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Glacial Stratigraphy of the Bulkley River Region: A Depositional Framework for the Late Pleistocene in Central British Columbia

Stratigraphie glaciaire de la région de la rivière Bulkley : un scénario de sédimentation datant du Pléistocène tardif dans le centre de la Colombie-Britannique

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Résumé de l'article

Un scénario de sédimentation datant du Pléistocène tardif est élaboré à partir de la stratigraphie glaciaire observée dans la région de la rivière Bulkley. Les dépôts non-glaciaires attribués à l’interstade d’Olympia sont surmontés d’un till d’une avancée glaciaire, d’un till datant du Wisconsinien supérieur (glaciation du Fraser) et de sédiments tardiglaciaires. Plusieurs unités ne sont pas continues dans la région et diffèrent par leur épaisseur et leur complexité, en raison de l’érosion locale et des taux de sédimentation variables. Au début de la glaciation du Fraser, l’avancée des glaces fut accompagnée d’une augmentation du niveau de base des rivières, la création d’étangs et d’une sédimentation près des marges glaciaires. La physiographie et la dynamique glaciaire influence l’emplacement des exutoires de drainage, la direction de l’écoulement des eaux et la création des bassins. La région fut alors entièrement couverte de glace et les directions d’écoulement glaciaire, très variables, furent fortement contrôlées par la migration des lignes de partage glaciaires. La déglaciation se caractérise par la sédimentation de sédiments fins dans les lacs proglaciaires, et des sables et des graviers fluvioglaciaires dans les zones de drainage libres.

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GLACIAL STRATIGRAPHY OF THE BULKLEY RIVER REGION: A DEPOSITIONAL FRAMEWORK FOR THE LATE PLEISTOCENE IN CENTRAL BRITISH COLUMBIA*

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ABSTRACT A depositional framework for late Pleistocene sediments in central British Columbia was developed from the composite stratigraphy of glacial sediments found in the Bulkley River region. Nonglacial deposits correlated to the Olympia Nonglacial Interval, are overlain in succession by sub-till, ice-advance sediments, Late Wisconsinan (Fraser Glaciation) till, and late-glacial sediments. Due to local erosion and depositional variability, some of the units are not continuous throughout the region and differ locally in their thickness and complexity. At the onset of the Fraser Glaciation, ice advance was marked by rising base levels in rivers, lake ponding, and ice marginal subaqueous deposition. Physiography and glacier dynamics influenced the position of drainage outlets, direction of water flow, and ponding. The region was completely ice covered during this glaciation and ice-flow directions were variable, being dominantly influenced by the migrating position of ice divides. Deglaciation was marked by the widespread deposition of fine-grained sediments in proglacial lakes and glaciofluvial sands and gravels at locations with unrestricted drainage.

RÉSUMÉ *Stratigraphie glaciaire de la région de la rivière Bulkley : un scénario de sédimentation datant du Pléistocène tardif dans le centre de la Colombie-Britannique.* Un scénario de sédimentation datant du Pléistocène tardif est élaboré à partir de la stratigraphie glaciaire observée dans la région de la rivière Bulkley. Les dépôts non-glaciaires attribués à l'interstade d'Olympia sont surmontés d'un till d'une avancée glaciaire, d'un till datant du Wisconsinien supérieur (glaciation du Fraser) et de sédiments tardiglaciaires. Plusieurs unités ne sont pas continues dans la région et diffèrent par leur épaisseur et leur complexité, en raison de l'érosion locale et des taux de sédimentation variables. Au début de la glaciation du Fraser, l'avancée des glaces fut accompagnée d'une augmentation du niveau de base des rivières, la création d'étangs et d'une sédimentation près des marges glaciaires. La physiographie et la dynamique glaciaire influence l'emplacement des exutoires de drainage, la direction de l'écoulement des eaux et la création des bassins. La région fut alors entièrement couverte de glace et les directions d'écoulement glaciaire, très variables, furent fortement contrôlées par la migration des lignes de partage glaciaires. La déglaciation se caractérise par la sédimentation de sédiments fins dans les lacs proglaciaires, et des sables et des graviers fluvioglaciaires dans les zones de drainage libres.

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INTRODUCTION

The glacial stratigraphy exposed in central British Columbia documents a complex depositional history encompassing multiple ice advance and retreat events during the Late Pleistocene (*e.g.* Ryder and Clague, 1989; Plouffe, 2000). The thickest sediments, representing the most complete stratigraphic record are present in coastal lowlands and river valleys. The sediment record in the Bulkley River region of central British Columbia (Fig. 1) is examined to infer depositional history, both on local and regional scales (*e.g.* Clague, 1987, 2000).

Thick sequences of Late Pleistocene glacial sediments infill the main Bulkley River valley and their tributaries. Sediments of the Fraser Glaciation are the most extensive and best preserved, but older deposits including interglacial sediments are locally present. Detailed studies in areas beyond the Bulkley River region have documented paleoclimate conditions and glacial and sedimentological environments during the Late Pleistocene (Plouffe, 1997a, 1997b; Plouffe and Levson, 2001; Mate and Levson, 2001).

STUDY AREA

Broad, u-shaped and elongated drift-filled valleys, bordered by high mountains, form the prominent topography of the Bulkley River region (Fig. 1). Much of the study area lies within the Interior Plateau physiographic region (Holland, 1976), and is bordered to the north and west by high ridges and peaks of the Skeena and Hazelton Mountains. These mountains rise 1 000 to 2 000 m above the lowest point in the Bulkley River valley (505 m above sea level, asl). An extensive drift cover mantles many rounded, gently sloping surfaces in the mountains indicating that actively-flowing ice overrode the area dur-

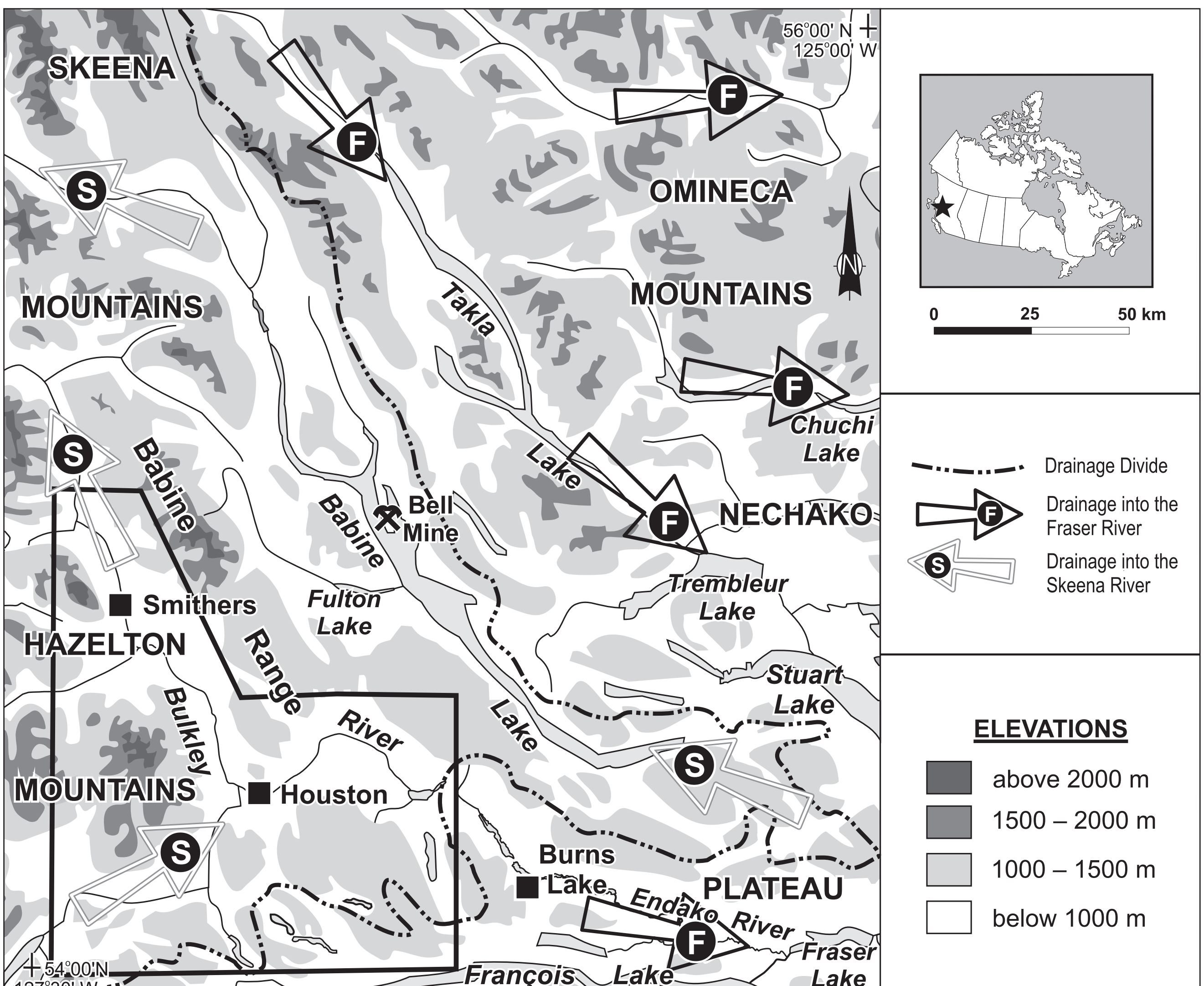

FIGURE 1. Location map of the Bulkley River region. The black box delineates the study area.

Carte de localisation de la région de la rivière Bulkley. L'encadré noir délimite la région à l'étude.

ing the Fraser Glaciation. At high elevations, modern glacier readvances and periglacial processes have locally removed or obscured evidence of earlier glacial events (Stumpf, 2001). Glaciers presently occupy northeast-facing cirque basins.

The eastern boundary of the study area lies along a divide between the Fraser River that flows eastward into the interior of the province and the Skeena River system that drains watersheds westward to the Pacific Ocean. The drainage divide is marked by undulating to rolling terrain and steep mountains lying at elevations between 720 and 1 950 m asl. At several locations, the headwaters of streams lie within broad, open-ended valleys and channels that transect present drainage divides.

REGIONAL SETTING

The landscape in the Bulkley River region has been modified by multiple glacier advances during the Late Pleistocene. Sediments predating the Fraser Glaciation are rarely exposed being covered by younger deposits or having been eroded by the Late Wisconsinan glaciers. However, deposits of such antiquity have been reported by a few authors (Harington *et al.*, 1974, 1996; Levson *et al.*, 1998; Mate and Levson, 2001; Plouffe and Jetté, 1997; Plouffe and Levson, 2001).

During the Fraser Glaciation (29 000-10 000 BP) (Clague, 1981; Ryder *et al.*, 1991), the Bulkley River region experienced complex patterns of glacier movement, meltwater flow, and sedimentation associated with multiple phases of ice flow. During the ice advance, alpine glaciers flowed southeast from ice accumulation centers in the Skeena and Omineca mountains and east to northeast from the Hazelton Mountains onto the Nechako Plateau (Clague, 1984; Stumpf *et al.,* 2000). With continued ice accumulation and expansion, these glaciers coalesced to form the Cordilleran Ice Sheet which, at its maximum extent, locally attained sufficient thickness (>2 000 m) to flow unconstrained by topography. During the maximum phase, an ice divide migrated eastward from the Coast Mountains onto the Nechako Plateau east of the study area (*e.g.* Stumpf *et al.*, 2000). As a consequence, the direction of glacier movement shifted from eastward to westward within the study area, and ice flowed across the Skeena and Hazelton mountains to the Pacific Ocean. Many glacially abraded landforms and striae are oriented parallel to this flow direction (Clague, 1984; Stumpf *et al.,* 2000).

As ice thinned rapidly during the latter part of glaciation, the ice divide moved back into the Skeena and Hazelton mountains (Stumpf *et al.*, 2000). The direction of glacier movement again became locally controlled by topography (*e.g.* Babine Lake and Takla Lake valleys; Fig. 1), and ice flowed east and southeast into the interior.

During deglaciation, an integrated valley drainage system carried meltwater away from recently deglaciated areas and downwasting stagnant ice. However, in many valleys, proglacial lakes developed due to blockage of local drainage by ice (*e.g.* Plouffe, 1997a, 1997b, 2000). The level of these lakes was controlled in part by outlets that transect drainage divides.

METHODS

Exposures of Late Pleistocene sediments were examined in vertical profile along major valleys in the study area (Fig. 2). Section elevations were determined from contours and spot heights on 1:20 000-scale Digital Terrain Resource Inventory Mapping (TRIM) maps, 1:50 000-scale National Topographic System (NTS) maps, 1:100 000-scale British Columbia Ministry of Environment maps, or by altimeter (to an accuracy of ±10 m). Exposures were located using a global positioning system (GPS) receiver with accuracy of ±50 m, and by compass-triangulation to identifiable points on topographic maps or aerial photographs.

Stratigraphic units were distinguished in the field by their sedimentological characteristics, unconformities, lateral continuity, and field examination of physical properties (*e.g.* texture, degree of consolidation, clast roundness, and percent

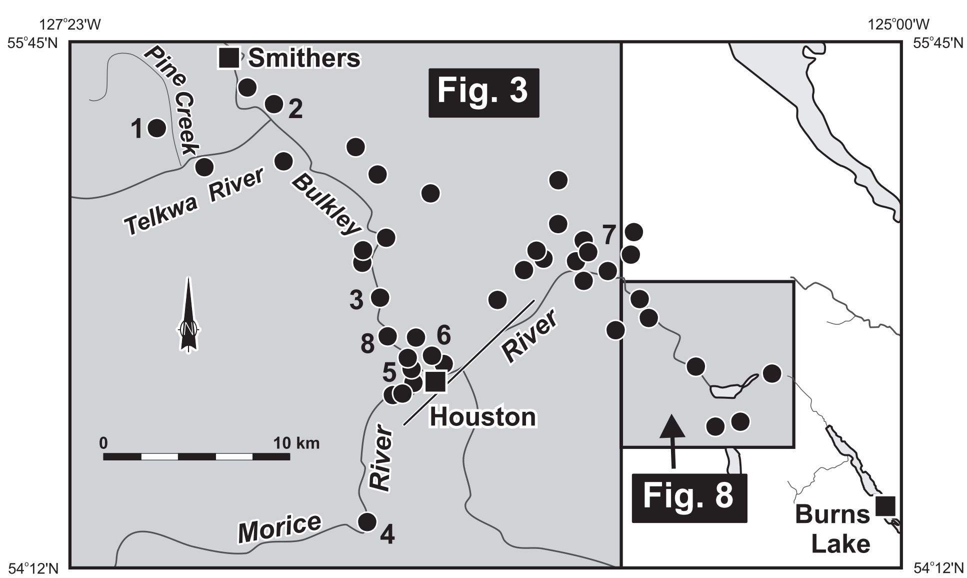

FIGURE 2. Locations of described and sampled exposures in the Bulkley River region. Reference sections shown in Figure 3, and an additional section described in the text are identified on the map. The shaded boxes outline geographical areas shown in Figures 3 and 8.

Carte de localisation des sites d'étude dans la région de la rivière Bulkley. Les sections de référence sont montrées à la figure 3, et la section additionnelle décrite dans le texte est identifiée sur la carte. Les zones ombragées délimitent les secteurs géographiques montrés aux figures 3 et 8.

matrix content). The textural classification follows the USDA scheme published by the Soil Survey Staff (1994). The directions of ice flow were inferred from striae and landform analysis and, locally, by the a-axis orientations of 25 elongate (prolate) pebbles sampled in basal till. Paleocurrent directions were determined from the orientation of bedding and clast imbrication in glaciofluvial sediments. The locations of recessional ice lobes, ice-marginal meltwater systems, and deglacial lake limits were delineated by mapping the distribution of ice-contact landforms and glacial lake sediments.

STRATIGRAPHY OF THE BULKLEY RIVER REGION

Late Pleistocene sediments were examined at 42 sites in the study area (Fig. 2). The stratigraphy at seven representative exposures is presented in Figure 3. Four informal units are identified according to the stratigraphic position and physical characteristics of the exposed sediments (Table 1). Stratigraphic units are correlated based on stratigraphic position, similarity of sequence, and sedimentologic characteristics.

PRE-LATE WISCONSINAN SEDIMENTS (UNIT 1)

Description. The lowest stratigraphic unit exposed (Unit 1) lies below the Late Wisconsinan glacial succession. The unit is poorly exposed, but where observed it is either a dense massive, dark grey clay loam diamicton or massive, black silt and clay that locally has a sulphurous odour. These sediments were characteristically extremely sticky and plastic and easily deformed when moistened. Typically, less than 5 m of the unit is exposed in cutbanks when the river level is low.

The silt and clay deposits of unit 1 lack organics, but are texturally similar and found in the same stratigraphic position as an organic-bearing silt deposit studied by Harington *et al.* (1974) north of the study area Bell Mine (Fig. 1). Organic materials obtained from the silt unit at Babine Lake were dated at between 43 800 ± 1830 BP (GSC-1687: wood) and 34 000 ± 690 BP (GSC-1754: bone collagen; Harington *et al.,* 1974), which corresponds to the Olympia Nonglacial Interval (Armstrong *et al.*, 1965)

Interpretation. Given its stratigraphic position, unit 1 was deposited prior to or at the onset of the Late Wisconsinan glaciation. Unit 1 might have been deposited as colluvium or lake sediments during a non-glacial interval, possibly the Olympia Nonglacial Interval, which predated the Late Wisconsinan Fraser Glaciation. Alternatively, unit 1 might have been deposited as glacial lake sediments and debris flows in a lake dammed by advancing glaciers at the onset of the last glaciation.

LATE WISCONSINAN ICE-ADVANCE SEDIMENTS (UNIT 2)

Unit 2a: Stratified sands and gravels

Description. Unit 2a is composed of laterally and vertically extensive fine- to coarse-grained sands interbedded with pebble- to boulder-sized gravels. At most of the sites studied, the sediment lies stratigraphically below finely laminated silt and clay of unit 2b or massive, matrix-supported silty diamicton of unit 3a (Fig. 3). Often the lower contact of the unit is not exposed, but drilling in the Bulkley River valley indicates these sediments lay above older Quaternary deposits (Fig. 4).

Generally, unit 2a is <10 m thick, but along the Pine Creek valley (site 1, Figs. 2-3), the sand and gravel sequence ranges from 10-30 m thick. Similar sand and gravel deposits were described by Levson *et al*. (1997) and Levson (2001) northeast of the study area, and by Clague (1984) northwest of Smithers (Fig. 1).

The sands and gravels are moderately dense to loose and moderately to well-sorted. They show both horizontal bedding and large-scale, low-angle trough cross-bedding. In the Pine Creek valley (site 1, Figs. 2-3), a thick sequence of horizontally bedded sand lies beneath trough cross-bedded strata (Fig. 5). Locally, the sand and gravel deposits contain trough-shaped channel fill sequences of medium- to fine-grained sand. Near the base of this unit, fluid escape and loading structures (*e.g.* flame structures) deform bedding. These sediments are exposed well above the levels of modern drainage channels.

Interpretation. The sands and gravels were likely deposited as glaciofluvial sediments during a period of elevated local base level, probably caused by aggradation in front of advancing glaciers at the onset of the Fraser Glaciation (cf. Levson *et al*., 1997; Levson, 2001). In the Pine Creek valley, sands forming horizontal beds (likely bottomset beds) and low-angle trough cross-beds (possibly foreset beds) were likely deposited as a fan or outwash delta (cf. Donnelly and Harris, 1989; Postma, 1990) by water flowing out of the Hazelton Mountains into a proglacial lake.

Unit 2b: Stratified silts and clays

Description. Stratified and horizontally-bedded sediments of unit 2b composed of repeated silt beds and clay laminae (*e.g.* Fig. 6) were identified in numerous vertical exposures in the Bulkley River region (Fig. 3). Sediment of unit 2b was also encountered during subsurface drilling for geological and engineering investigations (*e.g.* British Columbia Ministry of Forests, 1996). These fine-grained sediments lie beneath deposits of unit 2c or massive matrix-supported diamicton of unit 3.

Silts and clays of unit 2b range from reddish brown to grey in colour and contain scattered clasts, some up to boulder-size and a few with striae and facets. Locally, unit 2b may include massive or horizontally bedded fine-grained sands that may be interbedded with medium- to coarse-grained sand and small pebble gravel beds, or diamicton lenses with intraclasts of sorted sediment. At some sites, beds of sand grade upwards into the coarser sediments of unit 2c. The unit ranges from 2-15 m thick.

Moderate to intense deformation was locally observed, and included loading features, folding, and faulting. Also, the sediments are over-consolidated and bedding in the upper part of the unit is sheared. These characteristics are similar to glaciotectonic deformation found in glacial advance sediments at other locations (*e.g.* Broster and Clague, 1987).

Concretions and worm burrows are locally present along individual lamina. Several concretions were collected from site

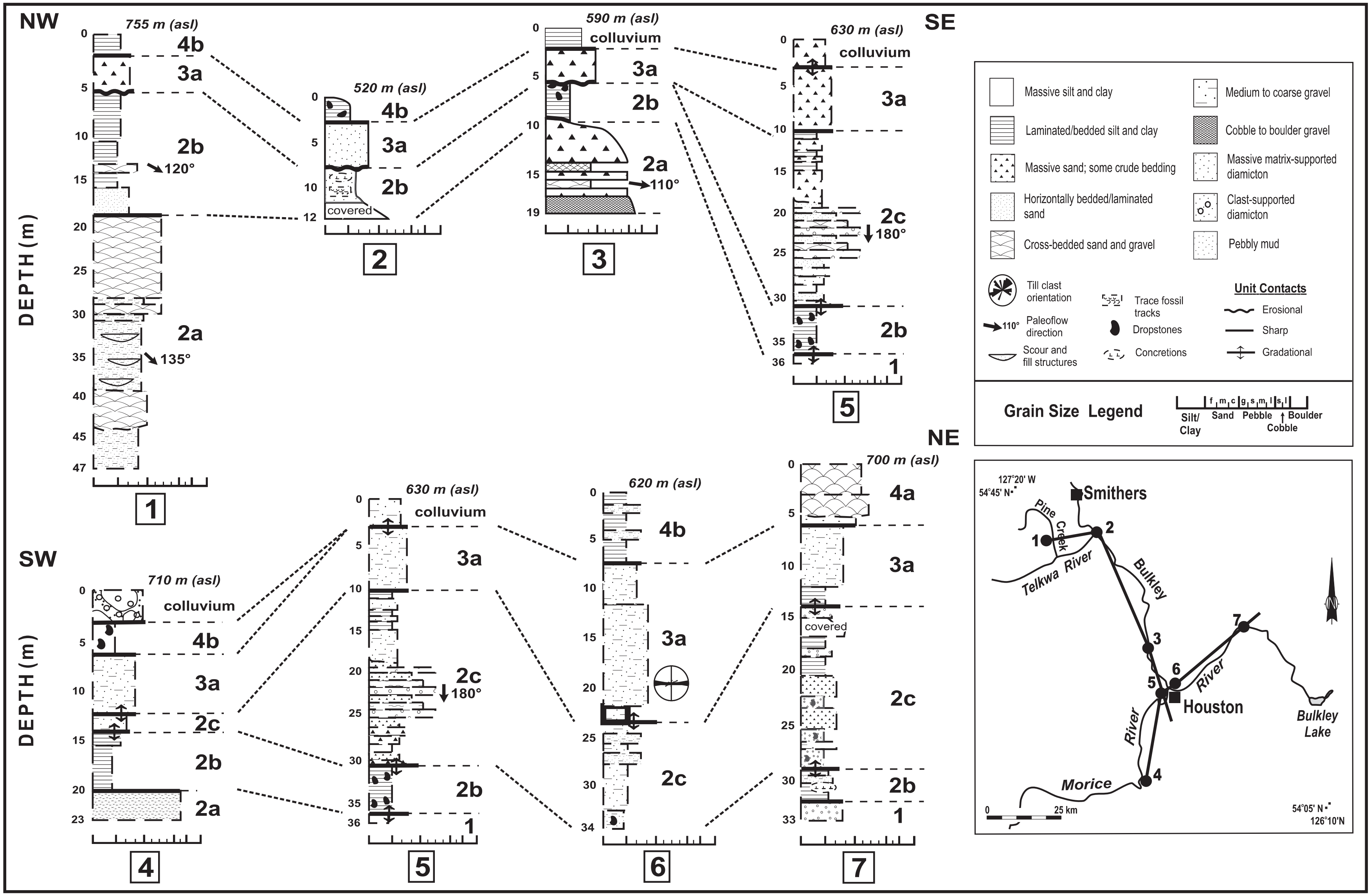

FIGURE 3. Correlation between reference sections from the Bulkley River region. Unit descriptions are discussed in the text. The stratigraphy at site 4 was compiled using borehole data from the British Columbia Ministry of Transportation and Highways (1991) and the British Columbia Ministry of Forests (BCMOF, 1993), and from field descriptions of exposed units.

Corrélation entre les sections de référence de la région de la rivière Bulkley. La description des unités est discutée dans le texte. La stratigraphie du site 4 a été compilée à partir de données provenant du British Columbia Ministry of Transportation and Highways (1991), du British Columbia Ministry of Forests (BCMOF, 1993), et la description des unités exposées sur le terrain.

TABLE I

Chronology and infrerred origin of each stratigraphic unit

Unit	Material	Inferred Origin	Relative Age
4b	Fine sand, silt, and clay	Late-glacial glaciolacustrine sediments	Glacial retreat, Fraser Glaciation (10 500-10 000 BP)[bci]
4a	Gravel and sand	Late-glacial glaciofluvial sediments	Glacial retreat, Fraser Glaciation (10 500-10 000 BP)[bci]
3b	Weakly stratified, matrix-supported diamicton	Late Wisconsinan (Fraser) Glaciation meltout or supraglacial till deposited by the Cordilleran Ice Sheet	Glacial retreat, Fraser Glaciation (10 500-10 000 BP)[bci]
3a	Massive, matrix-supported diamicton	Late Wisconsinan (Fraser) Glaciation basal till deposited during advance of the Cordilleran Ice Sheet	Glacial maximum, Fraser Glaciation (15 600-10 500 BP)[di]
2c	Pebbly silt, sand, diamicton, silt and clay, and gravel	Proglacial and ice marginal debris-flow deposits and rainout debris from icebergs	Glacial advance, Fraser Glaciation (29 000-15 600 BP)[bcde]
2b	Stratified silts and clays	Ice advance glaciolacustrine sediments deposited in ice-dammed proglacial lakes; ice becoming more proximal	Glacial advance, Fraser Glaciation (29 000-15 600 BP)[bcde]
2a	Stratified sands and gravels	Ice advance glaciofluvial sediments aggraded in valleys	Glacial advance, Fraser Glaciation (29 000-15 600 BP)[bcde]
1	Diamicton or bedded silt and clay	Nonglacial sediments deposited prior to Fraser Glaciation or early glacial sediments	Olympia Nonglacial Interval (over 29 000 BP)[abefgh]

Approximate ages in parentheses. Age constraint is provided by radiocarbon ages from (a) Harington *et al.* (1974), (b) Clague (1981), (c) Clague (1984), (d) Blaise *et al.* (1990), (e) Ryder *et al.* (1991), (f) Harington *et al.* (1996), (g) Plouffe and Jetté (1997), (h) Levson *et al.* (1998), and (i) Barrie and Conway (1999).

2 (Figs. 2-3). Carbon contained in the accretion rings (dated by Accelerator Mass Spectrometry; Levy and Jull, 1998) yielded a radiocarbon age of 37 700 ± 2100 BP (AA-331440). The carbonate was pre-treated with phosphoric acid and reacted at 625 °C with hydrogen, and iron filings catalyst.

Interpretation. Silts and clays of unit 2b were probably deposited in proglacial lakes during ice advance (cf. Eyles and Clague, 1991) suggesting that proglacial lakes developed in front of advancing glaciers at the onset of the Late Wisconsinan glaciation. Interbeds of medium- to coarse-grained sand and small pebble gravel within the unit were likely laid down by underflows (cf. Shaw and Archer, 1978). Lenses of diamicton and intraclasts of sorted sediment were probably deposited as ice-marginal subaqueous debris flows (cf. Broster and Hicock, 1985).

Well-developed laminae, probably rhythmites, are characteristic of sedimentation in ice-marginal and proglacial lakes with relatively constant sediment inputs and strong seasonal controls (Smith and Ashley, 1985). Sharp contacts between unit 2b and the underlying sands and gravels of unit 2a (*e.g.* site 1, Fig. 3) are indicative of a rapid transition between glaciofluvial and glaciolacustrine depositional environments. Moderate to intense soft-sediment deformation commonly observed in unit 2b likely occurred when the saturated sediments were buried. However, compressive deformation (shearing) and consolidation of the unit are attributed to stress from the overriding ice.

The occurrence of a concretion dated to the Olympia Nonglacial Interval, in sediments interpreted as Late Wisconsinan ice advance sediments, is problematic. It indicates that the concretions probably formed by precipitation of old carbonate from groundwater yielding a spurious radiocarbon age. Additional development of the methodology used to date concretions by radiocarbon is required before this date can be resolved.

Unit 2c: Interbedded sediment complex

Description. Unit 2c consists of an interbedded sequence containing pebbly silt, fine- to medium-grained sand, diamicton, silt and clay and fine gravel. The unit gradationally overlies silts and clays of unit 2b. The sediments are massive to crudely bedded and generally coarsen upwards (*e.g.* site 5, Figs. 2-3). Silt and clay beds contain numerous pebble- to boulder-sized clasts. Unit 2c ranges from 2-18 m thick.

Interbeds of diamicton increase in abundance toward the top of unit 2c. At many sites, the diamicton contains lenses of stratified gravel and sand, and blocks (intraclasts) of silt and clay with deformed bedding (Fig. 7). Often, bedding in these sediment packages is deformed by faults and folds, and ball-and-pillow, flame and fluid-escape structures.

Interpretation. Unit 2c is interpreted as proglacial and ice-marginal deposits that include subaqueous debris-flow deposits (cf. Eyles, 1987 and Ghibaudo, 1992) or rainout debris from icebergs (cf. Hambrey, 1994). Subaqueous debris flows probably remobilized submerged valley-fill sediments when moving downslope in a manner outlined by Eyles and Clague (1991) and Bennett *et al.* (2002). Pebbly silt and laminated silt and clay with clasts (dropstones) accumulated in proglacial lakes ponded in front of advancing glaciers. The upward increase in the abundance of diamicton, coarse sediments and dropstones, probably reflects the increased proximity of ice.

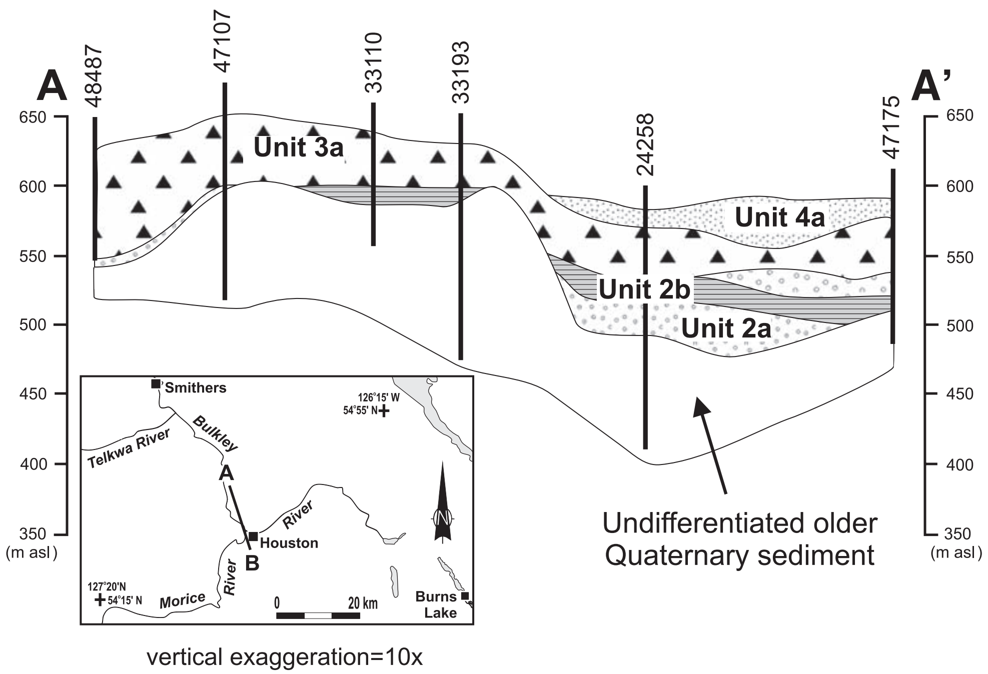

FIGURE 4. Stratigraphic cross section of Late Pleistocene sediments in the Bulkley River valley constructed from material descriptions submitted by water well drillers and engineering geologists to the British Columbia Ministry of Water, Land and Air Protection. Unit legend is same as in Figure 3.

Coupe stratigraphique des sédiments du Pléistocène tardif de la vallée de la rivière Bukley, basée sur les descriptions soumises au British Columbia Ministry of Water, Land and Air Protection. La légende stratigraphique est la même que celle qui apparaît à la figure 3.

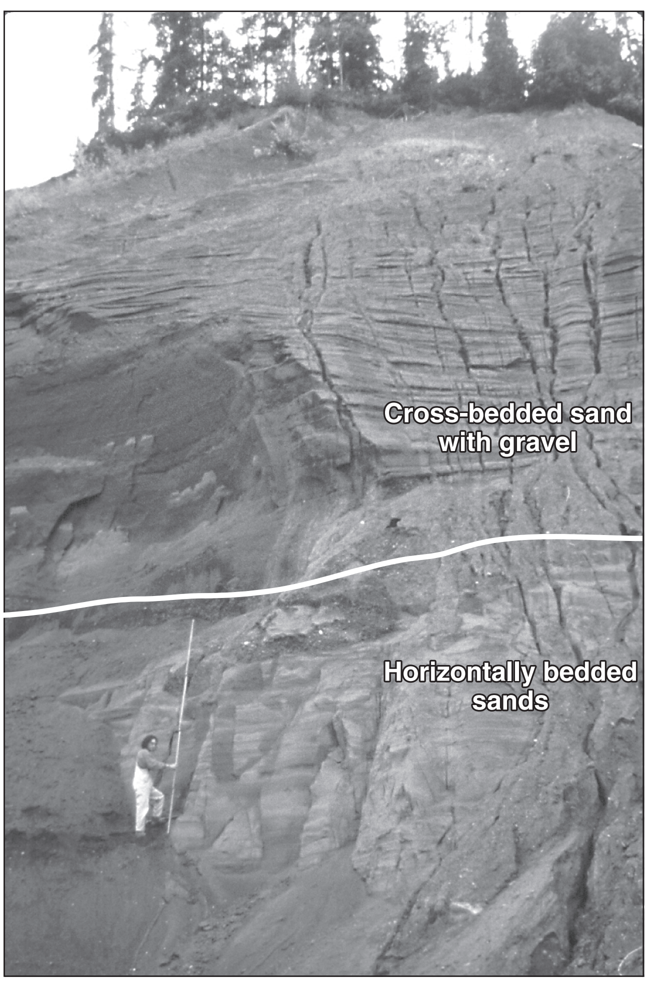

FIGURE 5. Bedded sand with gravel of unit 2a exposed along Pine Creek (site 1, Figs. 2-3). Here, horizontally bedded fine- to medium-grained sand lies beneath large-scale, low-angle, trough cross-bedded sand with gravel. The contact between beds is demarcated by the white solid line. The rod is about 4 m high.

Lits sablonneux avec des graviers de l'unité 2a exposée à Pine Creek (site 1, figs. 2-3). Les lits horizontaux de sable fin à moyen reposent sous une structure de grande taille et de faible pente, composée de lits de sable entrecroisés avec des graviers. La ligne blanche délimite la zone de contact entre les deux types de lits. La tige mesure 4 m de longueur.

Intraclasts of reworked sediment in debris flow diamicton were likely incorporated during downslope movement over previously deposited glaciolacustrine sediments. Also, incorporation of the underlying substrate by debris flows and glaciers may have produced gradational basal contacts (cf. Hart, 1995; Benn and Evans, 1996).

The ball-and-pillow and flame structures present in unit 2c are attributed to rapid deposition on saturated sediments and post-depositional dewatering. Folding and faulting of beds in the unit are interpreted to result from basal shear during subsequent glacier overriding (cf. Menzies, 1995).

LATE WISCONSINAN GLACIAL SEDIMENTS (UNIT 3)

Unit 3a: Massive, matrix-supported diamicton

Description. In the Bulkley River region, unit 3a is comprised of massive matrix-supported diamicton predominantly having a silt loam matrix texture; locally it varies from silty clay to sandy loam where the glacier eroded older lacustrine or fluvial sediments. Typically, the diamicton unconformably overlies either older sediments of unit 2 or bedrock.

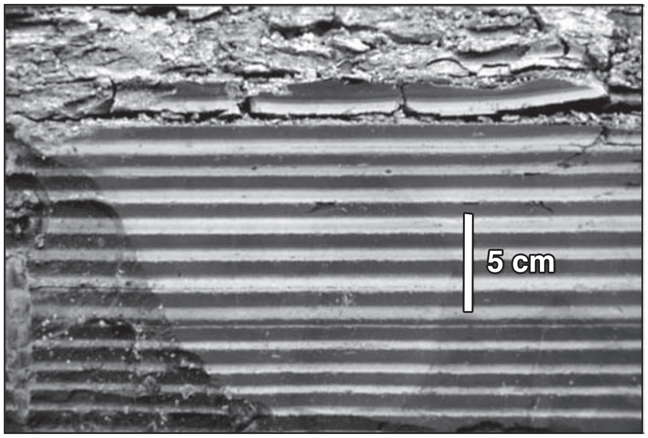

FIGURE 6. Rhythmically bedded silt and clay of unit 2b exposed in the Bulkley River valley (site 8, Fig. 2).

Alternance de limon et d'argile de l'unité 2b exposée dans la vallée de la rivière Bulkley (site 8, fig. 2).

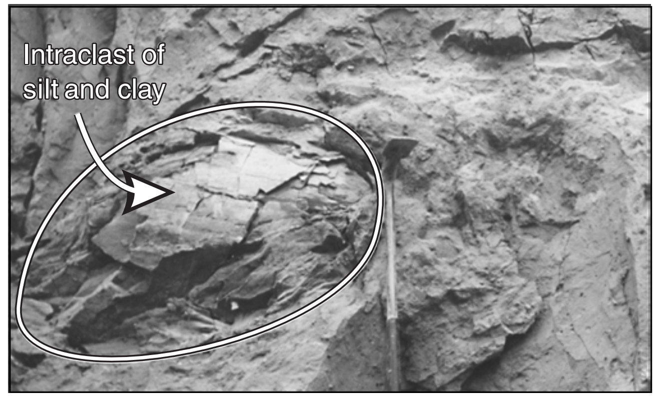

FIGURE 7. Intraclast of silt and clay of unit 2b within matrix-supported diamicton in the lower part of unit 2c. The pick is 0.5 m long.

Incrustation de limon et d'argile de l'unité 2b à proximité du diamicton formant l'unité 2c. Le marteau mesure 0,5 m de longueur.

The diamicton is moderately to very dense, contains striated and faceted clasts of diverse lithologies, and its overall colour and clast content largely reflect the character of the underlying sediments or local bedrock. For example, diamicton down-ice of maroon-coloured (Lower Jurassic) andesite has a distinctive reddish brown colour and contains a larger proportion of andesite clasts than elsewhere. Where measured, the a-axes of clasts generally parallel the main directions of ice flow at the glacial maximum in the region (site 6, Fig. 3; Stumpf, 2001). Moderate to strong fracturing and jointing are pervasive. Locally, the diamicton contains thin beds or lenses of pebble gravel, sand, silt, or clay. Locally, the upper part of the diamicton is crudely stratified in valley bottoms along the margins of deglacial lakes.

The diamicton is <0.5-40 m thick and commonly extends to the surface. Geomorphologically, this unit is expressed as: (1) drumlinoid ridges that parallel former ice flow; (2) a gently sloping or undulating terrain that completely mantles the topography of the underlying material; or (3) a thin veneer that lies on an undulating to ridged bedrock surfaces.

Interpretation. This massive, matrix-supported silty diamicton unit is interpreted as a basal till. This interpretation is supported by the presence of lithologically diverse and glacially abraded clasts, the high degree of consolidation, and the strong clast fabric. Crude stratification, locally present in the upper part of the till, likely resulted where slumping along the margins of deglacial lakes reworked the till, although, deposition by meltout of basal debris-rich ice is also a possibility.

Unit 3b: Weakly stratified, matrix-supported diamicton

Description. Massive, matrix-supported silty diamicton (basal till) of unit 3a is locally overlain by weakly consolidated and stratified diamicton of unit 3b. This material is distinguished from unit 3a by its generally sandier texture (sandy clay loam to loamy sand), presence of stratification, and weaker consolidation. It is pervasively oxidized, and contains interbeds of poorly sorted cobble- to boulder-sized gravels. Locally, the diamicton contains a higher proportion (>20%) pebble- to boulder-sized clasts derived from distal bedrock units than that of the underlying unit 3a (basal till).

Typically, unit 3b forms a thin, discontinuous surface blanket up to about 2 m thick that overlies either basal till or bedrock. Generally, the surface expression of the diamicton is hummocky, but in some areas, the topography is more subdued and ranges from undulating to level. This diamicton is most often present in areas where ice-contact sediments and deglacial landforms (*e.g.* kames, kame terraces, and eskers) are present.

Interpretation. The sandy diamicton of unit 3b is interpreted as till of a supraglacial or englacial origin (cf. Benn, 1992). Coarse gravel interbeds probably reflect the sorting of debris by meltwater as well as sedimentation within small ice-proximal channels. The increase in far-traveled clasts, compared to unit 3a, suggests that unit 3b debris was carried in englacial or supraglacial positions.

LATE WISCONSINAN LATE-GLACIAL SEDIMENTS (UNIT 4)

Unit 4a: Gravel and sand

Description. Unit 4a consists of beds of crudely imbricated, rounded pebble to cobble gravel and poorly to well sorted medium- to coarse-grained sand. These deposits form sinuous ridges, undulating to hummocky topography (Fig. 8), and elevated terraces or fan-shaped deposits at the outlet of tributary valleys or along margins of valleys. These sediments range in thickness from 3-10 m and are present up to 130 m above the bottom of modern river valleys. Generally, gravels in unit 4a are poorly sorted and clast-supported, and commonly have crude horizontal bedding. In some locations, the gravels show planar or trough cross-bedding, scour-and-fill structures, and interbeds of fine- to coarse-grained sand. Typically, the sand beds in unit 4a are well-sorted, and exhibit horizontal- and ripple-, or trough cross-bedding. These sediments locally contain striated clasts and interbeds or lenses of matrix- and

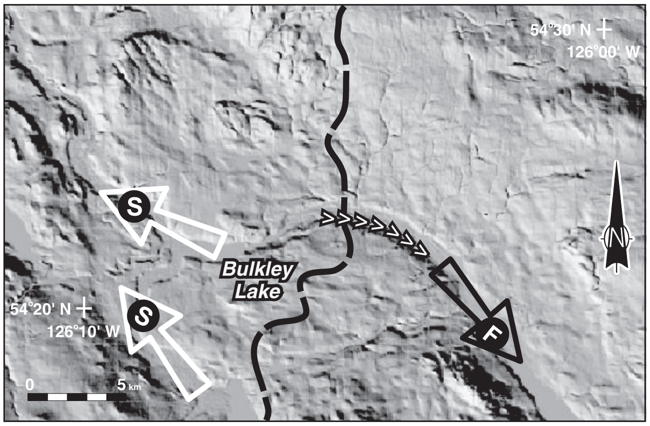

FIGURE 8. This digital elevation model (DEM) is shown covering the eastern part of the region outlined in Figure 3. The DEM is illuminated from the southwest and has a 3x vertical exaggeration. The black arrows delineate the direction of modern drainage. The dashed line marks the drainage divide between the Bulkley River (Skeena) and Endako River (Fraser) drainages. An esker-like ridge (>>>>) crosses the divide east of Bulkley Lake.

Le modèle numérique d'élévation (MNE) illustre la partie est de la région à la figure 3. Le MNE est illuminé du sud-ouest et a une exagération verticale de 3x. La lignée en pointillée montre la ligne de partage des eaux entre la rivière Bulkley (Skeena) et la rivière Endako (Fraser). Un esker (>>>>) traverse le lac Bulkley.

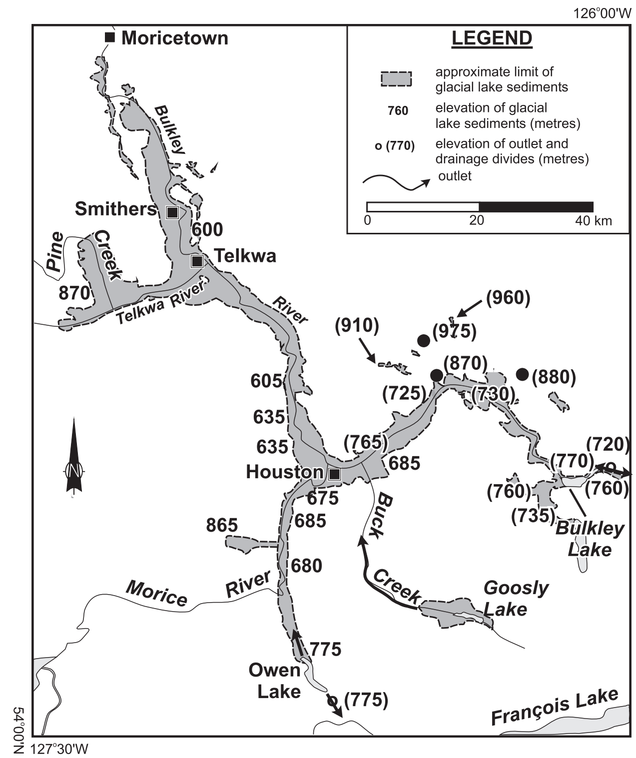

FIGURE 9. The maximum elevation of late-glacial glaciolacustrine sediments in the Bulkley River region. The limits of these proglacial lakes were defined using field data, interpretations of the surficial geology from 1:60 000- to 1:70 000-scale aerial photographs, and observations and data by Farstad and Laird (1954), Runka (1972), Clague (1984), and Church and Barakso (1990).

Élévation des sédiments glaciolacustres dans la région de la rivière Bulkley. La limite des lacs proglaciaires est déterminée à partir de données de terrain, de l'interprétation de la géologie de surface avec des photos aériennes au 1/60 000 et 1/70 000, des observations et les données de Farstad and Laird (1954), Runka (1972), Clague (1984), and Church and Barakso (1990).

clast-supported diamicton that are stratified or deformed. At some locations, gravels and sands of unit 4a fine upwards into laminated silts and clays of unit 4b.

Locally, gravel and sand beds in this unit are faulted and folded, or show scour-and-fill structures. Paleocurrent measurements indicate that meltwater flowed in various directions, not necessarily parallel to the alignment of modern valleys. In some areas (*e.g.* east of Bulkley Lake, Figs. 1, 9), meltwater flow was directed across modern drainage divides.

Interpretation. The gravels and sands of unit 4a are interpreted as glaciofluvial sediments deposited at the end of the Fraser Glaciation. These sediments compose ridges (eskers), elevated benches (ice-marginal terraces), fan-shaped deposits (fans and deltas), and flat-lying lowlands (outwash plains). Locally, fining-upward gravels and sands in the section indicate a shift towards a more ice-distal depositional environment. The diamicton layers were likely deposited as debris flows in an ice-proximal environment. Deformation observed in these sediments is attributed to the melting of supportive ice.

Unit 4b: Fine sand, silt and clay

Description. Unit 4b is composed of interstratified fine-grained sand, silt, and clay. These sediments overlie diamictons of unit 3, or unit 4a at elevations ranging from 520 and 975 m asl (Fig. 9). The fine-grained sands can be massive, horizontally stratified, ripple laminated, or cross-bedded. Generally, the silts and clays are crudely laminated, but they also form thick (>50 cm) massive beds. Typically, unit 4b ranges from 2-10 m thick, with the thickest deposits commonly exposed near outlets of major meltwater channels along the larger valleys.

Locally, these fine-grained sediments are interbedded with small- to large-sized gravels and coarse-grained sands, and massive or stratified diamicton. Scattered rounded and striated clasts, some up to boulder size, are present throughout the unit.

Interpretation. Fine-grained sediments of unit 4b are interpreted as late-glacial phase, glaciolacustrine sediments deposited distally from glacier margins. These lakes were ponded behind downwasting ice blocks and/or recessional moraines during deglaciation (cf. Plouffe, 1997a, 2000). The lack of thick sequences of rhythmic silts and clays, and the absence of recognizable glacial lake strandlines, suggests that these lakes were probably shallow and existed for a relatively short time.

GLACIAL HISTORY

Although glacial environments are inherently complex and vary across landscapes because of differing controls on sedimentation and preservation, our proposed stratigraphic framework (Table I) includes distinct units that are representative of the Late Pleistocene sequences in this part of central British Columbia. This framework would be applicable to other areas that contain broad glaciated valleys where drainage was constricted during glacial advance and retreat, partially by high flanking mountains, but also by ice damming along drainage divides in low relief areas.

Non-glacial sediments predating the last glaciation (unit 1) might be present within the area. The depositional environment and chronology of these deposits is still uncertain because of the small size of the exposure and the lack of material available (*e.g.* organic matter) for numerical dating.

At the onset of the Fraser Glaciation (29 000-25 000 BP) (Table I; Clague, 1981) the climate cooled and glaciers expanded outward from ice centers in the Skeena and Hazelton mountains and flowed down valleys into the Interior Plateau. In some valleys, such as Pine Creek, river base levels were raised as drainage was redirected, disrupted or dammed by glaciers. Glaciofluvial sediments (unit 2a) were deposited in these river channels and in deltas feeding into proglacial lakes.

Thinly laminated and bedded silts and clays of unit 2b were deposited in proglacial lakes during glacier advance downstream of channels that drained valley glaciers in flanking mountains (*e.g.* channels draining from the west into the Bulkley River valley; Fig. 1) where drainage was ponded by ice. These deposits are encountered underlying Late Wisconsinan till in the Bulkley River region over a much larger area than had previously been known. The presence of thick, well stratified sediments that contain evidence for seasonal control on deposition, suggest these ice-advance proglacial lakes were likely deeper, and persisted for a longer period of time than the deglacial (retreat) lakes in the region for which seasonality was not observed (see below).

Unit 2c is thought to record a period of glacial lake deepening and glacier advance. Reworked clayey diamicton and sorted sediment were deposited by subaqueous debris flows and landslides as steep slopes destabilized during lake infilling. Thick sequences containing beds of pebbly silt, sand, gravel, silt and clay, and diamicton interpreted as debris-meltout and ice-rafted material, accumulated near glacier margins during ice expansion into the proglacial lakes (cf. Huntley and Broster, 1994). The presence of glacigenic deformation features (folds and faults) in sediments of units 2b and 2c suggests that the lakes eventually drained and glaciers overrode the sediments.

During glaciation, older sediments and bedrock were eroded by ice and deposited as basal till (unit 3a). The Cordilleran Ice Sheet attained its maximum extent in the region between 15 600 BP and before 10 500-10 000 BP (Clague, 1984; Blaise *et al.*, 1990). At the glacial maximum, the Cordilleran Ice Sheet attained a thickness greater than 2 000 m (*e.g.* Stumpf *et al.,* 2000) at which time ice flowed southwesterly across the Bulkley River region.

According to Fulton (1967, 1991), the onset of deglaciation in central British Columbia was marked by rising of regional equilibrium lines (REL). Upland and montane areas below REL and where ice was thinnest became ice-free first, and downwasting occurred in valleys where ice was thick. In the Bulkley River region, downwasting occurred in some valleys, but late-glacial flow paralleling valleys and frontal retreat towards accumulation centers at higher elevations persisted for some time during deglaciation. Where downwasting occurred, the meltwater drainage system was controlled by the location of stagnant ice bodies. Locally, meltwater flowed subglacially along channels forming eskers. Glaciofluvial sediments (unit 4a) were deposited in front of ice margins and where meltwater entered proglacial lakes. Where debris-covered glaciers persisted, diamicton of unit 3b was deposited by meltout.

A series of proglacial lakes developed in the Bulkley River valley and its tributaries when a combination of downwasting ice and sediments blocked the drainage (Fig. 9) similar, to lakes in other parts of British Columbia described by Mathews (1944), Fulton (1967, 1975) and Plouffe (1997a, 1997b). The extent of these lakes is delineated by silt and clay deposits of unit 4b. The lack of thick, well stratified sequences, or traceable shorelines or beaches, suggests that these lakes were relatively short-lived. Some of these lakes had an eastward or southward outlet draining toward the interior of British Columbia (*cf.* Plouffe, 2000). Water levels in glacial lakes to the east (*e.g.* Glacial Lake Fraser) were at similar elevations (between 740 and 790 m asl; Plouffe, 1996, 2000) to the deglacial lakes occupying the eastern part of the Bulkley River region, but more work is required to decipher the details of the late-glacial lake history in the region. Westward drainage through the Skeena and Coast mountains was re-established following the melting of ice in the valley

CONCLUSIONS

The integration of sedimentologic, stratigraphic, and geomorphologic evidence examined here provides insights into the style of deposition for Late Pleistocene sediments in central British Columbia. The depositional framework developed for the Bulkley River region also provides a basis for an understanding of glacial stratigraphy at locations having similar geology, physiography, drainage, and proximity to ice centres.

Four stratigraphic units (units 1 through 4) identified in the Bulkley River region, were deposited in: (1) in a nonglacial or early glacial environment; (2) in front of glaciers advancing from high mountains into valleys and onto plateaux; (3) under glaciers as englacial meltout or supraglacial till; and (4) as glaciofluvial and glaciolacustrine sediments during deglaciation. Units 2, 3 and 4 thus represent, respectively, advance-phase, full glacial-phase, and retreat-phase sequences, deposited during the Late Wisconsinan glaciation.

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