

Glacitectonic Deformation in Sediment and Bedrock, Hat Creek, British Columbia

Déformations glaciectoniques dans les sédiments et la roche en place à Hat Creek, Colombie-Britannique

Glazialtektonische Verformung von Sediment und festem Gestein bei Hat Creek, British Columbia

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Article abstract

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GLACITECTONIC DEFORMATION IN SEDIMENT AND BEDROCK, HAT CREEK, BRITISH COLUMBIA

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ABSTRACT A variety of deformation structures attributed to glacial overriding occur in rock and sediment of an intermontane valley at Hat Creek, British Columbia. Sediments exposed in vertical outcrops along Hat Creek, display contrasting styles of deformation involving fluidization, as well as brittle and ductile deformations that appear to have been formed concurrently. Typical structures include: joints, faults, infillings, and clastic dikes comprising; fluid-escape structures, glacial injections, as well as fluidal and viscous hydraulic expulsions. A model is presented for the glacitectonic formation of hydraulic expulsions during compression of underlying partially saturated unfrozen sediments. Bedrock exposed in excavations at higher elevations displays joints, faults and wedge fillings possibly associated with subglacial freezing during glacial advance. Orientation of the structures are correlative with directions of glacier flow as inferred from fabric, striae and geomorphology. The structures are believed to have been the product of several interrelated factors, including: glacial dynamics, engineering properties of the glacier bed material, subglacial relief, and the variation between coalescing glaciers. Correlation with directions of glacial movement, association with glacial facies and infilling by glacial sediments, are conditions considered to be glacial signatures useful in differentiation of glacial from nonglacial (e.g. earthquake) origins for similar structures elsewhere.

RÉSUMÉ Déformations glaciectoniques dans les sédiments et la roche en place à Hat Creek, Colombie-Britannique. Certaines variétés de structures de déformation attribuées au chevauchement glaciaire se manifestent dans la roche en place et les sédiments d'une vallée intramontagnarde au Hat Creek, en Colombie-Britannique. Les sédiments mis à nu dans des affleurements verticaux le long du Hat Creek montrent des déformations aux styles contrastés qui semblent avoir été créées concurremment. Les structures caractéristiques comprennent des fissures, des failles, des remplissages et des filons clastiques incluant des structures à échappement fluidal, des injections glaciaires ainsi que des éjections hydrauliques fluides et visqueuses. On présente un modèle de la formation glaciectonique d'éjections hydrauliques durant la compression des sédiments sous-terrains non gelés partiellement saturés. La roche en place mise à nu dans des excavations à des niveaux supérieurs montre des fissures, des failles et des remplissages de fentes probablement associés au gel sous-glaciaire pendant l'avancée glaciaire. L'orientation des structures correspond aux directions de l'écoulement glaciaire déterminées à partir de la fabrique, des stries et de la géomorphologie. On croit que ces structures sont le résultat de plusieurs facteurs interreliés dont la dynamique glaciaire, les propriétés mécaniques des matériaux du lit glaciaire, le relief sous-glaciaire et la variation entre glaciers coalescents. La corrélation avec les directions du mouvement glaciaire, l'association avec les faciès glaciaires et le remplissage par des sédiments glaciaires sont des phénomènes que l'on considère comme étant des signes de glaciogénie qui peuvent servir à différencier l'origine glaciaire de l'origine non glaciaire (ex : tremblements de terre) de structures semblables trouvées ailleurs.

ZUSAMMENFASSUNG Glazialtektonische Verformung von Sediment und festem Gestein bei Hat Creek, British Columbia. Eine Vielfalt von Verformungs-Strukturen, die auf glaziales Überfahren zurückgeführt werden, findet man in Fels und Sediment eines intermontanen Tals bei Hat Creek, British Columbia. Die in vertikalen Aufschlüssen längs Hat Creek ausgesetzten Sedimente zeigen kontrastierende Verformungsstile, die Verflüssigung wie auch brüchige und geschmeidige Verformungen einschliessen, die gleichzeitig gebildet zu sein scheinen. Zu den typischen Strukturen gehören: Spalten, Brüche, Ausfüllungen und Trümmer-Quergänge einschliesslich Strukturen flüssigen Entweichens, glazigenen Injektionen wie auch flüssigen wie zähflüssigen hydraulischen Auswürfen. Ein Modell der glazialtektonischen Bildung hydraulischer Auswürfe während der Verdichtung der darunterliegenden, teilweise saturierten, nichtgefrorenen Sedimente wird präsentiert. Das feste Gestein, das in höheren Aushöhlen freigelegt wurde, zeigt Spalten, Brüche und Spaltenfüllungen, die wahrscheinlich mit subglazialen Frost während des glazialen Vorstosses zusammenhängen. Die Orientierung der Strukturen korreliert mit den Richtungen des glazialen Fliessens. Das lässt sich aus Textur, Striemen und Geomorphologie schliessen. Man hält die Strukturen für das Ergebnis mehrerer untereinander verbundener Faktoren. Dazu gehören die glaziale Dynamik, die mechanischen Eigenschaften des glazialen Bettmaterials, das subglaziale Relief und die Schwankungen zwischen zusammenverwachsenen Gletschern. Die Korrelation mit Richtungen der glazialen Bewegung, die Verbindung mit glazialen Fazies und Auffüllungen durch glaziale Sedimente sind Bedingungen, die als glazigene Signatur angesehen werden bei der Unterscheidung zwischen glazialen und nicht-glazialen (z.B. Erdbeben) Ursprüngen vergleichbarer Strukturen anderswo.

INTRODUCTION

In glaciated areas, faults, thrust blocks and clastic dikes found in bedrock or sediment may be the result of a variety of nontectonic causes including: periglacial conditions, mass movement, glacioisostasy or glacitectonic deformation. Because these structures can be produced by several mechanisms associated with glaciation, the significance of their occurrence is open to question when found in glaciated areas of unknown seismic potential.

The origin of local deformation structures is a major component of earthquake engineering studies and can exert a significant influence on seismic design criteria. In western Canada the historical seismicity record is inadequate, encompassing no more than 100 years. As a result, estimates of expected magnitudes and frequency of reoccurrence, based only on the historical record, contain uncertainties. However, *seismically induced deformation is commonly preserved in unconsolidated sediments and have been used to obtain realistic estimates of frequency and magnitude of postglacial seismic events* (Cluff *et al.*, 1980; Hall, 1984).

During 1981 and 1982, British Columbia Hydro and Power Authority (B.C. Hydro) was conducting preliminary engineering design for a coal-fired thermal generating station at Hat Creek, British Columbia (Fig. 1). As part of the overall project, Kohn Leonoff Consulting Engineers were retained to provide an assessment of seismic potential of the site. Typically, earthquake engineering studies involve examination of local faults and overlying sediments for signs of recent movement. In the

neotectonic context, faults showing evidence of recent movement (less than 10,000 years) are considered active. Thus, a key part of the field investigations at Hat Creek was to ascertain if any recent fault displacements had occurred.

The discovery of faults and clastic dikes in exposed sediments along the east bank of Hat Creek (section B81-1, Fig. 2) early in the program was considered particularly significant since this section is located almost directly over the youngest bedrock fault in this area as indicated by B.C. Hydro drilling. Subsequent geological investigations were focused on the origin of the deformation structures found in sediment at section B81-1, and also in bedrock exposed in trenches previously excavated by B.C. Hydro to sample coal-bearing units (trenches A, B, and C; Fig. 2). Results and interpretations of these and further investigations are discussed herein, including proposed mechanisms for glacitectonic origins of the faults and clastic dikes studied.

GEOLOGICAL SETTING

The study area is located in a currently stable part of the North American plate, several hundred kilometres from the

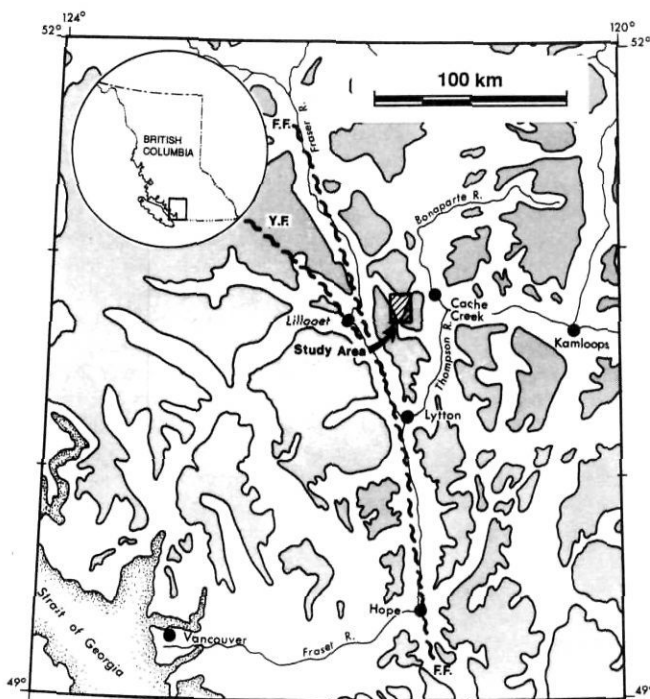


FIGURE 1. Location of study area and relationship to the Fraser Fault (FF) and Yalakon Fault (YF). The shaded area represents areas of topographic relief greater than 1200 m in elevation.

Localisation de la région à l'étude et relations avec la faille de Fraser (FF) et la faille de Yalakon (YF). Les zones en gris ont un relief de plus de 1200 m d'altitude.

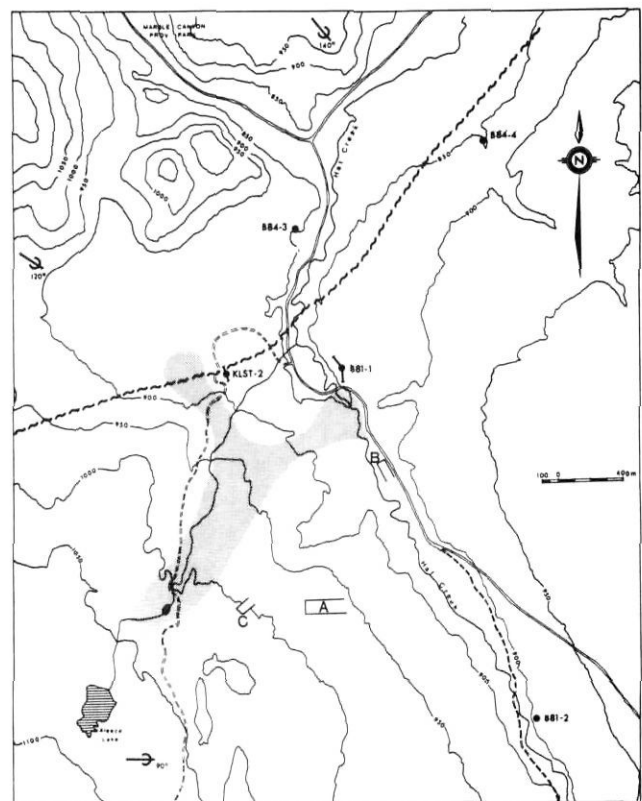


FIGURE 2. The study area and locations of sites discussed in the text. An area of visible surface deformation due to landslides and flowage is defined by stippling; glacial striae and the Marble Canyon fault are indicated by the usual symbols. A, B and C denote trenches excavated to sample coal and are discussed further in the text.

Région à l'étude et localisation des sites dont on parle dans le texte. Une zone de déformations superficielles visibles causées par des glissements de terrain et du fluage est définie par des tirets; les stries glaciaires et la faille de Marble Canyon sont identifiées par les symboles habituels. Les lettres A, B et C localisent les tranchées creusées pour l'échantillonnage du charbon (voir le texte).

plate margin off the west coast. Accordingly, it experiences relatively low levels of seismic activity, possibly related to local or nearby regional fault systems. The nearest regional fault system is the Fraser-Yalakom system lying approximately 20 km west of the study area. The Fraser Fault, believed to be inactive (Mathews and Rouse, 1984), extends north and south along the Fraser River, while the Yalakom Fault trends northwest from the Fraser at Lillooet (Fig. 1).

The study area lies in a north-trending valley at the junction of tributary branches trending to the NE and NW. Several local faults pass through the valley to the north and south of the study area from the surrounding mountains (Church, 1975). Drilling and subsurface mapping by B.C. Hydro delineated two faults (one south of the study area) inferred to be the youngest by cross-cutting relationships and not exposed at the surface. As part of the earthquake study, surficial sediments overlying the two youngest faults were trenched and observations made in trench KLST-2 (Fig. 2) will be discussed here. No evidence of recent displacement was found in either excavation.

STRATIGRAPHY

Quaternary sediments mask the bedrock at low elevations along the Hat Creek valley. A summary of the rock units occupying the valley is provided by Church (1975). Tertiary rocks exposed in excavated trenches include: claystone with minor coal of the Coldwater Formation exposed in trench C, and the overlying Hat Creek Formation consisting of coal with a colourful and deformed burnt coal zone in the upper part of the unit, in trench A (Fig. 2).

Surficial materials (Ryder, 1976) consist mainly of glacial sediments of the Fraser Glaciation, which attained its maximum effect about 15,000 yr. BP (Clague, 1981). Drilling indicates that the sediments range from a till cover less than a few metres thick on the uplands to a complex package of tills and waterlain sediments that increase in thickness eastward, to over 150 m thick 1 km east of trench B (Fig. 2). Genetic interpretations used in this study are based on the results of local studies by the

Geological Survey of Canada (e.g. Clague, 1981; Ryder, 1976) as well as several years of geotechnical and geological investigations of lithologic, granulometric and fabric relationships as part of the B.C. Hydro study and investigation of the deformation structures.

The Pleistocene succession exposed in the study area consists of five main units in ascending order: glaciolacustrine clay, silt and fine sand; advance glaciofluvial sand and gravel (coarsening upward); till; retreat glaciofluvial silt to gravel (fining upward); and surface colluvium. Recent landslide debris occurs as isolated deposits, although much of the surficial sediments have been involved to some degree in slope movements. A lower till is present, but was found only during excavation. The units were examined closely in trench KLST-2 and at section B81-1; although thickness and lateral continuity vary, the above descriptions typify the characteristics of the units seen along the valley.

OBSERVATIONS FROM TRENCH KLST-2

Drilling and mapping by B.C. Hydro identified a young fault, informally called the Marble Canyon fault, trending eastward in the immediate area of section B81-1 (Fig. 2). A 110 m trench (KLST-2) was excavated perpendicular to the fault trace, exposing up to 7 m of sediment, comprising four main units (Fig. 3). Two units are interpreted as basal tills because of their dense, poorly sorted matrix and abundance of local striated and flatiron clasts.

The lowermost unit consisted of a moderately stony, greenish brown, clayey silt till, exposed intermittently along the trench floor. The till is separated from an upper till of similar texture by a glaciolacustrine unit that consists of undeformed subhorizontal laminae of silt and fine sand with occasional dropstones.

The upper till is a brown to greenish brown compact stony sediment, silty in the upper 1 m and becoming more clayey with depth. A wedge of waterlain sediment occurs in the till at the

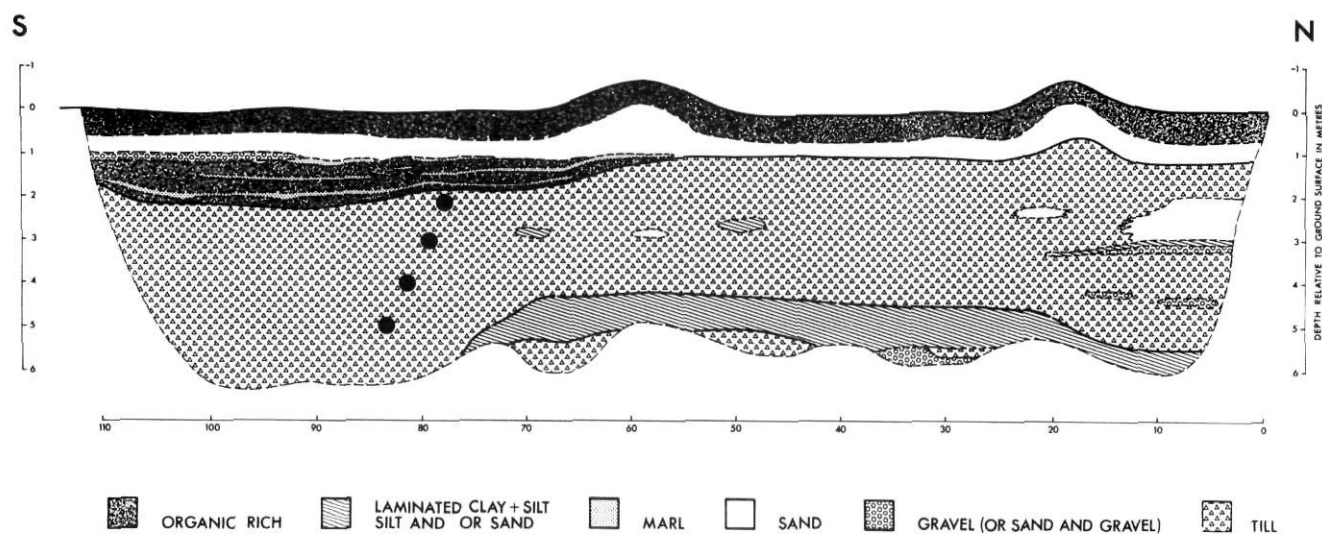


FIGURE 3. Sketch of units found in trench KLST-2 and the location (black dots) of fabric measurements sites in Figure 5.

Schéma des unités de la tranchée KLST-2 et emplacements (points noirs) des sites de mesures des fabriques (fig. 5).

northern portion of the excavation (Fig. 3). Angular clasts of waterlain sediment occur sporadically throughout the till and the wedge could represent a very large inclusion as well as a proglacial or subglacial ponding interval. The till appears to be a homogeneous unit in the southern end of the trench.

The upper 1.2-2.0 m of the trench consists mainly of glaciofluvial sand and pebbly sand, forming a sharp contact with the underlying till. In the southern portion of the trench, continuous and discontinuous layers of marl containing gastropod shells occur along the base of the unit. The marl was not considered to be a suitable material for radiocarbon dating (e.g., Karrow *et al.* 1984), and its exact age is not known. However, considering that the marl layers and the underlying older glaciolacustrine unit were undisturbed, it was concluded that recent (less than 10,000 yr. BP) movement is unlikely to have occurred along the underlying fault.

OBSERVATIONS FROM SECTION B81-1

Glacigenic deposits are exposed over a 160 m distance along the east bank of Hat Creek, approximately 1.5 km south of Highway No. 12 (Fig. 2). The bottom of the exposed section is approximately 15 m above river level, with the lower elevations generally covered by slump debris (Fig. 4). Up to 12 m of layered waterlain sediments are exposed along the base of the section. These sediments can be informally divided into upper and lower units representing respectively, proximal and distal facies of proglacial sedimentation. The upper part is predominantly a current-bedded sand and gravel unit while the lower part is rhythmically layered silt and sand.

The lower unit becomes finer-grained with depth and drilling indicates that it extends well below the slump cover. Exposures of laminated clay and silt can be found outcropping just above

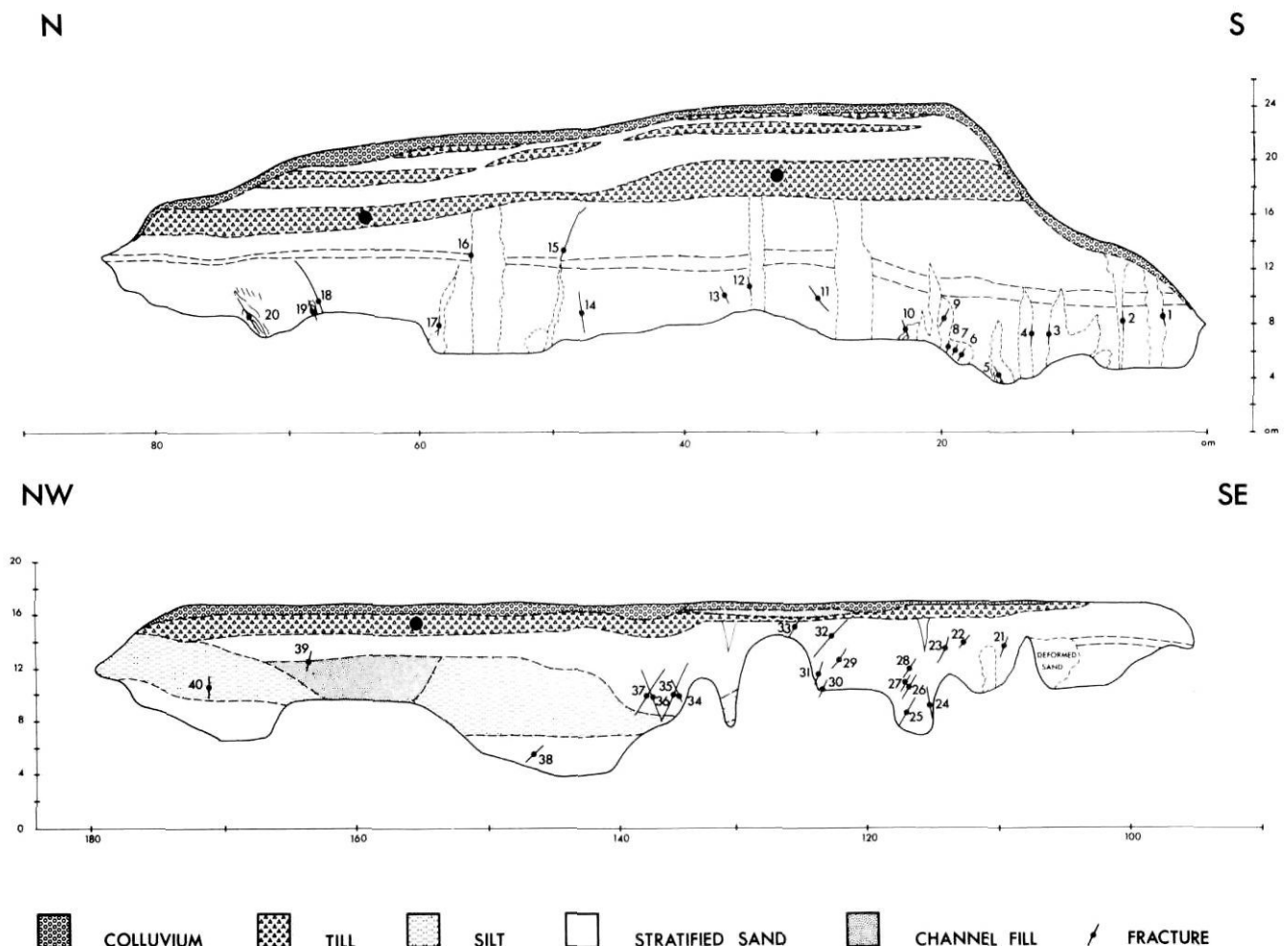


FIGURE 4. Sketch of section B81-1 indicating approximate size and location of fabric measurement sites (black dots) in Figure 5, clastic dikes, faults, and joints that were examined. Numbered sites correspond to data presented in Table I. The horizontal dashed lines in the middle of the stratified sand unit indicate a pronounced layer that was useful in separating lower fine-grained, from overlying coarse-grained, portions of the exposed waterlain sediments. The near vertical dashed lines outline the clastic dikes; the area below the exposure is slump covered.

Schéma de la coupe B81-1 donnant la taille approximative et la localisation (points noirs) des sites de mesures des fabriques (fig. 5) ainsi que des filons clastiques, des failles et des fissures qui ont été observés. Les chiffres correspondent aux données du tableau I. Les lignes tirées au centre de l'unité de sable stratifié localise une couche bien accusée qui a facilité la séparation entre les parties inférieure à grain fin et supérieure à grain grossier composées de sédiments mis à nu déposés dans l'eau. Les traits quasi verticaux soulignent les filons clastiques; la zone située en-dessous de la partie exposée est recouverte de matériaux de glissement.

river level, within 300 m north of section B81-1. Individual layers range from a few millimetres to a few centimetres in thickness and resemble lacustrine 'varves'. Lenses of coarse sand, up to 3 m thick, occur sporadically along the lower part of section B81-1 and contain easterly- and northerly-dipping interbeds of pebbly sand and silt. Load structures can be found in some silt layers and these may have resulted from the rapid deposition of overlying sand layers.

Occasional striated clasts occur within the uppermost layers within the upper unit, indicative of the proximity of glacial ice during deposition. Bedding is indistinct and the gravels occur as subtle, planar zones within coarse sand. Cursory examinations of cross-stratification in some layers indicated southward flow directions.

In the northern part of the section proximal gravel occupies a large channel that has been cut into the underlying sand and silt (Fig. 4). Examination of pebble orientations indicates flow towards the southwest, although present drainage directions are towards the northeast and northwest. In this part of the exposure coarse-grained layers are intercalated with fine-grained layers indicative of fluctuating discharge conditions or stream braiding during deposition.

Compact till forms a discontinuous bed, at times up to 3 m thick, overlying the proximal deposits. The contact varies from sharp (erosional) to gradual, both laterally and vertically within the section. At a few locations the base of the till is interbedded with sand and gravel layers that may indicate that portions have been waterlain. In the upper part of the unit the till merges vertically and laterally into ablation till and shows loose packing and improved sorting, inferred to be due to reworking by meltwater at some localities. Much thicker exposures of till occur to the south (station B81-2, Fig. 2) that also display the vertical gradation from waterlain, through compact, to ablation till.

At other locations (B81-2, B84-3; Fig. 2) the till is overlain by glaciofluvial sand and gravel that displays an overall fining upward trend interpreted as retreat meltwater deposits. At section B81-1 the unit ranges up to 3 m thick. Trough cross-bedding can be seen in some parts of the unit and interbedded diamicton occur as isolated lenses within the retreat meltwater deposits. A veneer of fine sand and colluvium up to 1 m thick is present along the top of the section.

INTERPRETATION OF LATE GLACIAL SEDIMENTATION

The exposed portion of the glaciolacustrine unit in section B81-1 may represent a transitional phase between glaciolacustrine and glaciofluvial facies, although, no evidence of subaerial deposition was found (e.g. ventifacts). Generally, the glaciolacustrine and glaciofluvial sediments display an overall coarsening upward, indicative of basin infilling and approaching ice masses.

Measurement of clast orientation at several depths within the till demonstrate a vertical change in preferred direction of pebble alignment (Fig. 5). Fabrics in the upper part of the till agree with near surface measurements of fabric at other locations (Fig. 2) and with the regional east-southeast directions of glacier movement indicated by striated bedrock and surface landforms studied by Ryder (1976). Fabrics in the lower part of the till, exposed during excavation of trench KLST-2, indicate a northeastward-southwestward trend, corresponding to the direction of valley widening (Fig. 2). This southwest orientation is not considered to represent a transverse fabric since clast alignment in basal tills are often strongly parallel to flow direction (Dreimanis, 1976). This direction is also indicated as a major mode at site B84-4 and by a minor mode in other fabrics, as is an eastward direction (Fig. 5). The minor modes could be indicative of the influence of coalescing glacier lobes (e.g.

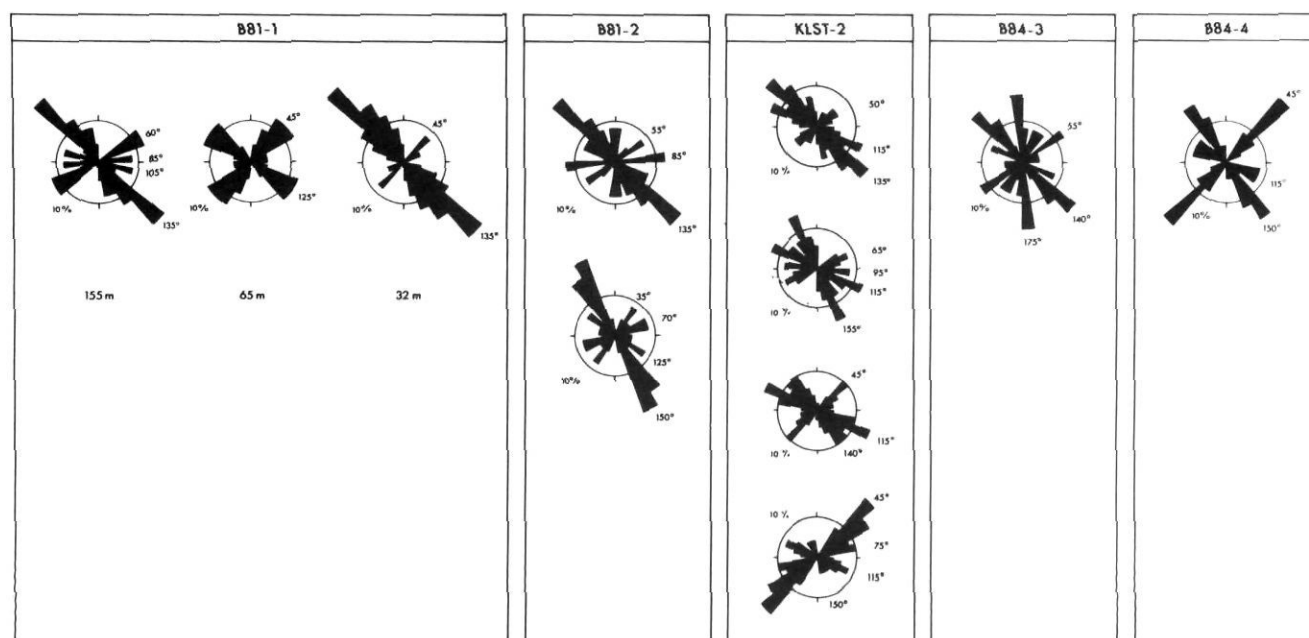


FIGURE 5. Till fabric data from the sites studied. The rose diagrams show the orientation of elongated stones. Each data set comprises 50 measured clasts.

Fabriques du till des sites à l'étude. Les diagrammes circulaires donnent l'orientation des pierres allongées. Chacun des ensembles de données comprend 50 fragments.

Broster and Dreimanis, 1981) and/or adjustments to subglacial topography during the early stages of glaciation.

In the northern part of the study area the valley divides into northeastern and northwestern draining segments (Fig. 2). Occupation of these valley segments by glacier lobes, and their advance southward into the area, could account for both: 1) underlying glaciolacustrine deposition due to blockage of the drainage outlets, and 2) southwest and southeast-trending fabrics. Striae representing eastward flow become prevalent in the southern part (and southward) of the study area. The eastward and southward glacier flow directions across the study area are in agreement with regional trends found by Ryder (1976), and are concluded to represent established flow directions during later stages of glaciation.

DEFORMATION STRUCTURES

DEFORMATIONS IN SEDIMENT

Deformation structures are exposed along the face of section B81-1 (Fig. 4). Deformation is mainly confined to the glaciolacustrine and glaciofluvial advance meltwater sediments, with only minor fracturing and faulting present in the overlying units. The structures are postdepositional and consist of joints, faults and clastic dikes. They do not resemble faults produced by melting of trapped ice (e.g., MacDonald and Shilts, 1975; Eyles, 1977) or permafrost induced frost wedges (e.g., Morgan, 1972), both commonly associated with particular styles of tilted or disturbed bedding.

Straight and curvilinear normal and reverse faults vary in length up to 12 m (Fig. 4). The faults occur at high angles as individuals and as sets (Table I). Some minor fractures (<3 m long) appear fresh (data not included in Table I) and are possibly due to unloading of the section face. Slickensides are present along some faults (Table I) and these are unlikely to have formed while the waterlain sediments were saturated. Their occurrence may be the result of faulting after dewatering of the waterlain sediments, or the result of recent movements along older glaciogenic fractures since local sediments are bentonitic and susceptible to mass movement at very low angles.

Some joints and faults have been widened and infilled by remobilized sediments forming clastic dikes. The dikes are the most obvious deformation structures exposed and the waterlain sediments are cut by as many as ten dikes. Two categories of clastic dikes were recognized: (type 1) glaciogenic injections (Fig. 6), the result of downward intrusion of material from the glacier sole into underlying beds, and (type 2) hydraulic expulsions (Fig. 7), clastic dikes originating from the upward expulsion of material through overlying beds. The expulsions can be further separated by rheology into fluidal expulsions demonstrating rapid fluid-escape or viscous expulsions that may have involved a somewhat slower and more viscous extrusion process.

All clastic dikes are near-vertical structures dissecting bedding; although, glaciogenic injections are commonly wedge-shaped, tapering downward with one side often forming a sharp contact with the surrounding unit (Fig. 8). Some dikes cannot clearly be identified as type 1 or type 2 (above) and are merely 1-10 cm wide fractures infilled by fissile silt and remobilized

TABLE I
Orientation of Planar Deformation Structures in Sediment at B81-1

Station	Dip Direction and Amount	Association with Deformation Structure
1.	175° at 75°	planar side of fluidization pipe
2.	040° at 80°	planar side of fluidization pipe
3.	245° at 85°	planar side of fluidization pipe
4.	245° at 80°	planar side of fluidization pipe
5.	200° at 50°	planar contact between fluidization pipe and deformed layers
6.	345° at 60°	minor joint along silt extrusion
7.	360° at 60°	minor joint along silt extrusion
8.	360° at 30°	minor joint along silt extrusion
9.	350° at 42°	minor joint along silt extrusion
10.	235° at 65°	planar contact between silt extrusion and deformed layers
11.	210° at 45°	minor joint infilled by sand
12.	225° at 87°	planar surface along major fluidization pipe
13.	340° at 82°	minor joint infilled with sand
14.	200° at 65°	minor joint infilled with sand
15.	230° at 50°	joint infilling extending from fluidization pipe
16.	235° at 85°	planar surface along major fluidization pipe
17.	360° at 60°	slickensides on planar contact of silt extrusion
18.	145° at 75°	slickensides on normal fault in contact with silt
19.	160° at 25°	minor joint extending from axis of deformed layers
20.	145° at 45°	planar surface separating silt extrusion from upward-curving deformed layers
21.	035° at 80°	major normal fault infilled with sand
22.	220° at 80°	minor joint infilled with sand
23.	320° at 80°	minor joint infilled with sand
24.	135° at 65°	minor joint infilled with sand
25.	240° at 78°	minor joint infilled with sand
26.	220° at 80°	minor joint infilled with sand
27.	050° at 82°	major joint infilled with sand
28.	060° at 74°	minor joint infilled with sand
29.	240° at 80°	minor joint infilled with sand
30.	040° at 82°	minor joint infilled with sand
31.	050° at 78°	minor joint infilled with sand
32.	060° at 76°	major normal fault infilled with sand
33.	040° at 70°	major normal fault infilled with sand
34.	220° at 58°	major normal fault infilled with sand
35.	035° at 52°	major normal fault infilled with sand
36.	220° at 60°	major normal fault infilled with sand
37.	040° at 56°	major normal fault infilled with sand
38.	025° at 75°	minor joint infilled with sand
39.	090° at 78°	minor joint infilled with sand
40.	250° at 80°	minor joint infilled with sand

sediments (Fig. 9). The larger wedge-shaped structures typically contain a mixture of reworked sediment including exotic lithologies and clasts with parallel striations. Within the glaciogenic injections clast abundance increases upward and the infilling either merges into the till or forms an erosional contact with it (Fig. 8). Similar infilled-fractures have been noted in bed-

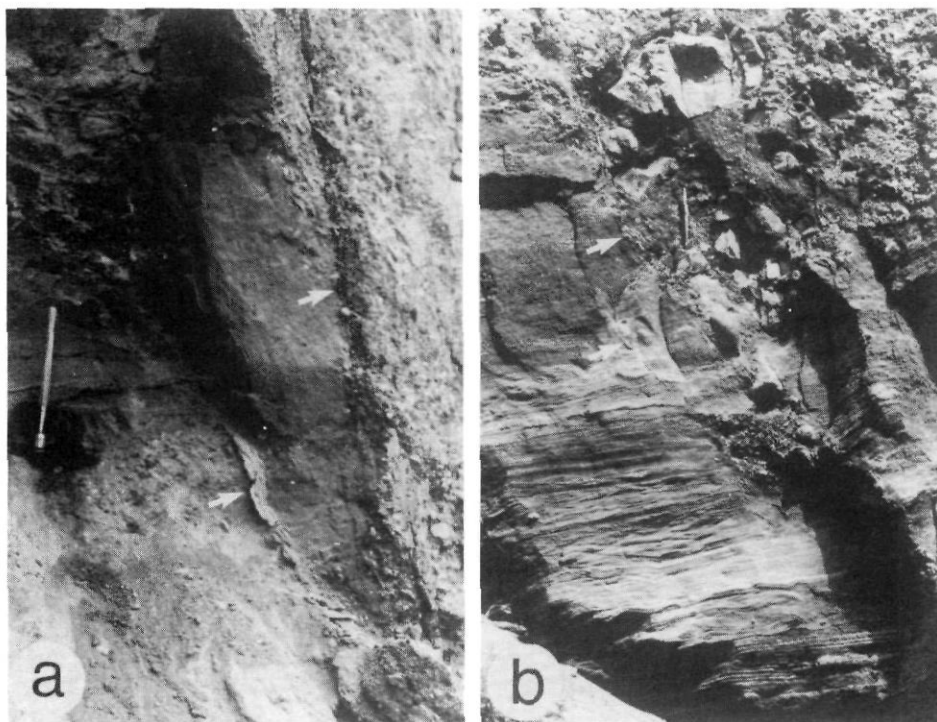


FIGURE 6. Clastic dikes formed by injection of remobilized sediments along fracture systems at (a) 36 m and (b) 58 m along section B81-1. Note the sharp planar contacts along fractures and dikes denoted by arrows.

Filons clastiques formés par injection de sédiments remobilisés le long des réseaux de fractures à 36 m (a) et à 58 m (b) le long de la coupe B81-1. À noter les contacts plans nets le long des fractures et des filons indiqués par les flèches.

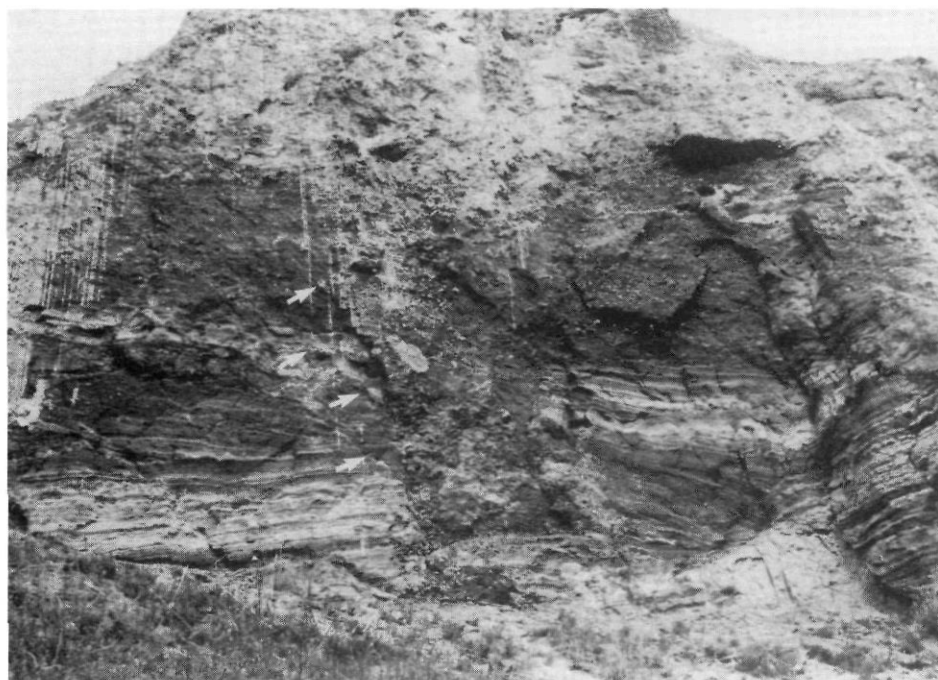


FIGURE 7. Oblique view of large clastic dike at 28 m along section B81-1, believed to be the result of catastrophic expulsion of pore water. Arrows denote infilled fractures tapering outward from the main zone of fluidization. At the base of the section the dike is approximately 2.5 m wide.

Vue oblique d'un important filon clastique à 28 m le long de la coupe B81-1, que l'on croit être le résultat d'une expulsion catastrophique d'eau interstitielle. La flèche montre des fractures remplies s'effilant vers l'extérieur à partir de la zone principale de fluidification. À la base de la coupe, le filon mesure environ 2,5 m de largeur.

rock (Broster *et al.* 1979) and sediment (Hicock and Dreimanis, 1985; Broster and Clague, 1987) and attributed to the injection of water-saturated silt along fracture systems during glacial overriding. Such fillings are considered to represent an early stage in the development of larger wedge-shaped glaciogenic injection structures (Broster *et al.*, 1979), although in the sediments exposed at Hat Creek injection is commonly associated with fluidization along the fracture system (Fig. 8a).

The hydraulic expulsions were commonly found as vertical pipes, indicating vertical expulsion in response to applied

stress. The largest clastic dike (Fig. 7) is delineated by a 14 m high zone of deformation concentrated over an area 2-2.5 m wide. The structure terminates at the base of the overlying lodgement till and extends downward below the covering of slumped material. Bedding in the surrounding sediments is displaced by approximately 30 cm across the dike. The dike comprises a mixture of sand and gravel with clasts of laminated glaciolacustrine material the size of small boulders. The absence of these sediments at higher elevations imply that the clasts may have been lifted from below. The dike forms a dis-

FIGURE 8. Wedge-shaped clastic dikes occurring along section B81-1. The structure at 116 m (a) is in contact with overlying till (base of till defined by arrows) and striated clasts appear to have settled into a zone of remobilized sediment. Material within the structure at 130 m (b) merges with overlying till and becomes finer grained towards the tapered edges (arrow).

Filons clastiques le long de la coupe B81-1. La structure à 116 m (a) est en contact avec le till sus-jacent (base du till soulignée par les flèches) et les fragments striés semblent avoir été déposés dans une zone de sédiments remobilisés. Le matériau à l'intérieur de la structure à 130 m (b) se mélange au till sus-jacent et devient plus fin vers les bouts resserrés (flèche).

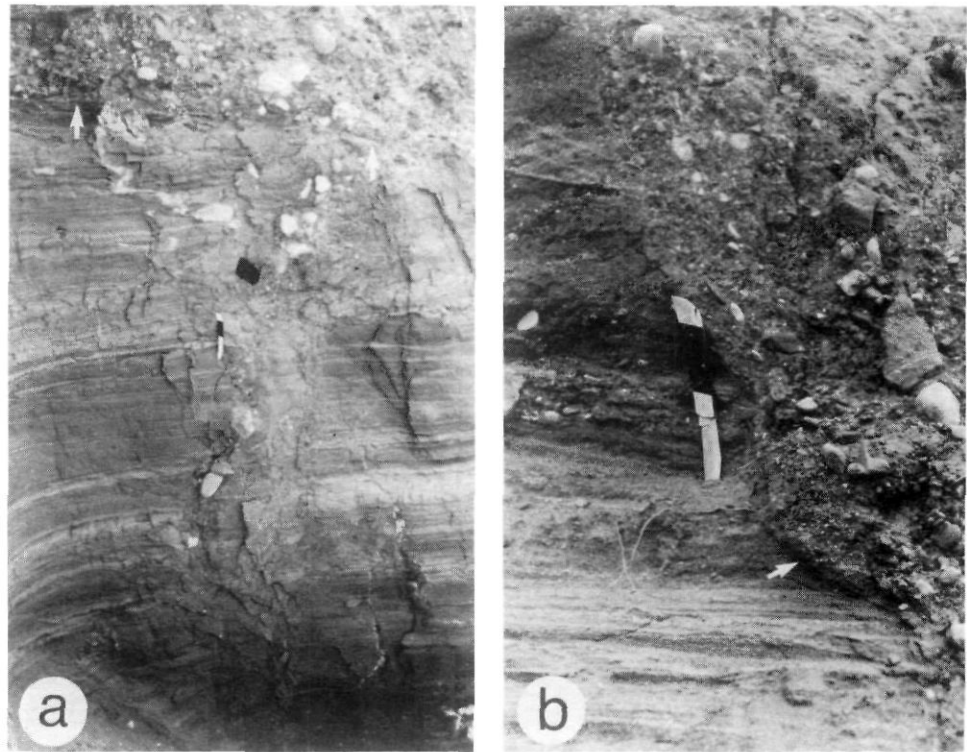
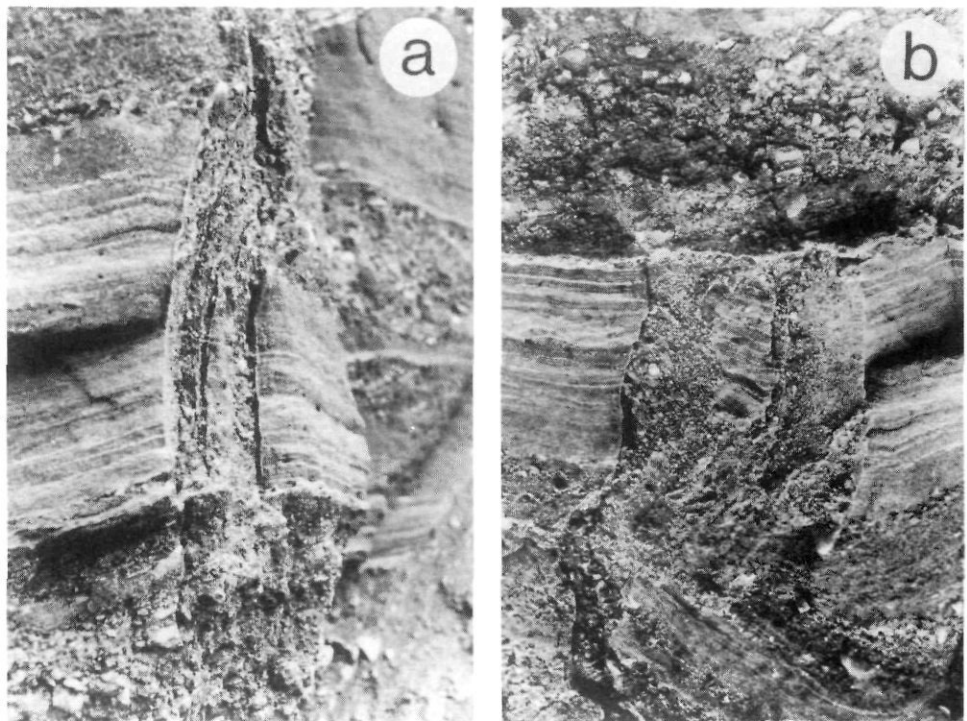


FIGURE 9. Minor fracture fillings found at 37 m (a) and 62 m (b) along the section at B81-1. Portions of the surrounding unit can be seen as clasts within the fracture filling; a thin coating of silt occurs along the sides of both fractures and across the top of (b). The width of the infilling in (a) is 7 cm and in (b) is 16 cm.

Remplissage de fractures mineures à 37 m (a) et à 62 m (b) le long de la coupe B81-1. Certaines parties de l'unité environnante ressemblent aux constituants trouvés à l'intérieur du remplissage des fractures; une mince couche de silt apparaît de chaque côté des deux fractures et à travers la partie supérieure de (b). La largeur du remplissage est de 7 cm en (a) et de 16 cm en (b).



tinct but irregular contact with the surrounding sediments, suggestive of fluid intrusion along fractures, bedding planes (Fig. 7) and into more permeable lenses at the contact. Brecciated and resedimented fracture-fillings taper upward and away from the main part of the dike, indicating that they were formed by forceful penetration of the surrounding materials during formation of the dike. The lack of striated clasts within the dike, and the

occurrence of fragments of glaciolacustrine material that appear to have been raised 0.5-1.0 m above the top of the glaciolacustrine unit, indicate expulsion from below. The hydraulic expulsions resemble structures of tectonic origin but their termination at the base of the till unit indicates formation during or prior to glaciation.

At several locations along the section hydraulic expulsions occur that are closely associated with both brittle and plastic deformation (Figs. 10a, b, c). This is best shown at station 20 along the section (Figs. 10b, c) where a normal fault displaces the lower waterlain sediments. Upward curving stratification adjacent to the fault give the false impression of thrust movement towards 325° . At the base of the exposure the fault borders a wedge of remobilized silt, suggestive of fluidization of the silt and its upward extrusion along the fault. The wedge of silt terminates at the upturned layers and extrusion of the silt along the (normal) fracture striking 055° and dipping to 145°

(Figs. 10b,c) was probably responsible for deformation of the layers. The appearance of curvature is due to shear along several minor faults (Fig. 10c) dipping towards the silt extrusion. Similar styles of deformation occur at stations 10 and 18 along the section (Fig. 4) and indicate a common association of deformation with fluidization, brittle and plastic failure of the waterlain sediments. Generally, the orientations of the structures were found to cluster around two directions of glacial movement, 140° and 045° (Fig. 11), with the latter bearing being the most common.

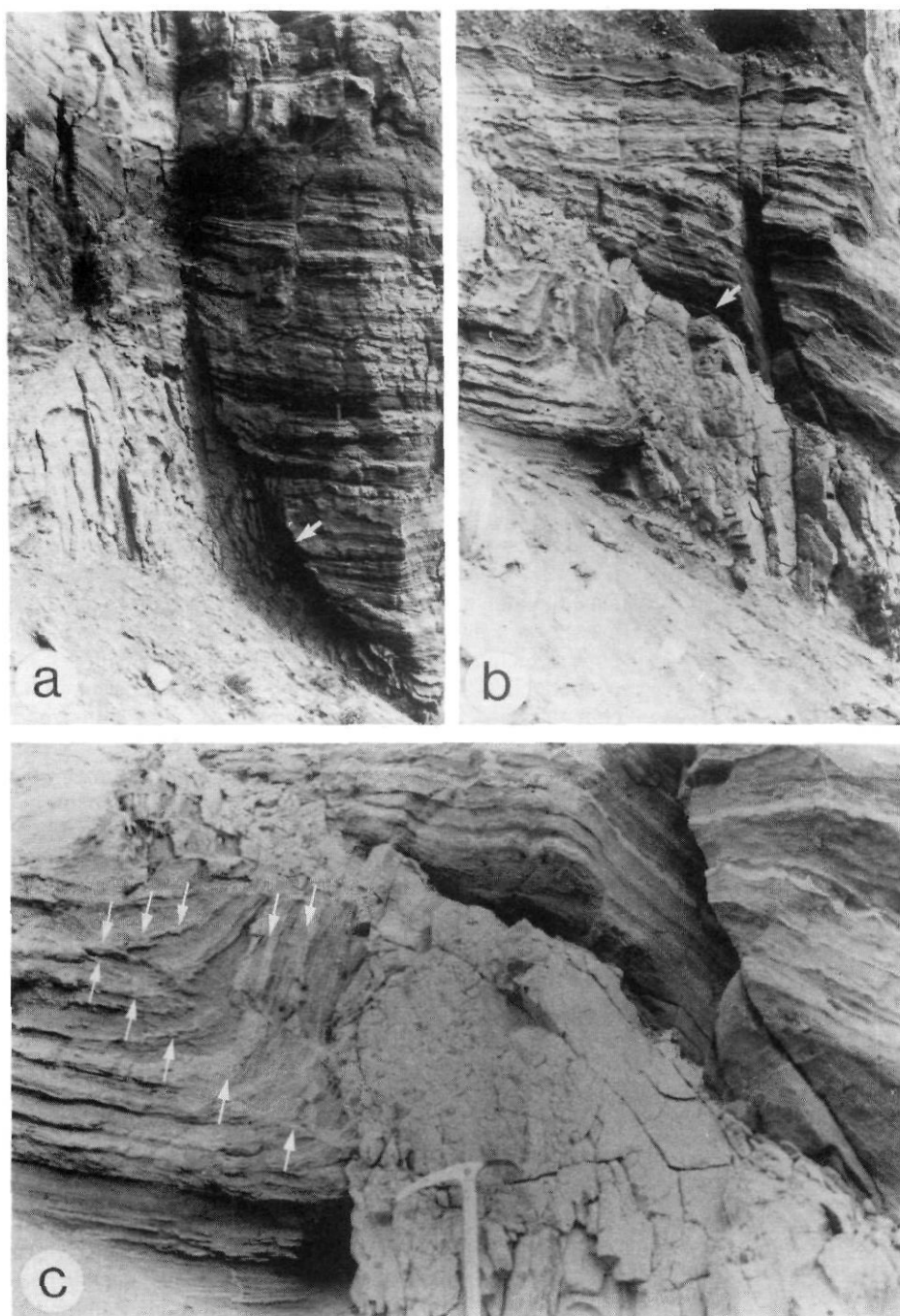


FIGURE 10. Silt diapirs adjacent to normal faults (arrows) at 22 m (a) and (b) 72 m along section B81-1; (c) is a closer view of a set of small fractures (arrows) produced by the displacement of layered sediments during silt extrusion at 72 m.

Diapirs de silt adjacents aux failles normales (flèches) à 22 m (a) et à 72 m (b) le long de la coupe B81-1; (c) offre un gros plan d'un ensemble de petites fractures (flèches) produites par le rejet de sédiments lités pendant l'extrusion du silt à 72 m.

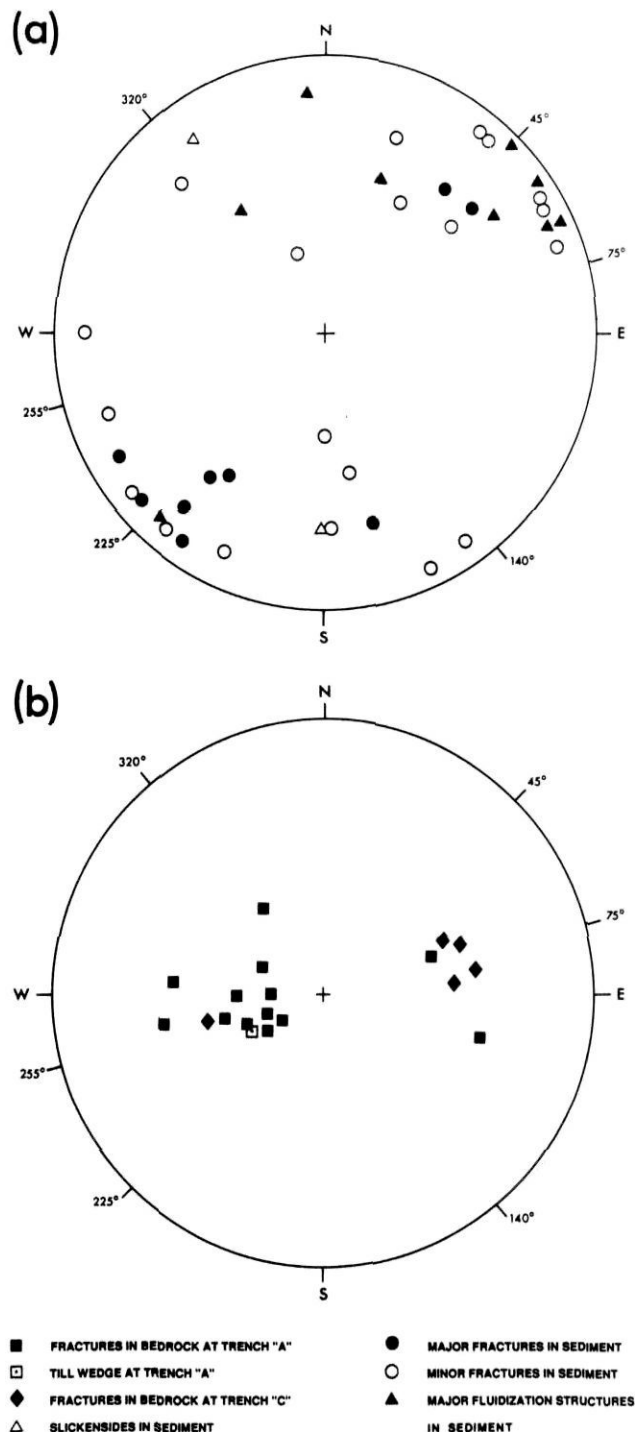


FIGURE 11. Poles of fractures (faults and joints) in sediment (a) and bedrock (b) plotted on lower hemisphere projection. Minor fractures have infillings less than 1 cm wide or lengths less than 3 m. Bearings relate to major ice-flow directions as determined by local striae and fabric measurements.

Projection sur l'hémisphère sud des pôles des fractures (failles et fissures) dans les sédiments (a) et dans la roche en place (b). Le remplissage des fractures mineures a moins de 1 cm de largeur ou moins de 3 m de longueur. Les orientations correspondent aux directions principales de l'écoulement glaciaire telles que déterminées par les stries locales et les fabriques.

DEFORMATION STRUCTURES IN BEDROCK

Deformation of bedrock was studied in trenches A and C (Fig. 2). The trenches occur to the south of a large landslide trending towards 030° (Fig. 2) delineated by obvious surface deformation (e.g. open fractures, disturbed terrain, tilted vegetation). Examination of surficial materials in bedrock trenches A and C found open fractures and slickensides attributed to the landslide suggesting that a much larger volume of sediment has been effected by this movement than is apparent at ground level.

Trench A is the largest excavation, over 300 m long and about 100 m wide. The trench is oriented E-W with the east side open, and is approximately 12 m deep midway along the excavation. Bedrock is exposed along the trench walls (Fig. 12), overlain by a less than 2 m cover of loose diamicton. Open fractures in the surficial materials, mixing and incorporation of underlying rock occurs in the upper 5-6 m of the west wall of the trench. These features were confined to the west wall and are attributed to deformation associated with the landslide (Fig. 2).

Claystone of the Coldwater Formation is exposed along the west wall. Coal of the Hat Creek Formation overlies the claystone and comprises the western third of the trench. The coal grades eastward into an overlying burnt coal zone which is exposed along the remaining part of the trench. The burnt zone is friable rock of contorted and steeply dipping layers, coloured in alternating shades of white, yellow, orange and red. The distinctive colouration enables easy recognition of younger structures in the unit.

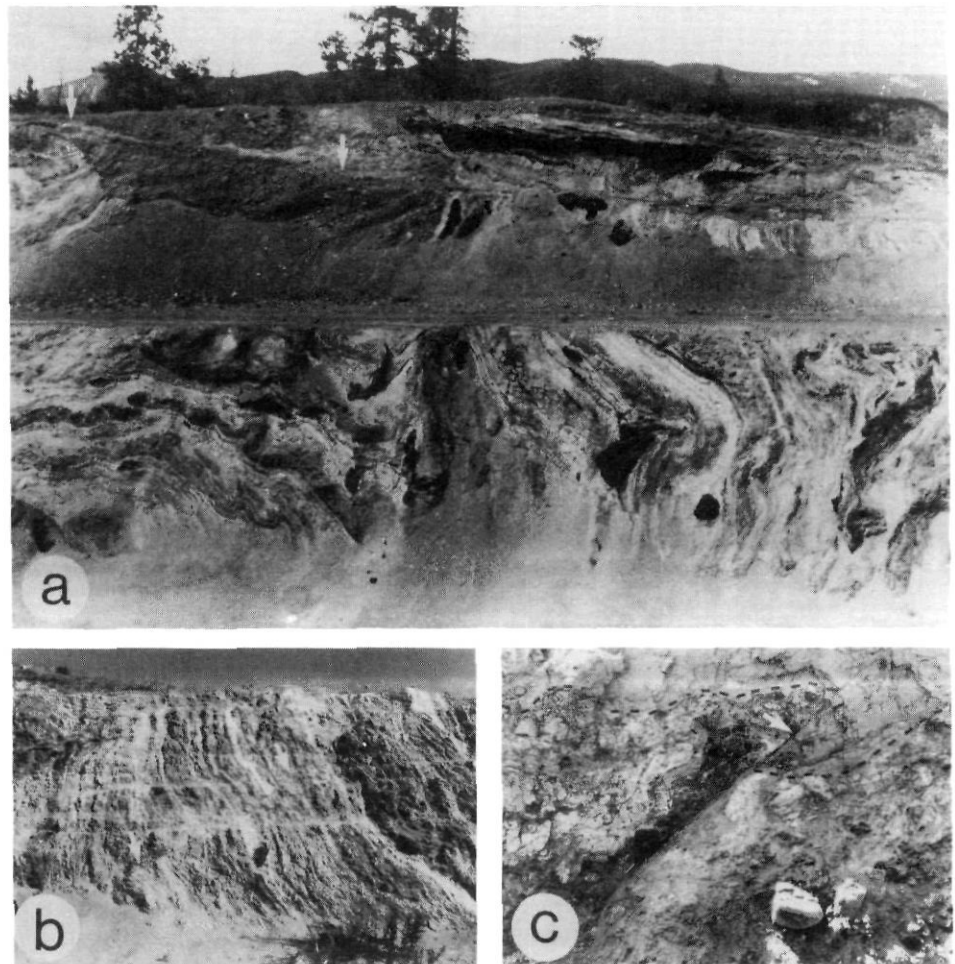
The largest deformation structure is an overthrust located along the top of the exposure at the eastern end of trench A (Fig. 12a). Here a wedge of burnt zone material containing a river channel forms a detached block ranging from 0.5-3.0 m thick, over a distance of approximately 20 m. The block has been detached and moved over bedrock containing another river channel (Fig. 12a), resulting in the superposition of two channels separated by sheared and attenuated "burnt zone" rock delineating the base of the detachment plane. Cross-stratification can be distinguished in the lower channel, while sediment in the upper channel appears chaotic, probably due to movement of the block. Both channels have been cut into burnt zone material and were probably part of the same meandering river. This unusual situation occurs on both sides of the trench, although more obvious in the northern exposure, indicating that the detachment block is at least 100 m wide.

In the northern exposure movement of the detached block has occurred over a 30 cm zone of fracturing. A major fracture plane has an apparent dip of 15° towards 060°, but has been cut and displaced by younger fractures. Slickensides parallel to 020°-035° suggest that the younger fractures are the result of recent mass-movements towards that direction. In the southern exposure movement has occurred along distinct normal faults dipping towards 030°, 070°, 090° and 115° (Fig. 11).

Faults occur throughout the burnt zone forming curving shear planes (Fig. 12b) striking 145°-205° and dipping both eastward and westward from 15°-65° (Fig. 11). Silt has been injected along some of the faults as part of the deformation

FIGURE 12. Deformation at trench A, showing (a) displaced portion of bedrock on the north face containing an abandoned river channel and separated from underlying channel-fill by a shear plane (between the arrows). The excavation exposes contorted and folded bedrock of the 'burnt zone' in an upper and lower face. The upper face is approximately 2.5 m high; (b) shows a reversed fault on the north face of the lower excavation (arrows), and (c) a wedge-shaped diamicton-filled injection (arrow) in the upper excavation on the south face.

Déformations dans la tranchée A, montrant (a) une partie décalée de la roche en place sur la face nord comportant un chenal abandonné et séparé du chenal remblayé sous-jacent par un plan de cisaillement (entre les flèches). L'excavation montre la roche en place déformée et plissée de la zone de charbon dans ses faces supérieure et inférieure. La face supérieure mesure environ 2,5 m de hauteur; (b) montre une faille inverse sur la face nord de l'excavation inférieure (flèches) et (c) une forme d'injection (flèche) en coin et remplie par un diamicton dans l'excavation supérieure de la face sud.



process. At the eastern end of the southern wall, silty diamicton has been injected along a fault forming a wedge dipping at 35° towards 065° (Fig. 12c). Striated clasts were found in the uppermost part of the injection wedge, 1-2 m below the till-bedrock contact, and other silt-filled fractures were traced to lengths of 10 m.

Trench C is located approximately 300 m west of trench A (Fig. 2). Trench C is about 100 m long, 50 m wide and oriented NE-SW, with the northeastern end open. The trench is about 20 m deep at its deepest point. Evidence of deformation due to recent mass movement is pervasive throughout the upper 6-8 m along the length of the trench (Fig. 13).

Along the southern wall, till is exposed in the lower 4 m and is continually being covered by slumped debris (Fig. 13). The till contains moderate striated and exotic clasts (predominantly oriented east-west) and is more clayey than found elsewhere, probably due to the incorporation of underlying bentonitic claystone. Coal and deformed slabs of claystone have apparently been sheared upward along curving shear surfaces, dipping towards 240° and 250° and incorporated within the till. Slide debris, comprised of silt and deformed claystone, overlies the till and forms most of the upper part of the section (Fig. 13). Faults and thrusts occur throughout the slide debris. Prominent slickensides, measured along a fault exposed in the north face, indicate movement toward 030° . This orientation agrees with

the general direction of movement involved in landsliding immediately north of trench C (Fig. 2). Therefore, it is likely that massive deformation of the upper part of trench C is the result of this postglacial mass movement.

DISCUSSION

Three main types of deformation were recognized in the study area: (1) fracture, (2) dikes formed by hydraulic expulsion or glacial injection, and (3) block detachment. However, the detachment block cannot be attributed exclusively to glaciation (as discussed later) and some faulting in sediment and bedrock is related to recent landsliding. Other structures examined are interpreted to be glacitectonic in origin because of their association with glacial deposits and orientation with inferred directions of glacial movement (Fig. 11).

The term glacitectonic is used to denote that type of glacial deformation related to the dynamic influence of glacial push or overriding (Broster and Clague, 1987: 1423). The occurrence of glacitectonic deformation structures similar to those examined here has been discussed by several authors (Kupsch, 1962; Lundqvist, 1967; Dreimanis, 1969; Moran, 1971; Banham, 1975; Dionne and Shilts, 1974; Broster *et al.*, 1979; Hicock and Dreimanis, 1985). Ice-marginal permafrost conditions (Mathews and Mackay, 1960) or basal freezing at the terminal zone of a glacier (Dreimanis, 1976), is commonly

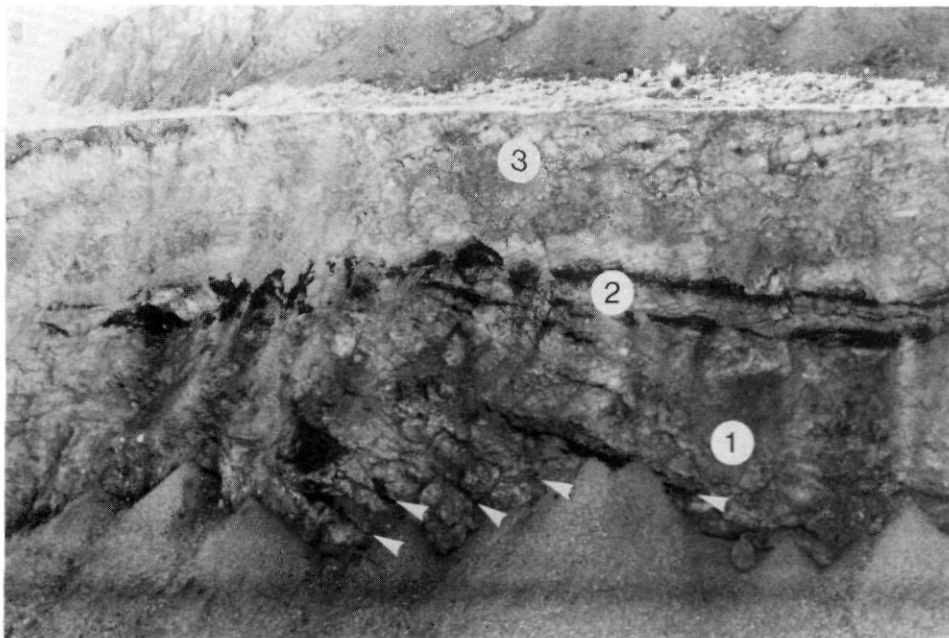


FIGURE 13. The southern face of trench C showing upward curving glacially-sheared claystone and coal (arrows) in diamicton (1) underlying pronounced subhorizontal shear surfaces (2) at the base of slide debris (3).

La face sud de la tranchée C montrant de l'argile indurée et du charbon (flèches) à cisaillement glaciaire courbés vers le haut dans le diamicton (1) sus-jacent à des surfaces subhorizontales de cisaillement bien marquées (2) situées à la base de matériel d'éboulis (3).

invoked to explain the origin of these structures. Disagreement exists as to the exact mechanism of formation, but there seems to be a general consensus in the literature that glacitectonic structures are recognized by the following evidence: (a) a close association with glacial deposits, (b) formation in an ice-marginal environment, and (c) a structural orientation relating to applied or relaxed stresses parallel with local direction of glacial movement (Broster *et al.*, 1979; Broster and Clague, 1987).

Tensile deformation by grounded ice is indicated by normal faulting, diamicton-filled glacial injections and hydraulic expulsions mainly oriented dipping northeast and southwest (Fig. 11a). This direction of glacial movement is indicated by the lowest till fabric from trench KLST-2, a near-surface fabric at site B84-4 and occurs as a minor mode in other fabrics (Fig. 5). Some of the minor fractures are indicative of stresses trending northwest-southeast. Both directions are inferred to be related to early arrival of coalescing glaciers although, eastward and southeastward flow later became the dominant directions.

The occurrence of interbedded till and waterlain sediments at the base of the surface till sheet at some locations in the study area indicates that the ice probably advanced into an environment with some areas of local ponding. Glaciolacustrine conditions probably existed during the early stages of the advance due to ice-blockage of drainage outlets to the northeast and northwest. Ryder (1976) has identified a major spillway to the south at around 1200 m that may have been the exit for the proglacial meltwater (Fig. 2). Glaciofluvial conditions probably became prevalent with advancing ice and the valley sediments likely retained high porewater content. This type of environment is not favourable for the development of basal freezing or permafrost (Dionne and Shilts, 1974) although, Von Brunn and Talbot (1986) have suggested that dike formation by grounded ice is still possible under certain conditions.

Elson (1975) and Worsley (1975) argued that, for any environment, brittle failure produced by subglacial freezing is incompatible with explanations involving thawing to allow infilling of subglacial cavities by meltwater or saturated diamicton along the ice-substrate surface. Conditions where freezing and thawing might occur in close juxtaposition would be areas subject to temperature fluctuations. Briggs *et al.* (1989) notes that in some areas, delicate preglacial features might be preserved at interfluvies surrounded by regions of faster-moving ice and higher ice temperatures. Such subglacial environments could arise from differences in valley topography where features at higher elevations might be preserved due to thinner, colder and slower moving ice in that area (Briggs *et al.*, 1989: 410). In areas of extending flow, basal warming could occur by the penetration of surface meltwater down crevasses or basal cooling might result from either the escape of meltwater or the downward movement of cooler ice if surface temperatures were much colder than at the base. In the terminal zone of a glacier undergoing compressive flow, basal melting may occur as sporadic seasonal events. However, in subglacial environments, the terminal zone is generally considered to be a zone of cold-based glacier ice and ice-marginal permafrost conditions (Dreimanis, 1976).

A southwestward flowing glacier lobe could have initially experienced extending flow conditions due to proglacial ponding. However, compressional flow conditions would have eventually developed in consequence of topographic confinement or interaction with other lobes.

The clustering of fault orientations in bedrock (Fig. 11b) supports the interpretation of glacial compression oriented east-west. An eastward-flowing glacier lobe would have experienced extending flow conditions in the area of the trenches if this lobe advanced into the valley off higher ground. However, it is possible that ice in the western part of the valley was initially

confined by a glacier flowing out of the northeast. In this event compressive flow conditions would have occurred in eastward flowing ice in the area of the trenches. Considering also that the elevation of the trenches is above that of the lacustrine sediments and was therefore possibly above lake level, basal freezing or ice-marginal permafrost could have contributed to the development of faults, dikes and shearing in bedrock at trenches A and C.

At section B81-1 faulting and dike development probably occurred in unfrozen sediment, although, the evidence of brittle fracture indicates that the beds must have been relatively coherent during brecciation. This interpretation supports an earlier speculation by Dionne and Shilts (1974) who suggested that freezing might not be required to form tension cracks in unconsolidated sediments under stress from an overriding glacier. Another process, not involving frozen ground, is presented by Pitts (1983:144) who concluded that faulting occurred in glaciogenic sediments as a result of sediment loading of confined groundwater which generated high porewater pressures and increased effective shearing stresses locally. This mechanism could explain faults and clastic dikes that do not show any orientation with direction of glacial movement. However, it is difficult to envision such a loading mechanism producing fault orientations specifically related to the direction of glacial movement, as inferred by till fabrics, without flow direction influencing the development of oriented structures.

Dreimanis (1969) has proposed that glacial drag could produce oriented 'friction cracks' and it is a reasonable assumption that overriding by glacial ice would apply a directional component to applied shear stress as the glacier advanced. Thus, glacial loading of sediments, accompanied by subglacial drag during overriding of grounded ice, would have produced differential compaction in the various subsurface layers and development of high porewater pressures in these sediments. This could have produced a stress gradient parallel to movement direction and is, therefore, a plausible mechanism for the development of oriented deformation structures at section B81-1.

MECHANISMS OF DEFORMATION

It is likely that ice advance over the waterlain sediments resulted in overconsolidation of some layers (Mathews and Mackay, 1960), particularly the fine-grained layers, while pore pressures were increased in all units. Such conditions would have forced contained water through permeable layers and along any existing or developing conduits. Rutten (1960) and Boulton (1972) have suggested that glacial advance over saturated sediments would produce an hydraulic gradient directing groundwater flow towards the ice margin (parallel to ice-flow direction). Considering the variability of individual beds within the waterlain sediments as Hat Creek, some porewater could have become trapped within discontinuous layers, forming confined aquifers. The loading of sediments at section B81-1 probably generated pore pressures of sufficient magnitude to penetrate overlying, less-permeable, confining layers at points of weakness or along fractures. Some fractures may have developed because of elevated pore pressure as the initial stage in the formation of hydraulic structures, that could vary in size depending on the volume of water released and the rapidity of the event. For some expulsions, fractures could have

been developed by drag (Dreimanis, 1969) or loading fluctuations (Broster *et al.*, 1979) at the glacier sole. In either case, fractures intersecting confined aquifers could have resulted in the sudden discharge of confined groundwater into the fracture system (Fig. 14); this mode of origin is indicated by some structures (Fig. 8a).

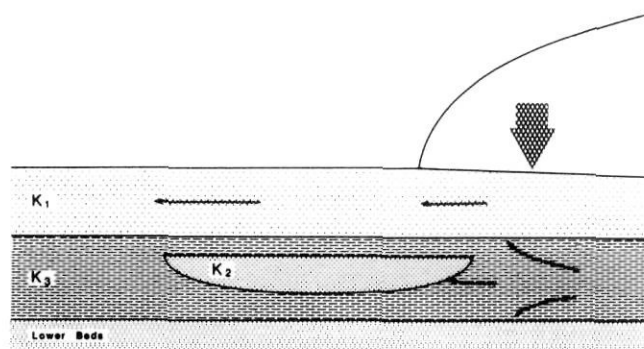
The expulsion of pore-fluids could result in fluidization of the surrounding sediment, in some cases reducing strength and allowing large clasts to sink to more competent levels within the zone of fluid escape (Fig. 8). Fluid escape may have resulted in collapse of overlying till into an underlying fluidized zone, producing oriented till-wedge structures if fluidization was controlled by fracture orientation or direction of applied glaciogenic stresses. At some critical limit the discharge of fluid might mobilize less-compacted sediments while buoying or lifting fragments of highly compacted less-permeable sediment. The morphology of the hydraulic expulsion dikes at section B81-1 (Figs. 7, 10a,b) attest to an origin by fluidization from below as a result of increased hydrostatic pressure.

From the observations above it is possible to envisage a model (Fig. 14) involving expulsion of porewater from confined layers, consolidation and fracturing of subglacial sediments by overriding grounded ice. Accordingly, most deformation structures formed by expulsion would be related to initial overriding and compaction of saturated sediments, providing hydraulic conditions favoured release of porewater. A greater degree of stress would then be needed to generate subsequent expulsion structures since dewatering and compaction would increase shear strength of the sediments. This could explain the prominent northeast-southwest trend for the majority of large structures (Fig. 11), particularly if the first application of major stress was due to glacial advance from the northeast.

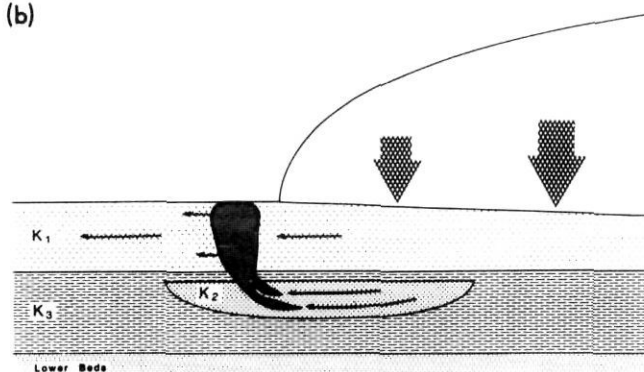
A different mechanism is proposed for development of the deformation structures in bedrock at trenches A and C. Several authors (Mathews and Mackay, 1960; Kupsch, 1962; Moran, 1971; Boulton, 1972; Banham, 1975; Moran *et al.*, 1980; Bluemle and Clayton, 1984) have suggested that under favourable conditions, advancing glacial ice could result in elevated porewater pressures at the glacier margin, that could lift and raft a section of bedrock for some distance. It would be unlikely that such a process could retain the integrity of the friable rock and channel infilling forming the detachment block, without it having been frozen during transport. Shearing of the block could have been facilitated by a hydraulic gradient and ice-marginal permafrost or a zone of freezing related to a cold-based terminal zone of an advancing glacier (Mackay and Mathews, 1964; Moran *et al.*, 1980; Weertman, 1961). However, slickensides on faults underlying the detachment block indicate that landsliding has caused some displacement. Thus, the origin of the block cannot be attributed exclusively to glacial action.

Since waterlain deposits were found only at elevations below the bedrock trenches, it is possible that basal freezing contributed to the development of the glaciogenic injections in trench A (*cf.* Broster *et al.*, 1979) and the faults and shears in both trenches A and C (*cf.* Dreimanis, 1976). The agreement in orientation of much of the deformations in trenches A and C, and also at section B81-1, with fabrics in basal till (Fig. 5),

(a)



(b)



(c)

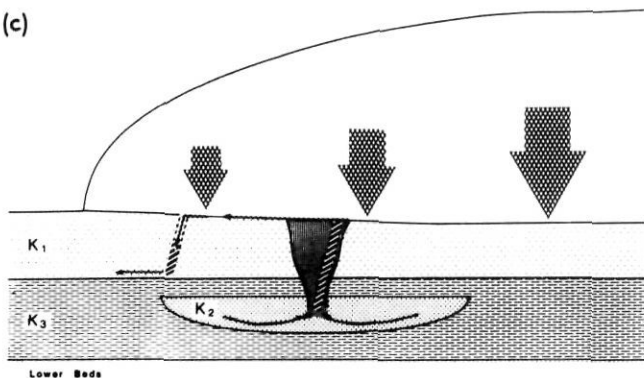


FIGURE 14. Model illustrating the increase in porewater pressure due to increase in load from advancing ice. As load is increased porewater is expelled from units with high conductivity (K1) but may be trapped in confined aquifers (K2) within less permeable units (K3). At some critical load, pore pressure may be sufficient to cause expulsion through a thin confining unit as in (b) or the confined aquifer may experience fracturing (c) resulting in catastrophic release and fluidization along the fracture system. Fluid may be free to exit the glacier margin or be injected into other fracture systems, depending upon hydraulic gradient and subglacial thermal conditions.

Modèle illustrant l'augmentation de la pression de l'eau interstitielle en raison de l'augmentation de la charge du glacier en marche. À mesure qu'augmente la charge, l'eau interstitielle est expulsée des unités à haute conductivité (K1), mais peut également demeurer prisonnière dans des aquifères restreintes (K2) à l'intérieur d'unités moins perméables (K3). Lorsque la charge devient critique, la pression interstitielle peut devenir suffisante pour entraîner l'expulsion au travers d'une unité restreinte comme en (b) ou pour fracturer l'aquifère (c) résultant en une décharge catastrophique et à la fluidification le long du système de fractures. Le fluide est alors évacué de la marge du glacier ou injecté dans d'autres systèmes de fractures, dépendant du gradient hydraulique ou des conditions thermiques subglaciaires.

is interpreted as indicating that deformation was associated with the different stages of glacial advance. Deformation in the sediments at B81-1 probably occurred at the ice-margin during extending flow into the Hat Creek Valley from the northeast. Deformation of bedrock at trenches A and C probably occurred at the ice margin of a confined glacier experiencing compressive flow. This was then followed by the establishment of regional southeastward and eastward flow patterns.

CONCLUSIONS

Deformation structures in rock and sediment studied as part of an earthquake engineering study at Hat Creek, British Columbia, are attributed to glacetectonic and landslide events rather than seismic causes. This conclusion is supported by the lack of postglacial fault-generated structures in sediments exposed during excavation overlying a known bedrock fault.

The study attests to the fundamental requirement for a thorough understanding of stratigraphic principles, depositional environments and glacial processes in similar investigations of deformation structures in glaciated areas of unknown seismic potential.

As a result of this study it is suggested that deformation structures can be attributed to glacial processes when displaying the following: a) an association with glacial deposits (e.g. termination at the base of overlying till); b) an infilling of glacially-derived sediment containing striated clasts; and, c) structural orientations consistent with local directions of glacial flow. At Hat Creek these data provided useful criteria for the recognition and timing of glacetectonic deformation, and should be beneficial to studies elsewhere.

The comparison of orientations of deformation structures with a vertical till fabric sequence is interpreted to indicate that glacial deformation continued throughout glaciation, with the majority of glacetectonic structures formed during the early stage. This implies that formation occurred in the terminal area while the glacier was thin and susceptible to variations in local relief. With continued advance, thicker parts of the glacier crossed the area or the ice thickened due to coalescing lobes. Subsequently, the glacier became less responsive to variations in local topography and regional flow patterns developed.

The majority of structures examined are interpreted to have been produced subglacially in sediments and bedrock by coalescing glaciers. In bedrock, faults and joints were likely developed under a glacier lobe experiencing compressive flow. Conversely, similar structures were developed in unfrozen sediments with elevated pore-water pressure under a grounded glacier possibly experiencing extending flow.

Glacial loading of a complex sequence of sediments varying in strengths and permeabilities and the resulting release of hydrostatic pressure from confined aquifers, is proposed as a viable mechanism for the formation of glacial hydraulic dikes. In this study the mechanism occurred in partially saturated sediments considered to be unfrozen. It is likely that the mechanism would be viable also in areas of intermittent permafrost (cf. Bluemle and Clayton, 1984). The results of the present study suggest that glacial hydraulic expulsions and

associated fractures will mainly be formed during initial compression of underlying sediments by an overriding glacier and that orientations of these structures will conform to this direction of glacial advance. These orientations are likely to be preserved even when younger deformation structures are produced by subsequent events.

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