardee, J. T., 1910. The glacial Lake Missoula. Journal of Geology, 18: 376-386.

Paterson, W. S. B., 1969. The physics of glaciers. Pergamon Press, Oxford, 241 p.

Porter, S. C., Pierce, K. L. and Hamilton, T. D., 1983. Late Wisconsin mountain glaciation in the western United States, p. 71-111. *In* S. C. Porter, ed., Late Quaternary environments of the United States, Volume 1, The late Pleistocene. University of Minnesota Press, Minneapolis, 407 p.

Prest, V. K., 1984. Late Wisconsinan glacier complex. Geological Survey of Canada, Map 1584A.

Prest, V. K., Grant, D. R. and Rampton, V. N., 1968. Glacial map of Canada. Geological Survey of Canada, Map 1253A.

Rampton, V. N., 1971. Late Pleistocene glaciations of the Snag-Klutlan area, Yukon Territory. Arctic, 24: 277-300.

Richardson, J., 1876. Report on explorations in British Columbia. Geological Survey of Canada, Report of Progress, 1874-1875, p. 71-83.

Richmond, G. M., Fryxell, R., Neff, G. E. and Weis, P. L., 1965. The Cordilleran Ice Sheet of the northern Rocky Mountains and related Quaternary history of the Columbia Plateau, p. 231-242. *In* H. E. Wright, Jr. and D. G. Frey, ed., The Quaternary history of the United States. Princeton University Press, Princeton, 407 p.

Roberts, B. L., 1990. A computer model of the Late Wisconsinan Cordilleran Ice Sheet. Ph.D. thesis, Kent State University, Kent, 288 p.

Roed, M. A., 1975. Cordilleran and Laurentide multiple glaciation, west central Alberta. Canadian Journal of Earth Sciences, 12: 1493-1515.

Russell, I. C., 1890. Notes on the surface geology of Alaska [with discussion by N. S. Shaler and T. C. Chamberlin]. Geological Society of America Bulletin, 1: 99-162.

Rutter, N. W., 1972. Geomorphology and multiple glaciation in the area of Banff, Alberta. Geological Survey of Canada, Bulletin 206, 54 p.

——— 1976. Multiple glaciation in the Canadian Rocky Mountains with special emphasis on northeastern British Columbia, p. 409-440. *In* W. H. Mahaney, ed., Quaternary stratigraphy of North America. Dowden, Hutchinson & Ross, Stroudsburg (Pennsylvania), 512 p.

——— 1977. Multiple glaciation in the area of Williston Lake, British Columbia. Geological Survey of Canada, Bulletin 273, 31 p.

Ryder, J. M., 1976. Terrain inventory and Quaternary geology Ashcroft, British Columbia. Geological Survey of Canada, Paper 74-49, 17 p.

——— 1981. Terrain inventory and Quaternary geology, Lytton, British Columbia. Geological Survey of Canada, Paper 79-25, 20 p.

Ryder, J. M. and Clague, J. J. 1989. British Columbia [Quaternary stratigraphy and history, Cordilleran Ice Sheet], p. 48-58. *In* R. J. Fulton, ed., Quaternary geology of Canada and Greenland. Geological Survey of Canada, Geology of Canada, no. 1, 839 p. [also Geological Society of America, The Geology of North America, v. K-1].

Shaler, N. S. and Davis, W. M., 1881. Illustrations of the earth's surface; glaciers. Osgood and Company, Boston, 198 p.

Sutherland Brown, A., 1968. Geology of the Queen Charlotte Islands, British Columbia. British Columbia Department of Mines and Petroleum Resources, Bulletin 54, 226 p.

Stalker, A.MacS. and Harrison, J. E., 1977. Quaternary glaciation of the Waterton-Castle River region of Alberta. Bulletin of Canadian Petroleum Geology, 25: 882-906.

Thorson, R. M. and Dixon, E. J., Jr., 1983. Alluvial history of the Porcupine River, Alaska: role of glacial-lake overflow from northwest Canada. Geological Society of America Bulletin, 94: 576-589.

Tipper, H. W., 1971a. Glacial geomorphology and Pleistocene history of central British Columbia. Geological Survey of Canada, Bulletin 196, 89 p.

——— 1971b. Multiple glaciation in central British Columbia. Canadian Journal of Earth Sciences, 8: 743-752.

Tyrrell, J. B., 1919. Was there a "Cordilleran glacier" in British Columbia?. Journal of Geology, 27: 55-60.

Upham, W., 1896. The glacial Lake Agassiz. United States Geological Survey, Monograph 25, 658 p.

Westgate, J. W. and Fulton, R. J., 1975. Tephrostratigraphy of Olympia Interglacial sediments in south-central British Columbia, Canada. Canadian Journal of Earth Sciences, 12: 489-502.

Willis, B., 1898. Drift phenomena of Puget Sound. Geological Society of America Bulletin, 9: 111-162.

Wilson, J. T., Falconer, G., Mathews, W. H. and Prest, V. K. [compilers], 1958. Glacial map of Canada. Geological Association of Canada, Toronto.

Wood, H. R., 1892. Glaciation in western Montana. Science, 20: 162-163.