GLACIAL HISTORY AND ICE FLOW DYNAMICS APPLIED TO DRIFT PROSPECTING AND GEOCHEMICAL EXPLORATION

Klassen, R.A.[1]

1. Geological Survey of Canada, Ottawa, Ontario, Canada

ABSTRACT

Mineral exploration by drift prospecting has long relied on glacial dispersal models to trace indicator erratics in glacial deposits and locate their bedrock source. In the past decade, advances in the fields of glaciology and glacial sedimentology have lead to more sophisticated interpretations of the Quaternary geological record in terms of glacial process, glacial sediment provenance, and glacial history. At the same time, models of the Laurentide Ice Sheet, and its adjacent glacier complexes, have included geological and physical properties of the ice bed, thereby providing more accurate portrayals of spatial and temporal variations in regional ice flow dynamics. Those models show that ice divides were long-standing, dynamic features of the ice sheet, affecting drift composition over large areas of glaciated terrain, and have indicated that ice streams served as important agents of erosion, transport, and deposition. Their accuracy has been refined by the empirical evidence of drift composition and ice flow history resulting from ongoing regional surveys of drift composition. Together, the empirical and theoretical models provide a regional framework for developing mineral exploration strategies in terms of glacial process and its effects on drift composition. For example, an exponential decrease in indicator concentrations with distance of glacial transport reflects glacial transport and abrasion as part of the basal debris load, whereas linear to no decrease reflects englacial transport with minimal to no deposition during transport. Linear profiles may be characteristic of ice streams. The linkages among distance and direction of glacial transport, glacial history, and ice sheet dynamics have thus enhanced the value of glacial dispersal models as predictive tools for exploration.

INTRODUCTION

Drift prospecting is based on the simple premise that indicators of economic mineralization in glacial deposits—lithological, mineralogical, or geochemical—can be traced to their bedrock source. In practice, its application to mineral exploration is seldom straightforward, reflecting the complex processes of glacial erosion, transport, and deposition that act to form glacial deposits, and their heterogeneous character. Despite those complications, drift prospecting has long been an integral part of mineral exploration in glaciated terrain, especially in Fennoscandia where many of the techniques of boulder tracing and geochemistry were originally developed and applied. There, a logistic infrastructure has long facilitated surficial geological and geochemical mapping, and Quaternary geology has been well supported by governments, universities, and the exploration industry itself. In contrast, the large size and remote setting of Canada have lead to greater emphasis on theoretical models of glacial dispersal as predictive tools in mineral exploration (e.g., Shilts, 1993).

Over the past decade the basis for drift prospecting in Canada has been significantly improved by developments related to theoretical models of the ice sheet and ice flow dynamics, to mechanisms of glacial erosion, transport, and deposition, and to mapping of glacial deposits and drift composition. Theoretical models have begun to accommodate diverse glaciologic, physiographic, and geological factors that can affect ice flow, and have been used to reinterpret the geological record in terms of glacial processes. At the same time, regional studies of glacial history and drift composition by provincial and federal Geological Surveys have been carried out in large parts of Canada, representing an unprecedented increase in our knowledge of drift composition. Through that work, tens of thousands of geochemical, mineralogical, and lithological till analyses have been reported, allowing glacial dispersal trains to be modelled in terms of distance and direction of glacial transport, glacial landform association, and geographic and glaciological context in the ice. Because those advances have occurred in diverse fields of Quaternary geology, including glaciology, glacial sedimentology and stratigraphy, paleoclimatology, and environmental study, their significance to exploration is not widely recognized. As a further complication, the glacial system is described at scales from continental (thousands of kilometres), to regional (hundreds of kilometres), local (kilometres to tens of kilometres), to detailed (hundreds of metres to kilometres) (Shilts, 1984; Clark, 1987), but the focus of mineral exploration typically remains either local or detailed, driven by an immediate need to locate a bedrock source of an indicator erratic. The parallel developments in

In "Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration" *edited by* A.G. Gubins, 1997, p. 221–232

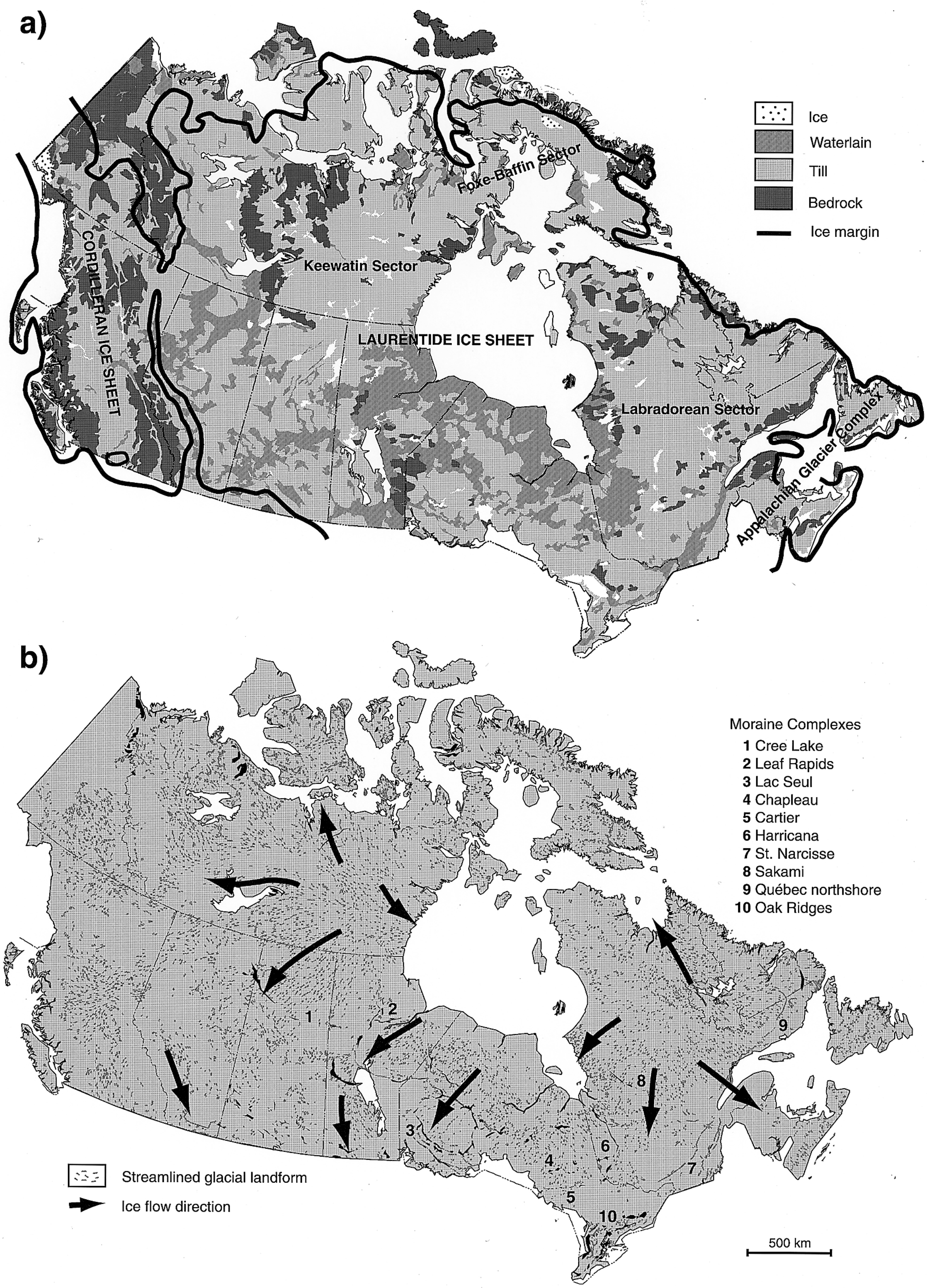

Figure 1: *Surficial Materials Map of Canada, emphasizing the distribution of bedrock, till, and waterlain sediments derived from till (**a**), and the trend and orientation of streamlined glacial landforms and morainic complexes (**b**) (modified after Fulton, 1995).*

Quaternary geology and ice sheet modelling have provided an important new set of tools for tailoring drift prospecting methods to suit regional variations in ice flow dynamics and glacial dispersal.

Through a selective overview, this paper links recent advances in Quaternary geology to drift prospecting in a broad perspective. Unlike a case history approach, which emphasizes current methods and exploration successes, this paper illustrates the diverse approaches available to the exploration community for the effective use of glacial deposits in exploration. Neither text nor references are intended to be comprehensive, but rather to serve as guides for further investigation; the results of numerous deserving studies have been omitted for lack of space. Although the focus is on Canada, and the area covered by the Laurentide Ice Sheet in particular, Fennoscandian research on glacial process and drift composition has direct application to Canadian exploration practice and as such is extensively reported.

ICE SHEET MODELLING

At all scales, the provenance and composition of glacial deposits reflects glacial history and ice flow dynamics. Thus, ice sheet models are important to mineral exploration because they can be used to illustrate regional variations in distances and directions of glacial transport, and in the relationship between bedrock and drift composition in terms of glacial process. During the last glaciation, the Wisconsin, the glacier complex that blanketed Canada and the northern United States comprised four distinct components, including the Laurentide Ice Sheet, which covered most of the interior plains and Shield regions, the Cordilleran Ice Sheet over the western mountains, the Appalachian Glacier Complex over the maritime provinces, and the Queen Elizabeth Islands Glacier Complex over the Arctic archipelago (Figure 1a). The Laurentide Ice Sheet, by far the largest component, has been further subdivided into the Keewatin, Labradorean, and Foxe-Baffin sectors. Although coalescent, the sectors were dominated by semi-independent ice divides that changed in size, shape, and extent during glaciation (Dyke and Prest, 1987).

Models of the Laurentide Ice Sheet are continually modified by acquisition of geological data such as striations, indicator erratics, and stratigraphy that are used to constrain the extent of ice and the trend and sequence of ice flow, and by advances in glaciology based as much on the physics and chemistry of ice as on the modern Antarctic and Greenland ice sheets. Early models assumed a rigid, unyielding bed, and uniform, plastic sheet flow in ice, with shear either at the ice-bed interface, where ice was at the pressure melting point (warm-based), or higher in the ice where it was frozen to the bed (cold-based). From those assumptions, the models showed a stable glacier monolith centred on Hudson Bay with broadly radial flowlines. The flowlines, however, were not consistent with known glacial dispersal, and they portrayed a uniform application of glacial process for interpretation of glacial deposits. Glacial landforms and their distribution were interpreted to reflect basal ice temperatures and the balance between crustal heat flow, ice surface temperature, and ice flux.

Through the 1980s, ice sheet models began to incorporate geology and physical properties of the ice bed, including topography, subglacial hydrology, and mechanical strength, as important controls on ice flow dynamics (Boulton *et al.*, 1985; Boulton and Hindmarsh, 1987; Budd and Smith, 1987; Fisher *et al.*, 1985). That has lead to the portrayal of a more complex ice sheet characterized by lower surface elevations, zones of differential ice flow velocity, and a complex network of ice divides with interconnecting ridges and saddles. From geological evidence, the divides were active throughout glaciation, although changing in shape, size, and location over hundreds or thousands of km (e.g., Shilts, 1979; Boulton *et al.*, 1985; Boulton and Clark, 1990a,b; Clark, 1993). That contrasts with earlier interpretations of ice divides as short-lived, deglacial features.

Recognized initially through Antarctic studies, ice streams are now inferred to have been prominent features of the Laurentide Ice Sheet, playing a vital role in its flow dynamics and mass balance (e.g., Marshall *et al.*, 1996). Ice streams are zones in an ice sheet that flow more rapidly than the surrounding ice (Bentley, 1987), reflecting a significant lowering of effective shear stress at the ice bed either through subglacial sediment deformation or meltwater between the ice and the bed, or both. The regional distribution of ice streams reflects bed topography, subglacial sediment properties, and subglacial thermal and hydrologic regimes (Boulton, 1996a,b; Marshall *et al.*, 1996). Because flow velocity relates directly to the effectiveness of ice as an agent of dispersal, ice streams are closely linked to regional variations in the properties and provenance of till. They may have been a principal mechanism for dispersal of carbonate-rich drift across large parts of northern Ontario, hundreds of kilometres from its bedrock source (e.g., Hicock *et al.*, 1989; Thorleifson and Kristjansson, 1993).

THE GEOLOGICAL RECORD

It is important to distinguish between the erosional and depositional records because they are spatially and temporally distinct, formed beneath the ice sheet at different times, in different locations, and by different processes (e.g., Boulton, 1984; 1996a,b) (Figure 2). Whereas erosion occurs at the outer margins of an ice sheet during expansion, deposition occurs later, either at the glacial maximum or during deglaciation. In central regions, near ice divides, ice tends to be protective of its bed, and there the geological record can represent multiple glacial events. Thus, the type, provenance, and relative age of the geological record, including striations, streamlined landforms, reflects geographic and glaciological context in the ice sheet, and can be expressed in terms of ice divides and ice flow dynamics, and spatial and temporal variations in them (e.g., Aylsworth and Shilts, 1989; Boulton, 1984, 1996a,b; Boulton and Clark, 1990a,b; Bouchard and Salonen, 1989, 1990; Kleman, 1990). The message for exploration is that relations among bedrock, drift composition, and ice flow history must be inferred in the wider context of the ice sheet and glacial history and in terms of both erosional and depositional records.

Erosional

Erosional features include striations and grooves on bedrock (millimetres to tens of metres long), as well as streamlined forms developed in bedrock and in sediments overridden by the ice (tens of metres to kilometres). Striations are created by debris dragged by ice across its bedrock surface and can define the trend and relative age of ice flow, although not the duration and distance of glacial transport associated with ice flow events (e.g., Prest, 1983; Kleman, 1990). They provide a more detailed and comprehensive record than glacial landforms alone, and are commonly used to reconstruct ice flow events and to unravel glacial transport paths for mineral exploration (e.g., Klassen and

Thompson, 1993; Kleman, 1990; Stea, 1994; Parent *et al.*, 1996; Veillette, 1986). In central areas of the ice sheet, striation trends are typically complex, reflecting the evolution in shape, extent, and location of ice divides, as well as outward migration in the zone of basal erosion (Boulton and Clark, 1990a,b). In contrast, in outer margins of the ice sheet striation trends are less variable, reflecting their greater distance from ice divides and corresponding stability in ice flow direction (Kleman, 1990).

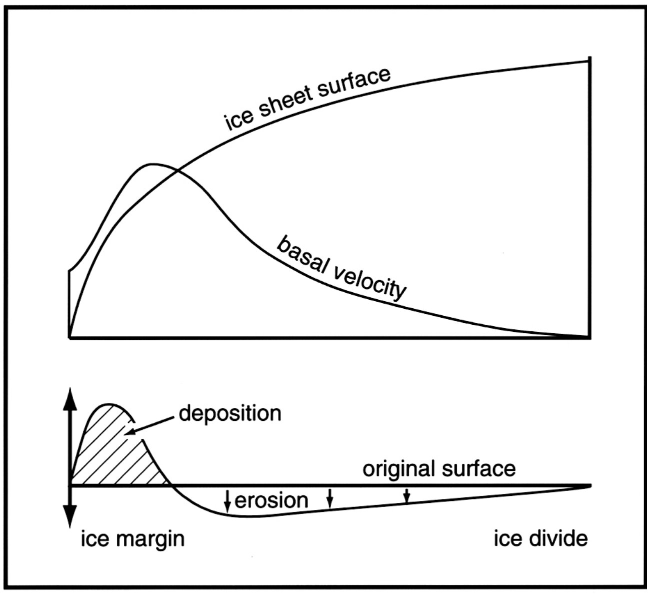

Figure 2: *Schematic ice sheet profile, indicating spatial variations in ice flow velocity and in areas of erosion and deposition (modified after Boulton and Clark, 1990b).*

Although 'older' striations pre-dating the last glacial event have long been known in Canada and Fennoscandia, recent mapping has shown them to be common and widespread. The older striations have significantly changed the basis for ice sheet reconstructions, defining temporal and spatial variations in paleoflowlines and ice divides, including early and pre-Wisconsinan events (e.g., Stea, 1994; Veillette, 1986). They occur on exposed outcrop surfaces as crosscutting sets, and on surfaces sheltered from later ice flow (e.g., Bouchard and Martineau, 1985; Klassen and Thompson, 1993; Kleman, 1990; Lundqvist, 1990; Parent *et al.*, 1996; Stea, 1994; Veillette and McClenaghan, 1996; Veillette and Roy, 1995). The widespread occurrence of older striated bedrock surfaces, preserved despite subsequent glaciation, indicates:

1. limited, differential glacial erosion of bedrock,
2. the importance of topography and bed roughness to the formation of glacial dispersal trains, and
3. the significance of ice flow direction and slope aspect in tracing indicator debris in the subsurface.

By inference, outcrop surfaces having different slope aspect are not equally represented in till because of differential erosion.

A new class of erosional marks, referred to as 'P-forms' is associated with subglacial meltwater erosion of bedrock (Kor *et al.*, 1990). The features, which represent metres to tens of metres of erosional relief, define coherent regional flow trends and are seen as key evidence for catastrophic, subglacial outburst floods (Shaw, 1990; Shaw *et al.*, 1996). Where the ice later came in contact with the bed, P-forms can be striated. Although P-forms are prominent erosional elements, their significance to drift composition and dispersal remains poorly known.

Depositional

As a regional context for drift prospecting, the recently published Surficial Materials Map of Canada shows the distribution of glacial deposits and landforms in Canada at 1:5 000 000 scale, illustrating their genesis, regional extent, and thickness (Fulton, 1995) (Figures 1a, b). It sets the continental and regional Quaternary context for exploration programs. For most provinces, comparable maps are available at 1:500 000 and 1: 1 000 000 scales. On the map, glacial landforms and sediments reflect a concentric succession of sub-marginal ice flow, with a prominent overprinting by landform-sediment associations associated with the final ice retreat areas of the Keewatin and Labradorean sectors (Fulton, 1989). The central sectors of the ice sheet are dominated by erosional landforms and superimposed late glacial depositional forms, and around them are intermediate zones of both strong erosional and depositional forms, and an outermost zone of strongly developed depositional forms (Boulton, 1996b). Glacial landforms such as crag-and-tail hills, drumlins, flutings, and lineaments, however, are variously described as erosional, created either by subglacial sediment deformation (Boyce and Eyles, 1991) or by subglacial meltwater (Shaw, 1990), and as glacial deposits (Boulton, 1996a). The meltwater discharge model interprets streamlined landforms such as drumlins to have been created by outburst floods of short duration early in deglacial time, recording flow across a significant part of the ice sheet. Vigorous debate is current on the role of catastrophic, meltwater floods on landscape evolution and glacial sedimentation. It is beyond the scope of this review paper to present that debate, only to note that it is a direct reflection of how little is known of glacial deposits and landforms, and their origins.

From ice sheet models, streamlined glacial landforms are inferred to become younger with distance from the ice margin, and ice flow patterns evident on the Surficial Materials Map have been used to reconstruct a history of late glacial ice flow (Dyke and Prest, 1987) (Figure 1b). Consistent with the striation record, crosscutting relations among landforms indicate that some of those flow trends could be much older, possibly pre-dating the last glacial maximum (Boulton and Clark, 1990a,b). Their preservation reflects differential erosion of bedrock among succeeding ice flow events, emphasizing spatial and temporal variations in ice flow dynamics (Kleman, 1994; Dyke, 1984, 1993; Stea, 1994). Locally, late-glacial lobate patterns of ice flow associated with ice streams appear youngest, truncating other landforms and terminating at arcuate morainic complexes (Punkari, 1984; Salonen, 1987, 1988).

The differences in the intensity of glacial erosion and deposition and in ice flow trends shown by the map can be used to infer a continental mosaic of ice flow dynamics and to model regional variations in glacial transport distance and in the compositional relations between till and underlying bedrock. For large areas, glacial erosion was minimal, on the order of a few metres, as indicated by debris volumes in glacial dispersal trains (Kaszycki and Shilts, 1980; Charbonneau and David, 1993; Lundqvist, 1990), and by the preservation of older glacial and interglacial deposits (DiLabio *et al.*, 1988; Thorleifson *et al.*, 1993) and preglacially weathered bedrock (Boyle, 1996; Hirvas, 1991) beneath till. In the

Arctic and along the eastern and northern continental margins, the ice sheet was cold-based, and protective of its bed (Dredge, 1995; Dyke, 1993; Dyke and Morris, 1988; Dyke *et al.*, 1992). There, glacial transport distances are minimal, and glacial deposits are difficult to distinguish from bedrock rubble; major landscape elements could be Tertiary age. Where flow was more rapid, either along major valleys and fiords, or in ice streams, the effects of glacial erosion and transport are much greater, and the linkages between bedrock and drift composition more complex (Charbonneau and David, 1993; Dyke *et al.*, 1992; Dredge, 1995).

The occurrence of older glacial and nonglacial sediments beneath surface till further demonstrates incomplete glacial erosion during succeeding glacial events, as well as compositional masking of underlying bedrock. Buried deposits are widespread across the Prairies (Fenton, 1984), Hudson Bay Lowlands (Thorleifson *et al.*, 1993), and the southern margins of the ice sheet (Hansel *et al.*, 1987), and recent work indicates they are likely more extensive. In northern Ontario and Québec, for example, overburden drilling has revealed numerous older deposits preserved as erosional remnants in topographic depressions, reflecting the relief and topographic orientation of bedrock relative to ice flow direction (DiLabio *et al.*, 1988; McClenaghan *et al.*, 1992; Smith, 1992). In Fennoscandia, multiple buried tills and interglacial organic deposits are characteristic of ice divide regions (Hirvas, 1991). Although little is known of the subsurface near the Keewatin and Labradorean ice divides, the Fennoscandian work indicates that a comparable record could exist there. Conversely, thick (>10 m) deposits of waterlain sediment deposited in glaciolacustrine and glaciomarine environments occupy huge areas, masking bedrock and till with sediment younger than the last glaciation (Figure 1a). In those areas, drift prospecting commonly requires either excavation or overburden drilling to sample till (e.g., Brummer *et al.*, 1992; Nichol *et al.*, 1992; Schreiner, 1984; Smith, 1992).

Till classifications have increasingly reflected glacial process (Dreimanis, 1989, 1990). Although the field evidence required to make those distinctions is commonly not available, especially in exploration practice, they reflect the growth and sophistication of glacial sedimentology that has occurred over the past decade. In addition to compositional analysis, the determination of depositional process will undoubtedly lead to a more effective use of glacial deposits in indicator tracing at detailed scales of investigation, resolving evidence for varied late glacial events affecting the compositional relation between surface till and underlying bedrock, including topographically directed ice, surging into glacial lakes, debris flow, and iceberg rafting.

To illustrate the potential utility of till classification to mineral exploration, and the linkages among regional ice flow dynamics, glacial process, and sediment composition, a recently identified till type, deformation till, is described here. Deformation of the ice bed most likely occurs in fine-grained sediment having low porosity and high porewater pressure, such as glacial lake and glaciomarine sediments overridden by ice, and in fine-textured till derived from them (Boulton and Hindmarsh, 1987; Hicock *et al.*, 1989). The resulting deformation till is characterized by:

1. an abundance of fine-grained till matrix and faceted clasts reflecting intense abrasion and the incorporation of fine-grained older sediment overridden by the ice,
2. either lack of structure through shear attenuation and homogenization of sediments overridden by the ice, or complex folding (Hicock and Dreimanis, 1992),
3. sharp lower erosional contacts reflecting the limit of shear deformation and the lower contact with undeformed glacial sediment, and
4. overconsolidation (Alley, 1991).

Because subglacial deformation may be characteristic of ice streams, the distribution of deformation till can in part be determined from landform-sediment associations, including:

1. lobate, radial patterns of ice flow defined by drumlins,
2. marked discontinuities in regional ice flow trends;
3. far-traveled (>50 km) debris extending down-ice from sources much wider than the train itself as well-defined plumes (Dyke, 1984; Dyke and Morris, 1988; Dyke *et al.*, 1992; Hicock *et al.*, 1989; Thorleifson and Kristjansson, 1993), and
4. areas where ice has overridden fine-grained sediment (Boulton, 1996a,b).

Thus, the occurrence of deformation till could indicate the wider distribution of a relatively thick, compositionally homogenous deposit characterized by significant glacial transport distance and bearing little or no compositional relation to underlying bedrock. Further, there could well be an abrupt lateral transition to adjacent areas where till is closely linked to underlying bedrock.

For indicator tracing, the origins and internal architecture of glacial landforms, including drumlins (Graves and Finck, 1988) and morainic complexes (Stewart and Broster, 1990) are important. Not only are the landforms widespread and areally extensive, but they are complex in facies, structure, and provenance, including glaciofluvial and other waterlain sediments as major components, as well as preglacial sediment overridden by the ice and organic deposits (Lundqvist, 1990). Thus, indicators of economic mineralization are difficult to trace if the varied sediment types comprising the landforms are sampled indiscriminantly (Aario and Peuraniemi, 1992). End and interlobate moraines, for example, mark either an ice flow terminus or suture zones between distinct ice lobes or Sectors of the Laurentide Ice Sheet. In northern Manitoba, for example, the Leaf Rapids Interlobate moraine marks the boundary between Keewatin and Labradorean ice (Figure 1b). To the east, Labradorean till is carbonate-rich through the incorporation of sedimentary bedrock from Hudson Bay, whereas to the west Keewatin till is 'crystalline', derived from Shield terrane (e.g., Dredge, 1988). Through drawdown, ice flow can laterally shift toward ice margins, locally redistributing glacial debris (Veillette, 1986).

GLACIAL DISPERSAL MODELS

In the past decade, both theoretical constructs of the Canadian and Fennoscandian ice sheets (e.g., Boulton, 1984; 1996b) and empirical models of glacial dispersal (e.g., Stea *et al.*, 1989; Puranen, 1988, 1990), have clearly linked glacial history and spatial and temporal variations in ice flow dynamics to drift composition. Theoretical models show that:

1. near ice divides there is minimal to no erosion of underlying bedrock, and a complex history of glacial transport resulting in their movement over hundreds of kilometres,
2. erosion is most effective in the earliest phase of glaciation, in the outer margin of an expanding ice sheet,
3. deposition occurs in the outer margin of the ice sheet at its maximum and during deglaciation, and

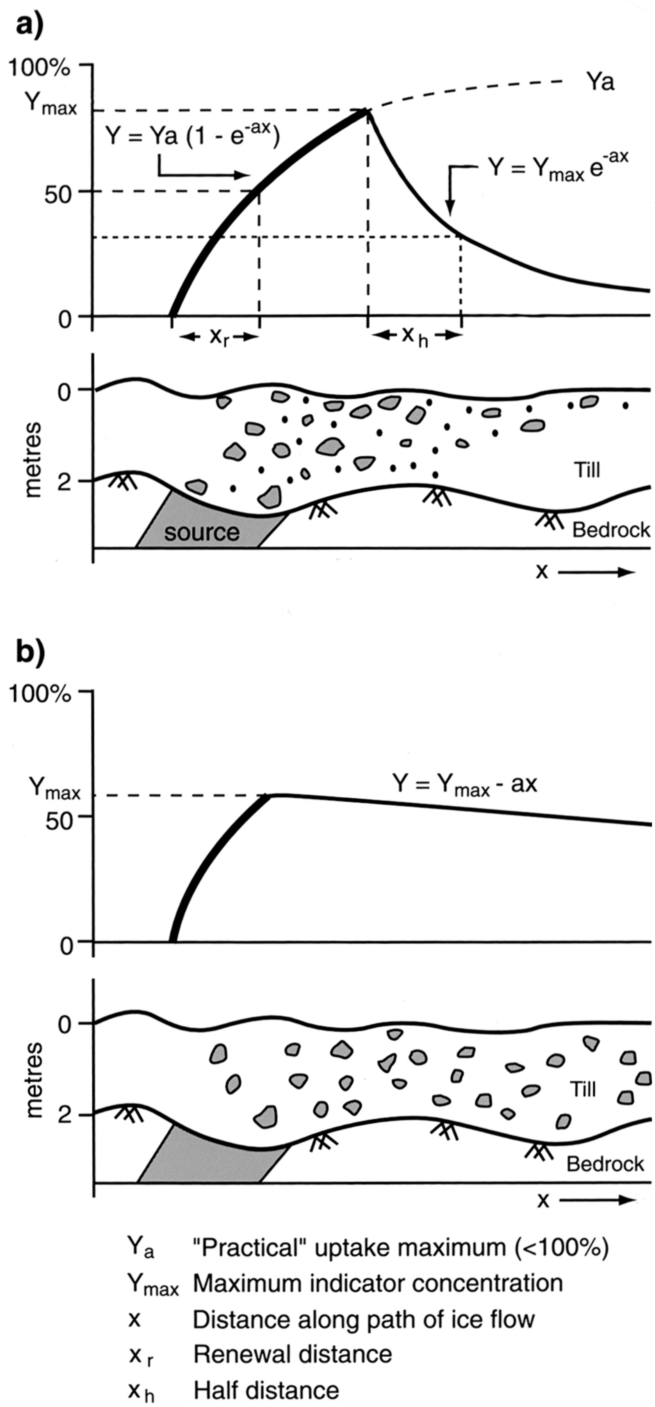

Figure 3: *Schematic profiles illustrating compositional variations of indicator erratics with distance of glacial transport, and their expected distribution in till. (**a**) Exponential 'uptake' and 'decay' curves reflect erosion, modification, and deposition of debris transported at the base of the ice. (**b**) Linear decay reflects englacial transport with little or no modification of debris, and may be characteristic of dispersal by ice streams where flow occurs by deformation in the ice bed.*

4. the proportions of far-traveled to local debris in till increase upward in glacial deposits, and with distance outward from the ice divide; far-traveled debris is more characteristic of glacial deposits in marginal areas than near ice divides (e.g., Boulton, 1984, 1996a,b; Clark, 1987).

Glacial dispersal trains of varied indicator erratics that extend hundreds to thousands of kilometres from their source (e.g., Clark, 1987; Prest, 1990) have been used to constrain paleoflowlines in ice sheet reconstructions (e.g., Boulton *et al.*, 1985; Fisher *et al.*, 1985). Because the transport of erratics over thousands of kilometres is not readily accommodated by a single ice flow event, the erratics indicate multi-cycle glacial erosion and transport.

In the past decade, empirical data have been used to further develop mathematical models of glacial dispersal and to identify regional differences among factors affecting dispersal. Numerous workers have shown that indicator concentrations in till decrease exponentially with distance down-ice from a source (e.g., Clark, 1987; Finck and Stea, 1995; Gillberg, 1965; Salonen, 1987, 1992; Shilts, 1976; Parent *et al.*, 1996). The relation is expressed in the form:

$$y = y_o \cdot e^{-ax} \qquad [1]$$

where: y is the debris concentration at a point along the path of ice flow, y_o is the maximum concentration achieved either at or down-ice of the source (100%), x is the distance of transport down-ice of the maximum, e represents the base of the natural logarithm, and a is a constant reflecting the rate of decay (Gillberg, 1965). With distance of ice flow across a source, it follows that indicator concentrations also increase exponentially as the result of uptake by the ice (Finck and Stea, 1995; Peltoniemi, 1985) (Figure 3). Together, the curves for uptake and deposition give the characteristic dispersal profile which rises rapidly to a 'head' either over or directly down-ice of the source, and decreases in a 'tail', defined by indicator concentrations slightly elevated above background concentrations, stretching down-ice (e.g., Shilts, 1976). Till in the tail is most likely to be sampled because it comprises the most extensive part of the dispersal train. Thus, in mineral exploration there is a need to discriminate the faint signal of mineralization in the tail from 'noise' related to glacial process and to geological variability, and it is in that context that glacial dispersal models contribute to exploration.

The shape of the exponential curve is reflected by 'a', which relates to:

1. the velocity and duration of ice flow (Aario and Peuraniemi, 1992; Bouchard and Salonen, 1990; Clark, 1987; Dyke, 1984),
2. the physical properties of the source, including its areal extent, topographic exposure (Clark, 1987; Salonen, 1992), and its susceptibility to glacial erosion and comminution (Gillberg, 1965), and
3. the balance between re-entrainment of older glacial debris and addition of new detritus from bedrock (Parent *et al.*, 1996).

From empirical studies, 'a' can be viewed as a sum of constants for each of the controls listed above (e.g., Gillberg, 1965; Clark, 1987).

Glacial transport distance is characterized as a 'geometric mean' or a 'half-distance' (Pertunnen, 1977), which is the distance for peak concentrations to decrease to half their maximum value (Gillberg, 1965) (Figure 3); the two terms are equivalent (Bouchard and Salonen, 1990). Half distance can vary widely, although numerous reports indicate that the bulk of glacial deposits have undergone limited transport, on the order of hundreds of metres to several kilometres (<10 km) (Clark, 1987;

Coker and DiLabio, 1989; Charbonneau and David, 1993; Bouchard and Salonen, 1989, 1990; Finck and Stea, 1995; Puranen, 1988, 1990). The shape and scale of dispersal curves can be empirically linked to regional ice flow dynamics through landform-sediment associations. Transport distances differ between the distal and proximal sides of end moraines, the core and surface of landforms, and the marginal regions of the ice sheet and ice divides, and vary according to landform–sediment associations (Aario and Peuraniemi, 1992; Bouchard and Salonen, 1990; Graves and Finck, 1988; Puranen, 1988, 1990). In Finland, for example, glacial transport distances are 5–17 km for drumlins, 0.4–3 km for hummocky moraine, and 0.8–10 km for cover moraine (Salonen, 1987, 1988, 1992). In addition, systematic variations in glacial transport distance relate to the context of flowlines in ice lobes (Figure 4).

Glacial dispersal models appropriate to a region can be difficult to define because they require areally extensive sampling and prior knowledge of an indicator source. In recognition, the concept of 'Transport Distance Distribution' (TDD) has been introduced (Salonen, 1988). It is determined from a log-normal plot of the concentration of each lithologic type present at a site against the distance in the direction of ice flow to its nearest bedrock source (Figure 5). From a linear approximation of the data, a half-distance for that site can be determined, and the transport distance for mineralized indicator erratics at the site estimated for exploration (Bouchard and Salonen, 1989, 1990). To model glacial dispersal independent of outcrop width, the 'renewal distance' (the distance of ice flow across a source required for an indicator concentration to become 50% of till) can also be determined (Peltoniemi, 1985) (Figure 3).

Recently a second type of glacial dispersal profile has been described in which debris concentrations decrease linearly with increasing distance of glacial transport, leading to a flat or gently sloping dispersal profile (e.g., Dyke, 1984; Dyke and Prest, 1987; Dyke *et al.*, 1992; Finck

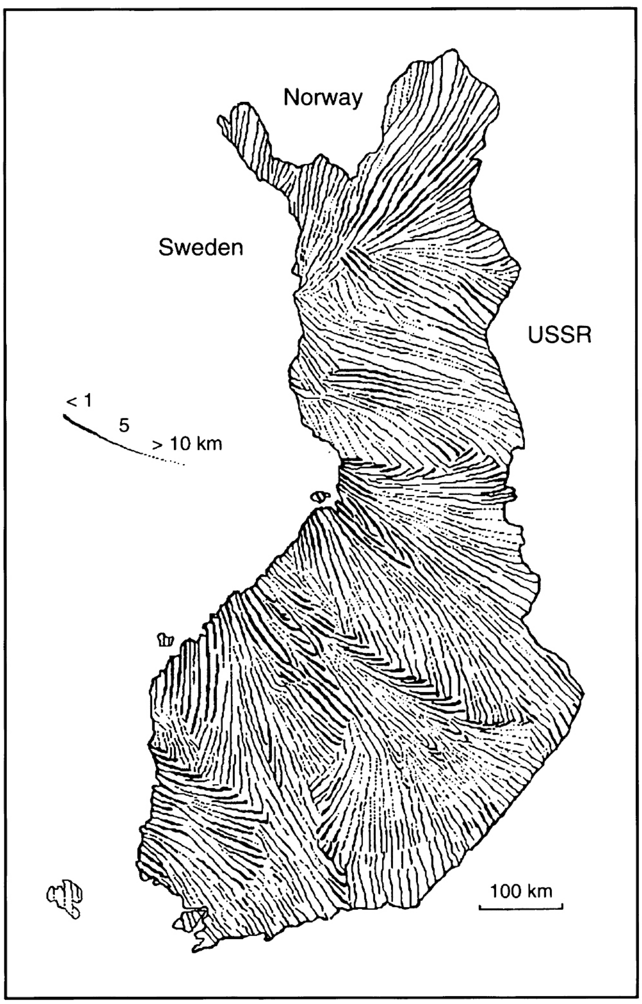

Figure 4: *Schematic characterization of boulder transport distances in Finland shown in the context of glacier flowlines. Glacial transport distance is reflected by line thickness (modified after Bouchard and Salonen, 1990).*

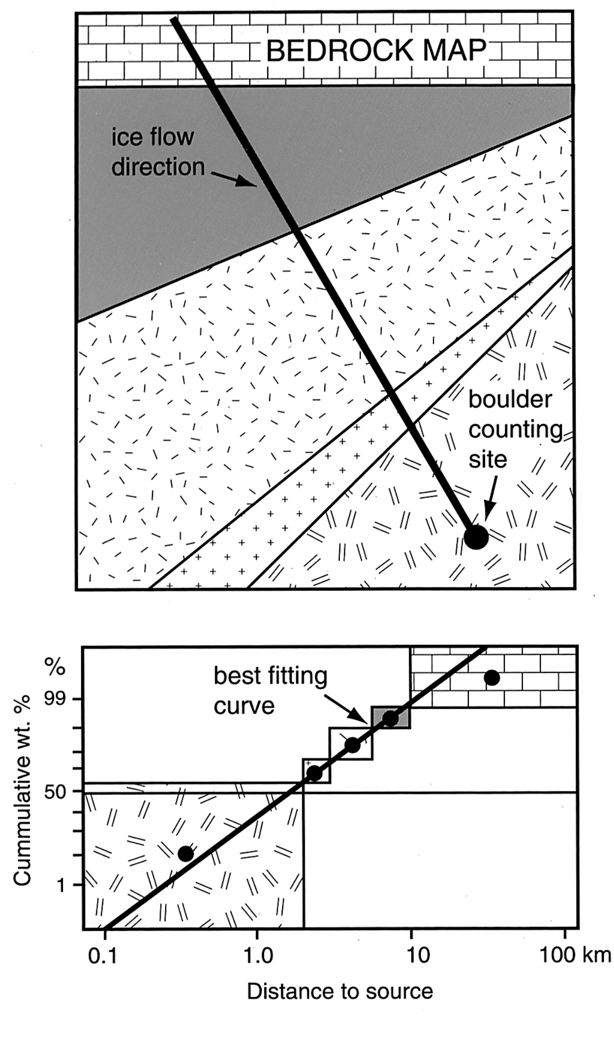

Figure 5: *Transport Distance Distribution applied to the determination of the geometric mean of glacial transport distance ('half distance'). For each rock type along the path of flow, the concentration and distance to source is plotted on a cumulative frequency graph (after Bouchard and Salonen, 1990). The estimate of transport distance can be used as a predictive tool for mineral exploration.*

and Stea, 1995; Kaszycki, 1989; Dredge, 1995; Thorleifson and Kristjansson, 1993) (Figure 3). In contrast to exponential profiles which relate to basal transport, the flat profile is more likely associated with englacial transport, indicating little or no modification of englacial debris by crushing and abrasion, and no ongoing addition of bedrock detritus during glacial transport. Such dispersal can be modelled as a conveyor belt, with no mixing between the ice bed and englacial debris, and may be characteristic of ice stream flow.

Shape of glacial dispersal trains

Recent mapping of glacial dispersal trains has emphasized the linkages between their size, shape, and orientation of glacial dispersal trains, geographic and glaciological context in the ice sheet, and ice flow dynamics. Where the Laurentide Ice Sheet merged with adjacent glacier complexes, as it did with the Appalachian glacier complex along its southeastern margin, drift composition can reflect both long-continued regional flow in the outer margins of a continental ice sheet and flow near ice divides comprising part of the smaller maritime ice sheet (Charbonneau and David, 1993; Stea *et al.*, 1989; Pronk *et al.*, 1989; Rappol, 1989; Shilts and Smith, 1989). Maritime ice caps are characterized by complex flow patterns that reflect topographic effects as well as interaction with the Laurentide Ice Sheet. To recognize the effects of competing ice sheets and changing ice divides, in Nova Scotia drift composition is described in a 'Zonal' context (Stea *et al.*, 1989) (Figure 6). Dispersal associated with the Laurentide Ice Sheet and Appalachian ice centres outside the province (Phase 1a, b) is along regionally prominent flow paths, and debris includes a significant component of far-traveled detritus. From local dispersal centres (Phases 2, 3, 4), there is greater areal variation in ice flow direction and glacial transport distance, and in the intensity of glacial process and comminution of glacial debris, reflected by the textural maturity of till. In till, differences in texture and drift provenance thus reflect the physical properties of bedrock as well as Zonation in the ice sheet.

The dispersal trains can be classified as 'ribbon', 'fan' or 'amoeboid', according to their outline shape. Ribbons are streamed along a single ice flow direction, with a width comparable to the outcrop source, measured perpendicular to ice flow. The more classical fan broadens down-ice, with its outer margins aligned in the two most divergent directions of ice flow. Striations have been used to estimate maximum fan divergence and to define a probability sector for tracing indicators in an up-ice direction (Hirvas, 1989). Near ice divides, where flow variation is marked, including reversal of flow, 'amoeboid' dispersal trains of indefinite shape extend in all directions about their source (e.g., Parent *et al.*, 1996). Compositional variations in drift result from continued erosion of bedrock, as well as recycling of debris during succeeding glacial events, and they can reflect differences in glacial process among events. 'End-member' till results from subglacial processes associated with a single ice event, whereas 'hybrid' till is the product of multiple glacial events (Finck and Stea, 1995) (Figure 6). Hybrid till results from either 'inheritance', where older glacial deposits are incorporated in younger till, or 'overprinting', where later glacial events impress a compositional record on underlying, older glacial deposits. Where older trains served as sources of indicator debris to later glacial events (e.g., Charbonneau and David, 1993; Klassen and Thompson, 1993; Parent *et al.*, 1996), 'palimpsest' glacial dispersal trains (Parent *et al.*, 1996) occur, comprising hybrid till with a component inherited from earlier advance and modified by later flow.

In some cases, the head of a glacial dispersal train terminates with no apparent surface connection to its bedrock source. Lithologic variation in vertical till profiles can indicate change in:

1. ice flow direction and provenance, and
2. distance of glacial transport associated with either change in ice flow velocity or in the position of debris in the ice (i.e., englacial vs. basal) (e.g., Boulton, 1984, 1996a,b; Hansel *et al.*, 1987).

In simple situations where only one till occurs, indicator concentrations are typically greatest at the base of the depoist, directly over the source, and it has commonly been observed that the dispersal train rises in a down-ice direction within the till sheet at a low angle of inclination. The distance between the bedrock source and the first appearance of the dispersal train at the surface tends to increase with till thickness. The vertical rise has been attributed to continued erosion of the source and addition of debris to the base of the ice sheet along the path of flow (Puranen, 1988, 1990), and more recently to upward 'shear diffusion' in a deforming bed (Charbonneau and David, 1995). In exploration, the up-ice gap between the head of the dispersal train and its bedrock occurrence must be prospected in the subsurface by trenching or drilling.

Where debris is introduced high into the ice from a topographic prominence it can be transported englacially with little or no modification by intra-clast contact. Deposition occurs where the debris is brought into contact with the bed farther down ice, for example at a topographic obstruction (Batterson, 1989; Puranen, 1990). Zones of non-deposition along the path of ice flow have been termed 'skip zones' (Finck and Stea, 1995). Separation between the head of a train and its source can also occur through glacial erosion and removal of debris during later events (Stea *et al.*, 1989), or where the train is partially covered by other glacial sediment. Topographic obstructions can also lead to non-deposition in lee sides of hills, and interruption in glacial dispersal patterns (Gillberg, 1965; Shilts, 1976).

SUMMARY

The incorporation of physical and geological factors in ice sheet models has lead to major revisions in our view of the Laurentide Ice Sheet and its landform-sediment record. The work clearly indicates how regional ice flow dynamics, and spatial and temporal variations in them, can be inferred from regional Quaternary mapping and used to determine effective strategies and practices for mineral exploration at local and detailed scales. The complex record of Quaternary geology that is characteristic of glaciated terrain, can be unraveled in the context of geographic and glaciological context in the ice sheet, and should not be simply viewed as an unexpected impediment to exploration. Over the next decade ice sheet models will undoubtedly be further revised with the inclusion of additional physical factors and glaciological principles. For mineral exploration, however, the value of these models is determined almost exclusively by their accuracy in describing particle transport paths and distances. For that reason, there is a continuing need to define glacial dispersal models through empirical evidence and to modify theoretical models according to it. Although the area of glaciated terrain is vast, the geochemical, mineralogical and lithological databases defined by regional surveys will continue to serve as important resources, providing a context for tracing indicator debris and interpreting till geochemistry.

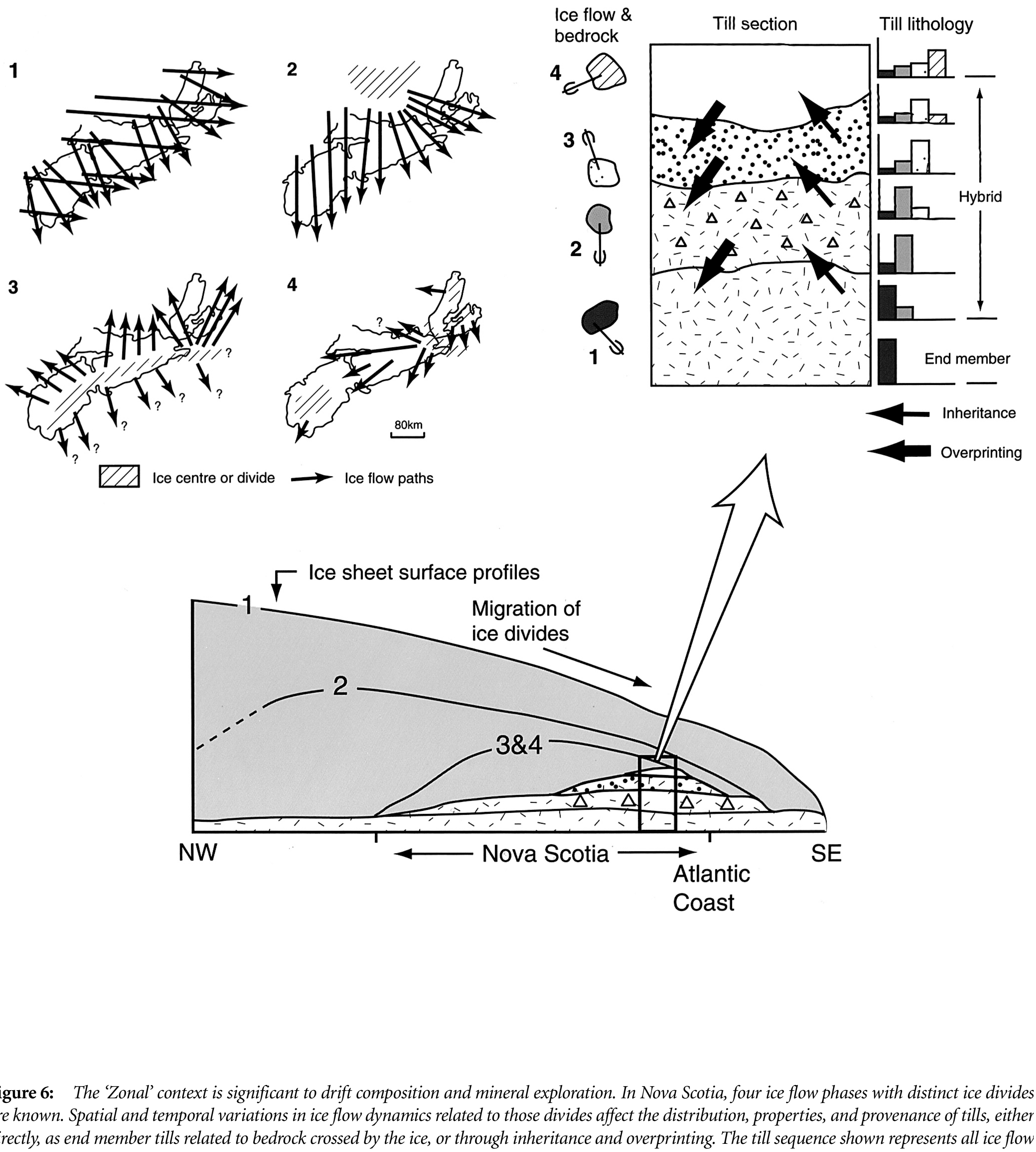

Figure 6: *The 'Zonal' context is significant to drift composition and mineral exploration. In Nova Scotia, four ice flow phases with distinct ice divides are known. Spatial and temporal variations in ice flow dynamics related to those divides affect the distribution, properties, and provenance of tills, either directly, as end member tills related to bedrock crossed by the ice, or through inheritance and overprinting. The till sequence shown represents all ice flow phases; where only part of that sequence occurs, the lowermost end member could represent any phase (modified after Finck and Stea, 1995; Stea et al., 1989; Stea, pers. comm., 1997).*

ACKNOWLEDGEMENTS

Ms. B. McClenaghan is thanked for her careful review, and Drs. R. N. W. DiLabio, P. J. Henderson, and R. R. Stea for their encouragement and suggestions, all of which have helped to improve the manuscript.

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