Article

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GLACIOLACUSTRINE SEDIMENTATION DURING ADVANCE AND RETREAT OF THE CORDILLERAN ICE SHEET IN CENTRAL BRITISH COLUMBIA*

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ABSTRACT Thick (400+ m) and well exposed sediment fills in the Fraser and Chilcotin river valleys of central British Columbia record contrasting glaciolacustrine environments of at least two glaciations. The oldest glaciolacustrine sequence comprises deformed gravel, sand, mud, and diamict facies deposited, in part, on stagnant ice trapped in deep narrow valleys at the end of the penultimate glaciation (Early Wisconsinan or older). Younger glaciolacustrine sequences date from the advance and retreat phases of the Late Wisconsinan Fraser Glaciation (*ca*. 25-10 ka) and infill a Middle Wisconsinan drainage system cut across older sediments. The Late Wisconsinan advance sequence is dominated by diamict (debris-flow) facies that pass upward into silts. The diamict facies consist largely of reworked older Pleistocene drift and poorly lithified Cretaceous and Tertiary sediments. They record the focusing of large volumes of sediment into one or more glacial lakes occupying deep narrow troughs. Weakly bedded silts in the upper part of the sequence may have been deposited when the lake(s) deepened as glaciers continued to advance and thicken over the study area. It is possible that some advance glaciolacustrine sediments accumulated in subglacial water bodies. Late Wisconsinan deglacial lake sediments form a relatively thin, discontinuous capping in the area and conform to classical notions of glaciolacustrine sedimentation involving a seasonal or 'varved' regime. In contrast, no seasonal pattern of sedimentation can be identified in older sequences where the overriding influence on deposition has been the presence of steep subaqueous slopes, buried ice masses, and high sediment fluxes; these, in combination, caused near-continuous downslope movement and resedimentation.

RÉSUMÉ *La sédimentation glaciolacustre au cours de la progression et du retrait de l'Inlandsis de la Cordillère dans le centre de la Colombie-Britannique*. Les épaisses accumulations de sédiments (>400 m) qui comblent les vallées du Fraser et de la Chilcotin River permettent de distinguer les milieux glaciolacustres issus d'au moins deux glaciations. La séquence glaciolacustre la plus ancienne comprend des faciès déformés de gravier, sable, boue et diamicton mis en place, en partie, sur une glace stagnante emprisonnée dans de profondes vallées étroites à la fin de l'avant-dernière glaciation (Wisconsinien inférieur ou avant). Les séquences glaciolacustres plus récentes datent des phases d'avancée et de retrait de la Glaciation de Fraser au Wisconsinien supérieur (vers 25-10 ka) et ont comblé un réseau de drainage du Wisconsinien moyen entaillé dans des sédiments plus anciens. La séquence d'avancée glaciaire du Wisconsinien supérieur est dominée par un faciès de diamicton (coulée de débris) remplacé vers le haut par des silts. Le faciès de diamicton est en grande partie constitué de dépôts glaciaires anciens du Pléistocène remaniés et de sédiments peu consolidés du Crétacé et du Tertiaire. Ils témoignent de l'accumulation de grandes quantités de sédiments dans un ou plusieurs lacs glaciaires resserrés dans des dépressions profondes et étroites. Dans la partie supérieure de la séquence, les silts faiblement stratifiés ont probablement été mis en place lorsque les lacs se sont approfondis avec l'avancée des glaciers. Il est possible que des sédiments glaciolacustres se soient accumulés dans des nappes sous-glaciaires au cours de l'avancée glaciaire. Les sédiments lacustres de retrait glaciaire du Wisconsinien supérieur forment une mince couverture discontinue et se sont déposés selon un régime saisonnier ou varvaire.

ZUSAMMENFASSUNG *Glaziallimnische Sedimentierung während des Vorstosses und Rückzugs der Kordilleren-Eisdecke im Zentrum von British Columbia*. Dicke (+ 400m) und gut ausgesetzte Sedimentfüllungen in den Fraser- und Chilcotin-Flusstälern im Zentrum von British Columbia bezeugen kontrastierende glaziallimnische Umwelten von mindestens zwei Vereisungen. Die älteste glaziallimnische Sequenz besteht aus deformierten Fazies aus Kies, Sand, Schlamm und Diamikton, die zum Teil auf stagnierendem Eis abgelagert wurden, das in tiefen, engen Tälern am Ende der vorletzten Vereisung (frühes Wisconsin oder älter) feststeckte. Jüngere glaziallimnische Sequenzen stammen von den Vorstoss- und Rückzugsphasen der Fraser-Vereisung im späten Wisconsin (etwa 25-10 ka) und haben ein Dränage-System des mittleren Wisconsin, das sich quer durch ältere Sedimente eingekerbt hat, ausgefüllt. Die Vorstoss-Sequenz aus dem späten Wisconsin wird von Diamikton (Trümmer-Strömung)-Fazies beherrscht, die nach oben hin in Schlamm übergehen. Die Diamikton-Fazies bestehen weitgehend aus umgearbeiteten älteren glazialen Ablagerungen aus dem Pleistozän und gering verfestigten Sedimenten aus der Kreidezeit und dem Tertiär. Sie bezeugen die Konzentration grosser Sedimentvolumen in einem oder mehreren glazialen Seen, die sich in tiefen engen Trögen befanden. Schwach geschichteter Schlamm im oberen Teil der Sequenz ist möglicherweise abgelagert worden, als der See/die Seen tiefer wurden, während die Gletscher über dem untersuchten Gebiet weiter vorstiessen und sich verdickten. Es ist möglich, dass einige glaziallimnische Vorstoss-Sedimente sich in subglazialen Wasserflächen akkumulierten. Glaziale Seen-Rückzugssedimente aus dem späten Wisconsin bilden in dem Gebiet eine relativ dünne, nichtkontinuierliche Decke und entsprechen der klassischen Vorstellung glaziallimnischer Sedimentierung mit periodischem oder "Warwen"-System.

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INTRODUCTION

Glaciolacustrine sediments are an important component of many Quaternary sequences in the Cordillera of western Canada (Fulton, 1984; Clague, 1989; and references therein). These sediments record a complex history of ice damming at the margins of glaciers during several Pleistocene glaciations.

The best known glaciolacustrine deposits in the Cordillera are the late-glacial 'White Silts' which are preserved in prominent terraces in Thompson and Okanagan valleys of south-central British Columbia (Fig. 1; Flint, 1935; Mathews, 1944; Fulton, 1965; Shaw, 1977; Shaw and Archer, 1979). These have been ascribed to sedimentation in lakes dammed by ice tongues that were downwasting and retreating to the north and east at the end of the Fraser Glaciation (Late Wisconsinan). The stratigraphy, structure, and sedimentology of these deposits have been described from surface outcrops by Fulton (1965), Shaw (1975, 1977), and Shaw and Archer (1978, 1979). Much of the exposed part of the White Silts comprises couplets of silt and minor clay. The internal structure of the couplets indicates that they are varves. However, they commonly contain massive and current-bedded sands which are products of slumping and strong underflows. These rhythmically bedded sediments locally overlie gravel, sand, and diamict facies deposited mainly by sediment gravity flows. Deformation structures attest to sedimentation near the margins of large masses of stagnant ice trapped in the valleys.

These facies dominate other late-glacial lake sequences in the Canadian Cordillera. Exposures, however, are commonly limited to the upper parts of glaciolacustrine sequences or to sites near the margins of the former lakes. Little is known of the character of deeper deposits in the centres of the basins, although recent seismic investigations in several valley-bottom lakes in southern British Columbia have revealed the presence of what are thought to be sequences of rapidly deposited glaciolacustrine sediments up to several hundred metres thick (Eyles *et al.*, 1990, in press; Mullins *et al.* 1990).

Older glaciolacustrine deposits, dating from the end of the penultimate glaciation (Early Wisconsinan or older) and the early part of the Fraser Glaciation, are well exposed in spectacular outcrops along the deeply incised valleys of Fraser River and its tributaries south of Quesnel (Figs. 2, 3). We have studied these outcrops to gain a better understanding of Pleistocene glaciolacustrine environments and of the factors that influence glaciolacustrine deposition in areas of complex topography and geology. The data also provide important 'ground truth' for subsurface seismic investigations.

In this paper, we describe three glaciolacustrine sequences in the Fraser and lower Chilcotin river valleys, and discuss their environments of deposition. To facilitate discussion, we subdivide the sequences into two groups: one sequence was deposited during a period of *glacier advance* and was overridden soon after it formed; the other two accumulated during periods of *glacier retreat*.

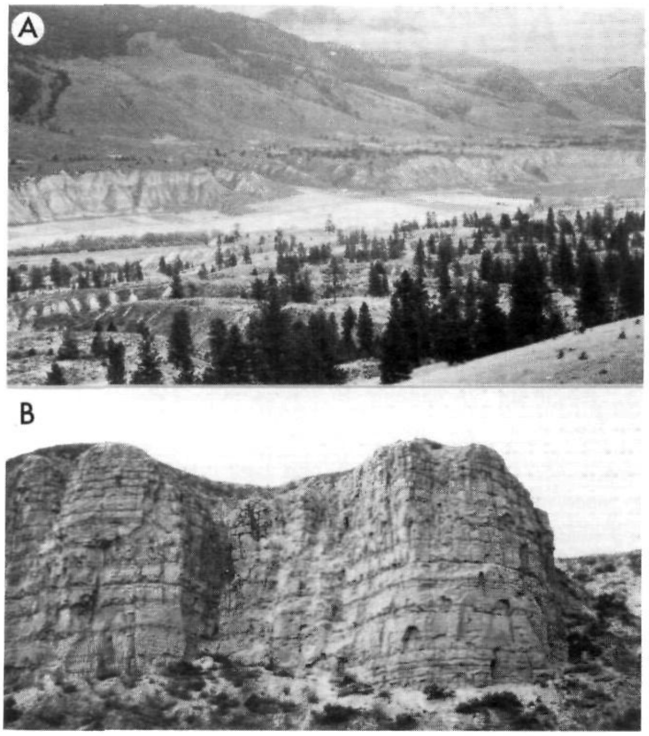

FIGURE 1. Glaciolacustrine sediments in the Thompson valley near Kamloops, British Columbia. These sediments were deposited over a period of 100-200 years at the close of the Fraser Glaciation (Fulton, 1965). The layers in the lower photograph are varves; section is *ca.* 10 m high.

Sédiments glaciolacustres dans la vallée de Thompson River, près de Kamloops, en Colombie-Britannique. Les sédiments ont été déposés à la fin de la Glaciation de Fraser, sur une période de 100 à 200 ans (Fulton, 1965). Les couches dans la photographie du bas sont des varves; le profil mesure environ 10 m de haut.

STUDY AREA

Field investigations were carried out in 1987 and 1989 at Farwell Canyon in the lower Chilcotin valley (Fig. 4) and at Gang Ranch in the Fraser valley (Fig. 5). Large sections at these sites are representative of the almost continuous exposure along Fraser River from Gang Ranch to the vicinity of Williams Lake, a distance of about 80 km.

The study area lies within the Interior Plateau physiographic region (Mathews, 1986), an area of low to moderate relief bounded by the Coast Mountains on the west and the Columbia Mountains on the east. The modern Fraser valley is 3-4 km wide and is incised up to 500 m below the level of the surrounding plateau, which ranges in elevation from about 1000 to 1600 m (Fig. 5). Chilcotin River flows southwest into Fraser River from source areas in the Coast Mountains and the Interior Plateau. At Farwell Canyon, the river flows in a valley 4 km wide and 500 m deep (Figs. 4, 6).

The central Interior Plateau is underlain by sedimentary and volcanic rocks of Pennsylvanian to Pliocene age and by granitic rocks of Jurassic age (Tipper, 1963; Roddick *et al.*, 1979; Mathews and Rouse, 1984). The uppermost rocks, which are widely distributed in this region, are Mio-Pliocene basalt flows of the Chilcotin Group. These cover an area of approximately 50,000 km² and, on average, are about 70 m thick. Within the study area, Chilcotin Group lavas unconformably overlie Tertiary and Cretaceous sedimentary and volcanic rocks which have been studied by Rouse and Mathews (1979) and Mathews and Rouse (1984). Some of the sedimentary rocks are poorly lithified and contain smectite-rich beds that have low shear strengths. These rocks are susceptible to large-scale mass movements, particularly on steep valley walls. Several large, slow-moving landslides ('earthflows') are present in the study area, most notably near Gang Ranch. The significance of such mass movements to Pleistocene glaciolacustrine sedimentation is that ponding may induce failure or accelerate downslope movement (Eyles and Clague, 1987), releasing large volumes of weathered debris into the lakes.

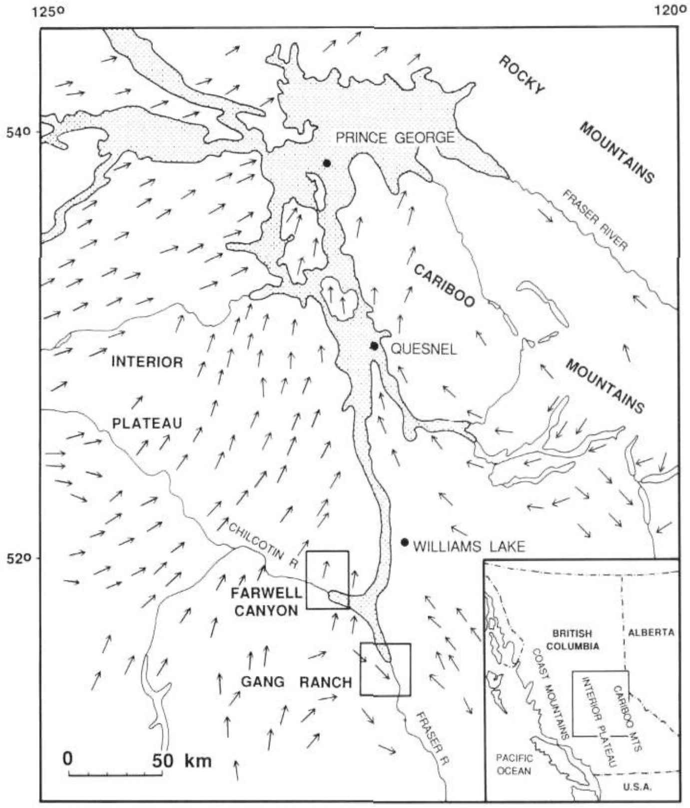

FIGURE 2. Study area in the central interior of British Columbia. Ice-flow directions (after Tipper, 1971b, Fig. 26) are for the Late Wisconsinan Fraser Glaciation maximum (*ca.*15 ka) (local ice-flow directions are shown in Figs. 4 and 5). Stippled area represents the regional lake system that developed during Late Wisconsinan deglaciation (*ca.* 11 ka).

Région à l'étude au centre intérieur de la Colombie-Britannique. Les directions de l'écoulement glaciaire (d'après Tipper, 1971B, fig. 26) sont celles de l'optimum de la Glaciation de Fraser (vers 15 ka) (directions locales d'écoulement glaciaire montrées aux fig. 4 et 5). La zone tramée identifie le réseau régional de lacs qui s'est développé au cours de la déglaciation du Wisconsinien supérieur (vers 11 ka).

FIGURE 3. View northward up Fraser River from near the mouth of Chilcotin River, showing dissected thick Pleistocene fill. This fill occupies a valley incised up to 500 m into the surrounding Interior Plateau (middle ground and distance) (Province of British Columbia 'Trimet' photograph BC363-2).

Vue vers le nord du fleuve Fraser, à partir de la source de la Chilcotin River, montrant les accumulations de sédiments disséqués du Pléistocène. Ces accumulations comblent la vallée incisant le plateau de l'Intérieur jusqu'à 500 m (photo BC363-2).

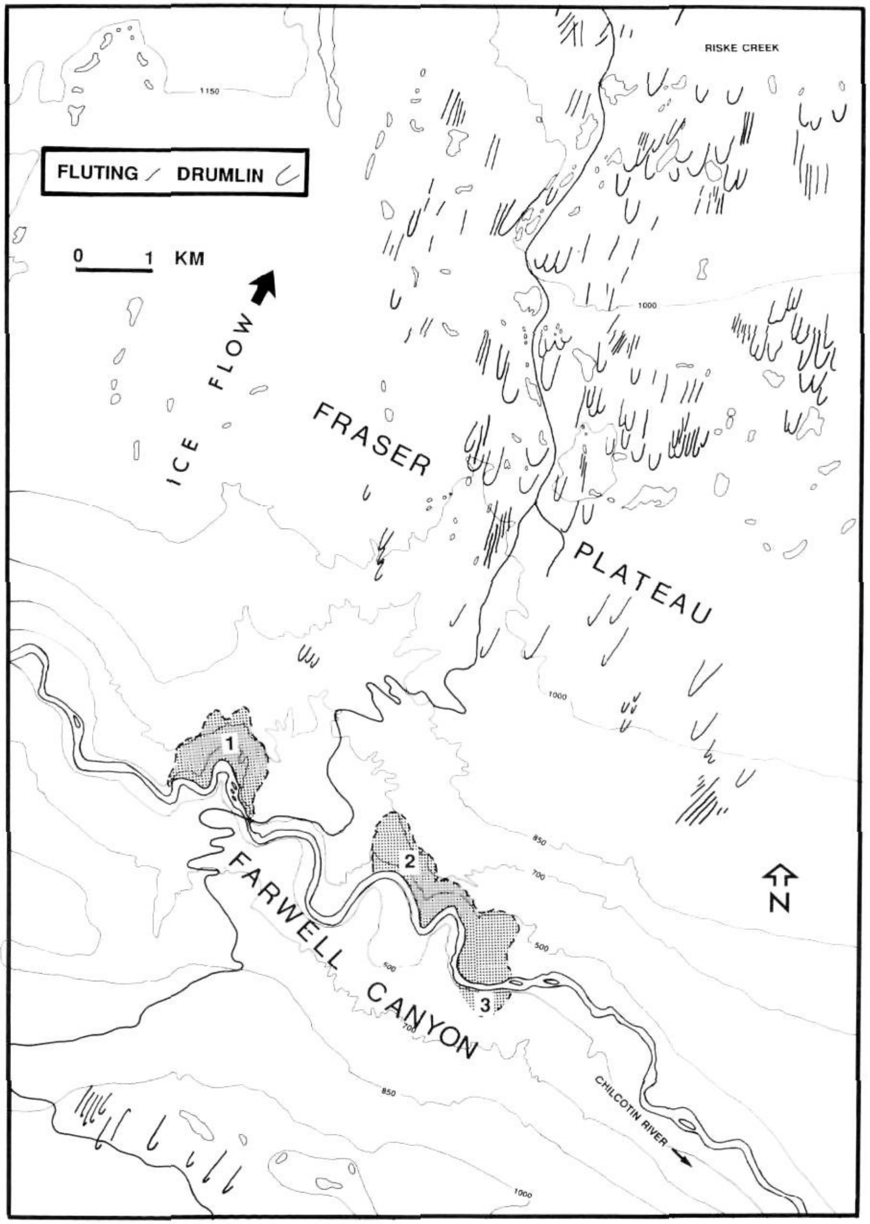

FIGURE 4. Locations of studied sections 1,2 and 3 (stippled) in the Chilcotin valley in the vicinity of Farwell Canyon. Late Wisconsinan ice-flow directions inferred from drumlins and flutings (see Fig. 2 for location.)

Localisation des coupes 1, 2 et 3 (trames) dans la vallée de Chilcotin River, près de Farwell Canyon. Les directions de l'écoulement glaciaire sont indiquées par les drumlins et les cannelures (la fig. 2 donne la localisation).

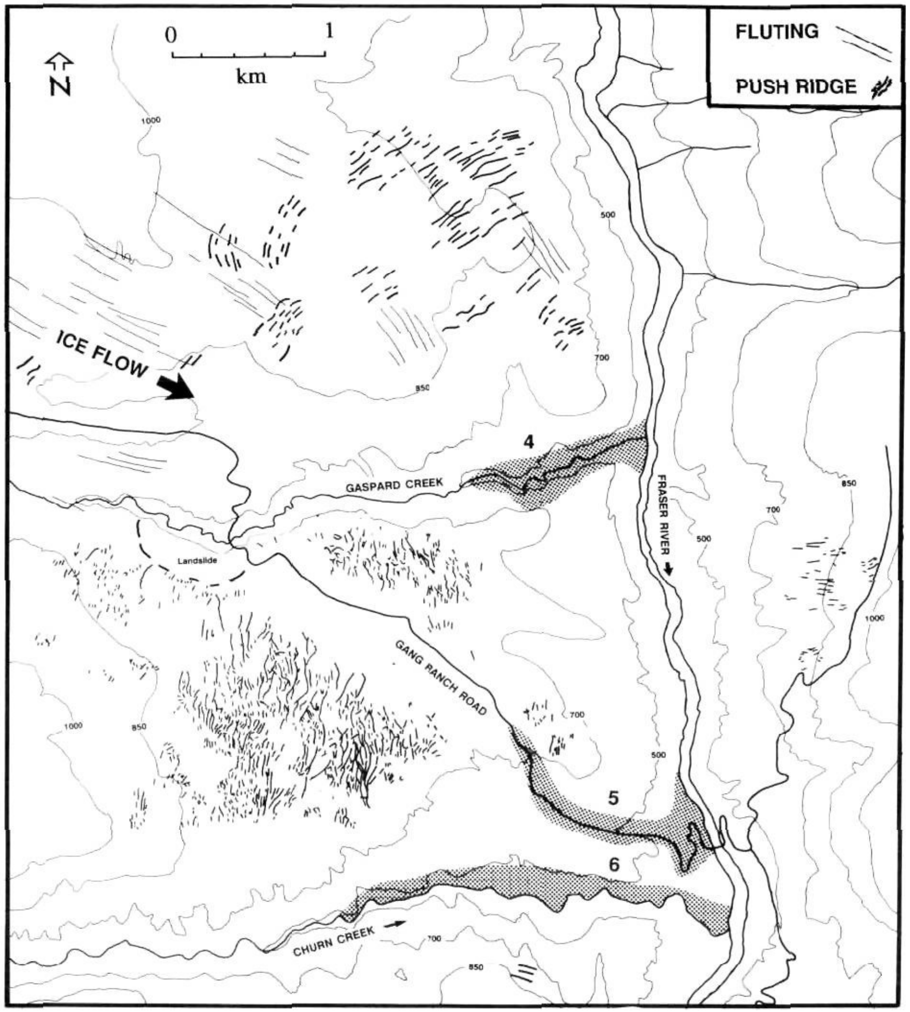

FIGURE 5. Locations of studied sections 4,5 and 6 (stippled) in the Gang Ranch area. Late Wisconsinan ice-flow directions inferred from flutings and closely spaced moraine ridges.

Localisation des coupes 4, 5 et 6 (trames) dans la région de Gang Ranch. Les directions de l'écoulement glaciaires sont indiquées par les cannelures et les crêtes morainiques rapprochées.

SUMMARY OF LATE PLEISTOCENE STRATIGRAPHY

During major Pleistocene glaciations, piedmont glaciers flowed across the central Interior Plateau from the Coast Mountains to the west and from the Cariboo Mountains (part of the Columbia Mountain system) to the east (Fig. 2), disrupting the drainage and impounding lakes. During the Fraser Glaciation, eastward-advancing ice blocked ancestral Fraser River south of the study area and ponded a lake that extended north up the Fraser and Chilcotin valleys (Clague, 1987, 1988). This lake probably grew in size and deepened as the ice thickened. Eventually, it was either destroyed or evolved into one or more subglacial water bodies when piedmont lobes from the Coast and Cariboo Mountains coalesced over the plateau to form the Cordilleran Ice Sheet.

Ice-dammed lakes also developed during periods of deglaciation. At the end of the Fraser Glaciation, for example, the Cordilleran Ice Sheet retreated to the south and west in this part of British Columbia, and lakes formed in the main valleys behind decaying ice masses (Fig. 2; Tipper, 1971a, 1971b; Clague, 1987, 1988).

Pleistocene deposits in the Fraser and lower Chilcotin valleys, in places, exceed 400 m in thickness and infill an irregular, high-relief bedrock surface. At Gang Ranch, these sediments fill a broad basin cut in bedrock, the southern margin of which is exposed along Churn Creek. Sediments also fill valleys that have been cut in older sediments and bedrock; these are exposed in cross-section in several places along Fraser and Chilcotin rivers (Fig. 7).

Figure 8 summarizes the stratigraphy of Pleistocene sediments in the study area, and Figure 9 provides detailed facies logs. The stratigraphy here is similar to that in the Williams Lake-Quesnel area to the north (Clague, 1987, 1988, 1991; Eyles *et al.*, 1987; Eyles and Kocsis, 1989; Eyles, 1990), reflecting a similar depositional history and indicating that sedimentation and erosion were controlled by regional, rather than local, factors. The oldest stratigraphic unit (A in Fig. 8) crops out sporadically in Fraser valley from Williams Lake to south of Gang Ranch and consists of yellow-stained, imbricated and cross-bedded, cobble-boulder gravels deposited by south-flowing, ancestral Fraser River. The gravels are well exposed in vertical cliffs along lowermost Churn and Gaspard creeks and along Fraser River in the vicinity of these two streams (Fig. 10). The cause of the yellow colouration is unknown, although weathering is one possibility. Whatever the cause, the colour helps distinguish these gravels from a younger fluvial unit, described below. The unit may date to the Early Wisconsinan, but could be much older (Clague, 1987).

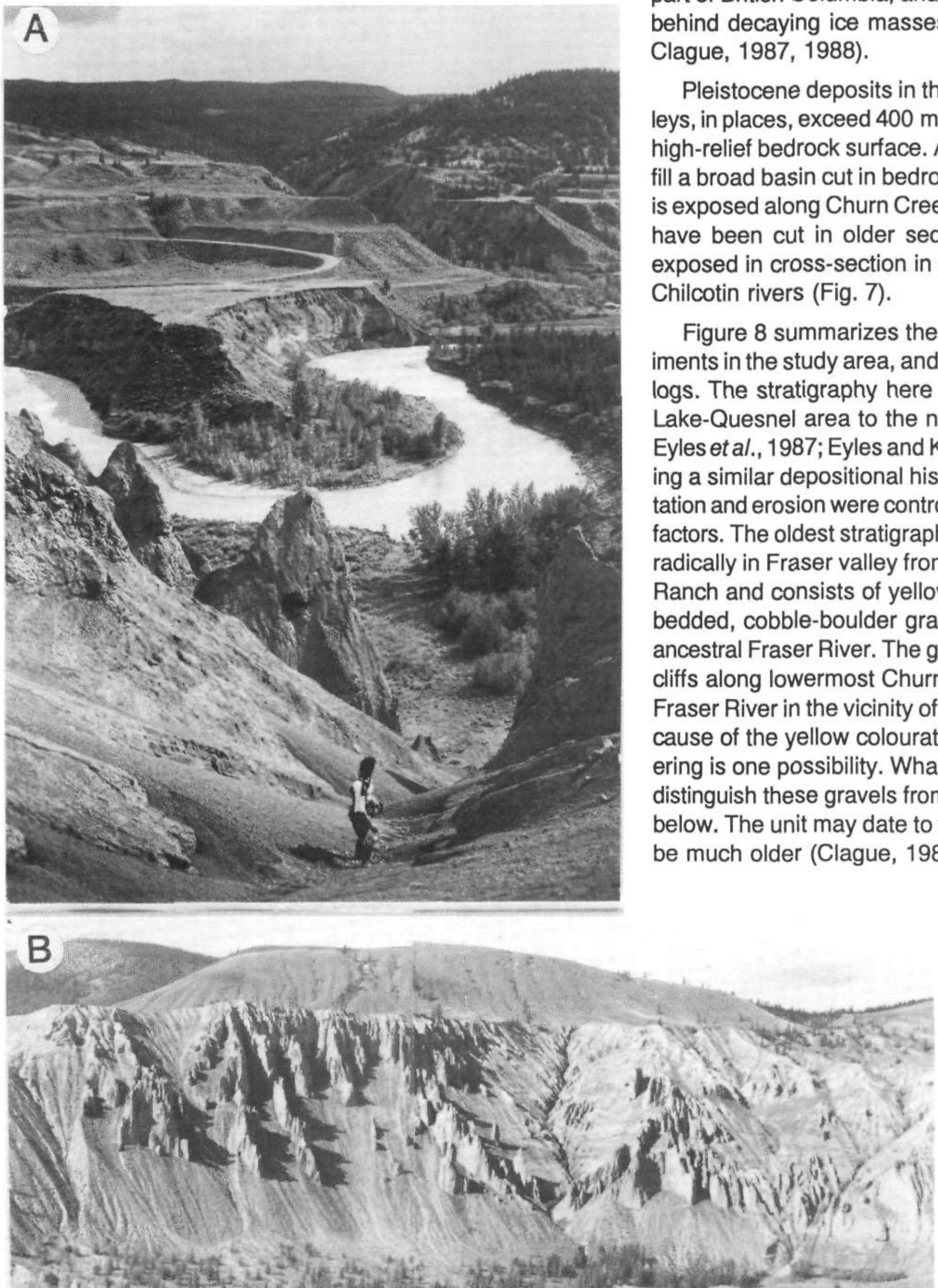

FIGURE 6. Farwell Canyon. A) Thick, terraced Pleistocene sediments in the Chilcotin valley; Interior Plateau in the distance. B) Older deglacial sequence, here consisting mainly of muds, silts, silty sands, and diamicts (unit B2; section 1, Fig. 4).

Farwell Canyon. A) Grande épaisseur de sédiments du Pléistocène disposés en terrasses: plateau de l'Intérieur au loin. B) Séquence plus ancienne de retrait glaciaire, composée surtout de boues, silts, sables silteux et diamictons (unité B2, coupe n° 1, fig. 4).

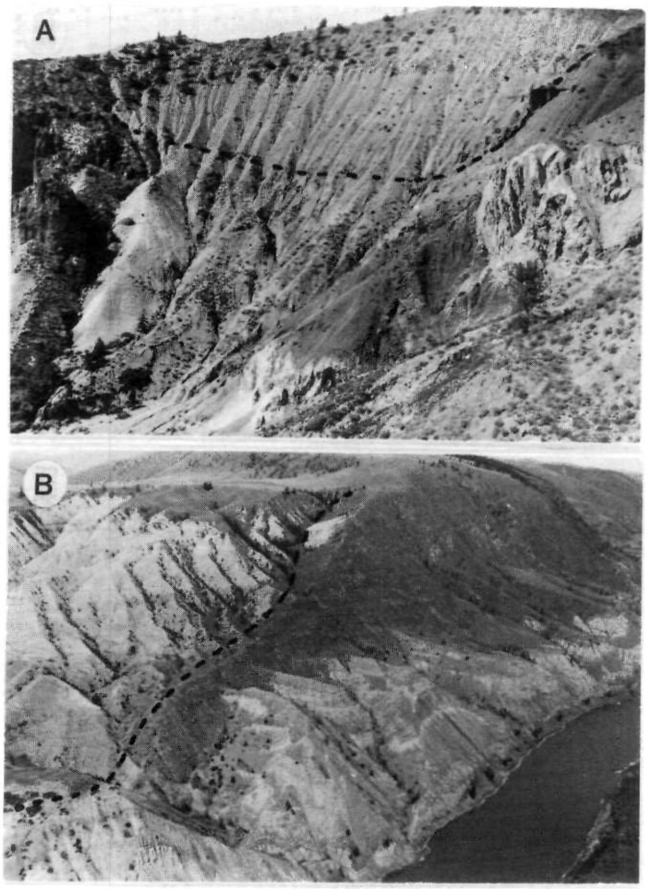

FIGURE 7. A) Bedrock valley (outlined) filled with Pleistocene sediments, Churn Creek at Gang Ranch. B) Margin of large buried valley (outlined) near the confluence of Fraser and Chilcotin rivers. This valley is about 1.5 km wide, and its floor is about 100 m above Fraser River. Note terraced Pleistocene sediments at lower elevation adjacent to the river.

A) Vallée entaillée dans le substratum (tirets) remblayée par des sédiments du Pléistocène, à Churn Creek (Gang Ranch). B) marge d'une grande vallée enfouie (tirets) près de la confluence du Fraser et de la Chilcotin River. La vallée fait environ 1,5 km de largeur et le fond est à 100 m au-dessus du Fraser. Noter les sédiments du Pléistocène disposés en terrasses aux bas niveaux près de la rivière.

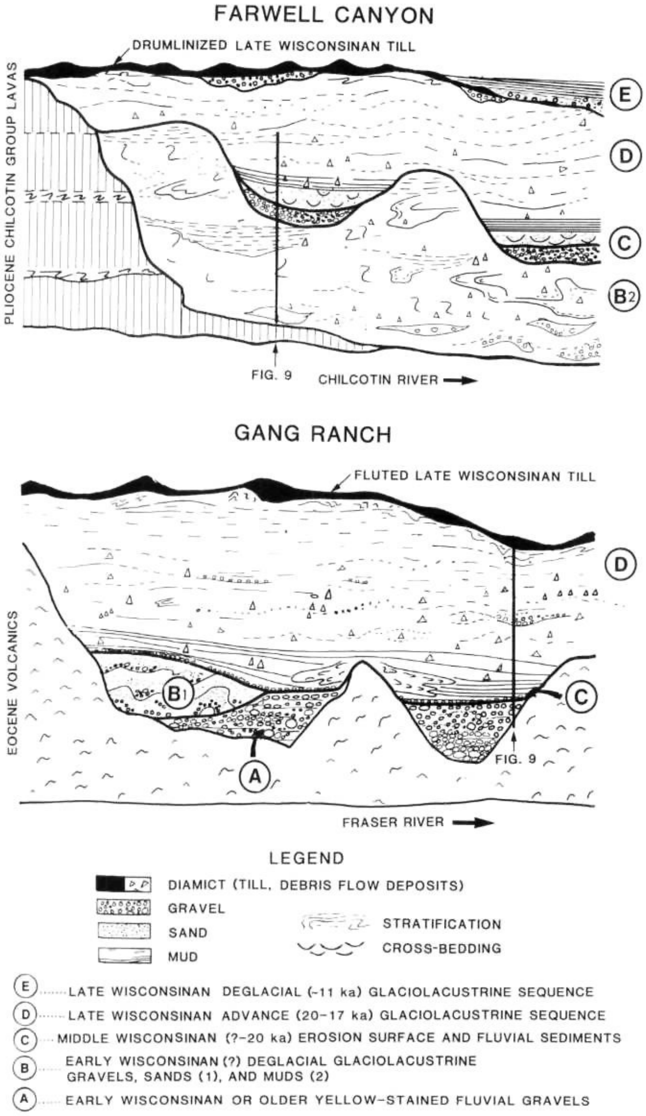

FIGURE 8. Generalized Pleistocene stratigraphy at Farwell Canyon and Gang Ranch. The total thickness of Pleistocene sediments exceeds 400 m.

Stratigraphie généralisée du Pléistocène au Canyon Farwell et à Gang Ranch. L'épaisseur totale de sédiments dépasse les 400 m.

In the Fraser valley, these coarse gravels are unconformably overlain by a heterogenous succession of diamict and graded gravel and sand facies, which are faulted, deformed into gentle anticlines and synclines, and cut by clastic dykes (B1, Fig. 8; see Eyles *et al.*, 1987, for a detailed description). These sediments are referred to in this paper as the 'older deglacial sequence' and were deposited in one or more glacial lakes at the end of the penultimate glaciation (Clague, 1987; Eyles *et al.*, 1987). The lakes were defined by Eyles *et al.* (1987) as 'supraglacial', in that they apparently contained large masses of stagnant ice. Much of the deformation of the older deglacial sequence in the Fraser valley is the result of syn- and post-depositional melt of these ice masses. New work, reported here, identifies correlative deformed fine-grained facies in the lower Chilcotin valley (B2, Figs. 8, 9).

The older deglacial sequence was dissected during a lengthy nonglacial period that spans at least the entire Middle Wisconsinan (*i.e.*, the Olympia Nonglacial Interval; Fulton, 1971; Clague, 1981). This is recorded by a major unconformity which separates 'older' glaciolacustrine sediments from overlying fluvial gravels and sands (Figs. 8, 9). During the Olympia interval, ancestral Fraser and Chilcotin rivers and their tributaries eroded valleys similar in size to those of today. In many places, however, stream courses dating to this period diverge significantly from their present-day counterparts, and infilled valleys can be identified (Fig. 7B).

The floors of these old valleys commonly are covered by a bouldery lag and planar and trough cross-bedded, pebble-cobble gravels and sand (C, Figs. 8, 9). The gravels are similar

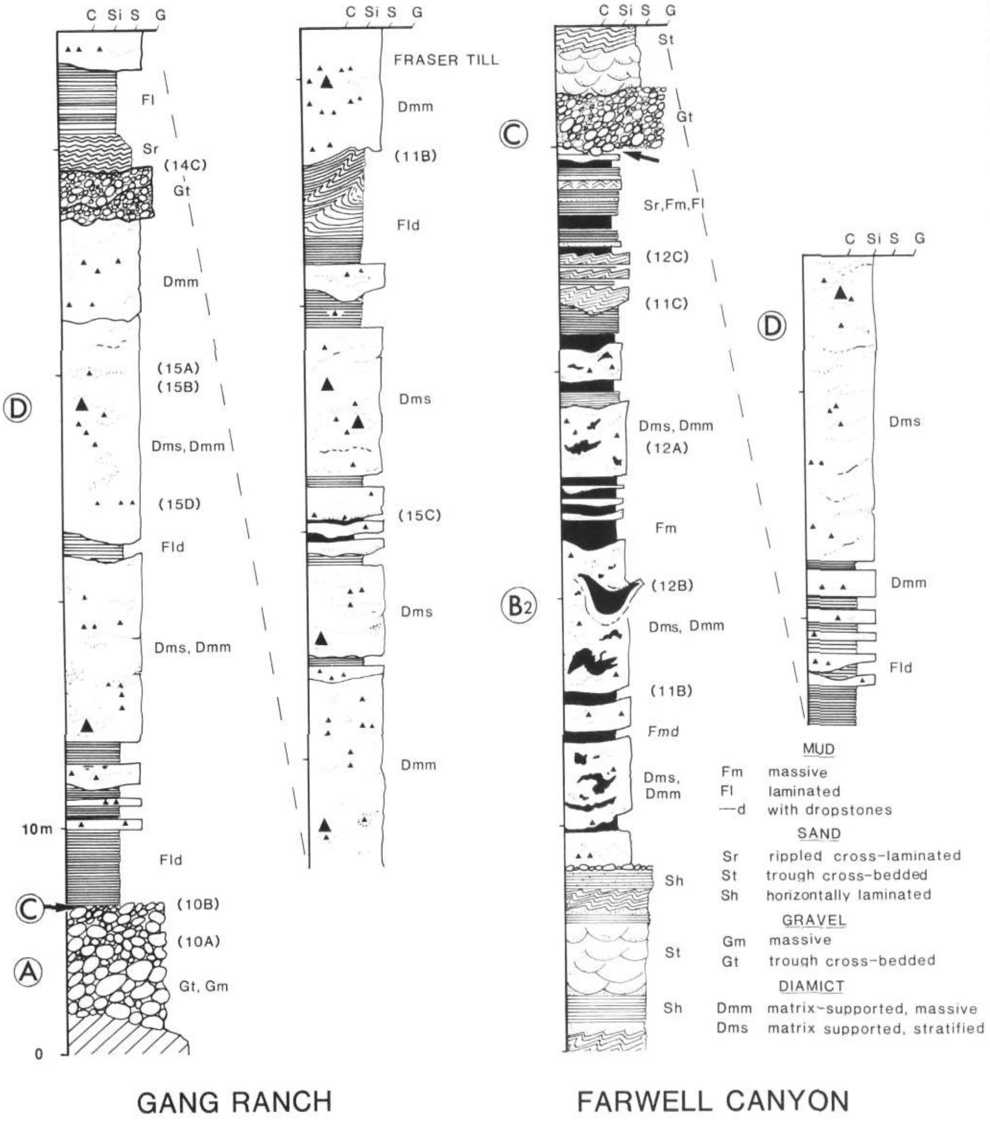

FIGURE 9. Representative lithofacies logs from Gang Ranch (Churn Creek area) and Farwell Canyon (see Fig. 8 for location in stratigraphic sequence). B2, fine-grained Early Wisconsinan (?) deglacial sequence; C, Middle Wisconsinan erosion surface (arrow) and fluvial gravels; D, Late Wisconsinan advance sequence. Numbers in parentheses identify figure numbers.

Lithofaciès représentatifs de Gang Ranch (région de Churn Creek) (la fig. 8 donne la position dans la séquence). B2. Séquence de sédiments de retrait glaciaire à grains fins du Wisconsinien inférieur (?); C, surface d'érosion et graviers fluviatiles (flèche) du Wisconsinien moyen; D, séquence d'avancée glaciaire du Wisconsinien supérieur. Les chiffres entre parenthèses donnent les numéros de figures.

to, although finer than, those underlying the older deglacial sequence (unit A) and, like them, were deposited by streams flowing generally to the south. Aggradation may have occurred in response to an increase in sediment supply caused by the expansion of glaciers into this region during the early part of the Fraser Glaciation (Clague, 1986, 1987).

The fluvial gravels fine upward and are overlain by sediments deposited in lakes ponded during the early part of the Fraser Glaciation (D, Figs. 8, 9). The contact between these two units is conformable and, in general, gradational. Although there are no dates from the study area, regional evidence suggests that these glaciolacustrine sediments began to accumulate about 20 ka and were overridden before 17 ka, indicating very high sedimentation rates (Fulton, 1971; Clague, 1981). Massive and crudely stratified, debris-flow diamicts, which are the dominant facies in the lower part of this sequence at Gang Ranch, record the focussing of large volumes of poorly sorted sediment into the relatively narrow lake along the Fraser valley. The upper part of the glaciolacustrine sequence, which consists mainly of silts, is truncated and deformed beneath Late Wisconsinan till (Fig. 8), recording the maximum extent of the Cordilleran Ice Sheet in this area during the Fraser Glaciation.

Drumlins, flutings and minor moraine ridges developed on the till sheet record ice flow in a north to southeasterly direction during the Fraser Glaciation (Figs. 2, 4, 5; Tipper, 1971a, 1971b). Flow was generally across or oblique to the Chilcotin and Fraser valleys, rather than along them, which may account for the good preservation of the sediment fills in these valleys.

Fraser Glaciation till and associated landforms are overlain, in places, by sediments deposited in lakes dammed by remnant masses of the Cordilleran Ice Sheet during deglaciation (E, Fig. 8). With final deglaciation, glacial lakes throughout this region drained, and rivers dissected Pleistocene fills.

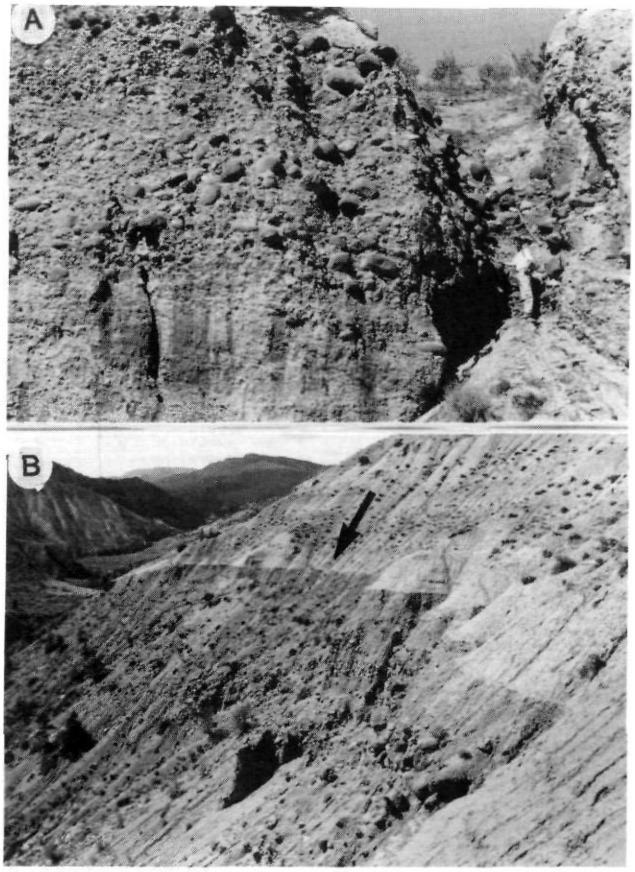

FIGURE 10. A) Yellow-stained, Early Wisconsinan or older, fluvial gravels exposed along Churn Creek. B) Sharp contact (arrowed) between yellow-stained gravels of A and Late Wisconsinan advance glaciolacustrine sequence.

A) Graviers fluviatiles colorés de jaune du Wisconsinien inférieur ou plus anciens, mis au jour, le long du Churn Creek. B) Contact net (flèche) entre les graviers fluviatiles en A et la séquence glaciolacustre d'avancée glaciaire du Wisconsinien supérieur.

DETAILED DESCRIPTION AND INTERPRETATION OF SEQUENCES

OLDER DEGLACIAL SEQUENCE

Glaciolacustrine sediments deposited at the end of the penultimate glaciation (B1, B2; Figs. 8, 9) crop out along Fraser River and some of its tributaries from north of Quesnel to south of Gang Ranch. These provide evidence for a lake (or series of lakes) ponded, at least in part, over stagnant ice in the trench-like valley of Fraser River (Eyles *et al.*, 1987). The precise paleogeography at this time is not known. In particular, it is not clear whether there was one extensive lake or a complex system of interconnected water bodies separated by large areas of downwasting ice; the latter appears to be more likely.

The dominant (60-65 %) facies types in the older deglacial sequence in the Fraser valley are thick, normally graded gravels and sands occupying steeply dipping multistorey channels up to 300 m wide and several tens of metres deep (Eyles *et al.*, 1987). Other common facies types include trough cross-bedded (12%), horizontally laminated (12%), and massive (8%) sands. Fining-upward units up to 50 m thick may be the product of sediment gravity flows triggered by large meltwater discharges or retrogressive failure of ice-cored sediments (Eyles *et al.*, 1987). Large-scale, syndepositional and post-depositional deformation structures, including folds, grabens, faults, and sedimentary dykes, record gravitational foundering of sediment and pore-water expulsion caused by melting of underlying and marginal glacier ice. Melting of buried ice masses also appears to have controlled the flow paths of sediment gravity flows by producing channels and sub-basins within the overlying sediment pile.

The coarse, ice-proximal facies, which dominate the sections studied by Eyles *et al.* (1987), record quasi-continuous resedimentation and sorting of outwash. Fine-grained facies (silts, clays) are uncommon (ca. 5%) in sections along Fraser River near Williams Lake, either because these sediments were not deposited in significant amounts there or because they were subsequently removed by erosion during the Olympia Nonglacial Interval (Shaw, 1988).

New data from the lower Chilcotin valley, emphasized here, show that thick deposits of fine-grained sediments, which are laterally continuous with the coarse facies described above, accumulated in other, more distal parts of the same lake system. These data provide further evidence for the regional extent of complex, supraglacial water bodies in central British Columbia at the close of the penultimate glaciation. Sections at and below Farwell Canyon are dominated by massive and stratified muds, silts, and silty sands (Figs. 11, 12) which have a pale yellow-brown colour typical of the older deglacial sequence. Some of the sediments contain scattered stones and, in places, have sufficient clasts to be designated as diamict. In the sections at Farwell Canyon, diamict facies are most common in the lower part of the unit (Fig. 9). The sediments also contain 'pillow-like' rafts of silts, sands, gravels, and diamict, up to several metres across (Figs. 12A, B), and lenses and stringers of well rounded to angular gravels. The rafts dip southward, down the depositional paleoslope towards the centre of the Chilcotin valley. These may be remnants of beds or channel fills that have 'foundered' down into the finer sediments or moved downslope in subaqueous flows. The rafts are commonly folded and flanked by diapiric deformation structures. Undeformed channel fills, which cut erosively across underlying deformed sediments, are filled with ripple cross-laminated fine sands, recording westward paleoflow up the Chilcotin valley (Figs. 9, 12C).

Almost continuous exposures along Chilcotin River between Farwell Canyon and Fraser River confirm an easterly sediment source for the older deglacial sequence in this area. Bodies of graded gravels and graded and cross-laminated sands increase both in frequency and thickness towards Fraser River. Many have foundered into surrounding silts and muds, accompanied by large-scale diapirism. A representative section (3 in Fig. 4) shows cross-cutting, multi-storey channels containing thick (up to 3 m) beds of graded gravels (Fig. 12D). Such sediments are representative of the coarse-grained supraglacial facies reported previously by Eyles *et al.* (1987) from the Williams Lake area.

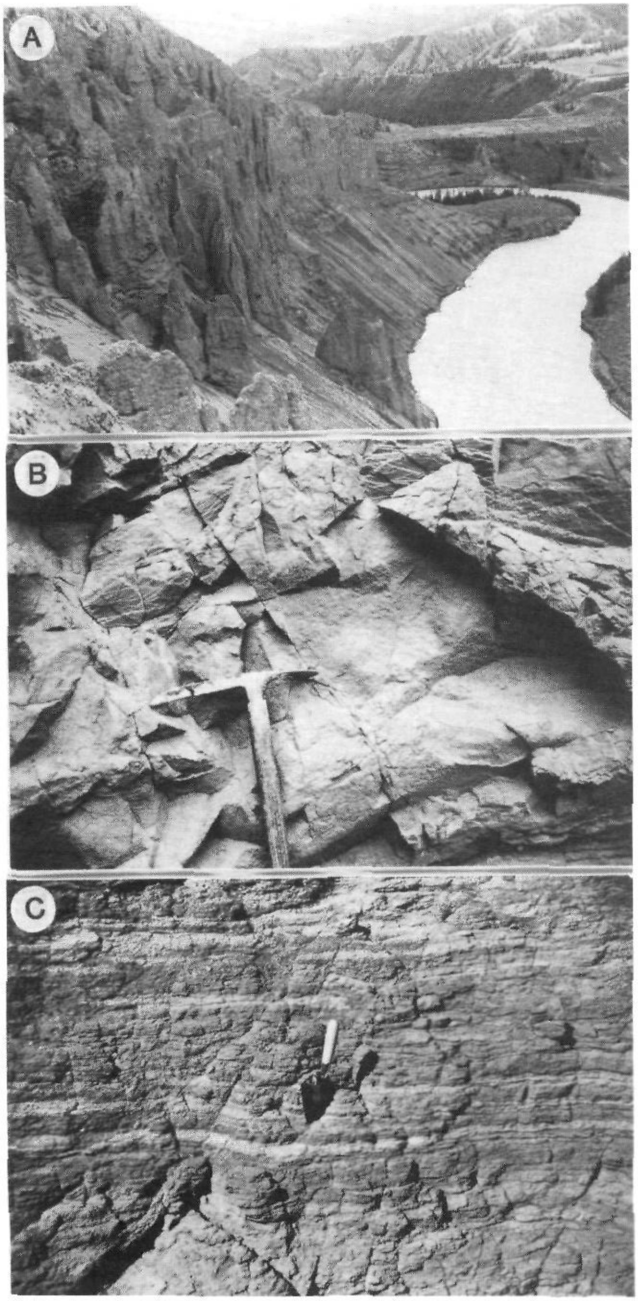

FIGURE 11. Older deglacial sequence, Farwell Canyon. A) Outcrop of deformed glaciolacustrine silts and sands (section 2, Fig. 4). Section is 100 m high. B) Massive mud facies. C) Laminated silt facies.

Séquence de retrait glaciaire plus ancienne (Farwell Canyon). A) Affleurement de silts glaciolacustres déformés (coupe n° 2, fig. 4); le profil mesure 100 m de hauteur. B) Faciès de boue massive. C) Faciès de silt laminé.

A tentative depositional model relating exposures along Chilcotin and Fraser rivers is shown in Figure 13. Tongues of gravel in the lowermost Chilcotin valley are thought to represent subaqueous outwash feeder channels, perhaps at the margins of a large subqueous fan prograding westward. Undeformed channels containing cross-laminated fine sands may be the distal equivalents of gravel-filled channels and represent the most distant parts of the subaqueous outwash feeder channel system. Silts and muds, which dominate upvalley sections in the Chilcotin valley at Farwell Canyon, were deposited from suspension and subsequently reworked by downslope movement (mainly slumps and flows). They record a large flux of sediment into the Chilcotin valley from a source to the east.

LATE WISCONSINAN ADVANCE SEQUENCE

Glaciolacustrine sediments up to 250 m thick were deposited as glaciers advanced across the Interior Plateau during the early part of the Fraser Glaciation (D in Figs. 8, 9; also Figs. 14, 15). The most striking characteristic of this unit is its tabular geometry and continuity of strata. The lower part of the sequence in many areas consists of diamict (debris-flow) facies, which record a rapid and substantial influx of poorly sorted sediment into one or more newly formed lakes. The upper part of the sequence is dominated by weakly bedded silts with few stones, which possibly were deposited as the lake(s) deepened before being overrun by advancing glaciers.

The Late Wisconsinan advance sequence fills valleys that were cut during the Olympia Nonglacial Interval. This is most clearly seen in the vicinity of Farwell Canyon where topographic highs cored by older deglacial glaciolacustrine sediments are bordered by lower, younger glaciolacustrine sediments (Fig. 8). Boulder lags delineate the floors of the old valleys and are overlain by well sorted, imbricated gravels which pass upward into ripple cross-laminated sands and laminated silts with dropstones. The sands and silts record the initiation of glacial lake ponding in the lower Chilcotin valley. Thin (<15 cm) beds of gravelly diamict, which are predominantly massive but, in places, show inverse and normal coarse-tail grading, are an important component of the lowest sediments of the advance sequence. These are products of sediment gravity flows, most likely turbulent water-rich slurries.

Superimposed diamict beds become dominant a short distance above the base of the sequence (Figs. 9, 15). These sediments are massive to crudely stratified and contain up to 35% clasts of varied lithology in a matrix of muddy sand. The most common clast type is basalt. Tertiary diatomite is abundant at some sites, giving rise to what might be called 'diatomite breccias'. Thick (>10 m) beds of diamict have been produced by the superimposition of several individual debris-flow layers. Diamict beds are separated by fine-grained facies, including rippled and laminated silts, fine sands, and massive muds. Some of the interbeds are truncated and deformed, showing that debris flows eroded their substrates. Rafts of mud, silt, and sand within diamict beds record incorporation by erosion or downslope slumping and mixing of previously deposited lacustrine facies. Very similar glaciolacustrine diamict facies have been described from the Copper River basin of Alaska (Eyles, 1987) and the Coppermine valley of Northwest Territories (St-Onge and Lajoie, 1986).

Several sections expose laterally continuous, shallow channels within the debris-flow succession. These are filled with stratified, well sorted sediments which commonly fine from gravels at the base to silts at the top (Fig. 9). One such, very large (ca. 1 km wide) channel is exposed along the north wall of the valley of Churn Creek. The floor of the channel is

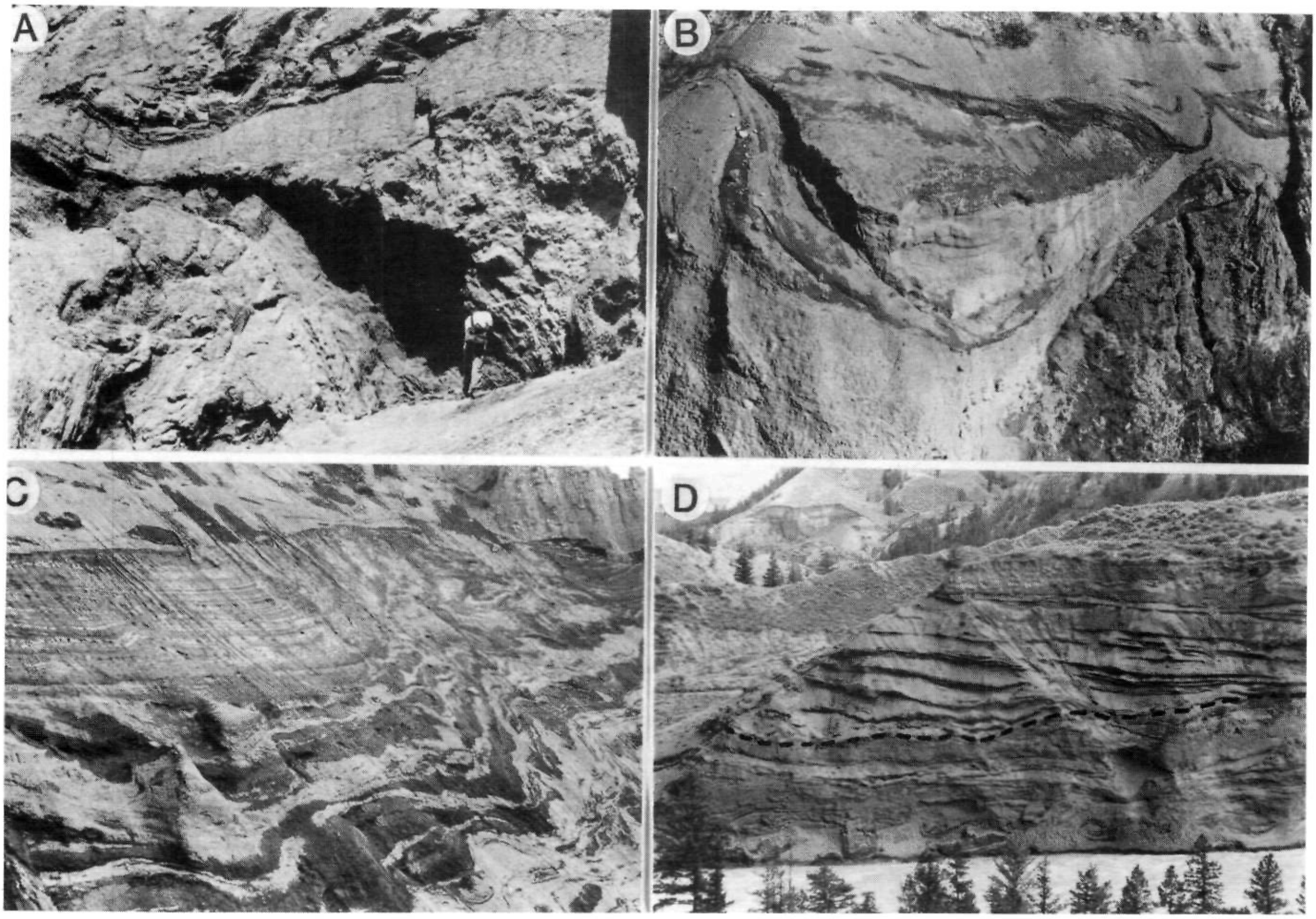

FIGURE 12. Older deglacial sequence. Farwell Canon. A) Silts and sands deformed by penecontemporaneous downslope movements. B) Large raft of stratified silts and sands within clayey silts; section is *ca*. 15 m high. C) Large undeformed, subaqueous channel filled with stratified silts and sands; this channel is cut into and overlain by deformed glaciolacustrine silts. D) Large channel (outlined) filled with graded sands and gravels and cut into deformed, finer-grained, glaciolacustrine sediments; section is 35 m high. Photos A, B and C were taken at section 1 (Fig. 4), and D at section 3.

Séquence plus ancienne de retrait glaciaire, (Farwell Canyon). A) Silts et sables déformés par des mouvements vers le bas pénécontemporains. B) Grand radeau de silts et de graviers dans des silts; coupe d'environ 15 m de haut, C) Grand chenal subaquatique non déformé remblayé par des silts et sables stratifiés; le chenal entaille des silts glaciolacustres déformés et en est recouvert. D) Grand chenal (tirets) remblayé par des sables et graviers stratifiés et entaillé dans des sédiments glaciolacustres à grains fins déformés; la coupe mesure 35 m de haut.

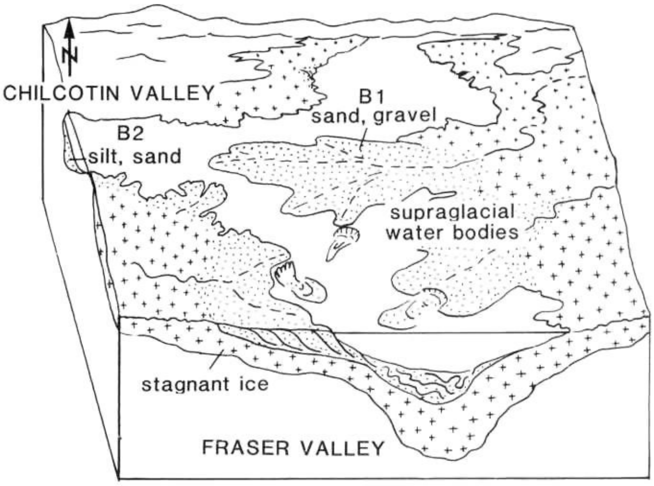

FIGURE 13. Depositional model for the older deglacial sequence. Sediments were deposited in a lake system in close association with stagnant ice. Coarse-grained facies (B1) accumulated in the Fraser valley, and fine-grained facies (B2) in the Chilcotin valley. Sediments have been extensively deformed by melt of underlying ice and by downslope movement during deposition.

Modèle de mise en place de la séquence de retrait glaciaire ancienne. Les sédiments ont été déposés dans un réseau de lacs associé à la glace stagnante. Le faciès à grains grossiers (B1) s'est accumulé dans la vallée du Fraser et le faciès à grains fins (B2), dans la vallée de la Chilcotin River. Les sédiments ont été en grande partie déformés par la fonte de la glace sous-jacente et par des mouvements vers le bas pendant la mise en place.

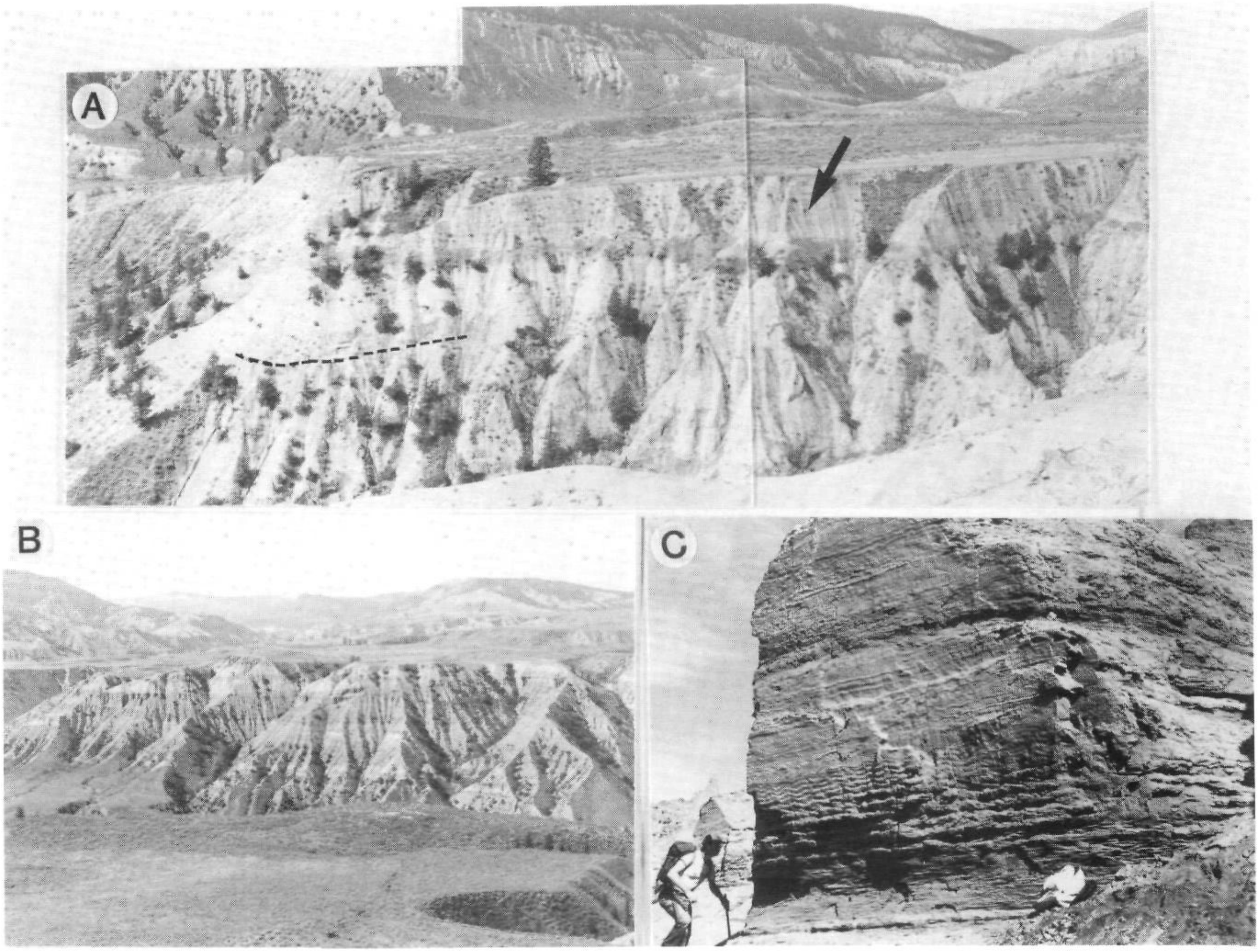

FIGURE 14. Late Wisconsinan advance sequence. A) Older deglacial sequence, truncated by Middle Wisconsinan erosion surface (dashed line), and overlain by fluvial sediments and Late Wisconsinan advance sequence; Late Wisconsinan glaciolacustrine sediments are unconformably overlain by Holocene subaerial fan deposits (arrowed); Farwell Canyon (northwestern end of section 2, Fig. 4). B) Well exposed glaciolacustrine sediments (mainly diamict and silts) of the Late Wisconsinan advance sequence along Fraser River at Gang Ranch. C) Channel fill within Late Wisconsinan glaciolacustrine sequence, Churn Creek; the channel base is overlain successively by a discontinuous boulder lag, gravel, sand, and silt (Fig. 9); only the sand and silt are visible in this photograph.

Séquence d'avancée glaciaire du Wisconsinien supérieur. A) Séquence de retrait glaciaire plus ancienne, tronquée par une surface d'érosion du Wisconsinien moyen (tirets), et recouverte par des sédiments fluviatiles et la séquence d'avancée glaciaire du Wisconsinien supérieur: les sédiments glaciolacustres du Wisconsinien supérieur sont recouverts en discordance par des dépôts de cône alluvial subaérien (flèche) de l'Holocène (Farwell Canyon; extrémité nord-ouest de la coupe n° 2, fig., 4). B) Sédiments glaciolacustres bien en vue de la séquence d'avancée glaciaire du Wisconsinien supérieur, le long du Fraser (Gang Ranch). C) Chenal remblayé dans une séquence de sédiments glaciolacustres du Wisconsinien supérieur: le fond du chenal est recouvert successivement par un pavage de blocs, du gravier, du sable et du silt, (fig. 9); on ne voit ici que le sable et le silt.

delineated by a boulder lag and is overlain by trough cross-stratified pebble gravels. The gravels, in turn, pass up into a 4-m-thick package of rippled fine sands that show an upward transition from A- to B- to C-type ripples (Fig. 14C). The sands are overlain by interbedded laminated silts and diamict.

Two possible explanations can be offered for such channels. First, they may record strong traction currents on the floor of the lake, possibly underflows resulting from sudden large influxes of meltwater. The upward transition in ripple types, from A to C, has been described from glaciolacustrine deltas and is typically produced by waning underflows as progressively more sediment is deposited from suspension (Gustavson *et al.*, 1975). Second, they may have been cut and lagged during lowstands of the lake. Most glacier-dammed lakes are unstable and are subject to periodic emptying and filling, and it is possible that the Late Wisconsinan lake in the Fraser valley behaved in a similar fashion. If so, the transition from trough cross-bedded gravels to rippled sands may record refilling of the lake after a period of low water levels. Channels formed in this manner should be continuous over much of the lake floor, but we have not been able to trace individual channels for any great distance.

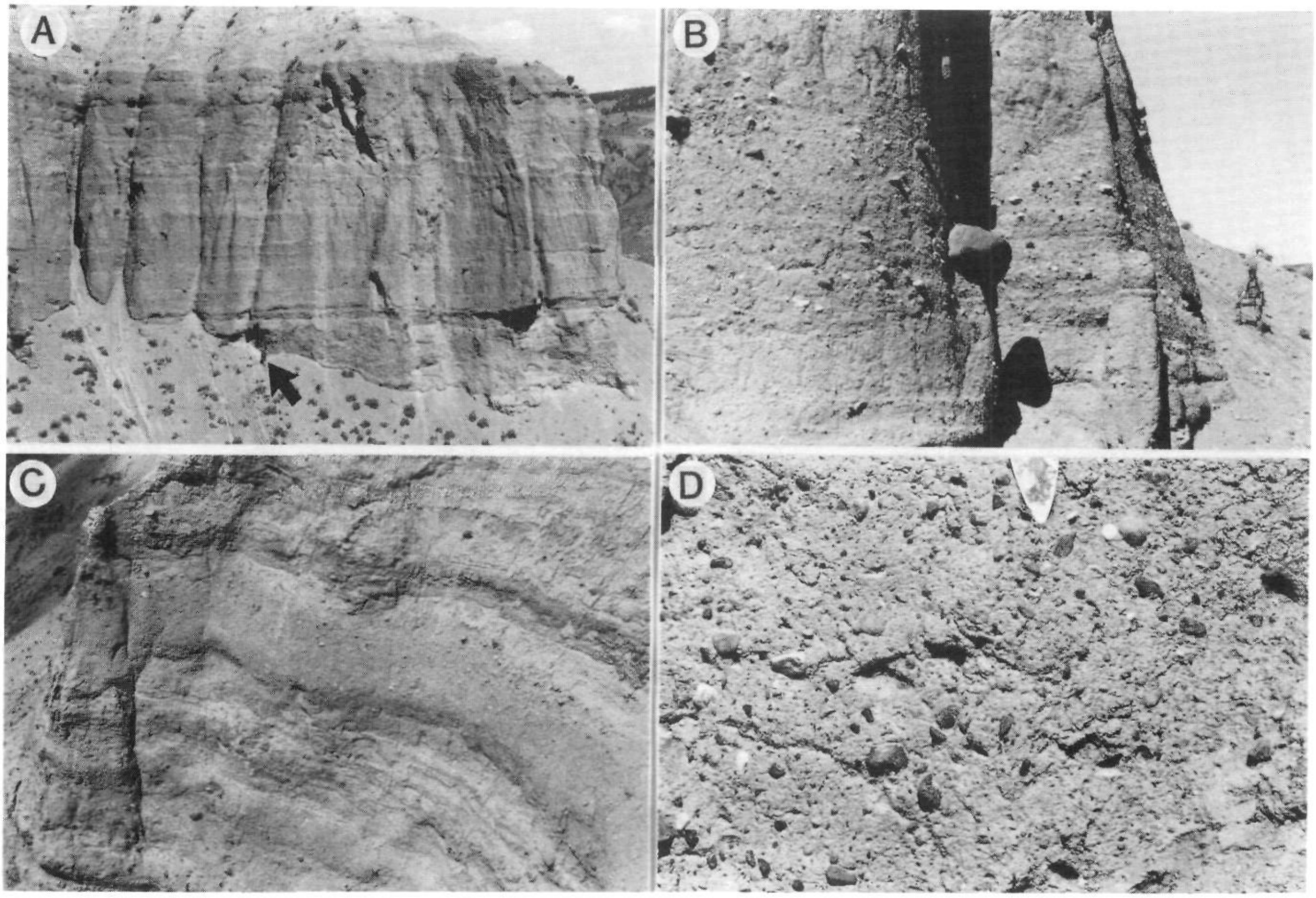

FIGURE 15. Diamict facies of Late Wisconsinan advance sequence at Gang Ranch (section 6, Fig. 5). A) Superimposed debris flows; arrowed figure for scale. B) Part of A, showing crudely stratified, amalgamated and partially amalgated debris flows with large ice-rafted or 'freighted' clasts. C) Superimposed debris flows; section is *ca*. 20 m high. D. Massive debris-flow diamict.

Faciès de diamicton de la séquence d'avancée glaciaire du Wisconsinien supérieur (Gang Ranch, coupe n° 6, fig. 5). A) Coulées de débris superposées. B) Partie de A qui montre des coulées de débris grossièrement stratifiées, plus ou moins mélangées avec de gros fragments de roches délestés (transportés). C) Coulées de débris superposées; la coupe mesure environ 20 m de haut. D) Diamicton massif de coulée de débris.

An important factor in the deposition of the thick, Late Wisconsinan, debris-flow diamicts in the study area has been the reworking of older glaciolacustrine sediments and weathered and easily eroded bedrock. The ultimate source of much of the debris in the diamicts is Tertiary volcanics and clastic sediments. Some of the Tertiary sediments are rich in smectite, which increase their susceptibility to mass movement. Indeed, modern earthflows in the Gang Ranch area consist largely of fragmented and mechanically mixed Tertiary lithologies and are very similar to some of the subqueous debris-flow deposits in the Late Wisconsinan advance sequence.

Large amounts of sediment derived from these sources were focused into lakes occupying deep, steep-walled valleys. The diamicts record subaqueous mobilization and downslope movement of poorly sorted debris across the surface of subaqueous fans or aprons. The debris may have been generated and transported subglacially (see Discussion), or derived from failures of older glaciolacustrine sediments outcropping on submerged valley walls. Slumps and earthflows mobilized by glacial-lake ponding or glacier overriding probably contributed to the debris flux. Eyles and Clague (1987) have documented examples of subaqueous debris flows and related slumps in Tertiary bedrock caused by Late Wisconsinan glacial-lake ponding near Quesnel; similar 'first-filling' failures probably were common in the study area.

LATE WISCONSINAN DEGLACIAL SEQUENCE

Glaciolacustrine sediments dating to the close of the Fraser Glaciation cap many sections in the Fraser valley north of Gang Ranch and in the lower Chilcotin valley. These sediments accumulated in one or more lakes dammed by ice or valley fill deposits during final decay of the Cordilleran Ice Sheet about 11,000 years ago (Clague, 1981). They are correlative with more widespread glaciolacustrine sediments in the central Interior Plateau to the north (Tipper, 1971a, 1971b; Clague, 1988). In the study area, these sediments occur sporadically below about 600 m elevation and are relatively thin compared to older glaciolacustrine units.

The Late Wisconsinan deglacial sequence comprises a variety of sediments, ranging from diamict to rhythmically bedded silts and clays. In general, coarse facies, including diamict and graded and massive gravels and sands, are restricted to the lower part of the sequence, where they overlie Fraser Glaciation till and older glaciolacustrine sediments. Some of the coarse sediments are subaqueous outwash deposited near ice margins; others were deposited by sediment gravity flows from adjacent valley walls.

The coarse facies pass upward into silts and clays which dominate the upper part of the Late Wisconsinan deglacial sequence. Where coarse facies are absent, silts and clays directly overlie Late Wisconsinan till, Late Wisconsinan advance sediments, or older deglacial sediments. The silts and clays typically are horizontally stratified; there is little or no evidence of the large-scale deformation and resedimentation so characteristic of older glaciolacustrine sequences. In wider parts of the lake basin, north of Quesnel, the fine facies consist of alternating layers of silt and clay which decrease in thickness upsection (Clague, 1988). Each silt layer typically grades upward into a thinner clay layer which, in turn, is sharply overlain by another silt layer. The couplets are thought to be varves, although there is no independent chronological evidence to prove this.

With complete deglaciation of the interior, glacial lakes drained and the present drainage system was established. Fraser, Chilcotin, and other rivers dissected valley fills to produce a series of terraces at successively lower levels (Fig. 6A).

DISCUSSION

Facies modelling has been defined (Walker, 1984) as a process of distillation whereby complex stratigraphic sequences or environments can be rationalized and comprehended. Given the complexity of many glacial environments, however, and the large number of controls on sedimentation and preservation, the possible number of facies for any single environment is potentially very large. This is clearly illustrated by the Pleistocene deposits of the Fraser and Chilcotin valleys which record a variety of styles of glaciolacustrine sedimentation. This, in combination with observations from other parts of British Columbia (*e.g.*, Shaw, 1977; Shaw and Archer, 1979; Eyles *et al.*, 1990, in press; Mullins *et al.*, 1990), would seem to preclude the formulation of any single comprehensive facies model for glaciolacustrine sedimentation in the Cordillera (see Shaw, 1988, however, for a discussion of this point). Noteworthy in this context is the fact that the deeper, subsurface, infill stratigraphy of valleys and modern lakes in the Cordilleran is still little understood. With these qualifications in mind, we can, at present, only compare and contrast sequences deposited at different times and under different circumstances, and offer some comments on depositional controls.

The older deglacial sequence provides evidence for large-scale ice stagnation and the development of an extensive supraglacial and ice-marginal lake system in central British Columbia during the closing stages of the penultimate glaciation. We suggest that the coarse-grained sediments of the older deglacial sequence originated as outwash deposited on stagnant ice trapped in deep narrow valleys. As the ice downwasted, these deposits were reworked by subaqueous mass movement processes. Although there are no existing supraglacial lakes as large as those in central British Columbia during the Pleistocene, debris-laden margins of some modern glaciers are downwasting in lakes and becoming progressively covered by water. Shaw (1979) and Shaw and Archer (1979) have inferred similar conditions from their studies of late Pleistocene glaciolacustrine deposits in southern British Columbia and Sweden.

In contrast, there is no evidence for ice stagnation and the development of an extensive supraglacial lake system in central British Columbia during the early part of the Fraser Glaciation, and supraglacial environments also were rare at the close of that glaciation. While peculiar climatic and/or glaciological conditions may be responsible for this difference, topography probably played an important role. The deeply incised Fraser valley, cut as much as 500 m below the level of the surrounding plateau, promoted the trapping of stagnant ice at the end of the penultimate glaciation. In contrast, at the end of the Fraser Glaciation, the Fraser valley was partially filled with older glaciolacustrine sediments, and thus was not as deep. Deposition of a relatively thin glaciolacustrine sequence during Late Wisconsinan deglaciation also suggests that Fraser deglacial water bodies in this area were sediment-starved compared to the older deglacial lake system.

The valleys of central British Columbia acted as effective sediment traps during growth of the Late Wisconsinan Cordilleran Ice Sheet. Large volumes of glacial debris were carried into lakes that filled these valleys and deposited by debris flows and other processes. In addition, older Pleistocene sediments exposed along the steep walls of submerged valleys probably were extensively cannibalized and contributed to the rapidly accumulating glaciolacustrine fill.

It is possible that the debris-flow-dominated part of the Late Wisconsinan advance sequence provides an ancient analog for 'till deltas' at the margins of Antarctic ice shelves. Alley *et al.* (1987) reported the existence of subglacial slurries below rapidly flowing outlet glaciers that feed ice shelves at the margins of the Antarctic Ice Sheet. This debris is dumped subaqueously at the grounding lines of ice shelves as 'till deltas', perhaps more appropriately termed subaqueous 'grounding-line' fans. The recent geophysical and glaciological literature provides some support for the existence of such subglacial slurries. Boulton (1987) and Boulton and Hindmarsh (1987) showed that drumlinization of a till substrate involves the removal of fluidized debris from around stiffer, better drained zones, thereby contributing to a large flux of overpressured, saturated debris beneath the ice.

Although some of the debris deposited in glacial lakes in central British Columbia during the advance phase of the Fraser Glaciation may have originated in this way, the upper part of the advance sequence in Fraser and Chilcotin valleys consists mainly of weakly bedded silts which clearly are not grounding-line deposits. Rather, the silts are thought to record deepening and expansion of the lake(s) immediately prior to glacier overriding.

The existence in Antarctica of large subglacial lakes in areas of relief comparable to the Canadian Cordillera (Fig. 16) suggests that some advance glaciolacustrine sediments in central

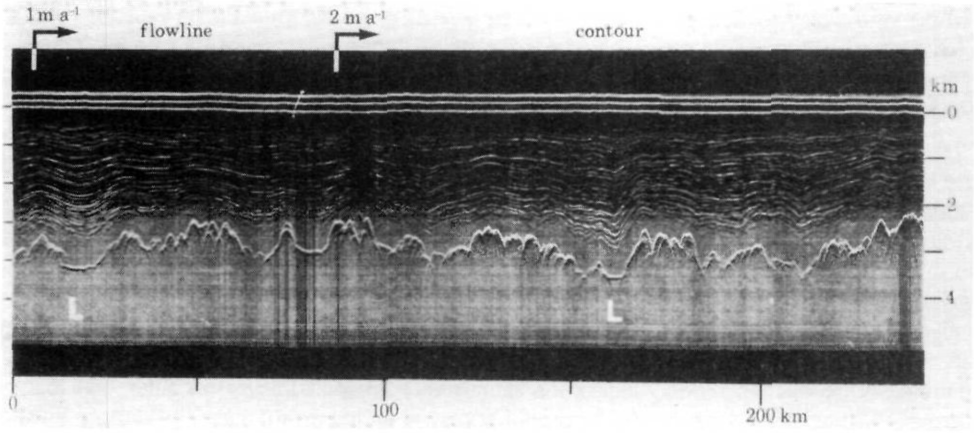

FIGURE 16. Seismic section from Antarctica showing lakes (L) at the base of the Antarctic Ice Sheet. Subglacial topography is comparable to that of the Interior Plateau of British Columbia (from de Q. Robin, 1983).

Profil sismique de l'Antarctique montrant des lacs (L) à la base de l'Inlandsis de l'Antarctique. Le relief sous-glaciaire se compare à celui du plateau de l'Intérieur, en Colombie-Britannique (de de Q. Robin, 1983).

British Columbia might be subglacial in origin. We have no sedimentological evidence to either support or refute this idea, although it seems possible that subglacial lakes could develop in relatively narrow, deep valleys oriented transverse to regional ice flow, such as the Fraser and Chilcotin valleys.

The three glaciolacustrine sequences in the study area differ in their degree of preservation. In general, the Late Wisconsinan deglacial sequence is the best preserved, mainly because it is the youngest and has not been overrun by glaciers. Advance glaciolacustrine deposits and till are well represented in the Late Wisconsinan succession, but have not been found in the older glacial succession. The simplest interpretation is that these sediments either were not deposited or were reworked as the ice sheet decayed at the end of the penultimate glaciation.

In addition to the contrasts noted above, the sequences share some similarities. The lower part of each glaciolacustrine sequence, in general, is coarser than the upper part. Silts occur above gravels, sands, and diamicts in the older deglacial sequence at Farwell Canyon and also intertongue with coarse materials toward the east. Likewise, gravels, sands, and diamicts are common in the lower part of this sequence at many sites, but are relatively uncommon in the upper part, except near steep valley walls. Finally, the lower part of the Late Wisconsinan advance sequence is dominated locally by diamicts and gravels deposited by debris flows, whereas the upper part consists mainly of silts.

Finally, no seasonal control on sedimentation is evident in either the older deglacial sequence or the Late Wisconsinan advance sequence. A well developed 'varved' style of deposition characterizes ice-marginal and proglacial lakes with relatively low sediment inputs and strong seasonal controls (Ashley, 1975). In contrast, in ice-contact lake basins receiving large volumes of coarse- and fine-grained sediment and abundant meltwater throughout the year, a seasonal cycle is either suppressed or cannot be discerned (Hsu and McKenzie, 1985; Eyles, 1987). A major factor acting to suppress seasonal signals in the sections described here is sediment focussing, whereby material eroded from a large area of the Interior Plateau, as well as from Pleistocene exposures in valleys, accumulated rapidly in lakes occupying deep, narrow troughs. The presence of steep subaqueous slopes and the burial and subsequent melt of stagnant ice may have allowed the year-round operation of sediment gravity flow processes and the masking of any seasonal pattern of deposition.

In conclusion, we wish to emphasize again the considerable variation in facies types in glaciolacustrine deposits of different ages in central British Columbia. Exposures of glaciolacustrine sediments along Fraser and Chilcotin rivers provide critical data on sedimentation patterns and glaciological conditions during the last two glaciations and consequently warrant further detailed study. A combination of outcrop work, seismic investigations, and drilling in this area should provide a more complete understanding of glaciolacustrine sedimentation in areas of moderate relief in the Canadian Cordillera. This, in turn, may help elucidate the history of growth and decay of the Cordilleran Ice Sheet.

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