Géographie physique et Quaternaire

The Cordilleran Ice Sheet and the Glacial Geomorphology of Southern and Central British Colombia
L'Inlandsis de la Cordillère et la géomorphologie glaciaire du sud et du centre de la Colombie-Britannique
Die Kordilleren-Eisdecke und die glaziale Géomorphologie im Süden undim Zentrum von British Columbia

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Volume 45, numéro 3, 1991

L'Inlandis de la Cordillère
The Cordilleran Ice Sheet

URI : https://id.erudit.org/iderudit/032882ar
DOI : https://doi.org/10.7202/032882ar

Aller au sommaire du numéro

Éditeur(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (imprimé)
1492-143X (numérique)

Découvrir la revue

Citer cet article

Ryder, J. M., Fulton, R. J. & Clague, J. J. (1991). The Cordilleran Ice Sheet and the Glacial Geomorphology of Southern and Central British Colombia. *Géographie physique et Quaternaire*, *45*(3), 365–377. https://doi.org/10.7202/032882ar

Résumé de l'article

On résume ici l'état des connaissances sur l'Inlandsis de la Cordillère du sud et du centre de la Colombie-Britannique. Les reconstitutions de l'inlandsis et les modes d'englaciation et de déglaciation sont fondés sur les formes et les sédiments glaciaires qui datent de la glaciation du Wisconsinien supérieur (Fraser). On décrit également les lacs tardiglaciaires et les changements du niveau marin en relation avec les conséquences sur les niveaux isostatique et eustatique. Les rythmes de la progression et du retrait glaciaire ont été tout à fait différents; la giaciation a commencé vers 29 000 BP, a connu son optimum entre 14 500 et 14 000 BP et la déglaciation était à toutes fins utiles terminée dès 11 500 BP. La plus grande partie de cette époque a été dominée par une glaciation de type alpin, qui a engendré des formes d'érosion remarquables. L'Inlandsis de la Cordillère n'a existé que de 19 000 à 13 500 BP. On a identifié une glaciation plus ancienne, probablement du Wisconsinien inférieur, à partir des affleurements répandus de dépôts glaciaires sous-jacents aux sédiments non glaciaires du Wisconsinien moyen. On a observé des dépôts glaciaires pré-wisconsiniens près de Vancouver. Les dépôts glaciaires datant du Tertiaire supérieur au Pleistocene moyen ont été datés par association aux séquences volcaniques du sud des montagnes Côtières et du centre de l'Intérieur et grâce à des études de paléomagnétisme menées dans le sud du système de l'Intérieur.

Géographie physique et Quaternaire, 1991, vol. 45, n° 3, p. 365-377, 13 fig., 1 tabl.

THE CORDILLERAN ICE SHEET AND THE GLACIAL GEOMORPHOLOGY OF SOUTHERN AND CENTRAL BRITISH COLUMBIA

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ABSTRACT This paper reviews the current state of knowledge about the Cordilleran Ice Sheet in southern and central British Columbia. Reconstructions of the ice sheet and the styles of ice expansion and deglaciation are based on extensive and varied glacigenic sediments and landforms that date from Late Wisconsinan (Fraser) Glaciation. Late-glacial lakes and sea level changes are also described and related to isostatic and eustatic effects. The timing of ice expansion and recession during Fraser Glaciation was markedly asymmetric: ice build-up commenced about 29 000 years BP, culminated between 14 500 and 14 000 years BP, and deglaciation was largely completed by 11 500 years BP. Most of this interval appears to have been dominated by montane glaciation, which produced striking erosional landforms. A Cordilleran Ice Sheet existed from only about 19 000 to 13 500 years BP. An older glaciation, probably of Early Wisconsinan age, has been recognized from widespread exposures of drift that underlies Middle Wisconsinan nonglacial sediments. Pre-Wisconsinan drift is present near Vancouver. Drifts of late Tertiary to Middle Pleistocene age have been dated by association with volcanic sequences in the southern Coast Mountains and the central Interior, and by paleomagnetic studies in the southern Interior.

RÉSUMÉ *L'Inlandsis de la Cordillère et la géomorphologie glaciaire du sud et du centre de la Colombie-Britannique*. On résume ici l'état des connaissances sur l'Inlandsis de la Cordillère du sud et du centre de la Colombie-Britannique. Les reconstitutions de l'inlandsis et les modes d'englaciation et de déglaciation sont fondés sur les formes et les sédiments glaciaires qui datent de la glaciation du Wisconsinien supérieur (Fraser). On décrit également les lacs tardiglaciaires et les changements du niveau marin en relation avec les conséquences sur les niveaux isostatique et eustatique. Les rythmes de la progression et du retrait glaciaire ont été tout à fait différents; la giaciation a commencé vers 29 000 BP, a connu son optimum entre 14 500 et 14 000 BP et la déglaciation était à toutes fins utiles terminée dès 11 500 BP. La plus grande partie de cette époque a été dominée par une glaciation de type alpin, qui a engendré des formes d'érosion remarquables. L'Inlandsis de la Cordillère n'a existé que de 19 000 à 13 500 BP. On a identifié une glaciation plus ancienne, probablement du Wisconsinien inférieur, à partir des affleurements répandus de dépôts glaciaires sous-jacents aux sédiments non glaciaires du Wisconsinien moyen. On a observé des dépôts glaciaires pré-wisconsiniens près de Vancouver. Les dépôts glaciaires datant du Tertiaire supérieur au Pléistocène moyen ont été datés par association aux séquences volcaniques du sud des montagnes Côtières et du centre de l'Intérieur et grâce à des études de paléomagnétisme menées dans le sud du système de l'Intérieur.

ZUSAMMENFASSUNG *Die Kordilleren-Eisdecke und die glaziale Geomorphologie im Süden und im Zentrum von British Columbia*. Dieser Artikel gibt einen überblick über den gegenwärtigen Forschungsstand zur Kordilleren-Eisdecke im Süden und im Zentrum von British Columbia. Die Rekonstruktionen der Eisdecke und der Art und Weise der Eisausdehnung und Enteisung stützen sich auf extensive und mannigfache glazigene Sedimente und Landformen, die aus der Spät-Wisconsin- (Fraser) Vereisung stammen. Spätglaziale Seen und Meeresniveauwechsel werden auch beschrieben und in Beziehung zu isostatischen und eustatischen Auswirkungen gesetzt. Der zeitliche Ablauf der Eisausdehnung und des Eisrückzugs während der Fraser-Vereisung war deutlich asymmetrisch: die Vereisung begann um etwa 29 000 Jahre v.u.Z., erreichte ihren Höchststand zwischen 14 500 und 14 000 Jahren v.u.Z. und die Enteisung war weitgehend vollendet um 11 500 Jahre v.u.Z. Der größte Teil dieses Zeitraums scheint von einer alpinen Vereisung beherrscht gewesen zu sein, welche eindrucksvolle Erosions-Landformen hervorbrachte. Eine Kordilleren-Eisdecke existierte nur von etwa 19 000 bis 13 500 Jahre v.u.Z. Eine ältere Vereisung, möglicherweise aus dem frühen Wisconsin konnte anhand ausgedehnter Anlagen von glazialen Ablagerungen, die sich unter nicht-glazialen Sedimenten des mittleren Wiskonsin befinden, identifiziert werden. Abgelagerte Bildungen aus dem Spättertiär bis zum mittleren Pleistozän wurden in Verbindung mit vulkanischen Sequenzen in den Bergen der Südküste und dem zentralen Landesinnern und mittels paläomagnetischen Studien im südlichen Landesinnern datiert.

Manuscrit reçu le 7 mars 1991; manuscrit révisé accepté le 20 septembre 1991

INTRODUCTION

This paper reviews those aspects of the Cordilleran Ice Sheet that are of current interest and have received considerable attention during the past three decades. The area of the review is that part of British Columbia south of the Skeena and Nechako Rivers (Fig. 1). We use the term "Cordilleran Ice Sheet" to refer to the contiguous ice cover that developed over southern British Columbia during several Pleistocene glaciations.

DESCRIPTION OF THE ICE SHEET

The morphology of the southern Cordilleran Ice Sheet has been reconstructed from evidence provided by landforms and sediments of the most recent (Late Wisconsinan or Fraser) glaciation. At the Late Wisconsinan glacial maximum, the ice sheet was a complex of mountain icefields and valley glaciers feeding into a vast system of contiguous ice masses and piedmont lobes. Striations, grooves, and drumlins show that ice flowed outward from the main mountain systems, and southward along major depressions such as the Rocky Mountain Trench, Okanagan Valley, and Strait of Georgia (Fig. 2). Over the interior plateaus, ice diverged northward and southward from a divide at about 52°N (Wilson *et al.*, 1958; Prest *et al.*, 1968). If ice flow direction indicators are considered to represent conditions at the glacial maximum, and assuming flow at the base of the ice sheet was controlled by ice-surface topography, then the ice sheet surface was highest within the Coast and Columbia mountains, moderately high at a saddle on the Fraser Plateau at 52°N, and lower elsewhere.

It has been suggested that a massive ice dome developed over south-central British Columbia during Fraser Glaciation (*cf.*, Wilson *et al.*, 1958; Flint, 1971; Fulton, 1975). However, a well defined, radiating ice-flow pattern, such as would be associated with an ice dome, is lacking. It is likely, however, that a thicker, domed ice sheet developed at times during earlier glaciations. Evidence that the Cordilleran Ice Sheet was more extensive during the "penultimate" glaciation (Early Wisconsinan or older) has been reported (*cf.*, Tipper, 1971; Waitt and Thorson, 1983; Ryder, 1989).

Within the mountains, the distribution of glacially scoured bedrock and erratics indicates that the surface of the ice sheet was generally above 2300 m (Clague, 1989c). High peaks projected as nunataks with a local relief of up to about 300 m (Figs. 2 and 3). Ice was more than 2000 m thick over major valleys. Along the coast, fiord glaciers terminated in coalescent piedmont lobes that covered the coastal lowlands and parts of the continental shelf, and extended, in places, to the shelf edge where they calved into deep water (Fig. 2) (Luternauer

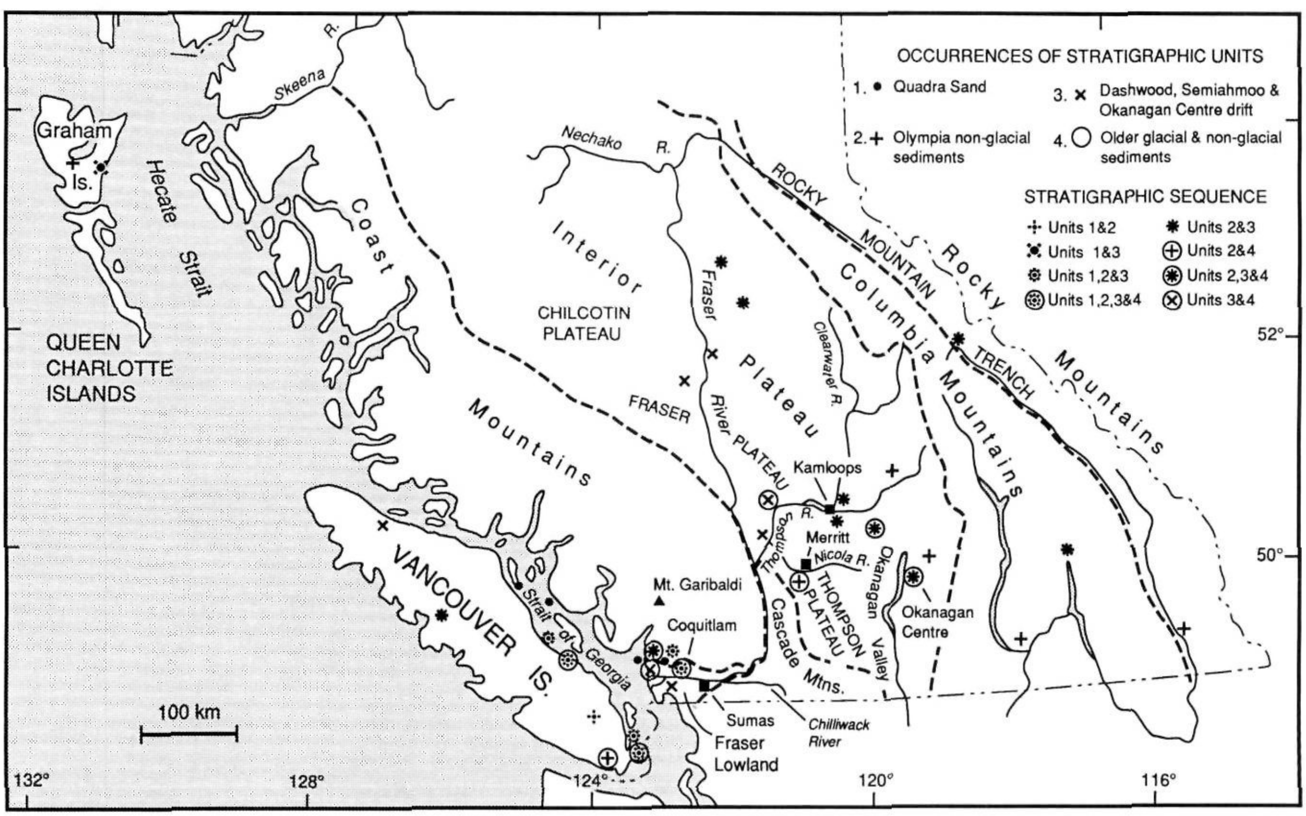

FIGURE 1. Location map for southern and central British Columbia, showing chief sites where Quaternary stratigraphic units have been described (sites from Alley, 1979; Clague, 1975b, 1987, 1988; Clague *et al.*, 1982a, 1990; Fulton, 1968, 1975; Fulton and Smith, 1978; Fyles, 1963; Hicock and Armstrong, 1981, 1983; Howes, 1981, 1983; Ryder, 1976, 1981).

Carte de localisation du sud et du centre de la Colombie-Britannique montrant les principaux sites d'où proviennent les unités stratigraphiques décrites (sites de Alley, 1979; Clague, 1975b, 1987, 1988; Clague et al., *1982a, 1990; Fulton, 1968, 1975; Fulton et Smith, 1978; Fyles, 1963; Hicock et Armstrong, 1981, 1983; Howes, 1981, 1983; Ryder, 1976, 1981).*

and Murray, 1983). The Queen Charlotte Islands were incompletely covered by an independent mass of mountain icecaps and interconnected valley and piedmont glaciers that coalesced with a lobe of mainland ice sheet in Hecate Strait (Clague *et al.*, 1982a). Intermontane plateaus and lowlands were totally buried by ice that was probably hundreds of metres thick over the highest ridges. Within these central parts of the ice sheet, surface gradients were relatively gentle and largely unrelated to the relief of the underlying terrain. Consequently, flow directions were commonly discordant to local topography, resulting in differential erosion and local preservation of older drift deposits (Fig. 4).

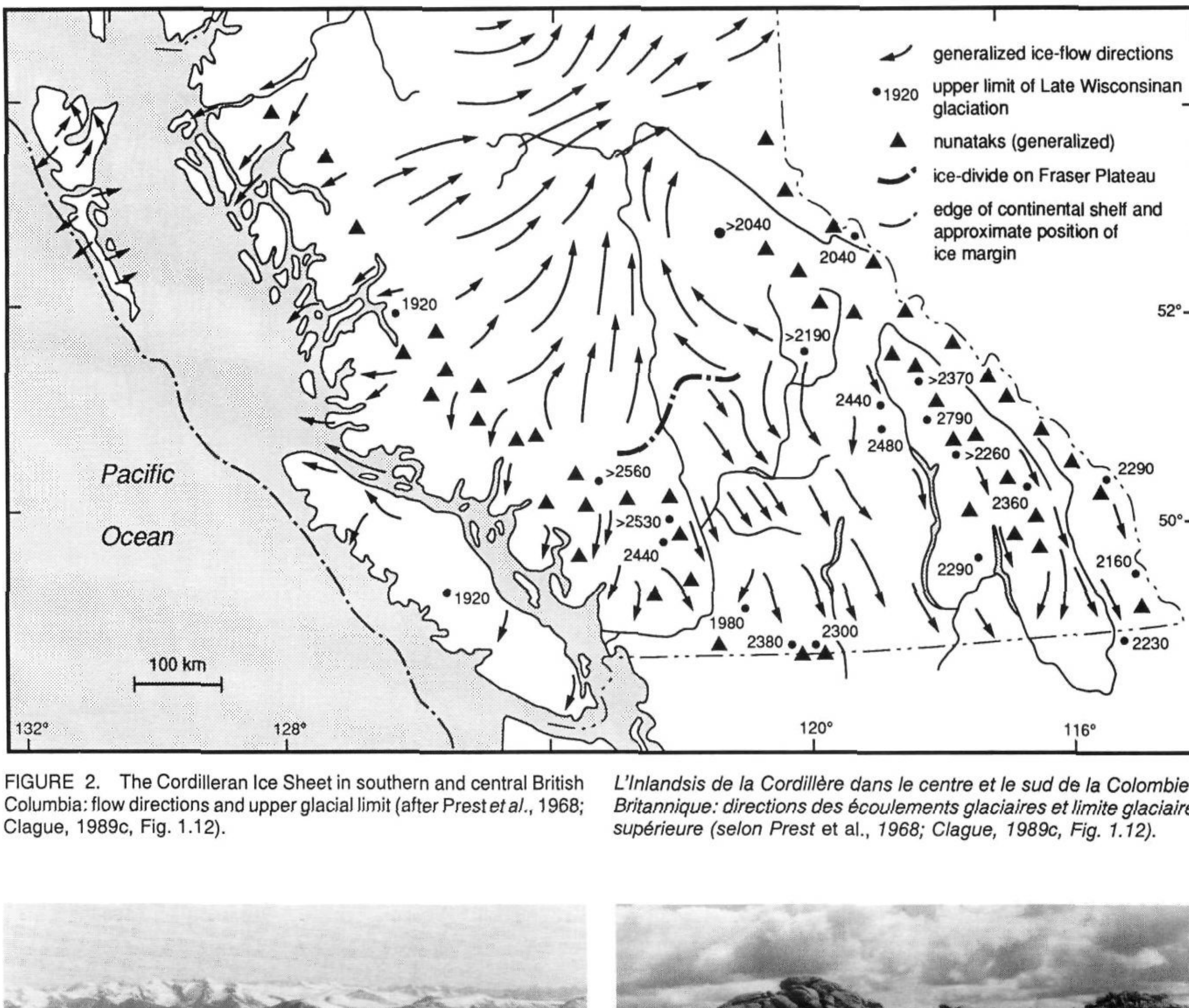

FIGURE 2. The Cordilleran Ice Sheet in southern and central British Columbia: flow directions and upper glacial limit (after Prest *et al.*, 1968; Clague, 1989c, Fig. 1.12).

L'Inlandsis de la Cordillère dans le centre et le sud de la Colombie-Britannique: directions des écoulements glaciaires et limite glaciaire supérieure (selon Prest et al., *1968; Clague, 1989c, Fig. 1.12).*

FIGURE 3. A. The central Coast Mountains at about 50°N. Rounded summits in the foreground were overridden by the ice sheet; distant horns were probably nunataks. B. Eastern side of the Cascade Mountains near 49°N: tors and deep grus on a summit plateau at 2500 m elevation, above the upper limit of Fraser Glaciation.

A. La partie centrale des montagnes Côtières vers 50°N. Les sommets arrondis au premier plan ont été recouvert par l'inlandsis; les pics au loin étaient probablement des nunataks. B. Le côté est des monts Cascades vers 49°N; tors et arènes sur le sommet du plateau à 2500 m, au-dessus de la limite supérieure de la Glaciation de Fraser.

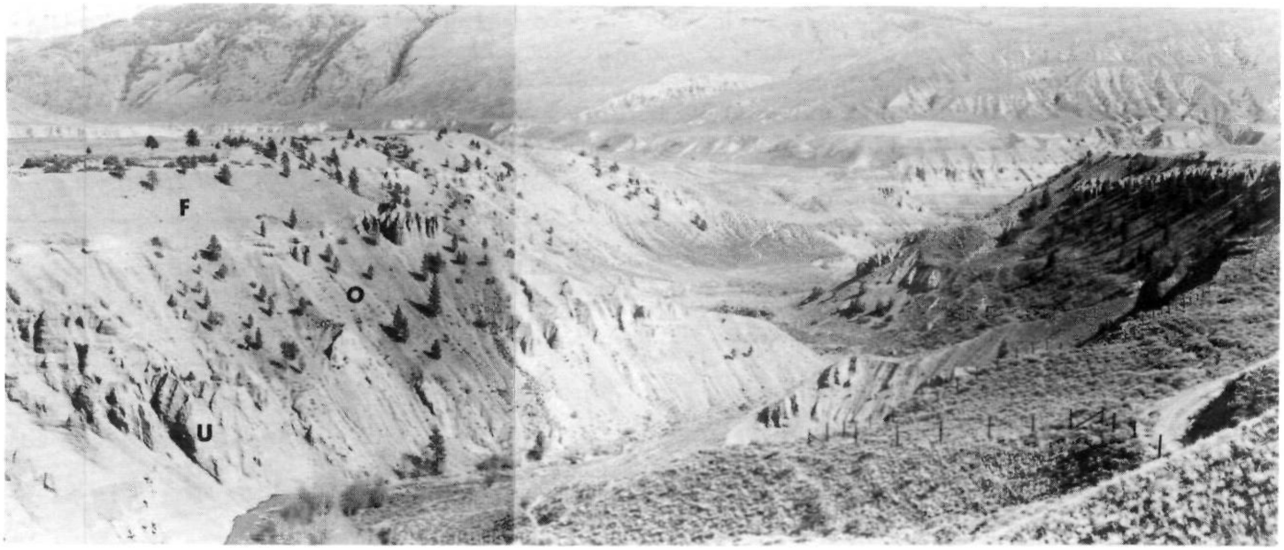

FIGURE 4. Thick sequence of Quaternary sediments in the lower Thompson River valley: drift of Fraser ("F") and Okanagan Centre ("O") glaciations, and older undated sediments ("U"). The preservation of the older sediments resulted from their location in a valley that was transverse to the direction of the ice flow.

La séquence de sédiments quaternaires de grande puissance de la vallée inférieure de la Thompson River comprend des dépôts des glaciations de Fraser ("F") et de Okanagan Centre ("O") et des sédiments glaciaires non datés ("U"). La conservation des sédiments plus anciens est attribuable à leur emplacement dans une vallée transversale à la direction de l'écoulement glaciaire.

CHRONOLOGY

A Cordilleran Ice Sheet occupied southern British Columbia at times during the Early and Middle Pleistocene, and probably even during late Tertiary time. Lavas that overlie till, and ice-contact volcanic rocks in the Chilcotin, Clearwater, and Garibaldi areas range in age from 0.3 to 1.2 Ma (Hickson and Souther, 1984; Mathews and Rouse, 1986; Green *et al.*, 1988) (Table I). A magnetically reversed paleosol and glaciolacustrine sediments near Merritt provide evidence of ice sheet glaciation > 790 ka (Clague *et al.*, 1987, p. 55-57; Fulton *et al.*, in prep.). Other undated drift that may have been deposited during the early and middle parts of the Pleistocene has been described from southern Vancouver Island, Fraser Lowland, and a few other scattered sites (Armstrong and Leaming, 1968; Armstrong, 1975, 1981; Ryder, 1976; Hicock and Armstrong, 1983;) (Fig. 5).

Drift of the penultimate glaciation underlies Middle Wisconsinan nonglacial sediments in many areas (see Fig. 1 for examples). This includes Semiahmoo and Dashwood drifts in the Strait of Georgia area and Okanagan Centre Drift in the southern interior (Fig. 5) (Fyles, 1963; Fulton, 1968; Fulton and Smith, 1978; Hicock and Armstrong, 1983). Dating control on these units if poor, however, and although most have been assigned to the Early Wisconsin Substage, some may be of Illinoian age, and thus older that 125 ka (Clague *et al.*, 1988b; Ryder and Clague, 1989).

The Cordilleran Ice Sheet developed most recently during Fraser Glaciation, although the ice sheet itself existed for less than 8000 years and was preceded by about 10 000 years of glaciation within the mountains (Fig. 5). During this period of mountain glaciation, which corresponds to the alpine and intense alpine phases described by Kerr (1934) and the first and second phases of glaciation of Davis and Mathews (1944), glaciers expanded from cirques to form great branching systems of valley glaciers. Subsequent glacier coalescence and thickening over lowlands and plateaus resulted in the development of a mountain ice sheet (phase three of Davis and Mathews, 1944). A true continental ice sheet (phase four), in which flow directions are controlled largely by the location of centres of accumulation rather than by the subglacial topography (Kerr, 1934; Davis and Mathews, 1944), does not appear to have developed over southern British Columbia at this time.

TABLE I

Ages of older glaciations interpreted from K-Ar dates on volcanic rocks

Location	Description	Date of Glaciation (Ma)	Reference
Clearwater-Wells Gray	ice-contact lavas (tuyas)	0.27, 0,38, 3.5 (?)	Hickson and Souther, 1984
"	lavas over till	> 0.56	"
Dog Creek, Cariboo Plateau	till sandwiched between lavas	1.2	Mathews and Rouse, 1986
Garibaldi volcanic belt	ice-contact lavas	0.17-0.21, 0.5, 0.6	Green *et al.*, 1988
"	lavas over till	> 0.09-0.13, > 0.3, > 0.6, > 0.7, > 1.2	"

The chronology of Fraser Glaciation is based on numerous radiocarbon ages (Clague, 1980; 1981) from many sites. The timing of the early phase of Fraser Glaciation is best known on the south coast, where radiocarbon ages from Quadra

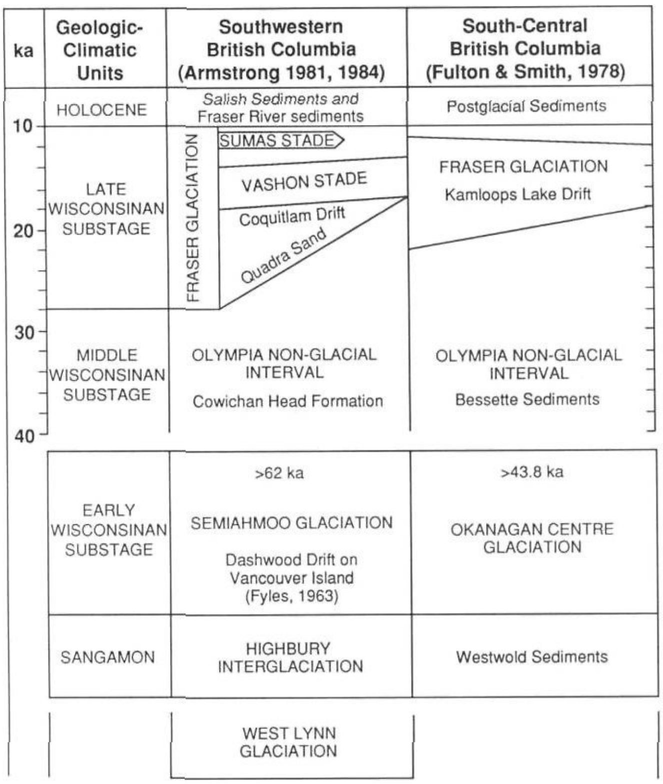

FIGURE 5. Quaternary events and stratigraphic units in southern and central British Columbia. Stratigraphic names are shown only where they differ from those of the glacial and non-glacial intervals.

Les événements du Quaternaire et les unités stratigraphiques du sud et du centre de la Colombie-Britannique. Les noms des unités stratigraphiques ne sont donnés que lorsqu'ils diffèrent de ceux des intervalles glaciaires et non glaciaires.

Sand, a widespread advance outwash unit (Figs. 1 and 6), indicate that climatic deterioration may have begun as early as 29 000 years BP (Clague, 1976, 1977, 1980; Alley, 1979). Gradual build-up of ice within the Coast Mountains resulted in the advance of valley and fiord glaciers, and aggradation of sand in the Strait of Georgia area. Although ice may have been fairly extensive in the northern Strait of Georgia and Hecate Strait by 25 000 to 23 000 years BP, most areas east of the Coast Mountains remained ice free until after 21 000 years BP, and some areas were not overridden until after 17 000 years BP (Clague *et al.*, 1980). A localized and short-lived expansion of valley glaciers into Fraser Lowland, the Coquitlam Stade, occurred about 21 500 years BP (Hicock and Armstrong, 1981). Most of the Lowland was not overridden until after 18 000 years BP, however, and adjacent Chilliwack River valley may still have been ice free 2000 years later (Clague *et al.*, 1988a). The ice sheet attained its greatest southerly extent 14 000 to 14 500 years BP, during the Vashon Stade of Fraser Glaciation (Mullineaux *et al.*, 1965; Hicock and Armstrong, 1985). In contrast, piedmont lobes near the Queen Charlotte Islands may have reached their climax positions a thousand years earlier (Blaise *et al.*, 1990).

Subsequent decay of the Ice Sheet was rapid. Deglaciation of the coast began before 13 500 years BP, and was largely complete (with the exception of some mainland fiords) 2000 years later (Clague, 1981). Coastal glaciers receded rapidly by calving due to destabilization resulting from eustatic sea level rise. Within the interior, deglaciation was dominated by downwasting rather than by frontal recession, resulting in the emergence of uplands and the isolation of large masses of stagnant and ablating ice in valleys and lowlands (Fulton, 1967). The upstream parts of many drainage basins became ice free before the valleys downstream, resulting in the formation of many proglacial lakes. Some montane valleys on the drier east side of the southern Coast Mountains were ice free and forested prior to 11 500 years BP (Souch, 1989), suggesting that deglaciation may have been well underway in the southern interior by that time.

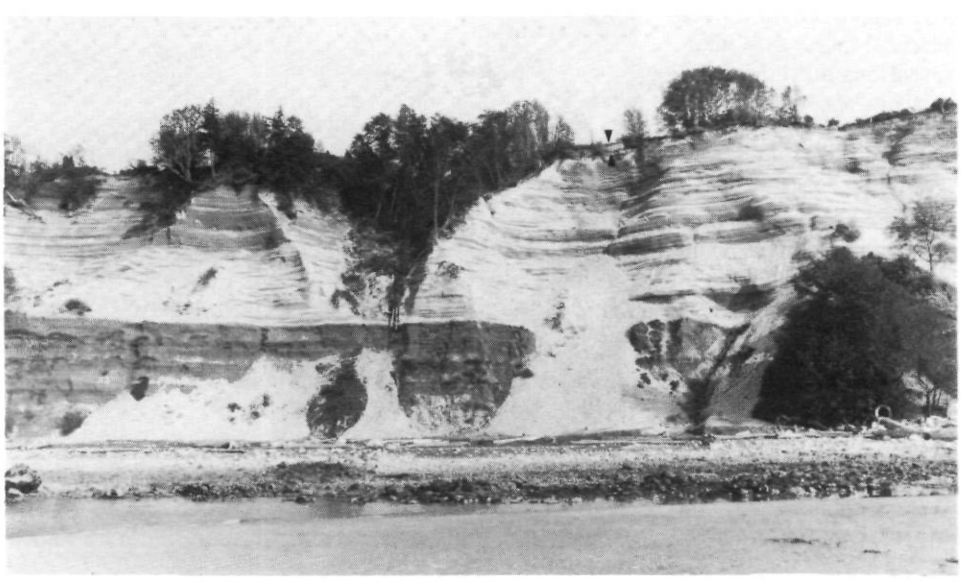

FIGURE 6. Quadra Sand exposed in the sea cliffs at Point Grey in western Fraser Lowland. The lower (dark grey on photo) part of unit consists of sand and interbedded silt and peat. Boulders on the beach are derived from the Vashon Till (between arrows).

Le sable de Quadra mis au jour dans les falaises de Point Grey, dans la partie ouest des basses terres du Fraser. La partie inférieure de l'unité (gris foncé) est composée de sable et de limon et de tourbe interstratifiés. Les blocs sur la plage proviennent du Till de Vashon (entre les flèches).

A few minor readvances occurred at various times during the period of general recession. The best known of these is the Sumas advance in Fraser Lowland, about 11 500 years BP (Armstrong, 1981; Saunders *et al.*, 1987). In most areas, however, recession appears to have occurred rapidly and continuously.

GLACIAL SEDIMENTS AND THE STRATIGRAPHIC RECORD

Although nonglacial intervals were of longer duration than glaciations, particularly intervals of ice-sheet glaciation, glacial deposits are more significant than non-glacial deposits in the sedimentary record of southern British Columbia. Increased rates of mass wasting that accompanied climate deterioration, glacial and meltwater erosion, and rapid reworking of glacigenic sediments on unvegetated slopes gave rise to rates of sediment accumulation in glacial and proglacial environments that were not matched during non-glacial intervals (Church and Ryder, 1972; Clague, 1986, 1989b). Glacigenic sediments and associated landforms remain the most prominent features of the present day "nonglacial" landscape.

A wide variety of glacigenic sediments is associated with the southern part of the Cordilleran Ice Sheet (see comprehensive descriptions in Clague, 1989a). Information about their distribution is available from Federal and Provincial surficial geology maps which cover about two-thirds of the area of the southern part of the province. Till is most widespread; it is variable with regard to texture and consolidation, reflecting derivation from a variety of bedrock lithologies and older Quaternary sediments, and various modes of deposition. Glaciofluvial sediments, which consist predominantly of sand and gravel, include hummocky ice-contact deposits (Figs. 7a and 7b), and outwash that accumulated in subaerial and subaqueous environments. Glaciomarine sediments, consisting chiefly of mud and diamicton but locally including sand and gravel, are widespread in coastal lowlands. Glaciolacustrine sediments are extensive in interior regions, and are described in more detail below.

Topography exerted the strongest single control on the nature and distribution of these sediments: mountains, intermontane plateaus, and lowlands and valleys each display a characteristic pattern of drift accumulation. Within the mountains, till is widespread and generally consists of large angular clasts in a matrix that is rich in sand and silt, although texture varies locally with provenance (Clague, 1989a). Typically, lower mountain slopes are draped with thick till which commonly includes stratified drift and colluvium, whereas drift is thin and patchy in higher areas. Benches underlain by thick till and glaciofluvial sediments may be present on lower slopes, and glaciolacustrine sediments occur on and near valley floors.

The upland areas of the intermontane plateaus have a discontinuous till cover, with local variations in till thickness controlled, in part, by bedrock topography. Thick till occurs as tails on rock knobs, and as drumlins which may consist partly of glaciofluvial sediments. Swarms of well-developed drumlins cover large parts of the plateaus (Fig. 7b). Eskers, kame terraces and other ice contact features, as well as outwash are locally abundant in low-lying parts of the plateaus and in some valleys (Fulton,1967). Some small valleys and basins are completely filled with older sediment, including nonglacial deposits and drift from previous glaciations (Clague *et al.*, 1990).

Large valleys and extensive lowlands, such as the Rocky Mountain Trench, Okanagan Valley and Fraser Lowland, commonly contain drift accumulations that are tens to hundreds of metres thick (Fig. 4) (*cf.*, Fulton, 1972; Clague, 1975b; Armstrong, 1984). In these areas, glaciolacustrine, glaciofluvial, and, in coastal areas, glaciomarine sediments are more abundant than till; till typically occurs in discontinuous thin sheets within stratified sequences, or it may be completely absent. In general, tills underlying lowlands and valleys are less stony and more silty than mountain tills, and clasts tend to be well rounded because most are derived from pre-existing fluvial gravels.

In general, Late Wisconsinan tills of the Cordilleran Ice Sheet occur as relatively thin, plain-surfaced layers and are

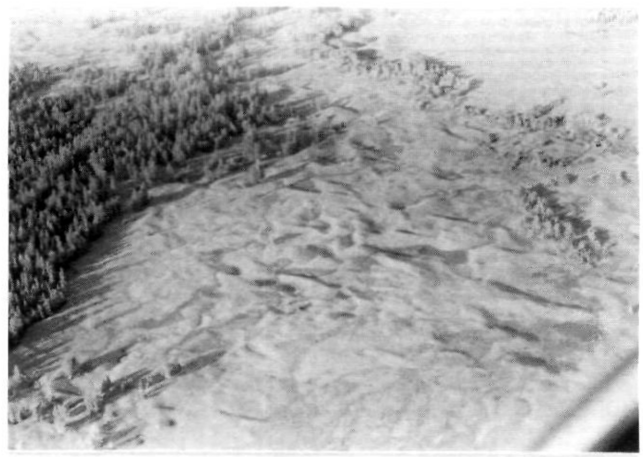

FIGURE 7. Dead-ice topography, western Thompson Plateau: hummocks and ridges are underlain by supraglacial till and ice-contact glaciofluvial gravels. B. Hummocky ice-contact glaciofluvial terrain (foreground and depressions) and drumlins (middle distance) on the Thompson Plateau, southeast of Merritt.

A. Relief de glace morte, partie ouest du plateau de Thompson. Les buttes et les crêtes recouvrent un till supraglaciaire et des graviers fluvio-glaciaires de contact glaciaire. B. Relief en bosses et creux de matériaux fluvio-glaciaires de contact glaciaire (premier plan et dépressions) et drumlins (à distance moyenne) sur le plateau de Thompson, au sud-est de Merritt.

associated with subglacial streamlined forms. This contrasts with the Late Wisconsinan tills of the Laurentide Ice Sheet on the Interior Plains, which in many places are thick and dominated by rolling and hummocky ablation landforms (Klassen, 1989, p. 147). Also, thick stratified sediments are common in the Cordillera, but are uncommon in the area of the Laurentide Ice Sheet. These contrasts are due largely to differences in topography and its influence on the distribution and efficiency of meltwater streams and sediment traps.

Glacial lakes played a significant role with regard to the distribution of stratified drift since they were effective sediment traps. Large volumes of proglacial materials accumulated in the lakes during deglaciation, but lake outlet streams carried relatively little sediment out of the basins. Because of this, extensive outwash deposits and glaciofluvial terraces were not formed downstream from the lakes. For example, in the lower Thompson River valley, the main terraces are kame deltas and Holocene river terraces cut into glaciolacustrine sediments, rather than outwash.

Older Pleistocene glacial and non-glacial deposits are found locally beneath Fraser drift at sites that were protected from glacial erosion, and in lowlands near the periphery of the ice sheet. In many places they occupy valleys that were transverse to the direction of ice flow (Fig. 4); in some places they form benches and skirts on bedrock hills (Fulton, 1975). The most extensive old deposits that have been recognized, occur on eastern Vancouver Island (Fyles, 1963), on eastern Graham Island (Clague *et al.*, 1982a), in Fraser Lowland (Armstrong, 1984), and in Fraser, Thompson, and Okanagan valleys (Fulton, 1975; Ryder, 1976; Clague *et al.*, 1987).

SUBGLACIAL CONDITIONS

No work has yet been directed specifically toward the question of thermal conditions at the base of the southern Cordilleran Ice Sheet. Investigation of glaciotectonic structures has revealed no unequivocal evidence of frozen substrate (*cf.*, Broster and Clague, 1987). A cursory assessment of subglacial features, which include extensive areas of streamlined forms (roches moutonnées, grooves, drumlins) and abundant evidence of subglacial streams (eskers and meltwater channels) (Fig. 8), suggests that large areas of the subglacial bed were unfrozen. This is supported by the rarity of large ice-thrust features and lack of evidence for permafrost in sediments immediately underlying till. In many places, sediment immediately underlying till is contorted and sheared, and weakly defined stratification is commonly visible in large exposures of lodgement till, suggesting that strong shear deformation (*cf.*, Boulton and Hindmarsh, 1987) may have been occurring beneath actively flowing ice.

By way of contrast, subglacial conditions on the Plains promoted widespread shearing and up-thrusting of substrate materials (Clayton and Moran, 1974; Mickelson *et al.*, 1983). Such processes do not appear to have been significant in the southern Cordillera, probably due to the presence of a mostly unfrozen subglacial bed, different bedrock lithologies and structures, and more variable subglacial conditions of hydrology and shear stress imposed by the highly irregular topography.

ALPINE LANDFORM ASSEMBLAGES AND THEIR RELATION TO THE TIMING AND MECHANICS OF GLACIATION

Cirques and associated landforms characteristic of alpine glaciation are well developed throughout the mountainous regions of the study area, but are absent (with rare exceptions — Fig. 8) from the interior plateaus. Analysis of the lowest, north-facing cirques shows that cirque floor elevations rise eastward. At about 52°N, elevations range from 300 m on the west side of Vancouver Island to 2100 m in the Rocky Mountains. This trend may represent the snowline at the onset of glaciation.

Cirques and troughs that are presently ice-free were sculpted most recently during the early alpine phase of Fraser

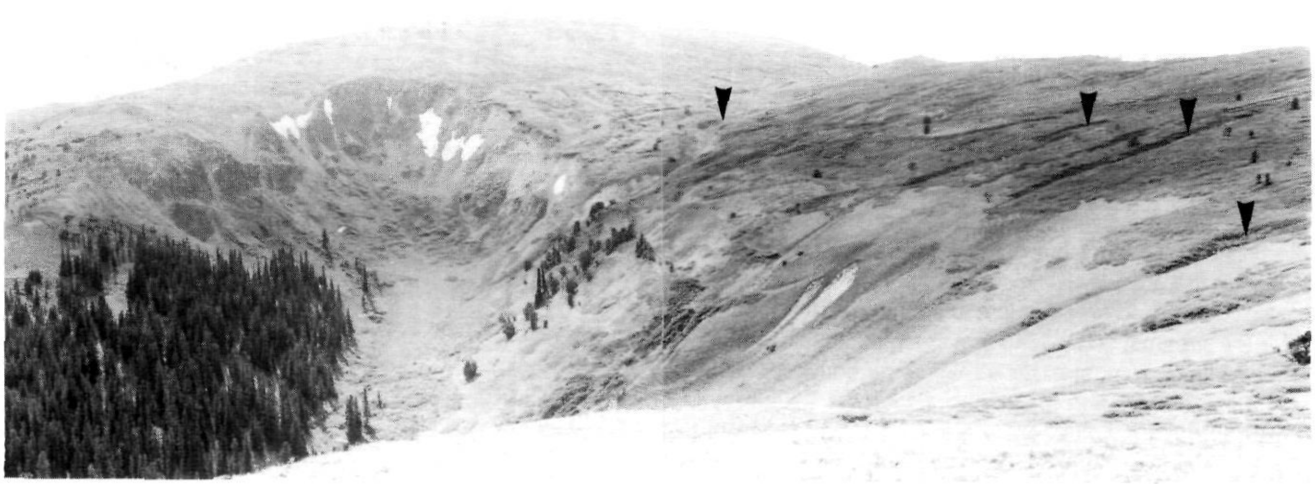

FIGURE 8. This small but well defined cirque on the high western rim of the Fraser Plateau was overridden by the Cordilleran Ice Sheet during the climax of Fraser Glaciation. Meltwater channels (arrows) carried drainage across the adjacent height of land.

Ce petit cirque bien défini, sur le rebord ouest du plateau de Fraser, a été recouvert par l'Inlandsis de la Cordillère durant l'optimum de la Glaciation de Fraser. Des chenaux de fonte sous-glaciaires (flèches) ont assuré le drainage vers les terrains élevés adjacents.

Glaciation. During the glacial maximum, they were totally buried by ice that in many places was not flowing in the local down-valley direction. The general scarcity of recessional moraines in such cirques suggests that they were not occupied by active glaciers for any significant length of time during recession of Fraser Glaciation. Also, the morphology of morainal mounds and ridges in some cirques suggests deposition from stagnant ice, whilst in others, emplacement by ice flowing into the cirques is indicated.

In many alpine valleys, the downstream limit of significant erosion by former glaciers is indicated by an abrupt change from a "U" — to a "V"—shaped cross-profile. Whether this morphological transition indicates the position of glacier termini during a time period when glaciers were relatively stable, or whether it indicates the location where alpine glaciers merged with the ice sheet, has not been determined. Preliminary work in the Cascade Mountains, however, favours the former explanation (Ryder, 1989). The preservation of this morphological transition, together with fresh-appearing cirques (Fig. 8) and troughs, in areas that were entirely overridden by the ice sheet, is attributed to the short duration of the ice sheet phase and to the presence, during the glacial maximum, of stationary, non-eroding ice within valleys that were not aligned parallel to flow.

GLACIAL LAKES

Thick sequences of glaciolacustrine sediments that underlie and overlie till attest to the presence of extensive glacial lakes in southern and central British Columbia during advance and recession of the Cordilleran Ice Sheet (Figs. 9 and 10). Ponding of lakes was due to rugged relief and to the non-alignment of many drainage systems with the directions of ice advance and retreat. In general, lakes formed in the same valleys during both advance and recession. The textures of sediments deposited in the two types of lakes are similar, but stratigraphy and the factors that controlled lake levels were slightly different. The following descriptions refer to lakes that were formed during Fraser Glaciation, but are also probably applicable to older lakes as well.

SEDIMENTS

These typically consist of horizontally laminated silt and fine sand with minor clay (Fulton, 1965; Shaw, 1977; Shaw and Archer, 1978). Gravel, medium and coarse sand, and diamicton are common locally, especially in some deglacial sequences, and were deposited by meltwater discharge from nearby ice and sediment gravity flows. Glaciolacustrine units range from discontinuous veneers, one or two metres in thickness, to major valley fills that are over 100 m thick (Fig. 9). They tend to thicken toward deltas and areas of ice-contact drift at the mouths of tributary streams, suggesting that much of the lake sediment was derived from streams draining recently deglaciated uplands, rather than from subglacial sources. Texture varies locally, but thin units generally are finer textured than thick. Recessional lake deposits become finer upward whilst the reverse has been observed for several advance sequences in south-central British Columbia. Many recessional deposits consist of couplets that are probably varves. These decrease in thickness upward from as much as 6 m in sandy basal units to less that 1 cm at the top of the deposit (Fulton, 1965) (Fig. 9a). In some sections, laminations in advance deposits become thicker upward, but most sequences display no consistent trend.

DISTRIBUTION AND ORIGIN

Advance lake deposits are common in valleys of the British Columbia interior, but are absent from major north-south trending valleys that drain in the same direction as the ice advanced and where materials might have been removed by subsequent glaciation. Even in sheltered locations, many advance lake deposits are of limited extent, suggesting that ponding of tributary valleys was closely followed by glacier overriding. Glacial lakes were uncommon in mountainous areas except in valleys that were blocked relatively early by the advance of glaciers from the Coast Mountains (Ryder and Clague, 1989, p. 53). Damming by glacier ice was the most important cause of ponding during glacier expansion. Although aggradation of glacier-fed trunk streams may have raised base levels in some tributary valleys, this is unlikely to have resulted in the development of major lakes.

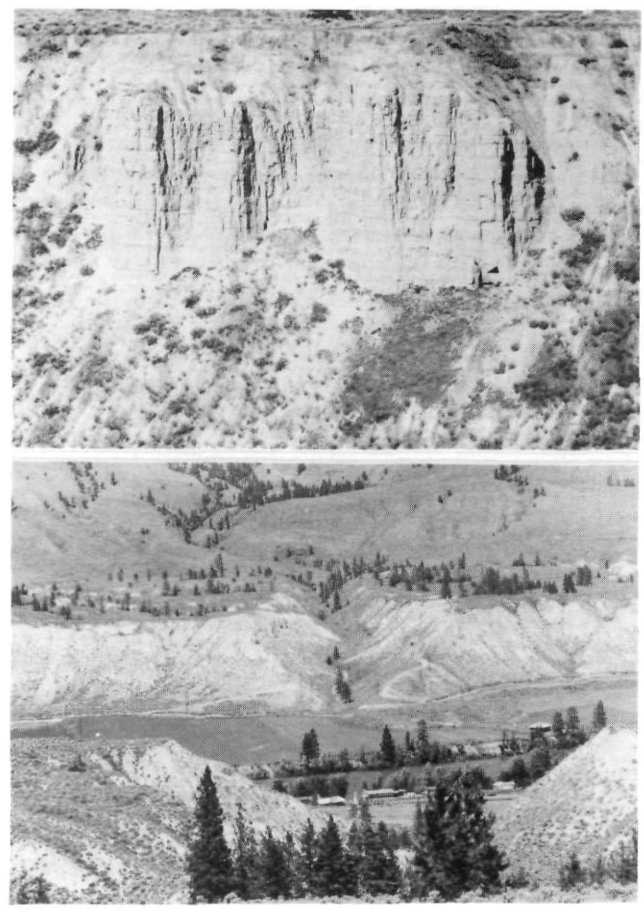

FIGURE 9. A. Varved glaciolacustrine silts near Kamloops; note marked upward decrease in varve thickness. B. View across South Thompson River, east of Kamloops, showing thick, dissected valley fill of glaciolacustrine sediments.

A. Silts glaciolacustres varvés près de Kamloops; noter l'amincissement des varves vers le haut. B. Vue au delà de la South Thompson River, à l'est de Kamloops, montrant d'épaisses accumulations disséquées de sédiments glaciolacustres.

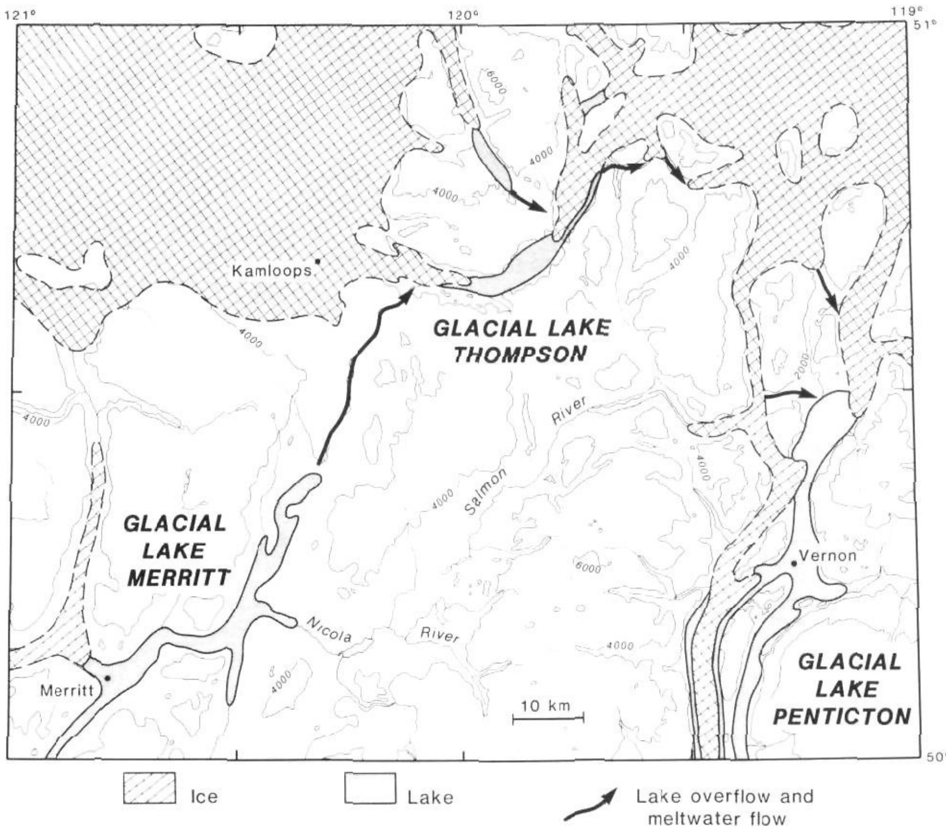

FIGURE 10. Late-glacial lakes in the Thompson and Okanagan basins during recession of Fraser Glaciation (after Fulton, 1969). Glacial Lake Penticton drained southward through an ice-free outlet.

Lacs tardiglaciaires dans les bassins Thompson et Okanagan pendant la phase régressive de la Glaciation de Fraser (selon Fulton, 1969). Le lac glaciaire Penticton s'est écoulé vers le sud par un exutoire libre de glace.

Recessional glacial lakes were common and ranged from small ice-marginal ponds to major lakes in trunk valleys. In mountainous areas, small lakes formed in tributary valleys that became deglaciated while trunk valleys were still occupied by ice; drainage was via ice-marginal or subglacial channels. There are several examples of this in the southern part of the Rocky Mountain Trench (Clague, 1975b).

A complex system of recessional lakes developed in the valleys of the southern interior at the end of Fraser Glaciation (Mathews, 1944; Fulton, 1969). Ice sheet downwasting resulted initially in the development of short-lived glacial lakes in many upland valleys. At first, these lakes drained across divides into adjacent unglaciated valleys, but as the ice downwasted, subglacial or ice-marginal drainage developed. With further recession, glacial lakes expanded along the trunk valleys (Fig. 10). Some lakes, such as those in the Nicola basin, were dammed by ice downstream. Elsewhere, as in the Thompson Valley near Kamloops, lakes were enclosed by two ice dams. Others formed because isostatic tilting temporarily reversed the longitudinal gradient of the valley floor, for example the lake in the Okanagan Valley (Fig. 10).

ROLE OF LAKES REGARDING GLACIER DYNAMICS, DEGLACIATION, AND DEPOSITION

Since many valleys in the southern interior contained lakes during periods of ice sheet growth, some glaciers advanced into deep water. The exact effect of these lakes on ice expansion is unknown, but it might be expected that a floating glacier margin would have advanced more quickly than an adjacent grounded margin. However, the area occupied by proglacial lakes was small in relation to area covered by glaciers, so these lakes probably had little overall effect on the growth of the ice sheet.

Ice flow features indicate that many of the valleys occupied by lakes provided convenient channels for local glacier flow and lakes were the loci of much sediment deposition during both glacier advance and retreat. Some overridden lake sediments were remolded to form a till that is finer textured and better sorted than most Cordilleran tills. In other places, the soft lacustrine sediments were not removed and were barely modified, indicating that most of the ice load was supported by pore water pressure and the glacier was able to slip easily over the sediment.

It has been speculated that glacial lakes at the margin of the Laurentide Ice Sheet played a major role in triggering surges and accelerating ablation of the ice sheet (Dredge and Cowan, 1989). A similar role might be expected for the recessional glacial lakes of the southern Cordilleran Ice Sheet, but several factors argue against this. Although lake sediments are extensive, at any one time only a small percent of the ice margin was fronted by lakes (Fig. 10). Most lakes were long and narrow and hence, even though short segments of the ice margin might have become destabilized, pinning points were close together, so the ice sheet as a whole remained stable. Destabilization also requires rapid and continuous removal of calved-off ice, but the glacial lakes in the southern Cordillera were small and melting was the only means of removing ice from lake basins. Thus even if a surge occurred, the lake basin would have filled with ice relatively quickly and the glacier would have been restabilized. Finally, even the most proximal glacial lake sediments do not contain abundant dropstones (Fulton, 1965; Eyles *et al.* 1987), suggesting that calving was not a significant mode of ablation. In fact, kettled and tilted lake sediments are common in many valleys of southern British Columbia, indicating that ice tongues were buried by lake sediment. These facts suggest that ice lobes remained attached to their beds during deglaciation and were not significantly destabilized by the presence of lakes.

ISOSTATIC AND EUSTATIC EFFECTS

The load of the Cordilleran Ice Sheet caused major isostatic adjustments in the crust and mantle (Clague, 1983). At first, gradual growth of glaciers led to localized depression beneath the main mountain ranges. Lateral flow of asthenosphere material away from these areas produced outward-migrating forebulges, which, together with eustatic effects, may have led to an apparent lowering of sea level in coastal areas. As glaciers expanded beyond the mountains, however, isostatically depressed areas grew, coastal subsidence occurred, and eventually the sea rose above its present level relative to the land. At the climax of Fraser Glaciation, all of the glacier-covered area was isostatically depressed, with the greatest displacement beneath the central area of the ice sheet. Isostatic depression was at least 250 m along the mainland coast (Clague, 1983).

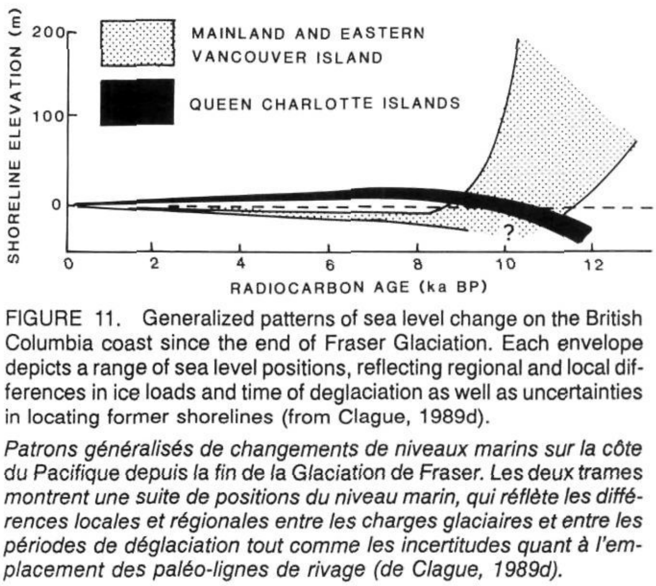

FIGURE 11. Generalized patterns of sea level change on the British Columbia coast since the end of Fraser Glaciation. Each envelope depicts a range of sea level positions, reflecting regional and local differences in ice loads and time of deglaciation as well as uncertainties in locating former shorelines (from Clague, 1989d).

Patrons généralisés de changements de niveaux marins sur la côte du Pacifique depuis la fin de la Glaciation de Fraser. Les deux trames montrent une suite de positions du niveau marin, qui réflète les différences locales et régionales entre les charges glaciaires et entre les périodes de déglaciation tout comme les incertitudes quant à l'emplacement des paléo-lignes de rivage (de Clague, 1989d).

Rapid deglaciation at the end of Fraser Glaciation was accompanied by isostatic uplift which, for the Vancouver Island and the mainland coasts, was greater than the coeval eustatic rise. Thus sea level fell as deglaciation progressed (Fig. 11). The elevation of the marine limit declines with increasing distance from the main centres of ice accumulation. In general, it is highest — about 200 m — on the mainland coast and declines toward the west and southwest to less than 50 m on the west coast of Vancouver Island near the ice sheet margin (Mathews *et al.*, 1970; Clague 1975a; 1981; Clague *et al.*, 1982b).

Isostatic uplift occurred at different times along the British Columbia coast due to diachronous retreat of the ice sheet (Fig. 11). In general, regions that were deglaciated first rebounded earlier than those deglaciated later, indicating that the crust deformed in a complex, non-uniform manner in response to unloading. Even within a region, the sea probably did not fall uniformly relative to the land due to variable rates and directions of eustatic changes, isostatic effects of local glacial stillstands and readvances, and possible displacements along faults due to earthquakes. Evidence of non-uniform emergence has been found in several areas, for example the Fraser Lowland (Mathews *et al.*, 1970).

The record of sea level change on the Queen Charlotte Islands differs from that just outlined (Fig. 11). Shorelines there were lower than at present during deglaciation, rather than higher; following deglaciation there was a marine transgression (rather than emergence) that culminated about 8000 years ago when shorelines were about 15 m above present sea level. These contrasts are best explained in terms of a lesser ice load on the Queen Charlotte Islands and forebulge migration away from the Islands as deglaciation progressed (Clague, 1983).

Isostatic deformation related to deglaciation is also recorded by tilted glacial lake shorelines in the southern interior of British Columbia (Fulton and Walcott, 1975). Surfaces fitted to strandlines in the Nicola basin slope from 2.5 to 1.6 m/km, with the best documented section of strandline sloping at 1.8 m/km (Fig. 12).

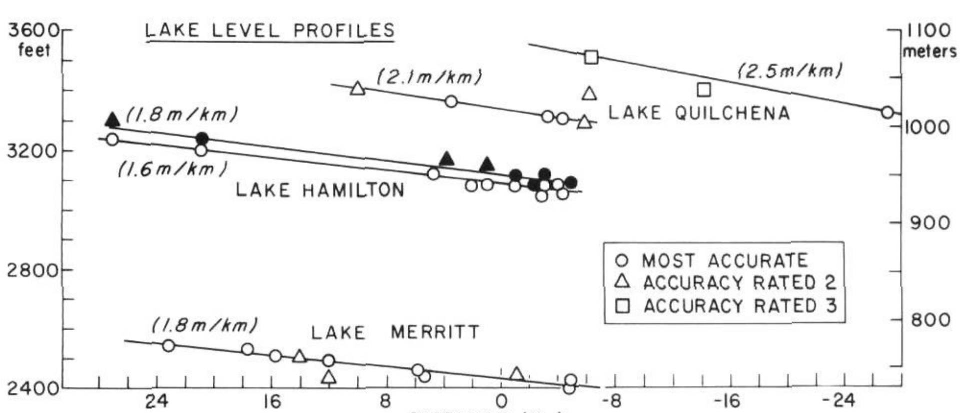

FIGURE 12. Isostatic deformation of glacial lake strandlines in the Nicola River basin, Thompson Plateau. Solid symbols are used for shore features related to the upper level of Lake Hamilton (from Fulton and Walcott, 1975).

Déformation isostatique des lignes de rivage du lac glaciaire dans le bassin de la Nicola River, plateau de Thompson. Les symboles pleins identifient les formes riveraines associées au niveau supérieur du lac Hamilton (de Fulton et Walcott, 1975).

Glacial loading and unloading of the crust may also have triggered volcanism (Mathews, 1958; Grove, 1974). In several areas, there are anomalous volcanic landforms, such as tuyas — flat-topped volcanoes — and esker-like lava flows, that formed during subglacial eruptions (Fig. 13) (Mathews, 1947, 1951, 1958; Hickson and Souther, 1984; Green *et al.*, 1988).

CONCLUDING STATEMENT

Information about the Cordilleran Ice Sheet in southern British Columbia has been derived largely from studies of landforms and drift of the Late Wisconsinan Fraser Glaciation. The styles of growth and decay of the ice sheet have been reconstructed, and the stratigraphy and physical characteristics of Fraser Glaciation drift are now well known, but questions remain about the thickness and surface morphology of the ice sheet at the glacial maxima, the thermal regime of the subglacial bed, and the effects of glacial lakes during glacier advance and recession. The chronology of Fraser Glaciation is generally well established, although dates obtained recently from montane valleys indicate that the period of ice-sheet glaciation may have been shorter than previously thought. Late Pleistocene sea level fluctuations indicate a complex and spatially variable pattern of crustal deformation caused by isostatic uplift and possibly tectonism.

Relatively little information is available about the age and style of pre-Late Wisconsinan glaciation. One Early Wisconsinan or older drift has been recognized in many sections throughout central and southern British Columbia, and an even older (Illinoian?) drift is present in the Fraser Lowland. Remnants of late Tertiary to Middle Pleistocene drift have been found, but there has been little work done on the significance of these deposits.

ACKNOWLEDGEMENTS

R. F. Gerath (Thurber Consultants Ltd) and A. Plouffe (Geological Survey of Canada) reviewed this paper and contributed to its improvement. T. Barry (Geological Survey of Canada) drafted several of the figures.

FIGURE 13. The Table near Mt. Garibaldi: lava from a subglacial eruption was confined by ice to produce this distinctive tuya, described by Mathews (1951).

La «table» près du mont Garibaldi: la lave issue d'une éruption sous-glaciaire a été réprimée par la glace pour donner cette forme à surface plate décrite par Mathews (1951).

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