# The environment in and around ice-dammed lakes in the moderately high relief setting of the southern Canadian Cordillera

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During decay of the Cordilleran Ice Sheet, ~13 000–10 000 cal. yr BP, numerous ice-dammed, ribbon-shaped lakes developed within the moderately deep valleys of the Interior Plateau of British Columbia. We describe the pattern and characteristics of lake sediments within the Thompson Valley, propose a palaeoenvironmental model for glacial lakes Thompson and Deadman and explore their implications for the palaeogeography of Cordilleran Ice Sheet decay. Seventeen glaciolacustrine lithofacies are identified within deltas, subaqueous fans and lake-bottom beds. Sediments accumulated at high rates and by a diversity of sediment dispersal and depositional processes: hyperpycnal and surge-type turbidity currents, grain flows and debris flows. Megascale subaqueous failures (tens of metres thick) were facilitated by high sedimentation rates. The palaeoenvironmental model highlights: (i) high rates of basin infilling; (ii) the dominant role of tributary rivers, rather than valley-occupying ice, in delivering water and sediment to lakes; and (iii) the role of melt cycles, jökulhlaups and hyperpycnal flows in sediment delivery. These conditions, in combination with a lack of organics and a fining upward sequence in lake sediments, suggest that glacial lakes Thompson and Deadman were coeval with dwindling plateau ice.

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The sediments and landforms of glacial lakes are important records of landscape and environmental change. During the decay of the Cordilleran Ice Sheet ~13 000–10 000 cal. yr BP (Fulton 1969; Eyles & Clague 1991; Ryder *et al.* 1991; Clague & James 2002) many ribbon-shaped, ice-dammed lakes developed within the moderately deep valleys that dissect the Interior Plateau of British Columbia (e.g. Fulton 1969). To date, interpretations of the palaeoenvironment of these lakes in the Cordillera have emphasized supraglacial lake development (e.g. Eyles *et al.* 1987; Ward & Rutter 2000) or proglacial lake development with sediment supply mainly from valley ice (e.g. Shaw & Archer 1979). Based on detailed field observations, we propose a third interpretation, wherein (i) proglacial lakes are dammed by valley ice, yet have minimum ice contact, (ii) sediments are mainly derived from tributary rivers rather than valley-occupying ice, and (iii) tributary rivers are fed by melting plateau ice. This interpretation has implications for understanding the palaeogeography of Cordilleran Ice Sheet decay and may have broader application. We document the pattern and characteristics of ice-dammed lake sediments in the Thompson Valley, British Columbia, and explore their implications for reconstruction of the palaeoenvironment and the palaeogeography of the Cordilleran Ice Sheet during deglaciation.

## Study area and previous research

The study area is situated within the southern Canadian Cordillera, in the southern Interior Plateau of British Columbia (Fig. 1). Fluvial and glacial erosion have dissected the Thompson Plateau resulting in deep valleys (up to ~2000 m in relief) that are filled with thick (up to ~800 m) Quaternary deposits (Fulton 1965; Ryder 1976; Eyles & Mullins 1997). High (up to >100 m) cliffs of Late Wisconsinan lake sediments occur in a near-continuous swath along a 75 km corridor of the Thompson Valley from the outlet of present day Kamloops Lake at Savona to a few kilometres south of Spences Bridge near Skoonka Creek – this section of the valley forms the study area (Fig. 1). There are numerous tributaries to the Thompson River. The largest of these are the Deadman, Bonaparte and Nicola rivers (Fig. 1).

Deglaciation is inferred to have proceeded by regional stagnation, resulting in downwasting and backwasting of the Cordilleran Ice Sheet toward ice divides, while, locally, stranded ice masses within the valleys dammed lakes (e.g. Fulton 1967, 1969, 1991). Lakes may have evolved from supraglacial to proglacial lakes through thermokarst processes (Eyles *et al.* 1987). Proglacial lake basins lengthened as the margins of the valley ice masses downwasted and backwasted. We evaluate this interpretation against field observations in the study area.

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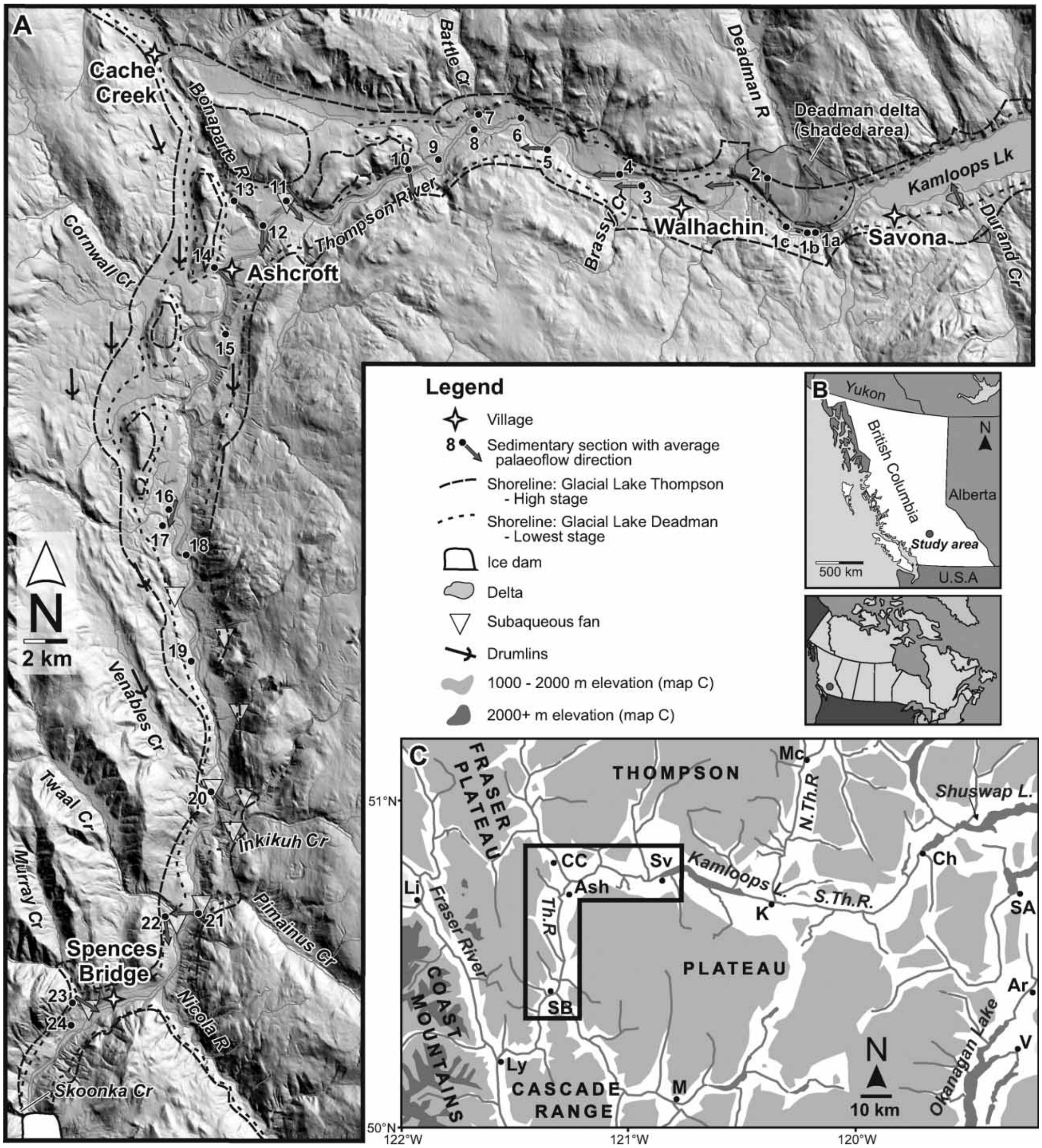



*Fig. 1.* A. Hill-shaded relief model showing locations of sedimentary sections and palaeoshorelines (Johnsen & Brennand 2004; DEM data, British Columbia Government 1996). B. Location of study area in British Columbia and Canada. C. Regional physiographic context and locations mentioned in the text. Map abbreviations: Li = Lillooet; Ly = Lytton; SB = Spences Bridge; M = Merritt; Ash = Ashcroft; CC = Cache Creek; Sv = Savona; K = Kamloops; Mc = McClure; Ch = Chase; SA = Salmon Arm; Ar = Armstrong; V = Vernon; Th.R = Thompson River; N.Th.R = North Thompson River; S.Th.R = South Thompson River. Plateau ice is not shown as correlative ice-marginal positions remain uncertain.

Previous research has documented two glacial lakes within the study area: glacial Lake Thompson and glacial Lake Deadman (Fulton 1969; Ryder 1981; Fig. 1A). These lakes have different outlets, yet similar palaeogeography within the Thompson Valley; they could reasonably be viewed as different stages of the same lake (Johnsen & Brennand 2004). Here, we retain the lake names of earlier workers (op. cit.) for consistency. Glacial Lake Thompson was deeper (~140 m) than glacial Lake Deadman (~50 m deep), and is older. Both lakes were dammed by ice south of Spences Bridge and drained eastward from outlets located in the Shuswap Basin and at Kamloops (Fig. 1C), respectively (Fulton 1969). Glacial Lake Deadman drained southward, catastrophically when the ice dam failed. Thus, drainage

*Table 1.* Lithofacies descriptions, occurrence and interpretation for Late Wisconsinan ice-dammed lakes in the Thompson Valley, British Columbia.

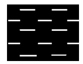
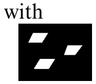
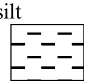
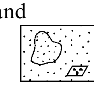
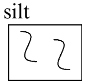
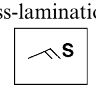
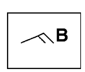
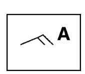
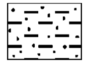
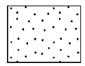
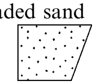
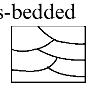
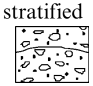
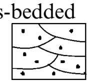
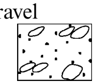
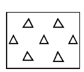
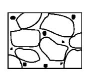
| Grain size | Facies Code | Lithofacies name and log symbol | Characteristics | Occurrence and distribution | Interpretation | | Refs[1] |
|---|---|---|---|---|---|---|---|
| | | | | | Process | Depositional Setting(s) | |
| Clayey Silt | Cl | Laminated clayey silt  | Laminated clayey silt (mm to cm scale thickness) and fine sand (mm scale thickness) | Very rare; most common near Deadman delta | Deposition from suspension; likely derived from turbidity currents (see text for explanation) | Lake-bottom | 2,19,20 |
| | Cin | Clayey silt with inclusions  | Clayey silt (convoluted) including irregular clasts of silt to medium sand; beds 5–25 cm thick | Very rare; most common near Deadman delta | Resedimentation by loading and subaqueous flow or slump | Lake-bottom | 1 |
| Silt | Zl | Laminated silt  | Laminated (planar to undulatory; grading sometimes visible) silt with minor fine sand separations ( <0.5 cm thick); beds 0.01–30 m thick; rare dropstone | Very common; found throughout area | Deposition from suspension | Lake-bottom; occasionally in subaqueous fans | 2,9,19,20 |
| | Zin | Silt with sand inclusions  | Massive silt[2] to highly contorted laminated silt including folded and rolled coarser-grained saucer to irregular shaped inclusions; beds 0.5– >50 m thick; inclusions (0.05 m–10 m apparent long-axis) are composed of contorted laminated silt and diffusely graded sand; mega-inclusions sometimes include contorted ripple cross-laminated sand; this lithofacies is somtimes associated with tilted blocks of lacustrine sediment | Common; found throughout area | Subaqeous slumping and soft sediment loading | Lake-bottom | 1,6,12,13, 15 |
| | Zc | Convoluted silt  | Silt with convolutions, load, fold and drag structures; sometimes massive[2]; sometimes coarser grains incorporated; beds 0.1–15 m thick | Somewhat common throughout area | Subaqeous slumping and soft sediment deformation | Lake-bottom | 1,6,15 |
| Sand | | Ripple cross-lamination: | | | | | |
| | Srs | type S   | Sinusoidally laminated very fine sand and coarse silt, near vertical angle of climb; cosets 0.5–20 cm thick; commonly drapes type B ripple cross-laminated sand | Somewhat common; found near Deadman delta and tributaries | Mainly suspension deposition from turbidity currents forming ripples | Lake-bottom; subaqueous fan | 1,3,14,16, 20 |
| | Srb | type B   | Stoss-side and lee-side cross-laminae preserved in fine sand; moderate angle of climb, variable amplitude; variable vertical associations – type B overlying type A most common; cosets 0.1–1 m thick | Somewhat common; found near tributaries | Deposition from suspension and traction from turbidity currents forming ripples | Lake-bottom; subaqueous fan; delta (foresets) | 1,3,14,16, 18,20 |
| | Sra | type A   | Lee-side cross-laminae preserved in fine to medium sand; low angle of climb, variable amplitude; lower contact erosional and sometimes loaded; most common ripple type; cosets 0.05–1 m thick | Somewhat common; found near tributaries | Deposition mainly from traction from turbidity currents forming ripples | Lake-bottom; subaqueous fan; delta (foresets) | 1,3,14,16, 18,20 |

*Table 1* (Continued)

| Grain size | Facies Code | Lithofacies name and log symbol | Characteristics | Occurrence and distribution | Interpretation | | Refs[1] |
|---|---|---|---|---|---|---|---|
| | | | | | Process | Depositional Setting(s) | |
| | Sp | Planar stratified sand  | Planar stratified fine to coarse sand with minor granule fraction; sometimes contains irregular-shaped clasts of silt; beds 0.5–20 m thick | Somewhat common; found near tributaries | Mostly deposition from traction from turbidity currents | Subaqueous fan; delta (foresets); lake-bottom | 1,5,8,11,16, 17,18 |
| | Sdg | Diffusely graded sand  | Diffusely graded (sometimes normal) medium and coarse sand sometimes with occasional granules; sometimes appears massive; often contains silt balls and stringers; lower contact moderately to severely loaded; occasional dish structures; beds 0.1–20 m thick | Somewhat common; found near tributries | Mostly rapid suspension deposition from turbidity currents; fluidization occasional | Lake-bottom; subaqueous fan | 1,5,8,10,11, 16,17,18,19 |
| | Srg | Reverse graded sand  | Reverse graded medium and coarse sand sometimes with occasional granules; lower contact sometimes loaded; occasional dish structures; beds 0.1–0.5 m thick | Uncommon; found near tributries | Mostly deposition from grain flow; fluidization occasional | Lake-bottom; subaqueous fan | 1,11 |
| | St | Trough cross-bedded sand  | Trough cross-bedded sand; cosets 0.5–2 m thick | Uncommon; found near Ashcroft and Deadman delta | Deposition from traction from turbidity currents forming dunes | Subaqueous fan; delta (foresets) | 1,8,18,19 |
| Gravel | Gus | Undulatory stratified gravel  | Undulatory stratification; sub-rounded to well-rounded clasts with small cobbles dominant; lenticular beds; cosets 3–15 m thick | Uncommon; found near Ashcroft | Deposition from traction and suspension from turbidity currents forming in-phase waves | Subaqueous fan | 1,4,5 |
| | Gt | Trough cross-bedded gravel  | Trough cross-bedded gravel; cosets 2–15 m thick | Uncommon; found near Ashcroft | Deposition from traction and suspension from turbidity currents forming dunes | Subaqueous fan | 1,8,18,19 |
| | Gi | Imbricate gravel  | Stratified (sometimes weakly stratified), imbricate, matrix supported, subrounded to rounded pebble to large cobble; beds 2–5 m thick | Uncommon; found near Ashcroft, Deadman delta and Section 20 | Deposition from traction from turbidity currents and avalanching | Delta (foresets); subaqueous fan | 10,17,18, 19, 20 |
| Diamicton | zD | Stony silty diamicton  | Matrix supported sub-angular to sub-round clasts (granule to small cobble); <40% clasts; silt to fine sand matrix; beds <30 cm thick | Uncommon; near lake edges and tributaries | Subaqueous debris flow | Lake-bottom; subaqueous fan | 7,8,16 |
| | bD | Boulder diamicton  | Martix or clast supported sub-angular to angular boulders (up to 2 m size); silt to fine sand matrix; >70% clasts; clast lithology traced to neighbouring outcrop; beds 0.5–15 m thick | Uncommon; found near Ashcroft | Subaqueous rockfall | Lake-bottom; proximal to bedrock cliff | |

[1]References supporting interpretations of lithofacies: (1) Allen 1982 and refs therein, (2) Ashley 1975, (3) Ashley *et al.* 1982, (4) Carling 1999, (5) Cheel 1989 and refs therein, (6) Cheel & Rust 1986, (8) Eyles *et al.* 1987, (9) Fulton 1965, (10) Gilbert 1975, (11) Gorrell & Shaw 1991, (12) Howard & Lohrengel 1969, (13) Hubert *et al.* 1972, (14) Jopling & Walker 1968, (15) Kuenen 1953, (16) Middleton & Hampton 1976, (17) Nemec 1990b, (18) Postma 1990, (19) Russell & Arnott 2003 and refs therein, (20) Smith & Ashley 1985 and refs therein.
[2]Hard, dry silt appears massive. Thin-sections and micromorphological analysis not attempted.

through Thompson Valley was reversed, flowing westward and southward as it does today. The former shorelines of both lakes have been tilted (up to 1.8 m km$^{-1}$ to the north–northwest) by differential glacio-isostatic uplift (Johnsen & Brennand 2004).

To date, local palaeoenvironmental interpretations have been made from limited study of the lake sediments. In the southern portion of the study area (Anderton 1970; Ryder 1970), it had been inferred that lakes lengthened southward in contact with receding stagnant ice in the valley, and that fining-upward trends in sedimentation reflected deposition at ever-increasing distances from this ice tongue. Ryder (1970) described one Late Wisconsinan lacustrine section and interpreted that sediment was emplaced by powerful density currents, slumps and mudflows; varved sedimentation was not noted. East of Kamloops (Fig. 1C), palaeoenvironmental research on glacial Lake Thompson – highest stage (Johnsen & Brennand 2004) suggests that the lake lengthened as stagnant ice tongues receded from both ends of the basin, and that rates of sedimentation were high (Fulton 1969). No organic material has been found within the sediments in this or any earlier study (Fulton 1965).

## Methodology

A total of 24 sediment exposures were examined in order to document the regional pattern and character of lake sediments. Ten of these exposures (>20 m in height) were logged at the centimetre to decimetre scale. The remaining 14 exposures were examined in a more general manner, as they were either too high or unsafe to access; some portions of these exposures were examined in detail (Johnsen 2004). Sediment texture and structure, palaeoflow direction indicators, bed contact relationships and lateral continuity and thicknesses of units were recorded. The grain-size distributions of fine-grained samples were quantified by sieving and sedigraph analysis.

Lithofacies are defined as the smallest homogenous sedimentary unit representing a discrete sedimentary process (e.g. Reading 1986). The lithofacies we describe are identified and interpreted based on their characteristics and associations, and their geomorphic (landform) and palaeogeographic (e.g. location with respect to possible sediment sources) context. Interpretation of lithofacies and landforms follows sedimentary principles (e.g. Middleton & Hampton 1976; Allen 1982) with reference to many examples in the literature (Table 1). Subsequently, landform genesis and deglacial palaeogeography are inferred from landform–sediment relationships.

## Character and setting of lakes in the Thompson Valley, BC

Geomorphic and stratigraphic relationships support an ice-contact origin for the Late Wisconsinan lake sediments in the Thompson Valley. Evidence of valley ice dams and buried ice within the Thompson and Shuswap basins during the time of glacial Lake Thompson and glacial Lake Deadman includes: (i) the presence of kettle holes adjacent to and below lake shorelines (Fulton 1969; Johnsen & Brennand 2004), (ii) abrupt, large changes in the thickness of neighbouring lake-bottom sediments (Fulton 1967), and (iii) the proximity of ice-marginal terraces near Kamloops (Fulton 1965). Additionally, the modern depths of Kamloops Lake and Shuswap Lake (maximum 150 m; Fig. 1C) required the presence of large ice masses during deglaciation; otherwise these depressions would have been filled with glaciolacustrine sediments (Fulton 1965).

Stratigraphic relationships suggest that glacial lakes developed in contact with ice. Typically, lacustrine sediments overlie patchy deposits of Late Wisconsinan (Fraser Glaciation) till that in turn overlies bedrock or older Quaternary sediments (Fig. 2; Clague & Evans 2003). Till and lacustrine sediments are separated by discontinuous lenses ( <3 m thick) of fluvially sorted gravel in some exposures (Fig. 2). The lowest 5 m of lacustrine sediments may contain thin ( <10 cm) interbeds of diamicton (Fig. 2). These stratigraphic relationships suggest that as soon as ice melted from a location within the Thompson Valley, a lake developed in which sediments accumulated. Gravel lenses and diamicton beds record proximal deposition in an ice-contact lake.

Were the lakes in the study area proglacial or supraglacial? The presence of kettle holes suggests that ice *blocks* were buried in the glaciolacustrine sediments (Johnsen & Brennand 2004), but the lack of widespread faulting of lake-bottom beds suggests that any supraglacial phase was likely short-lived. It is not unreasonable to imagine that lakes were initiated supraglacially (Eyles *et al.* 1987). Rapid ablation at the onset of deglaciation produced meltwater that ponded supraglacially in a topographic low aligned with the Thompson Valley. Thermokarst processes enlarged and deepened this basin, exposing subglacial sediments, and proglacial lakes evolved (Watanabe *et al.* 1994). A short supraglacial lake phase and longer proglacial lake phase is consistent with the stratigraphic and sedimentologic observations in the study area.

## Glaciolacustrine lithofacies

Seventeen glaciolacustrine lithofacies were identified within the ice-dammed lakes of the study area (Table 1). Examples of lithofacies are presented in

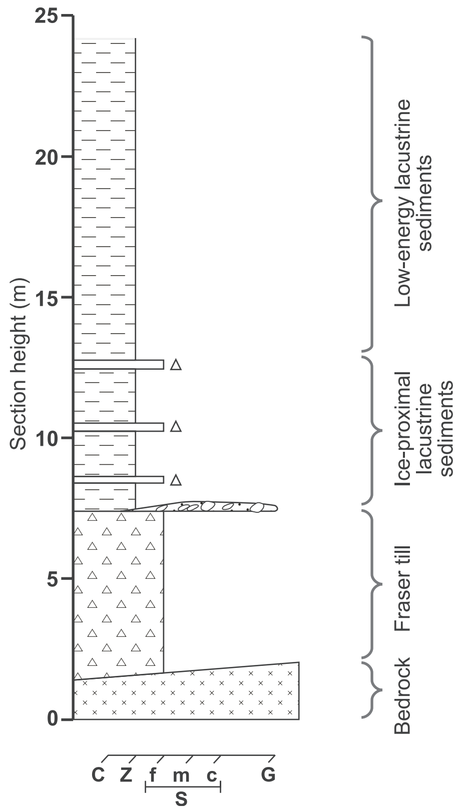



*Fig. 2.* Composite log illustrating the stratigraphic relationship of sediment deposited during and after the Fraser glaciation. Ice-dammed lakes developed in contact with valley-occupying ice. See text for discussion. Refer to legend in Fig. 7.

Fig. 3. The sediment ranges in grain size from clayey silt to boulders. Laminated silt (Zl, Table 1; Fig. 3A, B) is the most common lithofacies and is interpreted to characterize low-energy lake-bottom environments that are generally (i) sheltered from the direct influence of tributaries or (ii) present at a relatively high elevation within the lacustrine fill and thus record the latest lacustrine deposition. Most other lithofacies (Srs, Sra, Srb, Sp, Sdg, Srg, St, Gus, Gt, Gi, zD; Table 1) are associated with deltas, subaqueous fans and medium to high-energy lake-bottom environments (Table 1). Silt with sand inclusions (Zin), convoluted silt (Zc) and boulder diamicton (bD) occur in low-energy, medium-energy and high-energy lake-bottom environments (Table 1). Clayey lithofacies (e.g. laminated clayey silt, Cl and clayey silt with inclusions, Cin) are rare.

The variety of lithofacies identified in Table 1 reflects the range of processes by which sediments were delivered to, dispersed through and deposited in Late Wisconsinan ice-dammed lakes in the Thompson Valley. Three depositional settings provide the framework for the following explanation of the sedimentary environment of these lakes: deltas, subaqueous fans and the lake-bottom (low-energy, medium-energy and high-energy). We use the term subaqueous fan *senso stricto*; we do not require a subaqueous fan to have formed at the mouth of a submerged glacier tunnel (*quod vide* Rust & Romanelli 1975).

The location of deltas and subaqueous fans at tributary mouths, palaeoflow direction measurements (Fig. 1) and trends in lithofacies away from tributary mouths (discussed below) indicate that tributaries were the dominant source of sediment, not valley-occupying ice. Taken together, lithofacies, lithofacies associations and landform–sediment relationships record high rates of sedimentation and a dynamic and often high-energy lake environment.

Most sedimentary exposures are in erosional remnants of Holocene incision by the Thompson River and are capped by fluvial gravel. Well logs record lacustrine sediments well below the present river level. Consequently, most sections expose only a partial record of the lacustrine sedimentation. Only those sedimentary sections (Sections 1a, 2, 3, 10, 11, 20) that illustrate major findings are presented in this article. Additional sedimentary logs and photographs of lithofacies are presented in Johnsen (2004).

## Delta sedimentation

Three deltas are identified in the study area (Fig. 1); the Deadman River delta is the largest ($\sim$13 km$^2$). The Deadman River delta formed in deep water ($\sim$50 to 100 m deep depending on lake stage; Johnsen & Brennand 2004). It is composed of coarse-grained sediment. Topsets (Section 2; Figs 1, 4) are composed of imbricate cobble gravel recording braided channels on the delta surface. Foresets at variable directions of dip (090–270°), with dip angles from $\sim$25 to 32°, and composed of alternating gravel and sand beds record lobate delta progradation (Fig. 4). Gravel beds are stratified or weakly stratified and contain imbricate clasts (Table 1). Sand beds exhibit planar stratification, trough cross-bedding or type A ripple cross-lamination (Table 1). Some sand beds include lignite clasts. Foreset lithofacies suggest that sediments delivered to the delta edge avalanched down the delta front as grain flows, rolled down the delta front under the influence of gravity or flowed down the delta front as hyperpycnal flows (a sustained turbidity current formed directly from dense river effluent; Table 1). Inflows from the Deadman River dominated the sedimentary environment of the lake in its vicinity. Palaeoflow measurements (Sections 1a, 1b, 2, 3, 4, 5; Fig. 1) and the presence of lignite clasts in lake-bottom sediments near the delta (Section 1a) indicate that a large proportion of the lake basin sediments derived from the Deadman River (Cockfield 1948).

The anomalously large size and coarse-grained character of the Deadman River delta and the record of sediment delivery by hyperpycnal flows

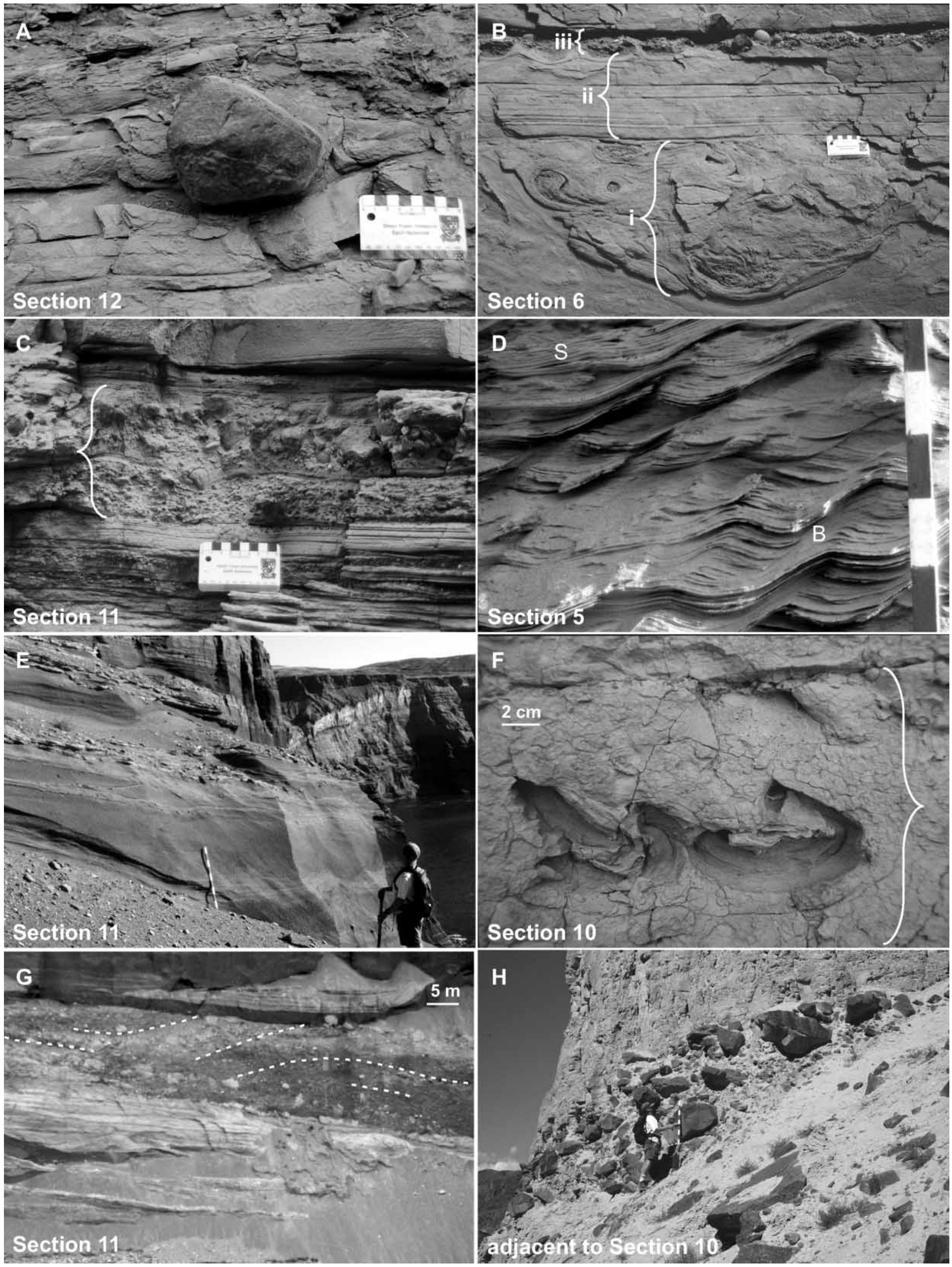



*Fig. 3.* Lithofacies examples. A. Dropstone (very rare) in laminated silt. B. Convoluted silt (i) underlying, loaded laminated silt (flames at top) (ii), and a thin bed of stony silty diamicton (iii). C. Stony silty diamicton beds (bracket). D. Ripple cross-laminated sand (type B and S). E. Thick beds of diffusely graded sand. F. Silt with sand inclusions (saucer-shaped pillows). G. Undulatory stratified gravel (white dashed lines) containing large blocks of silt (rip-ups), overlying laminated silt. H. Angular boulder bed with silt matrix. Scale card is 8 cm wide. Stick is 1 m long with 10 cm increments. Sedimentary section number indicated (see Fig. 1 for location). See Table 1 for interpretations.

suggest that remnant Cordilleran ice likely occupied the headwaters of the Deadman River. In addition, the present Deadman River is underfit and the Deadman River valley is considered to be a major meltwater channel (Fulton 1975). Thus, the Deadman River valley contained an outwash system that


*Fig. 4.* A. Sedimentary Section 2 (location in Fig. 1) below a terrace in Deadman delta. Person (circle) for scale. Topset-foreset contact indicated by dashed line. B. Close-up of foresets showing inclined, alternating imbricate gravel and plane-bedded sand lithofacies. Palaeoflow direction measurements (Sections 1a, 1b, 2, 3, 4, 5; Fig. 1) indicate that a large proportion of lake-basin sediments were derived from flows coming from the delta.

deposited a braided outwash plain and delivered large amounts of sediment to lakes in the Thompson Valley.

Glacio-isostatically tilted lake shorelines suggest that crustal loading was greater and/or lasted longer to the north and northwest of the Thompson Valley (Johnsen & Brennand 2004). Consequently, northern ice may have been thicker or persisted longer than ice to the south. Deltas along the northern side of the Thompson Valley and the western side of the North Thompson Valley are larger than those on the opposite side of the valleys (Johnsen & Brennand 2004: Fig. 1). This distribution of large deltas supports the interpretation of remnant ice within tributary headwaters on the Fraser and northern Thompson plateaus during delta progradation.

## Subaqueous fan sedimentation

There are nine subaqueous fans in the study area (Fig. 1). All are located where tributaries meet the main valley and all lie below the level of glacial Lake Deadman. They are fan-shaped and their sedimentary architecture is inclined ( $\sim$5–25°) downwards from the tributary mouth into the main valley. Most subaqueous fans occur in the higher relief southern portion of the study area, where there are a greater number of steeper tributaries than in the north.

Stratigraphically, subaqueous fans lie toward the base of the lacustrine fill and thus were deposited largely during the early stages of basin infilling (the largest subaqueous fans dominate the lacustrine fill, e.g. Sections 11, 21 and 22; Figs 1, 5). Fine-grained, lake-bottom sediments overlie them (e.g. Sections 11, 20; Figs 1, 5, 6). This vertical transition to fine-grained sediments suggests a reduction in meltwater discharge and sediment supply over time.

Sediments within subaqueous fans are typically composed of interbedded coarse-grained (gravel and sand) and fine-grained (silt) lacustrine sediments. Below, we describe the sedimentary environment associated with two subaqueous fans in the study area (Sections 11, 20, 21 and 22; Fig. 1).

### *Bonaparte River subaqueous fan*

The Bonaparte River subaqueous fan is exposed in an extensive river bluff (100 m high, 2 km long) $\sim$4 km east of Ashcroft along the Thompson River (Section 11; Figs 1, 5). Five units are identified in the bluff (Fig. 5). Units 1 to 3 accumulated in the Late Wisconsinan lakes and units 4 and 5 record Holocene river and alluvial fan deposits, respectively. Units 2 and 3 are dominated by laminated silt and minor sand characteristic of quiet-water sedimentation on the lake bottom. Units 1–4 exhibit faulting and flow structures characteristic of collapse resulting from the melting of buried ice. Unit 5 fills this kettle hole. Lithofacies associated with each lacustrine unit are listed in Fig. 5C.

Unit 1 is dominated by coarse-grained lithofacies characteristic of high-energy sedimentation dominated by hyperpycnal flows (e.g. Gorrell & Shaw 1991; Plink-Björklund & Ronnert 1999; Russell & Arnott 2003; Table 1). Undulatory stratified gravel (Fig. 3G) and diffusely graded sand (Fig. 3E) suggest very high rates of deposition from suspension (e.g. Cheel 1989; Carling 1999; Russell & Arnott 2003). Planar stratified sand, trough cross-bedded gravel and sand, and imbricate gravel beds suggest deposition from traction transport (e.g. Eyles *et al.* 1987; Cheel 1989; Russell & Arnott 2003). Diamicton beds record subaqueous debris flows (e.g. Costa 1988). Beds (0.1–10 m thick) of laminated silt punctuate unit 1 (Figs 3G, 5). They record deposition from suspension and represent quiet-water sedimentation during pauses in inflow. Gravel and sand beds overlying laminated silt beds often contain large laminated silt rip-ups (up to 3 m thick) and exhibit sharp, irregular

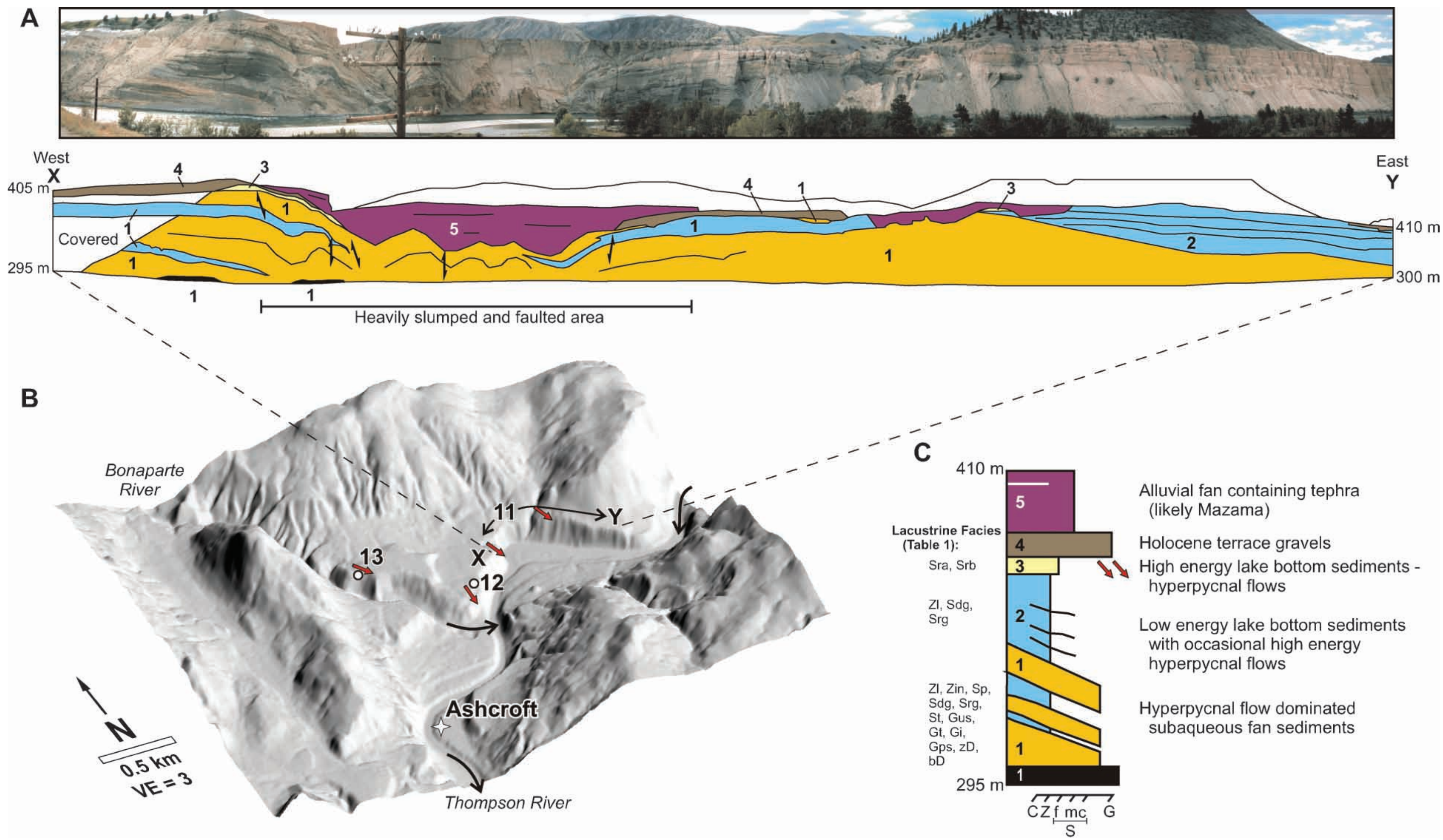



*Fig. 5.* A. Photographic panorama and interpreted sedimentary sequence of Section 11 (2 km long, 110 m high; location in Fig. 1). Colluviated portions of section inferred. B. Perspective of hill-shaded relief model showing geomorphic context of sections 11, 12 and 13, palaeoflow directions (short arrows) and present river direction (valley-bottom arrows) (DEM data, British Columbia Government 1996). C. Generalized sedimentary sequence of Section 11.

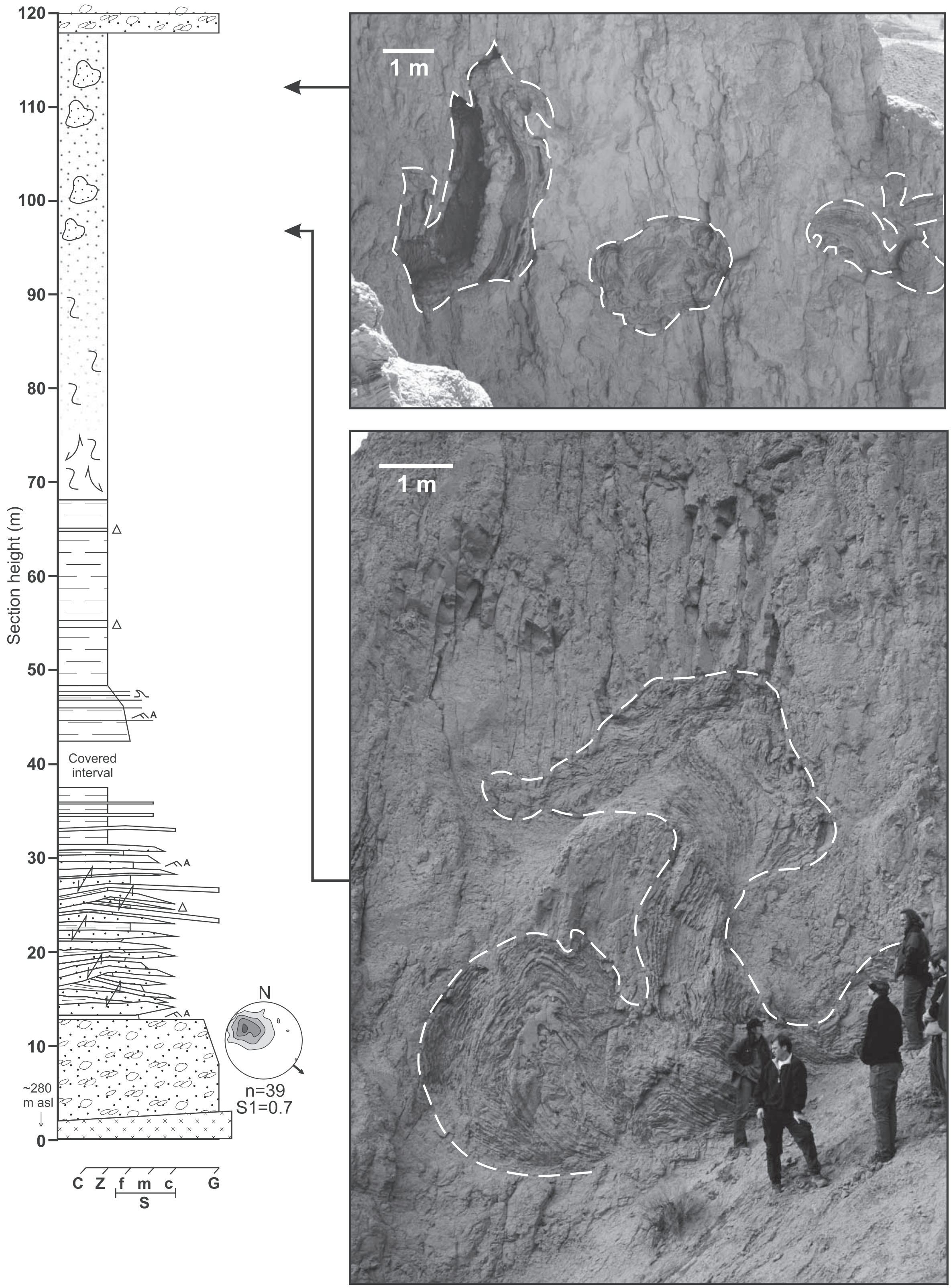



*Fig. 6.* Sedimentary Section 20 (location in Fig. 1) records subaqueous fan sediments (2–32 m), low-energy, lake-bottom sediments (32–68 m) and deeply loaded low energy lake-bottom sediments (68–118 m). Deep loading and slumping is indicated by megascale sand inclusions (dashed outline) in contorted to massive silt (68–118 m). Holocene fluvial gravel (118–120 m) caps the sequence. Refer to Fig. 7 for legend.

or loaded (>5 m thickness: load structures and mega-flames) lower contacts, evidence of the erosive power of, and rapid sedimentation from, hyperpycnal flows. Clastic dikes injected through diffusely graded sand beds record rapid loading and dewatering of deeper sediments.

The southeast dip (~5°) of the subaqueous fan beds (unit 1), local topography (Figs 1, 5B) and palaeoflows measured in unit 3 (Fig. 5) suggest that sediments were delivered from the northwest along the Bonaparte River valley rather than being supplied by ice occupying the Thompson Valley. Lithofacies associations in unit 1 are similar to those described by Bornhold & Prior (1990) and Russell & Arnott (2003) as being of jökulhlaup origin. The Chasm, at the head of the Bonaparte Valley (~60 km north of Ashcroft), may be evidence of an extreme discharge event(s) related to the Bonaparte River subaqueous fan. The Chasm is a dry falls canyon, ~300 m high and ~8 km long, cut into basalt at the edge of the Fraser Plateau. It is V-shaped in plan view and a ~35 km long esker terminates at the entrance to the Chasm. This dry falls is similar to those in the Channelled Scablands of Washington State, U.S.A., eroded into basalt by jökulhlaups (Baker *et al.* 1987), yet its association with an esker suggests a subglacial or ice-marginal origin (e.g. Sollid & Reite 1983).

### *Venables Creek subaqueous fan*

The lower ~30 m of Section 20 records a hyperpycnal flow-dominated, subaqueous fan (Figs 1, 6). Fluctuations in energy and sediment supply are recorded by erosional contacts and vertical contrasts in the grain size and sedimentary structure of lithofacies (e.g. diffusely graded sand, planar stratified sand, laminated silt and beds of imbricate gravel) and are characteristic of melt-cycle dominated sediment delivery (hourly to seasonal and/or episodic). The position of these sediments at the tributary mouth and the fabric measurements in the lowest imbricate gravel bed (at ~10 m, Fig. 6) indicate sediments were derived from the Venables Creek valley (Fig. 1) rather than from an ice mass in the Thompson Valley, as suggested by Ryder (1970).

Subaqueous fans rather than deltas may have preferentially formed in the lakes in the southern part of the study area due to the moderately high-relief setting, the presence of a deep basin, and the short lifespan of the lakes (discussed below). The high sediment load required for hyperpycnal flows could have been generated and maintained in the steep, confined creeks draining plateau-remnant ice and bordered by erodable, unvegetated slopes. The large accommodation space afforded by a deep basin and the short duration of the lakes precluded delta growth at the mouths of many tributaries.

## High-energy to medium-energy lake-bottom sedimentation

Trends in lithofacies away from tributary mouths record the transition from deposition in deltas and subaqueous fans to deposition in high-energy, medium-energy and low-energy lake-bottom environments. Lake-bottom depositional settings are identified based on their near-horizontal sedimentary architecture and lithofacies associations. This section explores the sedimentary record of the high-energy to medium-energy lake-bottom environment.

Given the moderately high relief and numerous tributaries in the study area, the lake-bottom environment is dominated by high-energy and medium-energy lithofacies recording a range of sediment delivery mechanisms downflow from deltas and subaqueous fans. The most common lithofacies include type A, B and S ripple cross-laminated sand and diffusely graded sand (Figs 7, 8; Table 1). These lithofacies record sand transport and deposition by turbidity currents (Table 1; after Middleton & Hampton 1976; Costa 1988). Inversely graded sand beds with lignite clasts at their upper contact record deposition from grain flows (e.g. Plink-Björklund & Ronnert 1999). Sandy lithofacies commonly alternate with thinly laminated, infrequently convoluted, silt lithofacies and rarely with clayey silt lithofacies (Figs 7, 8). Silt lithofacies mainly record quiet-water deposition from suspension (Table 1). Infrequent beds of stony silty diamicton record sediment remobilization in subaqueous debris flows (Table 1).

The lake-bottom sedimentary environments proximal to a major tributary inflow, Deadman River, are discussed below.

### *Lake-bottom sediments downflow from the Deadman River delta*

In Section 3 (Fig. 7), stacked turbidites dominate the lake-bottom sedimentary sequence and indicate rapid sedimentation. Climbing-ripple sequences are decimetres to >1 m thick (Fig. 7). Palaeoflows are consistently westward away from Deadman delta (Figs 1, 7). Westward flowing turbidity currents may have been generated by (i) failure of the delta foresets or delta-proximal lake-bottom sediments (surge-type turbidity currents), or (ii) the plunging of denser sediment-laden river water into the lake (hyperpycnal flows) (e.g. Weirich 1986; Lambert & Giovanoli 1988). Slump deposits, recorded by convoluted silt and clayey silt with inclusions, are in low abundance (Fig. 7; Table 1). Thick sand beds with highly variable structural successions (type A, B and S ripple cross-laminated sand) and/or reverse-to-normal grading suggesting deposition from hyperpycnal flows characterized by varying velocity, turbulence and sediment concentration (e.g.

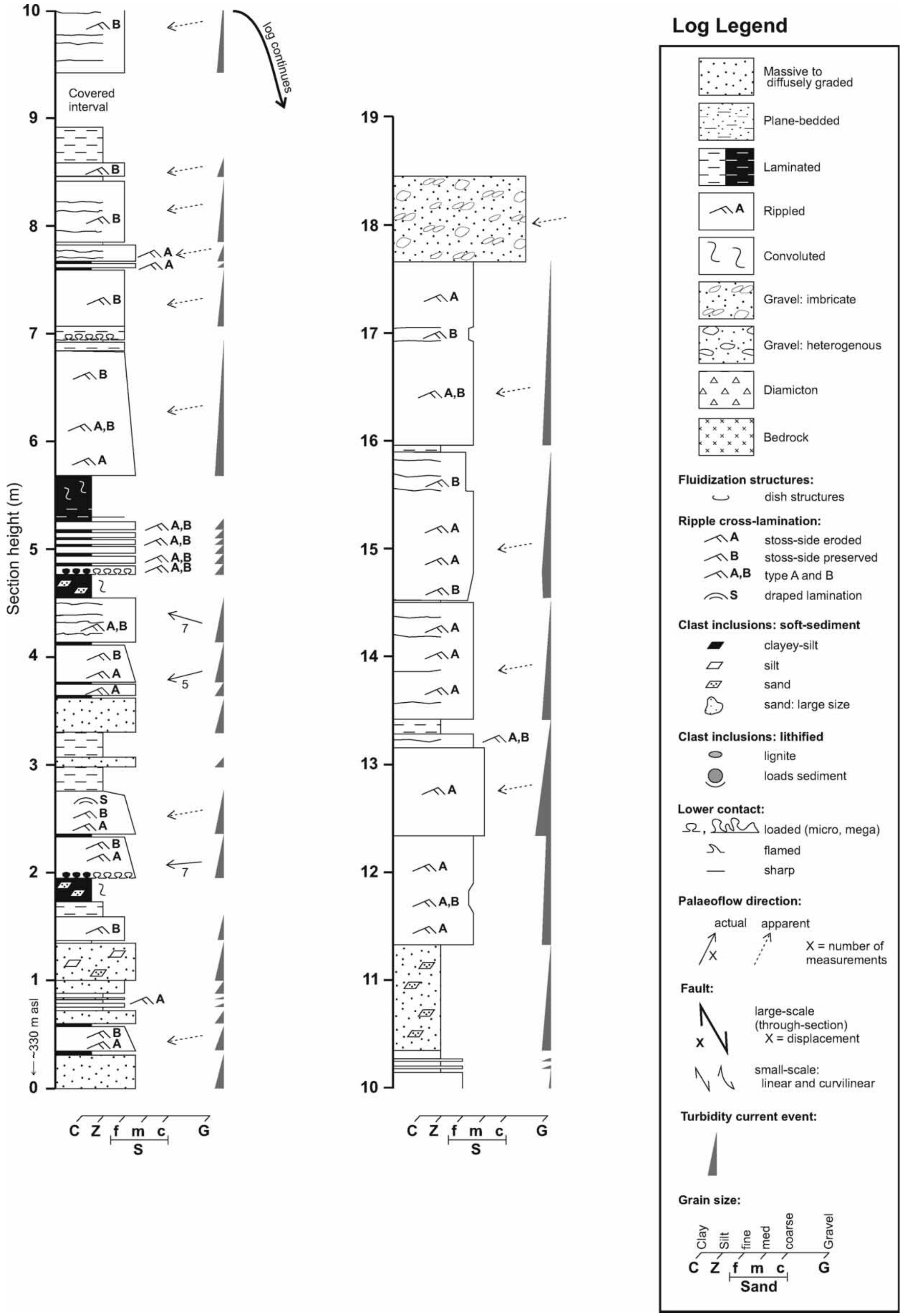



*Fig. 7.* Sedimentary Section 3 (location in Fig. 1) records a high-energy lake-bottom environment dominated by deposition of sand from hyperpycnal flows (see text for explanation). Palaeoflows are consistently westward from the nearby Deadman delta. Holocene floodplain gravel caps the sequence (17.7–18.5 m).

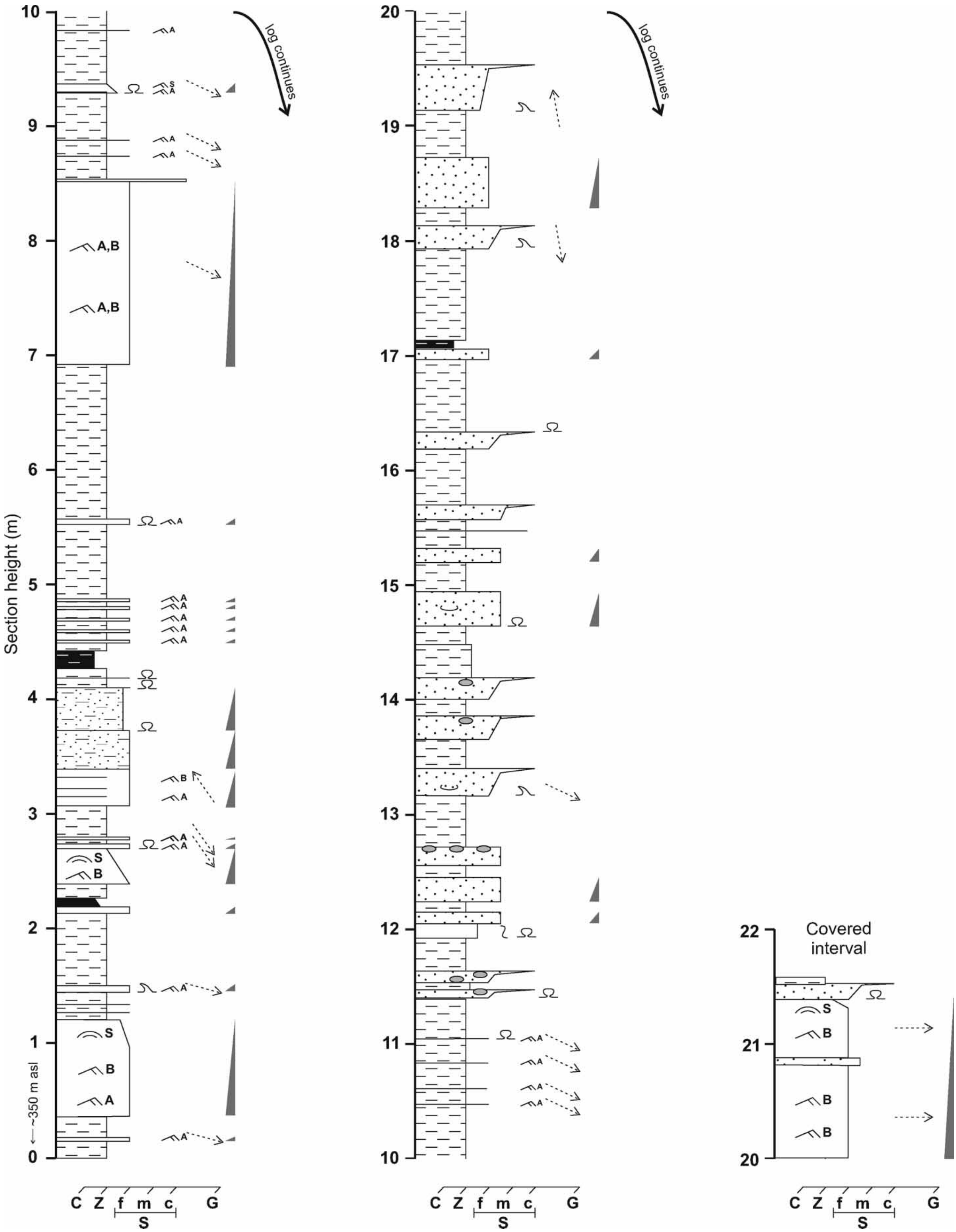



*Fig. 8.* Sedimentary Section 1a (location in Fig. 1) records a medium-energy lake-bottom environment. Deposition of silt from suspension is punctuated by deposition of sand from surge-type turbidity currents and grain flows (see text for explanation). Refer to Fig. 7 for legend.

Plink-Björklund & Ronnert 1999; Felix 2002; Plink-Björklund & Steel 2004). Deposition from hyperpycnal flows is also suggested by the presence of cross-bedded and cross-laminated sand within the foresets of Deadman delta (Fig. 4). Hyperpycnal flow turbidites alternate with laminated silt and laminated or convoluted clayey silt. Silt lithofacies may record the tails of turbidity currents or quiet-water deposition from suspension (Table 1).

Section 1a contains laminated silt with only a minor amount of rippled sand (1a; Figs 1, 8). Based on this, we consider these sediments to represent a medium-energy, lake-bottom environment. Elsewhere, more abundant rippled sand beds indicate a high-energy lake-bottom environment. Thus, deposition by suspension is more common in medium-energy than in high-energy lake-bottom environments. In section 1a, most turbidites are normally or diffusely graded suggesting deposition by surge-type turbidity currents (e.g. Plink-Björklund & Ronnert 1999). Reverse-graded sand beds containing lignite clasts near their upper contact often punctuate laminated silts above 11 m in the section (Fig. 9). These beds probably record deposition from grain flows (Table 1; e.g. Plink-Björklund & Ronnert 1999) issuing from Deadman delta (Cockfield 1948). Intervening, relatively quiescent periods allowed deposition of silt from suspension. The strong rhythmic pattern of these beds may be related to daily, seasonal or annual changes in sediment flux to the basin and may be sourced to changes in meltwater discharge. However, they may also represent episodic avalanching down delta foreset beds.

## Low-energy, lake-bottom sedimentation

Low-energy lake-bottom sediments are dominated by laminated silt (Table 1). Laminated silt records deposition from suspension, and this silt is mainly derived from the hypopycnal flows, interflows and hyperpycnal flows issuing from tributary rivers. Low-energy lacustrine lithofacies occur throughout the valley (e.g. Figs 2, 3A, 3B, 5, 6, 7, 8, 9). However, *thick* undisturbed sequences of low-energy lake-bottom sediments are uncommon due to the dominance of tributary inflows. Section 10 is dominated by low-energy lake-bottom lithofacies (Fig. 9) deposited in an area relatively sheltered from tributary inflows. Beds of massive and convoluted silt with irregular-shaped sand and silt inclusions punctuate thick beds of laminated silt and record subaqueous slumping. Steep lake bed slopes (recorded in the sedimentary architecture with bed dips of 5–10° towards the valley centreline) and sediment loading by infrequent turbidity currents, grain flows and rockfalls nearby (Fig. 3H) likely caused subaqueous slumping, although slumping resulting from changes in the hydraulic gradient following drops in lake level (Vesajoki 1982; Johnsen & Brennand 2004) or earthquake triggers cannot be ruled out. Saucer-shaped pillows record the foundering of sand into underlying silts (Fig. 3F; at 8.2 m in section, Fig. 9).

### *The paucity of clay layers in ice-dammed lakes of the Thompson Valley*

Clay and clayey silt lithofacies are rare in exposed lake-bottom sediments from the Late Wisconsinan ice-dammed lakes of the Thompson Valley. Bedrock lithology around Ashcroft indicates that clay would have been delivered to the lakes (Cockfield 1948). So why was it not deposited in greater abundance? The lack of distinct clay layers can be attributed to (i) sediment stratification within the lakes discouraging settling (Johnson *et al.* 1999), (ii) lake currents (enhanced by the narrow, ribbon-like geometry of the lakes, numerous tributary inputs and katabatic winds) preventing settling even in winter, (iii) a deep basin requiring too much time for the settling of clay (i.e. longer than the winter period), (iv) clay flushing during high discharge events (e.g. jökulhlaups), (v) a climate warm enough to prevent lake freezing in winter, (vi) turbidity currents depositing clay fractions within turbidites, or (vii) a combination of these factors.

Of all 24 sections examined in the Thompson Valley, Section 3 (Fig. 7) contains the most clayey silt in laminated and convoluted clayey silt beds recording both settling from suspension and lake-bottom instability. Laminated clayey silt beds are generally ~0.5–15 cm thick. Samples from the finest layers contain ~10–20% clay (Fig. 10). The deposition of clay requires quiet-water conditions. However, Section 3 mainly records high-energy conditions dominated by hyperpycnal turbidity currents off the Deadman River delta. At this site, clay may have been deposited on the lake bottom either (i) when inflows temporarily switched away from the site (i.e. towards Kamloops Lake), or (ii) when turbidity currents delivered clay to deep water. The latter mechanism may explain the common association of clayey silt laminae overlying ripple cross-laminated sand (Fig. 7). Beds of convoluted clayey silt with sand inclusions record periodic slumping of clayey silt perhaps from quieter, shallow inshore areas.

## Large-scale subaqueous deformation

Soft-sediment deformation is common in the lake sediment of the Thompson Valley, recorded by millimetre to centimetre-scale flames, convolutions and ball-and-pillow structures. Most ball-and-pillow beds are <5 m thick and contain engulfed/loaded, elongate

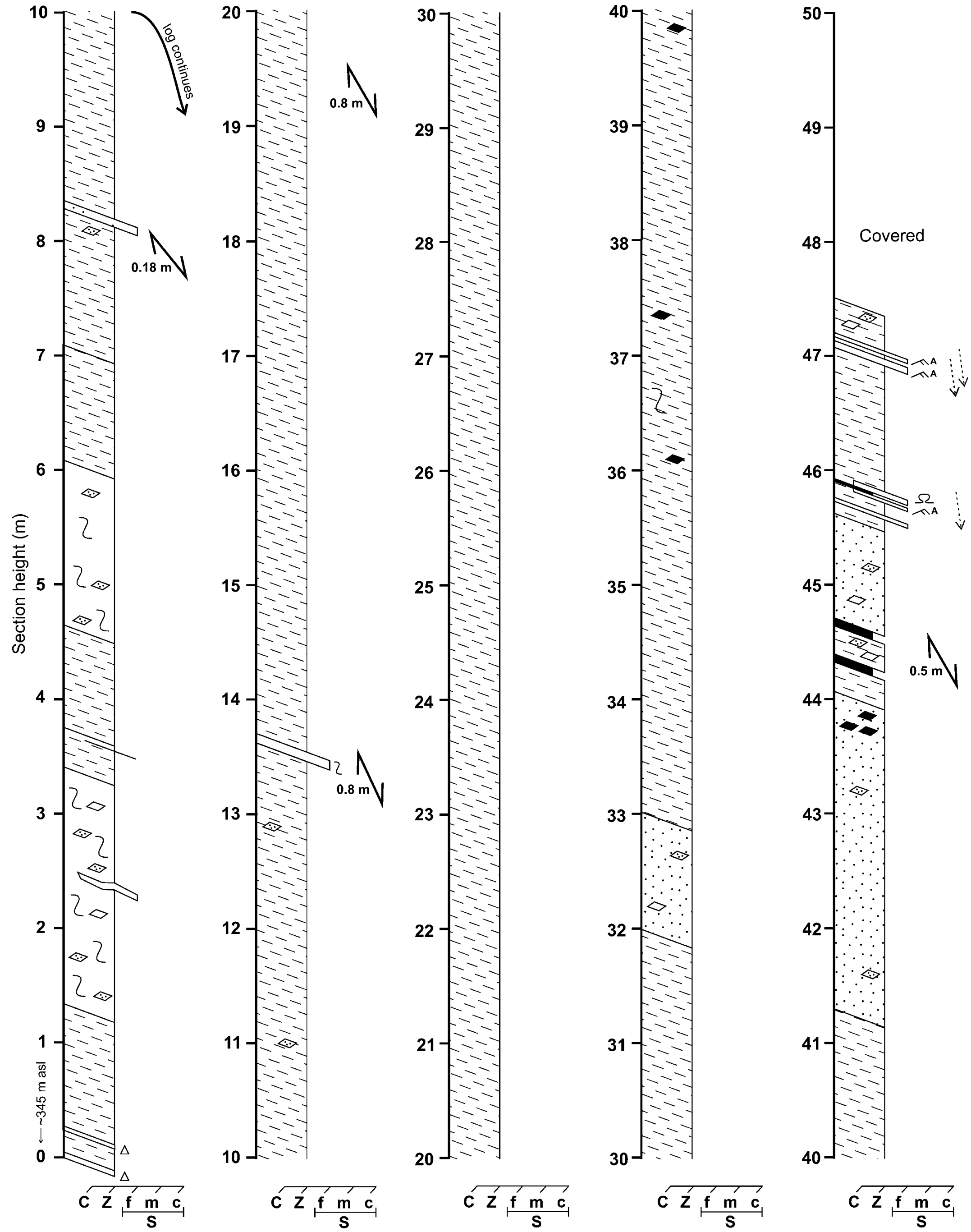



*Fig. 9.* Sedimentary Section 10 (location in Fig. 1) records a low-energy lake-bottom environment. Thick beds of laminated silt dominate and record quiet-water sedimentary conditions. Occasional subaqueous slumps produced beds of massive and convoluted silt with irregular shaped sand inclusions. Large faults extend through the whole exposure and intersect the logged section at 8, 13.5 and 44.5 m. They likely formed as Holocene river incision removed lateral support. Refer to Fig. 7 for legend.

clasts with their long-axis parallel to the bed (Fig. 3F). However, very thick beds (tens of metres thick) of massive to highly contorted laminated silt with mega-scale (up to 10 m long axis) sand inclusions are also fairly common (Table 1; Fig. 6). To our knowledge, such megascale ball-and-pillow structures have not been reported in any study of glacial lakes and are rarely described from the rock record (e.g. Howard & Lohrengel 1969). Independently of scale, ball-and-pillow structures are created by foundering of coarser

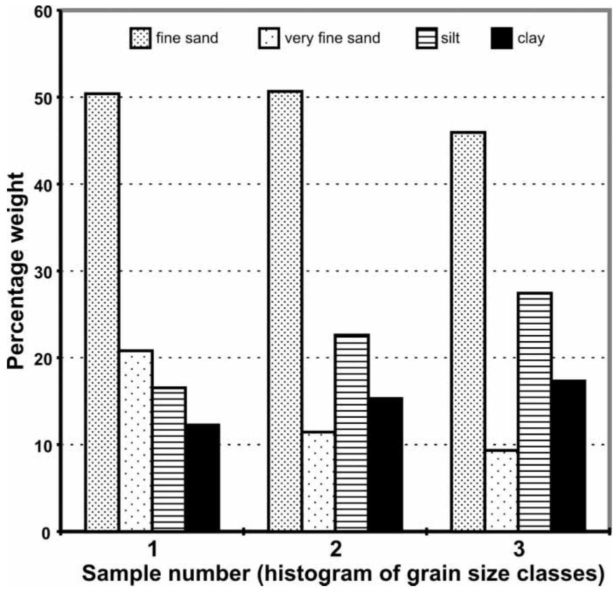



*Fig. 10.* Grain-size histograms for selected fine-grained samples from Section 3. Sample 1 from 5.3 m, sample 2 from 1.75 m and sample 3 from 2.3 m (Fig. 7). Grain size ranges: fine sand (125–250 μm, 2–3 phi), very fine sand (63–125 μm, 3–4 phi), silt (3.9–63 μm, 4–8 phi), and clay ( <3.9 μm, >8 phi).

sediments into underlying finer sediments (Howard & Lohrengel 1969; Allen 1982 and references therein). Subaqueous slumping or sliding may complement this process (Howard & Lohrengel 1969; Hubert *et al.* 1972). The higher the rate of deposition of either the fine-grained or coarse-grained units, the more the system is unstable. This condition was probably frequently met in the lakes of the Thompson Valley because hyperpycnal turbidity currents were common and rates of sedimentation were high. At Section 20, a 50-m-thick unit (at 68–118 m; Fig. 6) of contorted, laminated to massive silt contains very large sand inclusions (ball-and-pillow structures). Curvilinear shear planes ( <1 cm thick) are also observed (at ~70 m; Fig. 6). The presence of convolutions, ball-and-pillow structures and shear planes suggests that this unit was subject to both ductile and brittle deformation. Loading was accompanied by slumping and flowing. Slumping is inferred from shear planes. The asymmetric shapes of sand inclusions imply a lateral flow component (Fig. 6).

Large-scale, subaqueous failure events may have been triggered by (i) sediment loading, (ii) changing lake levels (including lake drainage; Vesajoki 1982), (iii) lake currents, or (iv) seismic events. Presently, earthquakes are relatively infrequent in the interior compared to the coast of British Columbia. Earthquakes were likely more frequent during deglaciation during hundreds of metres of glacio-isostatic rebound (Johnsen 2004) and associated fault instability (e.g. Johnston 1989; Stewart *et al.* 2000).

## Model of the sedimentary environment of ice-dammed lakes in moderately high relief settings

A conceptual model of the sedimentary environment of ice-dammed lakes in moderately high relief settings, consistent with observations from the Thompson Valley, is presented in Fig. 11. Glacial lakes Thompson and Deadman were ice-dammed lakes, and their waters covered remnant ice blocks in places. However, the water and sediment supply for these lakes came primarily from the rivers that drained into them from the adjacent plateau (Ward & Rutter 2000; Bennett *et al.* 2002; Lesemann & Brennand 2003). Remnant ice masses within the headwaters of some tributaries delivered large amounts of meltwater and sediment to the lakes resulting in very high sedimentation rates, the formation of numerous deltas and subaqueous fans, and the deposition of extensive, high-energy, lake-bottom sediments. Elements of the model (Fig. 11) are summarized and rationalized below.

### *Sedimentation processes*

Sediments were dispersed in the lake by hyperpycnal and surge-type turbidity currents, grain flows, debris flows, overflows and interflows, and were deposited from suspension and traction. Sediment gravity flows frequently eroded and loaded underlying saturated sediments to produce a variety of ductile deformation structures (e.g. flames, convolutions, dish structures, ball-and-pillows) and brittle failure structures (e.g. synsedimentary faults). Large-scale, subaqueous loading and failure produced megascale sand inclusions. Rockfalls triggered some lake-bottom instabilities. Finally, the melting of buried ice resulted in sediment collapse (faults and folds) and the creation of kettle holes (Fig. 5; Johnsen & Brennand 2004).

### *Spatial and temporal patterns of sedimentation*

A well-defined spatial pattern of sedimentation is related to sediment delivery and dispersal from tributary inflows. Spatial patterns in sedimentation related to the valley-occupying ice dam were not discerned. Considerations of lithofacies, their associations and architecture, and their geomorphic context allow the classification of lake sediments into depositional settings: deltas, subaqueous fans and lake bottom. High-energy sand and gravel deposits in deltas and subaqueous fans give way to sandy turbidites in high-energy and medium-energy lake-bottom environments and finally to laminated silt in more distal or lower-energy lake-bottom environments. Hyperpycnal flows derived from deltas travelled at least 10 km along the lake bottom (Fig. 1). Subaqueous rockfalls, slumps and debris flows are located throughout the basin. In contrast to areally extensive deglacial lakes, clay layers and dropstones are rare and classic varves were not

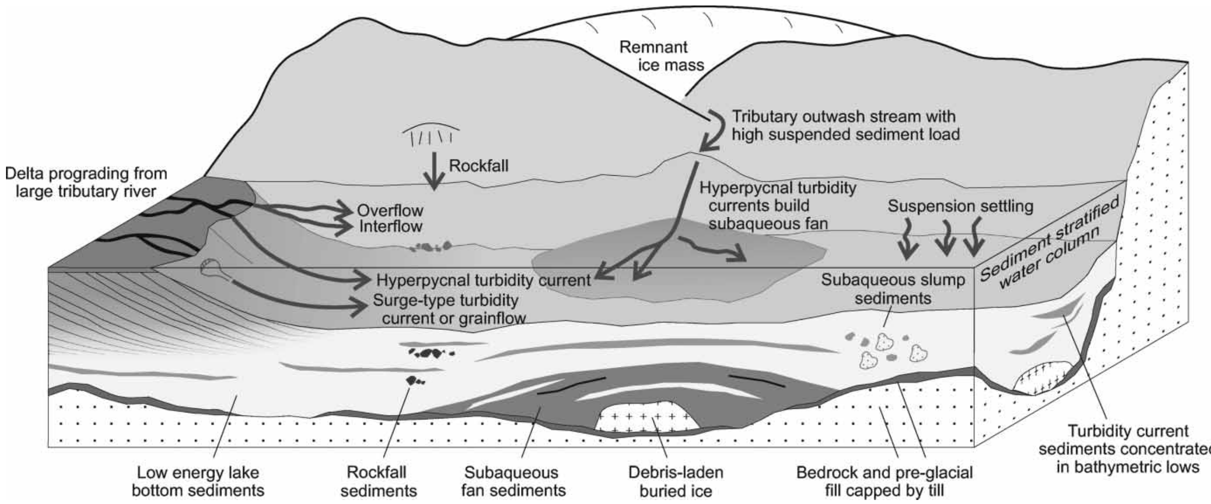



*Fig. 11.* Conceptual model of the sedimentary environment in and around ice-dammed lakes in the moderately high relief setting of the southern Canadian Cordillera. Ice dam not shown.

identified (*quae vide* Antevs 1951; Wolfe & Teller 1983). The absence of classic varves and the paucity of clay are attributed to hindered settling of clay due to sediment stratification in the water column, energetic lake conditions throughout the year and deposition of clay within turbidites.

Temporal patterns in sedimentation reflect (i) changes in meltwater discharge and sediment supply, likely on daily, seasonal or episodic scales, and (ii) an overall reduction in meltwater discharge and sediment supply to the lakes over deglaciation and prior to lake drainage. Melt cycle dominated sedimentation is recorded in laminated silt and stacked turbidites. Classic varves are not present and consequently varve chronology cannot be used to constrain lake duration or inflow periodicity. High-energy turbidites become less dominant and laminated silt dominates upsection (e.g. Fig. 6).

The lake-bottom sediments observed in the study area contrast with those in the neighbouring South Thompson Valley (Fig. 1C). Sediments in the South Thompson Valley are varved and dominated by laminated silt (Fulton 1965). Quieter water conditions here were likely encouraged by (i) fewer large tributaries delivering sediments to the basin, and/or (ii) by a relatively minor amount of remnant ice in the headwaters of tributaries (Fulton 1965, 1969).

### *Rate of sedimentation*

High rates of sedimentation are indicated by: (i) the presence of large deltas and subaqueous fans at tributary mouths, (ii) the presence of landform and lithofacies associations attributable to jökulhlaups, (iii) extensive, thick, lake-bottom turbidites recording frequent hyperpycnal flows, (iv) thick beds of laminated silt, (v) mega-scale subaqueous deformation, and (vi) a paucity of clay. Rapid sedimentation was accomplished by (i) energetic meltwater and sediment delivery via outwash streams draining dwindling plateau ice and transporting high sediment loads derived from steep, unvegetated, unstable slopes and (ii) sediment focusing from a regional catchment to a relatively small basin (Fig. 1C).

### *Duration of ice-dammed lakes*

The duration of Late Wisconsinan ice-dammed lakes in the Thompson Valley can only be estimated. Very limited radiocarbon data show that the maximum lifespan of glacial lakes in the Thompson Valley was 540–1130 years (Johnsen & Brennand 2004). Based on lithofacies analysis, sedimentation rates were probably high, corroborating a short lifespan for the lakes. East of the study area, in the South Thompson Valley (Fig. 1C), tens of metres of varves may have been deposited in only 80 years (Fulton 2000). Consequently, the duration of lakes in the Thompson Valley was likely a few hundred years, or even much less.

## Implications for deglaciation of the southern Canadian Cordillera

### *Regional stagnation*

The stratigraphic record in the Thompson Valley corroborates the view that the Cordilleran Ice Sheet decayed by regional stagnation (e.g. Fulton 1967, 1991). If active ice within the valleys retreated, fluctuations of the ice margin would have occurred. In the ice-contact lake environment, this process may have produced recessional moraines and/or caused over-riding of previously deposited lake sediments producing interdigitation of thrust lake sediments and till. Rather, no moraines are observed and the stratigraphic record shows an abrupt transition from till or older Quaternary sediments to deglacial lake sediments (Fig. 2). If deglaciation occurred by calving, abundant dropstones would be expected. Dropstones are rare within lake-bottom sediments. The paucity of dropstones may also indicate that (i) valley ice was too thick and grounded, (ii) valley ice contained enough debris to prevent flotation, or (iii) only a small length of the lake (e.g. at the dam) was in contact with ice.

### *Coeval plateau-remnant ice and ice-dammed lakes*

Existing interpretations of Cordilleran Ice Sheet decay suggest that rapid downwasting of the Cordilleran Ice Sheet over high relief terrain resulted in ice-free plateaus when ice-dammed lakes occupied the valleys (e.g. Clague 1989). We refine this interpretation by proposing that dwindling plateau ice was coeval with ice-dammed lakes in the Thompson Valley. This interpretation is consistent with (i) the lack of organics in lake sediments (Matthews *et al.* 2000), (ii) the fining upward sequence observed within lake sediments, (iii) rapid sediment delivery, including possible jökulhlaup events, from rivers with their headwaters on the Plateau, and (iv) patterns of glacioisostatic rebound (Johnsen & Brennand 2004).

## Conclusions

Based on observations from the study area, a number of general conclusions can be drawn regarding the Late Wisconsinan lakes of the Thompson Valley, British Columbia:

- The lakes were ice-dammed proglacial lakes led by a short-lived supraglacial stage. Some ice blocks were buried within the lake-bottom environment; however, extensive masses of ice were not buried.
- The ribbon-shaped geometry of the lakes and numerous tributary rivers, some of which were fed by remnant ice masses on the plateau, greatly influenced sedimentation processes. Large deltas and many subaqueous fans developed at tributary mouths. Sedimentation patterns are almost completely dominated by deposition from tributary outwash streams, rather than from meltwater outflows from the valley-occupying ice dam. In some places, sediments were transported from tributary river inflow points over 10 km along the basin floor.
- A diversity of sediment lithofacies in deltas, subaqueous fans and lake-bottom depositional settings record a generally high-energy lacustrine environment with rapid basin infilling. Sediments were dispersed in the lake by hyperpycnal and surge-type turbidity currents, grain flows, debris flows, overflows and interflows, and were deposited from suspension and traction. Sediment deformation occurred at various scales, including mega-scale subaqueous failures, and was facilitated by the high sedimentation rates. Rockfalls into the lake triggered some lake-bottom instabilities.
- Temporal patterns in sedimentation reflect changes in meltwater discharge and sediment supply, probably on daily, seasonal or episodic scales, and an overall reduction in meltwater discharge and sediment supply to the lakes over deglaciation and prior to lake drainage.
- In contrast to areally extensive deglacial lakes, clay layers and dropstones are rare and classic varves were not identified. The absence of classic varves and the paucity of clay are mainly attributed to hindered settling of clay due to sediment stratification in the water column, energetic lake conditions throughout the year and deposition of clay within turbidites.
- The stratigraphic record in the Thompson Valley corroborates the view that the Cordilleran Ice Sheet decayed by regional stagnation. However, we refine previous models of deglaciation by proposing that dwindling plateau ice within lake catchments was coeval with ice-dammed lakes in the Thompson Valley. This conclusion has important implications for palaeogeographic reconstructions of antecedent ice thickness and leads us to question whether ice over all Interior valleys was necessarily thicker than plateau ice at the onset of deglaciation.

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