

A SEQUENCE OF GLACIAL DEFORMATION, EROSION, AND DEPOSITION AT THE ICE-ROCK INTERFACE DURING THE LAST GLACIATION: CRANBROOK, BRITISH COLUMBIA, CANADA

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ABSTRACT. A comparison of bedrock fractures with orientation of structures and fabric in the overlying late Pleistocene basal till indicates a sequence of common glacial origin. The deformations in bedrock and till, and the deposition of the till layer, were accomplished by two glacial flows that were part of a mountain ice sheet: the regional (moving south-south-east) and the local (moving south-south-west) along Peavine Valley.

The following sequence of events is postulated from this investigation: the initial glacial advance from the north-north-west that produced conjugate low-angle shear fractures in the bedrock was followed by competition of both the regional and the Peavine Valley glacial flows which also produced low-angle fracture systems. As the over-riding ice became thicker, high-angle conjugate fractures were formed by both glacial flows. Subsequently, south-east-dipping injection wedges were formed by the regional ice, which was concurrently eroding the down-glacier parts of the wedged blocks, depositing local till, and producing sigmoidal deformations in this till. The main deposition of the overlying lodgement till was accomplished by an interaction of both the regional and the Peavine Valley glacial flows, and the lodgement was supplemented by shearing of the till, producing fissility. Bedrock wedging, as a significant process of glacial erosion, is believed to be discussed here for the first time.

RÉSUMÉ. Une séquence de déformation, d'érosion et dépôts glaciaires à l'interface glace-roche pendant la dernière glaciation; Cranbrook, Colombie Britannique, Canada. Une comparaison des failles du lit rocheux avec les orientations des structures et des grains dans la moraine de fond qui recouvre tout le Pléistocène récent, indique une séquence d'origine glaciaire ordinaire. Les déformations dans le lit rocheux et les moraines et le dépôt du niveau morainique ont été accomplis par deux écoulements glaciaires qui appartenaient à une calotte glaciaire de montagne: l'un régional (se mouvant Sud Sud-Est) et l'un local (se déplaçant Sud Sud-Ouest) le long de la Peavine Valley.

De ces investigations on déduit que la succession des événements a été la suivante: l'avance glaciaire initiale depuis le Nord Nord-Ouest qui produisit des cassures conjuguées au cisaillement sous un angle faible dans le lit rocheux fut suivie de la combinaison des courants de glace régionaux et du Peavine Valley qui produisit aussi des systèmes de cassures à angles faibles. Comme la glace surmontante devint plus épaisse, des cassures conjuguées à angles forts furent formées par les deux courants de glace. Par la suite, des coins d'injection s'enfonçant vers le Sud Est furent formés par la glace régionale qui érodait en même temps la partie aval des blocs en coin, déposait une moraine locale et produisait des déformations sigmoïdales dans cette moraine. La plus grande partie des dépôts de la moraine de couverture se fit par une interaction des écoulements des courants régionaux et du Peavine Valley et le dépôt fut complété par le cisaillement de la moraine, produisant un système de failles et une réorientation des grains sous-jacents. Le découpage en coins du lit rocheux est un processus significatif d'érosion glaciaire qui est décrit, croit-on, ici pour la première fois.

ZUSAMMENFASSUNG. Eine Abfolge glazialer Deformation, Erosion und Ablagerung an der Grenzfläche zwischen Eis und Fels während der letzten Eiszeit; Cranbrook, British Columbia, Kanada. Ein Vergleich von Bruchlinien im Felsuntergrund mit der Orientierung von Strukturen und Gefüge in der überlagernden spät-pleistozänen Grundmoräne deutet auf eine Abfolge gemeinsamen glazialen Ursprungs hin. Die Verformungen in Felsbett und Moräne sowie die Ablagerung der Grundmoräne gehen auf zwei Gletscherströme zurück, die Teil eines Inlandeises waren: dem regionalen, nach SSE fließenden, und den lokalen, nach SSW fließenden Strom längs des Peavine Valley.

Die Untersuchung lässt folgende Abfolge des Geschehens annehmen: Dem ursprünglichen Gletschervorstoß von NNW, der konjugierte, spitzwinklige Scherbrüche im Felsbett hervorrief, folgte ein Wettbewerb zwischen dem regionalen und dem Peavine-Gletscherstrom, der ebenfalls zu spitzwinkligen Bruchsystemen führte. Als das überfahrende Eis dicker wurde, erzeugten beide Gletscherströme stumpfwinklige konjugierte Brüche. In der Folge bildete das regionale Eis SE-gerichtete Injektionskeile aus, wobei die gletscherabwärts liegenden Teile der Keilblöcke erodiert, lokal moräne abgelagert und sigmoidale Verformungen in dieser Moräne erzeugt wurden. Die Hauptablagerung der überlagernden Moräne wurde durch eine Wechselwirkung zwischen beiden Gletscherströmen hervorgerufen. Die Ablagerung war mit einer Scherung der Moräne verbunden, die zur Bruchschieferung und Unmorientierung des Gefüges führte. Keilspaltung des Felsbettes als wesentlicher Vorgang der glazialen Erosion dürfte hier zum ersten Mal beschrieben sein.

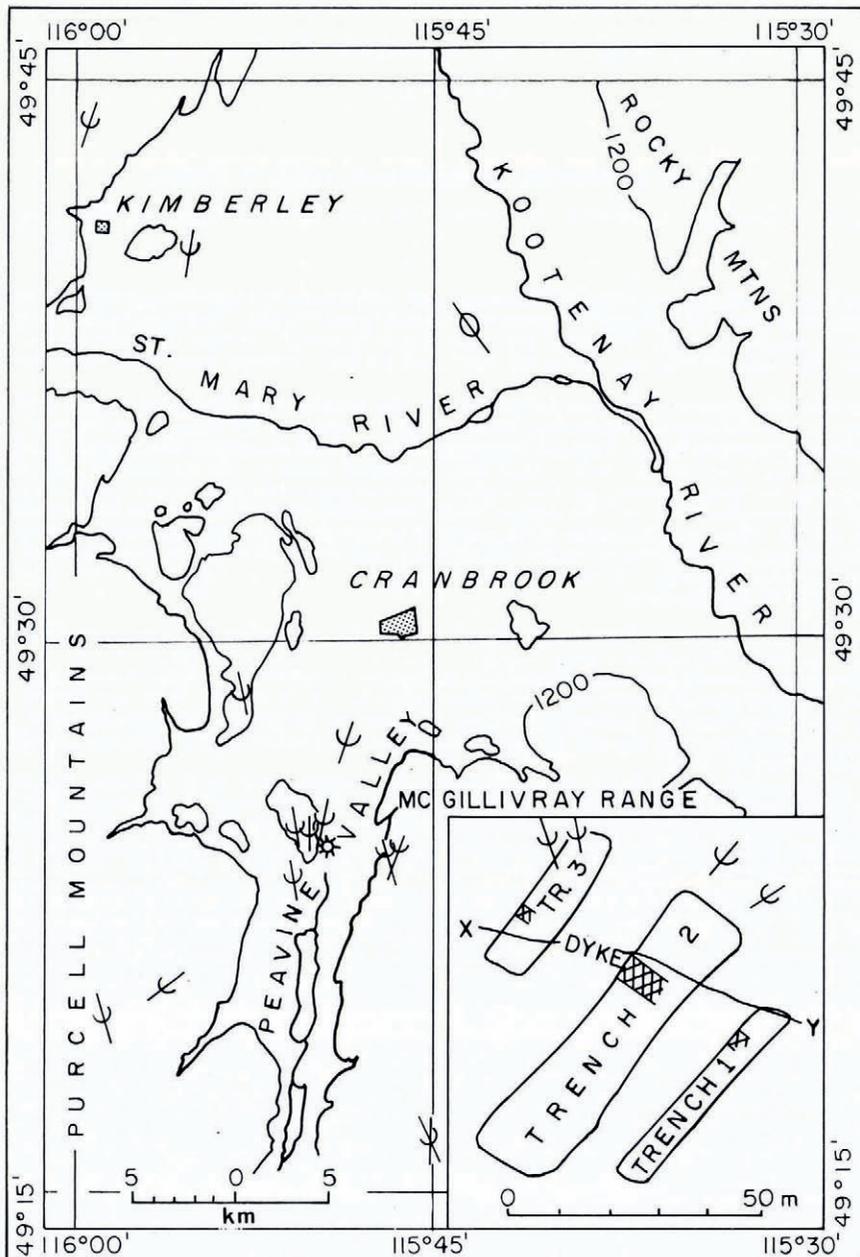


Fig. 1. Area map, with the location plan for the lower three trenches in the lower right corner. The contour line is approximately 1200 m above sea-level. The study area is indicated by an asterisk. Alignments of drumlins and striae are marked by standard symbols.

INTRODUCTION

This paper describes and discusses glacial deformations and fractures in bedrock south of Cranbrook, British Columbia (Fig. 1) and relates them to the glacial movements that have been deduced from fabric and deformations in the overlying basal till. From field observations and measurements, conclusions are drawn on the possible mechanisms of shearing, wedging, and erosion of the bedrock, and the contemporaneous and subsequent deposition and deformation of local and lodgement tills by two competing glacial flows: a regional south-south-eastward ice movement and a local, weaker south-westward movement along Peavine Valley.

GEOLOGICAL SETTING

The study area is situated along the eastern side of the Purcell Mountains at the western edge of the southern Rocky Mountains trench. The trench is a long inter-montane valley extending northward from Montana into British Columbia and is bounded by the Rocky Mountains on the east and the Purcell Mountains of the Columbia Mountains system on the west.

During the Pleistocene, the southern Rocky Mountains trench served as an outlet for the Cordilleran ice sheet, which had been formed by the coalescence of large valley and piedmont glaciers in the Rocky and Columbia Mountains (Clague, 1975). Observations of striae and other geomorphological features, along both sides of the southern region of the trench, indicate that maximum thickness of the ice sheet was about 1 600 m above the present trench floor (Daly, 1912; Monger and Preto, 1972; Clague, 1975).

A southward glacial movement dominated in this area with minor deviations caused by local valley systems. North of Cranbrook a significant split in glacial direction appears to have taken place. Drumlinized ground moraine and striae to the north-east indicate a south-eastward (140°) glacial movement roughly parallel to the Kootenay River. North-west of Cranbrook, however, the topographic features and striae indicate a south-south-westward ($190\text{--}200^\circ$) ice flow. In the area investigated, in addition to the regional direction of movement (170°), a local south-westward ($200\text{--}240^\circ$) movement was encountered along Peavine Creek Valley. This was caused by a localized glacial flow along the valley.

FIELD INVESTIGATIONS

As a result of geologic investigations by Cominco Ltd in 1977, seven trenches were excavated 12 km south-south-west of Cranbrook, at the eastern fringe of the Purcell Mountains, on the north-west side of Peavine Creek Valley (Fig. 1). The trenches were located at successively higher elevations along the valley side which slopes at $22\text{--}24^\circ$ towards 125° . The lowest one (No. 1) was at the valley floor, about 1 000 m above sea-level, the highest (No. 7) about 100 m above it. Seismic studies by Cominco Ltd have shown that here the valley floor is approximately 100 m above the bedrock and has been filled by unconsolidated sediments. The trenches were cut through 0.2–7 m of Quaternary deposits, mainly till and/or colluvium, into 1–3 m of bedrock, exposing up to 3 m of fractured and deformed quartzite. The nearly vertical trench walls were mapped in detail, using a mosaic of photographs as base maps. The strike and dip of about 600 fractures were measured in the bedrock and compared with the fabric measurements in the overlying till (Broster and Dreimanis, unpublished).

GENERAL DESCRIPTION OF TRENCH EXPOSURES

Bedrock—general

Trenches 1–3 were chosen for detailed study because they contained both bedrock and 2–7 m of till (Figs 2 and 3). The bedrock is Middle Aldridge siltstone, a fine-grained competent quartzite striking $35\text{--}40^\circ$ and dipping north-westward at 20° ; it contains a gabbro dyke striking 115° and dipping south-westward at 70° (Figs 1 and 3).

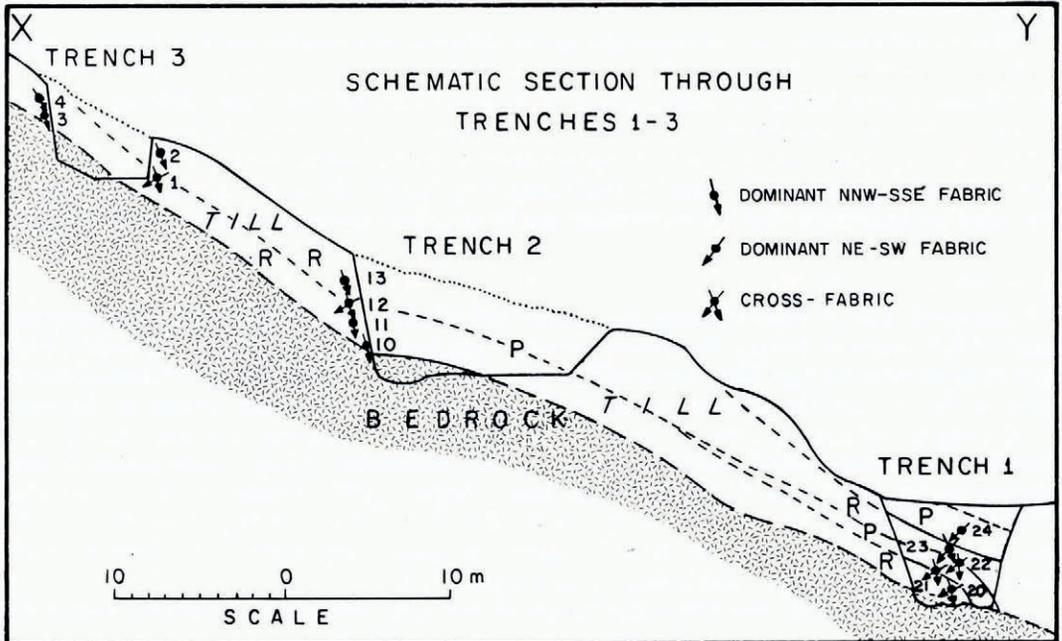


Fig. 2. Cross-section X-Y. P, Peavine Valley till or shear plane; R, till deposited by regional ice flow; 1-24, till sampling sites. For location see Figure 1.

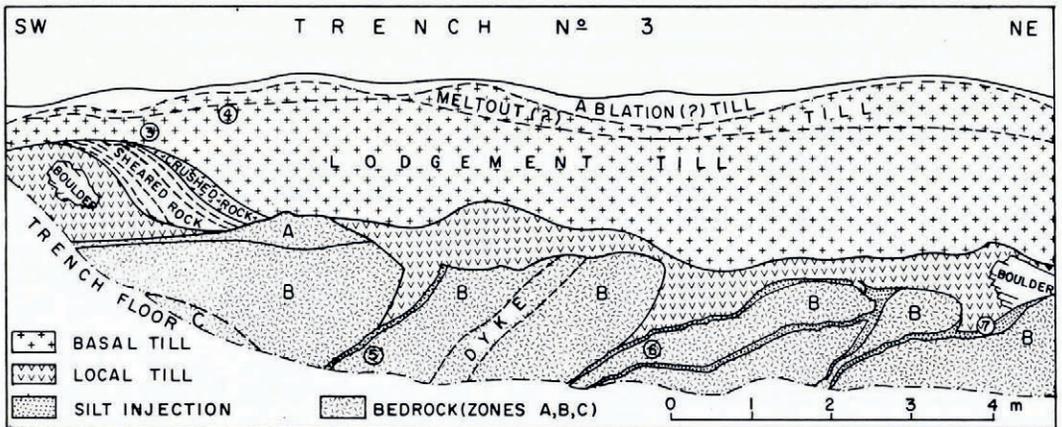


Fig. 3. Section along the western wall of trench 3. Numbers 3-7 are sample locations.

Weathering of the bedrock is seen only adjacent to the dyke and along those fractures which strike parallel to it. Fresh fractures which have not been cemented, and in some cases contain injected unconsolidated sediment, are abundant in the rest of the bedrock, but most of them are oriented differently from the dyke. The bedrock-till contact is distinct in the lower two trenches (1 and 2) but is less clearly defined in the upper trench (3). Here, the bedrock surface has been extensively fractured and also contains wedge-shaped injections (Fig. 3).

Bedrock zones

The upper part of the bedrock exposed in the trenches may be subdivided into three zones, A, B, and C, according to the degree of fracturing with downward decreasing intensity (Fig. 4). The uppermost zone A is generally about 10 cm thick and is characterized by a very high degree of fracturing; in trenches 1 and 2 the bedrock has been broken into small trapezoids less than 5 cm² in surface area. In trench 3 (Fig. 3), zone A is represented by an even finer crushed bedrock. These fragments appear to be aligned in a somewhat platy orientation sub-parallel to the bedding with silt and rock flour separating them. Slickenside-like polish and striations, in varying degrees of preservation, can be found on the surface of the rock fragments. The slickenside-like striae trend from north-north-west to south-south-east, parallel to the regional glacial movement, and are indicative of displacement. No other displacement parallel to the bedding planes is evident below this zone.



Fig. 4. Bedrock zones A, B and C in trench 2; A is overlain by lodgement till. The knife is 26 cm long.

The next deeper zone B is 1–2 m thick and moderately fractured, with horizontal fracture spacing usually about 5–50 cm. Occasional wedge-shaped injections of brecciated rock or sediment cut across this zone and even extend into the lower, still less fractured zone C. In zone C the injections are present but they taper off downwards and contain only silt-sized materials. The horizontal spacing of fractures varies from 0.5 to 1 m in zone C. Both zones B and C are present in all the trenches and grade into each other, while a distinct contact exists between zones A and B.

Fractures

Fracture orientations, and their relative abundance in the three bedrock zones, show that they belong to four groups. The first group of fractures, spaced at 2–50 cm intervals, is

sub-parallel to the bedding and may reflect the original bedding planes accentuated by stress relief (Leech, 1966) during and after deglaciation. They are present in all three zones A, B, and C. The second group is most abundant in bedrock zone C and least abundant in zone B. The majority of these fractures are parallel to the dyke, striking 115° , but some sets are random and unrelated to the orientation of the dyke or to glacial activity. Most fractures of this group are cut by fractures of the third and fourth groups.

The third group are those fractures which strike perpendicular to the direction of movement of the regional ice. These fractures are fresh with moderate infillings of fine sediment and occasional injections along southward-dipping fractures planes. This group consists of the most prominent and best-developed fractures in bedrock zone B and they are the second most abundant fractures in zone C. The wedges are related to this fracture group.

The fourth group are those fractures which strike perpendicular to the south-westward movement of the local Peavine Valley glacier. This group is the second most abundant in bedrock zone B and is the least abundant in zone C. Both third and fourth group fractures occur in conjugate sets which consist either of: (a) low-angle fractures dipping $5-20^{\circ}$ from the horizontal, or (b) high-angle fractures dipping $65-80^{\circ}$.

Injection wedges

Sediment-filled, wedge-shaped fractures can be found in all three trenches, striking 80° and dipping towards 170° . These are most clearly developed in trench 3 (Figs 3 and 5). Here the wedges are slightly curving. In section they are steeply dipping at their upper end ($45-70^{\circ}$), closest to the bedrock-till contact. The dip is generally less steep at their lower tapered end but varies depending on the orientation of the bedrock fractures that were encountered during formation of the wedges. The width of the wider upper end ranges from 4 cm to about 1 m. The maximum length of the wedges is unknown because many extend



Fig. 5. A wedge north of the dyke in the west wall of trench 3.

below the excavated floor of the trenches. One of them can be traced for more than 3 m along the exposure face before disappearing below the trench floor. The wedges are filled with debris (Table I, samples 5-7) ranging from clay to brecciated rock and a few contain till. The silt-rich parts of the wedges are mainly along their base, and they are laminated parallel to the rock wall. The wedges resemble similar structures which have been found in bedrock and unconsolidated sediments, and described by several authors, e.g. by Goldthwait and Kruger (1938) as clastic dike injections in bedrock, by Lundqvist (1967) as till dikes, and by Dreimanis ([1969]) as till wedges.

TABLE I. SELECTED ANALYTICAL DATA. SAMPLE LOCATIONS IN FIGURE 3

Station number	Material	Glacial flow	Texture of - 4 mm				Percentage carbonates in - 0.063 mm
			% granules	% sand	% silt	% clay	
3	Lodgement till	Regional (R)	4	49	46	2	1.5
4	Lodgement till	Regional (R)	7	61	32	0	1.5
5	Wedge filling	Regional (R)	11	29	50	10	0.5
6	Wedge filling	Regional (R)	24	28	43	5	1.0
7	Wedge filling	Regional (R)	12	46	38	4	1.5

The boundaries between granules-sand-silt-clay are 2 mm, 63 μ m, and 2 μ m, respectively.

TILL

The till overlying bedrock (Figs 3 and 4) consists of two sub-units: a local till (LcT) and a typical lodgement till (LgT), both stratigraphically comprising one till layer.

Local till

It is thickest in trench 3 (up to 1.5 m), consists mainly of fractured angular local bedrock fragments, in some parts of the section separated by fracture patterns similar to those of bedrock zone B. When viewed from a distance, these parts resemble bedrock rather than till. However, on closer examination, interstitial till material and silt are noticeable along the fractures, as well as the presence of distally derived clasts. At the south-western end of trench 3 (Fig. 3) a 2 m long strongly fractured and sheared slab constitutes most of the local till. The dominant fractures in this slab strike 80°, dip up-glacier, and have been deformed into a sigmoidal shape. Similar deformations can be found in small bedrock blocks incorporated in local till elsewhere in the trenches.

Lodgement till

In trenches 1 and 2, the bedrock is in sharp contact with typical lodgement till, while in trench 3 the lodgement till grades downward into local till, which overlies bedrock. The lodgement till consists mainly of sandy silt or silty sand and contains occasional pebble-rich zones. Well-developed fissility is present in some parts of the till, grading in places into shear planes, particularly in trench 1. The lodgement till consists of two alternating sub-units (Fig. 2), one of them (R) having been deposited by the regional glacial flow from north-north-west, and the other (P) by the local Peavine Valley glacier. These sub-units have been described in more detail by Broster and Dreimanis (unpublished), and the dominant alignment of till pebbles measured at 13 sites (Fig. 2) is included for clarity.

The alignment of pebbles has some common trends in the fabric diagrams. Most diagrams display well-developed bimodal or single maxima: (a) 160-170°, parallel to the regional glacial movement of the area, as recorded by striae (Fig. 1), and (b) 040-050°, parallel to the dip of the north-east, dipping fissility and shearing in the local Peavine Valley till (P) in trench 1.

DISCUSSION

Fractures F_1 - F_3

The principal compressive stress direction, τ_1 , is assumed to bisect the acute angle formed by conjugate shear planes (Price, 1966). Analysis of the shear fracture orientation in bedrock reveals several sets which show consistent relationships in time and space (Fig. 6). The earliest set of low-angle shear fractures (F_1) appears to have been initiated by a compressive stress plunging at 20° towards 170° . It is followed by the formation of two distinct sets of mutually cross-cutting low-angle conjugate fractures with principal compressive stresses plunging at 5 - 20° also towards 170° (F_2^R) and at 20 - 30° towards 210° (F_2^P). Succeeding these low-angle fractures are two sets (F_3^R and F_3^P) with τ_1 pointing in about the same directions as F_2^R and F_2^P , respectively, but plunging at 70 - 80° , resulting in high-angle, normal shear fractures. (The direction of the F_3^R points slightly more towards the south-east at 150° , rather than the 170° of F_2^R .)

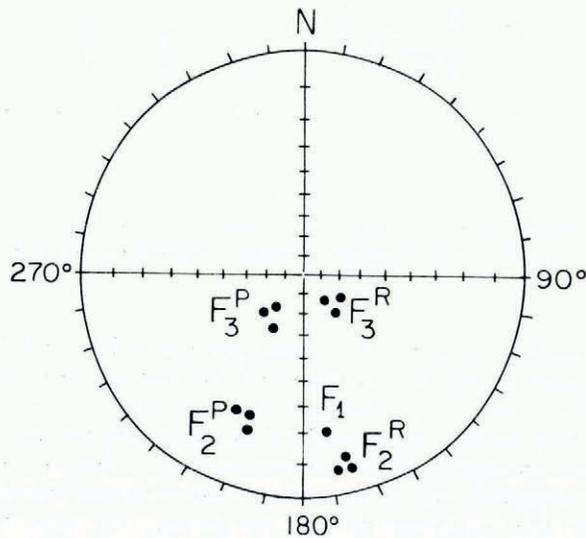


Fig. 6. Lower-hemisphere Lambert projection showing mean principal compressive stress directions τ_1 for conjugate fracture sets F_2 - F_3 in trenches 1-3. F_1 is the mean of all three trenches.

The principal compressive stress directions for F_1 - F_3 correspond to one or both of the directions of the two independently derived glacial movements: the regional (R) south- to south-eastward and the south-westward Peavine glacial flow (P) as deduced from striae and clast fabrics. Both of them are unrelated to the deeper bedrock fractures trending parallel to the mineralized dyke at 115° .

The early fractures (F_1 and F_2) are characteristically low-angle shears that imply low ratios of vertical stress to horizontal stress. In addition, the initial south-south-eastward stress is followed by two principal stress directions. This may be explained by the development of variable stress systems during the approach of the regional and Peavine Valley glaciers that created low-angle compressive stresses in the underlying bedrock. Concomitant with the expected increase of ice thickness with time is the development of high-angle shears, for which the principal compressive stresses plunge steeply, but still parallel the directions of the two glacial movements. A continuum of stress systems between the low- and high-angle shears was not observed. This continuum may have been absent because the rock failure occurred

only under specific conditions during the ice advance. The presence of silt along some shear fractures suggests water movement under warm or temperate ice undergoing pressure-melting during or after fracturing, and the injection of silt from above.

Generation of low-angle shear stresses would be expected at the beginning of the glacial advance: first by the regional glacier from the north-north-west followed by the Peavine Valley glacier joining it from the north-north-east. The combined effect of two coalescing, rapidly moving, and thickening glaciers on the sloping face of a mountain could subsequently create a complex stress system that would produce fast strain-rates and large shear stresses within the bedrock. The evidence for two directions of glacial movement affecting bedrock matches the pattern of ice advance also deduced from the till data.

When a multi-fractured bedrock surface with numerous planes of weakness had been developed by the above stresses, the bedrock would have been susceptible to further deformation and erosive effects during continued glacial over-riding.

Injection wedges

One of the deformations associated with downward injection of watery sediments was the formation of injection wedges (W) in the fractured bedrock underneath the base of the moving ice. A close examination of the injection wedges (Figs 3 and 5) shows that detrital material (Table I, samples 5-7) has been forced down pre-existing cracks dipping down-glacier to the regional movement. Only this particular orientation of fractures was found to contain distally derived clastic debris.

The following model (Fig. 7) is proposed for the formation of these glacially induced injections. Movement by the regional ice had displaced the upper (down-glacier) bedrock block relative to the lower (up-glacier) one. This had taken place either by freezing the block to the sole of the glacier or because of friction along the glacier bed. The result was circular

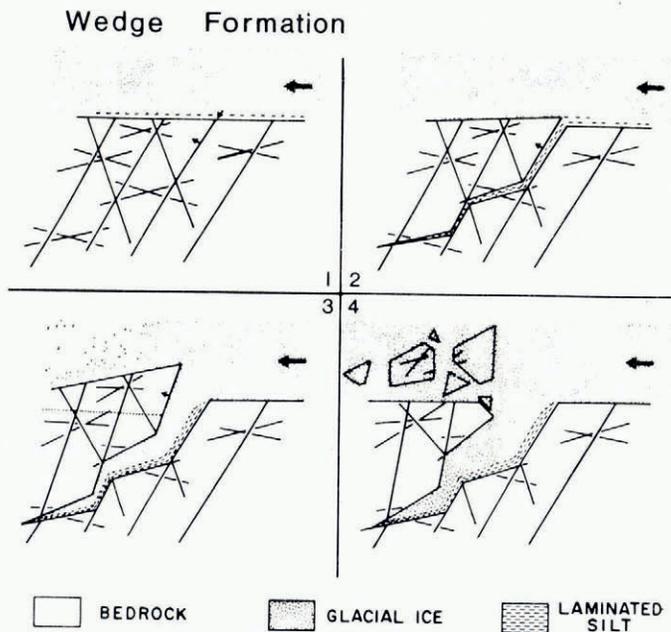


Fig. 7. Sequence of wedge formation. (1) Seepage from base of glacier into glaciotectionic fractures; (2) deposition of fine sediment-water slurry displaying laminated fissility parallel to the fracture walls; (3) displacement of down-glacier block by glacial drag and/or freeze-thaw and injection of debris-rich material from base of glacier; (4) fracturing and incorporation of the projecting down-glacier block by glacial over-riding.

rotation of the down-glacier block, such that the up-glacier side of the block would be rotated upward into the sole of the glacier. Protrusion of this block into the glacier sole would cause an obstruction and the initiation of pressure-melting at the point of contact. The production of water by pressure-melting would explain the injection of the 0.5–10 cm thick silt laminae (Table I, sample 5) that form the narrower injections and are also noticeable along the base of the wide wedges (Fig. 3). The presence of abundant small fractures in the bedrock adjoining the silt wedges suggests repeated freezing of water along the silt injections, resulting in the further widening and extension of the fractures. It is likely that the bedrock was frozen prior to and at the beginning of the formation of the wedges. In such a case, initiation of the wedge formation may have been by a process similar to the “tensional” model of glaciotectionics as suggested by Banham ([^c1975], p. 79, fig. 7), but on a much smaller scale. Further development of the wedges by continued injections would, in contrast, require temperate ice and pressure-melting.

With continued glacial movement of the upper block into the glacier sole would cause further widening of the fracture and a downward extension of it at a gentler dip angle, or along pre-existing fractures at various angles, but dipping down-glacier (Fig. 3). During the widening of the fracture(s), water-saturated silt and glacial debris would be injected from the glacial sole above. The widening of the top part of the wedge would continue until such time that the pressure exerted by the movement of the glacier resulted in failure of the down-glacier block. Failure is believed to have been aided by pre-existing shear fractures and bedding-plane fractures. The upward protrusion would have been eventually eroded (piece by piece if it consisted of the highly fractured bedrock zone A, or as larger masses of bedrock, if the erosion extended into zone B). This process would have continued until the protrusion ceased to be an obstacle to glacial movement.

The size and amount of infilling is dependent on: (a) the amount of protrusion (upward rotation) of the down-glacier block, (b) the relative displacement of the blocks imparted by the over-riding glacier, (c) the resistance of the rock to brittle failure, and (d) the intensity of pressure-melting and freezing during the initiation of the wedge. The timing of wedge formation, in terms of the thermal regime of the glacial base and underlying substratum, is believed to begin during the existence of cold ice and to continue during a change to temperate ice.

Deposition of local till (LcT)

The deposition of local till coincides in time with the widening of the wedges and erosion of the protruding tops of the displaced bedrock blocks. During this combination of erosion and deposition by the regional ice, displacement (F_4) of bedrock is noticeable above the bedrock-till contact, particularly in the bedrock inclusions in the local till. This is believed to have been initiated by propagation of fractures parallel to the south-south-east dipping F_2^R planes. These planes supplied a zone of weakness along which there were high effective shear stresses for movement parallel to the main direction of glacial movement.

Percolation of water and formation of high hydrostatic pressures along these zones (Boulton, 1972; Clayton and Moran, [^c1974]) would aid both in propagation of the fractures and reduction of friction during movement. Some frictional effects can be seen in the deformation of a rock inclusion in the local till: the deformation of earlier fractures into a sigmoidal shape (Fig. 3). The following mechanism is suggested for the sigmoidal deformation of this block. The block represents a region in the base of the glacier that moved at a speed less than that of the ice above it. This displaced the pre-existing fractures, flattening them up-glacier in the lower zone of traction. After the block became stationary, the glacier continued to over-ride the upper area of the block, flattening the upper area. Ductile, cataclastic processes are thought to accommodate this deformation (F_4), leading to further disaggregation of the bedrock block. In this case, this was accomplished by the infilling of sediment during separation of the

individual rock fragments along shear planes, and also by continued comminution of the rock fragments. This resulted in the block having been stretched out in the direction of glacial transport. Initially, only local rock flour is likely to occur along fracture surfaces. This is followed by silt from the glacier sole and finally till, as the spaces between the rock fragments increase. Eventually, the fragments are dispersed until they become disseminated clasts in the till. As glaciation proceeds, comminution and shearing is still imparted by the movement and weight of the glacier but, as the till thickens, the effects are absorbed by the till.

Deposition of the lodgement till (LgT)

Lodgement was initiated by the same regional south-south-eastward glacial movement that was active during the formation of (W), (LcT), and (F₄). Lodgement by the regional glacial flow alternated with deposition by the Peavine Valley flow. Both glacial flows were apparently part of a common mountain ice sheet, rather than being simple competing glaciers. This conclusion is supported by the near-continuous interaction of both ice flows during the formation of (F₂), (F₃), and (LgT). The absence of the effects of Peavine Glacier at (W), (LcT), and (F₄) indicates that the combined action of both glaciers existed at the beginning of the glacial advances, when (F₂) and (F₃) were produced, and at the end, during deposition of (LgT). Further details of the interaction of the regional and the Peavine glacial flows during the deposition of the lodgement till have been discussed by Broster and Dreimanis (unpublished).

As this present paper deals with glaciodynamic deformations, it should be mentioned that a shear fracture, about 3 m long, striking 080° and rising south-eastward at various angles, was observed cutting through a 25 cm long boulder in the local till at a level halfway between sites 11 and 12, and then rising steeply through the lodgement till. The displacement in the boulder is only a few centimetres. It is believed that this shearing took place during the final stages of glaciation, as the shear plane rises past sample site 13 (Fig. 2).

CONCLUSIONS

The orientation of till clasts, bedrock striae, fracture systems, and other evidence suggest that during the last glaciation the area investigated was affected by two glacial bodies belonging to a mountain ice sheet: a regional glacier flowing from north-north-west and a glacier flowing south-south-westward along Peavine Creek Valley. Both glaciers merged into a mountain ice sheet and deposited till which, although internally complex, is stratigraphically a single layer. The till is deposited over fresh bedrock which is weathered only along a gabbro dyke.

Several erosional and partially depositional phases can be recognized as having occurred in the following sequence:

1. The earliest conjugate fracture systems (F₁) appear to be related to the initiation of a main compressive stress from the north-north-west concurrent with the direction of regional glacial flow. Since it is a low-angle compressive stress, this implies that the low vertical pressures could be due to the arrival of thin ice.
2. This was followed by the formation of two synchronous sets (F₂^R and F₂^P) of low-angle shear fractures with main compressive stresses parallel to 170° (regional) and 030–040° (local). These suggest the interaction of two thin-ice glaciers or glacial flows within the mountain ice sheet.
3. The ice began to thicken, leading to the formation of high-angle conjugate fractures (F₃^R and F₃^P) in the bedrock related to both of the above ice-movement directions.

4. Concurrent with the dominant action of the regional glacier on the bedrock, wedges (W) developed along pre-existing shear fractures perpendicular to glacial movement and dipping down-glacier (south-south-eastward). The formation of these wedges resulted in the development of rock protrusions upward into the sole of the glacier, that were eroded and deposited into the local till (LcT) and subsequently deposited over and down-glacier of the wedges. The deposition of the local till was followed by sigmoidal deformation (F₄) of fractures within bedrock inclusions by continued movement of the regional glacier.
5. The main depositional phase was accomplished by lodgement of till (LgT) during which both glacial flows competed for superiority. Shearing and fracturing continued concurrently with lodgement to a decreasing degree, producing fissility and shear planes rising down-glacier.

Wedging (see phase 4) may be considered as a process aiding glacial erosion but it has rarely been described previously, and warrants future investigation.

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DISCUSSION

R. W. MAY: I would like to make a plea that those who are measuring fracture and joint orientation in tills also provide as part of the information the orientation of the face and/or the valley walls on which the measurements are made. In Alberta we have found on occasion that fracture or joint systems in tills are related to stress release parallel to the face of the exposure.

A. DREIMANIS: In our study the information you request has been provided in the location plan of trenches 1-3 (Fig. 1) and in the descriptive comments in the text. None of the fracture patterns discussed in our study was parallel to the slope of the valley side, and therefore they were not caused by stress release parallel to the face of the exposure.