CORDILLERAN GLACIERS AND QUATERNARY STRATIGRAPHY

Peter T. Bobrowsky,
Geological Survey Branch, Victoria

INTRODUCTION

Geologic evidence suggests that upwards of 30% of the Earth's surface was once covered by glaciers. Glaciation was most pronounced in the Northern Hemisphere and affected land areas on both sides of the Atlantic. In North America, few areas of Canada and the northern United States escaped glaciation (Photo 1). However, there are pronounced differences in the style of glaciation and the types of deposits associated with the many events as one proceeds across the continent. In general, those areas affected by the Cordilleran glaciers in the far west differ markedly from those areas affected by the Laurentide Ice Sheet to the east. Consequently, the method and theory of mineral exploration which rely upon drift prospecting techniques must also be different within the two regions (Bobrowsky *et al.*, 1995). This paper addresses characteristics unique to the Cordillera which have significant impact on drift prospecting. In particular, discussion will focus on the type and style of glaciation in mountainous terrain, glacier characteristics and the influence of glaciers on the nature and distribution of deposits in the Canadian Cordillera. Some discussion regarding the implications to drift prospecting is also presented.

BACKGROUND

The Canadian Cordillera has been covered by variety of glaciers throughout the last two million years of the Pleistocene. The variability in types of glaciers present at various times in the region has ranged from small cirques and valley glaciers to larger piedmont glaciers and ice caps. Under maximum glacial conditions, these smaller forms of glaciers would have coalesced to form a larger ice sheet known as the Cordilleran Ice Sheet. During such a maximum phase, ice covered much of British Columbia, the southern parts of Alaska and Yukon Territory and extended southwards into northern Washington, Idaho and Montana in the United States. Evidence indicates that ice would have extended westward beyond the limit of land and into the Pacific Ocean west of Vancouver Island, Queen Charlotte Islands and the Alaska Panhandle. In the east, ice would have reached beyond the Rocky Mountains and in many cases past the Foothills onto the western Prairies where it would have coalesced with parts of the Laurentide Ice Sheet (Figure 1). The configuration of ice in the Cordillera and its relationship to the larger and approximately coeval Laurentide continental ice sheet has been a source of interest, research and debate for well over a century. Although considerable progress has been achieved in many respects regarding the dynamics and history of Cordilleran ice, much remains to be addressed.

Geologic evidence indicates that the Cordilleran Ice Sheet was roughly centred over British Columbia where it occasionally reached elevations in excess of 2500 meters. We can speculate that from its highest points in the Interior Plateau and along the Coast Ranges, the surface of the ice sheet would have gradually diminished in all cardinal directions, eventually terminating at the height of land at inland areas and at sea level on the coast. Along the margins of the ice sheet, one would have encountered a number of glacier types including a broad piedmont lobe extending into Puget Sound, small valley glaciers constrained by topography in the foothills, as well as narrow but thick fjord glaciers calving into the waters of the Pacific Ocean.

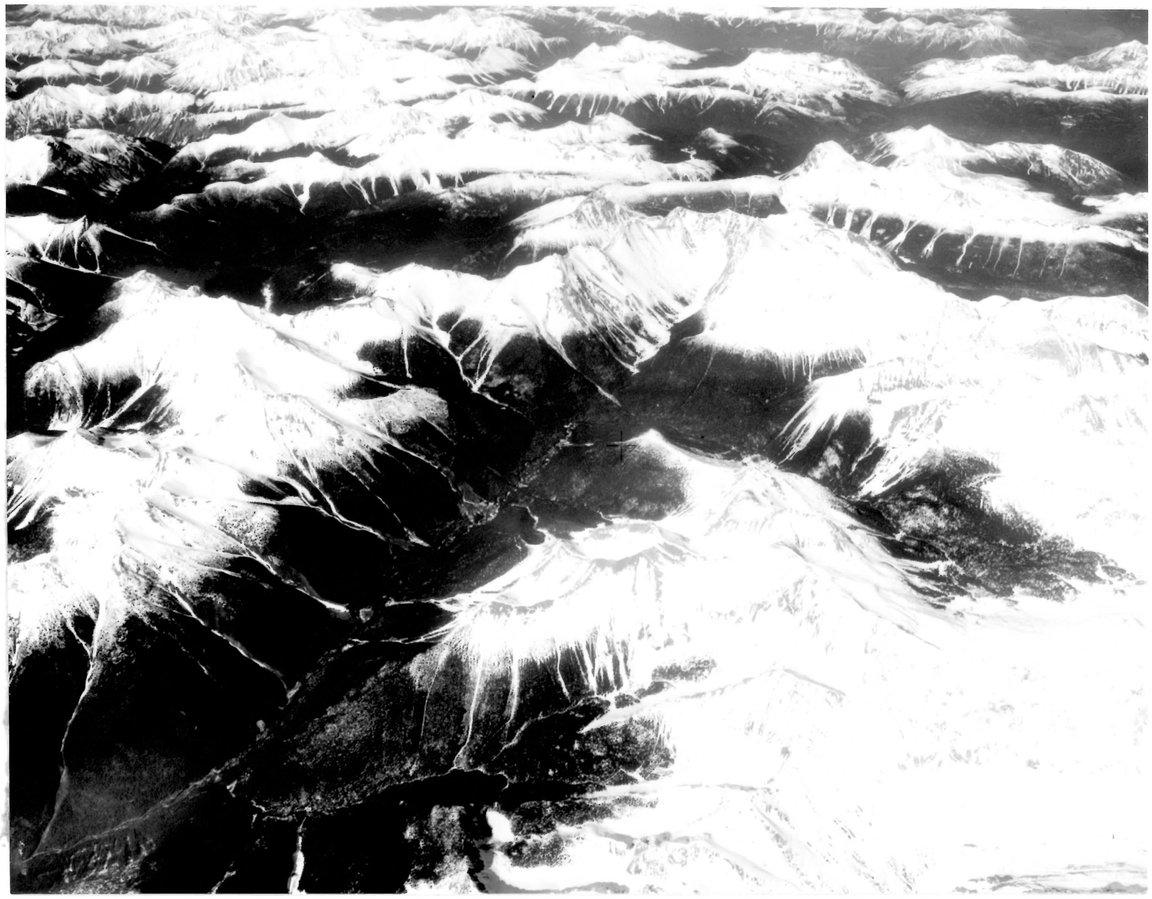


Photo 1. General view of the Canadian Cordillera illustrating rugged topography, ice covered peaks and complex nature of valley networks which typify this region of western North America. (Photograph BC 3022 #55).

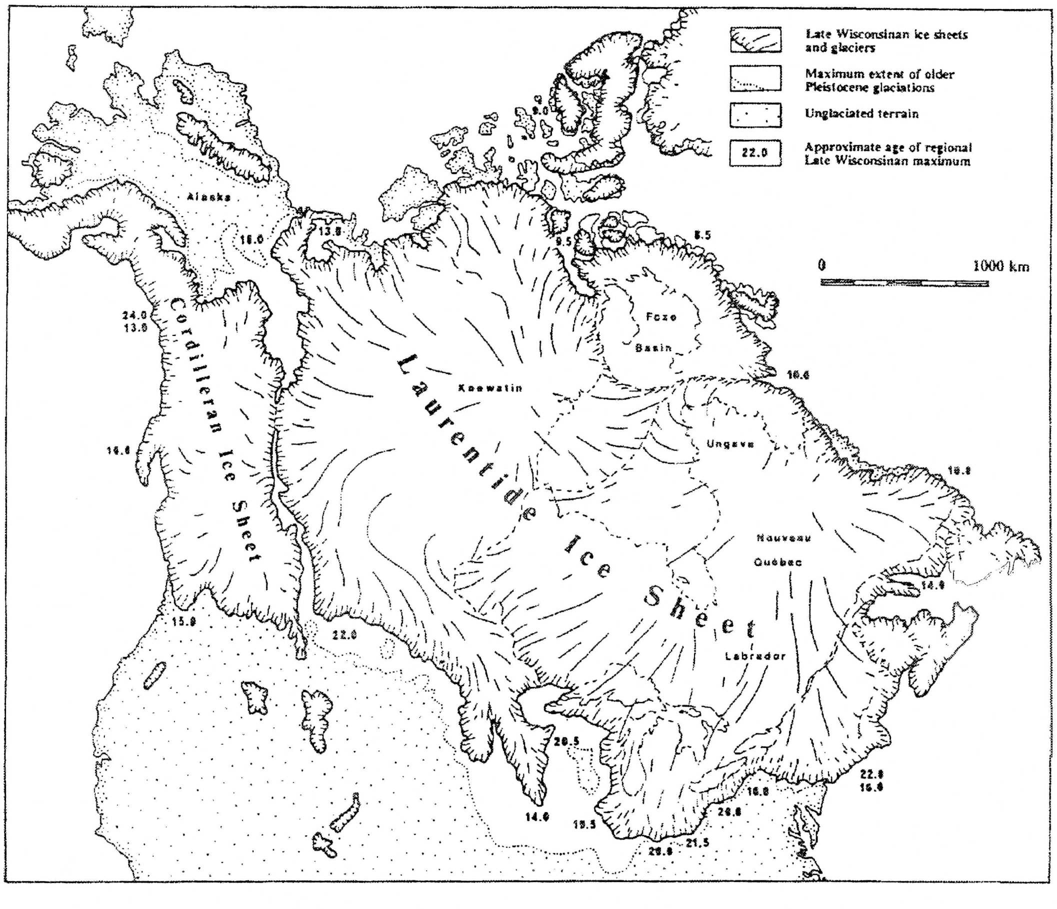


Figure 1. Reconstruction of Wisconsinan Glaciation and extent of earlier glaciations in North America. (Illustration from Ehlers, 1996 page 353).

The Pleistocene history of the Canadian Cordillera indicates that the region has been glaciated several times, but regionally no events were equally as intensive nor extensive and locally none occurred at the exact same time. In some cases, local ice growth, coalescence and expansion would have ended prematurely as climatic conditions improved, thereby precluding full scale development of ice sheet conditions. In other rarer cases, ideal cold and wet conditions would have prevailed to such an extent as to have permitted the formation of a full-scale ice sheet to develop and cover the northern Cordillera.

CORDILLERA GLACIERS

It is generally believed that throughout the Pleistocene most periods of major glacier expansion in the Cordillera followed a set pattern of four phases (Kerr, 1934) consisting of an alpine, intense alpine, mountain ice sheet and continental ice sheet phases (Figure 2). At first, remnant ice restricted to higher elevations in the alpine would have expanded as climatic conditions worsened. With continued deterioration and a regular supply of precipitation, the growing alpine glaciers would have further expanded to include larger areas of the mountainous regions. Prevailing cold conditions would have eventually seen glaciers covering both plateau areas and lowland regions, as they coalesced to form mountainous ice masses. Finally, under extreme and rare conditions, these large confluent mountain ice masses would have merged to form a pan-provincial ice sheet covering much of British Columbia. At this stage of glaciation, a number of ice domes would have been present over parts of British Columbia from which internal ice would have flowed radially away to the margins. Large scale erosive features such as drumlins, flutings and grooves scattered over the province provide a good indication of what the general pattern of ice flow may have been at one time (Photo 2). Figure 3 is a compilation of regional ice flow patterns during maximum glacial conditions. The compilation serves as a generalization only, since ice flow patterns in specific areas are known to have occasionally completely reversed in direction as a response to shifting ice divides.

The above four phase ice growth pattern forms the basis for complex but detailed observations. We know for instance that the growth and expansion of ice would have varied locally given the diachronic nature of such events. Full ice cover in one area (*e.g.* northern Coast Mountains) may have occurred at the same time as repetitive ice front fluctuations occurred in a second area (*e.g.* Fraser Valley) and cold desert conditions or ice absence in a third area (*e.g.* northern Rocky Mountains).

During each period of glaciation climatic conditions would eventually improve and lead to ice decay. As the environment warmed and sea levels rose, the low elevation margins of the glaciers would have been the first parts to respond by actively calving where affected by the sea whereas in inland areas, glaciers would have disappeared by frontal retreat of the ice margin. Elsewhere in the province, a different pattern of ice decay has been proposed by Fulton (1967). Fulton suggests a four stage model of ice decay which was predominantly based on ice stagnation and downwasting: 1) active stage where ice thinned but continued to flow, 2) transitional upland stage during which the highest most areas would have breached the ice but regional flow would have been maintained in the valleys, 3) stagnant ice stage where ice was confined to valley situations but still flowing, and 4) dead ice stage where ice was no longer capable of active flow.

Types of Glaciers

One of the paramount differences between the Cordillera and the remaining parts of North America which were affected by glaciers during the Pleistocene is the type of glaciers present at any one time. Extremely variable topography, high relief and close proximity to the Pacific Ocean are the principle factors which have controlled the unique suite of glacier types affecting the Cordillera. British

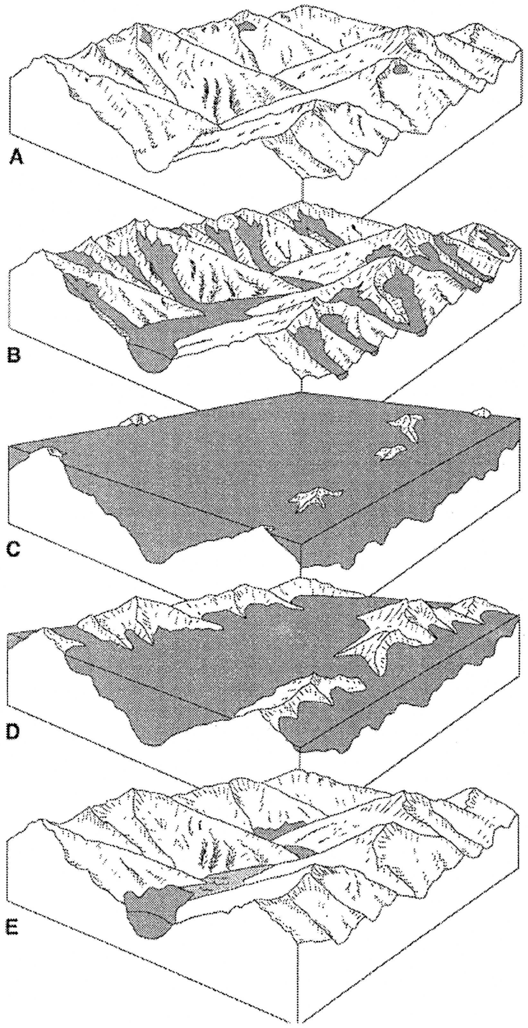


Figure 2. Model of growth and decay of Cordilleran glaciers. A) Mountain glaciation, B) Expansion to valley glaciation, C) Coalescence of glaciers, D) Early deglaciation in uplands, E) Final dead ice stagnation in valleys. (Figure from Clague, 1989, page 40).

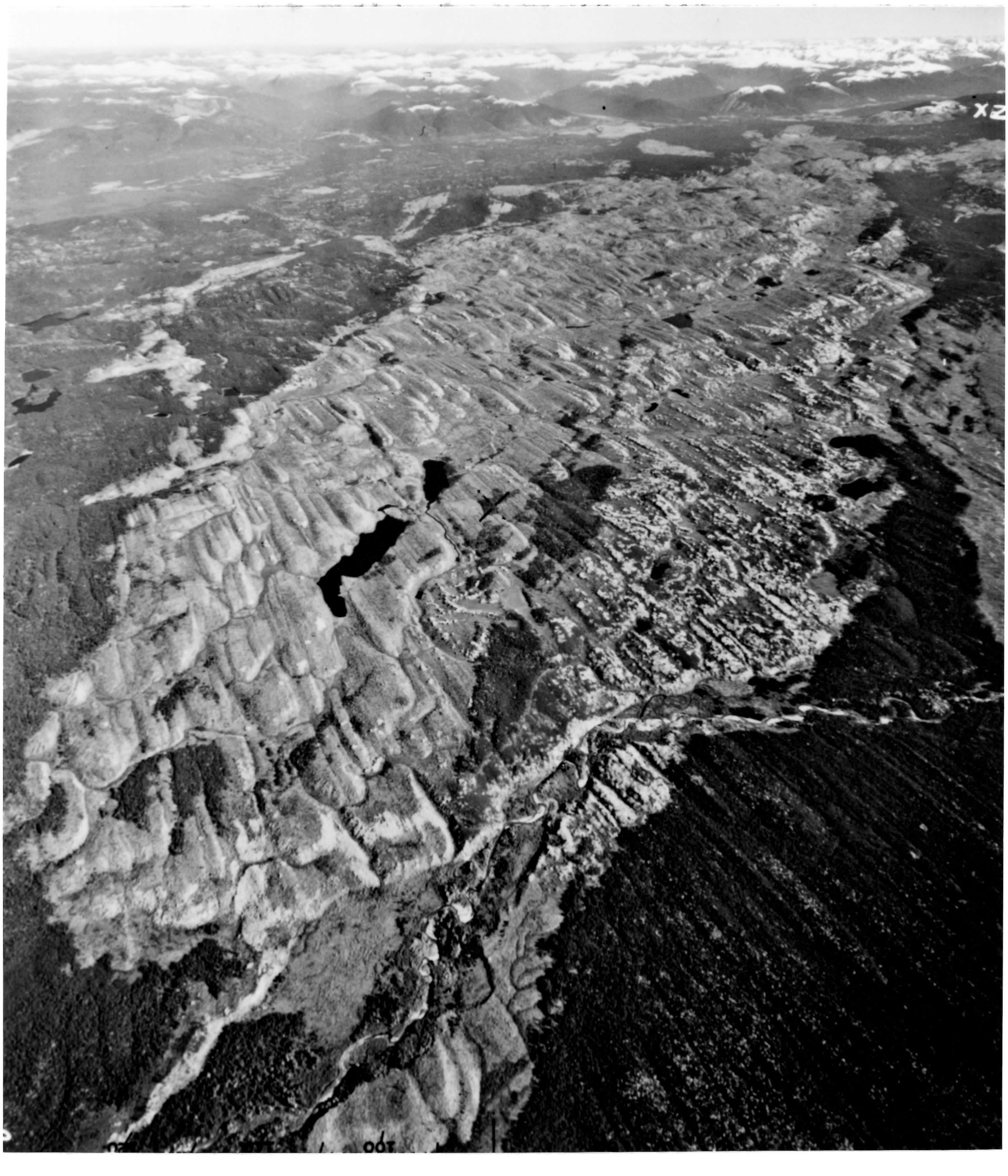


Photo 2. View towards the northeast of drumlinized plateau northeast of Prince George. (Photograph BC 761:70).

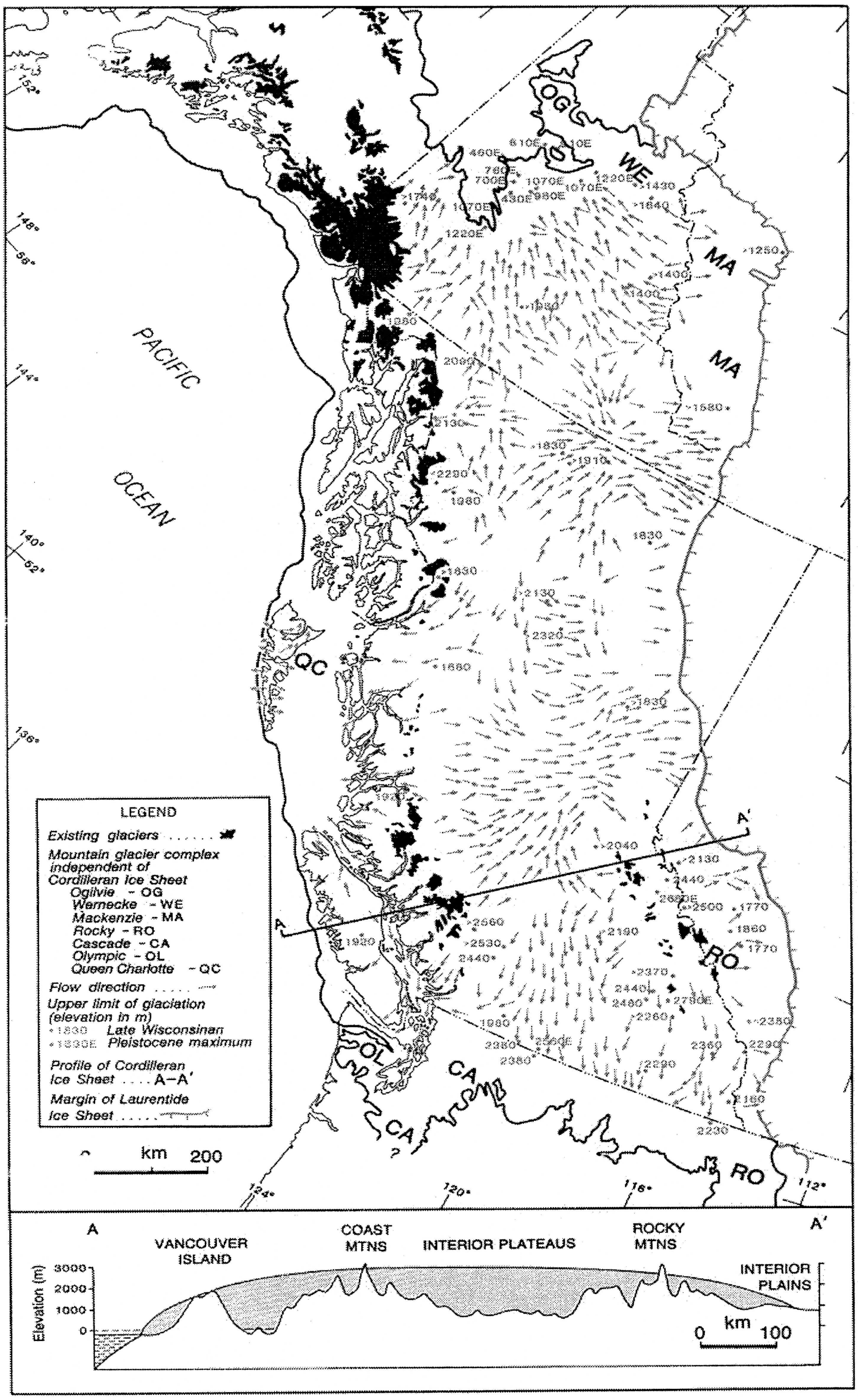


Figure 3. Maximum extent of glaciation in the northern Cordillera. The maximum ice limits shown did not occur during each glacial period during the Pleistocene and many areas were ice free when other areas were covered by ice. (Figure from Clague, 1989, page 41).

Columbia's terrain is ideally suited to support all traditional morphological forms of glaciers. Figure 4 details some of the major types of glaciers which would have been encountered in North America during glacial conditions. As expected the number of glaciers for each type would have decreased in frequency as one proceeds from the smallest type to the largest variety. Even today in the Cordillera, examples of cirque glaciers abound, whereas ice caps are rare features. During most glacial periods, the Cordillera was more affected by glaciers constrained by topography than by glaciers unconstrained by topography, the latter was a rare occurrence. This would have contrasted strongly with the general configuration of the Laurentide ice mass east of the Rocky Mountains where an unconstrained ice sheet dominated each period of glaciation.

During the full cycle of a glacial period, the Cordillera would have supported examples of all the major types of glaciers. Depending on the classification system used, this list can appear endless: alpine valley (snowdrift, reconstructed, cliff, apron, horseshoe, cirque, hanging, simple, dendritic), highland ice cap, outlet, reticular and piedmont (intermont, expanded foot, fringing) (Photo 3).

Another term frequently used in the Canadian Cordillera is Montane glaciers. This refers to a series of fairly large mountainous ice masses which originated in key but high elevation areas of the province including but not restricted to the northern Rocky Mountains, southern Coast Ranges, Cariboo Mountains, Vancouver Island Ranges and so on. Montane glaciers were always the predecessors to the rarer Cordilleran Ice Sheet, but more frequently glacial periods never intensified beyond the presence of numerous Montane glaciers. The more regional ice flow patterns of Montane glaciers may markedly contrast with the pan-provincial ice flow patterns of the Cordilleran Ice Sheet.

Besides the morphology of the glaciers involved in the glaciation of the Cordillera, the inherent properties of ice flow in these smaller warm-based glaciers show pronounced differences with that of the Laurentide Ice Sheet. Figure 5 is a schematic illustration showing the cross-sectional characteristics of an idealized ice sheet and valley glacier. As illustrated here, the most pronounced differences between the two includes a larger accumulation area, divergent and radial flow patterns from an ice divide and the lack of topographic influence on ice flow patterns for the ice sheet.

Ice Dynamics

All glaciers flow because they respond to the influence of gravity (Paterson, 1981). This flow is a response to shear stresses applied to the glacier and occurs via three mechanisms:

- internal deformation,
- basal sliding, and
- subglacial bed deformation.

When the net accumulation of snow and ice exceeds the net ablation of a glacier, not only will a glacier flow, it will also grow in size. Exactly how glaciers grow and how they move greatly affects the associated processes of erosion and deposition. This in turn, has pronounced affects on the principles of mineral exploration dependent on glacial deposits. One noteworthy generalization regarding ice flow is that ice flows fastest from the accumulation zone to the ablation zone in glaciers with a steep surface, hence glaciers with no slope will have no imbalance between accumulation/ablation and thus exhibit no flow (Bennett and Glasser, 1996). Warm, damp, maritime glaciers tend to display the highest net balance gradient with high accumulation and high ablation rates. Therefore, steep, confined topography coupled with a high precipitation rate favours the development of fast flowing valley type glaciers.

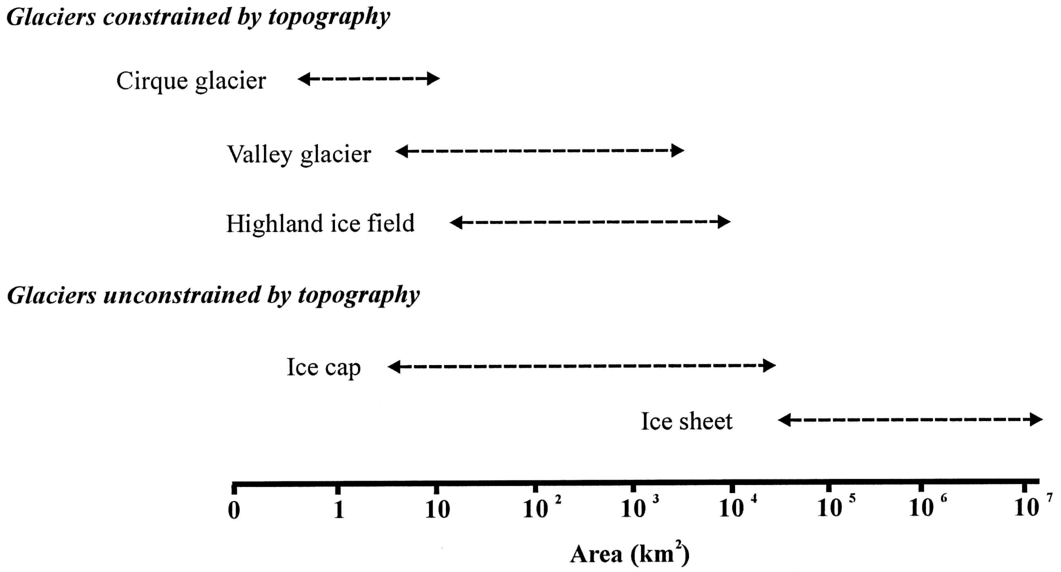


Figure 4. Morphological range in size of glaciers constrained and unconstrained by topography which would be encountered in the Cordillera.

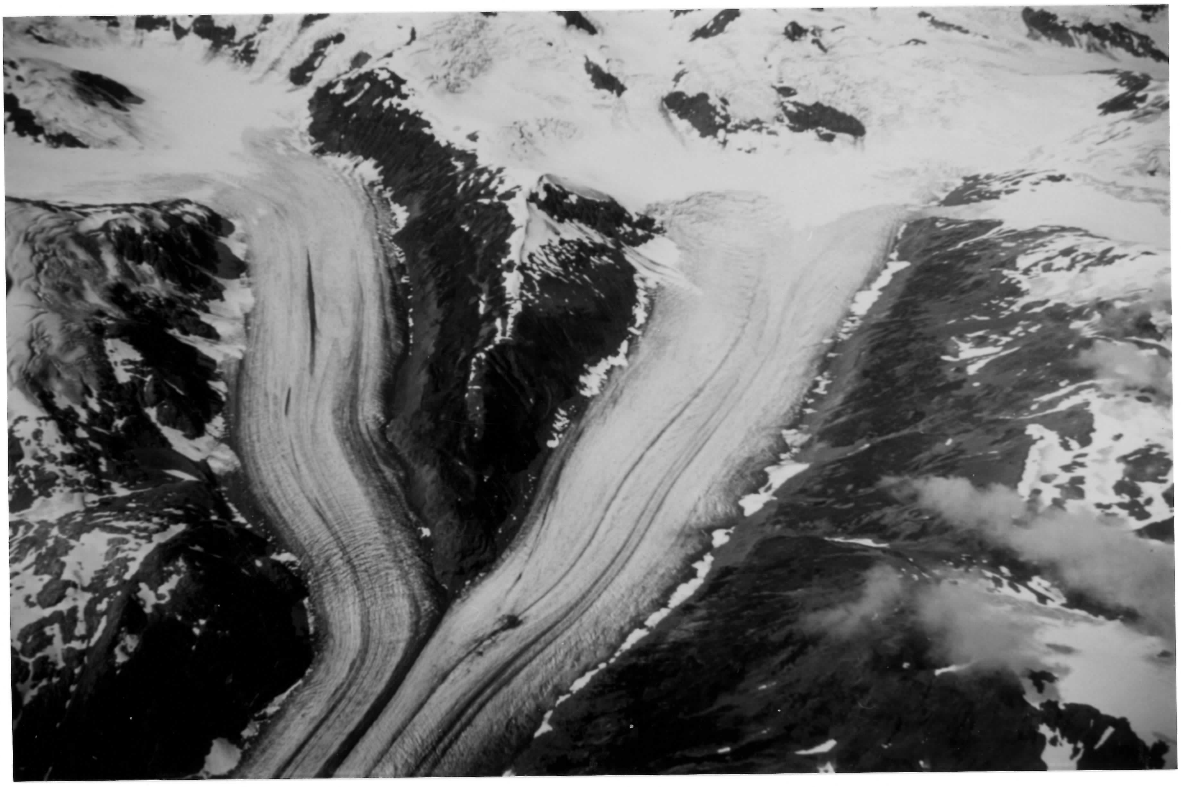


Photo 3. View of coalescing trunk glaciers exiting larger ice field in background. Note extensive debris on surface of the glaciers, medial moraine and crevasse patterns. (Photo by P. Bobrowsky).

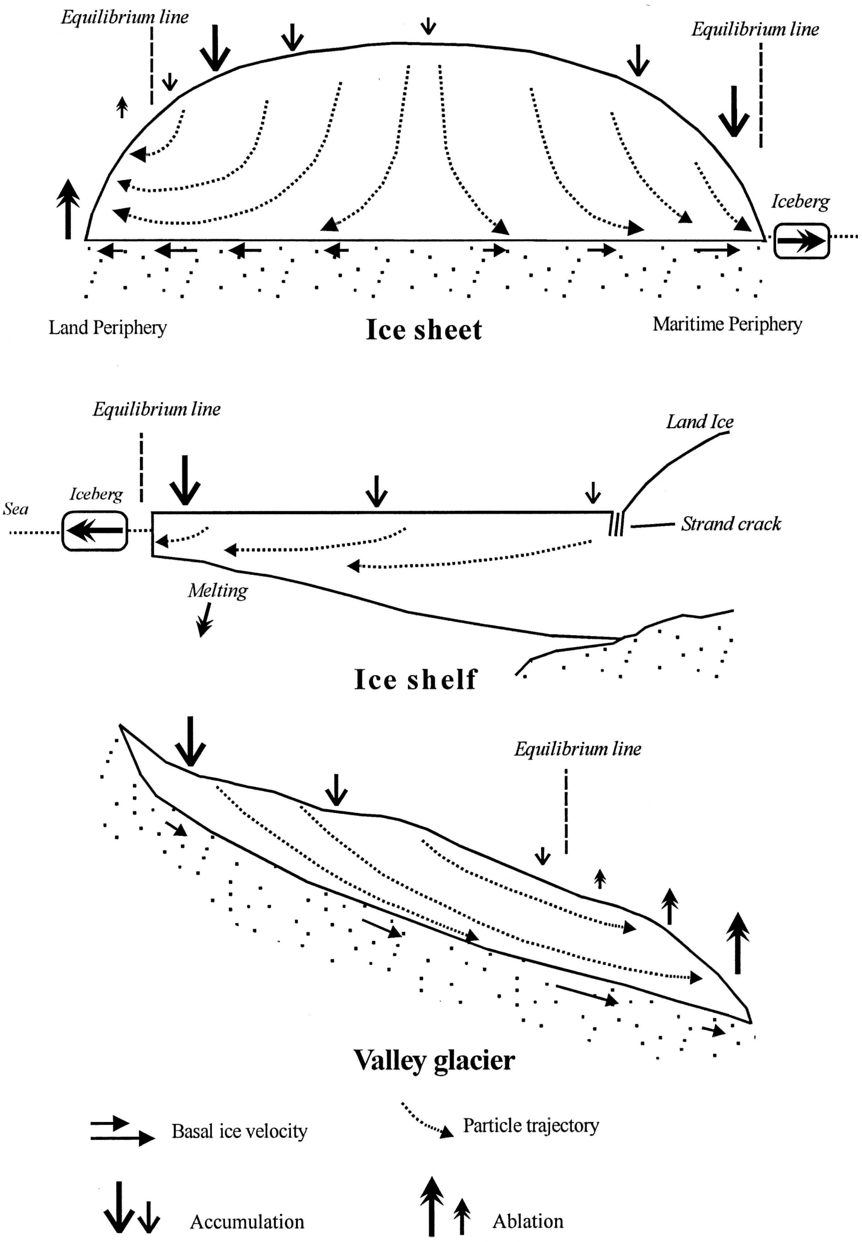


Figure 5. Schematic cross-sectional models of an ice sheet (top), ice shelf (centre), and valley glacier (bottom) showing relationship between accumulation and ablation. (Modified after Sudgen and John, 1976, page 63).

With respect to the mechanism of internal deformation, this typically involves the processes of either creep or large scale folding and faulting which can vary through a glacier depending on whether the ice is accelerating (extending flow) or decelerating (compressive flow). The patterns of crevasses evident on the surface of glaciers provides a good indication of the type of underlying flow occurring at any one point (Figure 6).

Basal sliding in a glacier can occur via two processes: enhanced basal creep or regelation slip. Basal sliding is a significant mechanism of ice flow in the glaciers of the Cordillera. The success of basal sliding depends largely on such factors as the size of the obstacles, the presence of water and the basal ice temperature at the bed ice interface. These factors will affect the level of friction at the bed ice interface.

Finally, subglacial bed deformation can occur when glacier ice moves across wet, unfrozen sediment which is capable of deforming under the shearing force of ice. In some cases, this style of ice flow can dominate the mechanisms involved in movement (Figure 7).

Without question, temperature is the primary factor to consider in the basal movement of glacier ice. Quite often, we define entire glaciers or parts of glaciers according to their basal ice temperatures as to whether they are either at or below the pressure melting point. Hence, the terms warm-based and cold-based glaciers. Cold-based ice is frozen to its bed, lacks meltwater as a lubricant at its bed ice interface and, therefore, has little erosive potential. On the other hand, warm-based ice is above the pressure melting point at its base, supports meltwater as a lubricant, is not frozen to its base, and therefore moves quickly and is capable of significant subglacial erosion (Figure 8). In the above, basal temperature plays an important role in the movement of ice and erosion/deposition of the underlying sediments. It is affected by a number of variables including, but not restricted to:

- ice thickness (thick ice ~ more insulation)
- accumulation rate (temperature of snow vs. temperature of ice vs. location)
- ice surface temperature (higher surface temperature ~ higher basal temperature)
- geothermal heat (higher geothermal heat ~ higher basal temperature)
- frictional heat (higher frictional heat ~ higher basal temperature)

The movement of sediment within ice is controlled primarily by the internal flow of the ice itself. Studies have shown that the velocity of ice increases from the periphery to the centre (Figure 9). Variations in ice velocity are also dependent on the presence/absence of basal sliding.

In glaciers, the intimate relationship between basal temperature and meltwater is clearly evident when one considers the role that meltwater plays in the erosion, transportation and deposition of materials. Although water can travel on the surface of a glacier (supraglacially), within a glacier (englacially) or at the base of a glacier (subglacially), the latter has the greatest impact on the erosion and deposition of sediments. At the base of a glacier, water under extremely high pressure often develops spectacular erosive forms in bedrock, called N-forms (Photo 4). Such features attest to the highly erosive nature and potential of glacial meltwater. Basal water pressure beneath ice is controlled by glacier thickness, rate of water supply, rate of meltwater discharge and the nature of the underlying geology.

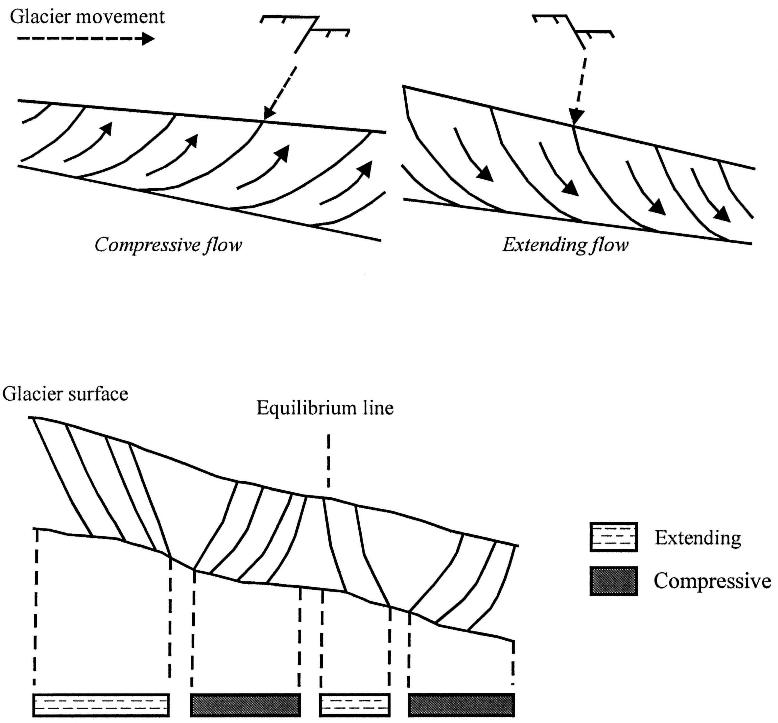


Figure 6. Model of compressive and extending flow with associated slip lines in a glacier. (Modified after Sudgen and John, 1976, page 44).

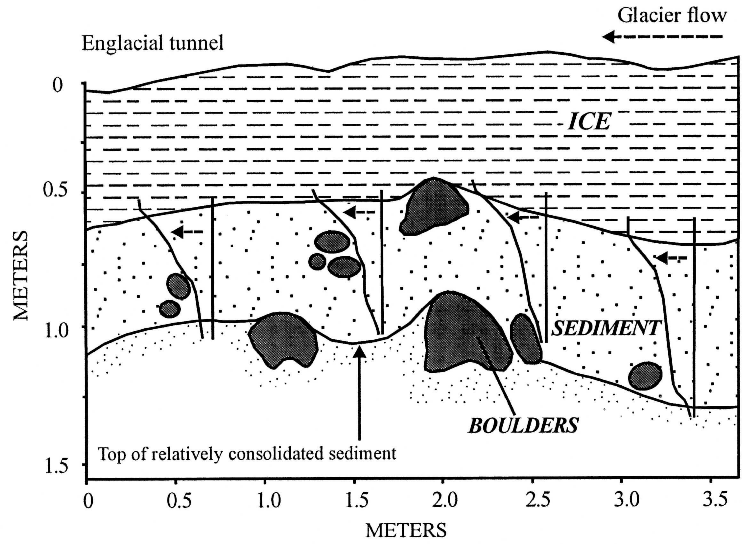


Figure 7. Subglacial deformation of sediment and incorporation of boulders beneath ice as interpreted by Boulton and Hindmarsh (1987). (Modified after Bennett and Glasser, 1996, page 42).

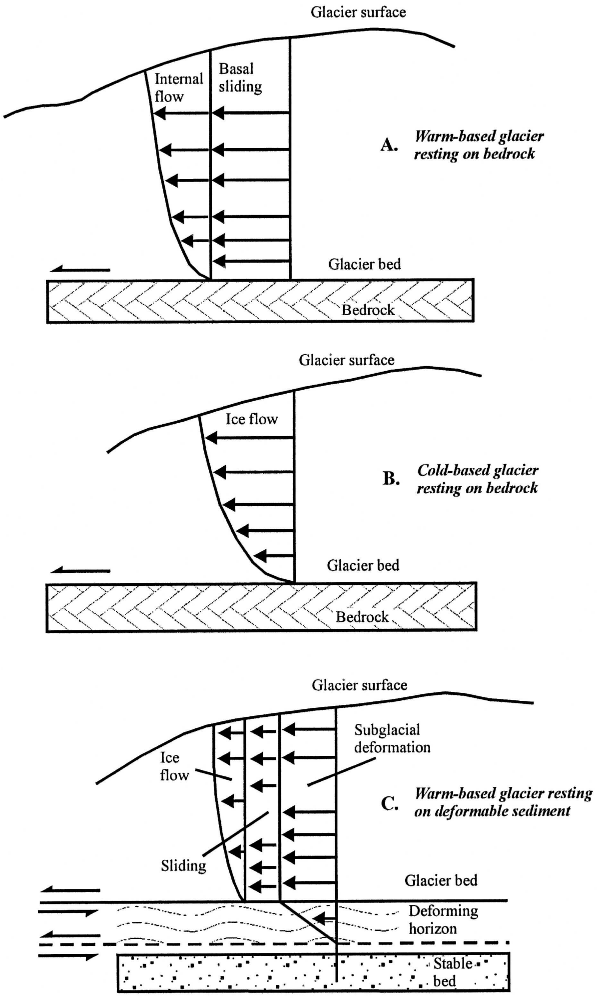


Figure 8. Schematic cross-section showing velocity gradients in glaciers with three types of basal thermal regimes. Upper figure is warm-based glacier overlying bedrock, middle figure is cold-based glacier overlying bedrock, and lower figure is warm-based glacier overlying deformable sediment. (Modified after Bennett and Glasser, 1996, page 43).

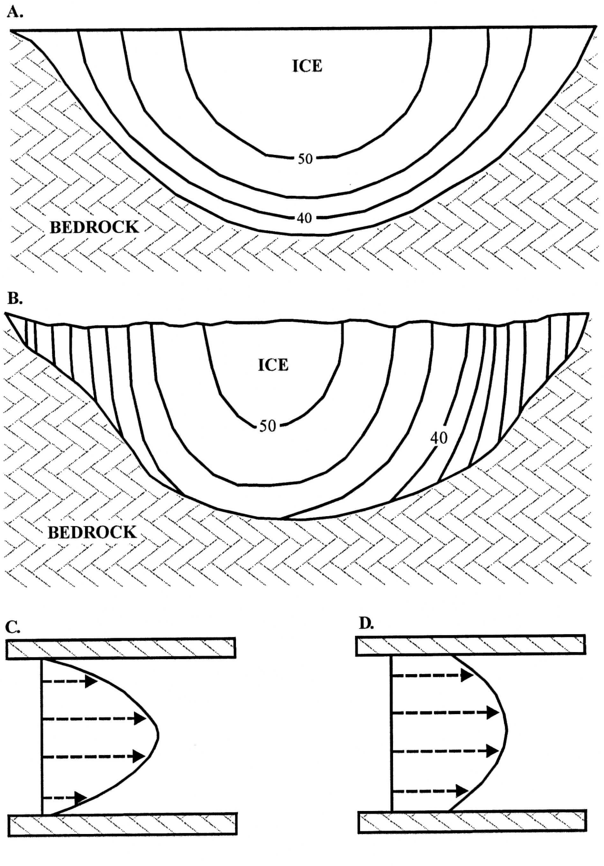


Figure 9. Longitudinal velocity profile in A) cold-based glacier and B) warm based glacier. Plan view of C) cold-based and D) warm-based glaciers. Units are in meters per year. (Modified from Sudgen and John, 1976, page 46, and Bennett and Glasser, 1996, page 51).

Photo 4. Typical Nye-forms developed in bedrock by subglacial meltwater. (Photo by P. Bobrowsky).

Ice Erosion, Transportation and Deposition

Erosion

As glaciers come into contact with bedrock or unconsolidated sediments, such materials can become incorporated and moved by the ice in the form of glacial debris. The main mechanisms of glacial erosion include: 1) abrasion, 2) plucking and 3) meltwater. Direct observation studies by researchers provides the best information on rates of abrasion. For instance, Boulton (1974) has shown that average abrasion rates for Icelandic and Argentine glaciers ranged from <1 mm/a to 36 mm/a as a direct function of increasing ice thickness and ice velocity. In Europe alpine glaciers tend to have erosion rates of 1-3 mm per year. The would translate to total depths of 100-300 meters when measured over a 10,000 year glacial period! The important conclusion here is that the thicker and faster the glacier the greater the erosion potential.

Glacial abrasion is the process by which resistant materials transported by ice scratch, gouge and erode away less resistant materials with which they come into contact during ice flow (Photo 5). Variables controlling abrasion include: 1) basal contact pressure, 2) rate of basal sliding, and 3) the concentration of debris at the base of the glacier. In general, increasing the basal contact pressure between ice and the underlying bed results in an increase in the erosion capability; where contact pressure ~ effective normal pressure ~ normal pressure-basal water pressure. Hence, effective normal pressure increases when ice is thick and basal water pressures are low. It is also evident from the above, that bedrock lithology plays an important role in controlling effective normal pressure, since porous bedrock can act to reduce water pressure. The role of basal sliding, as noted elsewhere, means that the rate of abrasion will increase as a function of the rate of basal sliding. Finally, the ability for ice to abrade is influenced by the concentration of debris at the base of the ice (Figure 10). Although debris is required as the "tools" of erosion, excessive debris can choke the glacier and retard further erosion.

Plucking or glacial quarrying involves the processes of rock detachment, fracturing, crushing and entrainment into the ice (Figure 11). Mathematical modeling has shown that when ice travels over an obstruction, the greatest stress point is generated deep and on the lee-side of the bedrock feature (Figure 12). Unless such a rock is weak or fractured, failure is unlikely to occur simply because ice is overriding the surface. Similarly, the presence or absence of lee-side cavities at the bed ice interface strongly influences the potential for an obstruction to fail (Photo 6). In this case, water propagation into existing cracks and fractures increases the likelihood that the rock will detach and subsequently be plucked into the ice.

Besides ice, glacial meltwater is also a common medium for eroding and transporting materials in warm-based glaciers. Through the processes of mechanical and chemical erosion, meltwater can actively contribute to the erosion and transportation of bedrock and sediment.

Transport

Glaciers can transport debris in any position within the ice. The position of sediment transport is an important factor since this is directly related to the type of deposits left by ice. Briefly we recognize two avenues of incorporation: from above the glacier (supraglacially) and from below the glacier (subglacially). Once incorporated in the ice transport can occur in the upper or lower levels of the glacier. Transport paths of debris and sediment mimic those of the internal ice flow lines (Figure 13).

All types of debris encountered and transported by ice may be derived from above or below a glacier. In the Cordillera, source areas above a glacier are presently and always were very common,

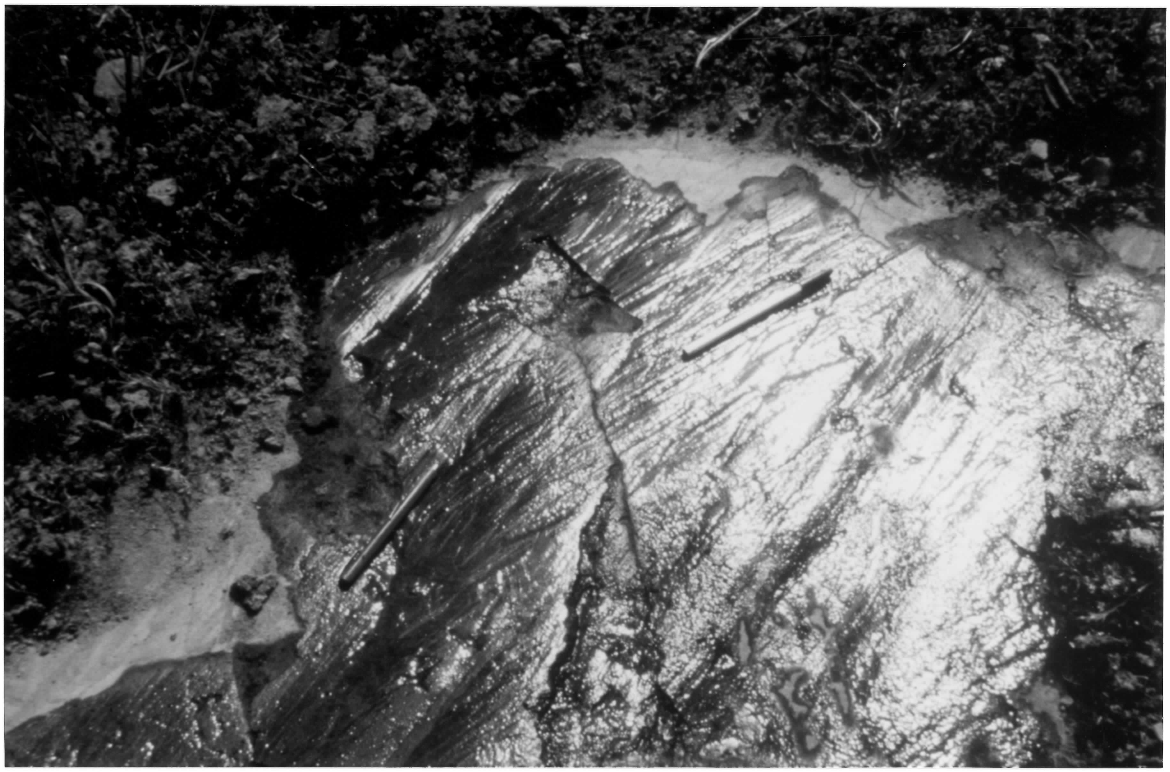


Photo 5. Bi-directional ice flow patterns in bedrock. Grooved surface is cross-cut but striations at oblique angle (Photo by P. Bobrowsky).

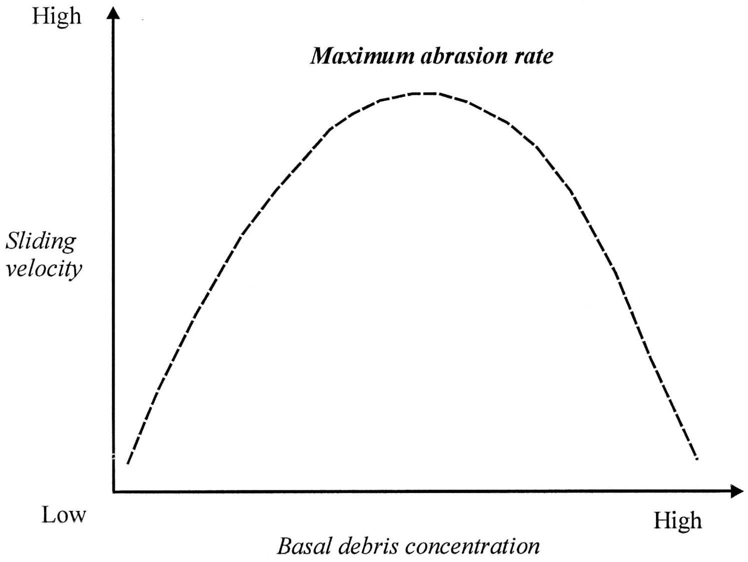


Figure 10. Idealized model showing relationship between concentration of debris in glacier and sliding velocity. Note theoretical peak for abrasion. (Modified from Bennett and Glasser, 1996, page 87).

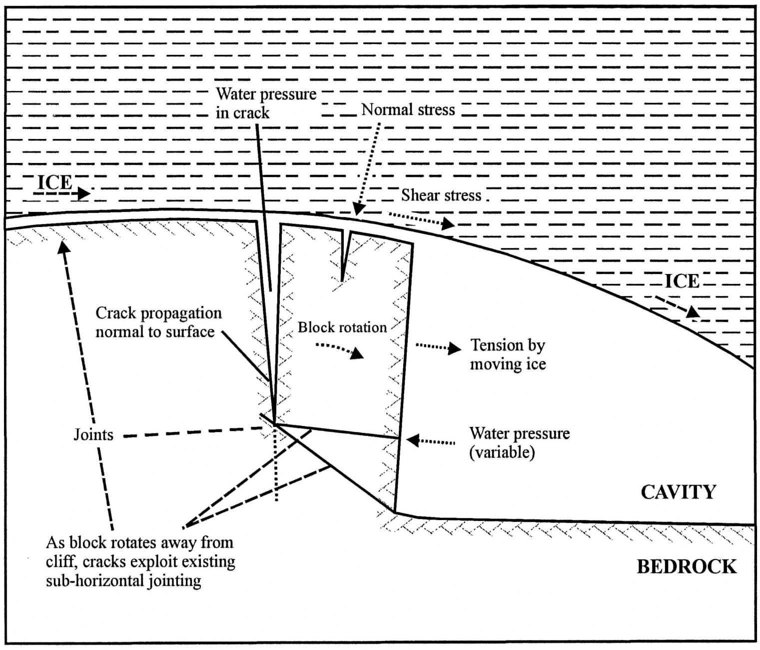


Figure 11. Schematic cross-section at base of warm-based glacier showing the effects of bedrock fracturing, water exploitation, plucking and lee-side cavities. (Modified after Bennett and Glasser, 1996, page 95).

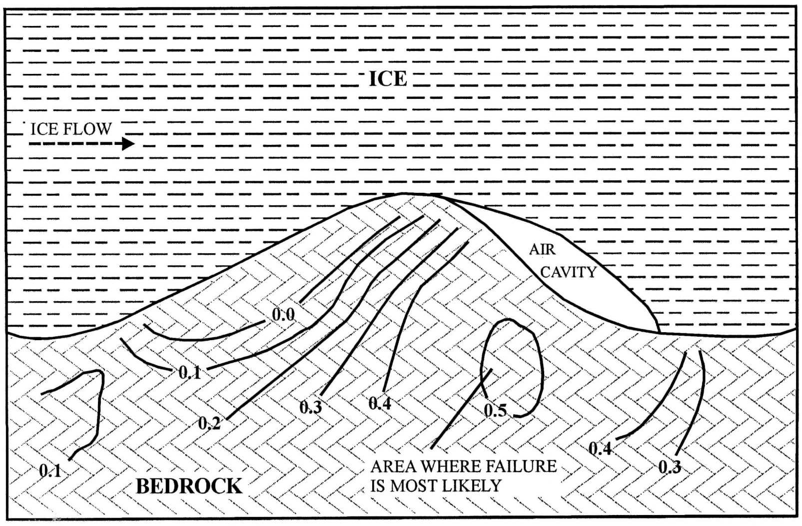


Figure 12. Schematic cross-section at base of glacier showing results of numerical modeling experiments indicating stress fields in bedrock over-ridden by ice. (Modified after Bennett and Glasser, 1996, page 93).

Photo 6. View up-ice showing glacier-bedrock interface beneath the Athabasca Glacier, Alberta. Note clasts in base of ice and fluting of ice surface in this lee-side cavity. (Photo courtesy of V. Levson).

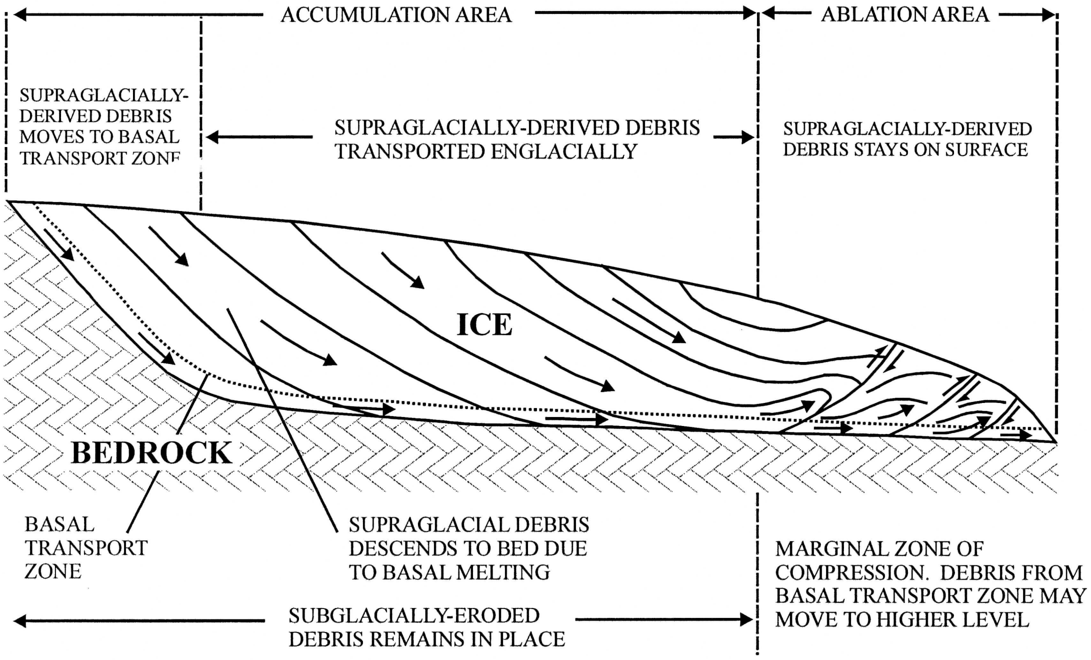


Figure 13. Longitudinal cross-section through a glacier indicating transport pathways of debris. (Modified after Boulton, 1993, page 425).

except under maximum ice sheet conditions when very few nunataks were exposed. In contrast to the Laurentide Ice Sheet, the numerous valley glaciers which typified the Cordillera glaciations would have been flanked by mountainous ridges and crests each capable of contributing abundant source material to the glacier's surface. Sediment accumulating on the surface of a valley glacier is primarily transported in the upper level of the glacier even if the material moves into the glacier body. This is because ice flow paths dictate transportation in the higher reaches of the glacier. Material falling on the glacier's surface will only move to the basal part of the ice if it originally collects near the edge of the glacier itself. Debris transported in the upper part of a glacier does not undergo the extensive comminution experienced at the base of the ice and hence the overall grain size distribution tends to be coarser with fewer fines (Figure 14). Winnowing of the fines by meltwater in the supraglacial zone contributes to the lower concentration of fine grained sediments.

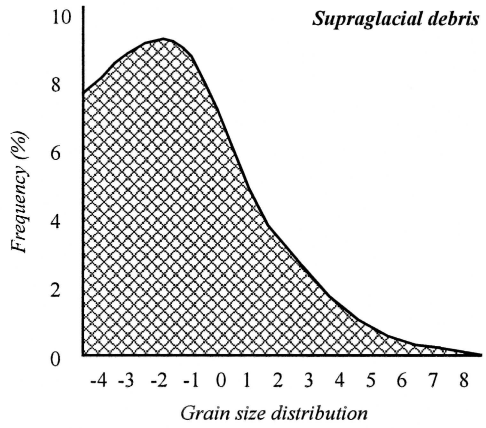
Material transported in the lower part of the glacier is further subdivided into two zones: a traction zone and suspension zone. The former includes all materials dragged along the bed of the glacier, whereas the latter includes debris directly above this contact zone. During transportation, glacial debris undergoes extensive commutation depending on the position of transport. As one moves from the traction zone to the suspension zone to the supraglacial zone, debris becomes less crushed, scratched, rounded, spherical or generally eroded. In the basal part of ice, debris reflects three distinct populations: lithic fragments, mineral grains and sub-mineral grains (Figure 15). Figure 15 shows the relationship between the three populations of debris in the traction zone of ice.

Another implicit consideration is position relative to the ice divide. Donner (1989) provides examples of glacier flow noting rates of 3 meters per annum near the ice divide and 135 meters per annum about 100 kilometers from the divide. Since basal velocity in glaciers increases with distance from the divide, it is expected that transport distances increase correspondingly. In mountainous terrain ice-flow rates are different and significantly greater. The greatest basal ice velocity is expected to occur at the equilibrium line (Paterson, 1981), the position of which drops progressively in elevation as individual glacial cycles reach their maxima. Normal ice velocities as high as 1.2 meters per day have been recorded for alpine glaciers and these can increase by 10 to 100 times during surge events. The latter are important in the Cordillera, 209 surging glaciers have been recognized in western North America (Paterson, 1981).

Deposition

The pathway that sediment is incorporated into glaciers and the position of sediment transportation in the ice strongly dictate the type of glacial deposits which result. Debris transported in the upper level of ice and deposited from this position commonly gives rise to ablation deposits, whereas debris transported and deposited in the lower level of a glacier often gives rise to basal deposits. Exceptions exist in the face of considerable potential for reworking and the dynamic nature of the glacial environment. The recognition of transport paths and the process of deposition of sediments is paramount to the success of any exploration project.

Moraine is a morphologic term used to describe landforms consisting of glacigenic deposits (Kupsch and Rutter, 1982). There are a number of landforms typically associated with the term moraine including: ablation, collapse, DeGeer, ribbed, ground, hummocky, ice-disintegration, medial, kame, ice-thrust, recessional, end, lateral, interlobate, stagnation, terminal, plateau, washboard and so on. Till is a genetic term used to describe glacigenic sediment directly deposited by ice with little or no reworking by water (Dreimanis, 1976). Several variations in terminology exist including ablation till, basal till, flow till, lodgement till, melt-out till, para-till, ortho-till, leeside till, etc. Diamicton is defined as a nongenetic term denoting any unlithified, poorly sorted mixture of gravel, sand, silt and



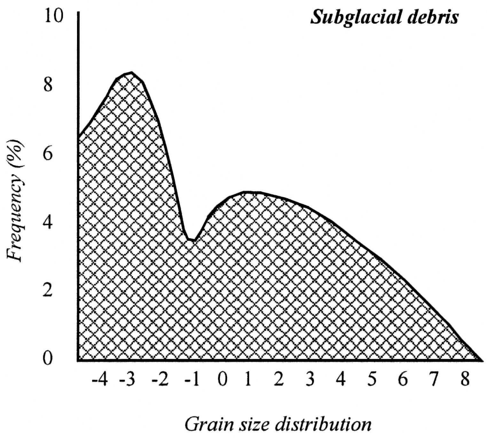


Figure 14. Idealized particle size and distribution in supraglacial debris (top) and subglacial debris (bottom). Coarser sediments to the left, finer sediments to the right. (Modified after Boulton, 1993, page 425).

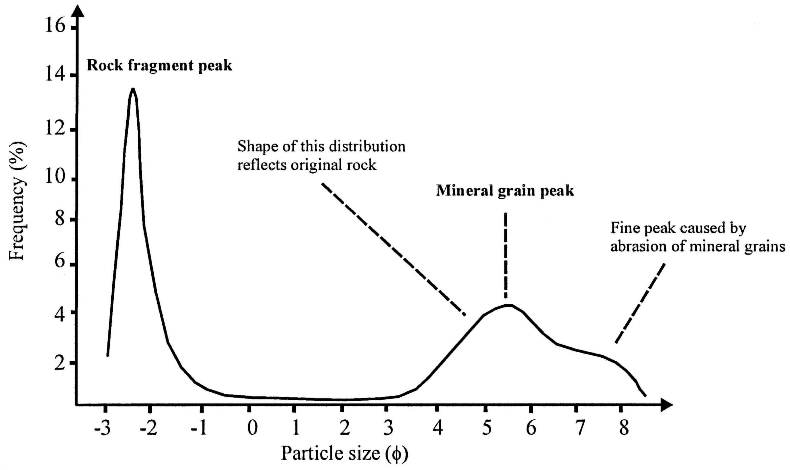


Figure 15. Idealized particle size distribution in subglacial sediments. (Modified after Bennett and Glasser, 1996, page 158).

clay (Flint *et al.*, 1960). The terms till, diamicton and moraine are not synonymous. Morainal deposits may contain till but can also contain other associated glacigenic deposits. Similarly, diamictons are not all till. However, quite often ground moraine consists of basal lodgement till which is frequently a diamicton.!

The most sought after glacigenic deposit in a drift prospecting program is basal till. Photo 7 is an example of a typical lodgement till deposit often found in the Cordillera. Note the compact nature of this dense, poorly sorted, matrix-supported diamicton, with relatively low stone content (~20%), small size and rounded shape of clasts, and lack of stratification. Contrast this sediment with ablation till which is usually coarser, with a higher stone content, is less compact and contains angular clasts which have not undergone much erosion and/or erratics of distal provenance indicating considerable transport distance in the upper levels of the glacier (Photo 8).

A more realistic expectation is to encounter several glacigenic deposits at any one location (Figure 16). Given the dynamic nature of the glacial environment, deposition is rarely straightforward. Basal tills are often overlain by ablation till, parts of which undergo further resedimentation resulting in colluvium, etc. These in turn can be covered by lacustrine deposits, alluvial fans, wind blown sediments and so on. Proper mapping in the field by trained Quaternary geologists is essential to distinguish subtle differences in sediments. Many deposits are similar in their appearance but are genetically distinct (*e.g.* till vs. debris flow deposits) and their geochemical histories are not comparable.

CORDILLERA QUATERNARY STRATIGRAPHY

The Quaternary geologic history of the Canadian Cordillera is extremely complex. Given the diachronic nature of glaciations, in that one area can be covered by ice as a second area is still ice-free, resolving stratigraphic relationships can prove difficult. Evidence in the Canadian Cordillera indicates that during the last 2 million years there have been a number of glacial periods. Within each period of glaciation, the number of events and phases of glacial activity varied considerably. Frequently, the margins or peripheral reaches of glaciers undergo a greater number of glacial events within any one period than other areas within the interior of the zone covered by ice. This is because the margins are often subjected to fluctuating ice fronts as local climatic conditions dictate warming and cooling and thus advance and retreat of the glaciers edge.

Table 1 provides a summary correlation chart of the major regions within the Canadian Cordillera and their known Quaternary stratigraphic histories. Some of the events are considered only broadly coeval. Noteworthy in this compilation is the greater number of events near the coast of British Columbia as compared to the simpler history within the Interior. Obviously attempts at correlating such provincial stratigraphic variation with the stratigraphy of the Laurentide Ice Sheet would be unwise.

In practical terms, many areas within the Cordillera contain thick sequences of Quaternary sediments which can represent not only a variety of deposit types but can also reflect a number of glacial periods (Photo 9). This poses considerable problems in large catchment areas such as the Interior Plateau where drift thickness can be on the order of 100's of meters and the stacked stratigraphy resulting from several glaciations is not easily visible and must be inferred at best from drilling records. There is less of a problem elsewhere in the Cordillera, such as in the hilly and mountainous terrain surrounding central British Columbia, where evidence for multiple glaciation is rare, deep exposures are more common and the thinner nature of the deposits is usually a product of the last glacial event to affect the area.

Photo 7. Example of typical montane basal lodgement till encountered in the Canadian Cordillera. (Photo by P. Bobrowsky).

Photo 8. Supraglacial debris scattered on surface of till plain in the Adams Plateau area, British Columbia (Photo by P. Bobrowsky).

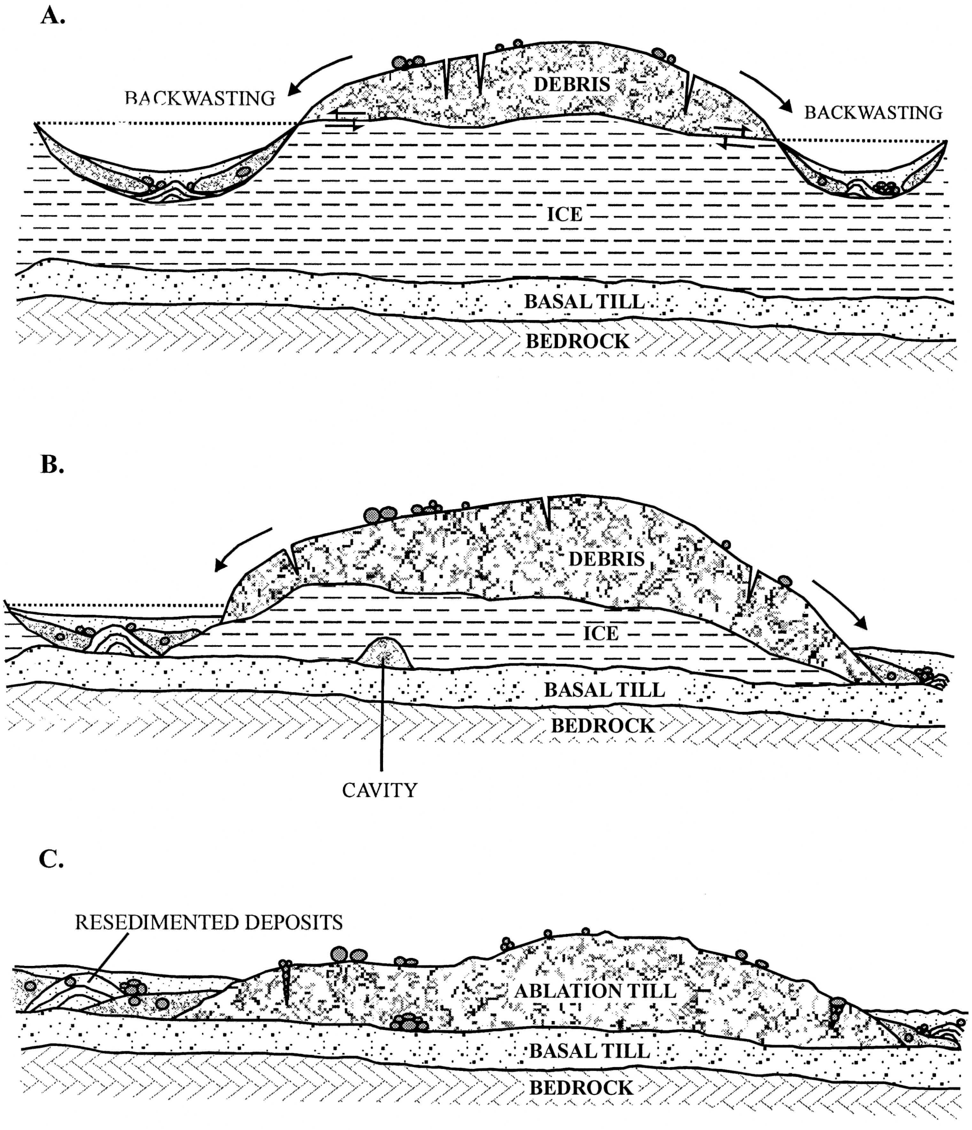


Figure 16. Schematic illustration of ice decay showing genesis of deposits and evolution of terrain as ablation till and resedimented deposits accumulate on top of a basal till. (Modified after Bennett and Glasser, 1996, page 182).

Table 1. Quaternary stratigraphy of British Columbia. Modified after Clague (1989)..

		Geologic-Climate Units	Southwestern British Columbia	Fraser Lowland Puget Sound	North-Central Vancouver Island	Northern Vancouver Island	South-Central British Columbia	Southern Rocky Mountain Trench	Northern Rocky Mountain Trench
ka 10	HOLOCENE	Post Glacial	Salish Sediments/ Fraser River Seds		Post Glacial Sediments	Post Glacial Sediments	Post Glacial Sediments	Post Glacial Sediments	Post Glacial Sediments
20	WISCONSINAN	Fraser Glaciation	Sumas Drift Ft. Langley Fm. Vashon Drift Coquitlam Dr. Quadra Sand	Fraser Glaciation: Sumas Stade Everson Interst. Vashon Stade Evans Crk. Stade	Gold River Drift	Port McNeill Drift	Kamloops Lake Drift	Younger Drift Inter-Drift Seds Older Drift < 26.8 ka	Late Advance > 15.2 ka
30 40		Olympia Nonglacial Interval	Cowichan Head Formation	Olympia Interglaciation			Bessette Sediments	'Interglacial' Sediments	
	PRE-WISCONSINAN		> 62 ka Dashwood Drift/ Semiahmoo Drift		> 40.9 ka Muchalat River Drift	> 38 ka Older Drift	> 43.8 ka Okanagan Centre Drift		> 44 ka Early Advance
			Muir Point Fm. and Highbury Seds.				Westwold Sediments		

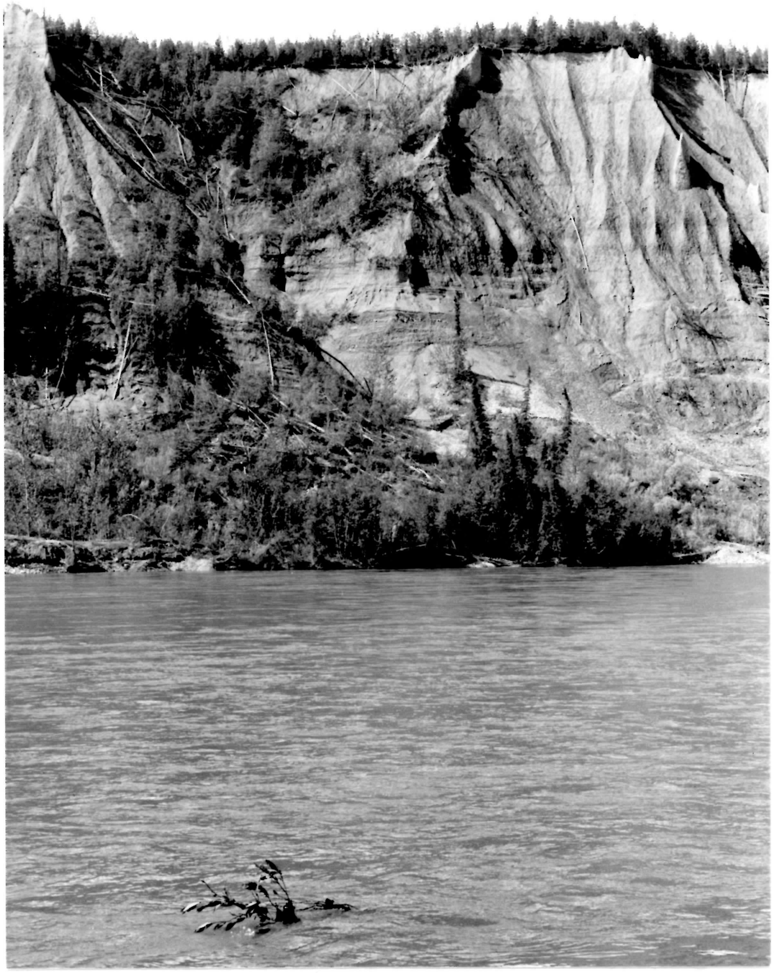


Photo 9. View of typical valley fill sequence found in the Canadian Cordillera. Photograph shows 60 meters of unconsolidated sediment alongFinlay River, British Columbia. A variety of glacigenic sediments are represented including deposits from two separate glaciations. (Photo by P. Bobrowsky).

IMPLICATIONS FOR DRIFT PROSPECTING

The nature and behaviour of ice masses during the Pleistocene within the Cordillera has significant bearing on any effort for drift prospecting in this unique terrain. In this regard, rates of erosion, entrainment, transportation and deposition are all reflective of glacier ice conditions (Figure 17). Clark (1987) argues the most important control of sediment dispersal is the basal ice velocity; where low sliding velocities can be associated with shorter dispersal distances in contrast to higher velocities which result in longer transport distances. Strobel and Faure (1987) view the position of sediment transport in the ice as the most important factor controlling dispersal patterns. For any ice mass, they propose that basal debris is deposited quickly, whereas englacially transported debris is transported much farther. Although not discussed in detail, they imply also that supraglacial debris would result in still greater transport distances. Strobel and Faure's conclusions are based on their interpretation of Shilt's (1976) description of a typical dispersal curve where the head proportion undergoes an exponential decrease and the tail portion approximates a linear reduction. The transition from head to tail in the curve is thought to reflect the transition in the transport position in the glacier from basal to englacial. However, the flat portion may also indicate convergent flow, ice streaming or even surging of the ice according to Bouchard and Salonen (1989). Although a considerable discussion of sediment transport in ice revolves on glacier behaviour, transport in the upper ice zone (supraglacial) is rarely emphasized, but in mountainous terrain of the Cordillera, a significant portion of the debris transported by ice is carried in the supraglacial position (cf. Dreimanis, 1990). If the supraglacial debris is exogenous in derivation, transport lengths are often considerable which contrasts with basally derived debris which can be transported both short (compressive flow) and long (extending flow) distances. Supraglacially transported debris is not necessarily disadvantageous for mineral prospecting, as it has been shown to be useful in certain situations (see Stephens *et al.*, 1983).

Position relative to ice divides and equilibrium lines controls ice flow rates and, therefore, transport distances. In the Cordillera all mountain glaciers flow fastest at their equilibrium line, velocity progressively decreasing in both an up-ice and down-ice direction. Moreover, during the Pleistocene, all glaciers in the Cordillera would have inherently moved faster than ice sheets elsewhere on the continent.

As a product of the above factors, glacial sediments most likely to be examined in a geochemical dispersal study often display widely divergent transport distances (Figure 18). According to Salonen (1989) increasing transport distances result as one progresses from hummocky moraines to cover moraines (till veneers) to drumlins and finally to ground moraines (Figure 19). As expected, even greater transport distrances are observed in glaciofluvial deposits such as eskers (Vallius, 1989). Aario and Peuraniemi (1992) examined a larger suite of morainic landforms in terms of their drift prospecting potential. They provide a detailed summary of several controlling properties and conclude applicability to ore prospecting is rated good for cover (veneer), Rogen and Sevetti moraines, moderate for ground moraine and moderate to poor for drumlins, flutings, Pulju and end moraines.

CONCLUSIONS

A number of factors are known to control the nature and character of geochemical dispersal patterns in the mountain environment including the Cordillera. Those factors not discussed here but reviewed elsewhere include bedrock lithology and structure, outcrop area, clast shape and size, deposition history and diagenesis (*cf.* Bobrowsky, 1995). Factors which profoundly influence drift prospecting and are directly related to both glaciers and Cordilleran terrain include relief, topography, glacier ice thickness, ice velocity, distance from equilibrium line, style of sediment incorporation, transport position and history, redeposition and complexity of the underlying stratigraphy.

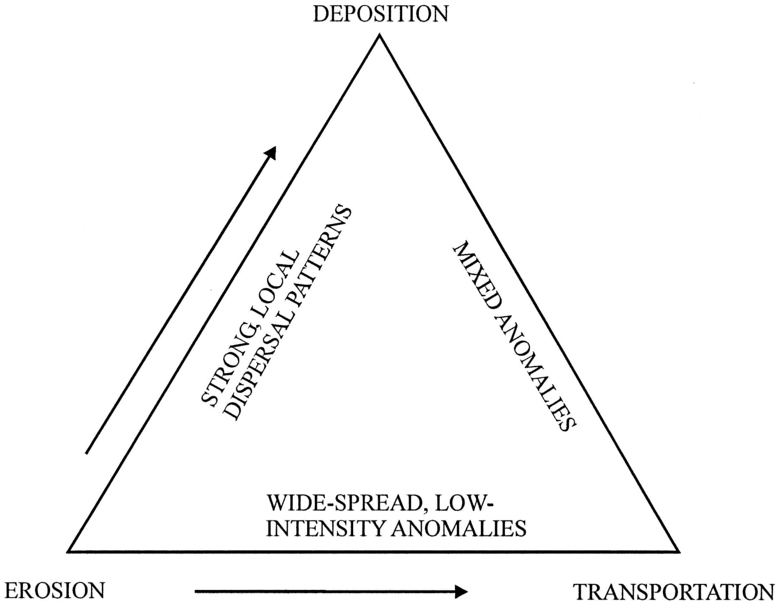


Figure 17. ternary plot of glacial processes indicating relationship between erosion and transportation and deposition and effects on dispersal patterns. (Modified after Salonen, 1989).

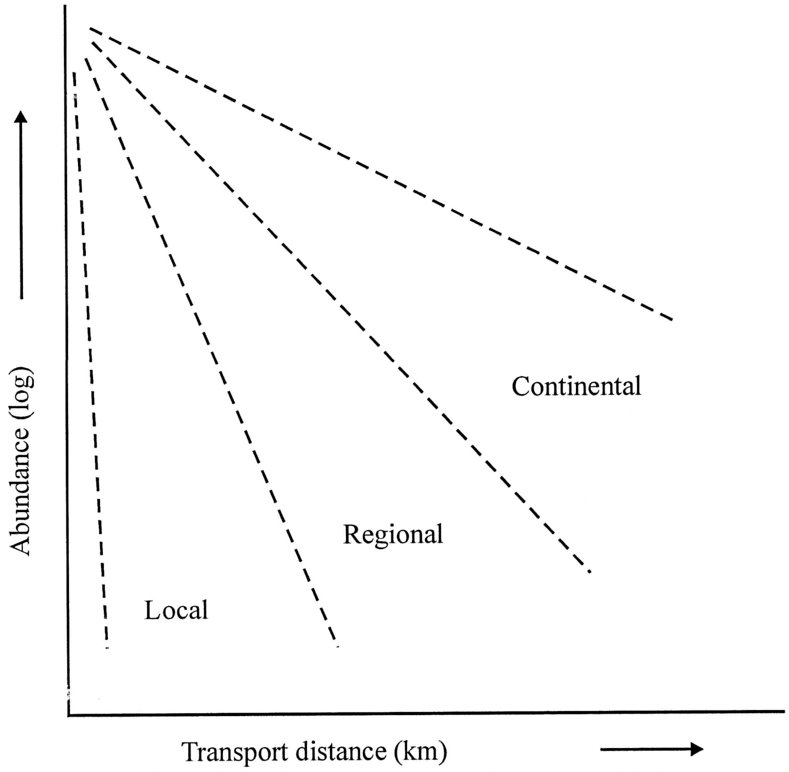


Figure 18. Idealized transport distances for dispersal curves for three scales of glaciation. (Adapted from Clark, 1987).

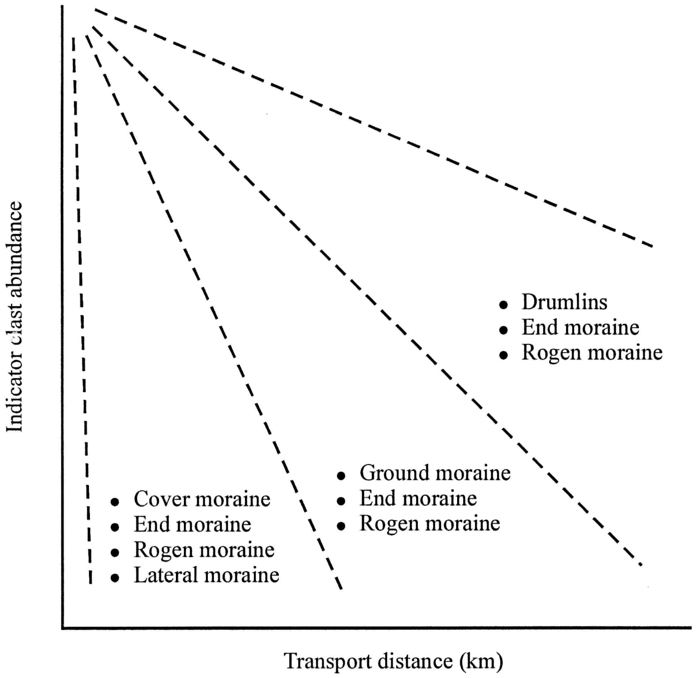


Figure 19. Bivariate relationship between abundance of indicator clasts and transport distance relative to the type of moraine. (Based on data from Strobel and Faure, 1987).

Glaciated mountainous terrain is fundamentally different from relatively flat, rolling terrain which is typically considered in the evaluation of glacial dispersal under ice sheet conditions. In the Cordillera of western Canada, confined valleys, steep gradients, rugged high-relief topography and rapidly changing landform deposits strongly influence the expected and observed dispersal patterns of glacially transported debris. Many of the controlling factors recognized as insignificant in the continental ice sheet environment assume a more prominent role when influencing geochemical dispersal patterns in the mountain glacier environment. Several generalizations concerning drift prospecting in glaciated mountainous terrain can be offered:

- For a typical valley glacier the greatest velocity (least deposition, greatest erosion and highest potential for subglacial input) occurs at the equilibrium line; slower ice velocities occur up and down-ice of this position.
- Fluctuations between compressive (high velocity) and extending flow (low velocity) are expected to be more common in the Cordillera because of the higher relief.
- In the Cordillera, glacial debris is dispersed farther down valleys than across intervening highlands and the compositional isopleths often mimic the topography.
- Steep, confined topography coupled with a high precipitation rate favours the development of fast flowing valley type glaciers.
- The thicker the ice mass the higher the basal temperature and the greater the erosion potential.
- Warm-based glaciers have a higher potential for subglacial erosion as compared to cold-based glaciers.
- The presence of subglacial meltwater is an important factor to increase ice movement, erosion and sediment redistribution.
- Supraglacial debris is an important component in the sediment load of Cordilleran glaciers.
- Transport distances increase for debris as one moves from basal to englacial to supraglacial ice positions.
- Dispersal trains in valley situations (mountains) have a higher length to width ratio as compared to continental ice sheets.
- Ice streaming, convergent and divergent ice-flow patterns are expected to be greater in the Cordillera than elsewhere.
- Redeposition or dilution (inwash) is more significant in the alpine environment where tributary glaciers contribute to the main trunk systems.
- Glacial landforms show considerable variability in their potential utility for ore prospecting and certain morainal deposits are more common in mountainous terrain, whereas others are less common to absent when compared to continental situations.

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