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POLYPHASE GLACIGENIC DEFORMATION OF ADVANCE GLACIOFLUVIAL SEDIMENTS, NEAR BIG CREEK, BRITISH COLUMBIA

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ABSTRACT Deformation structures were observed in glaciofluvial sediments near Big Creek, central British Columbia. These sediments record a sequence of polyphase deformation resulting from the advance and retreat of the Late Wisconsinan (Fraser Glaciation) Cordilleran Ice Sheet. Deformation is attributed to ductile then brittle failure resulting from: (a) horizontal compression and loading as ice advanced over saturated sediments; followed by (b) lateral extension then (c) compression under frozen conditions during glacier overriding; and finally (d) vertical extension during unloading upon deglaciation. Most deformation (a-c, above) appears to have occurred during the advance phase of the Fraser Glaciation.

RÉSUMÉ *Déformation polyphasée d'origine glaciaire des sédiments fluvio-glaciaires d'avancée, près de Big Creek, Colombie-Britannique*. Des structures de déformation ont été observées dans des sédiments fluvioglaciaires, près de Big Creek. Ces sédiments comprennent la séquence d'une déformation polyphasée résultant de l'avancée et du retrait de l'Inlandsis de la Cordillère (Glaciation de Fraser) au Wisconsinien supérieur. La déformation est attribuée à des fractures d'abord de type ductile, puis cassant résultant : (a) d'une compression et d'une charge horizontales à mesure que la glace avançait sur les sédiments saturés ; suivie (b) d'une extension latérale, puis (c) d'une compression en milieu gelé pendant la phase de chevauchement glaciaire ; et enfin (d) d'une extension verticale pendant la décharge au moment de la déglaciation. La plus grande partie de la déformation (a-c) s'est produite au cours de la phase d'avancée de la Glaciation de Fraser.

ZUSAMMENFASSUNG *Mehrphasige glazigene Verformung der fluvioglazialen Vorstoßsedimente nahe bei Big Creek, British Columbia*. Nahe bei Big Creek im Zentrum von British Columbia hat man Verformungsstrukturen in fluvioglazialen Sedimenten beobachtet. Diese Sedimente belegen eine Sequenz mehrphasiger Verformung, welche durch den Vorstoß und Rückzug der Kordilleren-Eisdecke im späten Wisconsin (Fraser-Vereisung) verursacht wurde. Die Verformung führt man auf zunächst geschmeidiges, dann sprödes Nachgeben zurück, veranlaßt durch: (a) horizontale Verdichtung und Anhäufung während das Eis über die saturierten Sedimente vordrang, darauf folgend (b) eine laterale Ausdehnung und dann (c) Verdichtung in vereistem Milieu während der Gletscherüberschiebung, und schließlich (d) vertikale Ausdehnung während der durch die Enteisung bewirkten Strömungen. Der größte Teil der Verformung (siehe a-c oben) scheint während der Vorstoßphase der Fraser-Vereisung geschehen zu sein.

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INTRODUCTION

In many glaciated areas it is possible to distinguish between deformation of unconsolidated sediments produced by the dynamic and passive application of glacigenic stresses (see examples in Croot, 1988 and Aber *et al.*, 1989). The former often relates to active deformation imparted by loading and overriding glacier ice; whereas the latter refers to deformation associated with the relaxation of stress during deglaciation (Broster and Clague, 1987; Broster and Burke, 1990).

Glacigenic deformation has been investigated at numerous localities in British Columbia. In the Williams Lake and Hat Creek areas (Fig. 1a), Broster and Clague (1987) and Broster (1991) described deformation associated with glacier advance and retreat over frozen and saturated sediments. Eyles *et al.*. (1987) and Eyles and Clague (1991) examined deformation of waterlain sediments associated with passive decay of underlying ice confined in the valleys of the Fraser and Chilcotin Rivers (Fig. 1b). At Cranbrook (Fig. 1a), Broster *et al.* (1979) described bedrock fracturing and dislocation associated with glacier overriding. These studies demonstrated that investigation of glacigenic deformation can provide insight into glacier dynamics, basal thermal regimes, ice-movement and patterns of ice decay during glaciation.

Within the study area (Fig. 1b), the Late Wisconsinan Fraser Glaciation was characterized by northward ice flow from the Coast Mountains and westerly flow from the Cariboo Mountains (Fig. 1a). In front of advancing glacier margins, thick sequences of glaciofluvial sediments were deposited and then overridden (Tipper, 1971; Huntley and Broster, 1993). Toward the end of glaciation, stagnation of the Cordilleran Ice Sheet resulted in deposition of glaciofluvial sediments in contact with, and onlapping, debris-laden remnant ice masses and earlier glacial sediments.

Deformation of glacial advance and retreat sequences was observed at several localities within the study area (Fig. 1b). This paper describes well-preserved deformation structures found near Big Creek (Fig. 1b). At this site, examination of these structures and their cross-cutting relationships enabled the development of a model of polyphase glacigenic deformation associated with the advance and retreat of the late Fraser Cordilleran Ice Sheet.

THE STUDY SITE

Big Creek is an underfit stream occupying a major late glacial spillway that drained into the Chilcotin River (Fig 1b; Tipper, 1971). This spillway dissects a gently undulating hummocky ground moraine (at an elevation of about 1250 m) and has exposed till overlying upwards of 15 m of glaciofluvial gravels and sands (Fig. 2). This depositional sequence is further exposed in natural sections, road cuts and borrow pits throughout the area. A borrow pit on the north-facing slope of the Big Creek valley exposes deformed gravels and sands in a section approximately 10 m high and 40 m wide (Figs. 1b, 2). The deformation structures preserved here are the subject of this study.

STRATIGRAPHY AND ORIGIN OF SEDIMENTS

The dominant sediments comprise a thick sequence of gravels and interbedded sands. Although the base of the sequence is not exposed in the borrow pit, it locally reaches up to 15 m in thickness (Fig. 2). The gravels comprise polymictic, well-rounded clasts ranging in size from 0.5 cm to

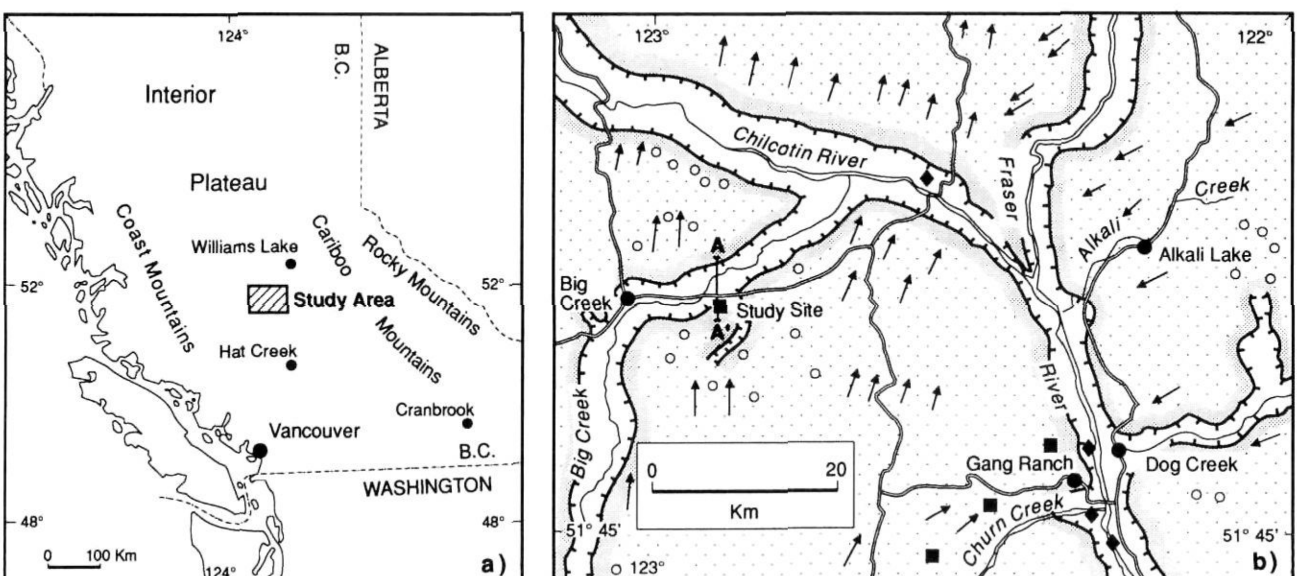

FIGURE 1. Location map showing: a) the study area; b) the glacial geomorphology of Big Creek area, showing study site. Key: location of section A-A' (see Fig. 2); hachured lines — limit of late glacial spillways and glacial lakes; → ice flow, inferred from streamlined landforms and striae; ○ hummocky ground moraine; ■ dynamic glacigenic deformation; ♦ passive glacigenic deformation.

Carte de localisation montrant : a) la région à l'étude; b) la géomorphologie glaciaire de la région de Big Creek où se trouve le site à l'étude. Localisation de la coupe A-A' (voir la fig. 2); Ligne à barbules: limite des canaux de trop plein tardiglaciaires et des lacs glaciaires; → direction du courant glaciaire; ○ moraine de fond bosselée; ■ déformation glaciaire dynamique; ♦ déformation glaciaire passive.

5 cm in diameter. Pebble fabrics measured at 0.5 m and 5 m below the contact with the overlying unit (see below) give pre ferred E-W and NE-SW alignments, respectively (Fig. 3a,b). Gravels are interbedded with two deformed faintly-laminated sand units. The lower sand unit reaches a maximum thickness of 1 m, while in the upper unit, bedding varies in thickness between 10 and 50 cm. Both sand units display normal grading. This gravel and sand assemblage is regionally widespread and is interpreted as a glaciofluvial deposit (Huntley and Broster, 1993). A preferred clast orientation (Fig. 3a) likely reflects the dominant northward palaeoflow direction.

In the NNW portion of the section, gravels and sands are disrupted by gravel and clast-supported diamicton-filled wedges (Figs. 2, 4). Wedge diamictons and gravels are lithologically similar to local gravels and contain rare, small (>10 cm long), vertically oriented irregular lenses of sand. Wedge deposits are near vertical and strike preferentially NE-SW (Fig. 3c). A vertical clast fabric overprints an earlier fabric reflecting inferred palaeoflow (Fig. 3d). The morphology, sedimentology and clast fabric of these structures are similar to dewatering features (Lowe, 1975; Postma, 1983).

A 3 m thick diamicton unit truncates glaciofluvial sediments and wedge deposits (Fig. 2). There is no evidence of subareal weathering along the contact between diamicton and the sands and gravels. This indicates little or no hiatus between erosion of underlying sediments and deposition of the diamicton. In the lower 1 m of this upper unit, minor warped sub-horizontal sand lenses are interbedded with diamicton. Above this, the diamicton is massive and matrix-supported. Clasts are polymictic and rounded to sub-rounded with occasional faceted, striated surfaces. Pebble orientations measured in the diamicton at 0.5 m above the basal contact demonstrate a strong alignment of prolate pebbles, with c axes of the clasts oriented predominantly SSE-NNW (Fig. 3e). A 3-dimensional plot of the clasts (Fig. 3f) show a strong unimodal concentration dipping towards the SSE. No preferred alignment is seen in the upper portion of the diamicton, as demonstrated by the measurements taken 2 m above the basal contact (Fig. 3g).

The diamicton is interpreted as a lodgement till (*sensu stricto*; Dreimanis, 1976) in its lower part, grading upward into melt-out till. The hummocky upper surface of this deposit resembles ice-stagnation moraine. This unit is correlated with the late Fraser Glaciation till exposed elsewhere in the Taseko Lakes area (Eyles and Clague, 1991; Huntley and Broster, 1993).

Glacial landforms in the vicinity of the study area indicate a northward ice flow direction (Huntley and Broster, 1993). The preferred alignment of clasts, with a strong SSE dip at 0.5 m (Fig. 3f) suggests lodgement deposition from NW flowing ice (*c.f.* Dowdeswell and Sharpe, 1986). The minor deviation from the regional ice flow may reflect local topographic

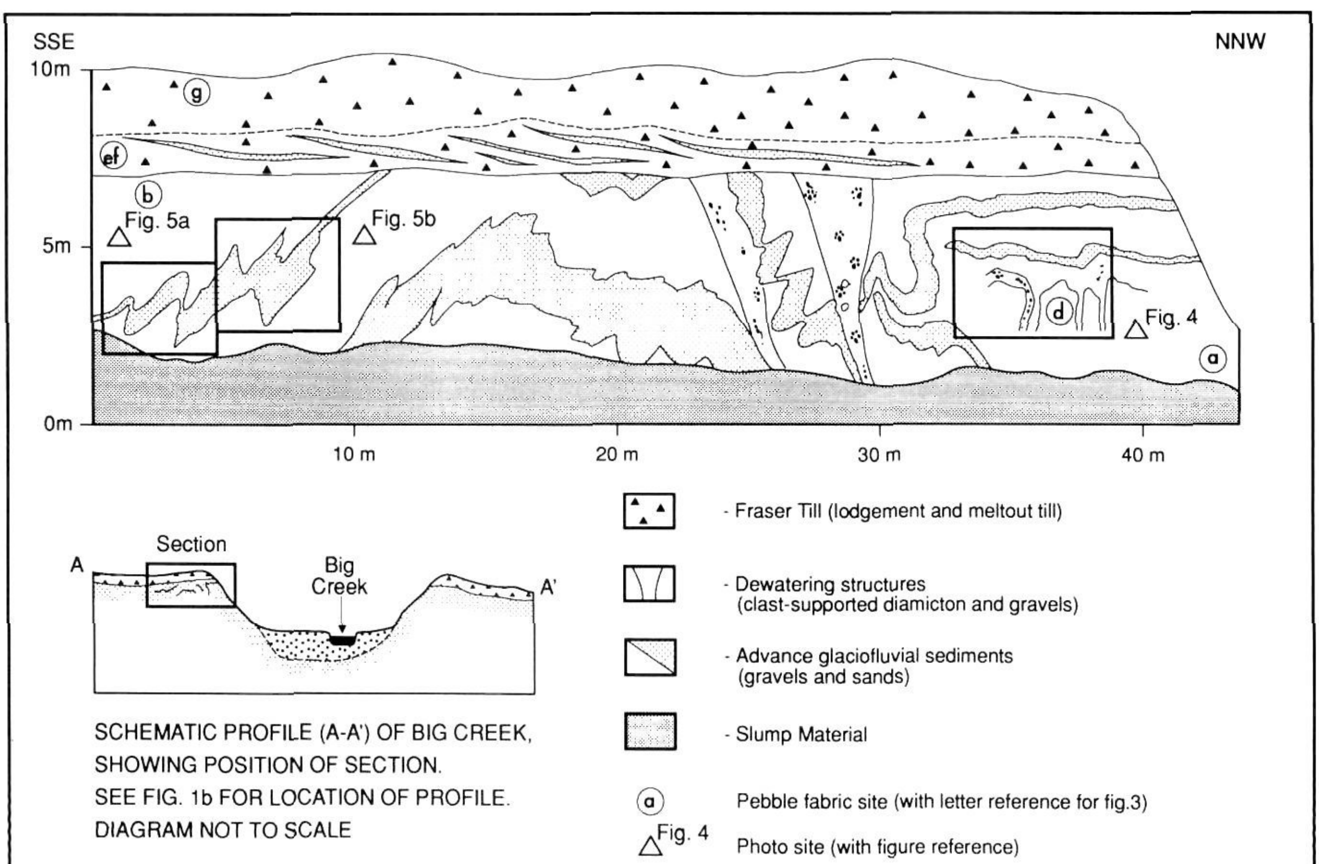

FIGURE 2. Detail of the Big Creek section and schematic cross profile along A-A' (see Fig. 1b).

Détail de la coupe de Big Creek et et schéma du profil A-A' (voir fig. 1b).

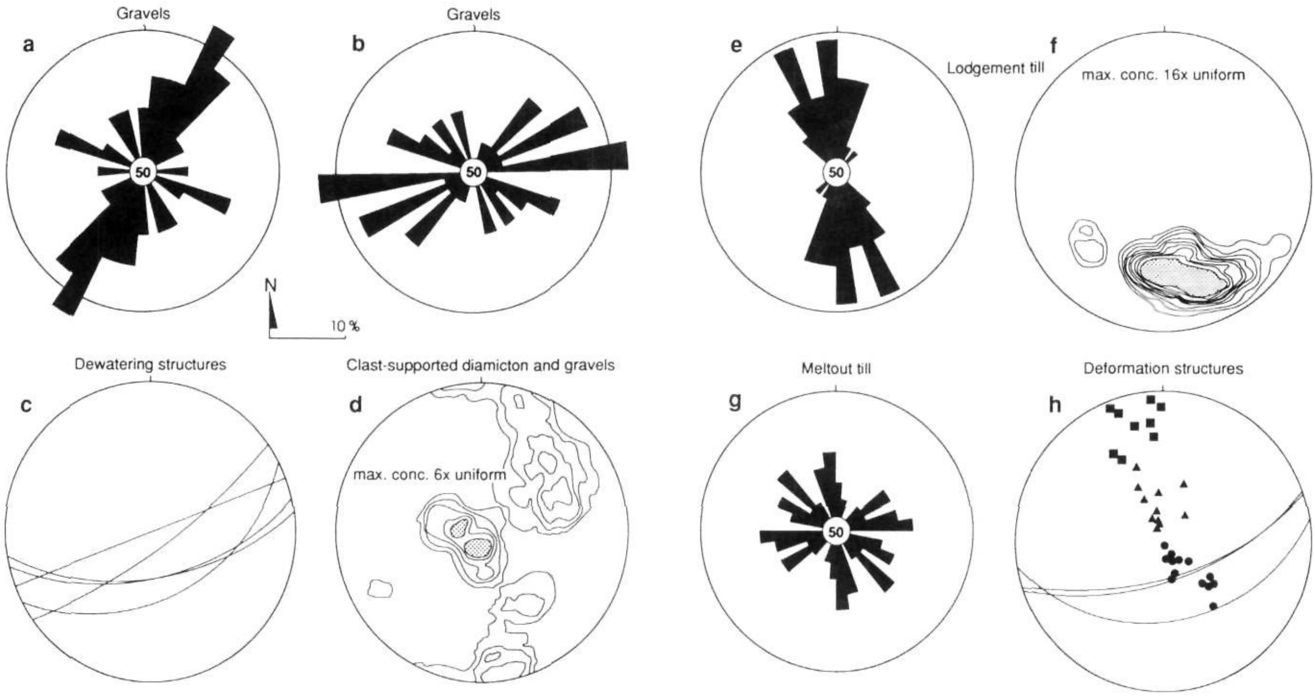

FIGURE 3. Pebble fabric and structural data plotted on lower hemisphere projection. a) glaciofluvial gravels (2D pebble fabric); b) glaciofluvial gravels (2D pebble fabric); c) dewatering structures (plotted as great circles); d) clast-supported diamicton and gravels in dewatering structures (3D c-axes pebble fabrics); e, f) lodgement till (2D and 3D c-axes pebble fabric); g) meltout till (2D pebble fabric); h) deformation structures, including: fold axes, high angle thrusts (■), normal faults (●) and low angle thrusts (▲) (folds plotted great circles, thrusts and faults as poles).

Orientation et inclinaison des cailloux et données sur la structure reportées sur l'hémisphère sud. a) Graviers fluvioglaciaires (orientation en 2D); b) graviers fluvioglaciaires (orientation en 2D); c) structures de déshydratation (reportées en grands cercles); d) diamicton à support caillouteux et graviers dans des structures de déshydratation (orientation et inclinaison des cailloux en 3D selon l'axe en c); e, f) till de fond (orientation et inclinaison des cailloux selon l'axe en c en 2D et en 3D); g) till de fusion (orientation en 2D); h) structures de déformation comprenant: axes des plis, failles de chevauchement à fort pendage (■), failles normales (●) et failles de chevauchement à faible pendage (▲) (plis reportés en grands cercles, failles traduites par des pôles).

FIGURE 4. Photograph of dewatering structures, note book for scale (see Fig. 2 for location).

Photographies de structures d'assèchement; le carnet donne l'échelle (localisation à la fig. 2).

control on glacier flow direction. The absence of a preferred fabric above 1 m (Fig. 3g) may be attributed to clast realignment during meltout.

The sediment assemblage exposed at the Big Creek site, comprising deformed glaciofluvial sediments unconformably overlain by relatively undisturbed till, resembles a glacier advance facies. This interpretation is consistent with regional studies (Tipper, 1971; Clague, 1981; Huntley and Broster, 1993).

DEFORMATION STRUCTURES

The majority of deformation structures are observed specifically within the sand units. The areal extent of deformation cannot be accurately assessed because of limited exposure. However, deformation was not observed at similar stratigraphic units elsewhere along the Big Creek valley.

Deformation structures recognized, include: folding, high angle reverse faults (thrusts), normal faults, low angle reverse faults (thrusts) and warping of fault and fold planes (Fig. 5a,b). Warping of the overlying till unit is also observed. The cross-cutting relationship of these structures (Fig 5b) allow reconstruction of the original bedding geometry and identification of a relative sequence of deformational events (Fig. 6a-d).

The earliest deformation structures (D1) are folds with NE-SW oriented axial planes, dipping to the SE (Figs. 3h, 5a). Bedding along fold limbs are boudined and the intensity of folding increases over the length of the section (Fig. 2). Folding reaches a maximum amplitude of 2 m in the NNW, where it is disrupted by dewatering structures (Figs. 2, 4).

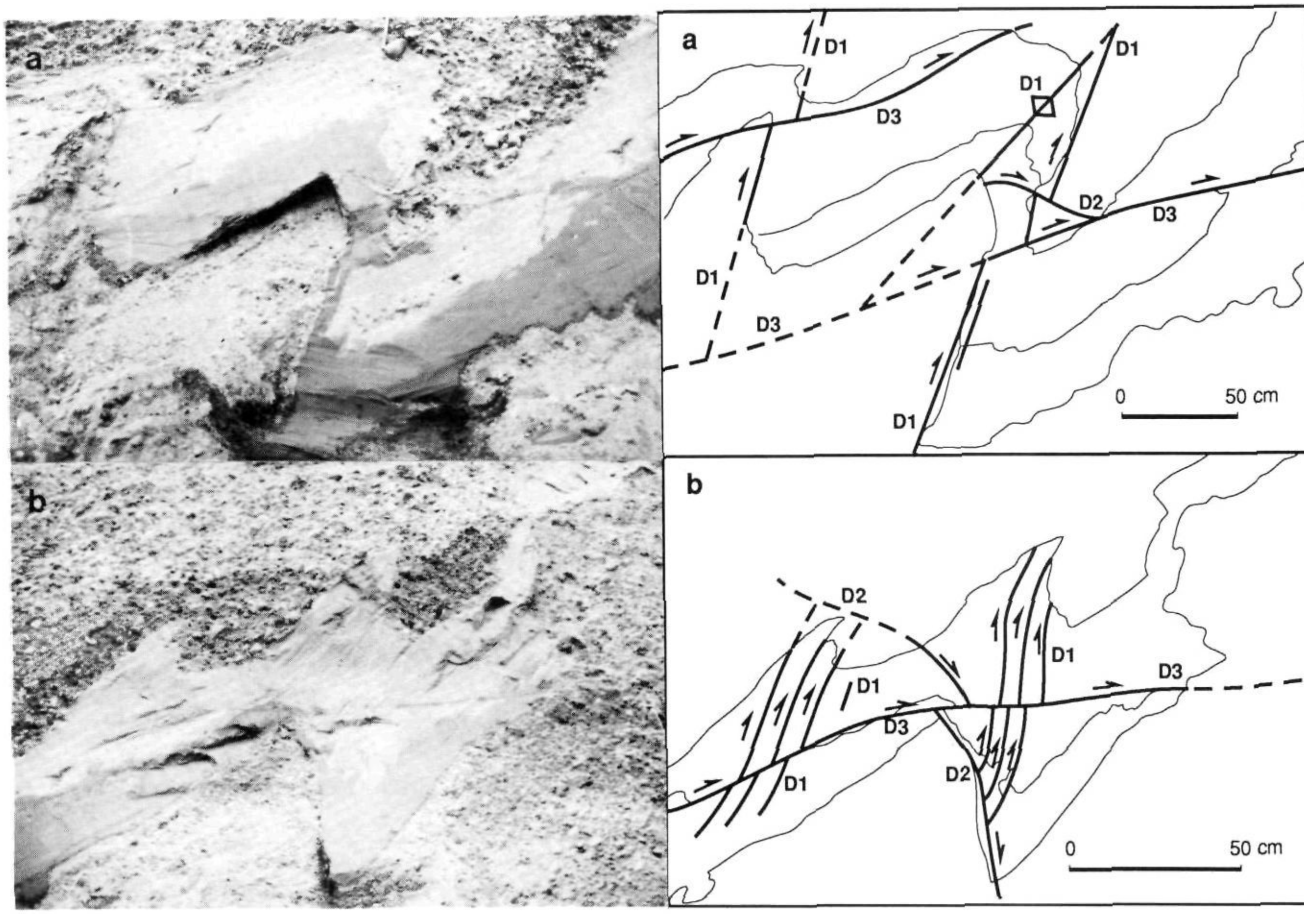

FIGURE 5. Photographs and simplified sketches of deformation structures. a) Early D1 folding offset by late D1 thrusts, a D2 normal fault and D3 low angle thrusts). b) Late D1 high angle thrusts in a fold limb, offset by D2 and D3 structures. Arrows indicate sense of motion.

Photos et schémas de structures de déformation. a) Début de la phase 1 (D1) par déplacement du pli jusqu'à la faille inverse en fin de phase, la faille normale en D2 et faille subhorizontale en D3. b) Failles à fort pendage le long du pli en fin de D1, décalées en D2 et D3. Les flèches donnent la direction du mouvement.

Folds are often disturbed by high angle thrusts (late D1), striking NE-SW and dipping SE (Figs. 3h, 5a, b, 6a). Thrust décollements are observed only within the sand beds and displacements rarely exceed 1 m. Folds and thrusts are cross-cut by NE-SW oriented normal faults (D2), dipping NW (Figs. 3h, 6b). Individual fault displacements do not exceed 2 m. Irregular lenses of sand occur along fault planes (Fig. 2). Folds, high angle thrusts and normal faults are further cross-cut in the SSE portion of the section by low angle thrusts (D3), dipping SW (Figs. 3h, 5b, 6c). Thrusting is partly focused along NE-SW striking décollements and reactivated high angle thrust planes (Fig. 6c). Rare gravel clasts have been incorporated along thrust planes. Displacement of sand beds by these low angle thrusts rarely exceeds 10 cm.

All structures are truncated and overlain by lodgement and meltout till. A slight upward warping of fold axes, fault planes and the overlying till unit (Fig. 2) indicates a final phase of deformation (D4; Fig. 6d).

ORIGIN OF DEFORMATION STRUCTURES

Glacigenic deformation is dependent upon the basal thermal regime and ice flow characteristics of the overriding glacier, and rheology of the bed material (Boulton, 1981; Begét, 1986; Hicock *et al.*, 1989). Current models of Wisconsinan ice sheets envisage a zone behind the glacier terminus where ice is below pressure melting point and basal substrate is frozen (Moran *et al.*, 1980; Tsui *et al.*, 1988). In this zone, glacigenic deformation may be facilitated through differentials in viscosity between partly-frozen substrate and moving ice and, or by slip along shear planes (Echelmeyer and Wang Zhonxiang, 1987). Semi-ductile, brittle extensional and compressional deformation structures (including folds, thrusts and normal faults) may be produced in a variety of subglacial environments and especially, during advance of a marginal frozen-bed zone over an area (Dreimanis, 1976). Up-glacier of this zone, ice is at pressure melting point and basal materials are saturated (Moran *et al.*, 1980). Because of the change in basal thermal regime, basal sliding rates increase and erosion of substrate produces streamlined terrain (Tsui *et al.*, 1988). However, deformation can still occur in areas of pressure melting-regelation (Broster and Park, 1993) or where patches of subglacial material can freeze to the glacier sole (*e.g.* Bluemle and Clayton, 1984; Broster, 1991).

Below, a model is proposed based on the concepts discussed above, in addition to stratigraphic and cross-cutting

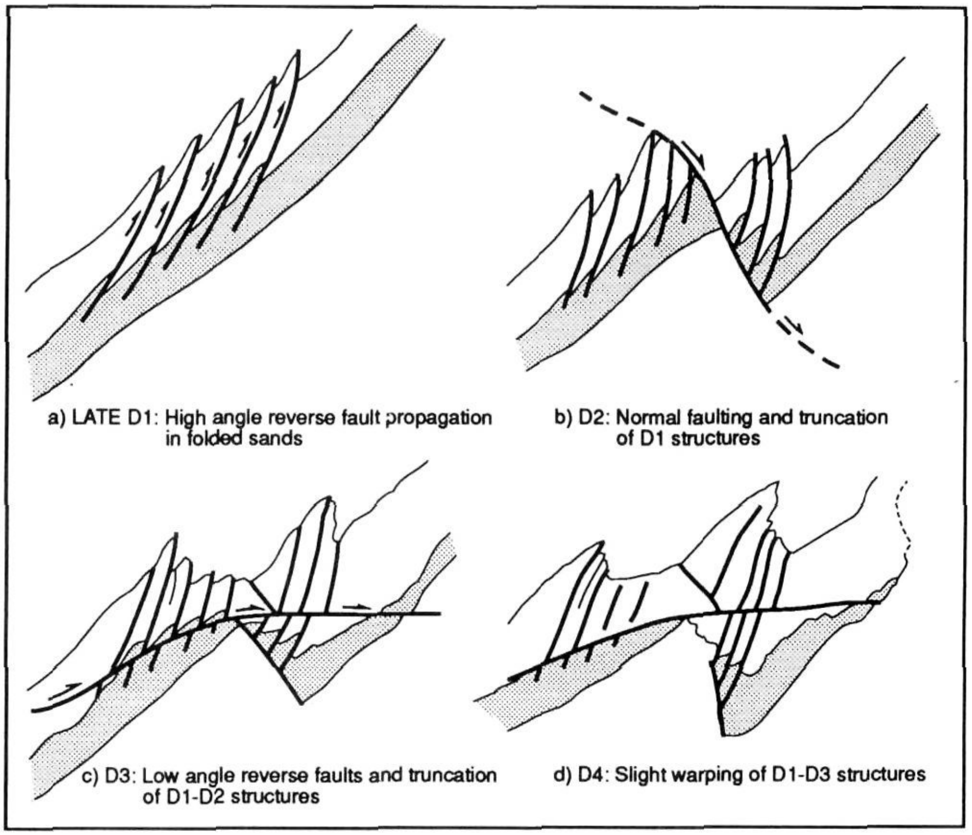

FIGURE 6. Glaciopalinspastic reconstruction of Figure 5b, based on cross-cutting relationships of glacigenic deformation structures, a) D1 structures: folds and high angle thrusts; b) D2 structures: normal faults; c) D3 structures: low angle thrusts; d) D4 structures: warping.

Reconstitution paléogéographique de la figure 5, fondée sur les liens transversaux entre les structures de déformation glacaires. a) Structures en D1: plis et failles subhorizontales; b) structures en D2: failles normales; c) structures en D3; failles subhorizontales; d) structures en D4: flexures.

relationships of sediments and deformation structures exposed at this site. Limitations are placed upon the model because basal thermal regimes and ice flow dynamics of the Cordilleran Ice Sheet are poorly understood.

DEFORMATION MODEL

Deformed advance glaciofluvial sediments are eroded and overlain by relatively undisturbed late Fraser Glaciation till. The morphology of most structures resemble those produced in response to glacier overriding (Croot, 1988; Broster, 1991) rather than by permafrost activity (*e.g.* Mathews and Mackay, 1960; Johnson, 1990). Fabric and structural data further corroborate a glacigenic origin for deformation. Although regional ice flow was generally northward (Tipper, 1971; Huntley and Broster, 1993; Fig. 1b), the preferred fabric in the lodgement till (Fig. 3e, f) suggests localized NNW glacier advance. All fold axes are transverse to inferred local ice flow, and poles to faults lie parallel to this direction (Fig. 3h).

Four phases of glacigenic deformation are recognized from the cross-cutting relationships at the site (Fig. 6a-d). Although the precise timing of events is not known, the absence of later glacigenic sediments suggests that deposition and deformation at this site were a relatively continuous event, related to the Fraser Glaciation (*circa* 23 ka-11 ka; Ryder *et al.*, 1991).

a) Deformation Phase I (D1)

The earliest phase of deformation was compressional and produced folds, dewatering structures and high angle thrusts. The alignment of fold axes transverse to inferred ice flow direction is consistent with a "push-from-the-rear" model (*e.g.* Croot, 1987). To this end, this phase of deformation may have occurred in an ice marginal setting. Boudined sand in fold limbs indicates that sediments were ductile, and therefore wet, during initial compression of the sediment pile. With ice advancing over saturated glaciofluvial sediments, increased porewater pressure in gravels, confined by less porous sand units, would have provided favourable conditions for folding and loading (Fig. 7a).

Compression of saturated sediments could have also caused groundwater discharge. In the NNW portion of the section, folded sand units are disrupted by NE-SW oriented wedge-shaped dewatering structures. Within the wedges, remnants of bedding are seen as small irregular sand lenses. The preferred alignment and vertical pebble fabric preserved in these structures (Fig. 3c, d) suggest localized groundwater escape along zones of low hydrostatic pressure, for instance a glacier margin (*cf.* Broster, 1991). Elsewhere in the gravels, the shift in preferred alignment and increase in scatter of clast orientations (Fig. 3b) may reflect volumetric adjustments within the dewatering sediment pile under a compressive stress regime operating during ice advance.

Folds are cross-cut by high angle thrusts, suggesting a change from a ductile to brittle deformational regime during compression. This change would be consistent with sediment consolidation due to progressive dewatering of the sediment pile (Broster, 1991; Hicock and Dreimanis, 1992). Thrusting can also be explained if sediments were frozen. A partly dewatered sediment pile would be susceptible to rapid freezing at the front of the glacier during advance and in contact

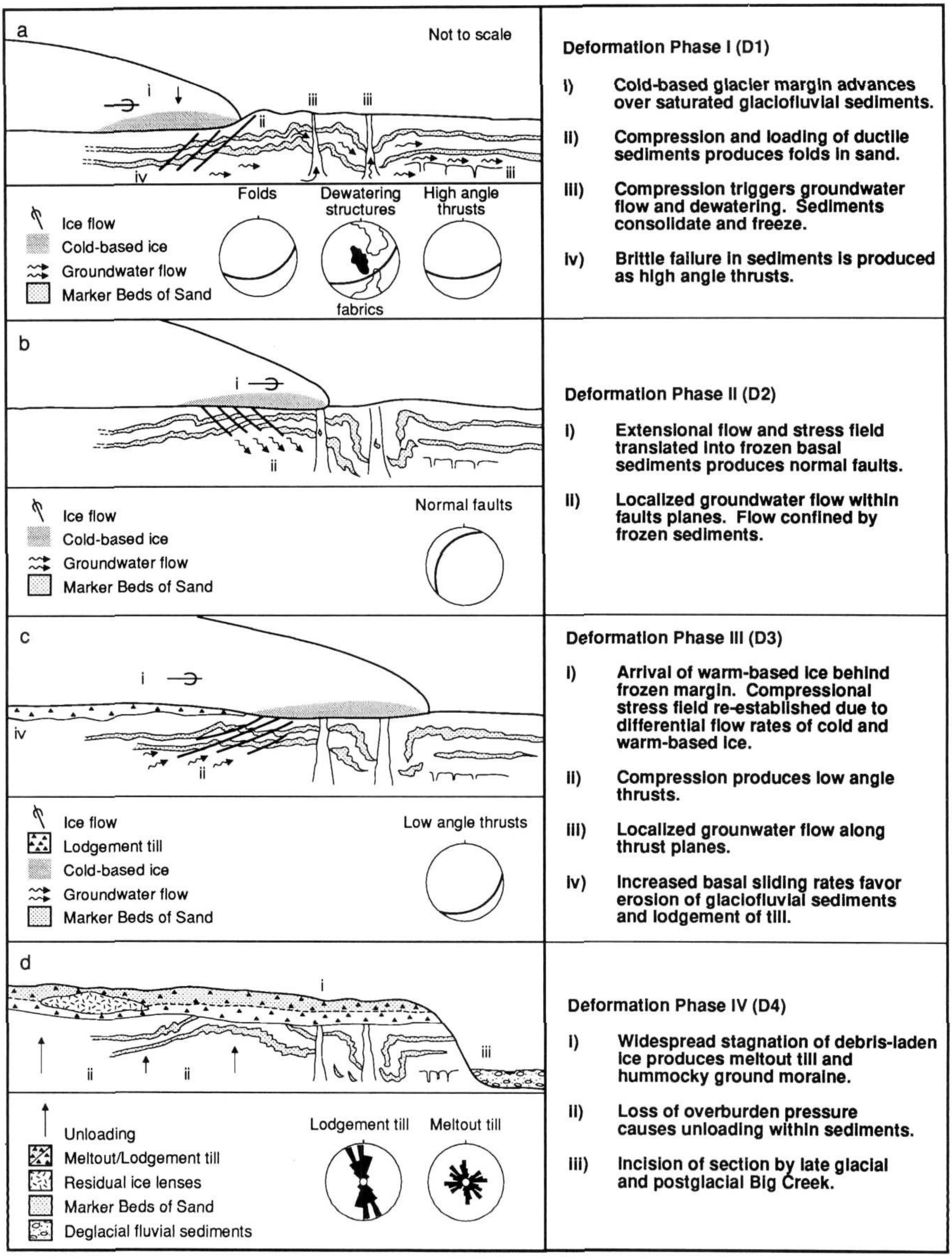

FIGURE 7. Polyphase deformational model for structures at Big Creek site.

Modèle polyphasique de déformation des structures du site de Big Creek.

with cold-based ice. The simplest method to freeze then thrust sediments in a compressional regime would be to assume that the advancing margin of the Cordilleran Ice Sheet in the Big Creek area was cold-based (*cf.* Moran *et al.*, 1980). In this way, compressional ice flow could be translated into frozen basal sediments.

b) Deformation Phase II (D2)

Early phase compressional structures are cross-cut by normal faults, indicating a change to deformation controlled by extension. Faulting could have occurred when extensional stress was translated into underlying frozen sediments during advance of a frozen glacier margin over the site (*cf.* Moran *et al.*, 1980; Broster and Clague, 1987). Extension may have been triggered by the loss of compressional stress upon brittle failure at the end of the D1 deformation phase. However, irregular sand lenses along normal faults planes suggests the presence of minor water flow focused along developing faults. Since this water was not free to flow through the gravel units it is likely that these units were frozen at this time.

Limited exposure prevents observations on how faulting was facilitated at depth. In other studies, the presence of a basal décollement is suggested to facilitate faulting (Croot, 1988). Normal faults may thus have an unexposed listric component; this is not depicted in the model (Fig. 7b).

c) Deformation Phase III (D3)

D1 and D2 structures are offset by low angle thrusts, indicating a change to a compressional stress regime (Fig. 7c). Compression within sediments could be produced by confining rapid flowing warm-based ice behind a slower moving frozen bed zone (Fig. 7c). Thrusts are partly propagated by décollement along reactivated high angle thrust planes. Failure may have been facilitated by residual porewater confined along fracture planes (Broster, 1991). It is not known how thrusting was propagated at depth, although individual faults may combine to form an upglacier listric décollement.

Glaciofluvial sediments and D1-D3 structures are eroded and overlain by till. The absence of subareal weathering along the erosional contact suggests that truncation and subsequent till deposition occurred subglacially. Elsewhere in this area, modified streamlined terrain indicates that regionally widespread wet-based and erosional conditions were associated with late Fraser Glaciation ice flow. These conditions would also have favoured truncation of consolidated glaciofluvial sediments and earlier D1-D3 deformation structures as basal sliding rates increased. This sequence of events would be consistent with arrival of wet-based ice behind a frozen glacier margin as ice advanced northward over the site (*cf.* Moran *et al.*, 1980).

d) Deformation Phase IV (D4)

The final phase of deformation involved upward flexing of faults, folds and overlying till suggesting vertical extension within the sediment pile. Elsewhere, postglacial deformation structures have been attributed to release of residual glacigenic stresses, for instance a loss of confining pressure upon deglaciation (*cf.* Broster and Burke, 1990). Passive deformation was not associated with fluvial entrenchment of advance glacial deposits at this site (*cf.* Broster and Clague, 1987). Thus, the final phase of deformation likely occurred in response to deglaciation, *circa* 11 ka (Clague, 1981; Ryder *et al.*, 1991; Fig. 7d).

CONCLUSIONS

Unconsolidated sediments and bedrock may preserve distinct deformation structures relating to the regional glacial deformation history of an area (*e.g.* Broster *et al.*, 1979; Hicock and Dreimanis, 1985; Broster, 1991). At our site, a clear relationship exists between different deformation phases affecting glacial sediments during and after ice advance.

Four phases of glacigenic deformation were recognized, related to movement of grounded ice over advance glaciofluvial sediments. The pattern of deformation suggests that wet sediments were dewatered, consolidated and then frozen during ice advance. As a consequence, sediments record a sequence of ductile, brittle and semi-brittle failure resulting from (1) horizontal and vertical compression during initial glacier advance into the area; (2) translation of lateral extensional stress; then (3) compressional stress into frozen basal sediments; and (4) erosion of underlying units and till deposition under wet-based glacial conditions followed by vertical extension in response to deglacial unloading. The majority of deformation (D1-D3, above) appears to have occurred in response to dynamic glacigenic deformation during the advance phase of the Fraser Glaciation. The sequence of events described is consistent with the advance of a cold-based glacier margin over the Big Creek area, followed by erosion and deposition under wet-based conditions (*cf.* Moran *et al.*, 1980).

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