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Glacial Dispersal - Principles and Practical Applications

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Article abstract

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Glacial Dispersal - Principles and Practical Applications

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Abstract
Glacial dispersal, the process of glacial erosion, transportation and deposition, has distorted the bedrock signatures on overlying surficial sediments and soils in most of Canada. Buffering components, such as carbonate minerals, which mitigate the effects of acid rain have been dispersed across Precambrian terrane in eastern Ontario in patterns that reflect several principles of glacial dispersal. Dispersal trains of boulders, minerals, and trace elements may enhance the size of mineral exploration targets by several times. By using appropriate analytical strategies and knowledge of dispersal, the source mineralizations can be found, as illustrated by an example of dispersal of nickel from the District of Keewatin. One other way dispersal principles have been applied has been to calculate the volume of material dispersed from a particular source outcrop. Dividing that volume by outcrop area yields average depth of glacial erosion, an important parameter to consider in selecting minimum depths for burial of long-lived radioactive waste.

Introduction
In 95 per cent of Canada and throughout the north-central and northeastern United States, the chemical and physical signature of bedrock on soils and surficial sediments has been distorted by glacial dispersal. Glacial dispersal is a term that describes the processes through which debris is entrained in ice at a source area, transported, and deposited some distance away.

The unique and most widespread surficial sediment produced by glaciation is till, generally defined as a heterogeneous mixture of various types and sizes of mineral and rock fragments. Till at any particular site, no matter what the details of its mode of deposition, is composed largely of a mixture of crushed and abraded fragments from bedrock outcrops located up glacier. The proportion of each bedrock component is dependent on a complex interrelationship of factors such as distance from source, topography of source and dispersal area, physical nature of minerals or rock, and diagenetic changes that have taken place at the site of deposition. In short, till is displaced bedrock with or without components derived from unconsolidated, previously deposited or formed glacial or non-glacial sediments and soils. Till can be described as the first derivative of bedrock - crushed, transported bedrock that has undergone little or no sorting by water or wind and has suffered little or no chemical alteration other than groundwater and soil-forming processes that act on it after deposition.

Other sediments of a glaciated landscape, pro- or subglacial marine, lacustrine, aeolian, fluvial sediments, and postglacial sediments formed in similar environments of deposition but without the presence of nearby ice, are closely related to till and can therefore be regarded as higher order derivatives of bedrock. The clastic constituents of these sediments have undergone additional transport after being liberated from the ice. Proglacial sediments are second order derivatives of bedrock, till that has been further transported and split into various size components by water or wind-sorting. Postglacial or modern sediments are third or higher order derivatives of bedrock, consisting of till or proglacial sediments that have been eroded, reworked, further dispersed, and subjected to chemical or biogenic alterations due to their exposure to surface weathering processes during thousands of years of postglacial time.

Because all galcial and postglacial sediments in the glaciated landscape bear some ancestral relationship to till (i.e, the load the glaciers were carrying), defining the controls on glacial dispersal of the material that comprises till is essential to an understanding of the composition and properties of the unconsolidated sediment that forms our present-day landscape.

Glacial Dispersal
In its simplest form, glacial dispersal may be described as the erosion of a type or

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component of bedrock by glacial ice and transport of the component by ice to a site of deposition. Some of the more important factors that influence the composition of a glacial sediment at any given site are described below.

1) As a glacier transports an indicator component away from a particular source, the frequency of the component is attenuated both by addition of debris from the dispersal area and by deposition of the indicator components along the way. Generally the decline in frequency of indicator components with distance can be plotted as a negative exponential curve, high frequencies declining rapidly to low frequencies, which are then maintained at levels above background for distances several times greater than the width of the source outcrop. The author has defined the zone of rapid decrease in indicator frequencies as the "head" of dispersal and the extended zone of lower frequencies as the "tail" of dispersal. The area of dispersal is called the "dispersal train", and the curve itself the "dispersal curve".

The apparent shape and dimensions of the dispersal curve and dispersal train are influenced in turn by a number of factors.

2) The lithologic nature and topography of the *source area* influences how much of a component will be eroded and available for transport. If the source area is a topographically positive feature and is composed of "soft" rock (limestone, serpentinized peridotite, etc.) or rock that is highly fractured as a result of structural (jointing) or periglacial (frost heaving) disruption, it is likely to provide a source of debris through repeated glacial events. Hard, massive outcrops, such as rhyolites or basalts, provide comparatively less debris, even if they stand as positive features.

Broad lowlands underlain by structurally or lithologically weak rock can also provide significant debris to glaciers, particularly if the glacier enters the lowland carrying relatively harder tools for abrasion, as is the case around the Canadian Shield where the Laurentide glaciers(s), armed with abundant hard, crystalline rocks derived from the Shield, accomplished much erosion on entering Paleozoic or Mesozoic sedimentary terrane.

3) The topography of the *dispersal area* has an important effect on the shape and continuity of both the dispersal curve and dispersal train. If the dispersal area has relatively little relief, the shapes of the curve and the train are controlled both by the rates of dilution by debris eroded from the dispersal area and mixed with the indicator component and by rates of deposition of indicator components in the dispersal area. In a topographically irregular dispersal area, ridges, escarpments, valleys, and other features may block or divert debris carried in the ice, destroying, displacing, or truncating dispersal curves or trains. Blocking or diversion is particularly common in geologically (and topographically) complex areas such as the Canadian Shield, the Appalachians, and the Cordillera.

4) Since there are several sedimentary environments associated with deposition of till, it is important to recognize its genesis and the circumstances under which the debris that formed the till was transported in glacial ice. In general, glaciers carry two types of sediment load - a dense concentration of debris near their base and a less dense load of debris scattered throughout or on the rest of the ice mass. Basal debris forms relatively dense, compact till which is lodged beneath a glacier or is melted out of the sole of the glacier during the waning stages of glaciation. Debris carried higher in the ice (englacial debris) or on the ice surface (supraglacial debris) is melted out with or without accompanying deformation or it slumps off the glacier ice by various mass wasting processes during the retreat of the ice sheet. The sediment deposited from the lower position is called basal, lodgment or basal melt-out till, among other names; sediments deposited from higher positions are called flow till, ablation till, supraglacial till or other terms. At a given site the latter deposits should be found, ideally, lying on the former, but generally one or the other group is absent or indistinct.

These two important groups of till facies are important to recognize during dispersal studies because they often vary radically in composition. In general, ablation depositis tend to be dominated by the lithologies of the higher (often local) or distant elements of the dispersal area, while basal deposits tend to be dominated by the lower elements of the disperal area. However, where valleys cut deep into highlands, glaciers may carry basal deposits far up the valleys, in which case the basal depositis throughout the valleys may contain significant amounts of components of distant origin.

5) Because glacial sediment is largely made up of crushed, unweathered bedrock fragments, it can contain any of the minerals common to the bedrock units across which its depositing glacier has passed, even minerals that are normally unstable in the weathering environment. Thus, except for the postglacially weathered upper parts of glacial sediment, such normally labile minerals as olivine, sulphides, carbonates, sulphates, etc. are likely to be present in till where appropriate sources were available. Conversely, where such sources of labile minerals were available, but where the glacial sediment has been weathered, tracing these labile components in their original form is difficult or impossible because they have been totally or partially destroyed by weathering processes. This is a particularly important problem in mineral exploration, since many of the important ore-bearing minerals are highly susceptible to postglacial oxidation.

6) Glacial crushing and abrasion cause communution of minerals into particle sizes that are determined by the relationship of the laws of crushing to the physical properties of the minerals. Reduced to simplest terms, this means that the harder and less likely to cleave a mineral or rock particle is, the more likely it is to be found in coarser size fractions of till and derived glacial sediment. Thus, given comparable intensities of abrasion, soft or easily cleavable minerals, such as micas, hematite, serpentine, graphite, etc. are likely to be concentrated in fine silt or clay sizes, whereas cleavable, but harder minerals, such as calcite, dolomite, siderite, barite, etc. are likely to be concentrated in the coarser silt-size grades. Hard minerals with no or poor cleavage, such as quartz, feldspars, pyrite, garnet, magnetite, etc. are likely to be concentrated in coarsest silt or sand-sized grades. This is not to say that particles of these minerals cannot be found in other grades, but the energy available to crush them tends to reduce each species to a characteristic size, depending on the physical properties of the particle. This is the concept of "terminal grade", which was introduced by Dreimanis and his students. In choosing analytical techniques and size fractions for studying glacial dispersal of particular components, it is important to bear this principle in mind.

7) The author has noted that in the vicinity of ice divides in Keewatin and Quebec the regional patterns of dispersal do not necessarily agree with the indicators of latest ice movement - striae in particular. In other regions, where directions of ice flow are known to have shifted through considerable angles during a single glacial event, tills deposited during that event can show considerable vertical variation, especially in geologically complex areas. The reasons for these observations are presently poorly known, but probably are related to the changing dynamics of the base of the glacier in a given region with time. In other words, erosion may be enhanced at some stage(s) of the glacier's development.

The length of time that a glacier was flowing at a particular azimuth may affect the distance that debris could be transported, a consideration that is particularly important in the vicinity of ice divides, many of which came into existence or moved to their last position late in the glacial event. It is known that basal ice flow velocities increase exponentially away from centres of outflow with the result that much of the debris in transit near the centre takes a great deal of time to move any appreciable distance.

8) The magnitude of dispersal and the proportion of "far-travelled" vs. "local" components in till (and its various varieties and derivatives) are concepts about which it is difficult to generalize. The complexity of factors governing actual and apparent dispersal in any particular region precludes the development of universal rules. Many studies have drawn conflicting conclusions with respect to these concepts, the conflicts being created largely by the local nature of the studies with attendant influence of local factors on the compositions of the till studied.

Because of the negative exponential character of the dispersal curve, the common observation that most material is dispersed a short distance from its source, and that the bulk of any till sample consists mostly of local debris can be considered generally true. However, the presence of abundant local pebbles and cobbles should not be taken to mean that the finer fractions of the till are of similar local origin nor should the opposite be taken on faith. The above generalization is particularly weak in regions downice from areas of constricted ice flow or from masses of soft, easily erodable bedrock or unconsolidated deposits, such as lacustrine or marine clayey silt or silty clays. In these areas preferential glacial erosion may produce such a mass of debris that the glacier was either hindered in eroding the dispersal area or was capable only of deposition in much of the dispersal area.

Practical Applications

Acid Rain

Concern has been expressed about the effects of acid precipitation on the lakes and sandy soils of the Canadian Shield and Appalachians. It is generally recognized that physical and chemical properties of the unconsolidated cover vary according to the way that underlying bedrock geology varies. What has been less apparent, however, is the extent to which glacial dispersal has distorted the bedrock signatures by transporting debris from one type of bedrock onto an area underlain by a different type. The effects of dispersal are most important where the dispersed debris is partially composed of components such as carbonate minerals, which have significant potential for buffering the groundwaters

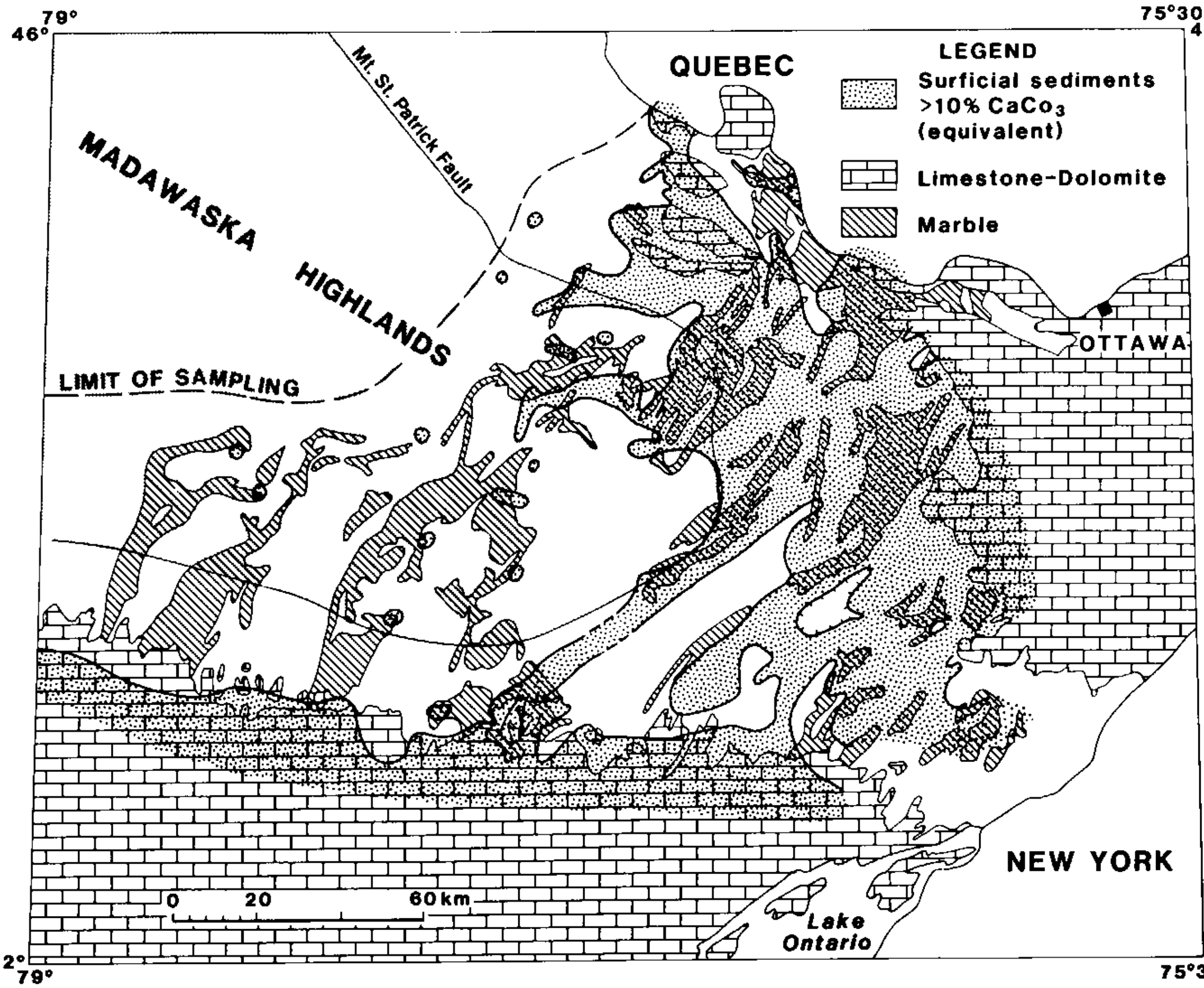

Figure 1 *Glacial dispersal of a buffering component (carbonate minerals) in a region threatened by acid precipitation, Frontenac Arch, Ontario (based on ~900 sample sites).*

that both participate in soil forming or weathering processes, and make up the bulk of the water in the surface drainage net.

Figure 1 shows dispersal patterns of carbonate-rich glacial debris from two principal groups of sources within or adjacent to the Precambrian outcrops of the Frontenac Arch of southern Ontario. Several of the principles of glacial dispersal are illustrated by this study of the fine (<64μm) fractions of till and derived sediments. Several "heads" of dispersal occur immediately down-ice (southwest) of outcrops of unmetamorphosed Paleozoic limestone. Tails of dispersal extend from areas of Paleozoic outcrop in the Ottawa Valley over the southeastern part of the Frontenac Arch.

The unmetamorphosed limestones of the Paleozoic succession have preferentially provided fine-grained cabonate debris for glacial transport. The coarser-grained marbles of the Frontenac Arch, while having provided some enrichment in carbonate in the fine fraction of till, did not produce carbonate contents as high as those of the Paleozoic limestones.

The topography of the dispersal area has had a dramatic effect on the patterns of dispersal. Carbonate-rich debris derived from Paleozoic terrane north of the Mount St. Patrick Fault escarpment has not been transported very far southward into the Madawaska Uplands, apparently being deposited as till against the escarpment. In contrast, carbonate-rich till has been transported and deposited across the Arch in the lowlands southeast of the escarpment, particularly along major valleys where no topographic obstruction existed to block the glacier's dense basal load.

Thus, the distribution of drift with high buffering capacities reflects some of the main principles of glacial dispersal. The lakes and soils of the areas covered by till with high buffering capacity are likely to be relatively insensitive to acid loading regardless of the lithology of the local bedrock.

Mineral Exploration

The principles of glacial dispersal have been applied most widely to problems in mineral exploration, particularly in Fennoscandia. Selected data from Keewatin illustrate how principles of dispersal can be brought to bear on mineral exploration problems (Fig. 2). This example illustrates the comparative usefulness of various size and specific gravity fractions of till and its higher order derivative, glaciofluvial sediment. All of the samples from which these data were derived were collected from the active layer within 50 cm of the surface in this area of deep permafrost. In spite of the cold climate of the region, labile minerals, such as sulphides, are commonly destroyed by oxidation in the seasonally thawed layer.

The bedrock that underlies the area sampled is Archean age, basic volcanic rock. Granitic and gabbroic rocks are intruded into the volcanic rocks along the northeast and southwest sides of the sample area. The direction of glacial flow is southeastward, and the esker is a segment of the 100 km-long Copperneedle Esker. The mineralization at the site shown on the map is thought to comprise a body of nickel-copper sulphides in the basic volcanic rocks.

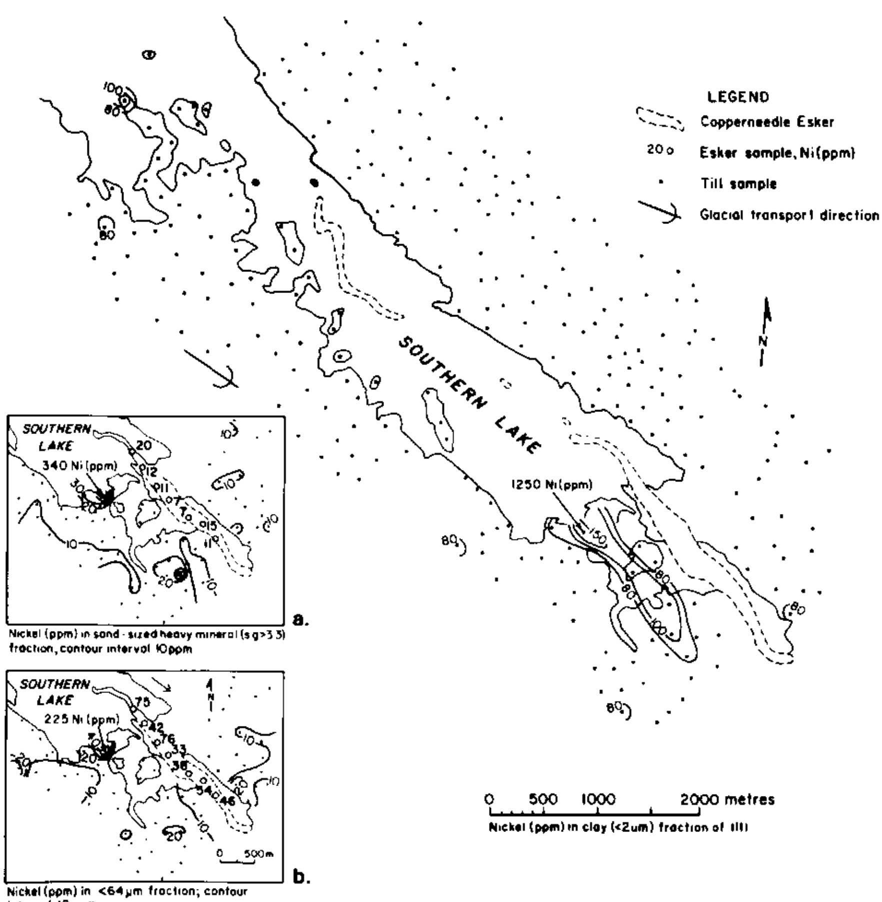

Figure 2 *Glacial dispersal of nickel from an area of potential economic mineralization, District of Keewatin, N.W.T. Note contrasting concentrations of nickel in sand sized (2a) and silt-clay sized (2b) fractions of till and in different glacial sediment facies. Site of mineralization is near till sample for which absolute nickel concentration is shown.*

Figure 2 illustrates a classic dispersal train of nickel from the area of known nickel mineralization. The map is based on atomic absorption analyses of the clay fraction of till. This fraction is thought to contain or scavenge metal (nickel in this case) released by weathering of labile components in approximate proportion to the original metal content of the unweathered sediment. Nickel values in the heavy mineral fractions of both till and esker sediment (2a) are uniformly low and show little variation except in the immediate vicinity of mineralization, in spite of the fact that any components of the mineralized zone should occur as heavy minerals. The reason for this apparent paradox is that the sulphide minerals of the mineralization are highly susceptible to weathering in the active layer and so have been effectively removed from most samples.

The uniformly low nickel concentrations of the <250-mesh (<64μm) fraction (2b) illustrates the dilution effect that occurs when the metal-poor, quartz-feldspar-rich silt fraction is not separated from the clay fraction. The strong differences in composition between till and esker sediment for this fraction are due to the differences in genesis of the clay-sized particles in which most of the metal is held. In the till, the clay-sized detritus is composed primarily of glacially crushed phyllosilicates with relatively low cation exchange capacity. The clay-sized detritus in the sandy, gravelly esker sediment consists largely of mixed-layer and expansible clay minerals and Fe-Mn oxides or hydroxides, both of which have high exchange capacity. The clay-sized particles in the esker sediments originated almost exclusively from postglacial weathering of sand sized silicate minerals or rock fragments.

Thus, the interpretation of these mineral exploration data is enhanced by consideration of dispersal principles. These principles can only be applied after fractionation of the glacial sediments has been made in such a way as to allow a meaningful dispersal pattern to emerge, given the genesis of the sample media and the nature of their postglacial alteration.

Depth of Glacial Erosion

Because of concern about the excavation of buried radioactive wastes by glacial erosion resulting from any future glacial event, the author was commissioned to carry out a study of past depths of glacial erosion in order to be able to predict probable depths of future erosion. In order to estimate "specific glacial erosion", that is the average amount of glacial erosion accomplished during a specific glacial event over a specific area or outcrop, a method was devised with which dispersal trains from particular outcrops were mapped and the amount of material that was dispersed from that outcrop during a single glacial event was calculated. The volume of dispersed material was divided by the area of the outcrop to arrive at an average thickness of rock removed, recognizing that glacial erosion is an asymmetric process. Figure 3 illustrates one study of specific glacial erosion based on the dispersal of geochemically distinct debris from the nickel-chromium-rich ultramafic rocks of the Thetford Mines asbestos belt.

The ultramafic rocks of the asbestos belt are known to contain uniform amounts of nickel, estimated conservatively to average 2000 ppm (0.2%). It was reasoned that if "background" till, that is till deposited by glaciers that had encountered no ultramafic outcrops, averaged

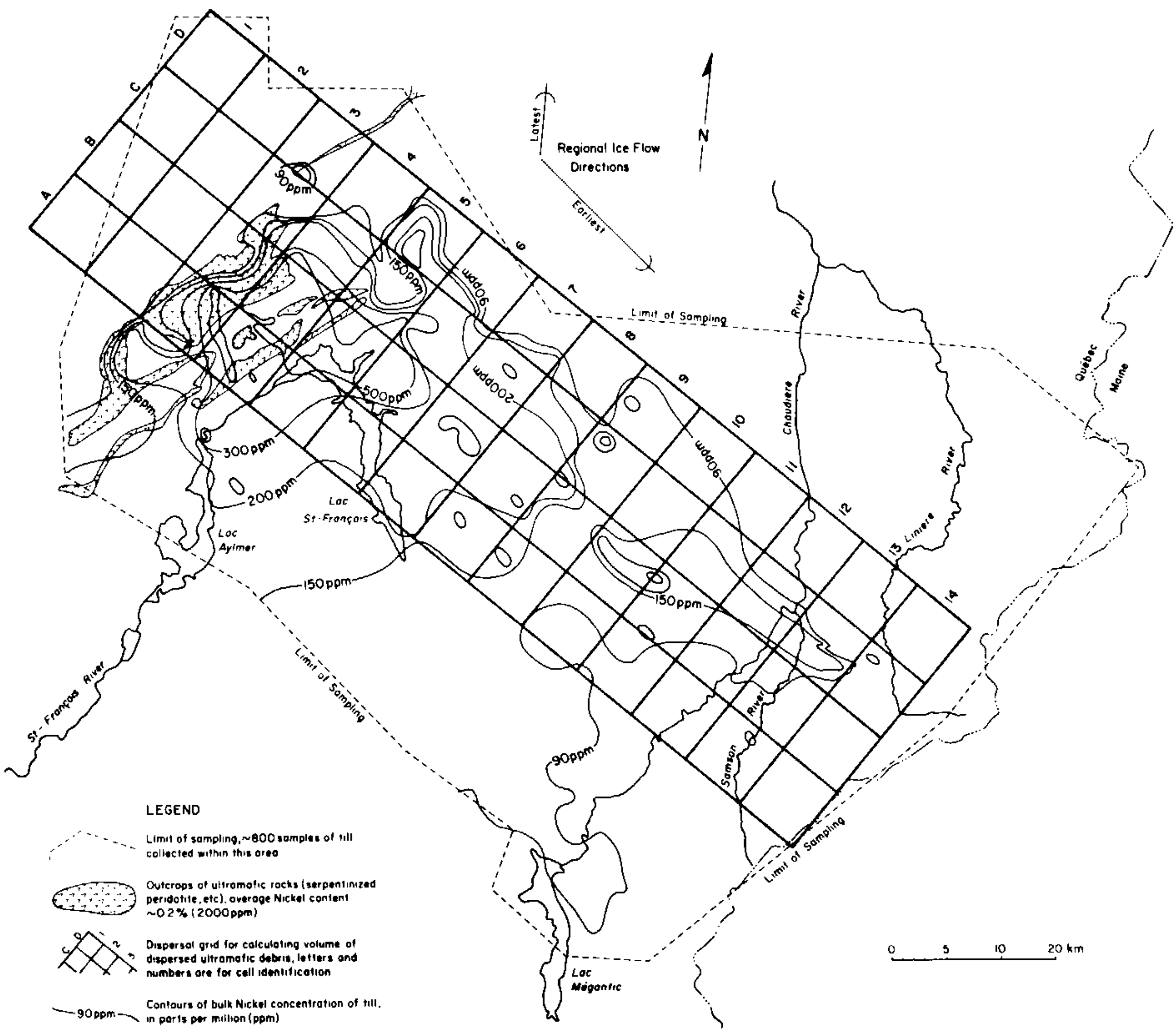

Figure 3 *Glacial dispersal of nickel from an ultramafic complex in southeastern Quebec. Average concentration of nickel in each of the cells of the overlaid grid was recalculated as a volume of ultramafic debris, the volumes were summed, and divided by the areas of the source outcrops to estimate average magnitude of glacial erosion.*

40 ppm Ni, then till containing 2040 ppm nickel could be considered to be 100% composed of ultramafic components, 1040 ppm of 50% ultramafic components, etc. Using these assumptions, the dispersal area was divided into cells and the volume of ultramafic debris in each cell calculated by the formula

$$\frac{\bar{C}_N - \bar{B}_N}{2000} \times KA_c = V_i,$$

where $\bar{C}_N$ is average nickel content (ppm) of the till in the cell, $\bar{B}_N$ is the average background nickel content of till (≃40 ppm), K is a constant representing average thickness of the till sheet studied throughout the dispersal area (taken to be 3 m in this case but known to vary from 0-25 m), A_c is the area of the cell, and V_i is the total volume of ultramafic debris in the cell. T_E, specific glacial erosion, or the average thickness of rock removed during a glacial event, is calculated by the formula

$$T_E = \frac{\sum_{i=1}^{i=n} V_i}{A_U}$$

where A_U is the area of ultramafic outcrop that served as a source for the debris. From these calculations we estimate that 393 x $10^6 m^3$ of ultramafic rock was removed from an outcrop area of about 92 km^2, yielding an erosion estimate of just over 4 m. Using similar dispersal techniques but other types of components in two other areas we arrived at various figures for specific glacial erosion of 2 to 6 m, estimates that in all cases were based on parameters chosen in such a way as to make them conservatively high. Using this technique we have been able to demonstrate that average erosion depths of 10's to 100's of metres estimated by some authors for vast parts of the Canadian Shield are clearly orders of magnitude too large and should not be used to estimate safe depths of burial of radioactive wastes. The dispersal data used in this study illustrate both the great magnitude of dispersal that can be mapped if components are sufficiently distinctive, and the exponential decline in concentrations of components away from the source area.

Conclusion

Glacial dispersal was an important process in redistributing the bedrock components of the glaciated terrain of Canada. The principles of dispersal are of fundamental importance in the interpretation of patterns of variation of chemical and physical properties of all surficial sediments, whether they be of glacial or postglacial origin. In the cases cited dispersal has been responsible for: (1) regional patterns of distribution of buffering components, in many places over bedrock with little or no inherent capability to buffer acid precipitation; (2) producing trains of metal-rich debris covering areas far greater than those of the source outcrops and which, if detected can lead to discovery of mineralization; (3) obtaining quantitative estimates of specific glacial erosion, a figure that can be used to allay environmental concerns over burial of long-lived radioactive waste.

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