

CONTRASTING STYLES OF GLACIAL DISPERSAL IN NEWFOUNDLAND AND LABRADOR: METHODS AND CASE STUDIES

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ABSTRACT

A review of practical approaches to drift exploration is presented; it is intended for use by exploration geologists working in drift-covered areas. There are contrasts in style of glacial dispersal between Labrador, dominated by the affects of the Laurentide Ice Sheet, and Newfoundland, affected by small, coalescing ice caps at the glacial maximum and smaller topographically controlled ice centres during deglaciation. The result has been to produce longer, ribbon-shaped dispersal trains in Labrador, except in the Labrador Trough near the centre of the Labrador sector of the Laurentide Ice Sheet; in Newfoundland the glacial-dispersal patterns are more diffuse.

INTRODUCTION

Labrador has a long history of mineral exploration, beginning in the 1800s. The advent of air travel in the 1920s opened up Labrador for exploration, and the iron ore deposits of western Labrador were discovered in 1929. Exploration in the supracrustal rocks of the Central Mineral Belt of Labrador (Figure 1) in the 1950s and 1960s discovered deposits of base metals (mostly copper), and rare-earth elements (beryllium and niobium). Reserves generally were insufficient for mining. Uranium deposits were considered to be of mineable quantities. Environmental concerns and plummeting prices stalled uranium production indefinitely. A surge of exploration activity occurred in the late 1970s to early 1980s following discovery, through drift prospecting, of the yttrium–zirconium–rare-earth deposit at Strange Lake on the Labrador–Québec border. Recently, intense exploration activity accompanied the discovery of the Voisey's Bay nickel deposit near Nain (Figure 1).

Mineral exploration in Newfoundland has a long history beginning in the 1500s (Martin, 1983), representing some of the earliest mines in North America. Most exploration has occurred in the central part of the Island (Figure 2), resulting in the discovery of a major Cu–Pb–Zn deposit at Buchans that was mined between 1906 and 1984, and the copper deposits around Notre Dame Bay resulting in the mines at Tilt Cove (1864–1917), Betts Cove (1874–1886) and Little Bay (1878–1902). Western Newfoundland contains past-producing base-metal (e.g., zinc at Daniel's Harbour), chromite (e.g., Lewis Hills) and precious-metal (e.g., Hope Brook gold) mines. The largest mine in eastern Newfoundland was the Bell Island iron ore mine that operated

between 1894 and 1966, although several smaller mines, e.g., near St. John's (copper), La Manche (lead) and Brigus (gold), existed for shorter periods.

A contribution to mineral exploration activity has been province-wide multi-element lake-geochemistry surveys, and follow-up till-geochemistry programs supported by detailed ice-flow indicator mapping. Several mineral prospects have been discovered through the use of drift-prospecting techniques, including the Strange Lake Y–Zr–REE deposit. Recent staking activities commonly are the result of the release of till-geochemical data (e.g., Batterson *et al.*, 1998), and mineral explorationists in Newfoundland and Labrador are increasingly venturing into drift-covered areas where surface bedrock exposures are fewer. Sampling of surficial materials, interpretation of ice-flow indicators, and definition of dispersal trains thus are becoming necessary skills of the successful prospector.

GLACIAL HISTORY OF NEWFOUNDLAND AND LABRADOR

The two parts of the Province have very different glacial histories, and glaciation styles. Labrador was glaciated by the continental-scale Laurentide Ice Sheet, whereas Newfoundland supported independent ice-caps (on a much smaller scale). The tip of the Great Northern Peninsula was the only area of Newfoundland covered by the Laurentide Ice Sheet during the last glaciation (Grant, 1987). Evidence of pre-late Wisconsinan glaciation is meager (e.g., Brookes *et al.*, 1982; Klassen and Thompson, 1993), and in both parts of the Province multiple till sheets are rare or absent.

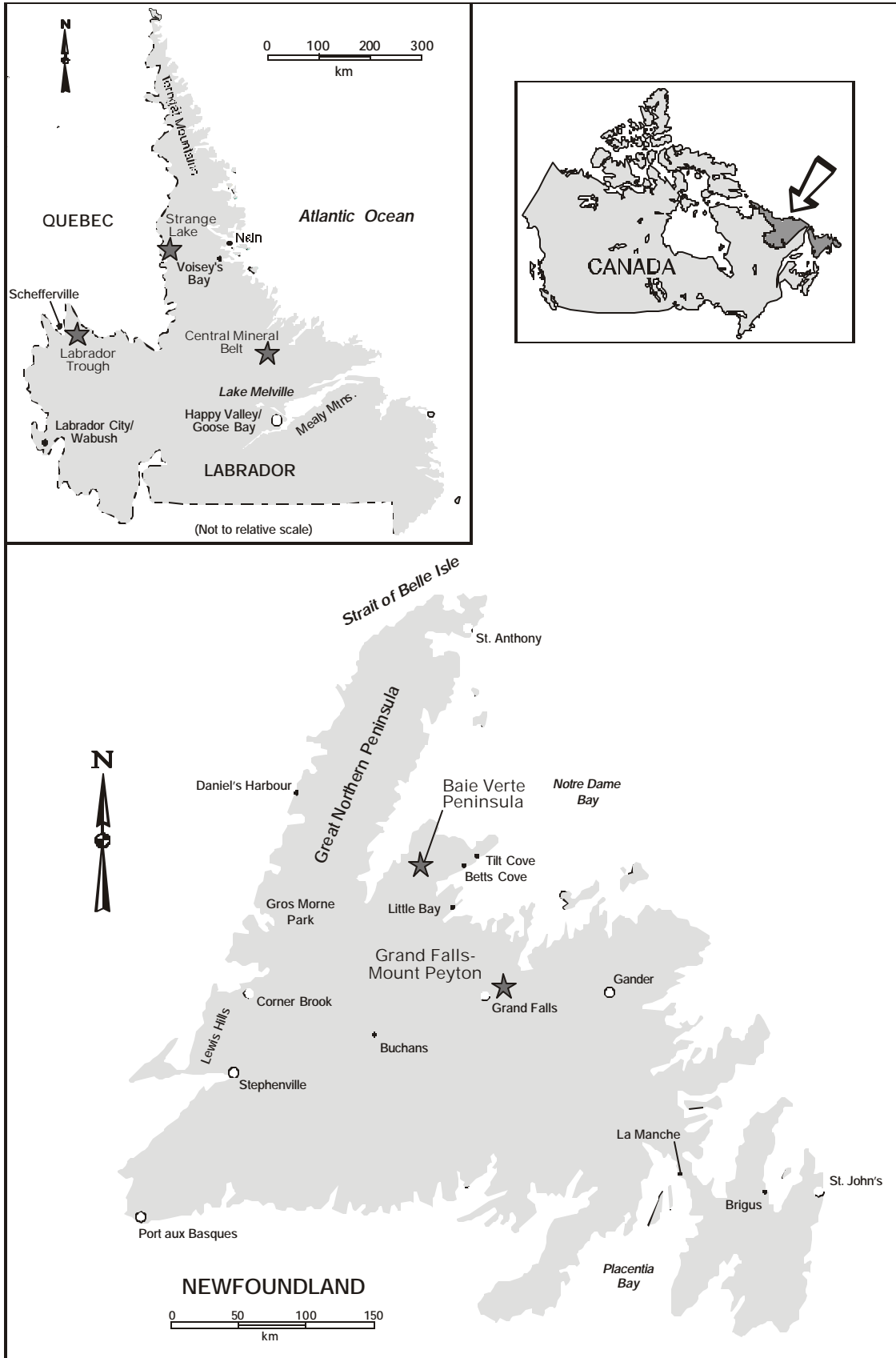


Figure 1. Place names mentioned in the text and locations of case study sites.

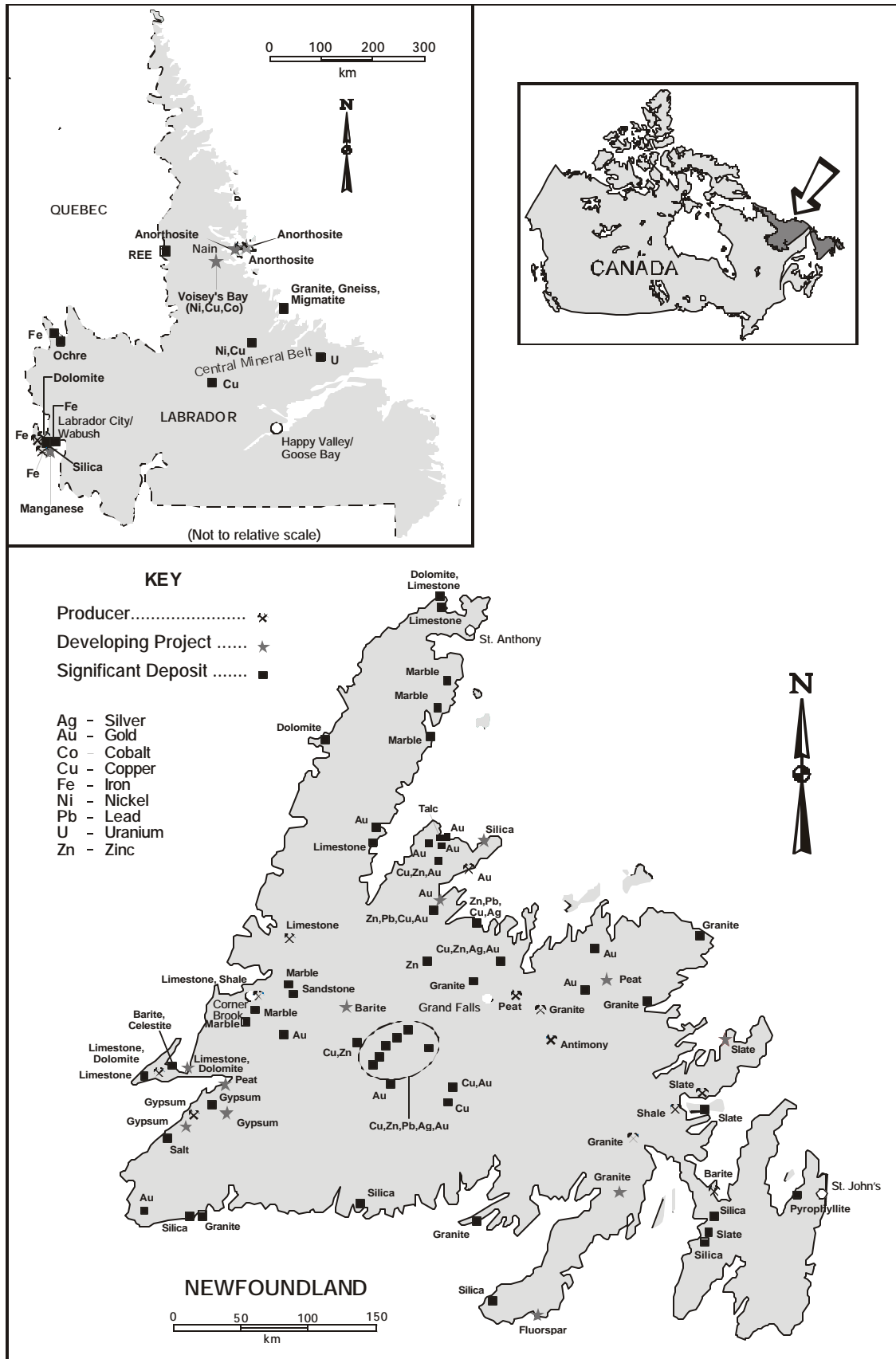


Figure 2. Mineral resources of Newfoundland and Labrador showing location of significant mineral prospects (as of Spring 1999).

LABRADOR

The Laurentide Ice Sheet covered most of Canada during the last glaciation; Labrador was covered by the eastern sector of the Laurentide Ice Sheet, except possibly the highest peaks of the northern Torngat Mountains and the Mealy Mountains south of Lake Melville. Ice flowed out from the centre of the Labrador peninsula in all directions. In northern Labrador, the Torngat Mountains were a barrier to ice movement. Glaciers reached the coast through the major valleys that cut through the mountain range. The farthest edge of the ice sheet is marked by end moraines and kames. The ice sheet may have had its outer limit in the sea in some areas.

The major valleys leading to the coast have thick sequences of glaciofluvial outwash, deposited as the ice sheet retreated. These are commonly underlain by marine sediments, deposited during periods of higher sea level following deglaciation. On the uplands, recessional moraines and eskers mark the pattern of retreat. As the ice melted, lakes formed where rivers were blocked by the ice sheet. The largest of these (glacial lakes Naskaupi and McLean) were trapped between westward-retreating ice and the drainage divide between the Atlantic Ocean and Ungava Bay. The main Laurentide Ice Sheet finally melted in the Schefferville area of western Labrador about 6500 years ago. Small cirque glaciers are still found in the Torngat Mountains and are all that remains of the ice sheet.

Glacial ice flow in the central Labrador Peninsula is complex, where records of several past glaciations may be only preserved in the ice-flow record. Klassen and Thompson (1993) described these ice-flow patterns, which is particularly complicated in the Labrador Trough. In coastal areas, ice-flow history is simpler.

NEWFOUNDLAND

The tip of the Great Northern Peninsula was the only area covered by the Laurentide Ice Sheet during the last glaciation (Grant, 1987). The rest of the Island was covered by a smaller ice cap independent of the Laurentide Ice Sheet. Separate centres of glacier accumulation existed on the Avalon Peninsula, in central Newfoundland, and on the Long Range Mountains. Complicated ice-flow patterns resulted when an area was, at different times, covered by ice from more than one ice cap (*cf.* Catto, 1998). As the ice melted, these accumulation areas became isolated from each other, and at least 15 smaller ice caps probably existed for a short time (Grant, 1974). The complex interplay of numerous small ice caps can result in a complicated ice-flow history, with further local topographic affects.

The farthest limit of glacial ice advance in many areas was past the present coastline out onto the continental shelf. As the glaciers melted, coastal areas became ice free between 11 000 and 14 000 years ago. The climate cooled again between 11 000 and 10 000 years ago, and some glaciers re-advanced for a short time. The ice finally melted rapidly about 10 000 years ago as the climate warmed again. Glaciers disappeared from the Avalon Peninsula about 9000 years ago.

SEA-LEVEL HISTORY

Along the Newfoundland and Labrador coasts, numerous raised beaches and deltas mark the former position of the coast as the sea level changed during the Holocene. Today, much of the Newfoundland coast is sinking as a result of continued settling of the crust; commonly the coast of Labrador continues to rise (Liverman, 1994).

In Newfoundland, landforms that mark the highest level of the sea before isostatic rebound occurred (the marine limit) are found at higher levels toward the northwest, with the highest marine limits found on the tip of the Great Northern Peninsula. Most of the Island shows raised beaches apart from small areas on the Avalon Peninsula. In Labrador, the highest raised beaches are in the southeast where the beaches are up to about 150 m above sea level. The marine limit decreases northward, to about 55 m in the Torngat Mountains, and 17 m at Cape Chidley. Understanding the distribution of marine sediments is important in planning a geochemical sampling program.

METHODS

The definition of glacial dispersal patterns may be accomplished through a combination of field and laboratory techniques. Geologists from the Geological Survey map and interpret striation patterns on bedrock outcrops, measure clast fabrics and define clast provenance from till exposures, as well as submitting samples for multi-element till-geochemistry analyses. Surficial geology mapping, completed as part of till-geochemistry programs, provides essential means by which to evaluate geochemical anomalies or trends. The following section provides a short description of each of the methods employed.

STRIATION MAPPING

Bedrock outcrop is common in most of the Province, and the favoured method of delineating ice-flow directions is by mapping of striations. Striations are excellent indicators of ice-flow direction as they are formed by the direct action of moving ice on the rock surface. Striations are

small-scale (cms) glacial erosion features caused by scouring or scratching of a bedrock surface at the base of the ice. Clasts embedded in the base of the ice are dragged over the bedrock surface, leaving a linear erosional mark (Iverson, 1991); the linear marks are parallel to local ice-flow directions. Striations tend to form at the margin of ice sheets, where ice is wet based, and, due to progressive overprinting or erosion of older striations, the preserved record is one of marginal retreat (Boulton *et al.*, 1985). However, older striation sets are commonly preserved and multiple striation sites are particularly important in interpreting ice-flow history (Figure 3). The data from striations should be treated with caution, as regional ice-flow patterns can show considerable local variation, with ice being deflected by topography, and regional flow patterns can only be deduced after examining numerous striation sites. The orientation of ice flow can be easily discerned from a striation by measuring its azimuth. Determination of the direction of flow can be made by observation of the striation pattern over the outcrop; where areas in the lee of ice flow may not be striated; by the presence of such features as "nail-head" striations, and miniature crag and tails (rat-tails; Plate 1); and by the morphology of the bedrock surface, which may show the affects of ice sculpturing (Iverson, 1991). At many sites, the direction of ice flow is unclear, and only the orientation of ice flow can be deduced. Striations produced by earlier flows can be eroded or obscured by striations produced by later events. Relationships can be interpreted for sites showing more than one striation orientation. These relationships are based on crosscutting of striation sets, and preservation of older striations in the lee of younger striations.

Methods

Systematic striation mapping in Labrador was initiated by Klassen and Thompson (1987). Techniques developed in this project were refined and used in the systematic striation mapping of Newfoundland (e.g., Liverman and St. Croix, 1989; St. Croix and Taylor, 1991). In Newfoundland, many of the best exposures are found along recently developed gravel roads, maintained for logging operations. Systematic traversing of such roads by all-terrain vehicles commonly yields numerous striations. Once a road is abandoned, progressive weathering and floral colonization obscures most striations after about 15 years. Once a polished outcrop is located, careful examination and cleaning of the surface is required to reveal all the striations. A shovel, scrubbing brush, and spray bottle are useful tools. Visibility of striations is highly dependent on lighting conditions, and bright sunlight is preferable to overcast conditions. Shading of the surface, or examination from different angles assists in identification. A useful technique on weathered surfaces is a close examination of resistant quartz veins, where very fine

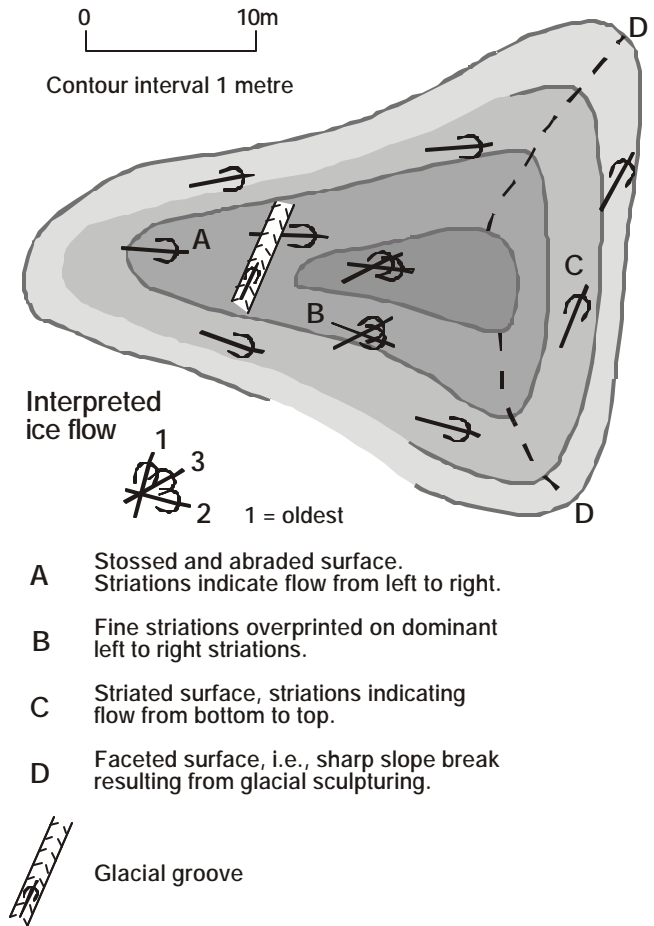


Figure 3. Schematic diagram showing striation types and their relation to ice-flow direction (after Klassen and Thompson, 1993).

striations can be preserved. Another important technique is examination of lee surfaces for preservation of older striations that can be used to develop an ice-flow history. Experience is a great asset, and the quality of striation mapping is highly dependent on having trained and able mappers. It is important to be able to differentiate striations from rock structure (e.g., slickenslides) or anthropogenic (e.g., bulldozer) markings on the rock surface.

To standardize observations, a basic form is used that lists location, outcrop dimensions, dimensions of erosional marks, confidence in the identification of the striations, confidence in assigning a flow direction as well as orientation, age relationships, and other factors (Figure 4). These are collected into a database that currently lists over 10 000 observations for Newfoundland (Taylor *et al.*, 1994). Striation data can be readily plotted on a variety of scales, or imported into GIS applications or viewers.



Plate 1. *Rat-tail from quartz grain in shale bedrock near Corner Brook. Ice flow was from left to right.*

CLAST-FABRIC ANALYSIS

Elongate clasts will align with flow lines in transporting ice and this orientation can be inherited if the clasts are deposited by basal melt-out, deformation, or lodgement processes in glacially deposited diamictons. Thus, measurement of the orientation of clasts in sediment (clast-fabric analysis) can be used to determine the direction of the ice flow that deposited the sediment. This method is particularly useful in drift prospecting in areas of complex ice-flow patterns. In such cases, it is difficult to relate the ice-flow patterns, as determined from striation evidence, to that ice-flow regime which deposited the sediment being sampled and analyzed for geochemistry studies; the two may be the same or different. Clast-fabric analysis uses evidence from the same medium being sampled, and reflects the ice-flow conditions at the time of sediment deposition. Clast-fabric analysis is also useful in determining diamicton genesis, although such studies must be supplemented by examination of the sedimentary structures of the diamicton (diamicton is a descriptive term referring to any noncalcareous, terrigenous sedi-

ment having a wide range of grain sizes). Detailed examination of a sediment is required to determine if it is a till (i.e., a sediment deposited directly by the action of glaciers). Strong unimodal fabrics are typical of basal melt-out and lodgement tills, and less well-oriented fabrics are found in supraglacial deposits and in diamictons produced by ice-rafting of clasts in lakes or oceans.

Methods

Caution must be exercised in the interpretation of clast-fabric analysis, as a number of processes other than glacial flow can result in alignment of clasts. The orientation of 25 clasts with an a-axis to b-axis ratio of 3:2 or greater is measured at each selected site, with clasts taken from a one square metre area of a vertical outcrop face. The results are plotted on a stereogram, analyzed statistically using the Stereo™ package for the Apple Macintosh® computer (MacEachren, 1990), and the principal eigenvectors and eigenvalues calculated. The principal eigenvalue divided by the sample size is known as the normalized eigenvalue (S_1)

SITE DATA				ICE FLOW DATA ENTRY						
NTS	Year	Site #	Geologist	Zone	Easting	Northing	Elev (m)	Quality		
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STRUCTURE DATA			AGE DATA		Site Data		
1	▼	plot?	1	relative	12H04	NTS	number of records
STRI	▼	structure	PIL	basis	92	YEAR	
H		structure conf	M	▼	142	site #	
		sense	COMMENTS				
292		direction					
STOS	▼	basis					
H	▼	confidence					
5		range					
SE		surface orientation					
S-FACE		location					
WIDE	▼	distribution					
20		% cover					

STRUCTURE DATA			AGE DATA		Site Data		
1	▼	plot?	2	relative	12H04	NTS	number of records
STRI	▼	structure	CC	basis	92	YEAR	
H		structure conf	M	▼	142	site #	
		sense	COMMENTS				
260		direction					
STOS	▼	basis					
H	▼	confidence					
3		range					
ESE		surface orientation					
S-FACE		location					
WIDE	▼	distribution					
20		% cover					

STRUCTURE DATA			AGE DATA		Site Data		
1	▼	plot?	3	relative	12H04	NTS	number of records
STRI	▼	structure	CC	basis	92	YEAR	
H		structure conf	M	▼	142	site #	
		sense	COMMENTS				
224		direction					
STOS	▼	basis					
H	▼	confidence					
4		range					
ESE		surface orientation					
S-FACE		location					
WIDE	▼	distribution					
30		% cover					

Figure 4. Striation form for a site in the Humber River basin. The striation database of Taylor et al. (1994) contains over 10 000 records.

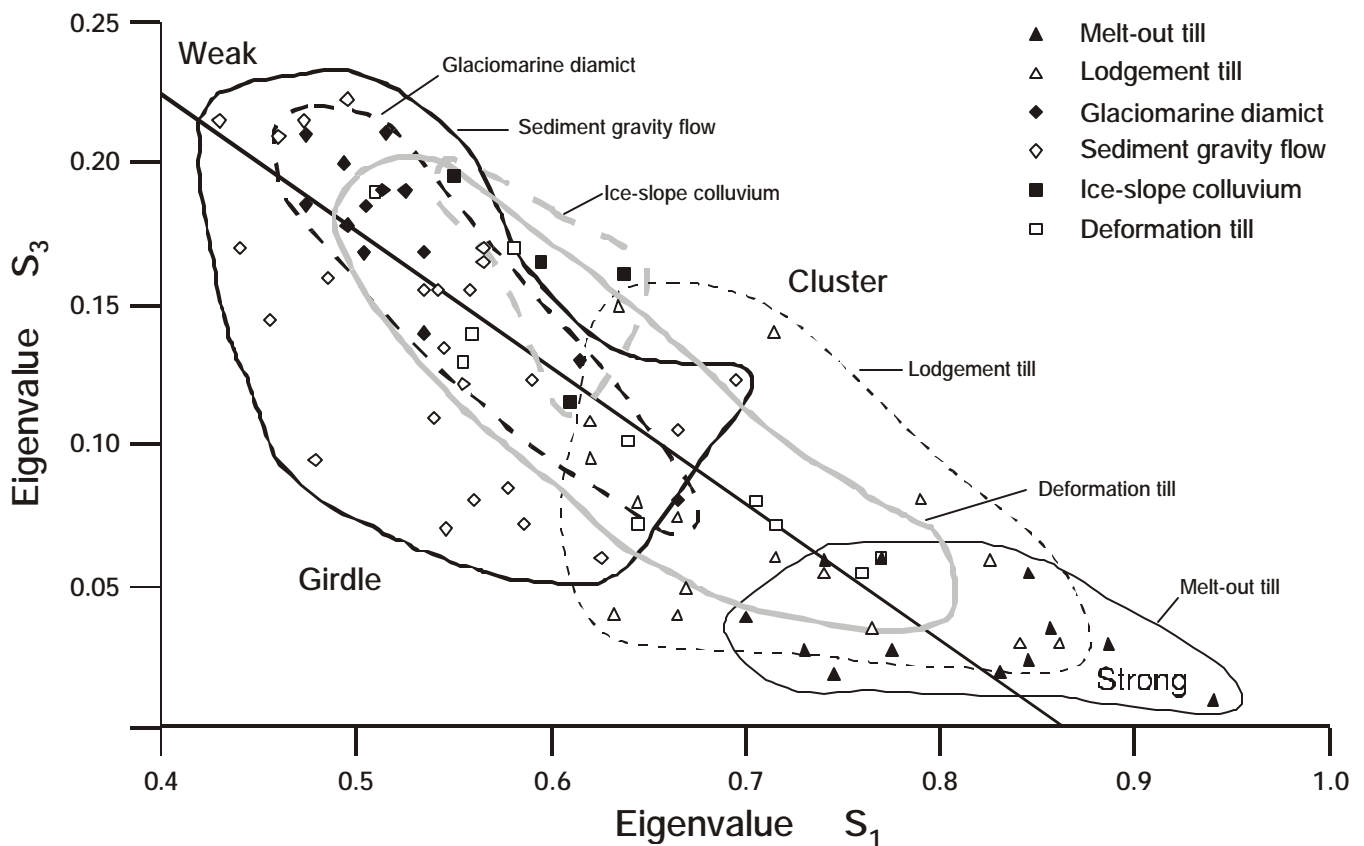


Figure 5. Plot of S_1 versus S_3 eigenvalues from diamicton deposited in different depositional environments. (Sources: Shaw (1982), Hicock (1992), Lawson (1979), Dowdeswell and Sharp (1986), Hart (1994), Hart and Roberts (1994) and Domack and Lawson (1985)).

(Mark, 1973, 1974; Woodcock, 1977), can range between 0.33 and 1.0, and is a measure of the strength of orientation of clasts. A sample with most clasts aligned with similar orientations will have a value close to 1, whereas a random sample will have a value close to 0.33. Only fabrics with $S_1 > 0.6$ are considered here as possibly indicative of ice flow (Figure 5). A second statistical parameter (K) indicates whether the distribution is unimodal or girdle. Low values of K (< 1.0) suggest a girdle distribution, atypical of basally deposited tills, and thus only those fabrics that show a K value greater than 1.0 are interpreted in this study as reflecting ice flow. Appropriate statistical analysis allows strong, unimodal fabrics to be identified, but relation of these fabrics to ice flow is dependent on examination and interpretation of diamicton sedimentary structures.

CLAST ROCK TYPES

Glacial sediment is eroded bedrock that is transported along specific flow-paths and deposited through the action of glacier ice. The ice-flow pattern from striations indicates the general direction of glacial flow, but commonly does not

provide data on the specific location of ice dispersal centres. Similarly, distances of glacial transport cannot be derived from striation or clast-fabric analysis. If the bedrock source is visually or chemically distinctive, the path of glacier movement may be recorded as a dispersal train. Mineralized boulders or geochemical anomalies may, therefore, form part of a dispersal train that may be traced back to its source in bedrock, the essence of boulder tracing or drift prospecting.

The amount of material dispersed by a glacier is mainly a function of the nature of the source of the sediment. The amount of bedrock eroded is dependent on its nature (hard versus soft, permeable versus impermeable), and the bedrock topography and structure (Shilts, 1982; Minell, 1978). If the bedrock is soft (e.g., limestone, shale), well-jointed or permeable, a large amount of material may be available for transport. Hard, massive, impermeable rocks (e.g., granite, rhyolite) will provide relatively little material. The texture of the till is also determined in part by the nature of the source bedrock. Haldorsen (1983) showed that contrasts in comminution processes, specifically between abra-

sion and crushing, causes mineralogical fractionation. This is partly related to the concept of "terminal grades" (Dreimanis and Vagners, 1969). Their research determined that the size fractions in which various rock-forming minerals are most abundant is primarily a function of mineral strength, with contrasts between harder, less cleavable minerals such as quartz, K-feldspar and barite that form coarse fractions, and softer, cleavable minerals such as micas, hematite and graphite that form silt-clay-sized material. Haldorsen (1981) noted that the grain size following disintegration retains the grain size of the original, unweathered bedrock.

The bedrock topography in the source area influences the amount of material incorporated into the ice. A bedrock obstruction may induce high subglacial pressure on the up-ice side of bedrock obstructions and a rough bed topography may cause pressure variations inducing shear stresses that may enhance erosion, e.g., around *rôches moutonnées*. A recessive rock type may provide a small amount of material for dispersal, unless it is found in a narrow depression aligned parallel to ice-flow, in which case a large amount of material may be eroded.

In sampling clasts for rock-type analyses, two approaches are recommended. A sample of at least 100 randomly selected clasts provides a reasonable indication of the gross composition of the till. This allows distances of glacial transport to be broadly defined, at least for the coarser component. The disadvantage is that rare exotic "indicator" clasts may not be sampled, and potentially important data is lost. The second approach is to select only exotic clasts (as identified from examination of bedrock geology maps) that have a distinctive physical appearance and discrete source area, allowing definition of a glacial-dispersal train (e.g., Batterson, 1989a,b, 1998; Liverman, 1992). A combination of both approaches is commonly employed. A sample of about 100 clasts is collected, and in addition rare exotic clasts are also noted. This may over-represent the exotic component, but has the advantage of providing a gross estimation of clast proportions while allowing definition of the dispersal of exotic clasts. In either case, proper interpretation of clast rock-type data is dependent on adequate bedrock mapping for the region in which sampling was undertaken.

The pattern of glacial dispersal may be determined from simply plotting the distribution of clasts on a map. In this manner, the gross shape of glacial dispersal trains may be shown. Numerous examples of this approach have been used in Newfoundland and Labrador (e.g., Liverman, 1992; Batterson, 1994, 1998).

Quantitative approaches to clast dispersal use various methods. Average transport distances can be estimated from

plots of clast lithology against distance of source (Salonen, 1986; Bouchard and Salonen, 1990). This transport distance distribution method identifies the rock type and probable source area of a number of clasts or boulders at a given site. The range of distance to source area for a given rock type is estimated by plotting the ice-flow direction onto a bedrock map, and measuring the distance up-ice to the proximal and distal contacts. The distance is plotted against cumulative percentage composition on log-probability axes. A straight line can usually be fitted to the distribution and the mean and geometric mean estimated by graphical methods (Salonen, 1986; Bouchard and Salonen, 1990). The half distance method is also used to estimate transport distance from clast lithology. The half distance is the distance at which the frequency falls to half its original value (Krumbein, 1937; Gillberg, 1965; Bouchard and Salonen, 1990). This approach differentiated the transport histories between contrasting glacial terranes in Finland demonstrating for instance that drumlins are formed of far-transported material (5 to 17 km), compared to hummocky moraine (0.4 to 3 km), and till blankets (0.8 to 10 km). The Transport Distance Distribution (TDD) approach of Salonen (1986) plots the log-normal distribution of each rock type found at a site against the distance to the nearest source. Half-distances are calculated using linear regression, providing an indication of the transport distance of indicator erratics.

TILL GEOCHEMISTRY

The optimum size fraction for geochemical analyses of tills is debatable (Shilts, 1972, 1975, 1982; Klassen and Shilts, 1977). Shilts (1982) demonstrated that for a small nickel showing in the Keewatin area, Northwest Territories, the clay fraction (finer than 0.002 mm) best delineated dispersal patterns compared to the patterns produced from the silt-clay (finer than 0.063 mm) fraction. This is because the clay fraction contains phyllosilicates that may either contain or scavenge metals released by weathering of labile components, whereas the silt fraction is generally metal-poor and is dominated by quartz and feldspar. Silt thus dilutes metal values in a silt-clay analyzed fraction. However, although analysis of the clay fraction produces a higher anomaly-background contrast, dispersal patterns are commonly distinguishable for each fraction analyzed. The increased sample preparation involved in centrifuging samples to produce a clay fraction increases analytical costs. In Newfoundland and Labrador, because some of the areas contain sediment with low clay concentrations, the Geological Survey only uses the silt-clay fraction in geochemical analysis and not the more expensive clay-fraction analysis.

Most of the survey's analytical work is carried out at the Geological Survey's geochemical laboratory; analytical work that cannot be done in-house is done under contract to

commercial/university laboratories. Analytical methods in the Survey's laboratory include atomic absorption spectrophotometry (AAS) for silver (Ag), gravimetric analysis (LOI–organic carbon), inductively coupled plasma emission spectrometry (ICP) for aluminium, barium, beryllium, calcium, cerium, cobalt, chromium, copper, dysprosium, iron, gallium, potassium, lanthanum, lithium, magnesium, manganese, molybdenum, sodium, niobium, nickel, phosphorus, lead, scandium, strontium, titanium, vanadium, yttrium, zinc and zirconium (Al, Ba, Be, Ca, Ce, Co, Cr, Cu, Dy, Fe, Ga, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Sc, Sr, Ti, V, Y, Zn and Zr, respectively). External analyses are by instrumental neutron activation analysis (INAA) for arsenic, gold, barium, bromine, calcium, cerium, cobalt, chromium, cesium, europium, iron, hafnium, lanthanum, lutetium, sodium, neodymium, rubidium, antimony, scandium, samarium, terbium, thorium, uranium and ytterbium (As, Au, Ba, Br, Ca, Ce, Co, Cr, Cs, Eu, Fe, Hf, La, Lu, Na, Nd, Rb, Sb, Sc, Sm, Tb, Th, U and Yb, respectively).

Data quality is monitored using laboratory duplicates (analytical precision only). Accuracy estimates are provided by the results from standard reference materials analyzed with them. For mineral exploration, the relative variation of an element is of primary concern. There is commonly some overlap in elements sampled by different methods. In these cases, the method producing the best quality, when compared to duplicates and controls, is selected for presentation.

Samples of till for geochemical analyses ideally are sampled using a grid. Surveys in Newfoundland and Labrador sample at about 2 km intervals in areas of poor access and where helicopter support is required. Areas with adequate road network allow a 1.5-km sample spacing. Sampling at this density provides a gross indication of glacial dispersal patterns, but is able to provide sample coverage of 1 to 2 1:50 000 NTS map sheets per year. Detailed sampling at the property level is largely the responsibility of individual exploration companies or prospectors.

Geochemical data is commonly presented as dot plots on a bedrock geology base. Supporting information includes a surficial geology map, complete data listing and brief descriptive notes. Geochemical data is increasingly being presented in a digital format allowing the rapid integration and presentation of several related datasets. Data for larger areas is commonly available on compact disc, providing exploration companies with the ability of performing their own analyses of raw data.

SURFICIAL GEOLOGY MAPPING

Mapping of Quaternary sediments, along with sampling for geochemistry, is critical in the interpretation of geo-

chemical data. Adequate mapping prior to sampling allows identification of sediments deposited by glaciers (glacial diamictons) and those produced by glacial meltwater, glaciomarine, modern fluvial or modern marine processes, all of which should be treated separately in the interpretation of data. Mapping the surficial geology commonly will guide the sampling component. Comparison of geochemical sampling locations with surficial geology maps during the data compilation stage allows modification of the dataset to reflect similar sediment types, commonly tills. The recognition of sediment types is particularly important in coastal areas, such as Newfoundland and Labrador because many parts of these areas were submerged following deglaciation.

Numerous linear landforms are thought to form parallel to the direction of ice flow, including drumlins, flutes, *rôches moutonnées*, and crag-and-tail hills and these can be used to infer ice flow. The most common of such landforms in Newfoundland are *rôches moutonnées*. Drumlins, flutes and crag-and-tail hills are more common in Labrador. Such landforms are commonly the only indicators of ice flow when mapping from aerial photographs. However, their formation is strongly controlled by bedrock geology, and interpretation based on landform evidence alone may be misleading. The greater detail, provided by striation mapping, may give a much different picture. An example of such differences may be taken from *rôches moutonnées* found as small islands in Micmac Lake, Baie Verte Peninsula, Newfoundland (Plate 2). They are well-exposed, and are oriented north–northwest, with lee faces developed on their northwest ends. As such, they indicate ice flow parallel to their long axes. However, the striations that are well preserved on these features mostly do not parallel the long axes. North–northwest-oriented striations are only found in local patches on the east side of the feature, whereas the rest of the outcrop is covered by well-formed striations oriented southeast. This suggests that the ice flow that moulded the *rôche moutonnée* was not the last ice flow in the area, with associated striations preserved only in the lee of a subsequent southeastward flow. *Rôches moutonnées* form through sculpting of resistant bedrock by flowing ice, but, in stratified bedrock, are more likely to be formed if the ice flow parallels bedrock strike. In this case, the later flow, although a significant agent of sediment dispersal, has very little effect on the morphology of the *rôche moutonnée*. Thus, in the interpretation of ice-flow history, more weight is placed on striation evidence than that obtained from oriented landforms.

CASE STUDIES

STRANGE LAKE, NORTHERN LABRADOR

The Strange Lake study in northern Labrador defined geochemical and clast-dispersal trains from a highly miner-



Plate 2. *Up-ice side of *rôche moutonnée*, Baie Verte Peninsula. The long axis of the feature trends directly away from the viewer, and indicates a north to northeastward ice-flow. The west side and top of the landform is covered by striations indicating east to southeastward flow. Striations related to the earlier north to northeastward flow are found only on the east side (not seen on photograph).*

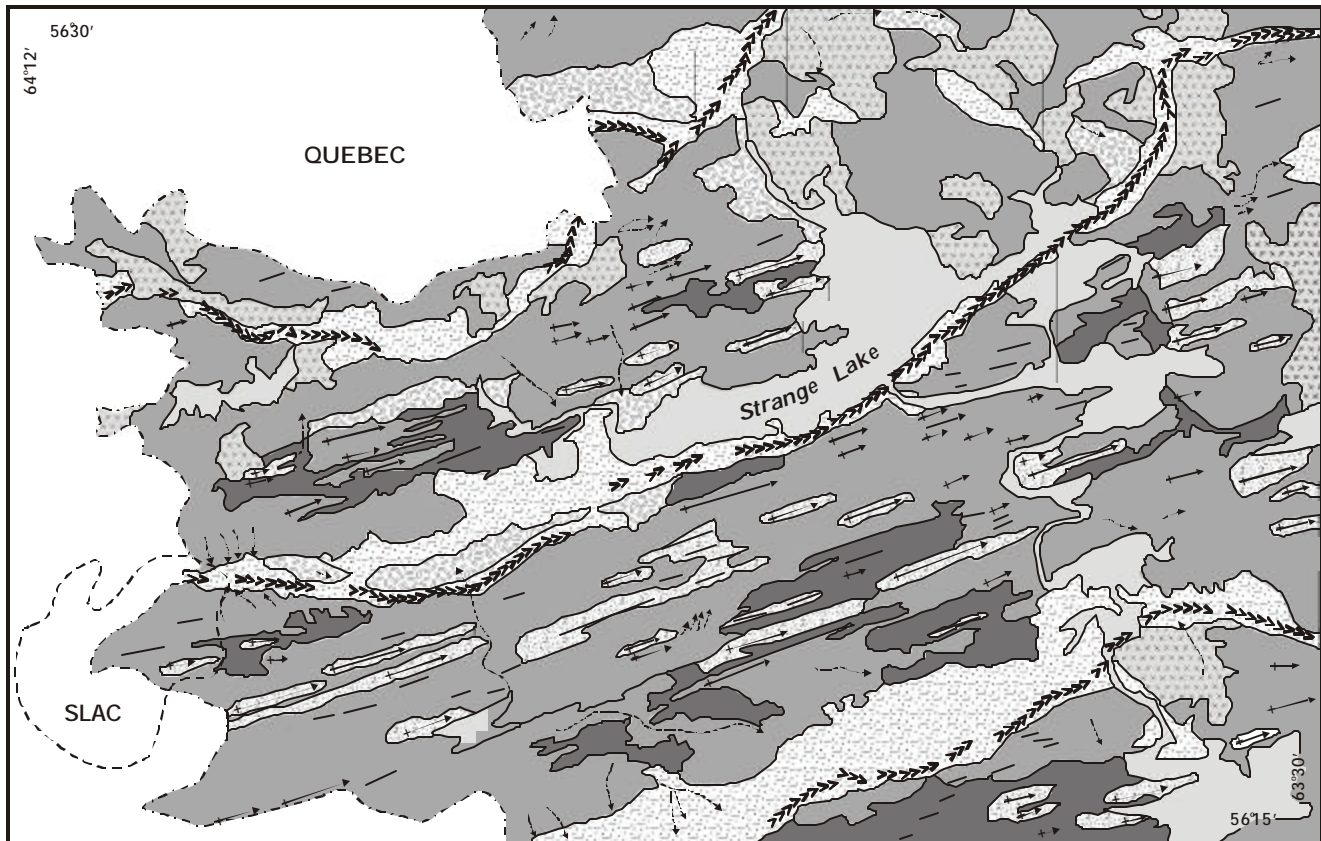
alized source over a plateau terrane from a single ice-flow direction. The resulting pattern is atypical of dispersal in most of Newfoundland and Labrador.

The Strange Lake alkalic complex was discovered in 1979 through boulder tracing during follow-up studies of lake-sediment anomalies. It is a peralkaline granite that hosts Zr–Y–Nb–Be–REE mineralization that intrudes gneiss and rapakivi granite. The deposit is situated on the Québec–Labrador border on the low-relief Nain plateau. The area was glaciated during the late Wisconsinan by the Labrador sector of the Laurentide Ice Sheet flowing coastward (070°). Most of the area is drift covered, commonly masking the underlying bedrock geology. Several large crag-and-tail hills, in excess of 5 km long, are found on the plateau, and several shallow valleys host glaciofluvial sediments and well-defined esker ridges (Figure 6).

Glacial dispersal from this area was described in detail by Batterson (1989a,b). Till samples were collected from


over 500 sites having an average depth between 40 and 60 cm (i.e., mostly BC- to C-soil horizon samples). This provided a nominal sample density of 1 site per 1.97 km², although sample density was increased to 1 site per 0.5 km² in the vicinity of the mineralization. At least 50 clasts were identified at each sample site, and the silt–clay fraction of the till analyzed for a wide range of geochemical elements.

The clast-distribution patterns show that adjacent to the complex, high concentrations (maximum 52 percent) of Strange Lake alkalic complex clasts occur (Figure 7). This generally decreases to below 10 percent within one kilometre down-ice of the complex, and continues to decline gradually down-ice. However, even at 40 km down-ice from the complex, 1 to 4 percent of surface clasts were derived from the Strange Lake alkalic complex. Within the dispersal train are a series of inter-related and overlapping boulder trains that originate from the subunits within the Strange Lake alkalic complex (*cf.* Miller, 1986). A transect anywhere across the dispersal train, perpendicular to ice flow, reveals





LEGEND


Post-glacial


 Organics : Poorly drained bog of variable thickness. Commonly overlies till

Glacial


 Glaciofluvial veneer : Thin (<1m) cover of fine- to medium-sand and associated gravels over till or bedrock

 Glaciofluvial : Generally fine- to medium-stratified sands and associated gravels. Generally, confined to paleochannels. Gravel-rich esker ridges (5-25 m) are common

 Streamlined Till : Till with fine sand matrix. 10-30% clast content, some fine sand to silt lenses. Probably of basal origin. Occurs as flutes or crag-and-tail hills up to 50m high and 5000m long

 Till : Description as above. Surface may have gullied or featureless expression. Commonly greater than 2m thick


Pre-glacial

 Bedrock : Area dominated by bedrock. Numerous pockets (<1m thick) of glacial sediment common

SYMBOLS

 Ridge parallel to flow

 Crag-and-tail hill

 Esker

 Meltwater channels

Figure 6. Surficial geology of the area down-ice of the Strange Lake alkalic complex (SLAC).

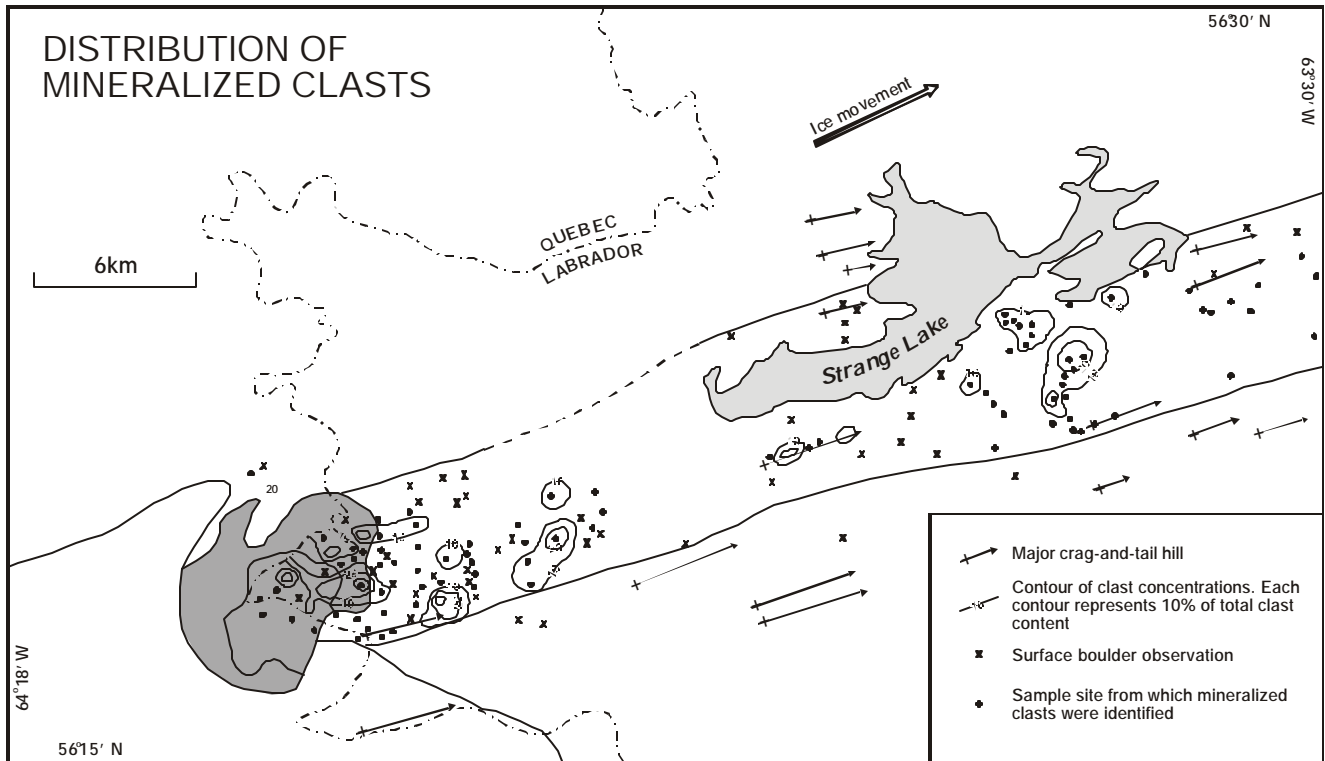


Figure 7. Distribution of mineralized clasts from the Strange Lake alkalic complex.

a sequence that mimics the outcrop distribution of the subunits in the bedrock source (Figure 8).

The concentration of clasts within the dispersal trains is highest on the crag-and-tail hills, representing up to 10 percent clasts at distances of 25 km down-ice of the complex.

The long, ribbon-shaped dispersal train of mineralized clasts is also seen in the till geochemistry. Geochemical pat-

terns were described by McConnell and Batterson (1987) and Batterson (1989a, b). The geochemical patterns for a group of elements including beryllium, lead, uranium, thorium, yttrium and zirconium match the train delineated by the mineralized clasts, whereas the patterns for others (e.g., cobalt, nickel and copper) reflect dispersal from the gneissic terrain to the north of the complex or the rapakivi granites to the south (McConnell and Batterson, 1987).

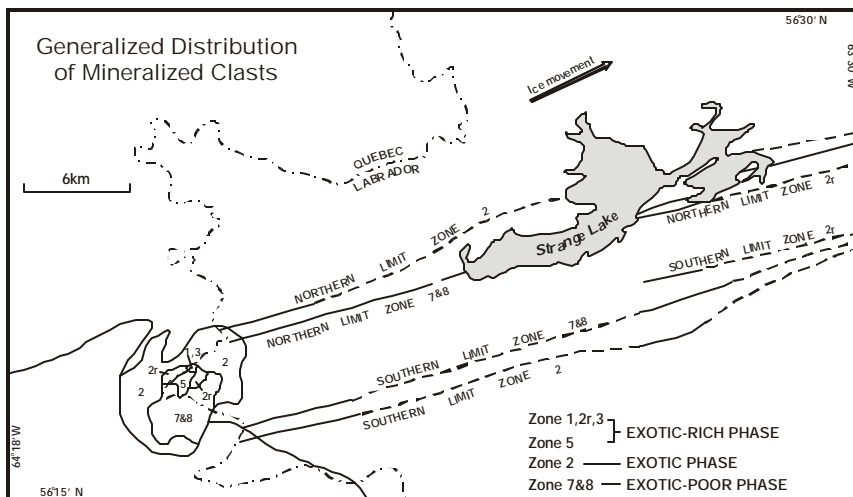


Figure 8. Distribution of mineralized clasts from subunits of the Strange Lake alkalic complex.

Several element associations are shown by the data. A cobalt–nickel–copper association reflects a mafic component in the gneiss complex. A beryllium–lanthanum–niobium–lead–thorium–uranium–yttrium–zirconium association is composed of lithophile elements associated with the ore minerals of the Strange Lake alkalic complex. Geochemical patterns of these lithophile elements are broadly similar (e.g., beryllium, Figure 9). The highest values occur over the peralkaline complex, particularly over the mineralized zone. The dispersal train extending down-ice from the source in the direction of ice movement is ribbon-shaped, and is clearly delineated for at least 40 km down-ice from the complex.

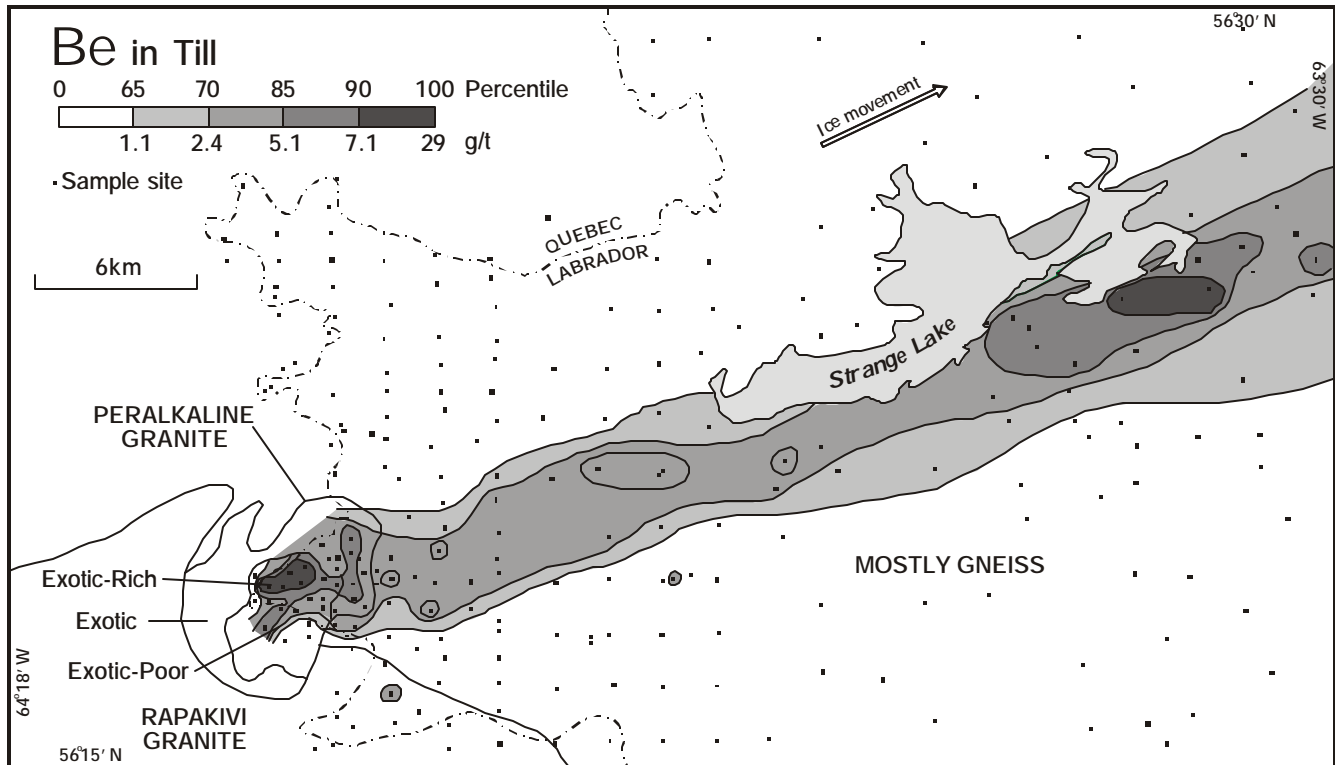


Figure 9. Distribution of beryllium in till at Strange Lake, Labrador.

The geochemical contrast between the peralkaline-related dispersal train and local background over the gneissic terrain to the north is sharp. The difference between the peralkaline dispersal pattern and the one overlying and down-ice from the rapakivi granite is clear, although less pronounced. This is a reflection of more elevated ore-related element values within the rapakivi granite. Crag-and-tail hills within the Strange Lake dispersal train have anomalously high geochemical and complex-related clast concentrations compared to the surrounding lowlands, somewhat independent of distance from source. At 40 km down-ice of the complex, geochemical values for beryllium (Figure 9) and yttrium are in the 95th percentile of values, leading Batterson (1989a,b) to speculate that these topographic highs acted as 'interceptors' of complex-derived sediment transported either englacially or high in the basal debris layer.

LABRADOR TROUGH

This study shows a different style of dispersal from that seen in Strange Lake because it is close to the disintegration centre of Laurentide ice in Labrador, characterized by multiple ice-flow directions. The dispersal patterns in this area are ameoboid-shaped and distances of transport are short.

The Labrador Trough extends from Labrador City into northern Québec, and has been the site of mining and explo-

ration for over forty years (Figure 2). In recent years, the Newfoundland part of the central Labrador Trough has seen little activity. Work by the Geological Survey indicated that this area shows high potential for PGEs and sediment-hosted massive sulphide mineralization (McConnell, 1984; Wardle, 1987; Swinden *et al.*, 1991; Swinden, 1991; Swinden and Santaguida, 1993). Much of the area has a thick Quaternary sediment cover with poor bedrock exposure. Mineral exploration companies thus have to incorporate drift-prospecting methods into their activities, and an understanding of the Quaternary history is important in interpreting results.

Klassen and Thompson (1993) described glacial dispersal trains in central Labrador, and suggested that their shape and orientation were related to their location within the ice sheet. Near ice-sheet margins, dispersal trains were ribbon shaped, oriented down-ice. In the centre of the former ice sheet, near ice divides, dispersal trains appeared as patches centred about their source. This shape was termed ameoboid (Klassen, 1997). In intermediate locations, fan-shaped dispersal trains were typical.

Klassen and Thompson (1987, 1989, 1993) identified five phases of ice movement in the Schefferville area through mapping of erratics and striation evidence. Phase I consisted of flow westward from the Schefferville area. It

was identified by dispersal of Labrador Trough erratics onto the Ashuanapi highlands, west of the study area. Phase II consisted of north to north-northeast flow affecting mostly the area north and west of the area considered here. Phase III consisted of flow both northwest and southeast from an ice centre located southeast of Attikamagen Lake, which migrated north of Schefferville. Phase IV consisted of strong eastward flow across the Archean Highlands into the Trough affecting mainly the area south of Schefferville. Phase V was considered to be minor and short lived, and resulted in northeastward flow in the Schefferville area that had little effect on outcrop morphology. Klassen and Thompson (1987, 1993) suggested that a red porphyritic rhyolite outcropping east of Martin Lake provides a useful indicator erratic, and outlined a dispersal pattern that was interpreted as showing dispersal in all directions from the outcrop (Figure 10).

MARTIN LAKE

In 1993, a till-geochemistry survey in the area was conducted, combining regional coverage with more detailed work in the vicinity of Martin Lake. In this study, copper showed a clear regional relationship with bedrock type, and the most anomalous values were found in the Martin Lake area (Figure 11). Copper values in the Martin Lake area show a broad zone of enrichment, having values comparable to those found adjacent to known mineralization. Detailed sampling around the Martin Lake #1 showing gave highest values to the northwest of the showing, with other areas of high copper to the west and east. Copper values to the southeast of the showing are comparatively low. This suggests that the southeastward ice flow had very little effect on dispersing the surface sediment in this area, and that the later, northeastward flow was the main agent of dispersal. This pattern is also shown by several other elements. The high values to the east of the Martin Lake #1 showing are unlikely to relate to dispersal from it. They are geochemically distinct in that Co and Ni values around the Martin Lake #1 showing are generally moderate to low, yet samples showing high Cu in this easterly zone also show high Co and Ni. This suggests that further areas of mineralization may be responsible for these anomalies. The more regional sampling to the south and southeast of the Martin Lake showings have enhanced copper values in association with the Menihék Formation, and Montagnais Intrusive Series 15 km away.

Results from the geochemical analyses allow some general conclusions to be drawn. Two major ice-flow directions

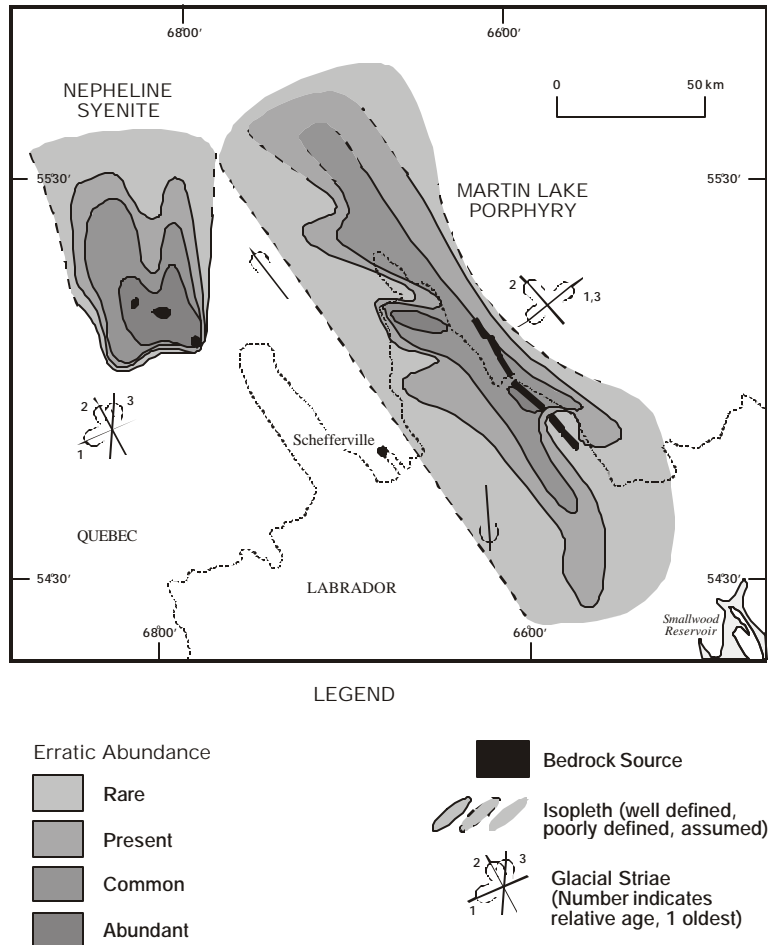


Figure 10. *Clast lithology and dispersal, Martin Lake, Labrador (adapted from Klassen and Thompson, 1993).*

have been identified in the east of the study area, and should be considered in evaluating glacial dispersion. The distribution of Cu in the area of the Martin Lake #1 showing indicate that southeastward dispersal has not taken place. Highest anomalous values are found 50 to 100 m northeast of the known mineralization, and decline rapidly thereafter. A clear dispersal train is not defined and this may be due to other sources of mineralization being present in the area, or reworking of the sediment by several ice-flow events. The latter alternative is indicated by the "patch"-shaped dispersion pattern of the Martin Lake rhyolite described by Klassen and Thompson (1993), but the absence of anomalous values to the southeast of the occurrence (a major regional ice-flow direction) suggests the first alternative is more likely.

Anomalous values east of the Martin Lake #1 showing are geochemically distinct. Samples around the Martin Lake #1 showing are enriched in Cu (Figure 11), but not in Ni or Co, whereas those to the east show elevated values for all

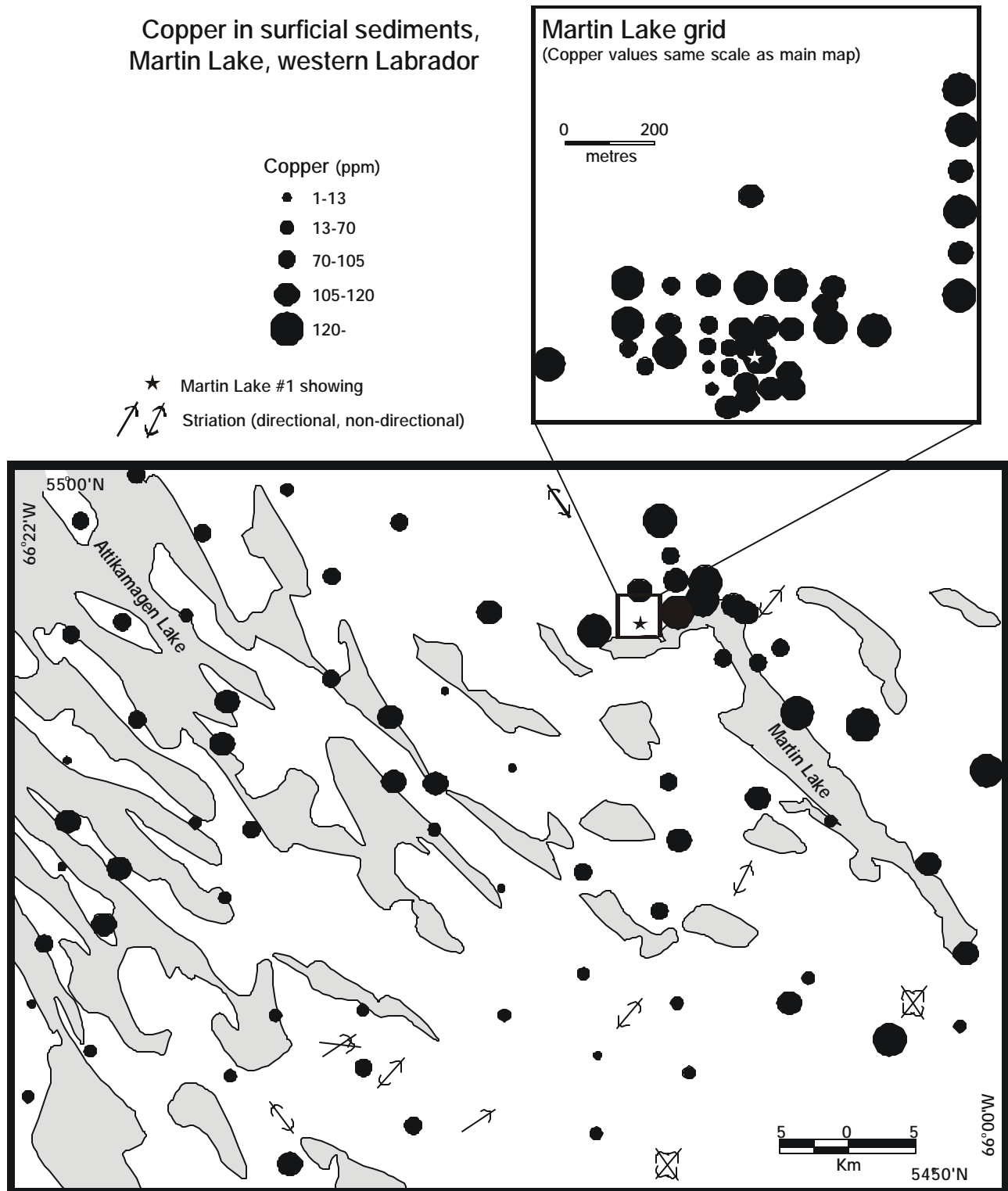


Figure 11. *Copper in surficial sediments, Martin Lake area, western Labrador.*

three elements. The highest gold value for the area was also from samples in this area. Thus, these samples likely indicate further areas of undiscovered mineralization. This area is south of the known Martin Lake #2 and #3 showings (not

shown), and Cu values in surficial sediment generally exceed reported assays from grab samples of bedrock at these showings (Swinden and Santaguida, 1993).

Implications for Mineral Exploration

Ice-flow history in the study area is complex and needs to be considered in the context of drift-exploration. Detailed striation mapping at the property level is advisable to provide information regarding local ice-flow conditions. The two main problems that can be resolved by drift-exploration methods are the tracing of mineralized boulders and interpretation of geochemical soil anomalies. Tracing a single mineralized boulder to its source will be extremely difficult due to the regions complex ice-flow history. A single boulder may have been transported by any of the major ice flows defined earlier. This difficulty is illustrated by the ameoboid-shaped dispersion pattern of the Martin Lake rhyolite described by Klassen and Thompson (1993). Careful mapping of boulder trains, and the relationship of the pattern thus defined to striation mapping may be successful. Individual boulders can be transported many kilometres from their source as illustrated by the dispersal pattern of the Martin Lake rhyolite, occurrences of Labrador Trough rocks in the Ashuanapi highlands, and gneiss derived from the Ashuanapi complex found in the Schefferville area.

Interpretation of the results of matrix geochemistry is more straightforward as the dispersal pattern for the most part, should reflect the last ice flow to affect the area. In the Martin Lake area, it appears that dispersal is mostly to the northeast, with the highest geochemical values within 100 to 200 m of a bedrock source. Clast fabric is a very useful tool for defining the direction of surface sediment dispersal, and further studies on a property-level may well be justified if difficulties are encountered locating a source to an anomaly.

CENTRAL MINERAL BELT, LABRADOR

This study illustrates the effects on dispersal of a regional ice-flow event followed by a topographically controlled event. Clast dispersal trains show a distinct 'dog-leg' pattern.

The Central Mineral Belt of Labrador is an east-trending belt of Proterozoic supracrustal sedimentary and volcanic rocks and associated granites (Ryan, 1985). Paleoproterozoic and early Mesoproterozoic rocks contain significant mineralization. Rocks of the Paleoproterozoic Moran Lake Group contain base-metal, precious-metal and uranium showings, many of which were found during exploration in the 1950s, particularly by AMCO (American Metals Company) and BRINEX (British Newfoundland Exploration). The early Mesoproterozoic rocks, particularly the Bruce River Group, host both base metals and uranium. Base-metal exploration produced disappointing results, although significant uranium showings were discovered near Moran Lake. Further east, uranium deposits at Kitts and

Michelin were of mineable grades and volumes, although development was stalled due to unfavourable market and environmental conditions.

The region has a diverse physiography. Valleys adjacent to the modern coast commonly are filled with marine muds, in some places capped by postglacial fluvial sediments, deposited as the sea level fell. Valleys above the marine limit of about 130 m above modern sea level (Batterson *et al.*, 1988), commonly are filled with sand and gravel deposited either by glaciofluvial meltwater from waning glaciers inland or postglacial fluvial sediments.

The area was covered by ice from the Laurentide Ice Sheet. Two separate ice flows were identified. The earliest flow was a regional event toward about 020°, crossing major valleys such as that of the Kaipokok River. The most recent ice-flow event is eastward. In the area west of Moran Lake, this flow is found across the whole area and shown by stossed bedrock forms showing evidence of earlier flows commonly preserved on the lee-side of outcrops. East of Moran Lake, the youngest flow is not found on hilltops but is restricted to valleys. Striations from the youngest flow are commonly found crosscutting striations produced by the earlier ice flow. This topographically controlled event affected glacial dispersal, likely cutting trains derived from the earlier ice-flow event, e.g., at Melody Lake (Batterson *et al.*, 1987). The influence of the two flows on dispersal patterns is seen by the dispersal of indicator erratics in the Central Mineral Belt. These clasts are visually distinctive and have a discrete source area, as indicated by the bedrock geology. The distribution of a grey to black plagioclase porphyry from the Bruce River Group, and a pink, red, green to buff porcelanite and a pink, red, green to buff volcanoclastic sandstone, both from the Brown Lake Formation, was used by Batterson *et al.* (1988) to illustrate dispersal patterns (Figure 12). Dispersal was based on presence-absence counting of indicator erratics from mudboil-dominated uplands or test pits. Porcelanite clasts form a fan-shaped dispersal train within the study area, from 7 km wide in the west to 20 km wide in the east. A similar pattern is found for the dispersal of plagioclase porphyry clasts. The patterns are consistent with ice-flow directions. Near Moran Lake, dispersal is eastward, i.e., parallel to the most recent flow. East of Moran Lake, the dispersal train 'dog-legs' northeastward, interpreted to represent the weakening influence of the eastward ice flow.

The distribution of uranium using till-geochemical data within the Central Mineral Belt is illustrated in Figure 13. It shows a concentration of elevated values adjacent to known uranium showings, and within areas defined by rock units having a known uranium content. Occurrences at Melody Lake, Michelin, and Moran Lake are highlighted, as are

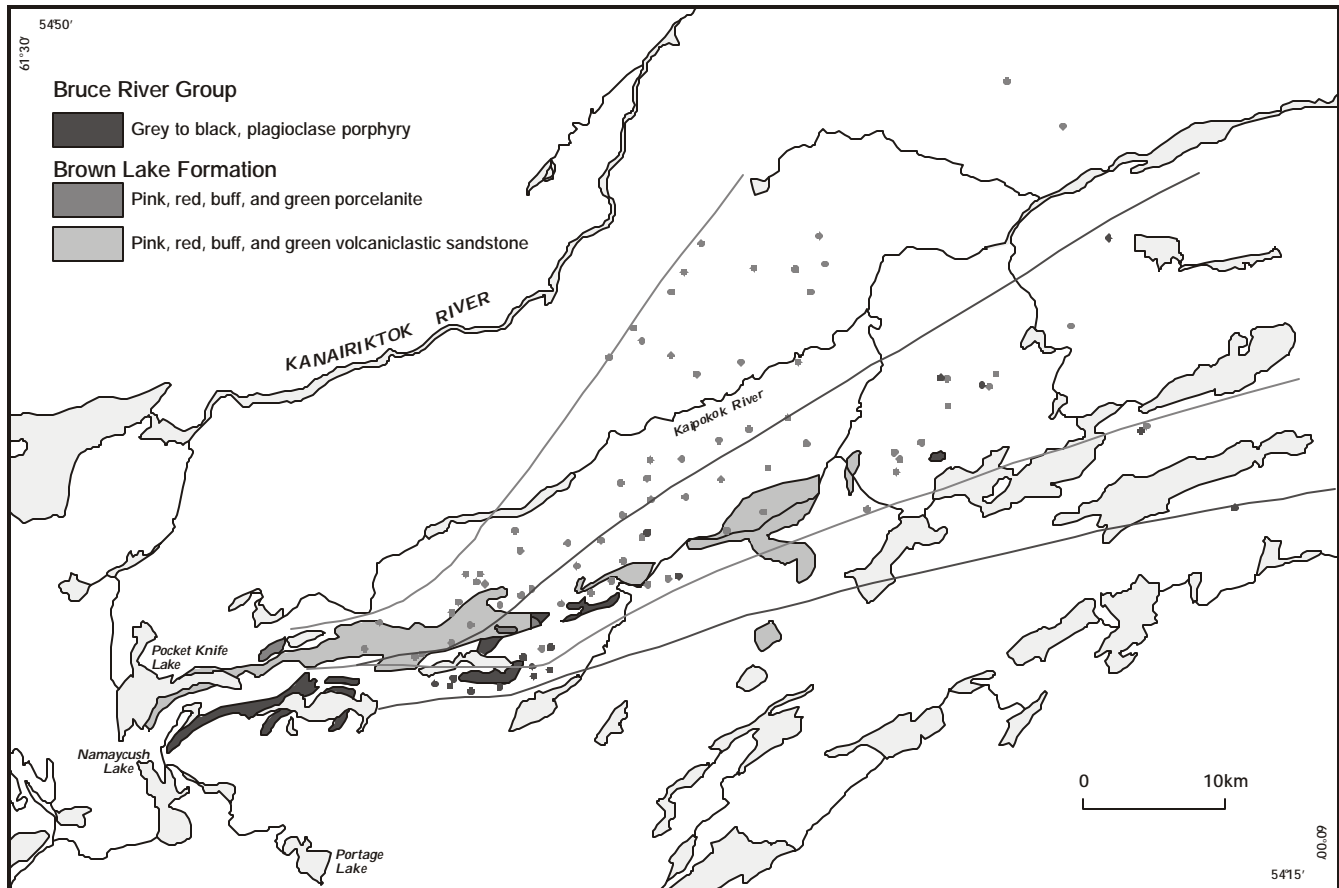


Figure 12. Dispersal of indicator erratics from the Bruce River Group and Brown Lake Formation. The occurrence of an indicator is shown as a dot of the same shade as the outcrop. Volcaniclastic sandstones of the Brown Lake Formation have similar characteristics to the porcelanite that was mapped near Pocket Knife Lake.

associated rock units, including the Upper Aillik Group, Petscapiskau Group, Trans-Labrador batholith and granite rocks north of the Batholith. Ice flow is generally parallel to bedrock strike, and dispersal trains are poorly defined. Several uranium showings in the western part of the study area were not associated with elevated values in surficial sediment. This is explained by the contrast in sediment types, between the till-dominated eastern part, and the marine or glaciofluvial sediments that are found in the west (Figure 14).

CENTRAL NEWFOUNDLAND

This study examines the geochemical dispersal patterns found in central Newfoundland. This area was covered by ice from small island-centred ice caps rather than the Laurentide Ice Sheet. Dispersal is commonly short with diffuse patterns. The effects of till geochemistry surveys on staking activity is also discussed.

Mineral exploration activity in central Newfoundland shifted focus from the traditional base-metal exploration

programs that followed discovery of the Buchans ore body, to precious metals, particularly gold. While the gold-bearing base-metal volcanogenic massive sulphide (VMS) deposits, such as at the former Buchans and Rambler mines are well known, exploration over the last two decades has resulted in the recognition of numerous epigenetic gold deposits and prospects in the Province. Important recent discoveries include the Hope Brook mine, near Burgeo, and the Pine Cove and Nugget Pond deposits, near Baie Verte. Other areas of interest include southwestern Newfoundland, the Avalon Peninsula, Burin Peninsula and the Grand Falls area. This latter area, which extends from Grand Falls eastward to the southwest Gander River, was the focus of a Geological Survey till-geochemistry and surficial-mapping project. Bedrock geology shows Cambrian to Middle Ordovician mafic to felsic volcanic rocks of the Victoria Lake Group, found south of Diversion Lake, and north of West Lake (Kean and Mercer, 1981). To the east are Late Ordovician and earlier sediments associated with submarine mafic volcanic rocks. The youngest rocks in the area are those of the Silurian–Devonian Mount Peyton Intrusive Suite, which

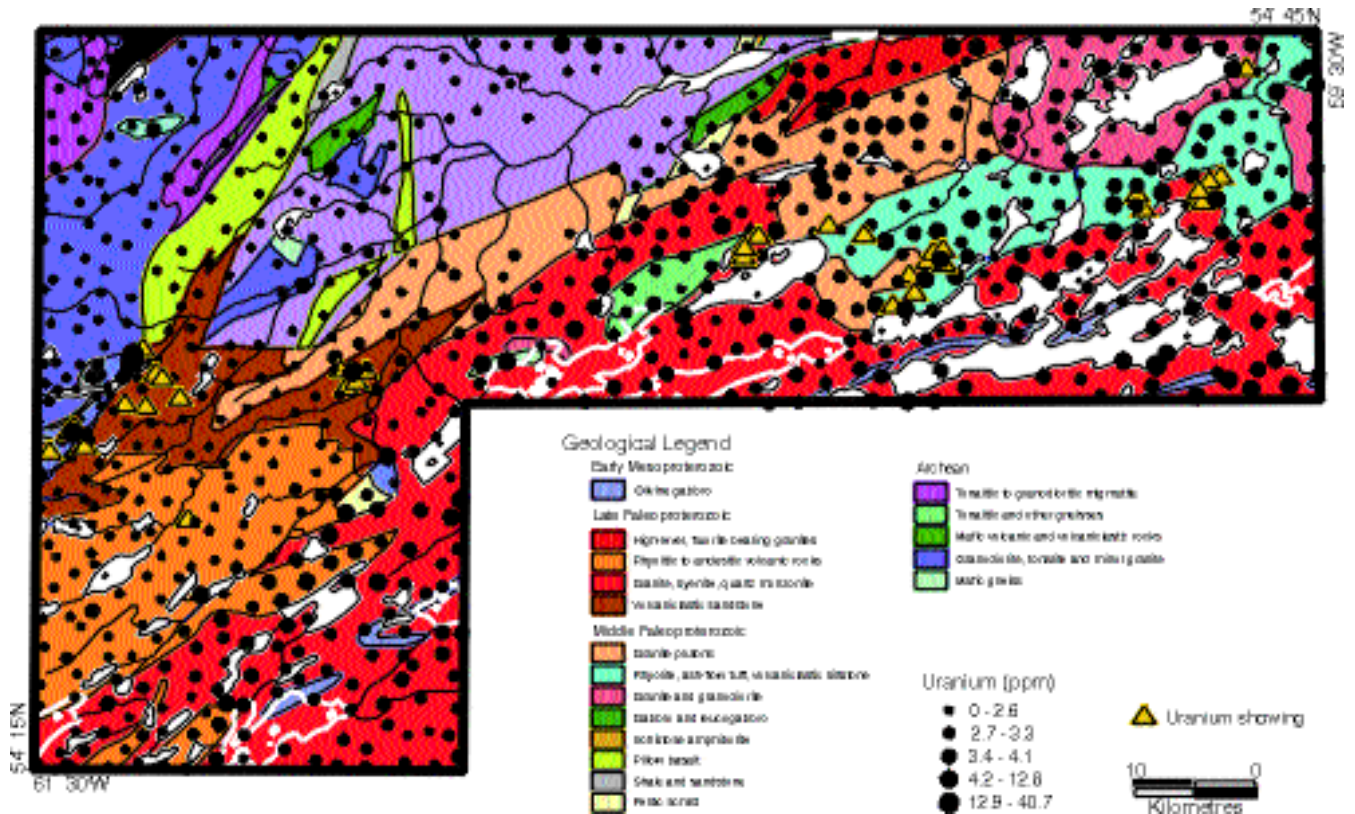


Figure 13. Simplified geology map of the eastern Central Mineral Belt, Labrador.

constitute the Mount Peyton batholith. The western and northern parts of the batholith are composed of grey, fine- to medium-grained gabbro, and the eastern and southern parts are a pink biotite granite (Dickson, 1992).

Mineral exploration activity is centred on areas underlain by volcanic and sedimentary rocks, and along the western margin of the Mount Peyton Intrusive Suite. Much of the area between Lemotte's Lake and Diversion Lake was staked in 1997; gold was the main target.

The area has a generally rolling topography dissected by northeast–southwest-oriented valleys, including that of the Northwest Gander River in the east, and the Rattling Brook, Sandy Brook and Stony Brook valleys, all of which trend northeastward into the Exploits River valley. The Exploits River flows westward across the study area to Grand Falls, downstream of which it flows northeastward to enter the ocean in the Bay of Exploits, northeast of Bishops Falls. The physiography is mainly controlled by bedrock structure, and hills commonly are oriented northeastward. Mount Peyton (482 m asl) is the highest point in the study area.

The ice-flow history was defined by ice-striation mapping. Three separate phases of ice flow were identified (Fig-

ure 15), similar to those described by St. Croix and Taylor (1991). An early eastward ice flow is recorded by striations over the northern part of the area. Bedrock outcrops were rarely stossed by this flow. This flow likely had its source within The Topsails, although no erratics were found to confirm this. The early eastward flow is recorded across much of northeastern Newfoundland (Batterson and Vatcher, 1991; Scott, 1994). A regional north to northeast ice flow is shown by striations and bedrock stossing on outcrops. Flow directions are generally more northward on the Mount Peyton and Botwood map areas, produced by ice flow into the Bay of Exploits (Batterson *et al.*, 1998). The most recent ice-flow event was an eastward flow identified on the north half of the Grand Falls map area and the northwest part of the Mount Peyton area. This flow is recorded by fine striations overprinting those striations produced by the regional flow event. This late eastward flow did not mould bedrock outcrops. The source of the late eastward ice flow is uncertain.

A detailed till sampling program was conducted across the area. Sample spacing was about one sample per 2.25 km² in areas of road access. In areas where helicopter support was required, sample spacing was about one sample per 4 km². Approximately 850 samples were collected, mostly from the BC- or C-horizon. Samples were sieved in the lab-

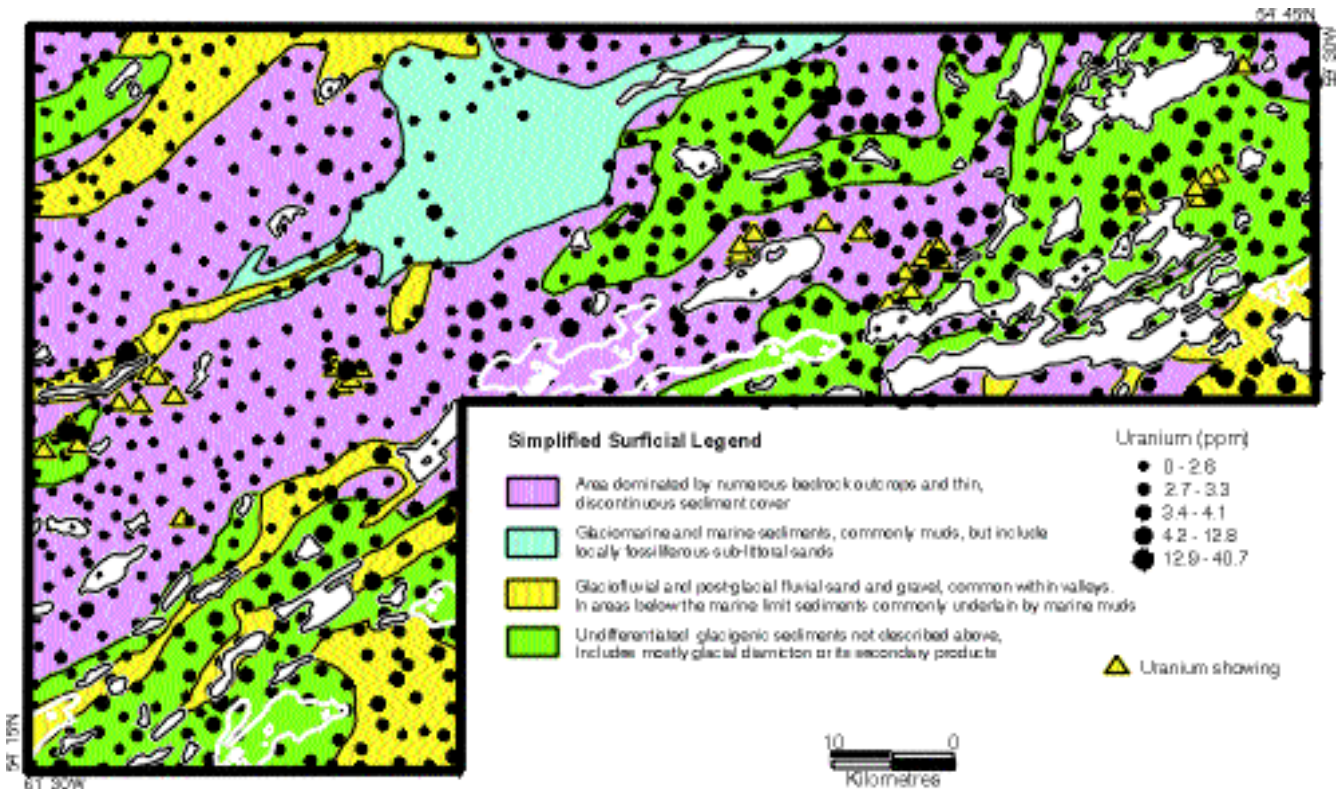


Figure 14. Distribution of uranium in surficial sediment in the Central Mineral Belt, Labrador.

oratory and the finer than 4ϕ (0.063 mm) fraction was retained for geochemical analysis.

The patterns of glacial dispersal are controlled by ice flow across the area, and are shown by displacement down-ice of clasts and sediment matrix. Directions and distances of glacial transport may thus be inferred from till geochemistry or boulder trains. The patterns of dispersal between Grand Falls and Glenwood suggest it is controlled by the regional north to northeastward ice-flow event. Clast dispersal is shown by the clast content of diamictons found across the area. Clasts from the Botwood Group, for instance, are found in till over the northwest margins of the Mount Peyton Intrusive Suite, and red conglomerate clasts from the Rogerson Lake conglomerate were found up to 10 km northeast of its source area, south of Diversion Lake.

Down-ice transport is also shown by a variety of geochemical elements including gold. Dispersal trains are commonly short (generally less than 5 km). A combination of bedrock geology, local glaciers (rather than the continental-sized ice sheets that characterize the Canadian shield) and the coarse sample spacing (1 per 4 km²) may be a contributing factor in the poor definition of dispersal.

The 44 elements and LOI that form the analytical data set are geochemically inter-related. To summarize inter-ele-

ment correlation, a series of Principal Component models were computed, applying a Varimax rotation to clarify the geochemical associations. A seven-component model was chosen that accounted for 80.9% of the overall data variance. Some elements were associated with a single Principal Component, whereas others contributed significantly to two or more Principal Components, suggesting their distributions were controlled by several geological and geochemical factors. Principal Component 1 (Sc, Mg, V, Ti, Fe, Cr, Co, Ca, Ga, Cu, Sr, and P, with Pb negatively associated) reflected mafic rock types. Principal Component 2 (Zr, Yb, Lu, Nb, Hf, Y, Rb, Be, Dy, K and U, with Ni negatively associated) is composed of incompatible elements suggesting a specialized or peralkaline granite affinity. Principal Component 3 (Sm, Nd, La, Ce, Tb, Eu and Th) is composed of the lighter rare-earth elements and thorium. Principal Component 4 (As, Sb, Au and Zn) is the most interesting from an exploration perspective, including both gold and its pathfinders, arsenic and antimony. The remaining three Principal Components, that account for about 20% of the data variance are harder to interpret geologically.

The mafic associated elements clearly define the gneiss component of the Mount Peyton Intrusive Suite, e.g., chromium (Figure 16). Glacial dispersal toward about 020° is shown by the low chromium in the southern part of the suite, and high values above the northern edge. This is inter-

preted to reflect the dispersal of chromium-poor till derived from the adjacent Botwood Group sediments over the southwestern edge of the batholith, and similarly the dispersal of chromium-rich till from the Mount Peyton batholith over Botwood Group sedimentary bedrock in the north. In both cases, dispersal directions parallel paleo ice-flow directions, and dispersal distances are less than 5 km. Similar trends are found in the distribution of all elements described by Principal Component 1. The incompatible elements identified in Principal Component 2, e.g., potassium, show high values over the granite component of the Mount Peyton intrusive suite, and generally low values elsewhere. Glacial dispersal is illustrated by northward transport from the northern edge of the granite, and from low potassium tills derived from the gneiss component of the Mount Peyton batholith that are dispersed over the southwestern edge. Background geochemical values are generally reached within 5 km.

The expression of glacial dispersal seen from the mafic and incompatible element component is important in the interpretation of gold geochemical data (Figure 17). The release of this data in late 1998, resulted in the staking of 377 km² of new claims, several over geological terranes previously little explored (Figure 18). These included the Mount Peyton batholith, where gold values in till were recorded up to 120 ppb.

Gold grain counts are not performed regularly on samples collected as part of regional geochemical surveys. A limited dataset is presented from a series of test-pits aligned parallel to ice flow on the Altius Resource Moosehead property near Grand Falls (Figure 19). The area contains gold mineralized boulders of local rock type, with gold hosted in quartz vein and hydrothermal breccia indicative of a bonan-



Figure 15. Ice-flow directions in northeast Newfoundland.

za zone in an epithermal system. These boulders occur over an area of anomalous gold in soil, and commonly assay within a range of 15 g/t and 400 g/t gold. Visible gold is common. The deepest pit shows a stratigraphy of 500 cm compact diamicton containing striated clasts of mixed provenance overlain by 450 cm of less compact diamicton dominated by locally derived clasts. Clast fabrics were strong in both diamictons ($S_1=0.76$ for lower diamicton; and $S_1=0.75$ for upper diamicton) with slightly different preferred orientations (142° and 171° for lower and upper diamictons respectively). Gold grain counts were completed on samples collected at 100 cm intervals through the till profile (Figure 20). These data are compared to the gold and regional pathfinder element (arsenic and antimony) geochemistry data collected at 50 cm intervals. The data shows relatively low gold grains counts (0 to 3 grains), and gold (8 to 39 ppb), arsenic (43 to 140 ppm) and antimony (3.8 to 9.3 ppm) values in the lower diamicton unit, increasing within

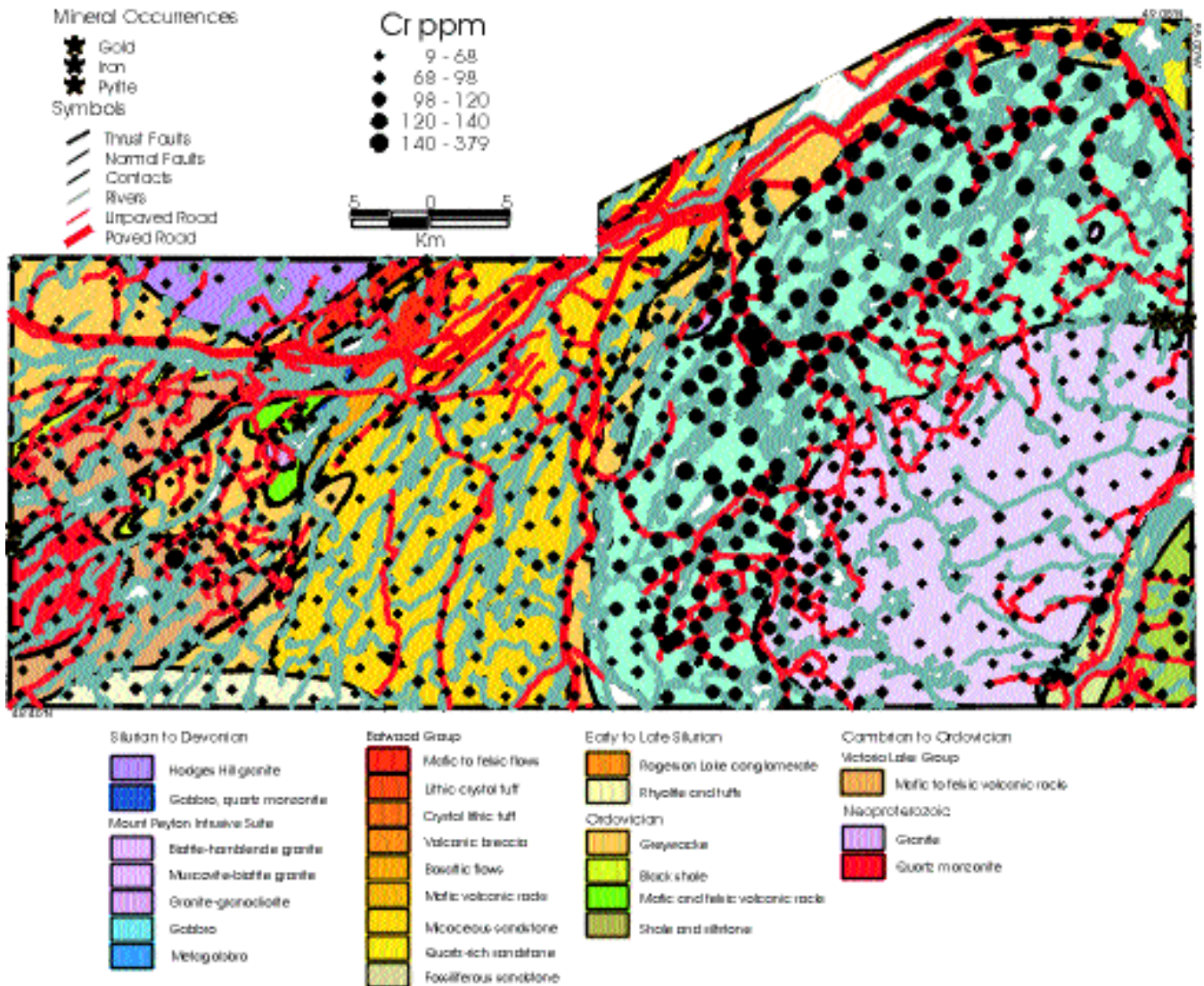


Figure 16. Distribution of chromium in till, Grand Falls – Mount Peyton area (after Batterson et al., 1998).

the upper diamicton (gold grains 2 to 8; gold 45 to 243 ppb; arsenic 140 to 560 ppm; antimony 9.3 to 26.0 ppm), and subsequently decreasing within the B soil horizon. Figure 20 shows a good correlation between the gold grain and till geochemistry data.

Data from other shallower pits show similar trends. In each case, maximum values were recorded above the till–bedrock interface. The diamicton in each case included large slabs of local sandstone, suggesting the sediment was locally derived.

BAIE VERTE

The use of clast fabric in an area of multiple ice flows is illustrated by this study. Methods for defining clast dispersal are also discussed with regard to transport distance.

As discussed previously, the relationship between ice-flow indicators, particularly striations, and sediment dispersal can be unclear because striations are erosional features, and sediment sampled in drift-prospecting studies are glacial deposits. Clast–fabric analyses use evidence from the same medium being sampled; this reflects the ice-flow conditions at the time the sediment was deposited, and allows the relationship between erosional evidence and dispersed sediment to be evaluated.

The use of this method in exploration is illustrated with two examples from the Baie Verte Peninsula. As discussed previously, on the southern Baie Verte Peninsula, two ice-flow directions, separated by approximately 90°, are possible agents of dispersal and must be considered in interpretation of geochemical anomalies (Figure 15). Clast–fabric analyses from exposures in this area allows the dominant

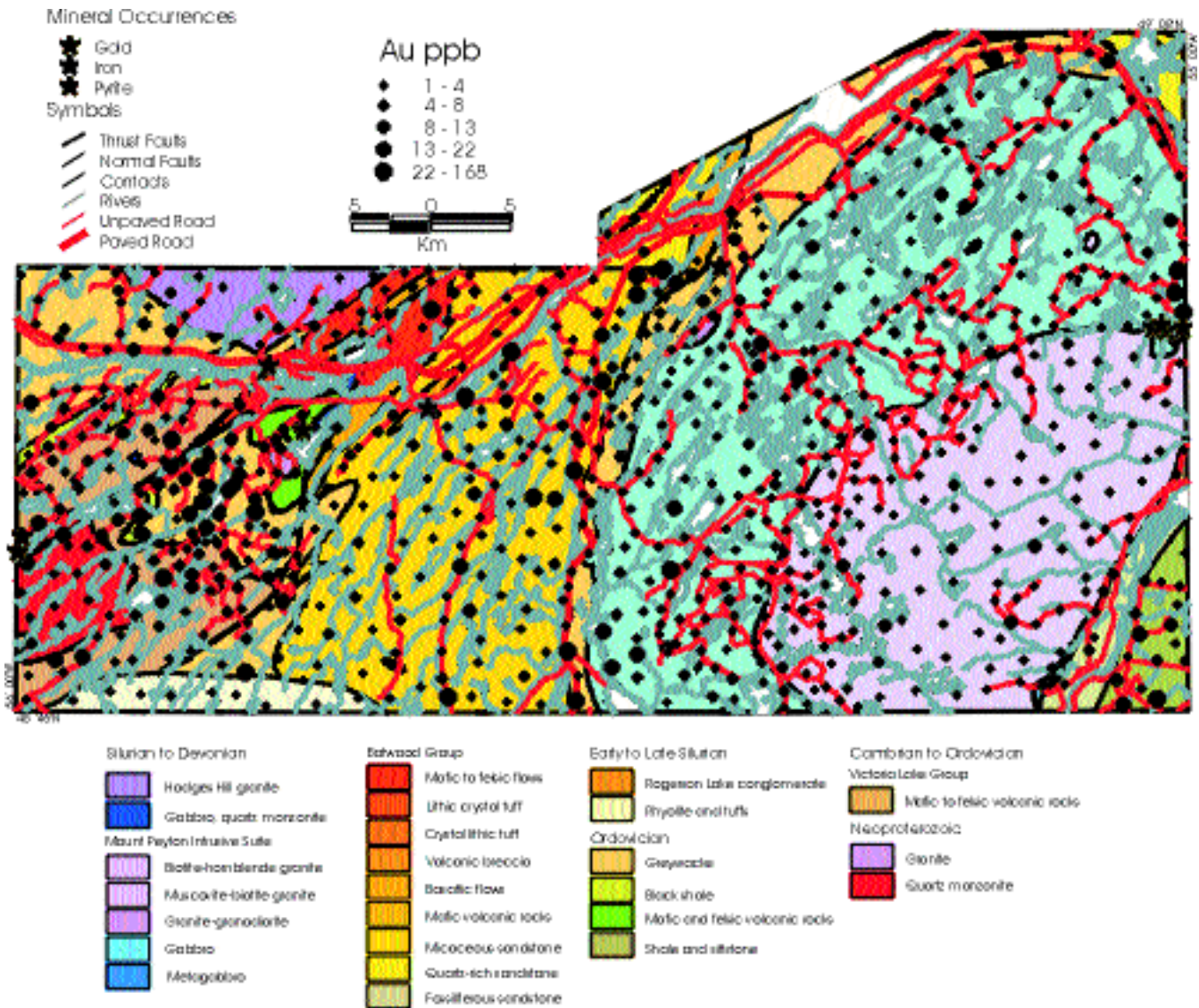


Figure 17. Distribution of gold in till, Grand Falls – Mount Peyton area (after Batterson et al., 1998).

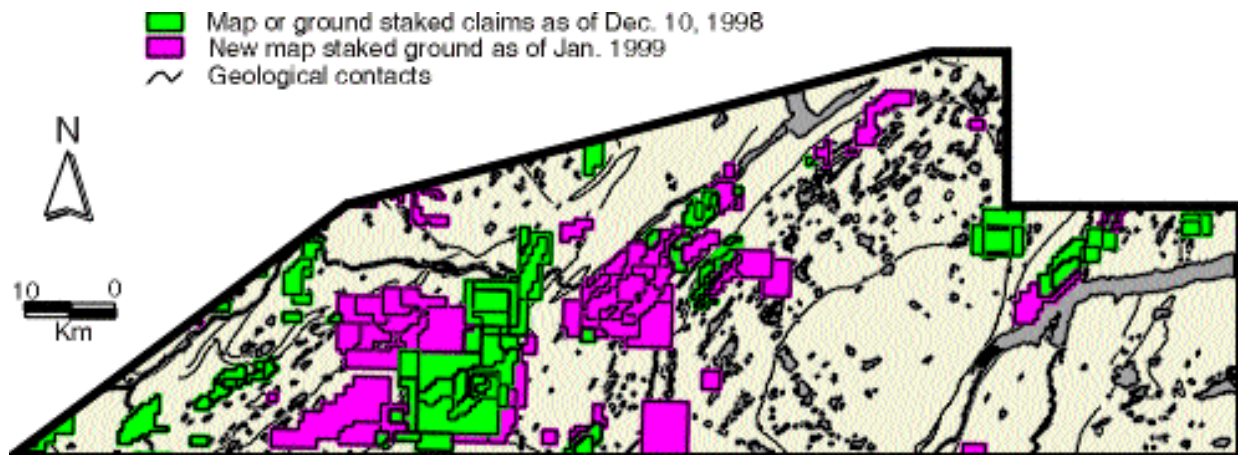


Figure 18. Impact of till geochemical survey on mineral exploration for gold within the Botwood basin, central Newfoundland.

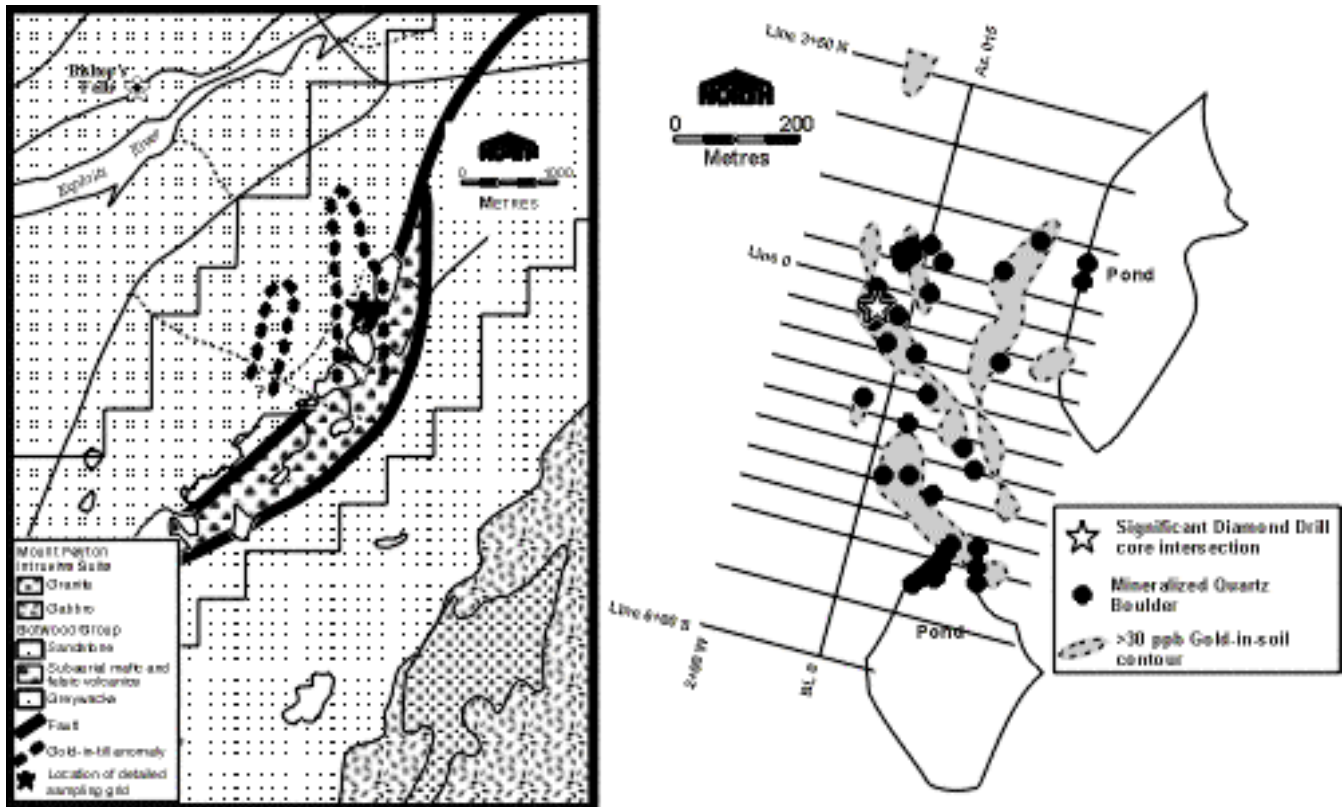


Figure 19. Gold in soil at the Altius Moosehead Property, central Newfoundland.

sediment transporting ice flow to be identified. Exposures in the area show a sandy diamicton containing dominantly local clasts, some of which are striated. The diamicton is mainly structureless, but lenses and laminae of sand and gravel are common. Laminae generally are internally stratified, and lie horizontally, with no evidence of deformation. On the basis of sedimentary structures, it thus appears that the till genesis in this area is by basal melt-out processes (Haldorson and Shaw, 1982; Shaw, 1982). Using the criteria outlined, only 12 out of 44 clast-fabric analyses are considered to indicate ice-flow direction. Considerable variation may be found at a single site where analyses at different depths show different orientation patterns, or strengths of clast alignment; this may be due to post-depositional re-sedimentation of the diamicton. Of the twelve examples, only one did not show a mean orientation within 30° of at least one striation found within 3 km of the sample site. In several sites, local ice flow as indicated by striations diverges by over 90° , and the clast-fabric analyses succeeded in identifying the ice-flow direction that should be used in tracing the origin of geochemical anomalies, or mineralized clasts in these areas.

In the second example, thirteen fabrics were measured from diamicton units exposed in exploration trenches northwest of Flatwater Pond (Table 1). Exploration by Canustra

Gold Exploration Limited had located a number of anomalous gold values through soil sampling. Sampling of the diamicton and concentration of heavy minerals by panning identified visible gold having up to 100 grains in a 50 gm concentrate, from 5 to 10 kg of diamicton (Bradley, 1988). The SEM examination of the grains suggested that transport distances were small; most of the grains showed little evidence of abrasion or weathering (Bradley, 1988). Preliminary trenching of anomalous areas failed to identify a bedrock source for the gold mineralization.

Two striation sites in the vicinity were interpreted as showing an early flow to between 325° and 350° , followed by two subsequent flows at 310° to 320° , and 290° . Four other sites showed single sets of striations, oriented between 340° and 350° (Liverman and St. Croix, 1989).

Diamicton exposed in trenches has a sub-horizontal fissility but is otherwise structureless. Clasts are mostly angular and of local provenance. Coarse clasts constitute 60 to 80 percent of the diamicton; the sandy matrix forms the remaining 20 to 40 percent. Fragile clasts of highly weathered serpentinite are "smeared" along horizontal planes. Rarely, clasts are aligned along distinct sub-horizontal lines. Resistant clasts are commonly striated. Diamicton thickness is variable and controlled by bedrock topography; in topo-

graphic lows, diamicton is up to 2.5 m thick, but it thins to less than 1 m over bedrock highs.

The results of fabric analysis are variable (Table 1). Seven sites show strong to very strong unimodal fabrics (S1 values between 0.72 and 0.92). Such fabrics are considered typical of basal tills (Dowdeswell and Sharp, 1986; Shaw, 1982, 1987). The absence of sorted strata or lenses, dominance of local provenance material, and presence of fissility and "smeared" clasts suggest that the diamicton is a lodgement till (Kruger, 1979; Muller, 1983). Six of these seven sites show a mean orientation suggesting ice flow to be between 320 and 356°. Of the sites showing a less strongly oriented fabric, three show mean orientations between 322 and 002° (Sample #'s 88-28A, 88-60, 88-64). Thus, it is likely that the dominant direction of the sediment-moving ice flow was about 330°. This matches the dominant striation direction observed in the surrounding area and the earliest flow recorded in multiple striation sites.

The results of fabric analysis show considerable variability within a comparatively small area. As the flow direction suggested is the earliest recorded in the area (as determined from striations), it is possible that the variability in fabrics is due to the re-orientation of clasts by subsequent flow. This would have produced less well-oriented fabrics, with a secondary mode to the west of the primary mode. This is not the case here. Alternatively, Dowdeswell and Sharp (1986) suggested that typical lodgement tills show two layers with the upper showing less well-oriented fabrics. In this example, where two fabrics were taken at different vertical positions at the same site (Sample #'s 88-28 and 88-63), the strongest orientations were found at the higher site. Thus, it is unlikely that the diversity found is due to either primary depositional processes or re-orientation by

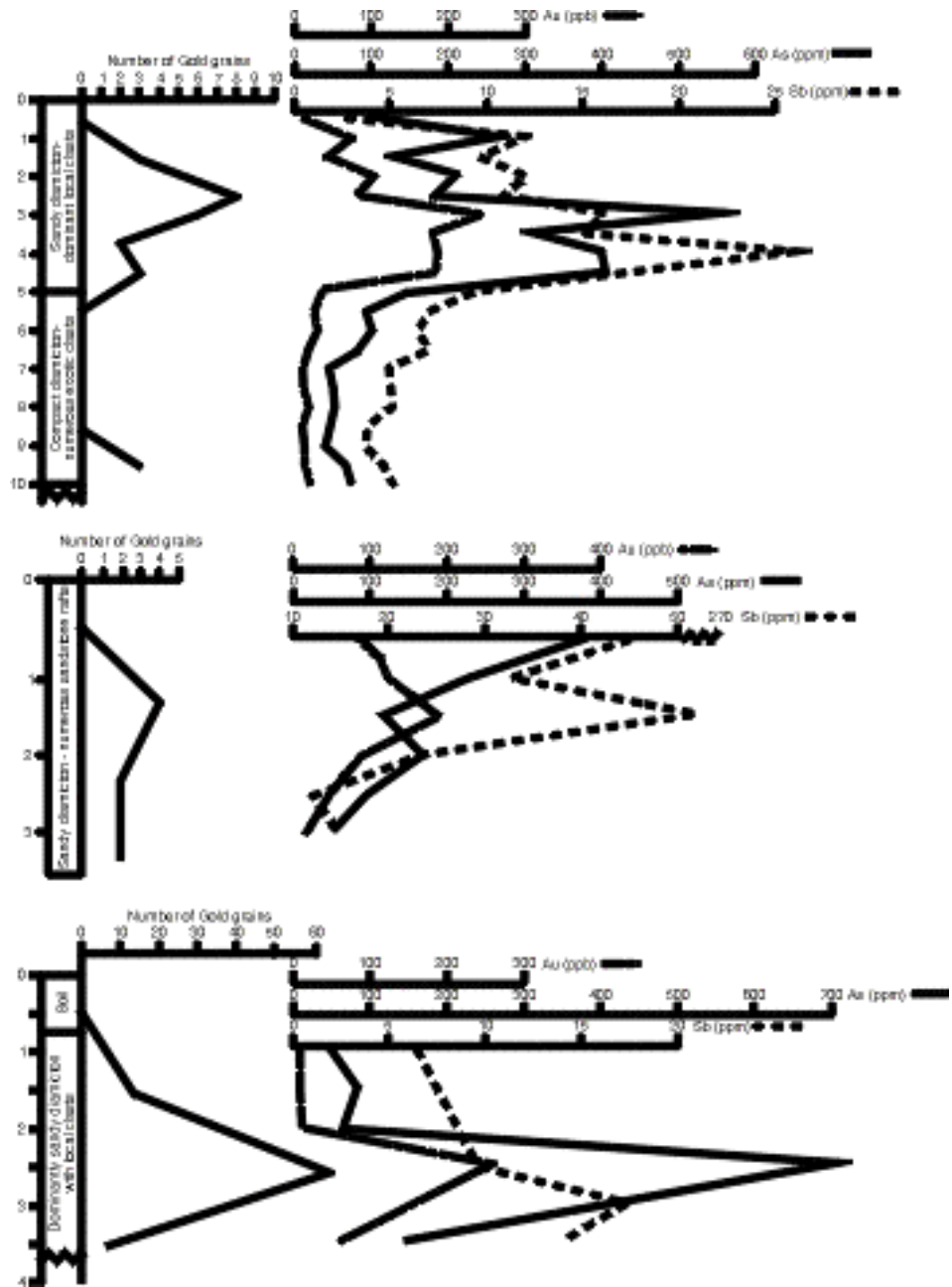


Figure 20. Comparison of gold grain counts with arsenic (As), antimony (Sb) and gold (Au) till geochemistry from the Altius Moosehead Property, central Newfoundland.

later ice flow. It is suggested that the main cause of the diversity is mass movement. Relief on the bedrock surface is considerable (30 to 40 m), and slopes are steep (up to 20°, generally dipping to the east). Mass movement of saturated sediment would take place either at the base of the ice, or postglacially. The vertical variation in fabric strength and orientation would be due to a series of minor mass movements taking place as cohesive debris flows, with most movement taking place along a zone of dislocation at the base of the sediment. The upper parts of the diamicton

Table 1. Clast–fabric data from the Flatwater Pond area, Baie Verte Peninsula

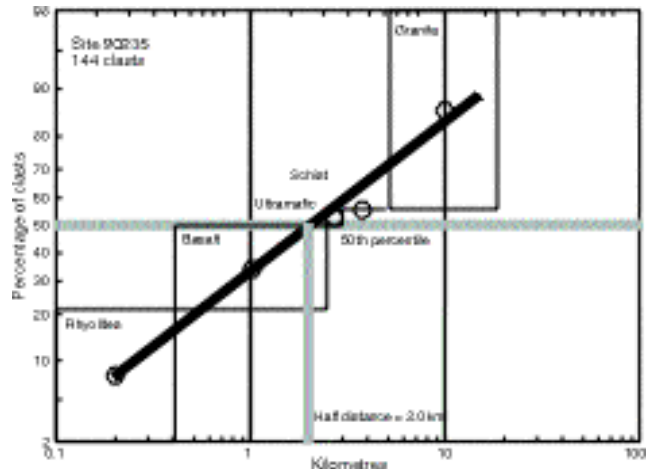
Site	S1	Mean orientation (direction/dip)
88-26	0.80	151/07
88-27	0.63	240/14
88-28a	0.60	322/00
88-28b	0.84	150/18
88-28c	0.92	140/07
88-28d	0.82	340/09
88-60	0.52	305/07
88-61	0.89	333/16
88-62	0.54	055/13
88-63a	0.48	261/25
88-63b	0.72	356/22
88-64	0.67	002/02
88-65	0.85	096/09

would be rafted relatively undisturbed, but clasts at the base would be re-oriented. Sediment at sites 88-27, 88-28A, 88-60, 88-62, and 88-63A have relatively weak girdle fabrics, typical of debris-flow diamictos (Lawson, 1982; Nardin *et al.*, 1979).

These examples demonstrate that clast–fabric analysis is a useful tool in drift prospecting in areas of complex ice flow. It is clear that a single fabric measurement is not sufficient to define ice flow in an area, but multiple fabric measurements may be useful in determining sediment moving ice flow. It is also important to use appropriate statistical criteria in evaluating the results of fabric analysis. Clast–fabric analysis is also useful in determining the genesis of glacial diamictos, and thus identifying appropriate sampling media.

The use of clast lithology has also proven an important tool in defining glacial dispersal on the Baie Verte Peninsula. As outlined, ice-flow history in the Baie Verte area is complex and widely divergent flows have been identified. In attempting to apply this method, only selected sites were chosen. These were sites where strong unimodal clast fabrics paralleling local striation measurements were obtained, thus identifying the transport direction. The bedrock geology of the area commonly makes precise determination of origin of a given clast difficult. Many of the units contain similar rock types and precise lithological identification is commonly difficult from a pebble-sized clast. When using this method, a very simplified interpretation of the bedrock geology based on the dominant rock type within a group or formation is used. In some cases, there is more than one potential source area for a given rock type, so the nearest source up-ice along the projected ice-flow vector was used, or the site was discarded.

The results for a site on the NTS map area 12H/9 are plotted in Figure 21. Geometric mean transport distances for pebbles derived by this method are in the range of 0.7 and 2.9 km. The effects of reworking are ignored but may well be significant. Calculation of mean transport distance assumes that all granitic rocks are derived from at least 8 km west of the site. Earlier northward flow would likely have dispersed large volumes of granitic rocks from extensive exposures 1 to 3 km south to southeast of the section, and these may well be the source of granitic clasts in diamicton. If reworking is considered, the effect is generally to decrease the estimates of average transport distances.

**Figure 21.** Geometric mean transport distances, Baie Verte Peninsula.

Estimates were also made on sites in the Springdale area (NTS map area 12H/8), southeast of the Baie Verte Peninsula, where in most cases only two rock types could be plotted. The fitting of a straight line to two points makes considerable assumptions concerning the distribution of the data, but results for six sites range between 5.8 and 8.8 km apart from a single site at 2.8 km.

Despite the limitations of the method, these results suggest that transport distances for pebbles are generally less for the southern Baie Verte Peninsula as opposed to the south of the NTS 12H/8 map area.

Estimates of half-distance value for the two areas discussed above were made by choosing distinctive rock types that could be related to an up-ice source area. Ultramafic rocks were chosen for the southern Baie Verte Peninsula, and granite from The Topsails for the southern part of the NTS 12H/8 map area. For each site, the distance up-ice to the proximal contact of the chosen rock type was estimated, and plots were made of percentage of that rock type against distance from source made (Figure 22). In each case, a second plot was made using a log-linear distribution. Simple

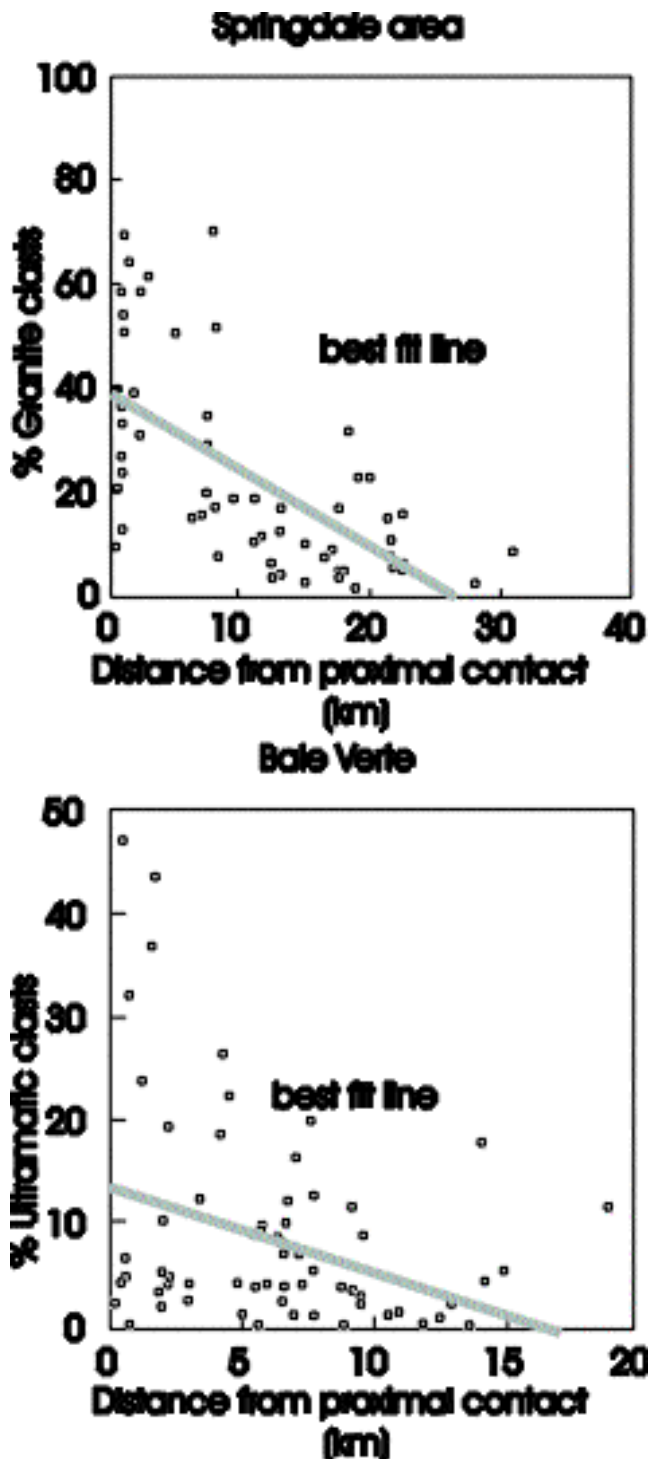


Figure 22. Graphs showing distance of selected rock types to the proximal bedrock source for sites on the Baie Verte Peninsula and in the Springdale area.

linear regression was used to fit straight lines to the data. For both areas investigated, the data is "noisy", but F-tests suggest that the regression analyses are significant. Once the relationship between distance from source and concentra-

tion is established, then the half distance can be calculated as follows. The intercept on the Y-axis is the concentration when distance is zero (or logarithm of the concentration in log-linear plots). Half this value can thus be substituted into the equation of the line to estimate the half-distance. The half-distance estimates for the southern Baie Verte Peninsula are 6.3 and 5.6 km, and the estimates for the southern part of the NTS 12H/8 map area are 13 and 21 km. Bouchard and Salonen (1990) suggest that the area of outcrop is a major influence on half-distance, and in this case the outcrop of granite covers a much greater area than that of ultramafic rocks. However, this method does again suggest that there is a significant difference in transport distance between the two areas.

The differences in transport distance estimates can be explained by considering the glacial history of the area, and likely sources of ice. The ice-flow history over most of the southern part of the study area is comparatively simple, and consistent throughout the last glaciation. Ice was derived from a major ice accumulation centre in The Topsails. The southern Baie Verte Peninsula has a complex ice-flow history, and the transport directions identified for sites are related to late, deglacial flow events, caused by flow from a small, local ice cap. The maximum transport distance can be no more than the distance from the site being investigated to the centre of the ice cap. In the case of the southern Baie Verte Peninsula, this is in the order of 15 to 25 km, whereas in the southern part of the map area, sites are located 20 to 50 km from the centre of the likely source of ice. Thus, average transport distances will be greater if sediment is transported by ice flow from a major ice centre, and the site is relatively distant from the accumulation centre.

This result implies that in drift prospecting, a given mineralized zone will be easier to recognize in areas dominated by local ice flow as opposed to regional ice flow, as the till will contain a greater proportion of local material. Greater transport distances will cause a longer dispersal train but of lower amplitude.

DISCUSSION

Newfoundland has a distinct glacial history from that of Labrador. The Island was covered by a series of coalescing ice caps during the late Wisconsinan, with only limited coverage from Laurentide ice. This is represented in glacial-dispersal patterns by short, diffuse trains, such as those described from the Baie Verte Peninsula and from around Grand Falls. Labrador was covered by the Labrador sector of Laurentide Ice Sheet having a dispersal centre in western Labrador. Dispersal patterns have an ameoboid shape in the Labrador Trough area, shown by a series of dispersal trains trending in several directions, commonly of limited extent.

Dispersal trains away from the ice dispersal centres are commonly longer and ribbon-shaped (e.g., Strange Lake) or fan-shaped (e.g., Central Mineral Belt).

There are other factors that contribute to the length and definition of dispersal trains. The Strange Lake dispersal train, for instance, is narrow, ribbon-shaped, and well-defined for greater than 40 km. This results from a fortuitous combination of unique geology, topography, and a simple glacial history. Dispersal trains on the Island of Newfoundland are commonly less well defined, especially geochemically, due to chemical similarities in adjacent rock units.

The adoption of a multi-faceted approach to the collection of geochemical data has proven useful in defining glacial dispersal. A combination of clast rock-type analysis, striation mapping, surficial mapping and geochemical sampling is employed by the Geological Survey of Newfoundland and Labrador. Clast rock-type analysis rarely focuses on mineralized material, but uses visually distinctive rock types having a discrete source area to define general patterns of dispersal. The use of surficial geology mapping has been shown to be essential to the interpretation of geochemical data, and in guiding sampling for geochemistry. Similarly, the use of striation mapping has provided exploration companies with paleo ice-flow data that may be incorporated into sampling programs.

Recent releases of geochemical data in central Newfoundland have shown that geochemical sampling on a regional basis, taking into account the Quaternary history, is vital base-line data for use by mineral exploration companies. Claim staking resulted in 377 km² of new claims for this area, representing about 8 percent of the total staking activity for 1998.

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Note: Geological Survey file numbers are included in square brackets.