THE SEDIMENTOLOGY OF PLEISTOCENE DEPOSITS ASSOCIATED WITH PLACER GOLD BEARING GRAVELS IN THE LIVINGSTONE CREEK AREA, YUKON TERRITORY

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ABSTRACT

Due to the depletion of traditional economic gold placer deposits in unglaciated areas of the Yukon, the study of the relationship of placer gravels to overlying glacial sediments in ice covered regions is important to future exploration activities. The Livingstone Creek area in south central Yukon has supported placer mining operations for over 90 years. Present activity is centred on gold-bearing gravels buried by thick Pleistocene glacial deposits. The placer gravels are associated with coarse interglacial stream and gulch deposits and they are overlain by fine grained, proximal, glaciolacustrine sediments.

During the last glaciation, damming of gold-bearing, high gradient interglacial tributary stream channels by main valley ice caused rapid environmental changes. Depositional processes dominated over erosion in the ice-marginal lakes, and thick sequences of fine grained suspension deposits, debris flow sediments, and deltaic sands and gravels accumulated. In addition, when glaciers expanded and overrode the area, these thick deposits protected the underlying placer gravels from subglacial erosion and dilution. Subglacial tills were probably deposited by lodgement, meltout and flow. During deglaciation, ice-marginal sedimentation again dominated. Post-glacial streams later cut through the glacial sediments and re-exposed the gold bearing gravels.

Stratigraphic, sedimentologic and geomorphic evidence from the Livingstone Creek area suggests that small tributary valleys, oriented transverse to the former direction of ice flow in the adjacent main valleys, would make good exploration targets in regions of new placer interest.

RÉSUMÉ

L'étude de la relation entre les graviers alluvionnaires et les sédiments glaciaires sus-jacents dans les régions recouvertes de glace est importante pour les activités futures d'exploration en raison de l'épuisement des classiques gisements rentables d'or placérien dans les régions non glaciées du Yukon. L'or placérien est exploité depuis plus de 90 ans dans la région du ruisseau Livingstone dans la partie méridionale centrale du Yukon. Actuellement, les activités sont centrées sur les graviers aurifères enfouis sous d'épais dépôts glaciaires du Pléistocène. Les graviers alluvionnaires sont associés à des dépôts de cours d'eau et de ravins interglaciaires à grains grossiers et ils sont recouverts de sédiments glaciolacustres proximaux à grains fins.

Pendant la dernière glaciation, l'endiguement d'affluents interglaciaires à forte pente par la glace de vallées principales a entraîné de rapides changements environnementaux. Les processus de dépôt, plutôt que l'érosion, ont été dominants dans les lacs de marges glaciaires et d'épaisses séquences de dépots à grains fins en suspension, de sédiments de coulées de débris et de sables et graviers deltaïques se sont accumulées. De plus, lorsque les glacier se sont agrandis et ont chevauché la région, ces épais dépôts ont protégé de l'érosion et de la dilution les graviers alluvionnaires sous-jacents. Les tills subglaciaires ont probablement été déposés sur le fond, par la fonte et l'écoulement. Pendant la déglaciation, la sédimentation aux marges glaciaires a de nouveau dominé. Les cours d'eau postglaciaires ont plus tard entaillé les sédiments glaciaires et de nouveau mis à nu les graviers aurifères.

Les indications stratigraphiques, sédimentologiques et géomorphologiques dans la région du ruisseau Livingstone suggèrent que les vallées de petits affluents orientées perpendiculairement à l'ancienne direction de l'écoulement de la glace dans les vallées principales adjacentes constitueraient de bonnes cibles d'exploration dans les régions d'intérêt pour les nouveaux gisements alluviaux.

INTRODUCTION

Yukon placer deposits have produced more than 11 million ounces (342 million grams) of gold since 1885 (Debicki, 1983). Record productions have occurred in recent years, with 1987-1990 ranked as the four best years in the last 72 (Latoski, 1991). In 1989, the highest production since 1917 was recorded: 165 571 crude ounces (5 151 510 million grams), valued at over Cdn $57.6 million (Latoski, 1991). Most placer mining activities in the Yukon have traditionally been in unglaciated regions such as the Klondike, Indian River and Sixtymile River areas but economic placer deposits also exist in glaciated areas, and generate about 25% of the total placer gold production (LeBarge, 1990). The focus of this study, an important placer occurrence in the Livingstone Creek area, is at least 125 km inside the limit of Pleistocene glacial advances (Hughes et. al., 1969). The reason for the preservation of the placer gravels in this area is unknown, although it has been suggested that they occur in valleys oriented perpendicular to the regional flow direction of Pleistocene glaciers (Bostock and Lees, 1938). Detailed stratigraphic and sedimentologic relationships of the placer gravels to the overlying glacial deposits were previously undocumented.

The objectives of this study were to investigate the sedimentary properties of the glacial sediments overlying the placer gold bearing deposits in the Livingstone area in order to document: (1) the stratigraphic and sedimentologic characteristics of the glacial sediments, (2) any relationship of these characteristics to the preservation of the gold bearing gravels, and (3) any unique features that might be used to identify potential exploration targets in other glaciated regions.

Placer gold was first discovered in the Livingstone Creek area (Figure 1) in 1898 and in the first forty years of activity the camp produced more than $1,000,000 in gold (Bostock and Lees, 1938). The area continued to produce gold over the next fifty years. Seven of the creeks had active operations between 1978 and 1990 which produced more than 3300 ounces of gold, a total value of about $1.3 million (Debicki, 1983; LeBarge, 1990; Latoski, 1991). Mining activities were observed on three creeks in the area during this study.

STUDY AREA

The Livingstone Creek area is located about 80 km northeast of Whitehorse (Figure 1, inset) and has two dirt airstrips and a winter road for access. Virtually all the gold production in the area has come from several small creeks that flow down the eastern slopes of the Big Salmon Range into the South Big Salmon River (Figure 1). Good exposures on Martin, Livingstone and Summit Creeks were the focus of this study. The creeks head in broad, shallow, glaciated basins that narrow into steep gradient canyons where the streams enter the main valley. A narrow, bedrock-walled valley along the eastern edge of the South Big Salmon River valley is responsible for the sharp northward diversions of Livingstone and Summit Creeks from their otherwise westerly drainage (Figure 1).

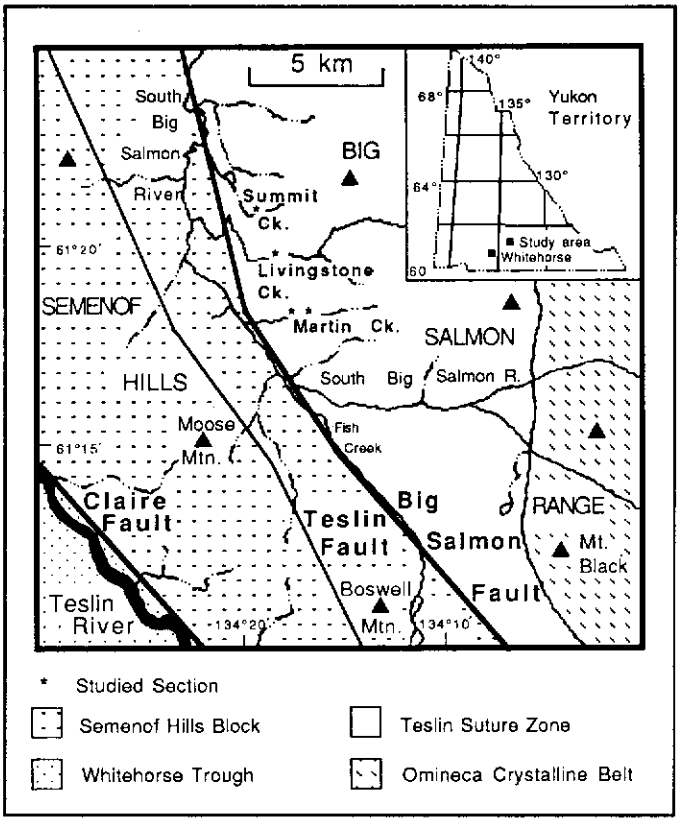


Figure 1. Locations of studied sections and bedrock geology of Livingstone Creek area.

Peaks on the Big Salmon Range rise to elevations of about 2000 m; Mt. Black (2158 m) at the SE end of the range is the highest mountain in the region (Figure 1). The Livingstone Creek area is separated from the Teslin River valley by the Semenof Hills. Several north-south trending valleys, such as between Moose and Boswell Mountains, cross the hills.

The gold-bearing gravels at the three creeks studied directly overlie bedrock. They are poorly exposed due to mining activity which has undercut the sections, resulting in the collapse of the overlying glacial deposits. This same collapse produced the fresh exposures in the upper part of the sections described in this paper (Figures 2 to 5).

PREVIOUS WORK

Few detailed studies of this nature have been carried out on placer deposits in glaciated parts of the Yukon. Morison (1983, 1984), however, provided a sedimentologic description of placer gold sediments and associated deposits in the glaciated Clear Creek basin. He concluded that placer deposits buried below till were preserved because the area is located near the limits of glaciation where subglacial erosion was decreased. The glacial sediments were probably deposited by mainly nonerosional processes such as meltout and resedimentation (Morison, 1984). Similar studies of placer deposits have recently been conducted in northwest British

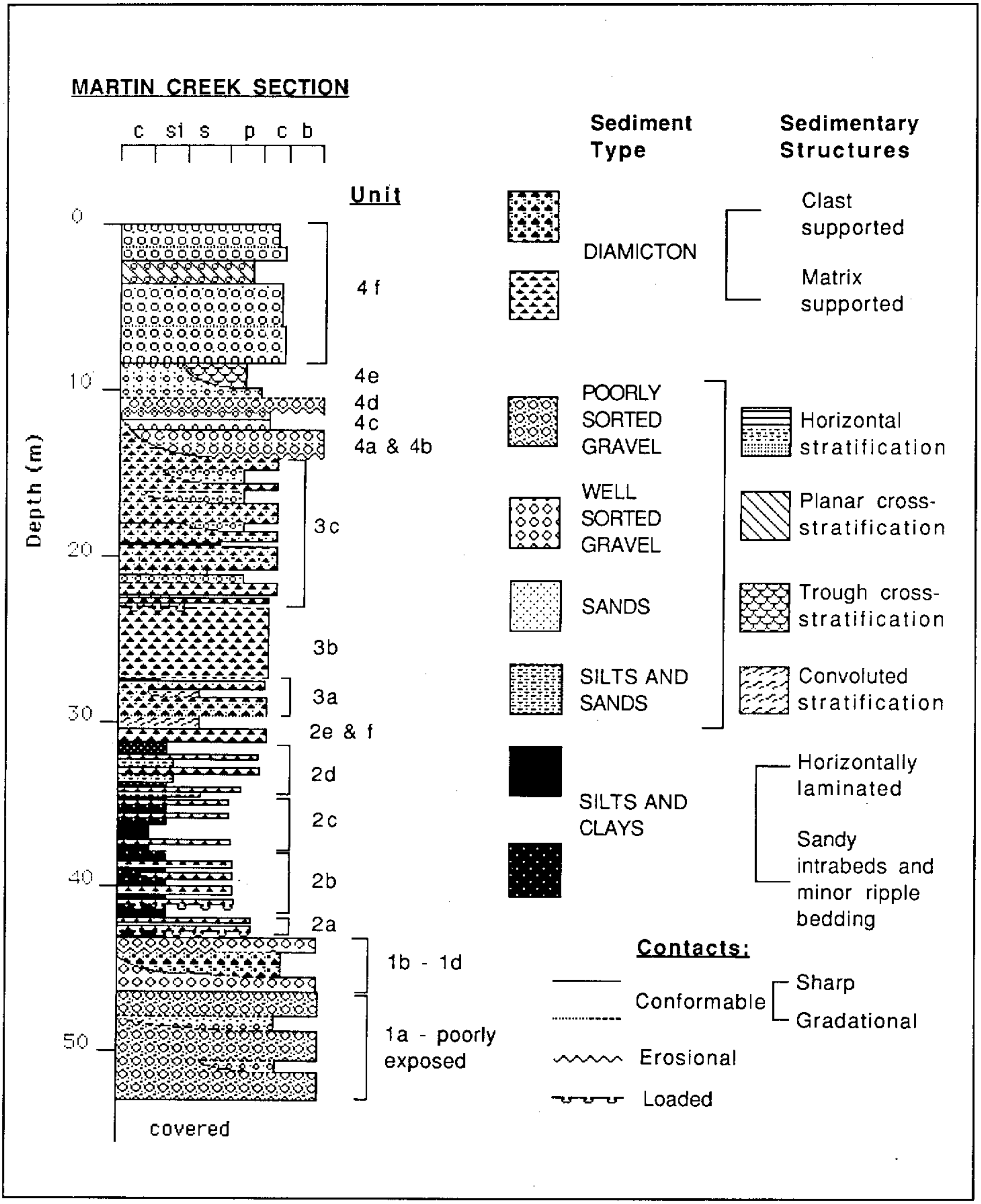


Figure 2. Composite stratigraphic column of the main Martin Creek section.

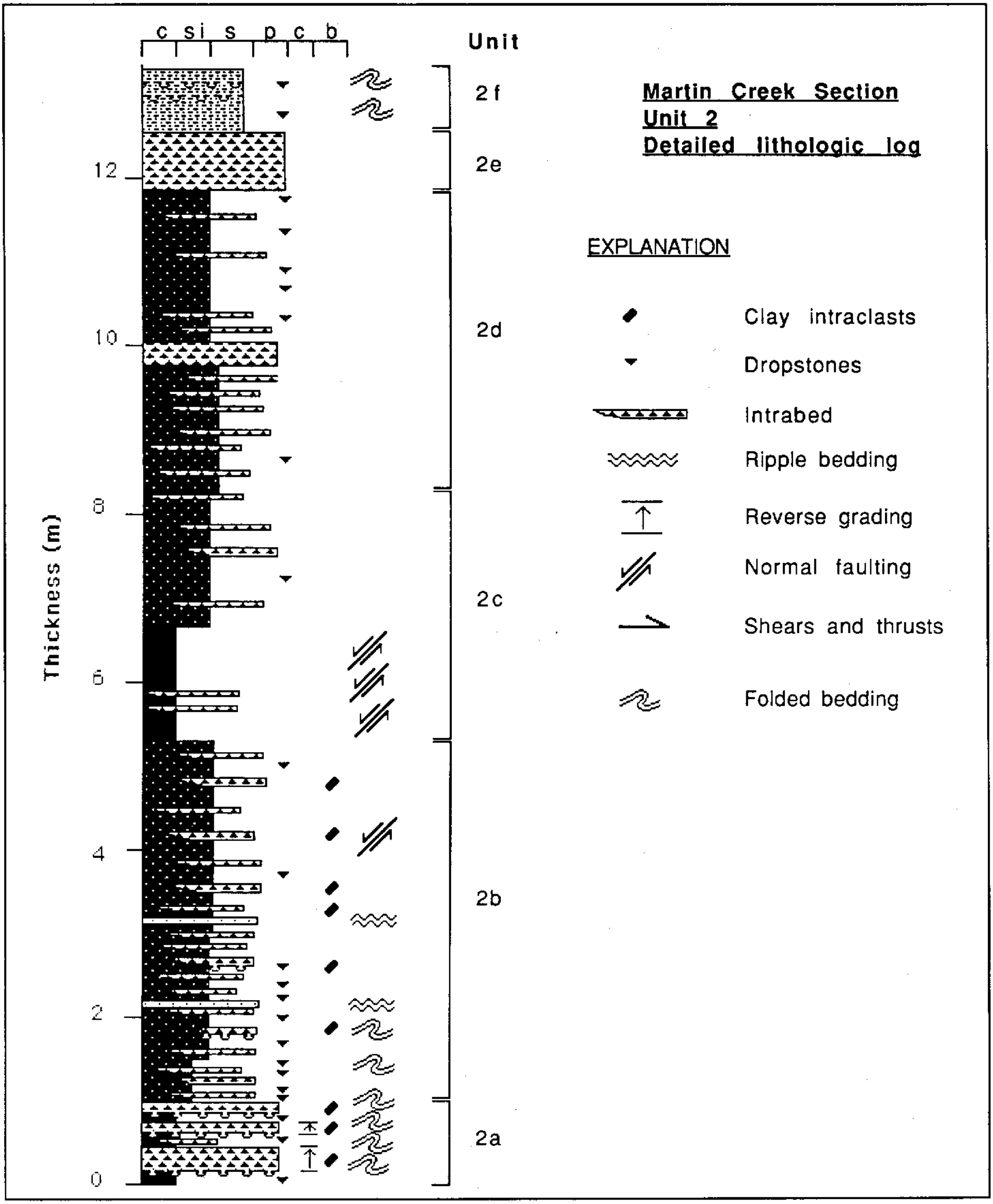


Figure 3. Detailed sedimentologic log of unit 2 at the Martin Creek section. Refer to Figure 2 for explanation of lithologic symbols.

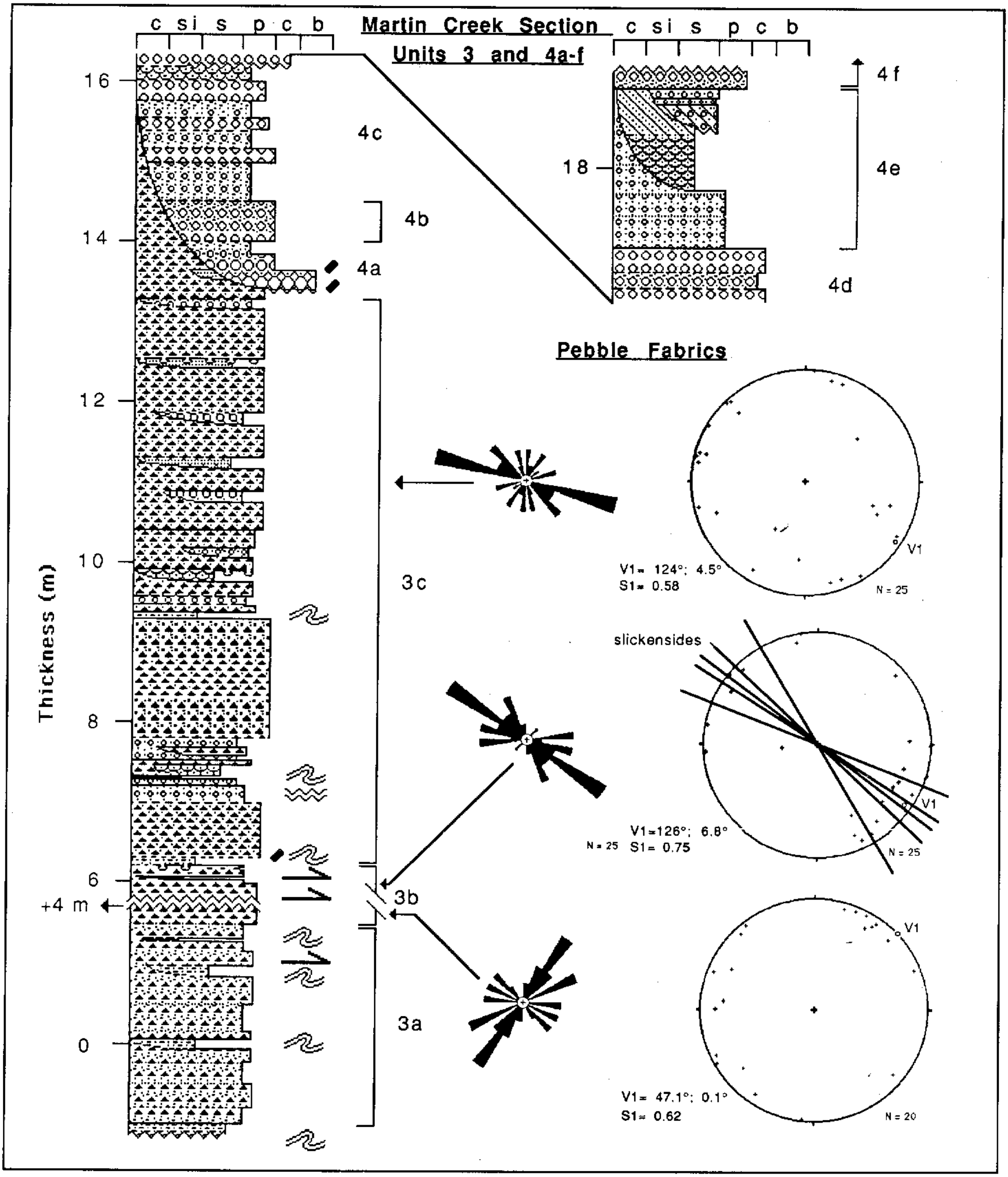
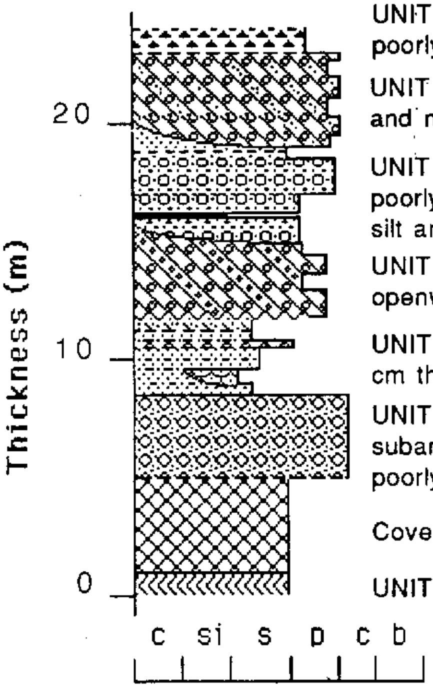


Figure 4. Detailed sedimentologic log of units 3a to 4f at the Martin Creek section. Rose diagrams and corresponding equal area density plots are shown for units 3b and 3c. V1 parallels the axis of maximum clustering of the a-axes of blade and prolate shaped clasts. S1 is the normalized eigenvalue corresponding to the V1 eigenvector. Refer to Figures 2 and 3 for explanation of symbols.

Summit Creek



UNIT 7: diamicton; massive; clast to matrix supported; unsorted to poorly sorted; poorly exposed.

UNIT 6: pebble to cobble gravels; beds dip 23-31° NE (055°); open work and matrix filled beds; lower contact erosional and dips gently (5°) NE.

UNIT 5: sandy gravel; horizontal bedding to gently inclined planar crossbedding; poorly sorted; clasts mainly angular to subangular; minor horizontally laminated silt and fine sand beds; lower contact erosional and dips gently (5°) NE.

UNIT 4: pebble gravel; beds dip 15-20° NE (052°); clast supported; mainly openwork; moderately to well sorted; clasts mainly angular to subangular.

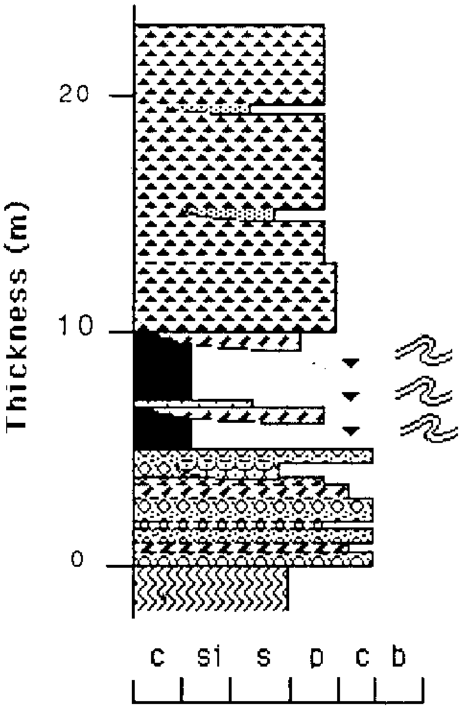
UNIT 3: sands; horizontally stratified; well to very well sorted; strata 0.1-10 cm thick; minor granule beds; some planar and trough cross-bedding; dropstones

UNIT 2: coarse gravel; clast supported; poorly sorted; 60-80% clasts, subangular to subrounded, up to boulder size; matrix sandy; disorganized fabric; poorly exposed; lower contact covered.

Covered interval.

UNIT 1: schist; vertical foliation; minor quartz veins and fracturing.

Livingstone Creek Section



UNIT 5: diamicton; massive; matrix supported; silty mud matrix; 20-40% clasts, up to bouder sized, subangular to subrounded, striations common; light brown color; minor sorted sand lenses; poorly exposed.

UNIT 4: diamicton; as above except sandy silt matrix and dark grey

UNIT 3: silts and clays; parallel laminated; intense folding; pebble breccia intrabeds of very angular, local lithology; rounded erratics common as dropstones but rare in intrabeds; minor oxidized sands.

UNIT 2: gravels; horizontal bedding; clast supported; matrix filled; clasts up to boulder sized, well rounded to sub rounded; poorly to moderately sorted; some imbricated, cobble breccia beds of local schist; minor open work pebble gravel and trough cross-bedded sands.

UNIT 1: bedrock; blocky quartzite and schist; vertical foliation; silicified with abundant pyrite crystals oriented parallel to foliation; numerous near vertical quartz veins

Figure 5. Composite stratigraphic columns for the Summit Creek and Livingstone Creek sections. See Figures 2 and 3 for explanation of symbols.

Columbia, just south of the Yukon border (Levson, 1991; Levson and Kerr, 1991) and in central British Columbia (Levson and Giles, 1990; Levson, 1991).

Glacial features and surficial deposits in the area were mapped by Hughes (1968), and Klassen and Morison (1987). Surficial deposits in the area are mainly thin till and colluvium. An irregular glaciofluvial complex occurs in the South Big Salmon Valley near the mouth of Martin Creek (Klassen and Morison, 1987). The prominent valley that diverts the westerly flow of Livingstone and Summit Creeks is an ice-marginal channel (Hughes, 1968). Indicators of former ice flow direction, mapped by Hughes (1968) and Klassen and Morison (1987), suggest that glaciers flowed north along the low valleys that cross the Semenof Hills into the South Big Salmon River Valley in the Livingstone Creek area.

BEDROCK GEOLOGY

The Livingstone Creek area occurs within the Teslin Suture Zone (Figure 1), which is separated from the Semenof Hills Block, to the west, by the Big Salmon Fault (Tempelman-Kluit, 1980 and 1984). This fault closely parallels the South Big Salmon River in the area directly west of the studied sections (Figure 1). Local bedrock in the drainage basins of the investigated creeks is dominantly dark green, cataclastic, fine grained amphibolite and amphibolitic greenstone that grades into massive, melanocratic, dioritic to quartz dioritic hornblende augen gneiss. These rocks belong to the Anvil allochthonous assemblage and are associated with muscovite-quartz schist and muscovite quartzite of the Nisutlin assemblage (Tempelman-Kluit, 1984). Outcrops close to the Martin Creek section are dark, fine grained, strongly foliated and faulted greenstone and schist with some soft, strongly altered (kaolinitic?) and silicified zones (Figure 6a). Quartz veins are conspicuous throughout. Schist and quartzite are exposed at the base of the Summit Creek and Livingstone Creek sections. Quartz veins are present at both locations and are particularly numerous at Livingstone Creek, where the bedrock is also strongly silicified and pyritized. A belt of sheared granodiorite extends north from Livingstone Creek across the headwaters of Summit Creek (Bostock and Lees, 1938).

The Omineca Crystalline Belt occurs just east of the study area in the eastern Big Salmon mountains, the headwaters of the South Big Salmon River (Figure 1). Rocks outcropping in this area include Middle Cretaceous biotite granite, dolomite, siltstone, quartzite and shale of the Paleozoic Hogg and Nasina Formations, and granodiorite gneiss with intercalated mica-quartz schist of the Proterozoic and Lower Cambrian Ketza Group (Tempelman-Kluit, 1984).

Phyllite, greywacke, chert, chert conglomerate, and limestone of the Boswell Formation outcrop directly west of the study area in the Semenof Hills Block. Volcanic rocks of the Semenof and Open Creek Formations occur further to the east and south. Even further southeast, beyond the Teslin River, the Whitehorse Trough (Figure 1) is dominated by shale, greywacke and conglomerate of the Laberge Group with minor limestone (the Hancock Member)(Tempelman-Kluit, 1984). The Whitehorse Trough is the most probable source of rounded monzonite, granodiorite and syenite erratics found in the study area, and their presence indicates long distance ice transport. Two small bodies of porphyritic granodiorite and monzonite intrude Whitehorse Trough rocks directly south of the study area (Bostock and Lees, 1938).

SECTION DESCRIPTIONS AND INTERPRETATIONS

Martin Creek Section

Two sections were described at Martin Creek. A summary of the sequence of deposits exposed at the main Martin Creek Section (units 1 to 4) is provided in Figure 2. Unit 5 is exposed further down valley in a shallow exposure about 140 m in length which is referred to as the west Martin Creek section (Appendix 1). Detailed sedimentologic logs of units 2 and 3 at the main section are provided in Figures 3 and 4, respectively. A complete description of the Martin Creek Sections is provided in Appendix 1.

Unit 1

The lowest exposed sediments at Martin Creek (units 1a to 1d; Figure 2 and Appendix 1) are poorly sorted, coarse, mainly clast-supported gravels (Figure 6b). Lithologic analyses indicate that a high proportion of the clasts are derived from the local drainage basin (Figure 7) and some very angular clasts have come from the bedrock directly upstream of the section.

Several gradationally interbedded facies are recognized:

(1) Clast supported, with matrix-filled gravels dominant (Figure 6c). These gravels are poorly sorted, containing clay to boulder sized materials. They are structureless with a disorganized fabric and contain numerous angular clasts.

(2) A second gravel facies, better sorted, with more rounded clasts, and minor open work beds (Figure 6d). Some beds exhibit weak imbrication and crude, sub-horizontal stratification due to variations in clast size and sorting between beds. Sorting is generally poor, but a few pebble beds are moderately well sorted. Stratified clay, silt, sand and pebbly sands occur around some clasts (Figure 6d). Clasts are mainly rounded to subrounded.

(3) The coarsest beds in unit 1 contain clasts up to 1 m in diameter, which occur in disorganized clusters surrounded by sorted beds of finer material (Figure 6e). Pebble and pebbly sand beds generally occur downstream of the clusters whereas pebble to cobble beds occur upstream. A weak imbrication is locally developed.

(4) Gravel facies grade into massive, matrix to clast-supported diamicton beds (eg. unit 1c Appendix 1; Figure 6f). The shape and size ranges of clasts in the diamictons are similar to gravels of facies 1 above but the diamictons contain a much higher proportion of matrix.

The massive structure, high matrix component, and the presence of angular clasts in the poorly sorted gravels (facies

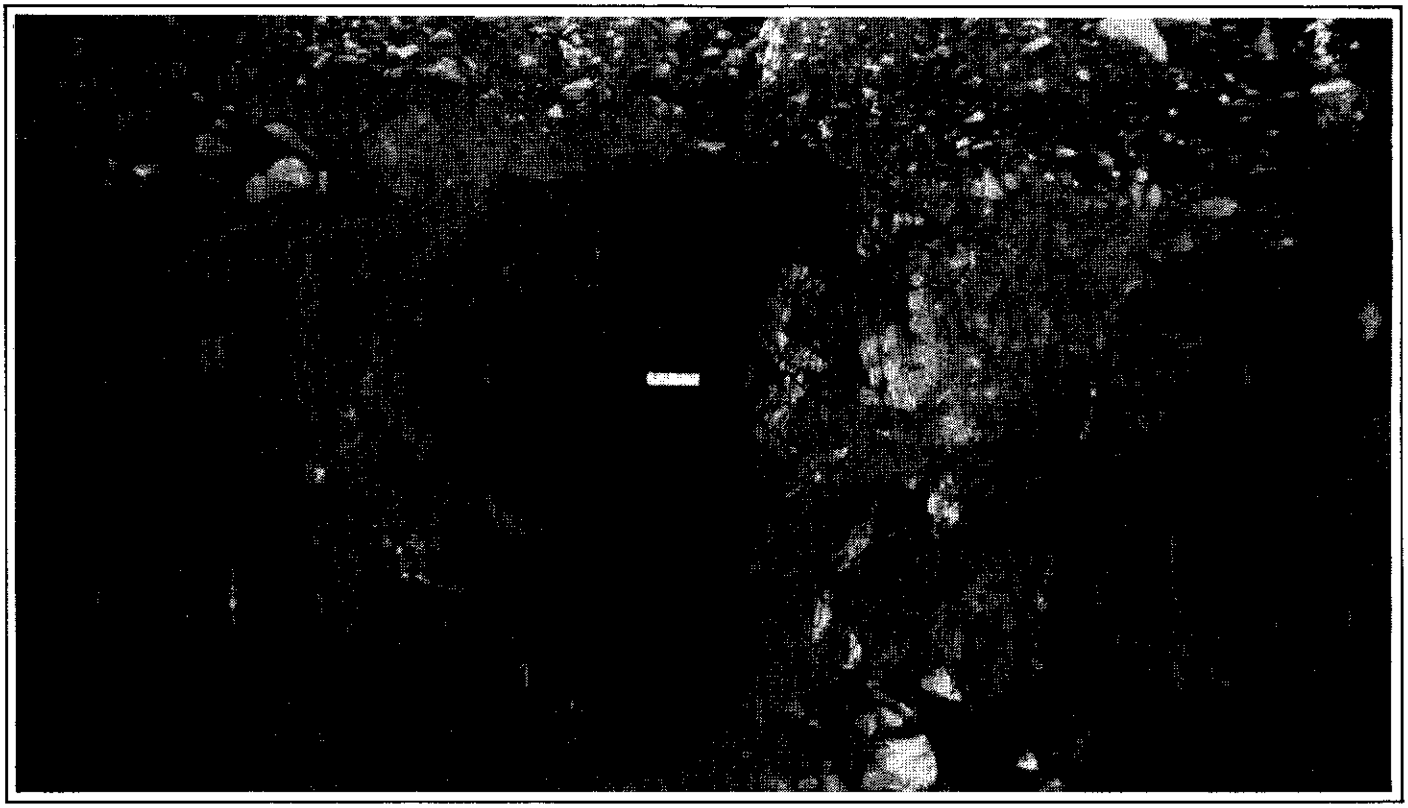


Figure 6. Bedrock and unit 1 gravels at Martin Creek. Paleo-flow is from left to right in all cases. (a) Local bedrock outcrop with a highly altered and silicified zone on the right in sharp contact with fine grained melanocratic rocks on the left. The outcrop has abundant quartz veins, is about 1 m high, and is overlain by gravel tailings.

Fig. 6(b). Poorly sorted coarse gravels typical of unit 1. Rod is 1.5 m long.

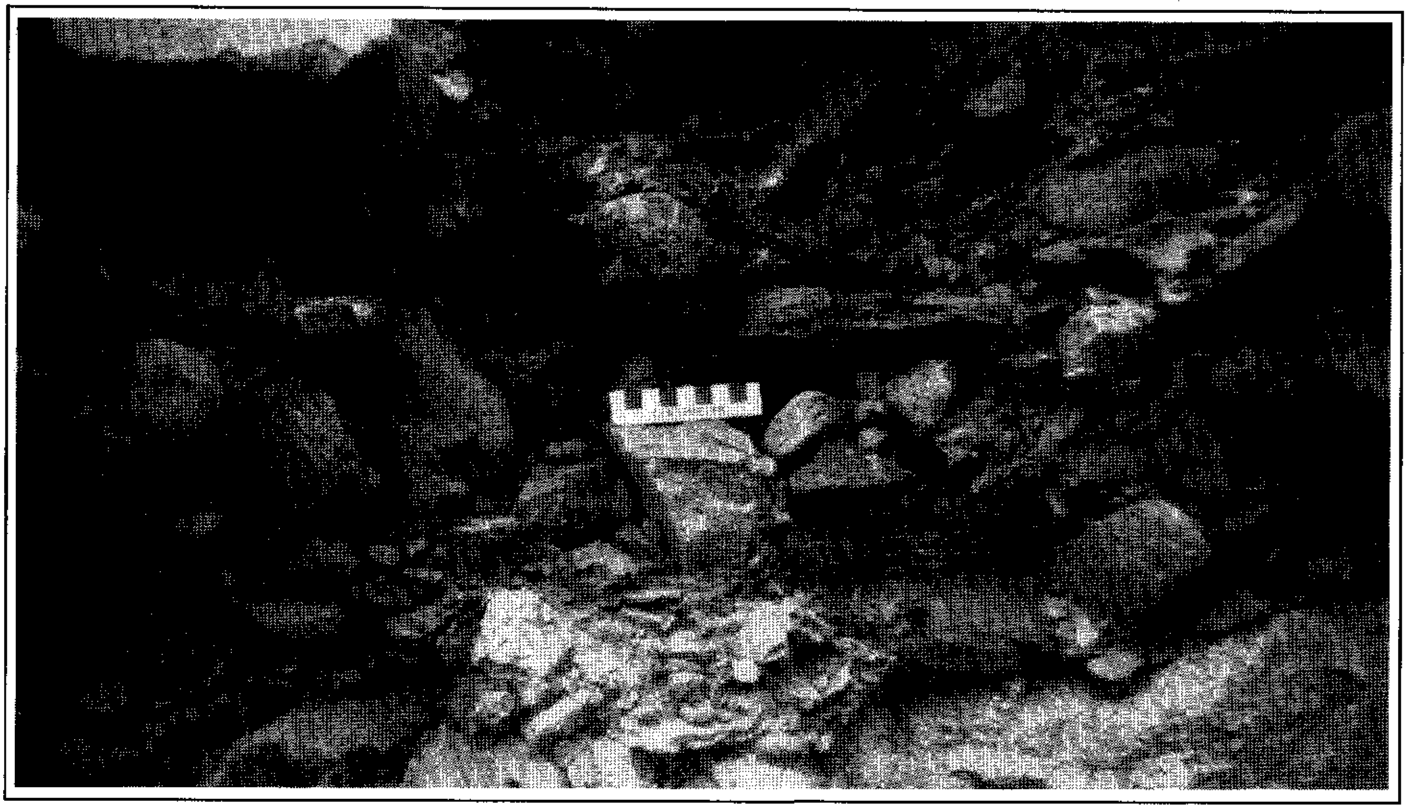


Fig. 6(c). Structureless, clast-supported, matrix filled gravels (facies 1).

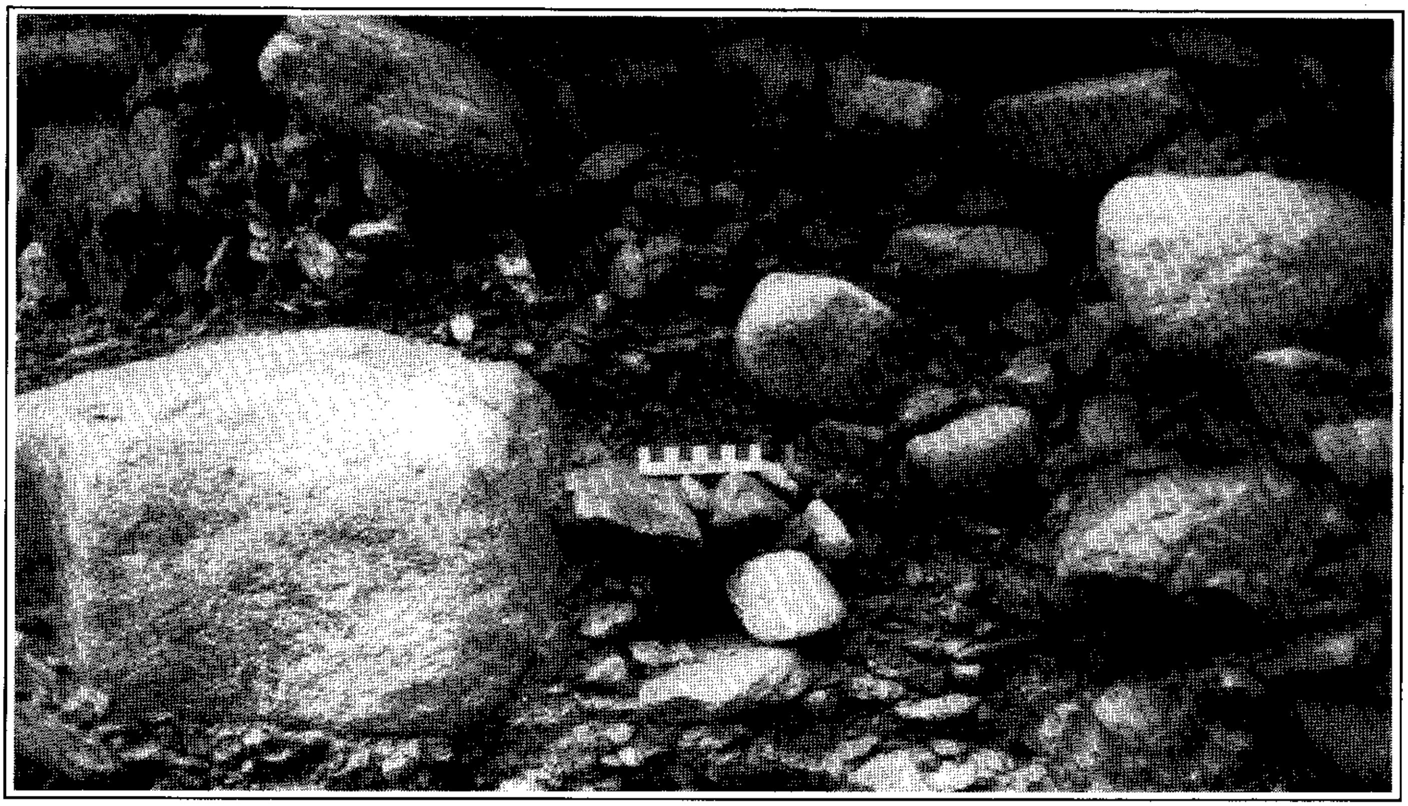


Fig. 6(d). Poorly to moderately sorted, clast-supported gravels with crude horizontal stratification and imbrication (facies 2). Note the open-work bed at the top and the finer gravel surrounding the cobble at the left. Scale in centimetres.

Fig. 6(e). Disorganized cobble and boulder cluster with an accumulation of coarse pebbles and small cobbles up flow (right) and mainly small to medium pebbles in the lee of the cluster. Pick is 65 cm long.

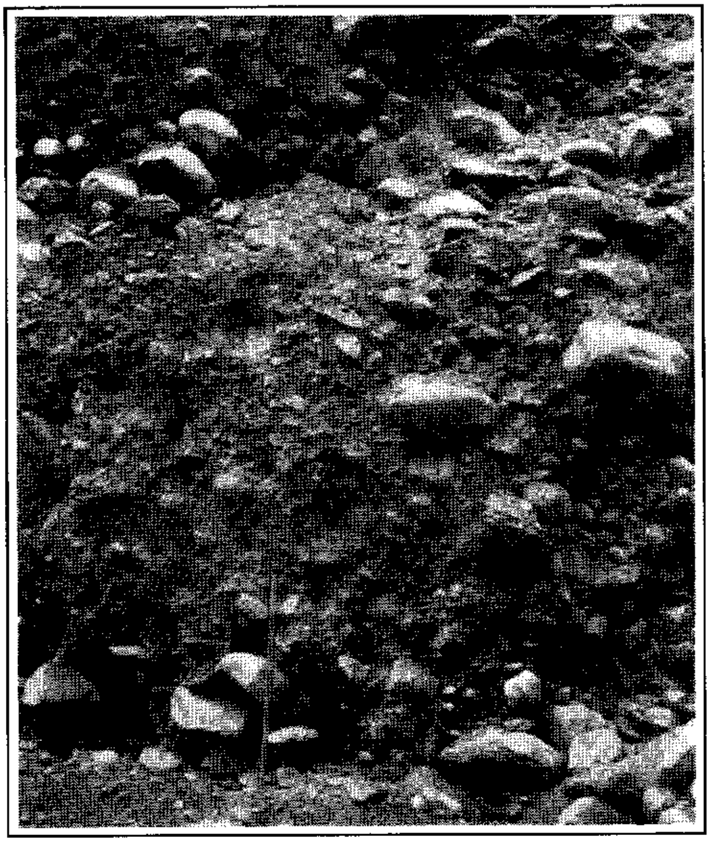


Fig. 6(f). Massive, matrix- to clast-supported debris flow deposits (facies 4) in unit 1c.

1) and diamicton beds (facies 4) suggest deposition by mass-flow processes. The large clast size and poor sorting indicate high energy flows with rapid deposition. Massive, poorly sorted sediments with a fine matrix, disorganized fabric and gradational bed contacts are typical of debris flow deposits (Fisher, 1971; Bull, 1972; Harvey, 1984; Kochel and Johnson, 1984; Wells, 1984).

Matrix support and higher mud contents in some facies 4 beds suggest that some flows were viscous and that clasts were supported by the cohesive strength of the matrix. Smeared and vertically slickensided clay coatings on clasts in some diamicton beds (unit 1c, Appendix 1) probably result from confined, vertical movement of the clasts through a highly viscous matrix. In contrast, the lower matrix content of some gravelly facies 1 beds suggests deposition from flows in which clasts remained mostly in contact with each other. Similar deposits with few fines and a massive, ungraded character were interpreted by Larsen and Steel (1978) and Burgisser (1984) as gravelly debris flows. Particles were probably suspended in these flows by buoyancy and grain to grain contact rather than by the cohesive strength of the matrix. These grain support mechanisms are typical of gravelly debris flows (Pierson, 1981; and Burgisser, 1984).

Better sorting and the presence of more rounded clasts and open-work beds suggests that some beds in unit 1 (facies 2) may have been deposited by more fluvial-dominated processes. Crude, sub-horizontal stratification has been well documented in shallow, gravelly, braided streams (Boothroyd and Ashley,

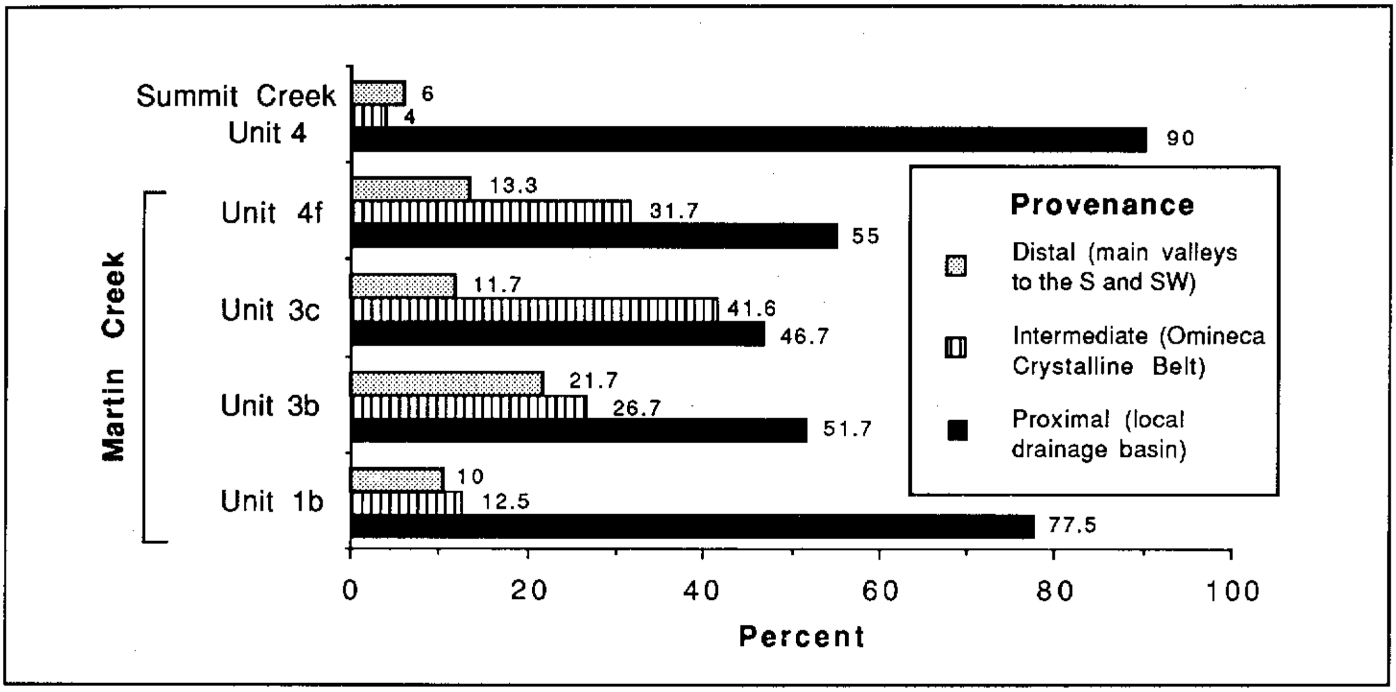


Figure 7. Provenance of pebbles from sampled beds at Martin and Summit Creeks.

1975; Church and Gilbert, 1975; Hein and Walker, 1977). Weak imbrication and rounded clasts indicate bedload transport. Sorting around clasts may be due to localized increases in turbulence in the more fluid flows or to the infiltration of finer materials as the flow waned. The distinction between deposits from watery debris flows and those from high velocity streams carrying high sediment concentrations is unclear and transitions from viscous to fluid flow may even occur during the same event (Johnson, 1970; Lowe,1979; Middleton and Hampton, 1976; Nardin et. al., 1979; Morison and Hein, 1987). Partly turbulent, hyperconcentrated flood flows, with sediment/water ratios intermediate between cohesive debris flows and normal stream flows, produce similar deposits (Smith, 1986,1987; Waresbach and Turberville, 1990).

Disorganized to weakly imbricated clast clusters, similar to those described above (facies 3), were observed by Brayshaw, (1984) in natural channels and flume experiments. The clusters developed subsequent to the deposition of large clasts (median size, D95, i.e. coarser than 95% of the bedload) which obstruct the flow. Fine grained (D8 to D46) wake accumulations are deposited in the obstacle shadow and comparatively coarse (D74 to D94) clasts accumulate in a cluster on the stoss-side (Brayshaw, 1984). The preservation of underlying fine grained sediments is due to the armouring effect of the cluster. Cluster bedforms develop during the falling stage of flood discharges.

Taken together, these facies are interpreted as high energy, stream channel or gulch sediments. Deposition occurred from both high velocity, channelized fluvial flows and debris flows. Large, lateral and vertical differences in grain size and sorting indicate substantial spatial and temporal variability in flow and/or sediment load. Unsorted beds, in part, matrix-supported, are probably debris flow deposits and form one end of a continuum. Weakly imbricated and stratified beds of poorly sorted gravel indicate more fluvial-dominated sedimentation. Discharges sufficient to move clasts up to 1 m or more in diameter probably occurred only after unusually large storm or spring runoff events. Gradational changes in grain size distribution suggest fluctuations in flow were gradual. The presence of clasts of erratic lithology (Figure 7) indicates that the gravels are interglacial (or interstadial) and not preglacial.

Unit 2

The gravels of unit 1 are overlain by almost 12 metres of interbedded fine grained sediments and diamicton (units 2a to 2f; Figures 2 and 3 and Appendix 1). Parallel laminated silts and clays dominate with minor ripple bedded sands (Figures 8a and 8b). Diamicton interbeds are matrix-supported and vary in thickness from a few centimetres or less (Figures 8a and 8c) to tens of centimetres (Figure 8d). Silt and clay beds commonly contain stones that are often striated, draped by overlying strata and deform underlying beds (Figures 8a to 8c). Folded bedding, faults, slump structures, load structures and mud intraclasts are abundant (Figures 8d to 8h). Beds dip about 10° to the northeast (50°), opposite to the regional slope. The abundance and thickness of diamicton beds and striated clasts increases up-section toward the southwest. Some diamicton beds are capped by gravel concentrations and exhibit inverse, coarse-tail grading (Figure 8d). Some clasts protrude from the tops of the beds (Figures 8d and 8f). In diamicton beds in the lower part of the unit (eg. unit 2a), numerous pebble to cobble sized clasts occur in a silty clay matrix. Many of the stones are angular and derived from the local bedrock.

Deposits similar to those in unit 2 are typical of proximal glaciolacustrine environments (Ashley, 1988; McCabe and Eyles, 1988). Parallel-laminated clay and silt beds and ripple-bedded sands are interpreted as quiet water suspension and density underflow deposits. The abundance of striated clasts, inferred to be dropstones, indicate the proximity of ice. Interbeds of matrix-supported diamicton are interpreted as debris flow deposits. Modern debris flow sediments have characteristics similar to those described above (Bull, 1972; Kochel and Johnson, 1984). Massive, disorganized, matrix-supported diamictons with sharp, non-erosional lower contacts were interpreted as debris flow deposits by Harvey (1984) and Wells (1984). Clasts that project above bed tops are characteristic of viscous debris flows (Johnson, 1970; Nardin et. al., 1979) and imply a high matrix strength. The presence of inverse grading also suggests a debris flow origin for these deposits (Fisher, 1971 and Lowe, 1979). This interpretation is further supported by the occurrence of recumbent and overturned isoclinal folds inferred to be flow structures, abundant evidence of loading, and numerous inclusions of silt and clay which are interpreted as rip up clasts (Figures 8e and 8f).

The upslope dip of beds, indicates that the flows were derived from a high surface to the southwest, probably a glacier in the main valley. This is also suggested by an increase in abundance and thickness of diamicton beds toward the southwest. Instability in the ice-marginal lake sediments is indicated by abundant folds and faults. Normal faults (Figures 8c and 89), common in unit 2 (Figures 3 and 8), probably developed as a result of movement in the adjoining glacier.

The fine grained matrix of the debris flows likely originated by intraformational slumping of the unstable silts and clays (Figure 8h). The abundant local, angular stones in some diamicton beds in the lower part of the unit were probably eroded by the glacier shortly before incorporation in the debris flows. Similarly, large clasts transported by the glacier were undoubtedly incorporated in the flows. Textural inversions, characterized by angular and/or large clasts in a fine grained matrix, are typical of sediments produced by mixing of deposits from two different environments (Folk, 1980). Similar, texturally inverted, matrix-rich conglomerates and granule sandstones with associated loading, slumping and faulting, were interpreted by Larsen and Steel (1978) as subaqueously resedimented deposits of mixed debris flow and lacustrine origin. Diamicton beds formed by gravitational flows of coarse grained material over fine grained glaciolacustrine sediments should typify ice-marginal deltaic environments (Cohen, 1983). The pronounced and widespread upvalley dip of beds in unit 2 is consistent with the interpretation of an ice-marginal deltaic or pro-deltaic depositional environment.

Gravel concentrations capping some diamicton beds (eg. Figure 8d) probably result from winnowing by bottom currents or subaerial exposure. Periodic traction deposition is indicated by minor ripple and cross-bedded sand, pebbly sand and pebbly gravel beds. The increase in thickness of diamicton beds and traction deposits up section indicates a gradual infilling of the ice-marginal lake. The upward increase in the total number of erratic and striated clasts suggests the increased influence of glacier expansion in the main valley.

Unit 3

Unit 3 is dominated by matrix-supported diamicton (Figure 9a). The lower part of the unit (unit 3a; Figures 2 and 4 and Appendix 1) exhibits weak, horizontal stratification due to textural variations in the diamicton and the presence of numerous silt and fine sand beds and laminae. Load structures and folded laminae are common.

Almost five metres of dense, massive diamicton (Figure 9b) with numerous striated and glacially shaped clasts and polished subhorizontal partings occurs in the middle of unit 3 (unit 3b; Figure 2). Small lenses of silt, clay and sand near the top of unit 3b commonly exhibit compressive deformation structures such as thrust faults, reverse faults, folds and sub-horizontal shear zones (Figure 9c). Slickensides on shear zones (Figure 4) trend 110° to 150°, approximately parallel to the South Big Salmon River valley. The lower contact of unit 3b is gradational.

Unit 3c consists of about 7 m of sandy, loosely consolidated diamicton interbedded with silt, sand and gravel (Figure 9b). Diamicton beds are matrix to clast-supported (Figure 9d) with the total clast and sand content increasing towards the top of the unit. Massive or horizontally stratified sand and silt beds and trough cross-stratified sand and gravel lenses are common throughout the unit (Figure 9e).

Diamicton beds in unit 3a are interpreted as debris flow deposits. The presence of folded laminae believed to be flow folds support this interpretation. Load structures and deformed bedding indicate that the diamictons were deposited rapidly over unconsolidated sediments. The horizontal stratification, fine grain size and excellent sorting of the silt and sand beds suggests that they are mainly lacustrine sediments. The abundance of silty laminae and the association of these sediments with the underlying glaciolacustrine deposits suggests that the debris flows were dominantly subaqueous. Similar stratified diamictons with silt and sand laminae were interpreted as ice-marginal, subaqueous debris flows by Boulton (1968), Evenson et al. (1977), Eyles (1987) and Levson and Rutter (1988).

The diamicton in unit 3b is interpreted as a subglacial till probably deposited by lodgment processes. The sedimentary characteristics of the diamicton are typical of lodgment tills (Dreimanis, 1988). Partings, faults and shear zones probably formed at or near the sliding base of an overriding glacier. This is supported by the orientation of slickensides parallel to the inferred direction of former ice flow down the South Big Salmon River valley. Pebble fabric data from the upper part of unit 3b (Figure 4) also support this interpretation. The long axes of pebbles have a strong ($S1 = 0.75$) preferred

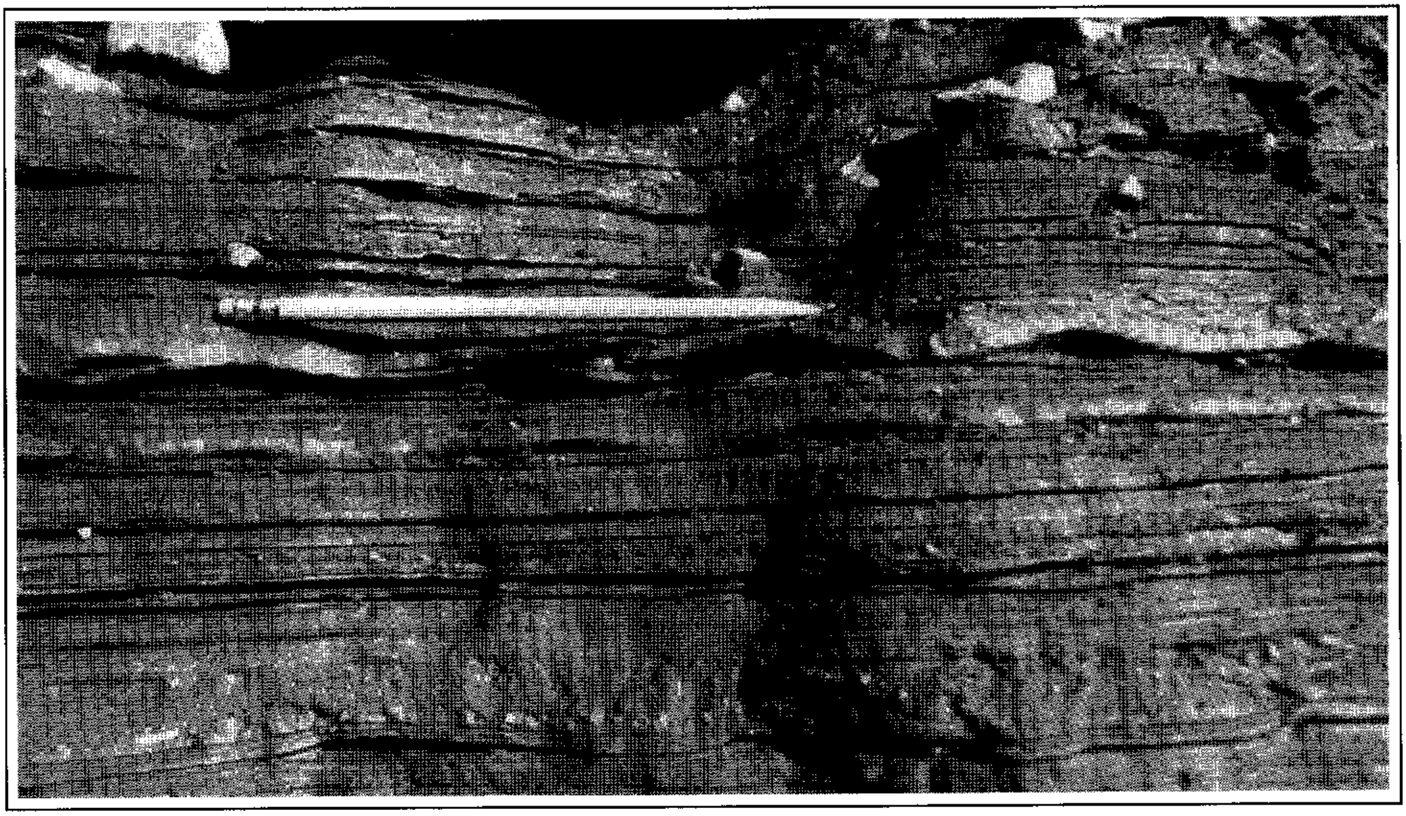


Figure 8. Proximal glaciolacustrine sediments of Unit 2 at Martin Creek. (a) Parallel-laminated silts and clays with thin intrabeds of diamicton and ripple-bedded fine sand and numerous dropstones.

Fig. 8(b). Deformed strata under dropstone in unit 2b. Note: 1 cm thick fine sand bed below scale and diamicton bed at top.

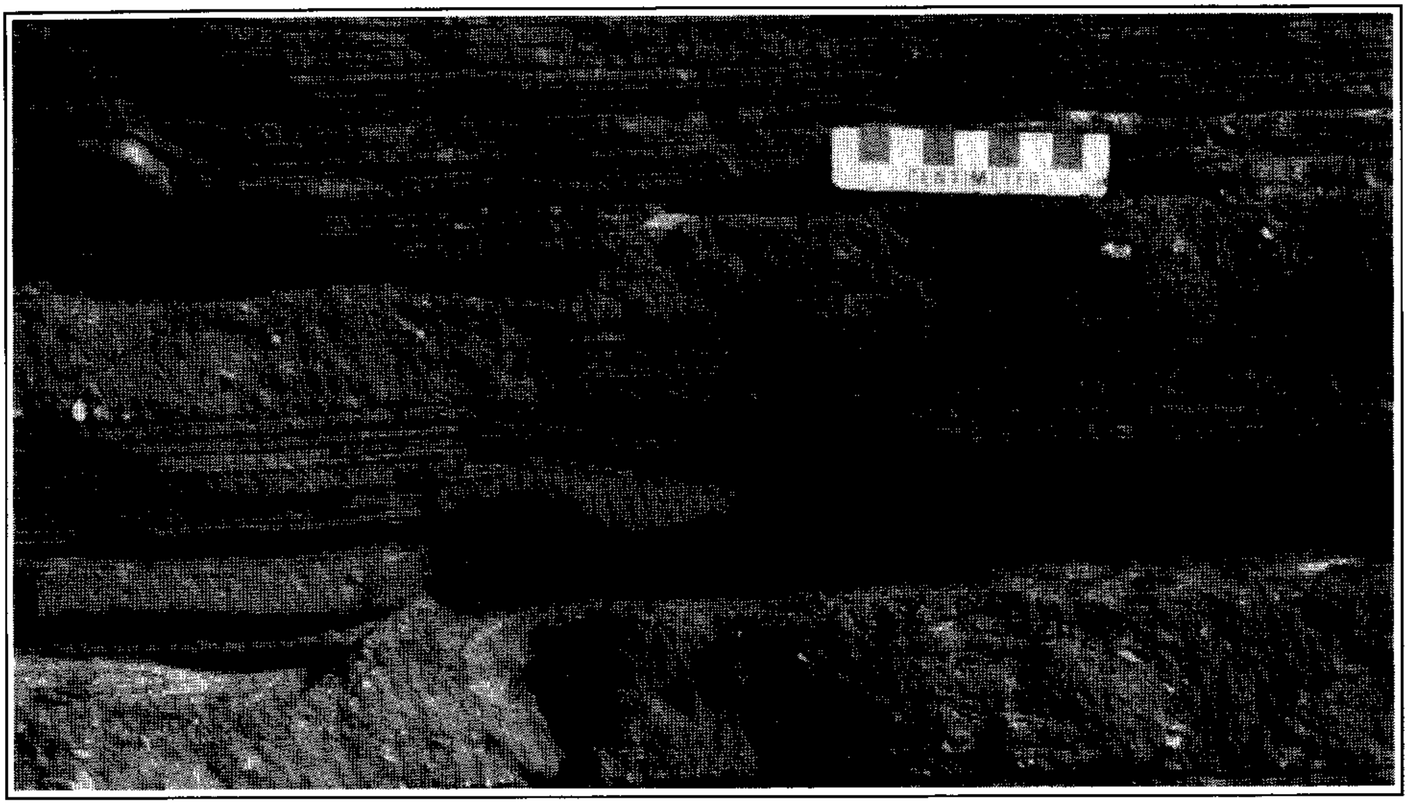


Fig. 8(c). Normal fault in interbedded diamicton and fines.

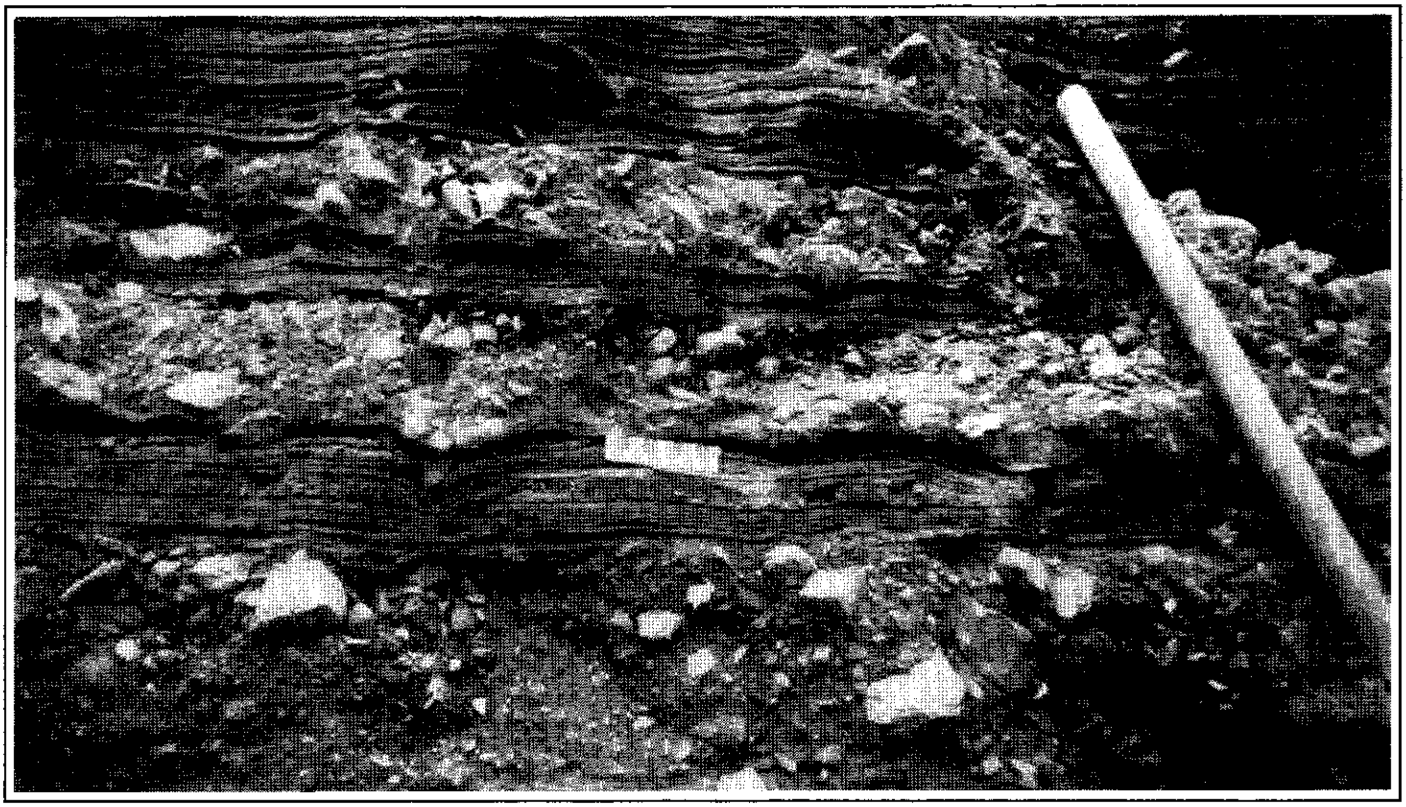


Fig. 8(d). Reversely graded debris flow deposits in laminated silts and clays. Note: gravel concentration at top of diamicton bed above small scale bar.

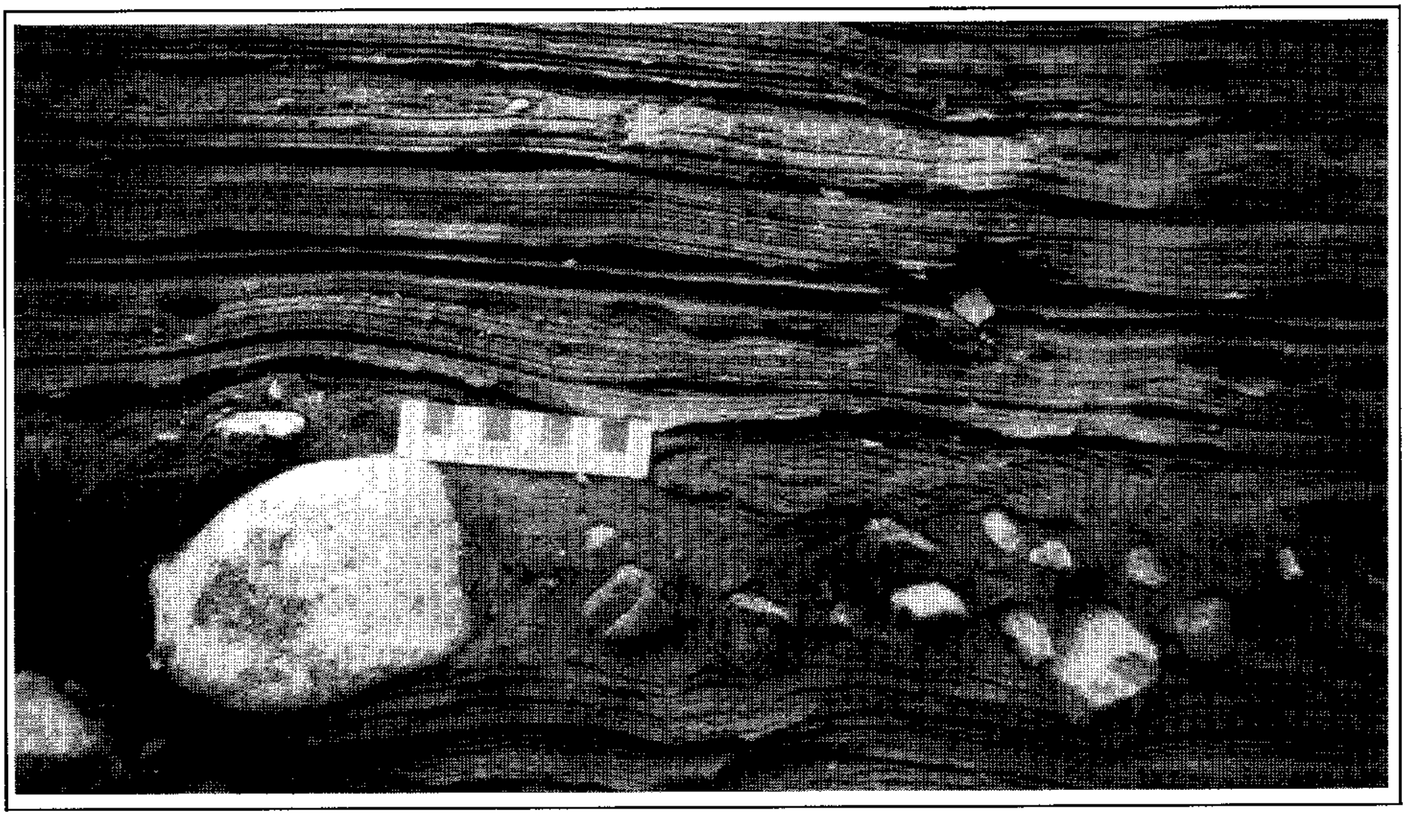


Fig. 8(e). Folded silt and clay intraclasts within diamicton bed.

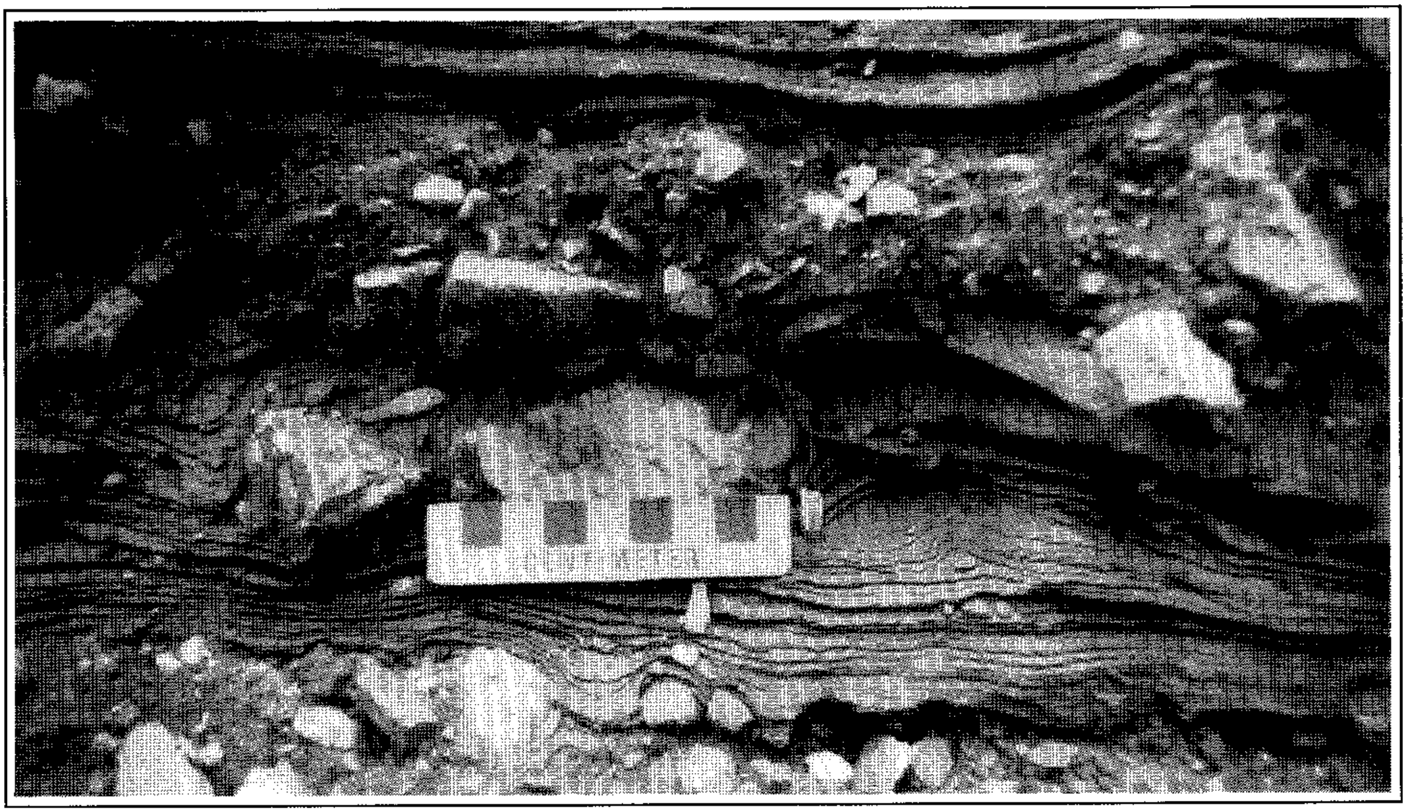


Fig. 8(f). Large mud intraclast in diamicton bed (above and right of scale) and mud drapes over clasts protruding from the top of the lower diamicton bed.

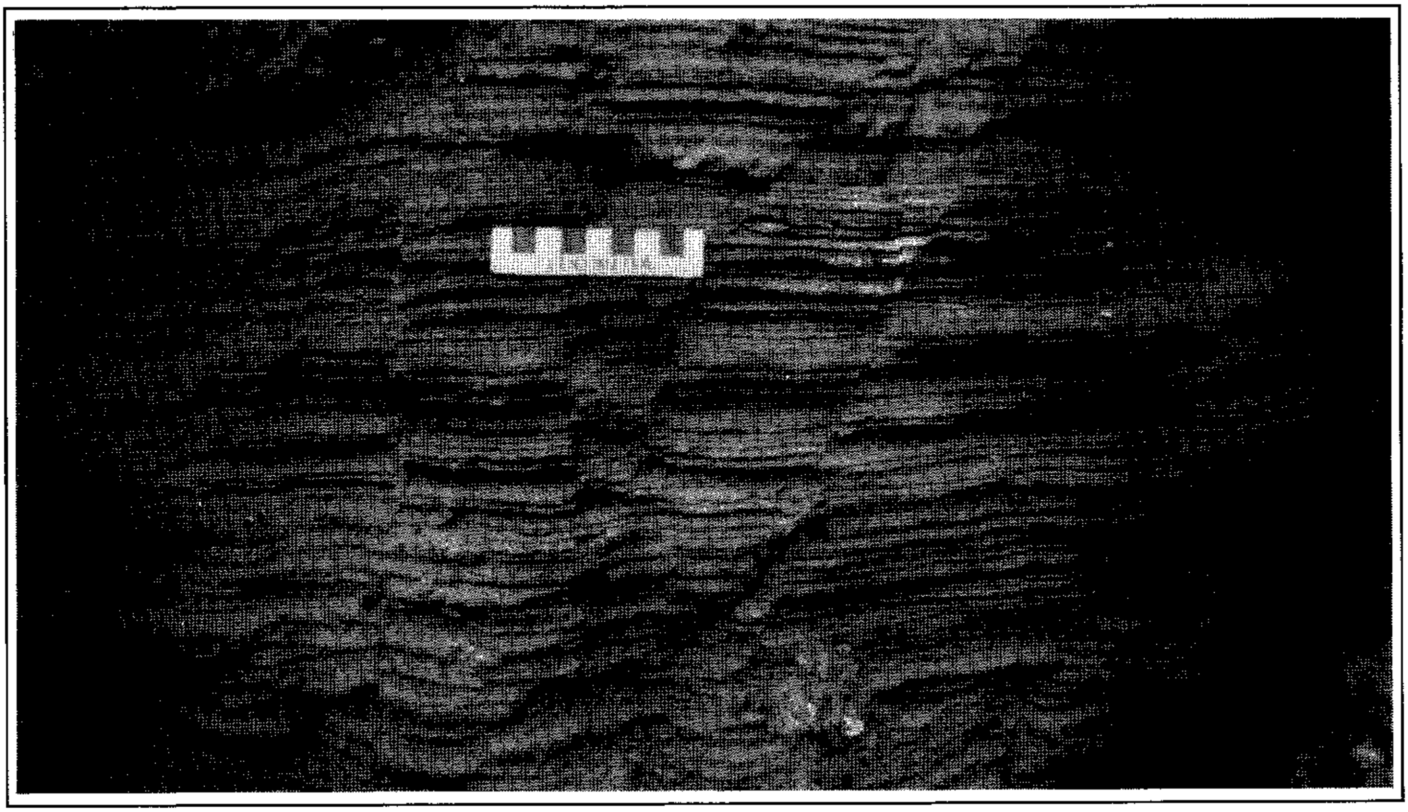


Fig. 8(g). Abundant normal faults in unit 2c.

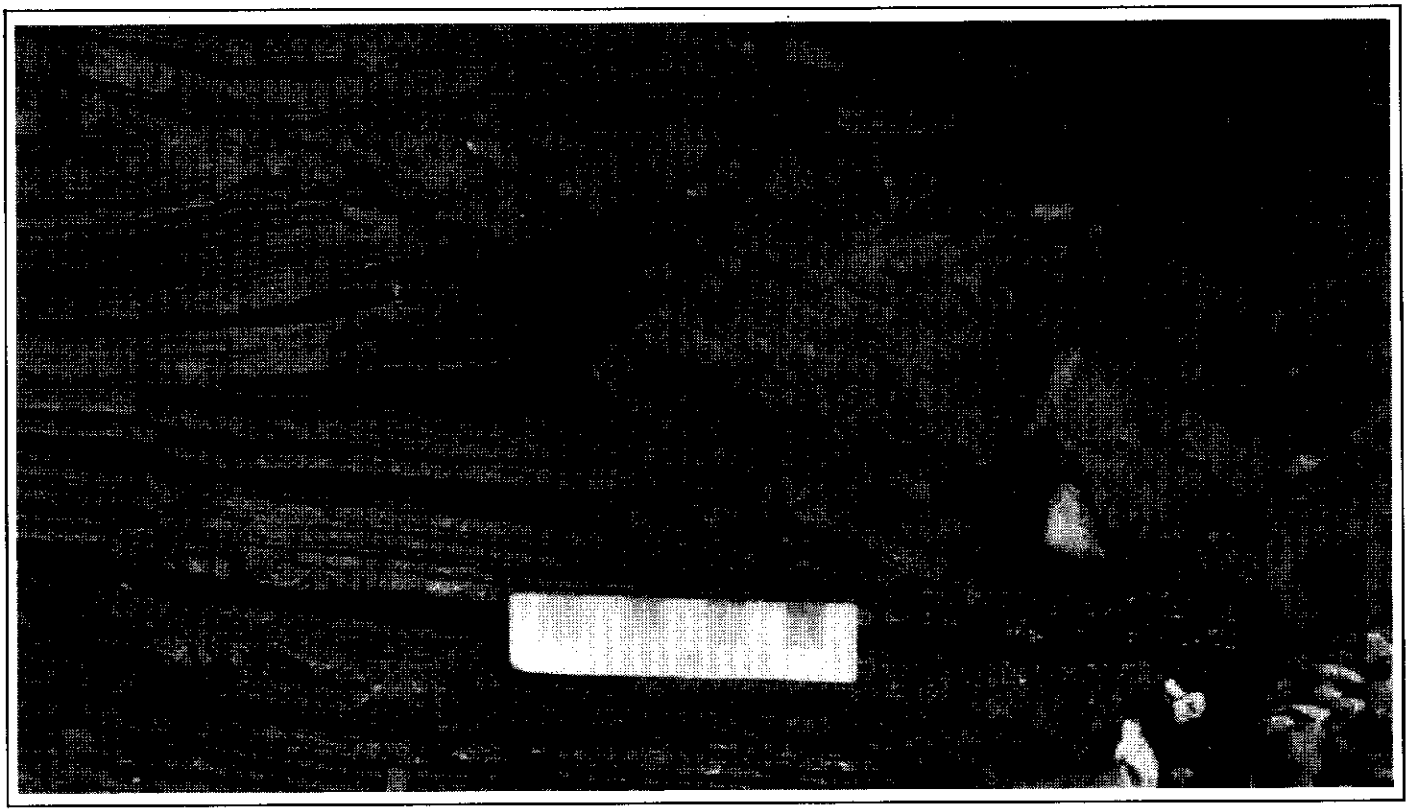


Fig. 8(h). Intraformational slump structure.

Figure 9. Sedimentary characteristics of units 3 and 4 at Martin Creek. (a) Matrix-supported diamicton with weak textural stratification in unit 3a.

Fig. 9(b). Massive diamicton of unit 3b grading up into unit 3c and unconformably overlain by unit 4.

orientation (V1 = 126°) parallel to the trend of slickensides and the main valley (Figure 4). Pebbles at the base of unit 3b have a relatively weak (S1 = 0.62) preferred orientation at right angles (V1 = 047°) to the trend of the main valley but parallel to the Martin Creek valley (Figure 4). This suggests that the lower part of unit 3b may have a debris flow origin similar to the underlying diamicton of unit 3a.

The large number of clasts of erratic lithology in unit 3b also supports a glacial origin. The provenance of the clasts indicates a substantial input of debris from glaciers which originated in the main valleys to the south and, to a lesser degree, in tributary valleys to the southwest. The higher percentages of clasts derived from the Omineca Crystalline Belt in overlying units (Figure 7) may reflect the increased influence of an inset tributary glacier that likely originated in the Big Salmon Range and flowed down the upper South Big Salmon River valley.

The high clast content and sandy texture of the diamictons in unit 3c is typical of debris flow deposits that have been washed during one or more cycles of resedimentation (Lawson,1979; 1981a; and 1981b). The weak (S1 = 0.58) preferred orientation of pebbles in unit 3c (Figure 4) is also typical of debris flow deposits. Lenses and beds of sorted material are interpreted as fluvial sediments deposited between debris flow events. Lawson (1979) found that thin layers of sand and silt often separate diamictons deposited by individual flows. A decrease in the number of striated clasts and increased sorting toward the top of the unit probably reflects greater dominance of fluvial activity. All of unit 3c occurs in a wide (> 50 m), trough-shaped body which is interpreted as a broad channel that presumably developed along the ice margin during deglaciation.

Unit 4

Unit 4 consists of about 12 m of mainly horizontally stratified gravels (Figures 9b, 9f, and 9h). Beds of open-work, poorly sorted, cobble to boulder gravel are interbedded with poorly to moderately sorted, matrix-filled, pebbly gravel and sand beds (Figure 9f). Some lenses of well sorted, horizontally stratified and planar and trough cross-stratified sand lenses also occur (Figure 9g). Lower bed contacts are commonly erosional. The lower contact of unit 4 is

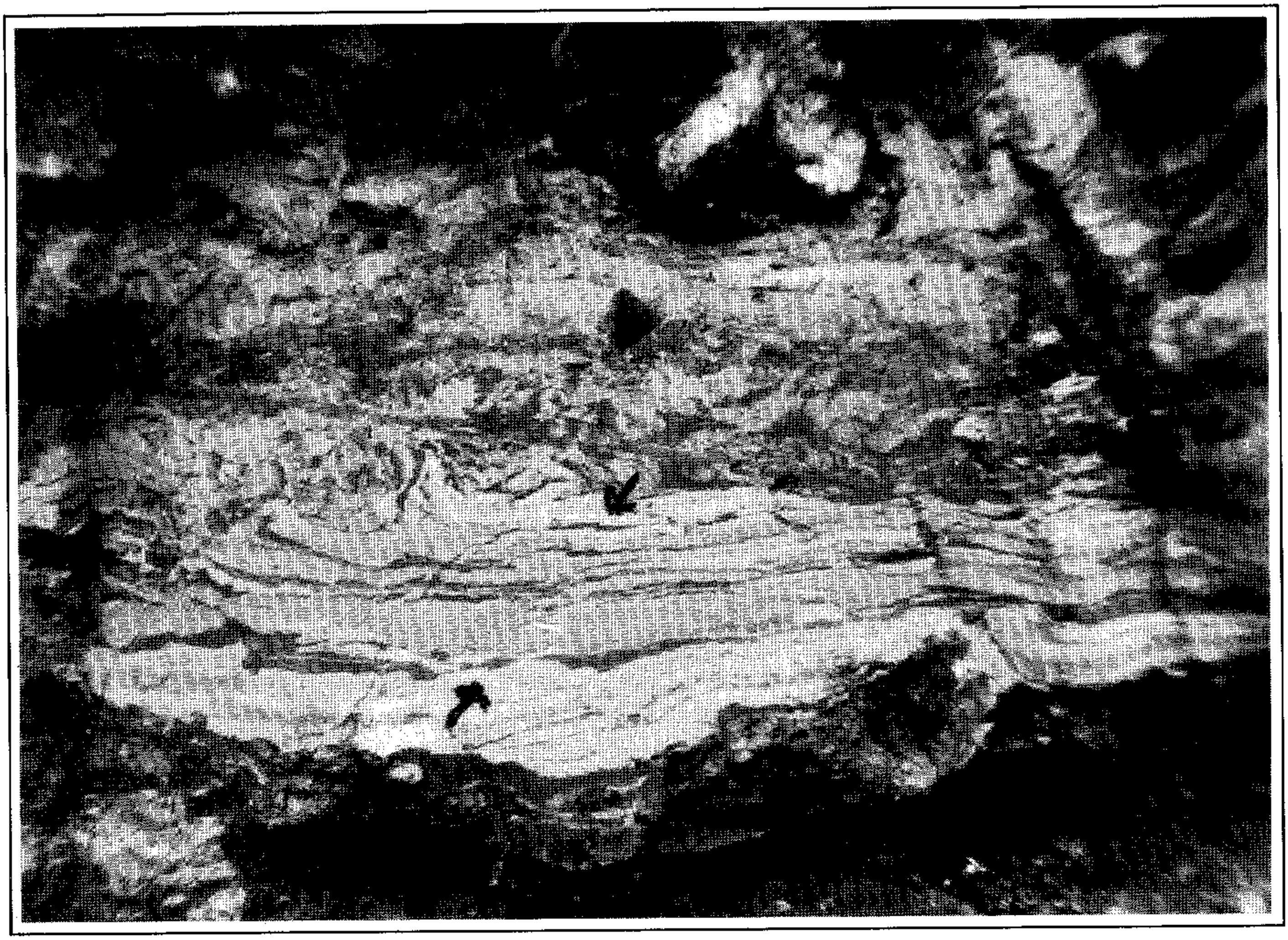


Fig. 9(c). Subhorizontal shear zones and compressively deformed strata (arrows are 1 cm long and point to a sample reverse fault) at the top of unit 3b.

unconformable and forms a large scour (Figure 9h) similar in size and shape to the channel shaped lower contact of unit 3c. Deposits of this type are typical of gravelly, proximal, braided rivers in glacial environments (Rust, 1972; Church and Gilbert, 1975; Boothroyd and Ashley, 1975).

Crude horizontal stratification is commonly formed in longitudinal bars which characterize gravel-bed braided streams (Smith, 1974). Scoured lower bed contacts and sharp variations in grain size distribution are typical of ice-marginal streams where large variations in discharge occur and sedimentation is highly episodic (Church and Gilbert, 1975). The similar size and shape of the lower contacts of units 3 and 4, suggests that unit 4 was deposited in the same ice-marginal channel as unit 3c. During deposition of unit 4, however, fluvial processes dominated over, or eroded any evidence of, debris flow sedimentation.

Unit 5

In an area of highly irregular or hummocky topography directly south of the main Martin Creek Section, shallow exposures reveal a complexly interbedded series of diamicton, gravel and sand beds described here as unit 5 (Appendix 1). Although the lower contact is not exposed, unit 5 apparently overlies unit 3 and is laterally equivalent to unit 4.

At the SW end of the exposure (Figure 10a) a large trough shaped unit of diamicton (unit 5a, Appendix 1) is conformably overlain by large scale trough cross-stratified sands (unit 5b). The NE limb of the trough grades into crudely stratified gravel, sand and diamicton beds (unit 5c) that dip upstream (NE) as much as 30°. These beds are conformably overlain by bouldery gravel (unit 5d). Strata in unit 5d are folded into a large (about 10 m wide) wedge-shaped feature (with beds dipping 60-80° in opposing directions). This is interpreted as a collapse structure (Figure 10b). The section here is capped by large troughs of well stratified sand and gravel (unit 5e). Folds and normal faults are common and increase in intensity towards the base of the unit (Figure 10c). At the NE end of the exposure, closest to the main Martin Creek Section, sand and gravel beds (unit 5f) dip about 20° downstream (Figure 10d). They are unconformably overlain by interbedded and convoluted diamicton, gravel and sand beds (unit 5g) that dip 20° upstream (Figure 10d).

Unit 5 is interpreted as an ice-marginal glaciofluvial complex. The unusually large and sharp changes in grain

Fig. 9(d). Sand bed and matrix to clast-supported diamicton at base of unit 3c.

size, sorting, bedding dip and dip direction support this interpretation. The presence of closely juxtaposed sorted deposits ranging from silts and sands to boulder gravels is typical of proximal glaciofluvial sediments (Boulton and Eyles, 1979; De Jong and Rappol, 1983). Large scale trough cross-stratification is interpreted as channel-fill bedding. The associated sands and gravels are inferred to be glaciofluvial sediments that infilled small ice-marginal channels. Diamicton and poorly sorted gravel beds were probably deposited by resedimentation processes. Such processes are common in ice-marginal environments (Lawson, 1979, 1981a, 1981b and 1982). The abundance of deformation structures is also typical of ice contact deposits (Schwan and Van Loon, 1979; and Hambrey, 1984). Normal faults and collapse structures probably formed as a result of melting of underlying or adjacent ice. The irregular and hummocky topography are also strongly suggestive of an ice contact origin. The stratigraphic position and surface expression of these sediments suggests that they were deposited along the ablating margin of the last glacier to occupy the area.

Livingstone Creek Section

A stratigraphic column and brief unit descriptions for the Livingstone Creek Section are provided in Figure 5. The general stratigraphy of the section is very similar to the Martin Creek Section and is not discussed in detail here.

The gravels immediately overlying the bedrock are coarse, poorly sorted and clast-supported. They exhibit weak horizontal bedding with minor open work pebble gravel and trough cross-bedded sand layers. Although most clasts are well rounded to subrounded some beds are dominated by very angular clasts of local origin. These gravels are similar to the gravel facies of unit 1 at Martin Creek. They are also interpreted as high energy stream channel and gulch sediments deposited by channelized fluvial flows and gravelly debris flows.

Parallel-laminated silts and clays with numerous erratic dropstones and pebble intrabeds in unit 3 are similar to those exposed in unit 2 at Martin Creek. They exhibit sedimentary structures typical of proximal glaciolacustrine sediments (Ashley, 1988). Intense folding of some silt and clay beds indicates remobilization of the lake sediments. Intrabeds of local, brecciated gravel with some rounded erratic clasts in a clay matrix were probably deposited by subaquatic debris flows that mixed pre-existing gravels with the finer lake sediments (Larsen and Steel, 1978). The lensoid shape of the beds and presence of soft-sediment intraclasts indicates that the flows were erosive.

The presence of lake sediments at similar stratigraphic positions in the Martin and Livingstone Creek valleys supports the interpretation that a glacier, flowing down the South Big Salmon River valley, blocked the tributaries and caused small ice-marginal lakes to form. Instability of the local bedrock slopes was probably caused by the presence of the lake water and the movement of the adjacent glacier, resulting in mass movements of local materials into the lake. This would explain the dominance of local, angular clasts in the pebble intrabeds.

The diamicton units capping the Livingstone Creek Section (Figure 5) are not well exposed. They are matrix-supported and contain numerous striated clasts suggesting a glacial origin. Units 4 and 5 have stratigraphic and sedimentary characteristics similar to units 3a and 3b at Martin Creek and may also have been deposited, respectively, as debris flows and subglacial tills. The upward decrease in sand content may be due to a vertical progression from resedimented deposits to mainly till deposited directly by ice (Levson and Rutter, 1988).

Summit Creek Section

Bedrock (unit 1) at the Summit Creek section (Figure 5) is overlain by clast-supported, disorganized, coarse gravels (Figure 11a) similar to unit 1 at Martin Creek. These gravels are also interpreted as stream channel and debris flow

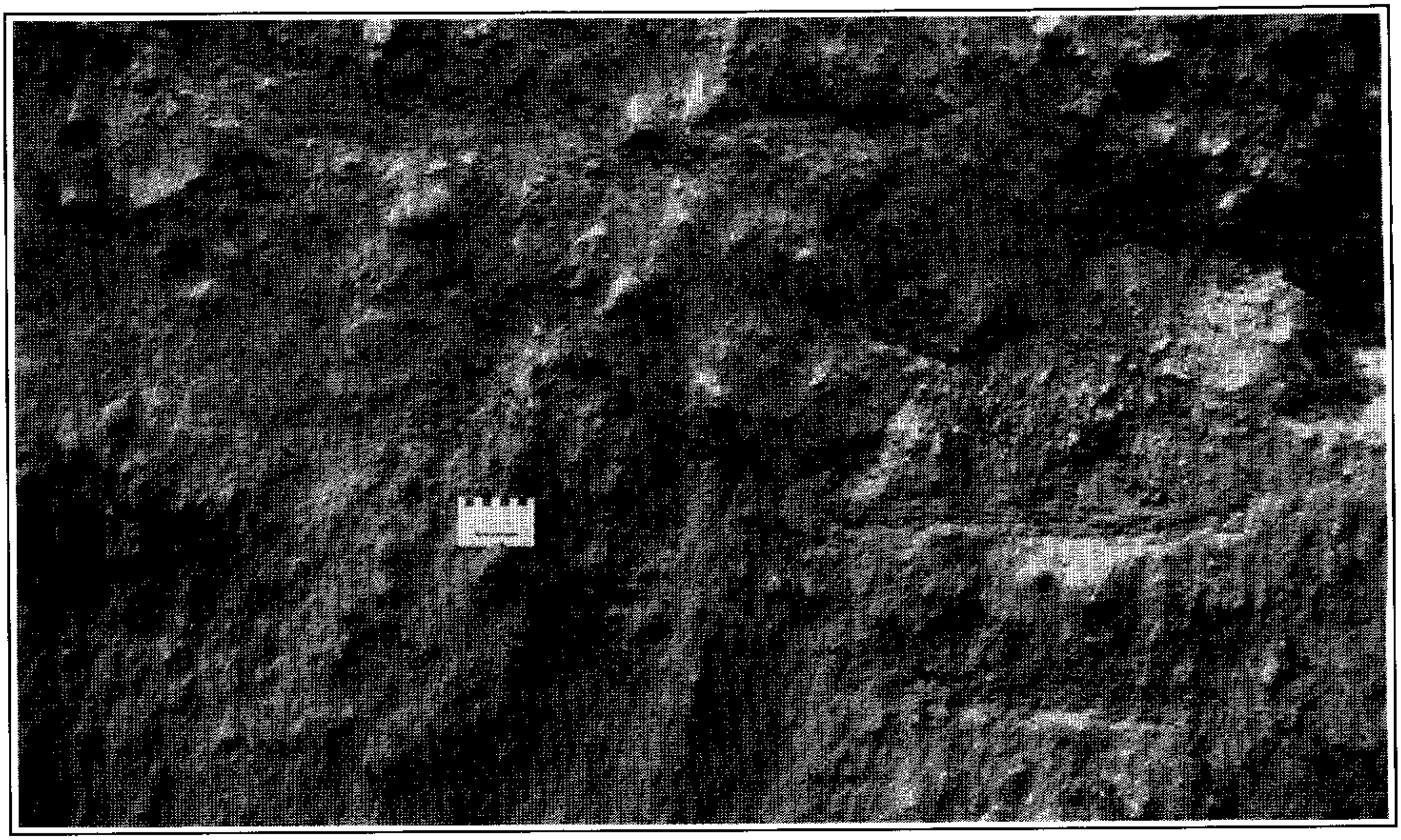


Fig. 9(e). Sandy diamicton with numerous stratified sand and gravel lenses near top of unit 3c.

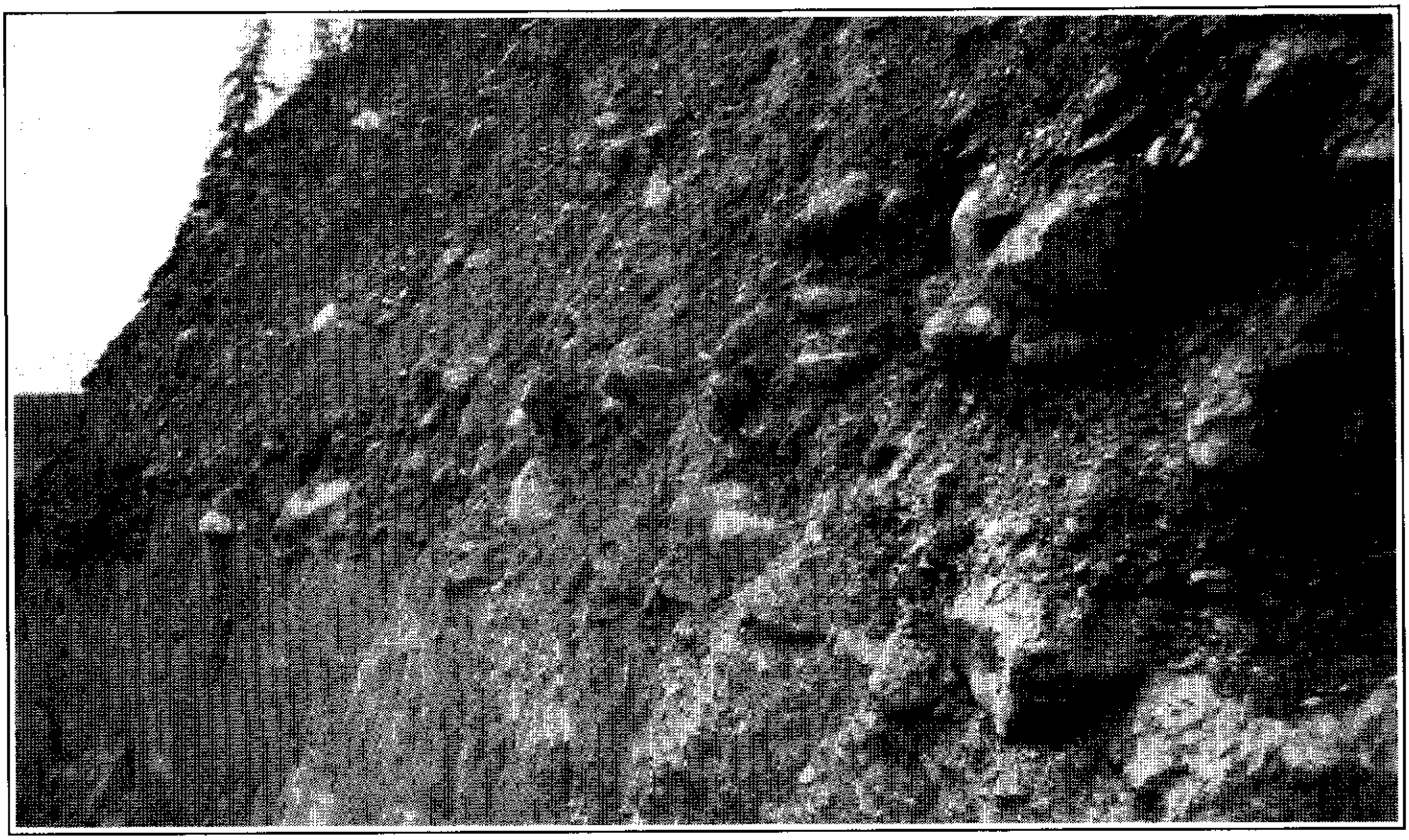


Fig. 9(f). Horizontally stratified, pebble to boulder gravels of unit 4 with erosional lower contact. Large boulders on right are nearly 1 m in diameter.

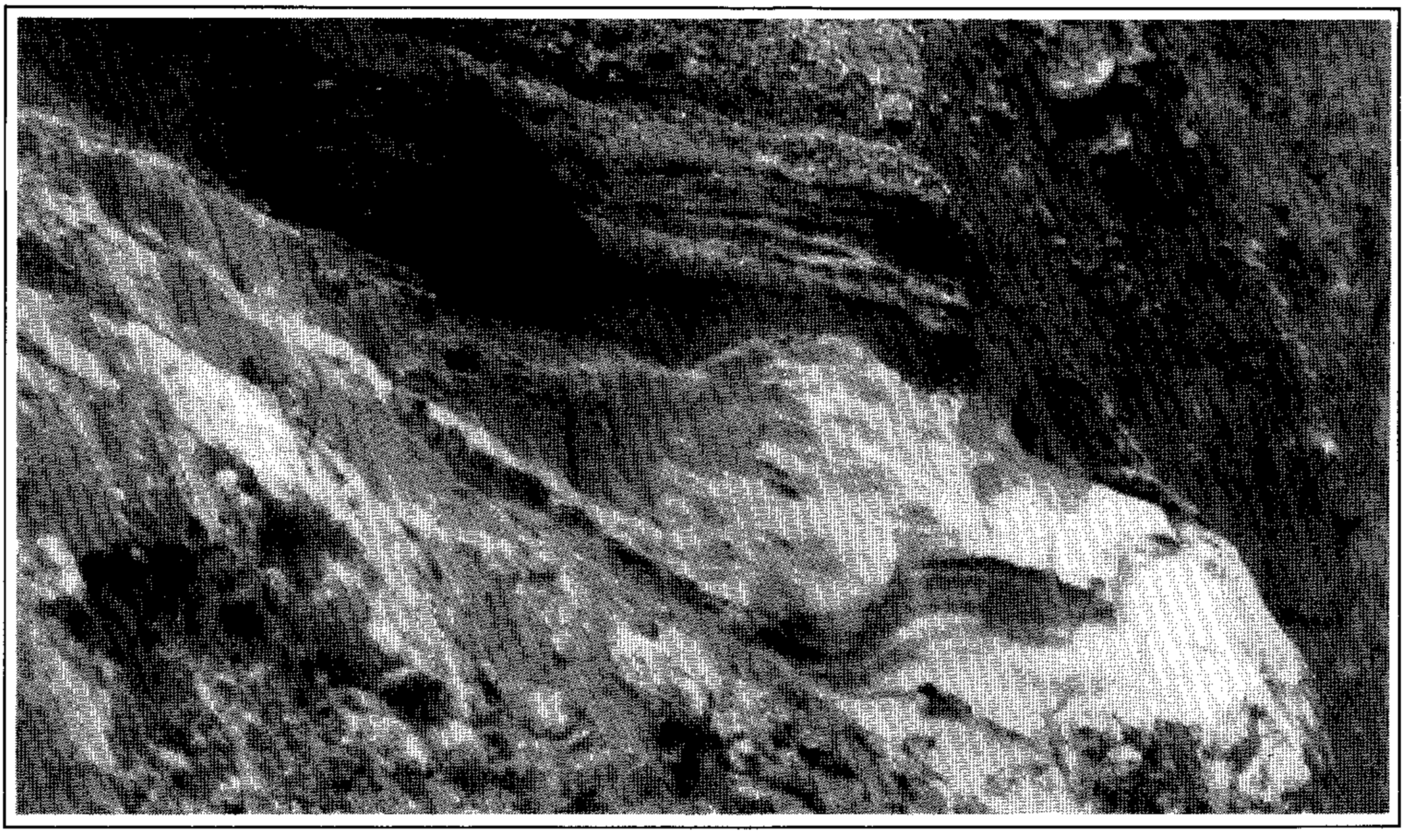


Fig. 9(g). Well sorted and cross-stratified sands interbedded with pebbly sands in a trough-shaped lens at the base of unit 4.

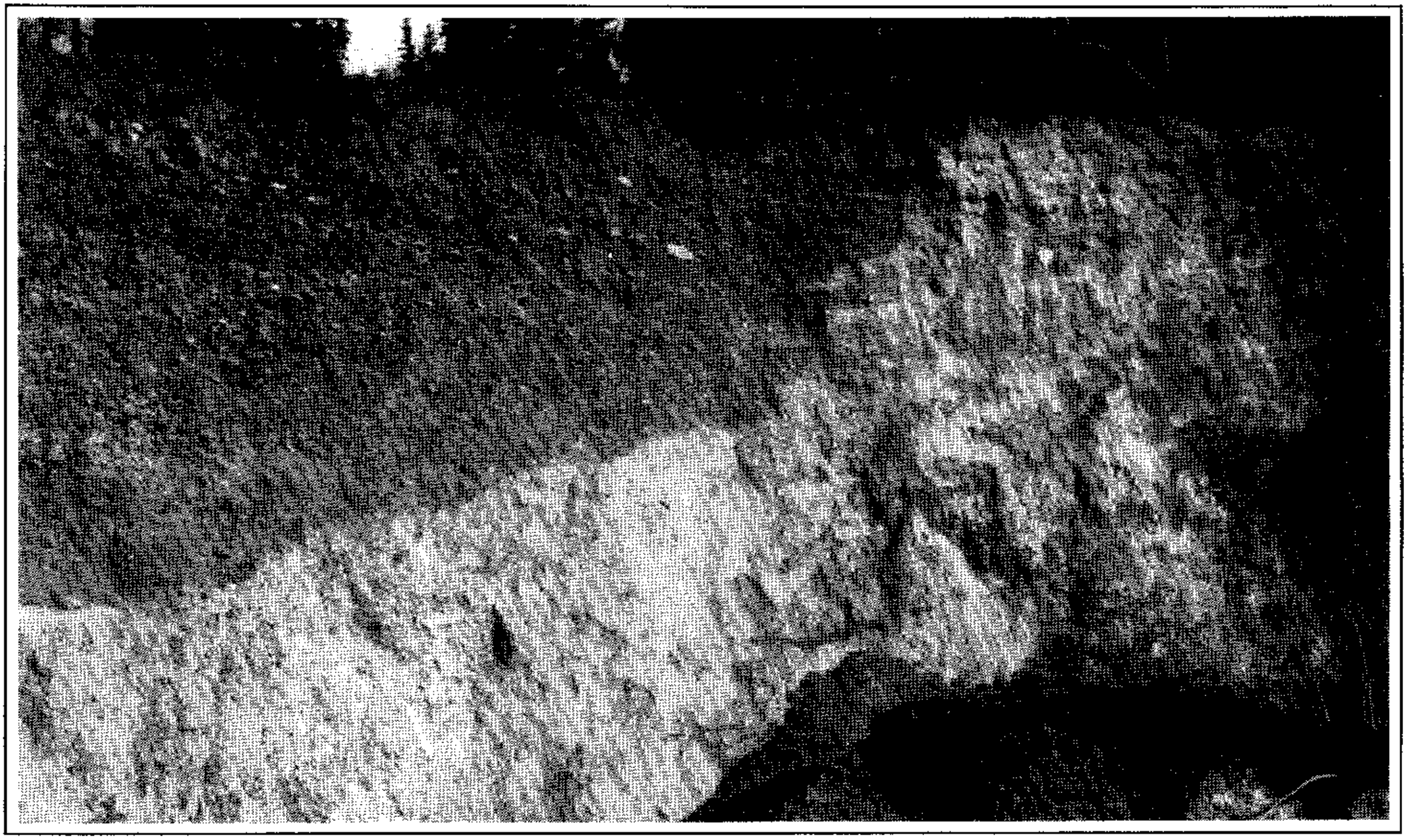


Fig. 9(h). Pronounced basal scour and channel shape of unit 4 gravels.

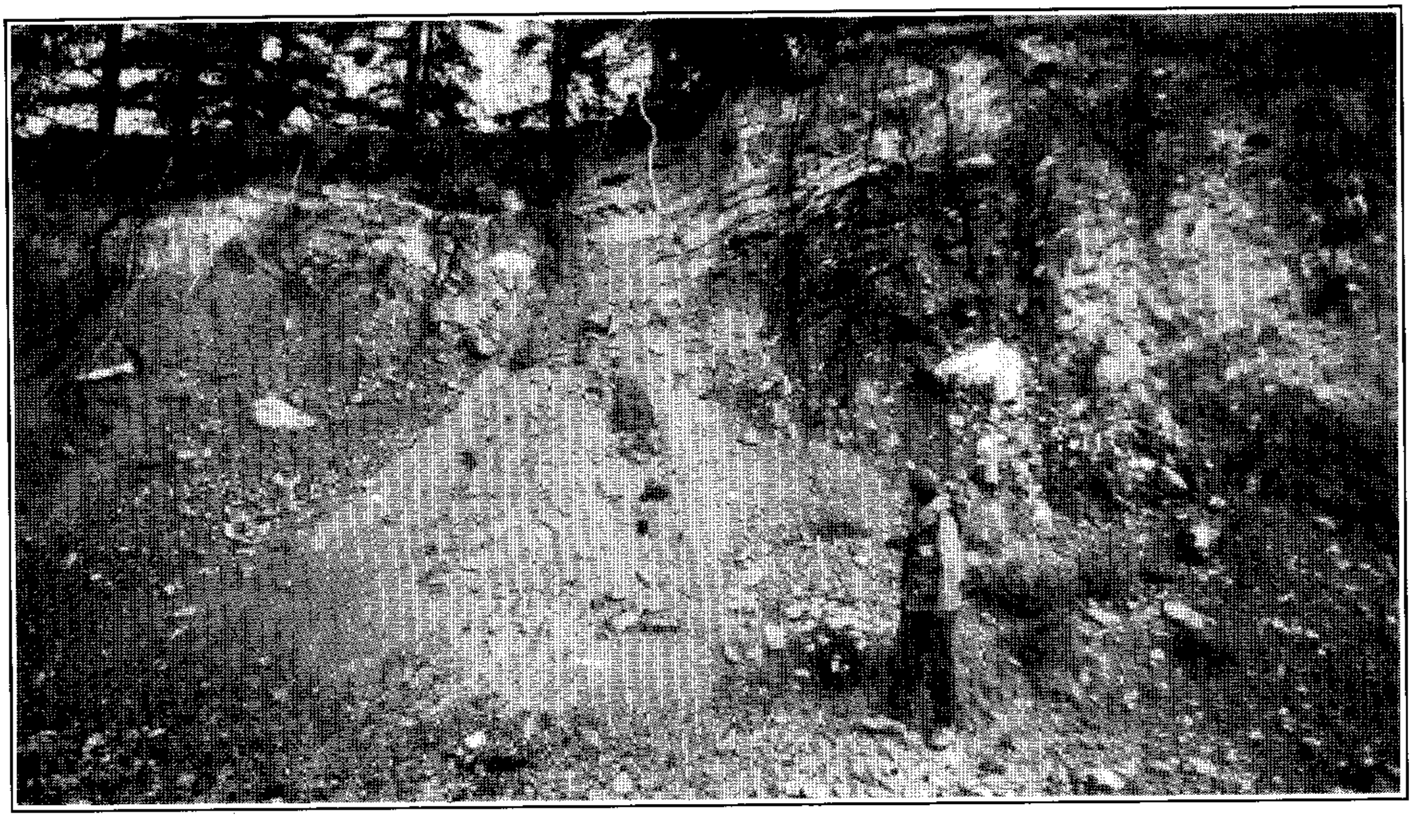


Figure 10. Ice-marginal, glaciofluvial deposits (unit 5) at the Martin Creek west exposure. (a) Diamicton of unit 5a overlain by channel sands and gravels (unit 5b).

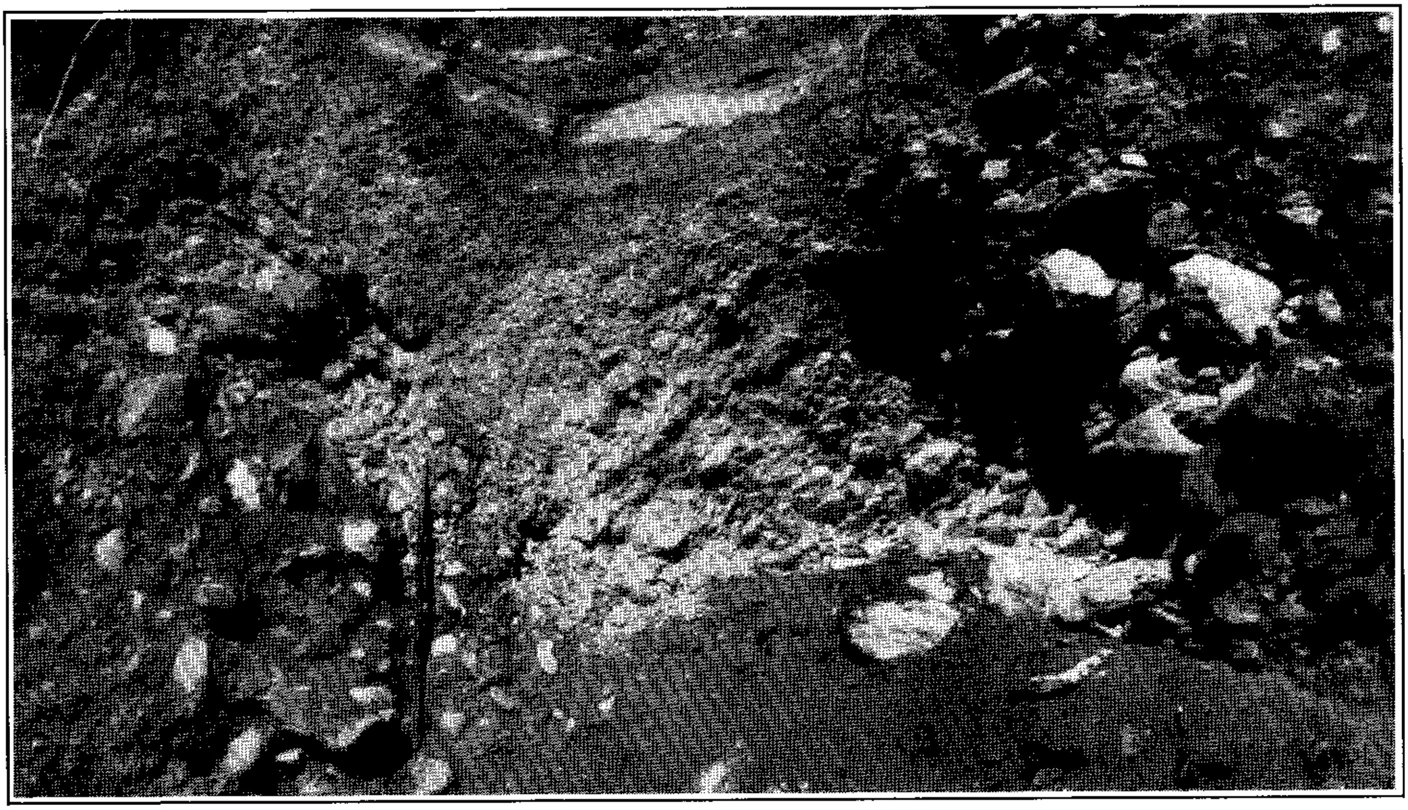


Fig. 10(b). Collapse structure in poorly sorted coarse gravel (beds dip towards photo center from both sides) (unit 5d) overlain by channel sands and gravels (unit 5e).

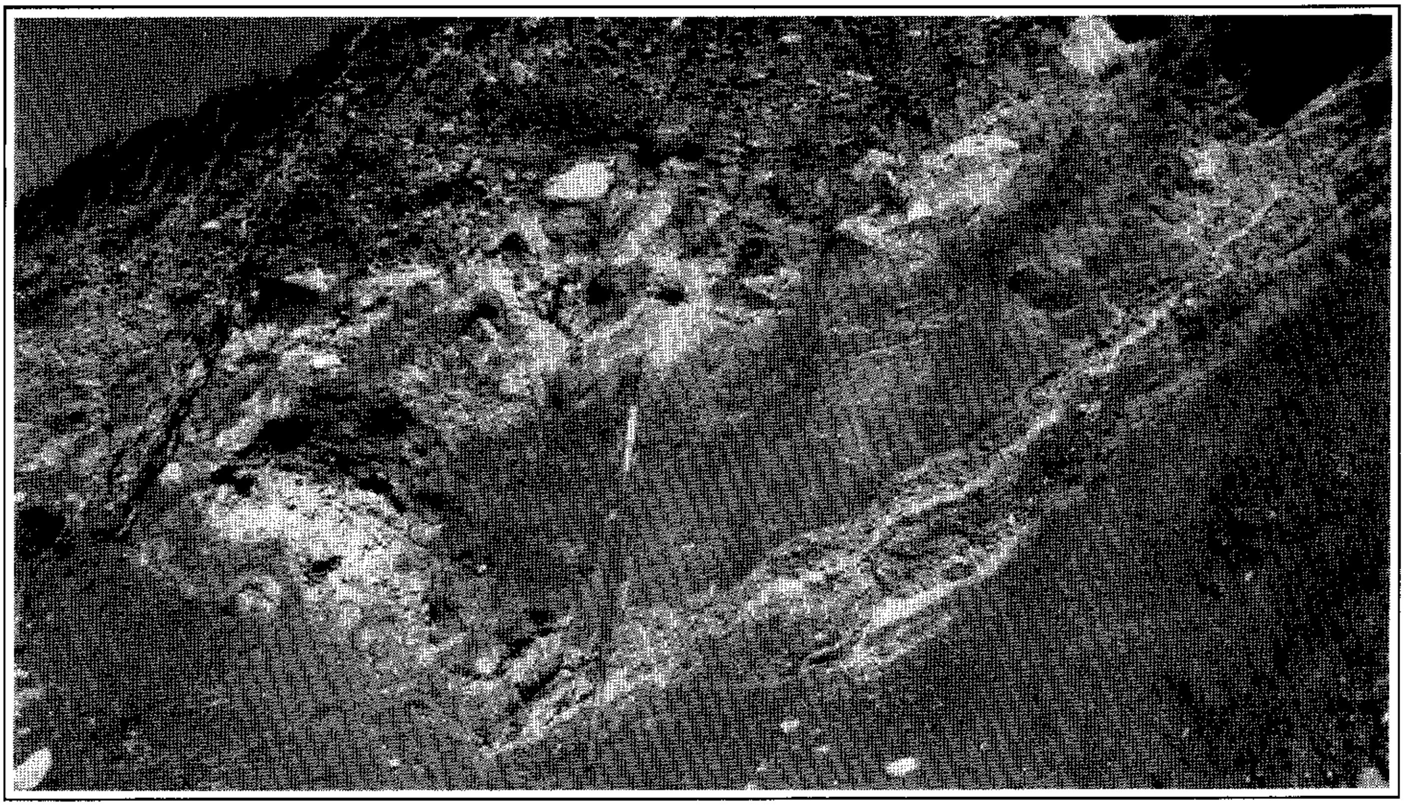


Fig. 10(c) Faults and folds at the base of unit 5e.

Fig. 10(d) Beds with opposing dip directions in ice-contact sand and gravel deposits of units 5f (right) and 5g (left).

deposits. They are overlain by horizontally stratified sands (Figure 11 b) which are interpreted as glaciolacustrine sediments. The lateral continuity of beds, uniform grain size, rarity of channelized features and presence of dropstones supports this interpretation.

Units 4 to 6 (Figures 5 and 11c) consist of clast-supported, well stratified, mainly open work, pebble to cobble gravels. A few boulder beds also occur. Planar cross-beds, dipping up to 31° to the northeast (opposite to the regional slope), dominate units 4 and 6 (Figures 11c and 11d). Individual cross strata are traceable for more than 5 m and are interpreted as deltaic foresets. In contrast to the good sorting and mainly open work structure of units 4 and 6, unit 5 gravels are poorly sorted and matrix-filled (Figure 11e). They exhibit horizontal to gently inclined planar bedding and are interbedded with parallel laminated silts and sands (Figures 11c and 11e). Pronounced erosional surfaces separate unit 5 from units 4 and 6 (Figure 11c).

The deposits of unit 5 are interpreted as delta front and pro-delta sediments, with the poorly sorted sandy gravels deposited by slumping and turbidity currents and the fine grained sediments representing quiet water sedimentation. Cohen (1983) interpreted similar interbedded fine grained and gravelly sediments in an ice-marginal deltaic sequence as the product of alternating foreset and bottom-set deposition induced by shifting sources of discharge and sediment supply.

The up-valley dip direction of bedding in units 4 to 6 indicates a debris source to the southwest in the South Big Salmon River valley. The only plausible explanation for this is that a glacier occupied the main valley and debris was washed from the ice surface or along the ice margin into the Summit Creek valley. This interpretation, combined with the presence of the delta and pro-delta sediments, indicates that an ice-dammed lake occupied the Summit Creek valley. Again, the presence of glaciolacustrine sediments in adjacent valleys at stratigraphically similar positions strongly supports this interpretation.

Clasts in units 4 to 6 are angular to subangular (Figure 11f) and up to 90% are locally derived (Figure 7), indicating that local bedrock was eroded by the ice or its meltwater and the clasts were transported only a short distance before being redeposited in the ice-marginal deltaic complex. The dominance of open-work beds of widely varying grain size is indicative of high and variable discharges typical of proximal glaciofluvial deposits. Changes from foreset (units 4 and 6) to pro-delta (unit 5) sedimentation indicate that the lake level must have fluctuated. Such variations are typical of ice-dammed lakes (Ashley, 1988). A rise in lake level must have occurred after deposition of unit 4 to allow for the deposition of the pro-delta sediments of unit 5. The prominent erosional surface separating units 4 and 5 probably formed as a result of slumping induced by the higher lake level. Progradation of unit 6 over unit 5 resulted in a sharp contact between the pro-delta (bottom set) sediments and the overlying delta front (foreset) beds.

The origin of the diamicton and poorly sorted gravel (unit 7) at the top of the section can not be determined due to poor exposure and inaccessibility. The poor sorting and high matrix component suggest that these sediments may be debris flow deposits or till, although a proximal glaciofluvial component is also likely.

SUMMARY

The coarse, dominantly local gravels exposed at the base of the Martin (unit 1), Livingstone (unit 2) and Summit (unit 2) Creek sections are interpreted as interglacial stream or gulch gravels. Concentrated fluvial and debris flow sedimentation likely occurred in response to unusually high storm or spring runoff events. The advance of a glacier down the South Big Salmon River valley resulted in damming of the channelized flows that deposited the underlying gravels. Ice-marginal lakes formed in each of the tributary valleys. Parallel-laminated clays, silts and sands were deposited in the ice dammed lakes along with debris flow deposits derived mainly from the ice margin (units 2 and 3a at Martin Creek and unit 3 at Summit Creek, and units 3 and 4 at Livingstone Creek). Ice-rafted debris and deformation structures characterize these sediments and are typical of proximal glaciolacustrine deposits. At Summit Creek a thick glaciofluvial delta complex (units 4 to 6) developed in the lake ponded in that valley.

As the glacier in the South Big Salmon River valley expanded, the lakes diminished in size and debris flow sedimentation increased until the area was overridden by ice. A thick till (unit 3b at Martin Creek, unit 5 at Livingstone Creek and unit 7 (?) at Summit Creek) was deposited at the base of the glacier. During deglaciation, a glaciofluvial complex developed along the ice margin in the Martin Creek area. Sedimentation occurred in an ice-marginal channel and was initially dominated by debris flow deposits (unit 3c). Glaciofluvial activity gradually increased in importance and eventually deposited a thick sequence of gravel (unit 4). Elsewhere the ice-marginal deposits developed an irregular glaciofluvial complex (unit 5). The series of meltwater channels that extend from south of Martin Creek to well north of Summit Creek, formed along the side of the South Big Salmon Valley in association with the ice-marginal deposits. Postglacial river erosion has incised through all of the overlying glacial deposits and has re-exposed the gold bearing gravels that have been mined throughout the twentieth century.

DISCUSSION

Damming of ice-marginal lakes in the all of the tributary valleys studied may have been critical for the preservation of the older gold bearing deposits. The lakes provided a quick transition from the subaerial stream gulch environment to a mainly depositional, quiet water environment. Sedimentation in the lakes was dominated by suspension settling, ice rafting, turbidity current, and debris flow processes. These processes are mostly depositional and none were sufficiently erosive to remove the underlying, coarse, interglacial gravels.

Figure 11. Summit Creek Section. (a) Poorly sorted, disorganized gravel (facies 1) in unit 2.

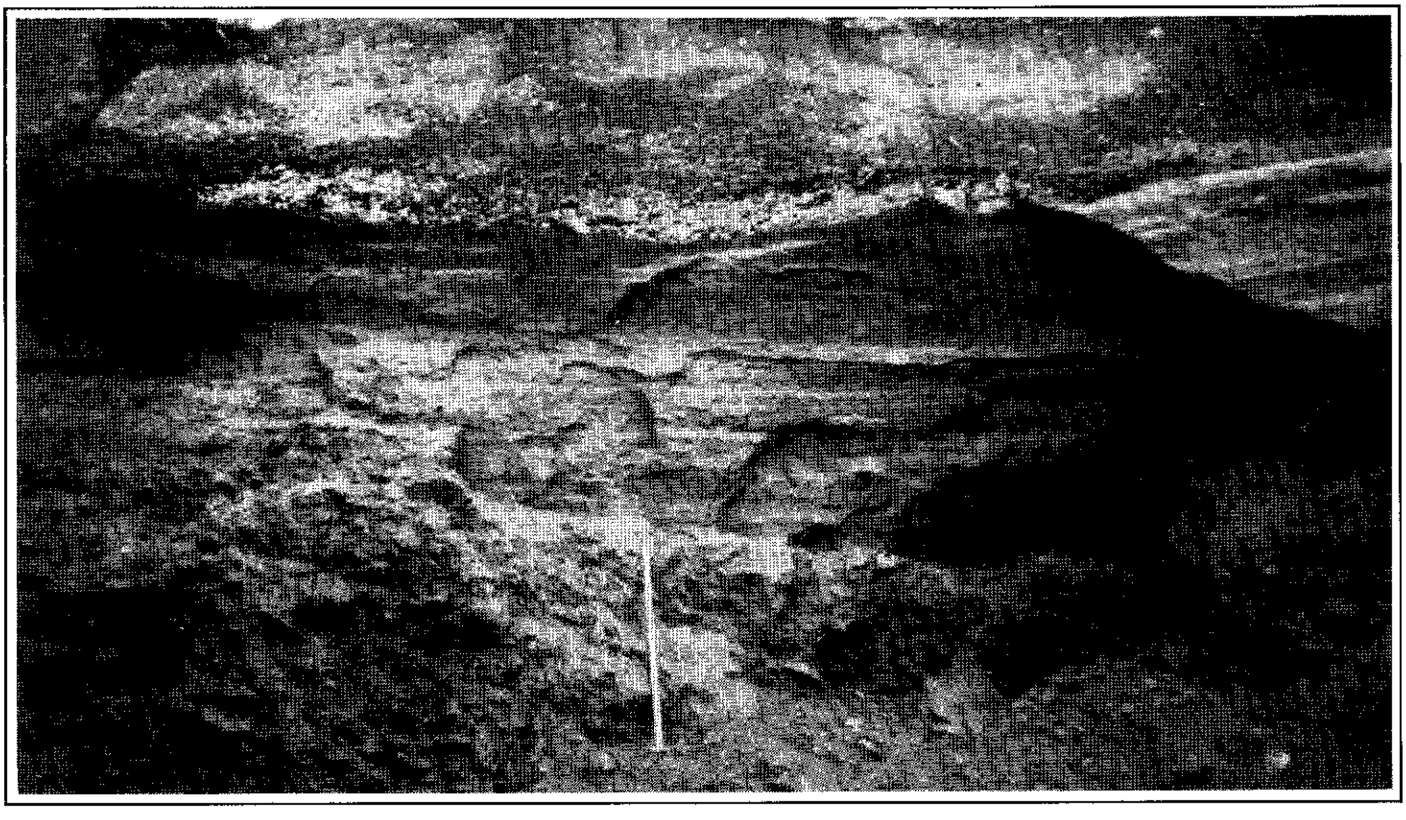


Fig. 11(b). Horizontally stratified bottom set sands (unit 3) overlying unit 2 gravels and unconformably overlain by unit 4 gravels. The top of the 1.5 m long rod is near the top of unit 2.

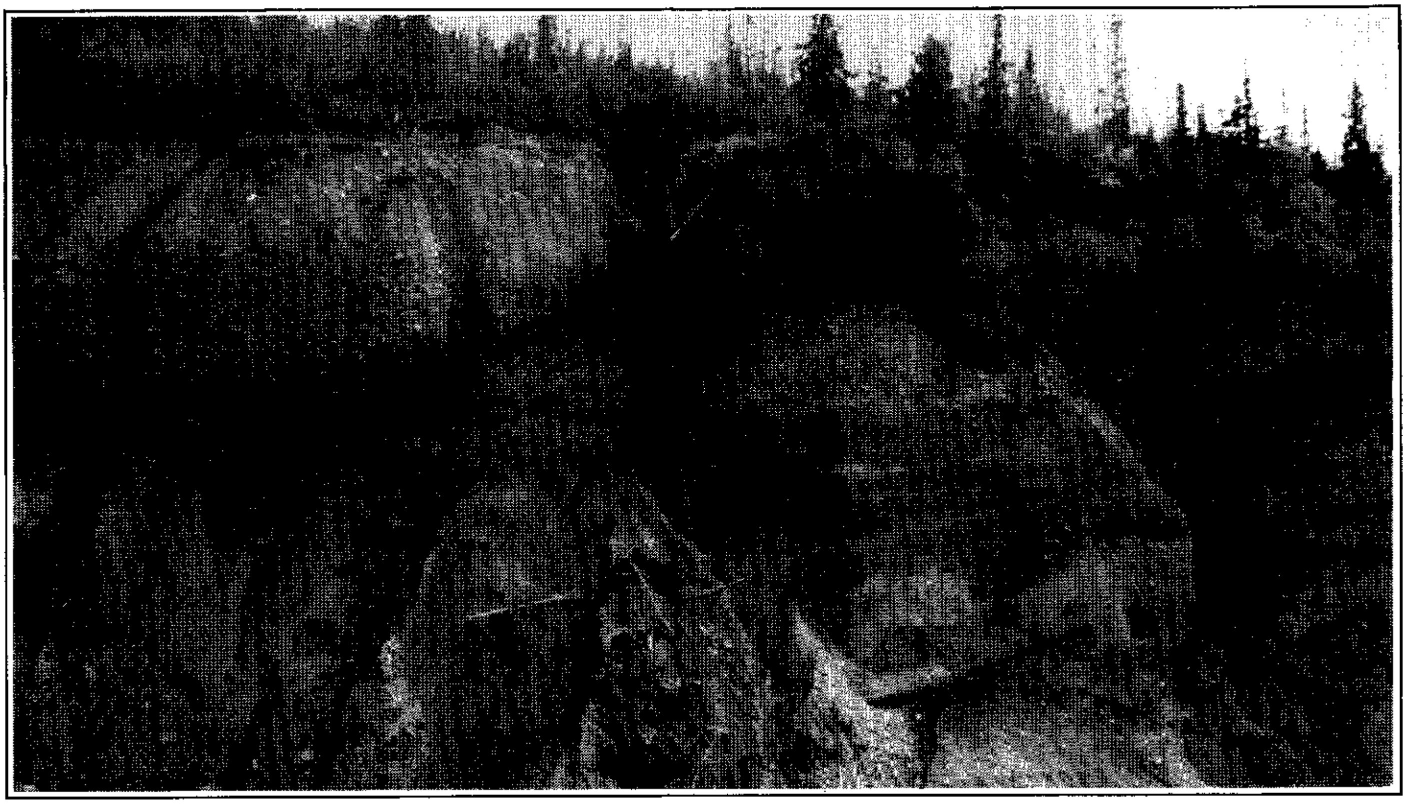


Fig. 11(c). Deltaic foreset gravels of unit 4 (lower right) and unit 6 (upper left) dipping steeply upvalley (left). Gently dipping, interbedded, sand and gravel strata of unit 5 (section center) are interpreted as delta front and pro-delta sediments. Pronounced unconformities separating unit 5 from units 4 and 6 probably resulted from major changes in water level or sediment source. Section is capped by a few metres of diamicton.

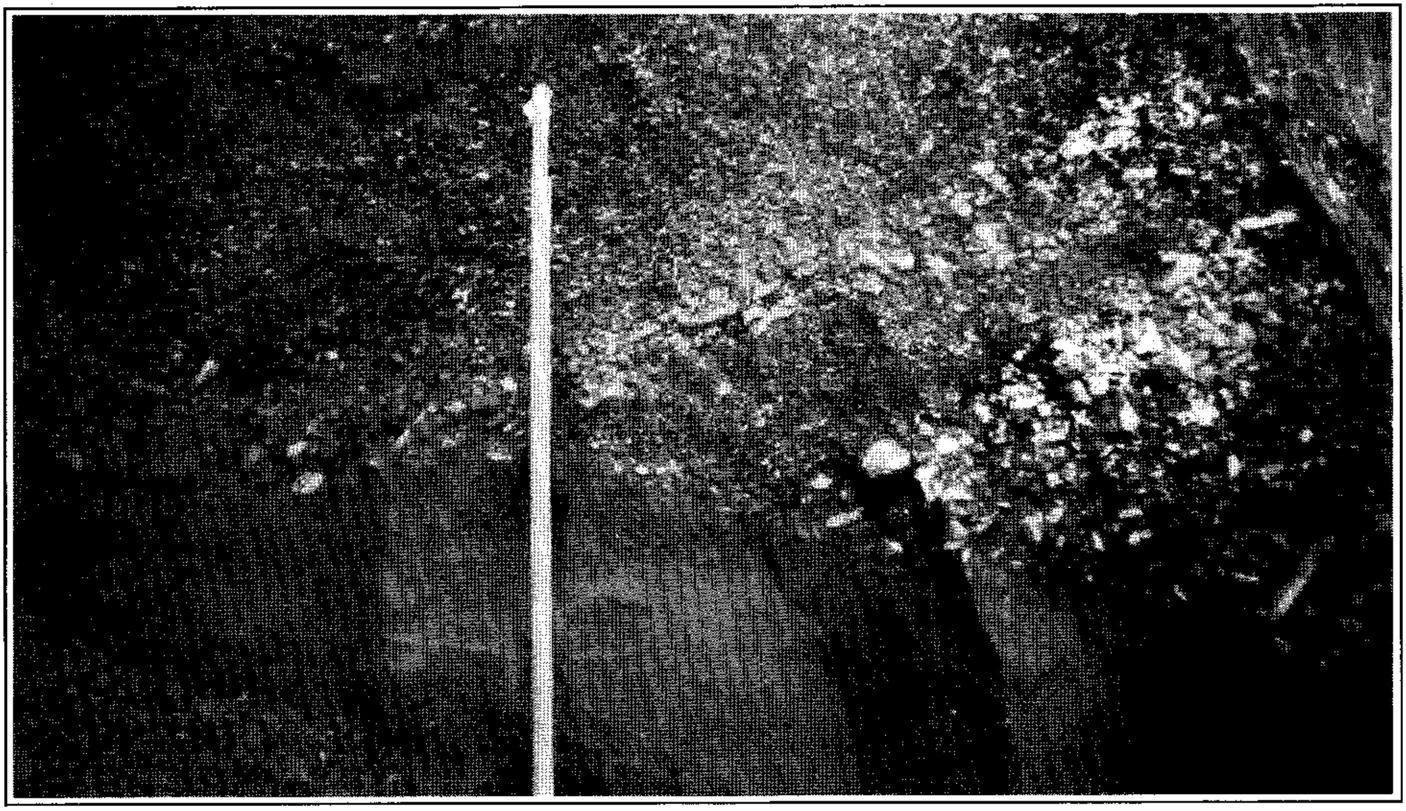


Fig. 11(d). Foreset gravels (unit 4) unconformably overlying bottom set beds (unit 3).

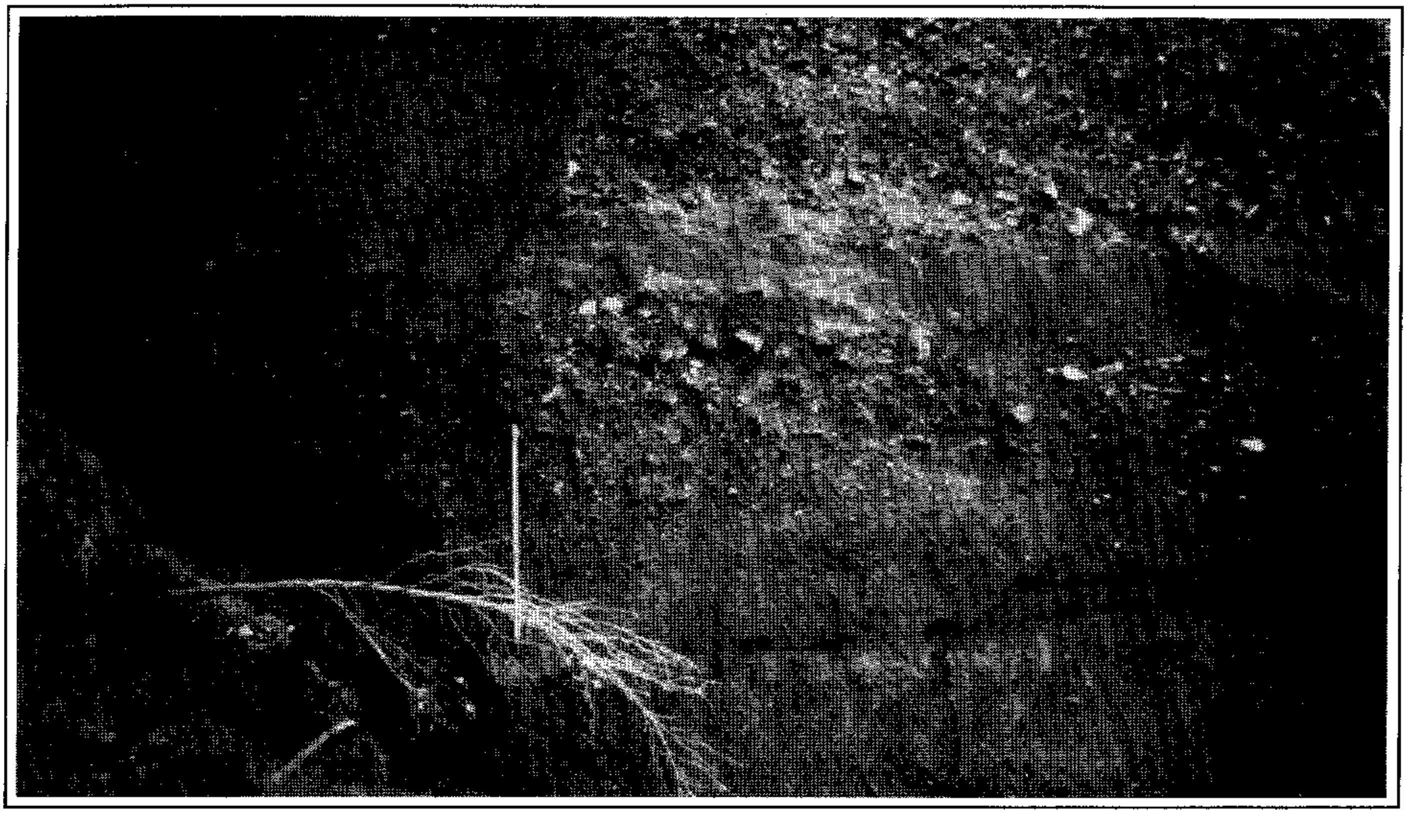


Fig. 11(e). Poorly sorted sediment-flow deposits of unit 5 (centre).

Fig. 11(f). Angular clasts in open-work bed typical of units 4 and 6.

Glaciolacustrine sediments overlie the interglacial gravels at all three of the studied sites and, at Livingstone and Martin Creeks, they are especially thick and have a high silt and clay content. The cohesive nature and low permeability of these fine grained sediments would also have acted to resist the erosive power of ice-marginal and subglacial meltwaters .

If ice-marginal lakes had not developed in the tributary valleys, the gold bearing sediments may have been eroded by meltwaters from the advancing glaciers. Such a situation might have occurred, for example, if glaciers developed in the Big Salmon Range to the east, and flowed into these valleys prior to the arrival of glaciers in the South Big Salmon Valley. Meltwater from the glaciers to the east would have had a free outlet and could have deeply eroded the gold bearing gravels. Discharges in these meltwater streams would potentially have been of much higher magnitude than normally encountered in the drainage basins in nonglacial times. In addition, as glaciers advanced down the tributary valleys, substantial erosion by the ice could have occurred.

During glacial advances, erosion of the gold-bearing gravels by the overriding glaciers was minimal, probably for two reasons. First, the gravels were buried by a thick sequence of glaciolacustrine, glaciofluvial and ice-marginal debris flow deposits. Second, these deposits accumulated in narrow and deep valleys that were oriented transverse to the regional direction of ice flow. The sediments within the tributary valleys were thus protected from ice erosion by the high bedrock walls flanking the valleys. The dominance of depositional over erosive processes in similar topographic situations has been observed in several other areas (egs. Garnes and Bergerson, 1977; Haldorsen, 1982, Levson and Rutter, 1986).

During deglaciation, glaciofluvial activity resulted in the deposition of a thick sequence of sand and gravel deposits and erosion of a meltwater channel system along the ice margin. The meltwater channels are incised partly into bedrock and probably removed or disrupted any underlying placer deposits. It is unlikely that any of the gravels deposited during deglaciation are gold bearing.

CONCLUSIONS

Three factors that contributed to the preservation of gold bearing gravels in tributary valleys in the Livingstone Creek region are: (1) Glaciers did not flow down the tributary valleys before ice occupied the main valley. This prevented the erosion of older deposits by water and ice moving down the valleys. (2) Ice-marginal lakes formed in the tributary valleys during the early stages of glaciation causing depositional processes to predominate. (3) The valleys are oriented transverse to the former regional direction of ice flow thus minimizing direct erosion by ice. As a result of these factors, the transverse valleys became depositional sinks, and erosion of the gold bearing deposits by glaciers and glacial meltwaters was minimal, both immediately prior to and, during glaciation. The recognition of areas with similar glacial histories may be important for the identification of potential exploration targets in other placer gold regions in glaciated terrains.

ACKNOWLEDGEMENTS

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Appendix 1. Martin Creek Section Description

Main Section

Unit 1a: Bouldery gravel: 6.7 m thick; very poorly sorted; clast-supported; 50% boulders up to 1 m in diameter, 20% cobbles, 20% pebbles and 10% silt to coarse sand; clasts mainly subangular to subrounded; some poorly defined pebble to cobble gravel lenses, generally about 25 cm thick and 100 cm wide, poorly to moderately sorted; disorganized fabric; strong oxidation in basal 2 m; unit is poorly exposed; lower contact covered.

Unit 1b: Boulder-cobble gravel: 3.5 m thick; clast-supported, matrix-filled; some crude horizontal to low angle stratification; beds are poorly defined with gradational boundaries on all sides; 50% cobble and pebble beds increasing towards the top; beds generally 25 to 50 cm thick (P28 R17); boulders occur in disorganized clusters and beds up to 2 m thick with a clast size distribution similar to unit 1a; sorting generally poor except for a few pebble beds with an open work to sandy matrix; sorted layers of laminated clay, silt and sand and pebbly sands (Figure 6d) occur around some clasts with thicker sorted layers below the clast; clasts mainly rounded to subrounded (especially boulders and cobbles) but some angular, local clasts of quartzite and schist; weak imbrication locally developed; some oxidized patches and heavily altered clasts; lower contact covered.

Unit 1c: Diamicton: up to 3.5 m thick; lens shaped; massive; mainly clast-supported with a silty sand matrix; a few pockets of matrix-supported diamicton and poorly sorted cobble or pebble gravel; 60 to 80% clasts; disorganized fabric; oxidation patchy; shape and size range of clasts similar to unit 1b; some clasts have 1 - 2 mm thick, smeared and polished silt and clay coatings; slickensides weak and near vertical; lower contact gradational and irregular.

Unit 1d: Boulder-cobble gravel: similar to, and laterally continuous with, unit 1b; discontinuous lenses and beds up to about 1.5 m thick; lower contact gradational to erosional.

Unit 2: Interbedded clay, silt, sand and diamicton: 11.85 m thick; *Silt and clay beds:* 5 - 50 cm thick, parallel laminated, locally with numerous dropstones that deform underlying laminae, minor convoluted laminae and flaser bedding, lower contacts generally sharp and planar, upper contacts mainly gradational. *Diamicton beds:* generally 10 - 60 cm thick although thin (1cm) intrabeds are also common; generally matrix-supported; matrix silty to silty sand commonly with angular inclusions of laminated silts and clays (Figure 8f); clay, silt and sand laminae and intrabeds are common and often are folded (Figure 8e); clasts are mainly small to large pebbles; total clast content 50 - 70% near the base of the unit to 10-20% near the top, some clasts striated, mostly subrounded and subangular although angular clasts locally dominate; beds are mainly ungraded or normally graded; clasts at the base of the diamicton beds commonly deform underlying sediments and clasts at the top commonly protrude into, and are draped by, overlying strata (Figure 8f). *Sands:* Some fine to medium sand beds with parallel laminae; cross laminae and ripple bedding and minor pebbly sand beds occur. Minor irregular pebble gravel layers; some normal faults. Thickness and abundance of diamicton layers increases towards the SW. Contacts between beds are mainly conformable except for loading and deformation structures at the base of some diamicton beds. Lower contact of unit dips steeply (25° - 30°) to the west (220° - 295°) at the SW end of section and is marked by a 20 cm thick layer of sheared (fractured and slickensided) clay, silt and gravel (probably due to "recent" slumping). At the NE end of the section beds consistently dip about 10° to the NE (50°). The lower contact at the NE end of the section is covered. Near the section centre the contact is inaccessible but appears conformable, and unit 2 is locally interbedded with unit 1.

Unit 2a: Diamicton: 1.0 m thick; beds mainly 10 - 20 cm thick, clast to matrix-supported, matrix silty sand, total clast content 50 - 70%. 60% of clasts clasts are angular, siliceous, rocks of local origin, some beds inversely graded and capped by gravel concentrations (Figure 8d), lower contacts loaded. Silts and clays as above.

Unit 2b: Silt, clay, sand and diamicton: 4.25 m thick; silts and clays with some fine sand laminae (< 0.1 mm to 0.5 cm thick), abundant dropstones; numerous thin (< 1 - 10 cm) granular to pebbly diamicton beds, commonly with flow folds and silt/clay intraclasts; minor ripple bedded sands with silts infilling ripple troughs; thickness of diamicton beds and sand laminae increases towards the top of the unit; minor normal faulting (Figure 8c) near top of unit (dip 49°, dip direction 245°); bed contacts mainly conformable except for small scale load structures.

Unit 2c: Silts and clays: 2.0 m thick; thinly laminated silts and clays with few diamicton beds; number of diamicton beds and sand laminae increase towards the top of the unit; abundant normal faults in lower half (Figure 8g).

Unit 2d: Silts and fine sands: 3.6 m thick; thinly to thickly laminated silts and fine sands with little clay; diamicton beds 2-5 cm thick except for one 30 cm thick bed; matrix silty clay in thickest beds, otherwise silty sand; numerous silt and sand laminae (partings) in diamicton beds; numerous dropstones in upper part; contacts distinct and conformable.

Unit 2e: Diamicton: 0.7 m thick; matrix-supported; matrix silty sand; clasts pebble to small cobble sized, mostly subangular with abundant striations; numerous rounded mud clasts; total clast content 30 - 40%; lower contact gradational and indistinct.

Unit 2f: Pebbly sands and silts: 0.75 m thick; parallel laminae with intense small scale folding; abundant load structures, especially in the upper half of the unit where stratification is very indistinct.

Unit 3a: Diamicton interbedded with silt and fine sand: 2.5 m thick; diamicton matrix-supported with a silty sand matrix (figure 9a); clasts up to cobble size, subangular to rounded; diamicton beds are 20 to 50 cm thick and contain numerous discontinuous sand laminae; bedding is horizontal but is weakly defined; it is due to textural and color banding in the diamicton, and is enhanced by the sand and silt beds; horizontal laminae within sand and silt beds are generally discontinuous and highly deformed (loaded and folded); some polished and lineated (sheared?) surfaces occur in the upper part of the unit; lower contact is gradational.

Unit 3b: Diamicton: 4.5 m thick; matrix-supported, silty clay to silty sand matrix; dense; polished sub-horizontal partings are common in clay rich areas. Clasts mainly medium to large pebbles, cobbles and boulders rare, mainly subangular to subrounded, numerous striated and glacially shaped clasts, total clast content 20 - 40%; unit oxidizes readily resulting in mottling with grey, recently exposed diamicton occurring in patches on the dominantly brown, weathered surface. Small (< 20 cm thick), poorly defined, irregular, lenses of silt, clay and sand occur in the upper part of the diamicton; the lenses commonly exhibit compressive deformation structures such as thrust faults, reverse faults, folds and subhorizontal shear zones; slickensides on shear zones trend 110° to 150°. Lower contact gradational.

Unit 3c: Diamicton interbedded with silt, sand and gravel: *Diamicton:* (Figure 9d) matrix- to clast-supported, matrix silty sand to sand, little silt or clay; loosely consolidated; clasts pebble to cobble sized, subangular to subrounded, striated clasts common at base but decrease in abundance up section, 50 - 80% total clast content; sand and gravel content increases towards the top of the unit; beds 5 cm to 1.5 m thick. *Sands and silts:* beds 2 - 10 cm thick; massive to crudely horizontally stratified; minor ripple bedding and convoluted laminae; some irregular clay inclusions; trough cross-laminated sand (and gravel) lenses 2-10 cm thick and 10 - 100 cm wide occur throughout the unit (Figure 9e); moderately to very well sorted; beds laterally continuous for up to several metres before grading into diamicton. *Gravels:* occur in thin beds and lenses with horizontal to gently inclined planar bedding and some trough cross-bedding; poorly to moderately sorted, clasts mainly granule to medium pebble in size; lower contacts locally erosional. All of unit 3c occurs in a broad (50 m wide) trough-shaped body. Beds generally are near horizontal and contacts are diffuse, irregular and locally exhibit load structures. Lateral variations in sorting and stratification are common, especially in the lower part of this unit where horizontal and cross-stratified sands and pebbly sands locally dominate.

Unit 4a: Gravels: 0.6 m thick; open-work bouldery gravel fining up into matrix-filled pebbly gravel; poorly to very poorly sorted; clast-supported; crude horizontal stratification marked by pebbly beds about 10 cm thick; fabric disorganized to weakly imbricated [a(p), a(i)] indicating paleoflow to the NW (320°); some diamicton intraclasts; trough-shaped, erosional lower contact.

Unit 4b: Boulder gravel: 0.5 m thick; clast-supported, clasts large pebbles to boulders; open work; oxidized.

Unit 4c: Pebble gravel: 1.7 m thick; clast-supported; matrix filled; poorly to moderately sorted; horizontal stratification due to very large pebble to small cobble open work beds about 20 cm thick; unit fines up into trough cross stratified sands and pebbly sands.

Unit 4d: Boulder gravel: 0.8 m thick; same as unit 4b.

Unit 4e: Pebbly gravels and sands: 2.0 m thick; horizontally stratified; gravels clast-supported, matrix filled and moderately sorted; sands horizontally laminated with some trough cross laminae; unit grades laterally into well to very well sorted, trough and planar cross-stratified, fine to medium sands and horizontal and planar cross-stratified sands and pebbly sands (Figure 9g); lower contact erosional.

Unit 4f: Large pebble to boulder gravel: 8.4 m thick; crude horizontal stratification; clast-supported; matrix filled with some lenses of open-work, oxidized gravel; some well sorted pebbly layers with weak planar cross bedding; blade shaped clasts common; mostly rounded to subrounded; poorly to moderately sorted; sorting and stratification are poorer to the NE and SW; this unit is in almost vertical contact with diamicton of unit 3 to the NE.

West Section

Unit 5: Complexly interbedded sand, gravel and diamicton: (Note: This unit is exposed only at the west exposure of the Martin Creek Section.) The unit thickness varies laterally from about 1 to 10 m. At the SW end of the section the unit is dominated by a large trough of diamicton (unit 5a) overlain by sands (unit 5b). Unit 5a grades upstream into interbedded gravel, sand and gravelly diamicton (units 5c and 5d) over a distance of about 50 m. These sediments are overlain by two large troughs of sand and gravel (unit 5e), and they grade laterally (upstream) into interbedded diamicton, gravel and sand (unit 5g) unconformably underlain by sand and gravel.

Unit 5a: Sandy diamicton: up to 5 m thick; 70-80% clasts; unsorted to poorly sorted; interbedded with well stratified sand lenses; weak, large scale (20 m wide), trough shaped, cross bedding; lower contact covered.

Unit 5b: Fine to coarse sands and pebbly sands: 3 m thick; moderately to very well sorted; large scale trough cross-stratification as above (channel-fill bedding); lower contact conformable.

Unit 5c: Interbedded gravel, sand and diamicton: 9 m thick; gravels are pebble to cobble sized, clasts supported, poorly sorted, disorganized and have a silty sand matrix; sands and pebbly sands are poorly to well sorted and massive or planar cross-stratified; diamicton is matrix-supported and gravelly; gravel grades laterally and vertically into diamicton; the unit is crudely bedded with horizontal beds at the base; beds dip 25-30° up-valley (025°) in the middle of the unit; lower contact covered.

Unit 5d: Bouldery gravel: about 3 m thick; poorly sorted, clast-supported, some open work beds and vertically oriented clasts; beds dip (60-80°) in opposing directions to form a wedge about 10-15 m wide and 3-5 m high; these beds can be traced up-valley into nearly horizontal bedding; lower contact conformable.

Unit 5e: Interbedded sands and gravels: 3-6 m thick; sands fine to coarse, well sorted and parallel-laminated; minor silt beds occur with sands; gravels are pebble to boulder-sized, clast-supported, matrix-filled and poorly sorted; unit occurs in two large (20 -30 m wide) trough-shaped bodies at the top of the section; deformation (folding and normal faulting) increases towards the base; lower contact erosional.

Unit 5f: Sands, pebbly sands and pebble gravels: 2-5 m thick (unit thickens to the NE); well to poorly sorted; planar cross-stratified; beds dip about 20° downstream (250°); lower contact covered.

Unit 5g: Diamicton, gravel and sand: about 5 m thick; diamicton sandy, matrix to clast-supported; similar to unit 3c above; interbedded gravels are clast-supported, matrix-filled to open-work, and mainly pebble sized except for a large bouldery bed at the top of the unit; sands are planar cross-laminated, well to moderately well sorted; some pebbly sands; beds dip 20° upstream (070°) and unconformably overlie beds of opposing dips in unit 5f; beds in the centre of the unit are convoluted; the proportion of diamicton initially increases to the SW (downstream) and then decreases as the unit grades laterally into unit 5d; lower contact erosional.