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Abstract

Large portions of the Earth's surface have been glaciated several times during the last two million years. The overburden in these areas is made up of glacial drift, which has been laid down by the action of glaciers and their meltwaters, and thereafter subjected to postglacial processes. In glacial terrane, therefore, geochemical dispersion can be divided into two main classes, (1) syngenetic dispersion, i.e. principally mechanical or particulate dispersal which took place during glaciation and (2) epigenetic dispersion, i.e. chemical and mechanical dispersion which has taken place after glaciation. In combination these processes may result in intricate geochemical dispersion patterns and anomalies that are difficult to interpret. The sampling and analytical methods used should, therefore, be those which will disclose anomalies that are genetically not too complex.

Interpretation of syngenetic patterns presupposes a thorough knowledge of the glacial history. To obtain meaningful results it is frequently necessary to sample tills in section to the bedrock surface. This often requires heavy equipment, and sampling costs may be relatively high. The analytical methods used should employ rigorous chemical digestion as well as mineralogical determination of resistant minerals.

Epigenetic dispersion patterns in glacial overburden can be produced downslope due to metal dispersion in groundwater, or immediately over the bedrock source due to capillary forces, biological activity or gaseous movement of volatile compounds. Mineral deposits in contact with groundwater may act as natural galvanic cells which may result in electrochemical dispersion of metal into the overlying glacial drift. Epigenetic dispersion patterns may be detected in near-surface soils at relatively low sampling costs and by weak chemical extraction.

Empirical evidence supporting these principles is provided by published and unpublished data. This paper reviews those data that have appeared in the western literature during the last decade, the intention being to outline the present state of art in utilizing analysis of soil samples as an exploration tool in a glacial terrane.

If we are to advance the applicability of soil geochemistry in glaciated environments, more research into dispersion mechanisms is required.

Résumé

Au cours des deux derniers millions d'années, les glaces ont recouvert plusieurs fois de grandes parties de la terre. Dans ces régions, les morts-terrains sont constitués d'alluvions glaciaires qui se sont accumulées sous l'effet du déplacement des glaciers et de l'écoulement de leurs eaux de fonte, pour ensuite être soumises aux phénomènes postglaciaires. Dans les terrains glaciaires, on peut donc diviser la dispersion géochimique en deux grandes catégories: 1) la dispersion syngénétique c.-à-d. surtout mécanique ou dispersion des particules survenue au cours de la glaciation et 2) la dispersion épigénétique, c.-à-d. la dispersion chimique et mécanique survenue après la glaciation. Ces phénomènes combinés peuvent donner des modes compliqués de dispersion géochimique et il est difficile d'interpréter les anomalies. Il faut donc avoir recours aux méthodes d'analyse et d'échantillonnage qui permettent de déceler les anomalies dont la complexité n'est pas trop grande sur le plan génétique.

L'interprétation des configurations syngénétiques présuppose une bonne connaissance de l'histoire de la glaciation. Pour obtenir d'excellents résultats, il est souvent nécessaire de prélever des échantillons de till par section jusqu'à la roche en place. Il faut souvent du matériel lourd pour exécuter les travaux, et les coûts de l'échantillonnage peuvent être relativement élevés. Les méthodes analytiques utilisées doivent comporter une digestion chimique rigoureuse et une détermination minéralogique du minerai résistant.

La dispersion épigénétique dans les morts-terrains des glaciers peut se produire vers le bas en raison de la dispersion des métaux dans les eaux souterraines ou immédiatement au-dessus de la roche en place à cause des forces capillaires, de l'activité biologique et des déplacements gazeux de composés volatiles. Les gisements de minerai en contact avec les eaux souterraines peuvent constituer des piles électriques naturelles qui provoquent éventuellement la dispersion électro-chimique des métaux dans les alluvions glaciaires sus-jacentes. La dispersion épigénétique peut être détectée dans le sol près de la surface, au moyen d'un échantillonnage relativement peu coûteux et d'une faible extraction chimique.

Ces principes sont justifiés par les preuves empiriques que constituent d'innombrables données tant publiées qu'inédites. La présente étude a pour objet d'examiner les données fournies dans les revues scientifiques publiées en Occident au cours de la dernière décennie. Il s'agit d'exposer la situation en utilisant l'analyse des échantillons de sol comme instrument d'exploration dans les terrains glaciaires.

Si nous voulons, dans l'avenir, faire progresser l'application de la géochimie des sols dans les milieux glaciaires, il faudra intensifier la recherche sur les mécanismes de dispersion.

INTRODUCTION

In geochemical exploration the word "soil" is commonly used as a synonym for overburden, although in a stricter sense it refers to the upper layered part of the regolith. In this paper the term will be applied to all or part of the earthy unconsolidated material overlying bedrock. Soil sampling will include any type of overburden sampling except sampling of recent stream sediments and other drainage channel material.

Soils can be classified into residual and glacial. Residual soils accumulate in place as a result of weathering of the underlying rock (e.g. tropical soils). Glacial soils or glacial drift, however, are the result of the action of glaciers and their meltwaters on fresh or weathered bedrock and preglacial soils. The use of soils in geochemical exploration in glaciated areas, therefore, creates special problems distinct from those in the tropics and other areas covered by residual soils.

Large parts of the continents have been glaciated several times during the last two million years of the Earth's history. The glaciated regions include nearly all Canada, large parts of the United States north of 40°N (New York), most of Europe north of 50°N (London) and extensive regions of Asia, in particular north of 60°N (Leningrad) (Fig. 13.1). These glaciated regions include some of those parts of the world that are being most actively explored for mineral deposits. This fact is reflected in the large number of publications describing the use of soils for prospecting in glaciated areas that have been published in recent years.

This paper summarizes trends from these works. Our main sources have been Exploration Geochemistry Bibliographies published by The Association of Exploration Geochemists (Hawkes, 1972, 1976), textbooks (Hawkes and Webb, 1962; Levinson, 1974), monographs and symposia proceedings (Cameron, 1967; Kvalheim, 1967; Canney, 1969; Boyle and McGerrigle, 1971; Bradshaw et al., 1972; Jones, 1973a, 1973b, 1975, 1977; Bradshaw, 1975a; Elliott and Fletcher, 1975; Govett, 1976b; Kauranne, 1976a; Legget, 1976), and articles in scientific journals in particular the Journal of Geochemical Exploration. Much of the information on glacial deposits and processes have been taken from Flint (1971); Goldthwait (1971a); Nickol and Björklund (1973) and Dreimanis (1976).

In glaciated areas, geochemical dispersion from a bedrock source to the soils, can be divided into two separate classes, (1) syngenetic dispersion, i.e. principally mechanical or particulate dispersal which took place during the glaciation, and (2) epigenetic dispersion, i.e. chemical and mechanical dispersions which have been taking place during the postglacial period. Any geochemical dispersion pattern presently found in glacial soils will, in principle, be a result of these two types of processes. To interpret the geochemical results of soil surveys in glaciated terrane, it is important to have a thorough understanding of both the syngenetic and epigenetic dispersion processes. A brief account of these two types of processes are given in the following two sections.

SYNGENETIC DISPERSION

Syngenetic geochemical dispersion patterns in glacial soils are formed contemporaneously with the glacial deposits, that is, they are a result of the process of glaciation.

Process of Glaciation

The climate has changed several times during the Quaternary, and in cooler periods there have been extensive glaciations (Flint, 1971). From one or more central areas, the glaciers flowed outwards and towards the sea, the general movement being more or less independent of small variations in the local topography. In most cases only the very high peaks escaped glaciation. On the lowlands, the ice moved as a sheet or spread out as piedmont glaciers. The rate of movement varied considerably over short distances, especially in the marginal zones where subglacial valleys caused locally high velocities. Through abrasion and quarrying, the glaciers eroded and dispersed bedrock and proglacial sediments in fragments ranging from fine powder to large boulders. As the climate gradually became more temperate, a point was reached where the lowland ablation of the glaciers (melting, evaporation and calving) occurred at a faster rate than the accumulation of ice and snow. The glacier front then started to retreat leaving behind a great variety of glacial deposits, collectively called glacial drift.

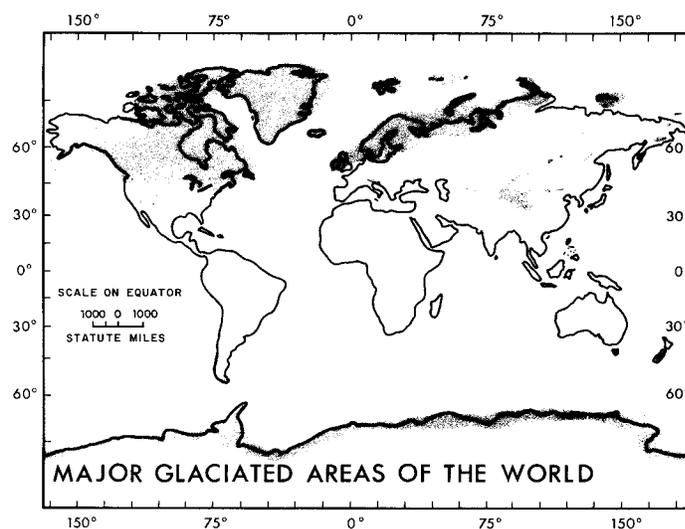


Figure 13.1. Major glaciated areas of the world. After Flint (1971).

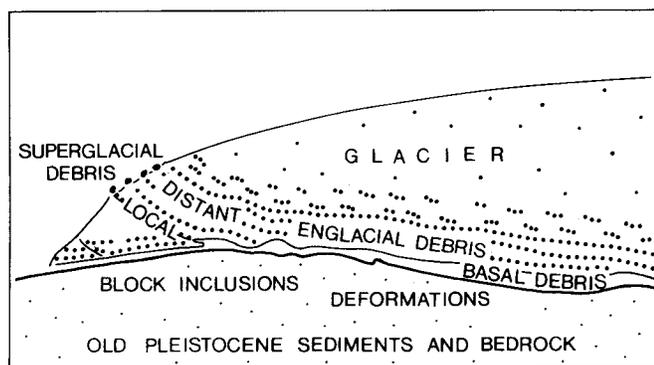


Figure 13.2. Schematic radial section of ice sheet in its terminal zone. After Dreimanis (1976).

According to Dreimanis (1976), glacial drift may be transported by the glacier as (1) basal, (2) englacial and (3) superglacial debris (Fig. 13.2).

1. The basal 1-3 m of a glacier contains most of the rock debris carried by a glacier. This is the main zone of comminution and by crushing and abrasive action the basally transported debris becomes comminuted to its constituent minerals with less than 0.1 per cent of any lithology of clasts surviving beyond 35 km (Goldthwait, 1971b).
2. Compressive flow may move debris upward from basal into englacial positions. Englacial debris and fragments can be observed up to 30 m above the base of a glacier. If englacial debris is transported more or less parallel to the base of a glacier it may survive transport for hundreds of kilometres.
3. Superglacial drift is derived in part, from rock debris falling onto the surface of the glacier and from the transport of englacial debris into the superglacial position at the glacial terminus. Rock may withstand superglacial transport for hundreds of kilometres.

The material carried by the glacier may be reworked and redistributed by meltwater adjacent to the terminus of the glacier.

During the last stages of glaciation, removal of glacier ice resulted in release of impounded proglacial lake waters and in isostatic raising of areas of marine submergence, exposing formerly hidden glacial deposits at the surface.

Classification of Glacial Drift

Based on its sedimentological character glacial drift can be divided into two main groups (1) till and (2) stratified drift (Dreimanis, 1976).

Till is that part of the drift which is nonstratified, poorly sorted and closely packed with a variety of rock and mineral fragments of different sizes.

Stratified drift are sorted and layered sediments showing signs of being deposited in or redistributed by water.

For geochemical exploration purposes, classification of drift based on genesis is of greatest interest, because such classification is the key to tracing syngenetic geochemical anomalies in the drift back to the bedrock source.

Till can be classified genetically into two main groups as shown in Figure 13.3 taken from Dreimanis (1976).

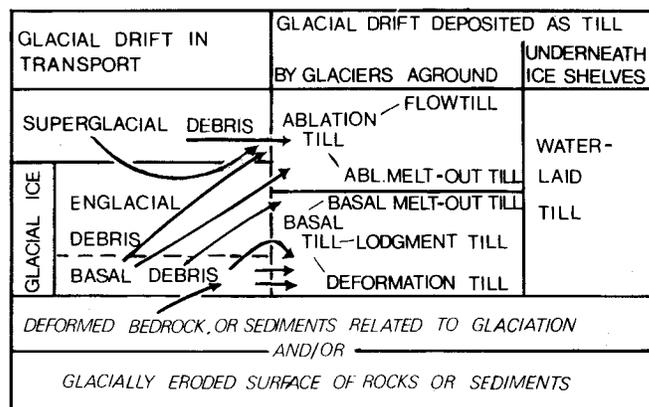


Figure 13.3. Classification of tills. After Dreimanis (1976).

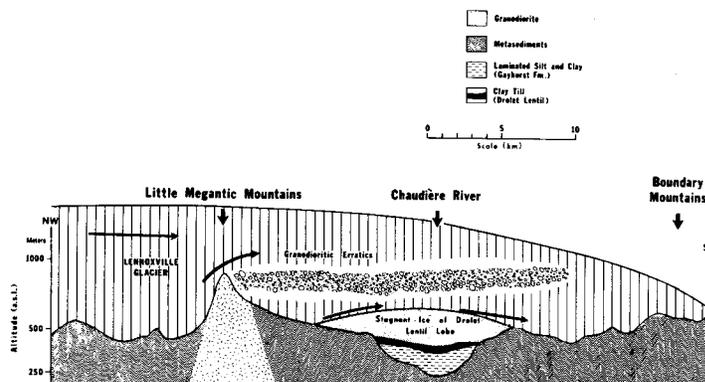


Figure 13.4. Diagrammatic cross-section of glacier showing how englacial debris can form ablation mantle to till. After Shilts (1973a).

Basal till (Lodgment till) is chiefly made up of basal debris (Fig. 13.2). The transportation length could be from a few centimetres up to several kilometres.

Ablation till originates mainly from englacial and superglacial debris (Fig. 13.2) and may have been transported long or short distances depending on circumstances (Shilts, 1976).

If a glacier advances over relatively flat terrain, particles apparently work their way up through the glacier. In this case the ablation till will normally be transported much longer than the basal till.

In mountainous areas where the glacier is flowing through valleys or over peaks, debris may slide or roll on to the ice from adjacent slopes, or be supplied from peaks throughout the thickness of the ice (see Fig. 13.4). In such cases ablation till may be locally derived and contrast sharply in composition with the basal till, which in valleys may be distal. If both basal and ablation till are derived locally, the ablation facies may reflect the resistant rock types that form hills, whereas the basal facies usually reflect softer rocks that form valleys. In all cases the density of sediment carried in the englacial or superglacial mode is less than that carried basally. Ablation till, therefore, has undergone less severe comminution than basal till. Ablation till may also have been reworked by meltwater to a greater extent than basal till. Consequently, ablation till is normally coarser than basal till.

Stratified drift can be divided into (1) ice-contact stratified drift and (2) proglacial sediment (Flint, 1971).

Ice-contact stratified drift deposits are derived from till by partial reworking and redistribution by water adjacent to the terminus of the glacier; esker materials belong to this type.

Proglacial sediments have been transported by meltwater from glaciers and have been deposited at varying distances beyond the ice margin. Glaciolacustrine and glaciomarine sediments belong to this type.

Glacial Epochs

In most areas, the climatic variations have resulted in several advances and retreats of the glaciers. Even though most of the present day landform and glacial deposits were formed during the last glaciation, preglacial or interglacial sediments would, to a varying degree, be intermixed or interbedded with these deposits. Indeed, in many cases older sediments may repeatedly have survived younger glaciations. Glacial deposits formed during the last glaciation, may therefore be underlain by older glacial sediments or preglacial weathering products (Dreimanis, 1976).

Shilts (1975a) has shown that concentrations of ultrabasic components in a till section may change abruptly at certain levels, indicating till sheets of differing provenance (Fig. 13.5). Other descriptions of glacial-event stratigraphy in Canada with relevance to geochemical exploration are given by Alley and Slatt (1976) and Shilts (1976).

In parts of Finland, glacial transport and till stratigraphy have been thoroughly investigated by Kujansuu (1967, 1976), Korpela (1969), Hirvas et al. (1976), Kokkola (1975), Kokkola and Korkalo (1976) and Hirvas (1977).

As reported by Hirvas (1977), observations in 1288 test pits in northern Finland indicated that there have been at least five different episodes of glacial transport that differ in

age and direction of ice flow (Fig. 13.6). Various till beds occur that correspond to each of these five stages (Fig. 13.7). The distance travelled by various components in the different till sheets varies, and no formula could be given for the transport distances applicable to the whole of northern Finland.

These findings concerning overburden stratigraphy have important implications when applied to the use of till and other types of glacial drift as sample media in geochemical surveys. To obtain interpretable syngenetic dispersion patterns it is essential that the samples be collected consistently from the same strata.

Glacial Transport

Shilts (1976) stated; "Glaciers appear to disperse material in the form of a negative exponential curve, with the concentration of elements, minerals or rocks reaching a peak in till at or close to the source, followed by an exponential decline in the direction of transport. The parameters of the curve appear to be determined by the physical characteristics of the components and the mode of transport". Shilts then introduced the terms (1) head and (2) tail of the dispersal curve signifying (1) rapid decrease in metal concentration immediately down-ice of the source and (2) a gradual decrease at greater distances (see Fig. 13.8). The tail would normally be the target in reconnaissance sampling, and as such it is often difficult to detect due to low metal contrast in the till. The head, however, shows much better contrast, but needs denser sampling to be detected.

The size of the indicator train is more or less proportional to the area and orientation of the source exposed to glacial erosion (Holmes, 1952; Dreimanis and Vagners, 1969 and Shilts, 1976). Shilts also pointed out that there are two additional factors that determine whether an indicator train can be detected: (1) how easily and accurately the component can be determined with the analytical methods available, and (2) how distinct the component is, i.e. how common the component is in barren rocks of the dispersal area.

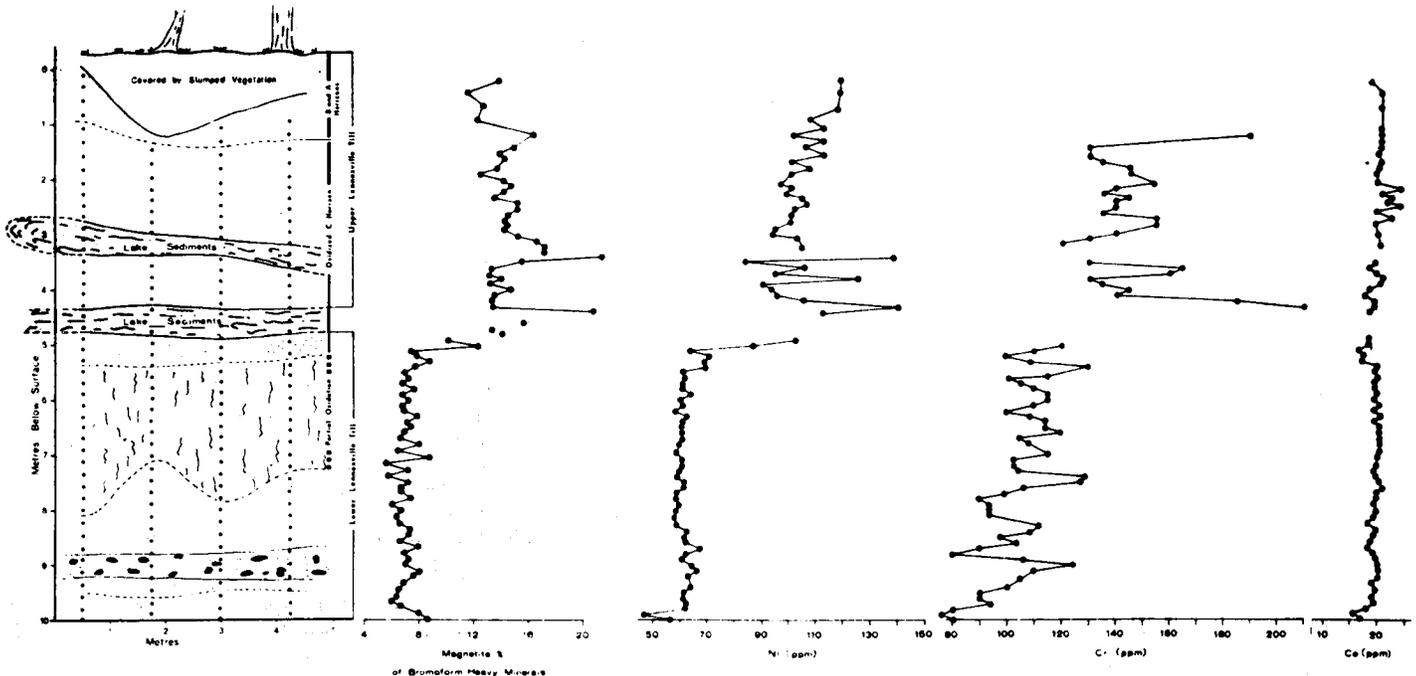


Figure 13.5. Ultrabasic components in multi-till stratigraphic section showing how concentrations can change abruptly at certain levels. After Shilts (1975a).

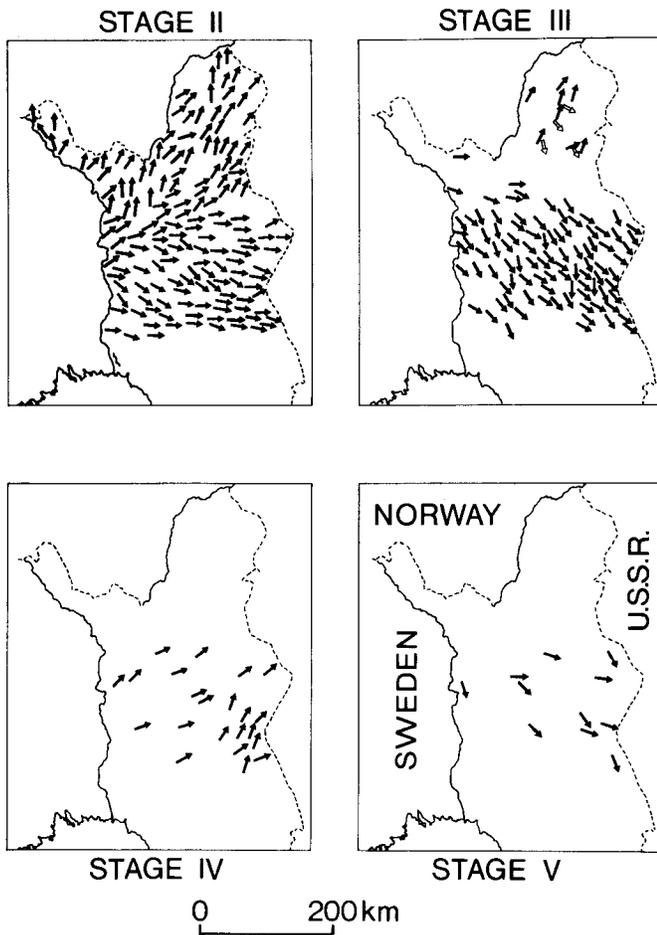


Figure 13.6. Four of the five stages of glacial transport found in northern Finland. After Hirvas (1977).

Information on transport direction may be obtained from a variety of glacial features including: (1) striations, crescentic marks and ice flow forms; (2) indicator trains and (3) fabrics.

Striations and crescentic marks are grouped by Flint (1971) as small-scale features of glacial abrasion. They are abraded surfaces formed by material at the base of a glacier grinding to the bedrock surface. Most striations and grooves indicate the orientation but not the sense of glacial movements. However, "rat tail" striations, that is tails of soft material in the lee of small, hard inclusions in the bedrock, do indicate the sense as well as azimuth of movement. Crescentic marks gouged out of bedrock are formed at right angles to the direction of glacial movement.

Large ice-flow forms include stoss and lee topography which may consist of knobs or small hills of bedrock each with a gentle abraded surface on the upglacier (stoss) surface and a steeper, rougher, quarried slope on the lee side. Streamlined molded forms such as drumlins have their long axes oriented approximately parallel to the main flow direction of the ice movement.

Typical indicator trains are finger- or ribbon-shaped and sometimes fanlike. They have been used extensively as a reliable method of determining the direction of glacial movement. Flint (1971) presented several examples from North America and Scandinavia, and the results of other studies can be found in articles by: Sauramo (1924), Grip (1953), Okko and Peltola (1958), Dreimanis (1958 and 1960),

Pollock et al. (1960), Geoffroy and Koulomzine (1960), Lee (1963, 1965), Wennerwirta (1967 and 1968), Karup-Møller and Brummer (1970), Muntanen (1971), Shilts (1973a, b, 1975a, 1976), Freeman and Ferguson (1973), Nichol and Björklund (1973), Szabo et al. (1975) and DiLabio (1976).

It must be remembered that these dispersal trains are three-dimensional; they may surface close to the subcrop of the source or they may come to surface some distance down-glacier from the bedrock origin. Hence to define this third dimension it is necessary to sample the trains in section. The picture may become more complicated if the till is subsequently covered by later glacial deposits such as tills,

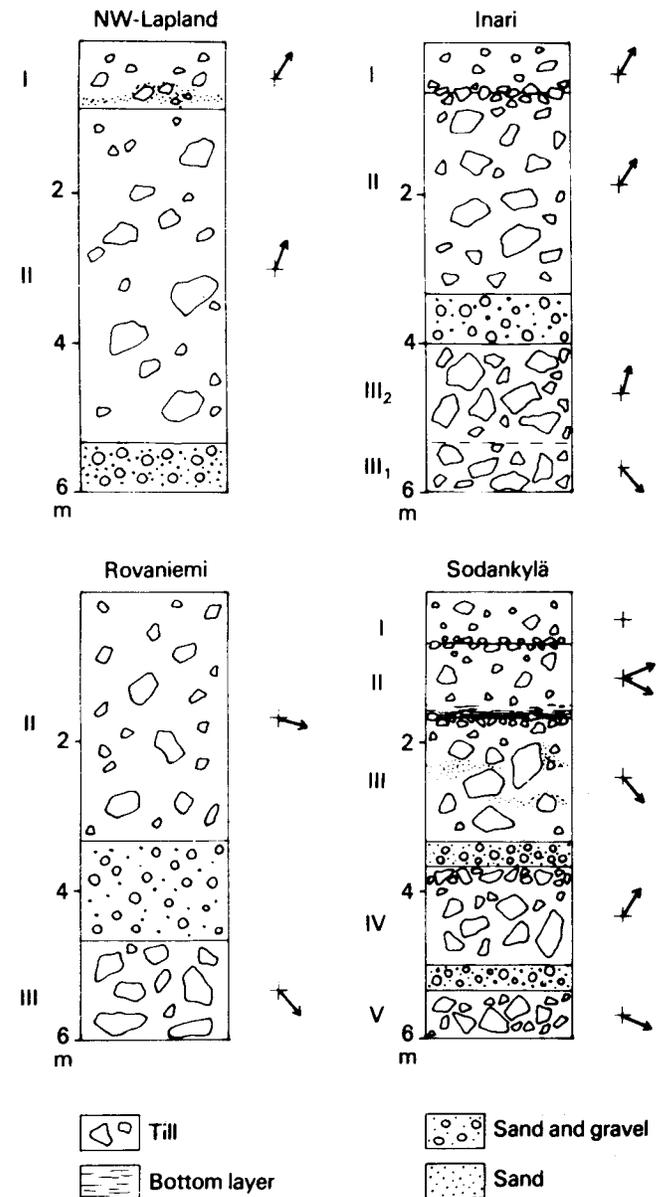


Figure 13.7. Examples of till stratigraphy in northern Finland. Roman numerals to the left of the sections correspond to stages of glacial transport in Figure 13.6. Arrows indicate average direction of glacial flow (north at the top). After Hirvas (1977).

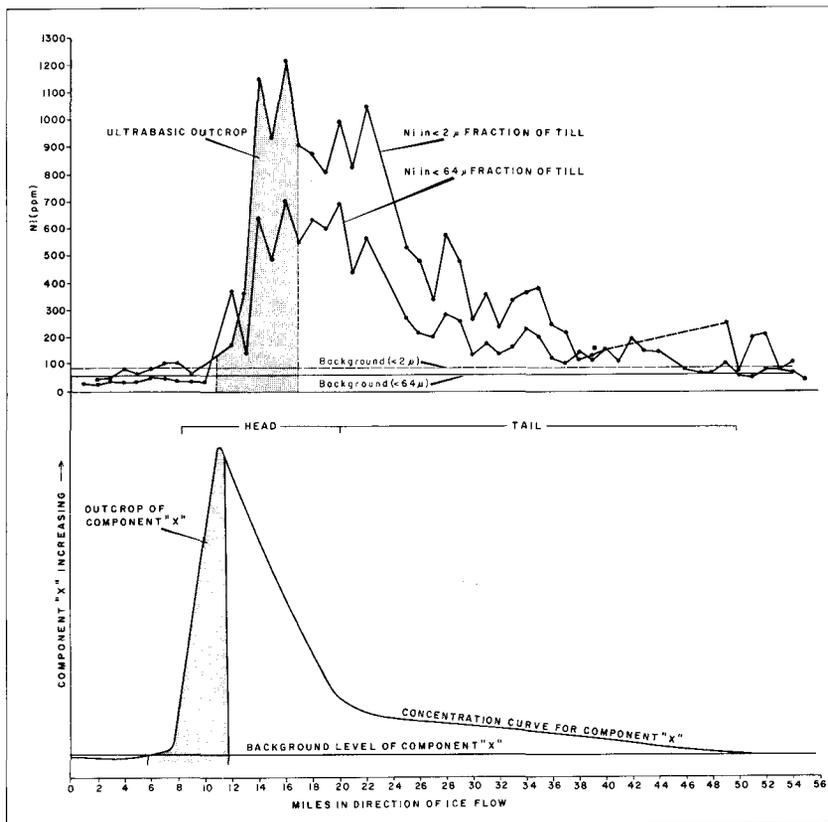


Figure 13.8. Example of actually found (top) and idealized (bottom) glacial dispersal curves showing relationship of the head and tail of the negative exponential curve. After Shilts (1976).

glaciolacustrine, fluvial and bog deposits. In such cases there may be no chemical or physical surface expression of the presence of the concealed metal zone, and the only practical geochemical way to search for the indicator train is to section sample by drilling the lodgment till under the superposed overburden.

Fabric studies may be used in determining the direction of glacial flow. The fabric of till results from the arrangement of its component rock particles; these are often organized so that the majority of clasts lie with their long axis parallel to the direction of flow, while a smaller number lie transverse to this direction (Flint, 1971). Elongated pebbles may dip up-ice; recording of their orientation in till sheets may, therefore, indicate both the sense and azimuth of the movement of the glacier that deposited them. This way of determining the direction of glacial flow was systematized by Krumbein (1939) and Holmes (1941), and has later been used by many workers; the results reported by Toverud (1977) are reproduced in Figure 13.9. Puranen (1977) compared data from such till fabric studies (which is rather laborious) with results obtained by simple measurements of the anisotropy of magnetic susceptibility in oriented till samples. He showed that the estimated magnetite grain orientation in most cases agreed with grain orientation determined by conventional orientation analysis. Puranen also found that measurements of the magnetite content or bulk susceptibility of till could be used to trace magnetite dispersion trains from a bedrock source, and thus may prove to be a valuable method for other aspects of glacial transport studies.

Syngenetic Geochemical Dispersion Patterns in Glacial drift

During glaciation chemical elements were (a) released from their preglacial locations; (b) transported by various mechanisms a short or long distance depending on the circumstances; and (c) deposited at a postglacial position in glacial drift. The resulting geochemical dispersion patterns can be classified according to the type of glacial drift in which they occur. In the following pages various types of syngenetic geochemical dispersion patterns are grouped into (1) anomalies in till, and (2) anomalies in stratified drift.

Syngenetic Anomalies in Till

Till is the most common glacial sediment used for drift prospecting because according to Shilts (1975b):

1. Till is the most widespread type of glacial drift;
2. till sheets can easily be related to specific directions of ice movement;
3. unweathered till usually represents groundup, fresh bedrock;
4. till is easily recognizable; and
5. dispersal trains are larger than the source of the trains.

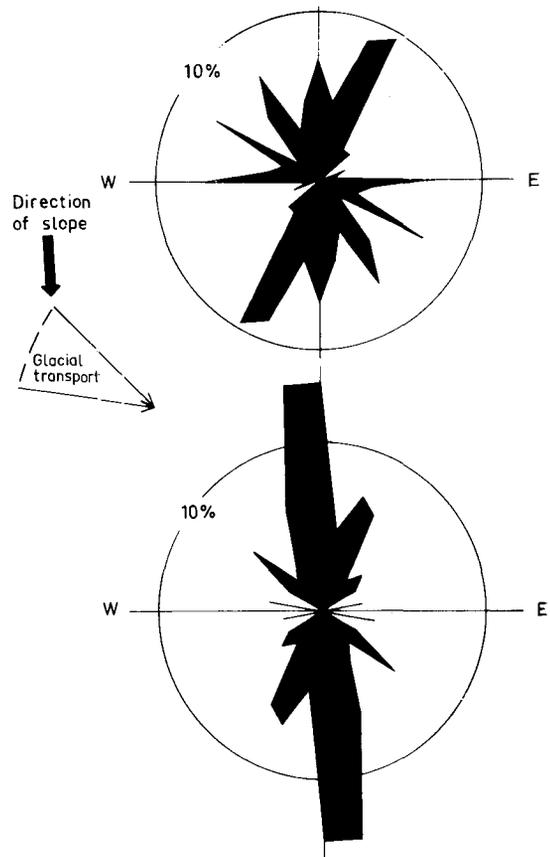


Figure 13.9. Examples from northern Sweden of diagrams showing particle orientation in till. After Toverud (1977).

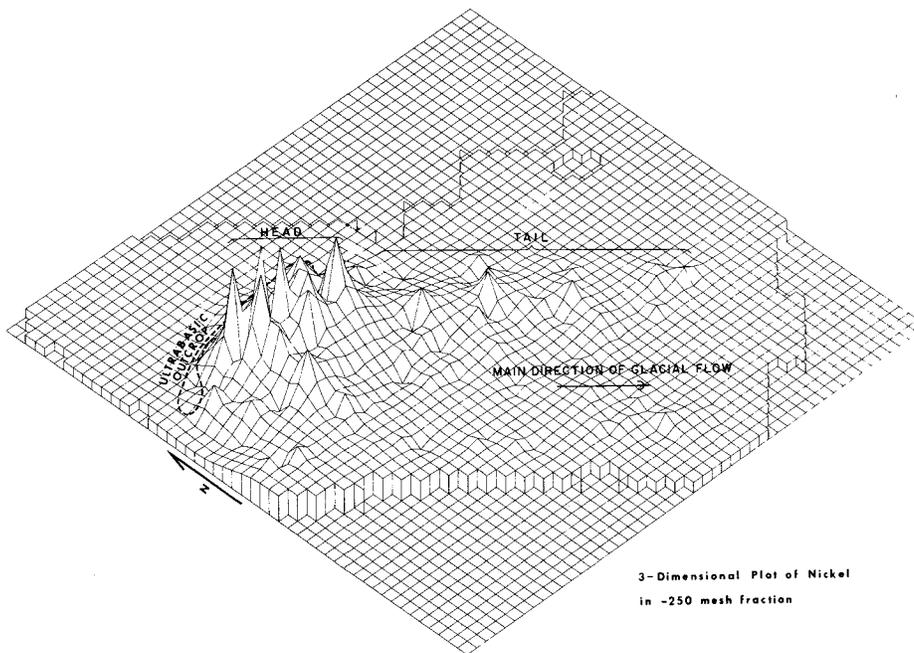


Figure 13.10. Perspective plot of nickel values in the $< 64 \mu\text{m}</math> fraction of surface till in the Thetford Mines ultrabasic indicator train, showing graphically the head and tail regions of dispersal. The tail is traceable for about 60 km in the main direction of glacial flow. After Shilts (1976).$

Traditionally basal till has been most extensively used as a sampling medium but, as pointed out by Shilts (1976), ablation till could in some cases also be used provided sampling of the same type of material is possible throughout the survey area.

It is important at an early stage in a mineral exploration program to recognize if one is dealing with a glacial fan. Misinterpretation of geochemical results has occurred all too often in the past because of the inability of geologists to recognize such dispersion patterns. DiLabio (1976) has cited one example of such an error which led to the Icon copper deposit north of Chibougamau, Quebec being missed. The ore zone lay undetected for nine years after the initial geochemical soil survey and drilling program was done on the down-ice extension of a geochemical copper indicator fan (i.e. the tail). Two wrong assumptions were made in the interpretation of the geochemical results: (1) It was assumed that the copper soil anomaly was in place when in fact it formed part of a dispersal train; and (2) It was assumed that the source of the anomaly had a steep dip when in fact it was a shallow dipping orebody. In time Icon Sullivan Joint Venture mined some 47 400 tons of copper from this deposit.

In the Thetford Mines area, Quebec, Shilts (1975a, 1976) has shown that a complete syngenetic geochemical indicator train exists. Nickel and chromium values in the minus $62 \mu\text{m}</math> fraction of surface tills from the down-ice area of ultrabasic outcrops show clearly defined anomalies with developed heads and tails, the tail for nickel being traceable for about 60 km in the main direction of glacial flow (Fig. 13.10).$

Garrett (1971), Gleeson and Cormier (1971), Skinner (1972) and Shilts (1976) have described situations in the Abitibi clay belt of Ontario, where glaciolacustrine sediments overlie lodgment till. Garrett (1971) sampled lodgment till under glaciolacustrine deposits at the Louvem deposit, Val d'Or, Quebec. The heavy mineral concentrates from the 80-230 mesh ($64\text{-}180 \mu\text{m}</math>) fraction of the till were analyzed for copper and zinc. Both in horizontal plan and in a vertical section (Fig. 13.11), an anomalous dispersal train occurs in the direction of the regional ice movement. Close to the subcrop of the ore, the anomalous levels for copper and zinc are found at the base of the till, further down-ice the anomaly rises to higher levels in the till.$

In Sweden, Brundin and Bergström (1977) collected C-horizon till samples from roadcuts at 1-3 km intervals (sample density about 1 per $10 \text{ km}^2</math>). Heavy minerals from the till samples were preconcentrated in the field, the concentrates were later investigated mineralogically and analyzed for 27 metals. The distribution pattern of the tungsten in the concentrates (Fig. 13.12) was similar to the results obtained from scheelite grain counting; both analyses disclosed "tail" anomalies greater than $100 \text{ km}^2</math>. Follow-up work, using the same field techniques and a sample density of 3-5 samples per $\text{km}^2</math>, delineated a strong "head" geochemical tungsten anomaly within which some 200 scheelite-bearing surface boulders were found. Further exploration work outlined scheelite occurrences in the bedrock. These are now being evaluated.$$$

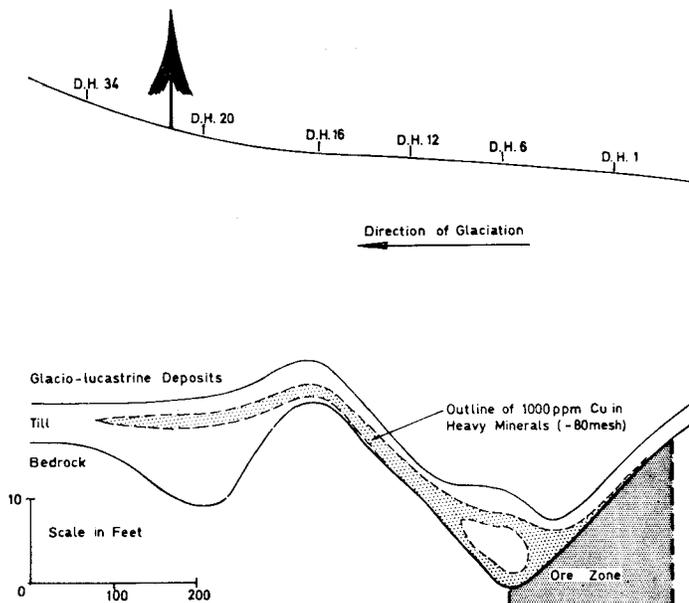


Figure 13.11. Vertical profile of glacial dispersal train in till under glaciolacustrine deposits at Louvem, Val d'Or, Quebec. After Garrett (1971).

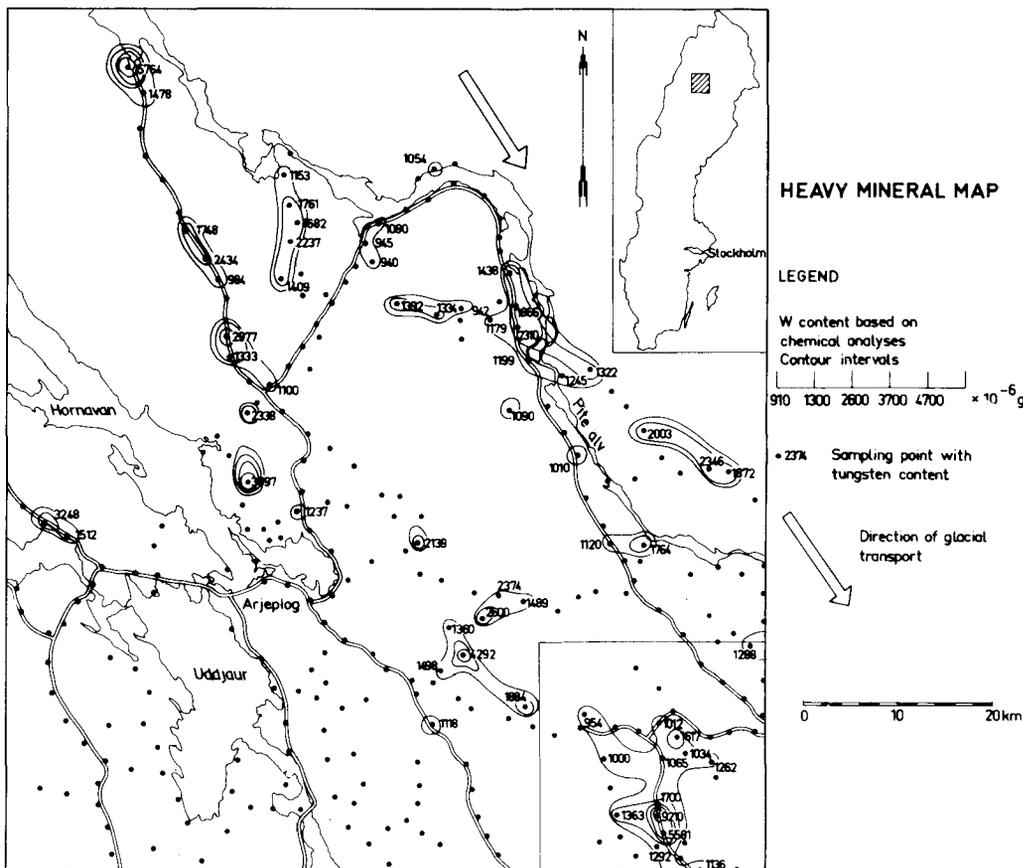


Figure 13.12.

Tungsten content of the 20-500 μm fraction of till from the Østansjö region, Sweden. Figures are given only for anomalous sampling sites. After Brundin and Bergström (1977).

From Finland, Lindmark (1977) has reported results for scheelite in till which agree well with those from Sweden. Till samples were collected along profiles more or less at right angles to the ice direction and from depths that varied between 0.5 and 2.0 m. Scheelite grains from heavy mineral concentrates were identified using an ultraviolet lamp and grain counts were made. The resulting map, showing the distribution of scheelite in the till (Fig. 13.13), outlined a scheelite anomaly approximately 2 km long and 300 m wide, which led to the discovery of a scheelite source near the head of the anomaly.

Syngenetic Anomalies in Stratified Drift

Glacial debris found associated with stratified drift, which includes ice-contact stratified drift and proglacial sediments, generally does not reflect the composition of local bedrock. Therefore such types of glacial sediments should normally not be used to define syngenetic dispersion fans at the detailed level. However, sometimes ice-contact stratified drift is derived from reworking of till of fairly local origin so that it may reflect the local geology. Holmes (1952) showed, for example, that kame terraces in central New York State are composed of material derived only a few kilometres up-ice. Nichol and Björklund (1973) cite an example from south-central British Columbia adjacent to the Valley Copper deposit where the bulk of the material in kame terraces along the valley sides consists of local bedrock found upslope. One of these ridges has a copper content locally exceeding 1 per cent in the minus 80 mesh (180 μm) fraction and greater than 0.1 per cent over a considerable area. The source of the copper anomaly is not known.

Eskers are an important type of ice-contact stratified drift which has been used in reconnaissance and semireconnaissance geochemical surveys. In Finland, Virkala

(1958) showed that about 60 per cent of the esker material has been transported less than 5 km. The nature of esker sedimentation and the use of Canadian eskers as a sampling medium in geochemical exploration have been studied by Lee (1965, 1968), McDonald (1971), Shilts (1973b), Shilts and McDonald (1975), and Banerjee and McDonald (1976). On the Munro esker in the Kirkland Lake - Larder Lake gold belt of Ontario, Lee (1965, 1968) found that anomaly peaks for counts of diagnostic mineral grains were displaced 5-13 km downstream from the source.

In the Abitibi Clay Belt of Quebec, Cachau-Herreillat and La Salle (1969) sampled 165 km of the Matagami esker at 0.8 km intervals. They found that metals generally were leached from the minus 80 mesh (180 μm) fraction of the weathered near-surface material and that higher trace metal values could be obtained from unoxidized samples at depth (3-4 m). In the latter, higher base metal values, especially for copper, correlated with the presence of volcanic belts crossed by the esker. At one location lead, zinc, silver and gold anomalies were found near known gold-silver occurrences.

Shilts and McDonald (1975) demonstrated that a dispersal train in till can serve as a source for a "fluvial" dispersal train in an esker. Studying the distribution of clasts and trace elements in the Windsor esker, Quebec, which intersects a dispersal train of ultrabasic rocks, they found that the downstream fluvial transport of material may be in the order of 3-4 km. They concluded that hydraulic sorting as well as lateral and vertical variation of depositional environments greatly complicate the study of dispersal of trace elements and clasts in an esker. Shilts (1976) considered that where till (the first derivative of bedrock) is present over wide areas, it is a superior sampling medium to eskers (which may be second derivatives) that traverse only narrow portions of the terrain.

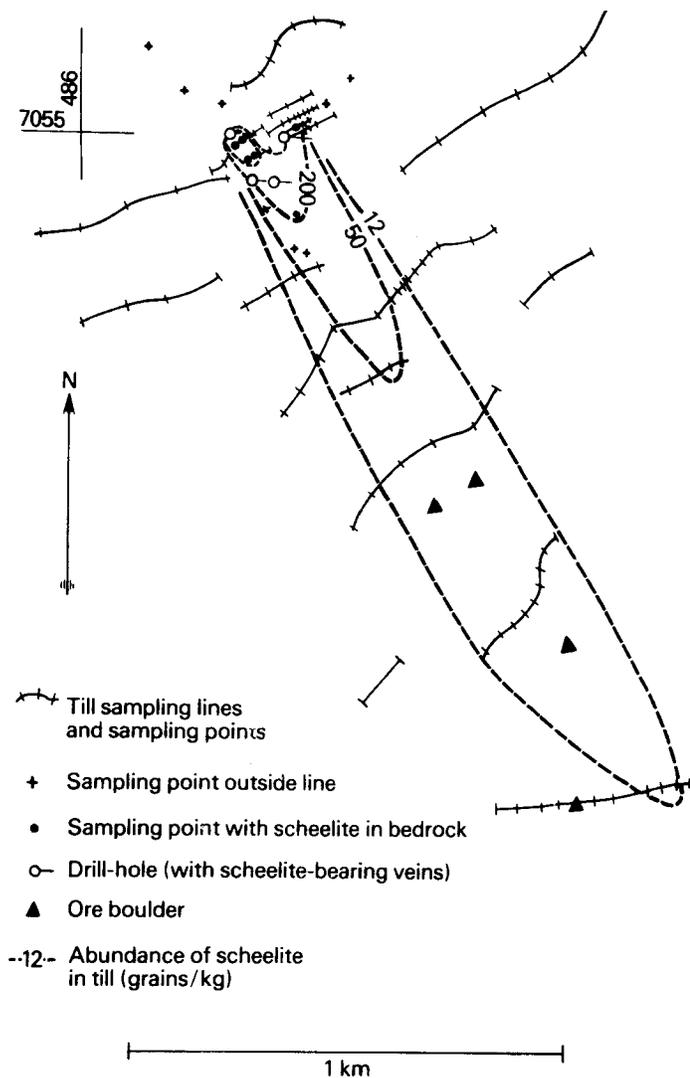


Figure 13.13. Scheelite grains in boulders and till at Tastula, Finland. After Lindmark (1977).

However, where eskers are abundant and especially in areas covered by extensive glaciolacustrine deposits (e.g. Abitibi Clay Belt), eskers provide a unique medium for sampling where they protrude through these sediments. Investigations to date show that eskers may give a good indication of the lithology and geochemistry of the bedrock on a reconnaissance scale.

The materials which make up other types of stratified drift, like glaciolacustrine and glaciomarine deposits, are distal in origin and cannot be expected to produce syngenetic anomalies. Low base metal values in clay were noted by Gleeson (1960) over Mattagami Lake Mines, Quebec where the Zn-Cu-Pb deposit was covered by 6-10 m of glaciolacustrine clays and silts. Similarly, a uniformly low base metal concentration has been noted in varved clays in the Cobalt area, Ontario even directly over the Ag-Ni-Co-As veins (Boyle, 1967). Similar findings have been reported from the Timmins (Fortescue and Hornbrook, 1967) and Uchi Lake (Davenport, 1972) areas of Ontario. In Finland, Kauranne (1976b) has reported little variation in metal concentration between glacial clays over mineralization and clays over barren bedrock.

EPIGENETIC DISPERSION

Epigenetic dispersion processes can be grouped into two classes: (1) Processes involving postglacial weathering of the bedrock as well as transportation and deposition of the products of this weathering. In this connection glacial drift could be considered as a more or less indifferent sheet of overburden responding to the transportation and deposition processes; (2) Postglacial processes leading to modification or reorganization of syngenetic dispersion patterns that already exist in the glacial drift.

In principle, processes (1) and (2) have been occurring simultaneously since the formation of the glacial drift, the result being combined syngenetic and epigenetic dispersion patterns in the drift. However, sometimes the epigenetic dispersion processes may have been negligible: such cases have been treated in the preceding section. Occasionally, the effect of the epigenetic processes may dominate over that of the syngenetic processes. Such cases are discussed in this section. Occurrence of complex syngenetic and epigenetic patterns, probably the most common situation, will be treated in the following section.

Dispersion of the products of postglacial weathering of the bedrock can be grouped into (1) hydromorphic dispersion, (2) electrochemical dispersion and (3) gaseous dispersion.

Hydromorphic Dispersion

Sulphide and other mineral deposits in the bedrock will undergo postglacial weathering some products of which are dissolved in groundwaters. These soluble compounds may later be precipitated, complexed or absorbed in the soil, and, in time, there will be a build-up of metal in the regolith. It has been shown that such processes may be significant for the concentration and distribution of metals in soil even in very cold climates. In subarctic Canada for example, formation of gossans over sulphide deposits is a common feature. Two Scandinavian examples of hydromorphic dispersion are referred to below.

1. The Tverfjellet massive sulphide deposit, Hjerkin, Norway, Vokes (1976) is located at an elevation of 1000 m above sea level in an area with a mean temperature of 0°C and an annual precipitation of 300 mm. Despite the cold and dry climate (discontinuous permafrost), the deposit has suffered intense postglacial chemical weathering as indicated by strong subsidence phenomena in the subcrop area, very low pH values and high metal contents in the drainage, as well as extensive precipitation of secondary iron oxides downslope in the tills. (Bølviken, 1967; Mehrtens and Tooms, 1973; Mehrtens et al., 1973; Bølviken and Låg, 1977.)
2. At Snertingdal near Gjøvik, Norway there is a lead deposit of the Laisvall-Vassbo type (galena disseminated in quartzitic sandstones) (Bjørlykke et al., 1973). The mineralization which subcrops under 1-2 m of till, is about 2 km long and contains up to 1 per cent Pb over a width of 15-20 m. The lead content of the soil samples shows an anomaly displaced downhill from the lead mineralization (Fig. 13.14). Ice direction is towards the southeast (Sveian, 1979) i.e. uphill, and the anomaly must, therefore, be hydromorphic. This is also demonstrated in Figure 13.15, which shows that directly over the upper (southern) zone of mineralization there is more Pb in the deepest part of the soil than in the topsoil, while farther down the hillside the Pb is enriched in the topsoil.

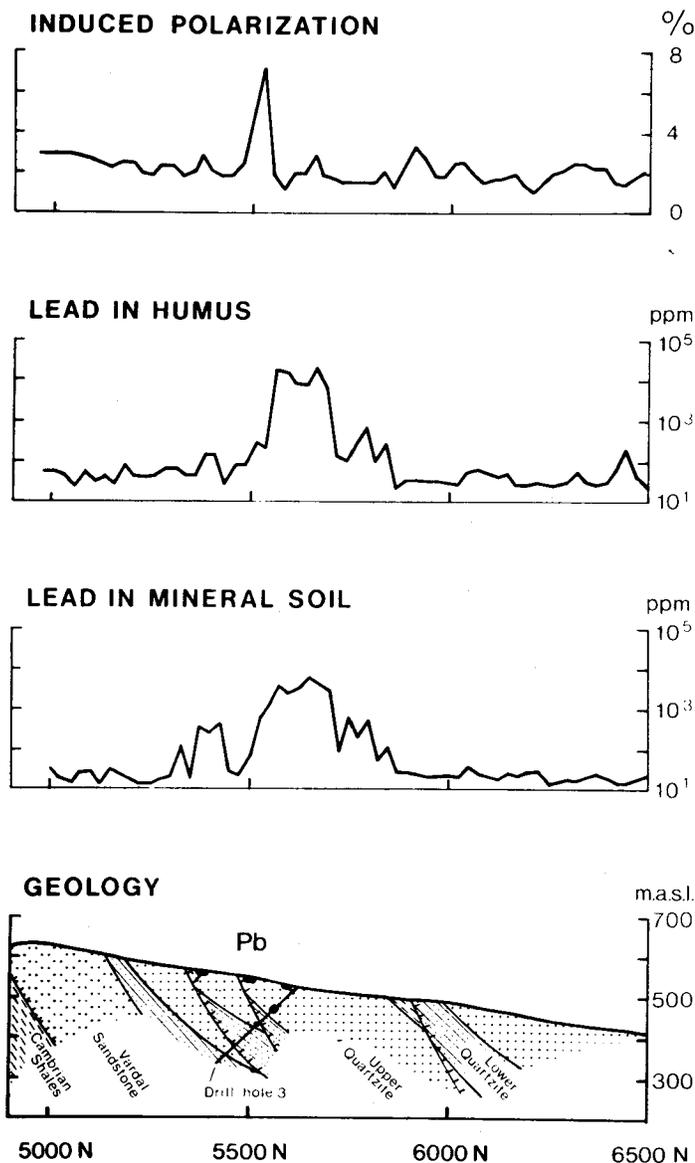


Figure 13.14. Geology, lead in mineral soil (B_2), lead in humus, and induced polarization results, profile 4900 W over the Snertingdal lead deposit, Norway. After Bjørlykke et al. (1973).

Humus plays an important role in the postglacial enrichment of heavy metals. If humus containing soils receive a steady supply of heavy metals, they may gradually become metalliferous and restrictive for natural plant growth, in some cases to the extent of being completely toxic, so that atypical vegetation or even patches of barren soil appear (Fig. 13.16) (Låg et al., 1970; Låg and Bølviken, 1974). Such patches, which may contain as much as 10 per cent of Pb and 5 per cent Cu in the top soil seem to be rather common in the vicinity of sulphide deposits in the hilly parts of Scandinavia, and can be used as a prospecting tool (Bølviken and Låg, 1977). In fact, a 30 million ton copper deposit was recently discovered at Kiruna, Sweden by drilling uphill from areas of natural metal poisoning (Lisbeth Godin, pers. comm.).

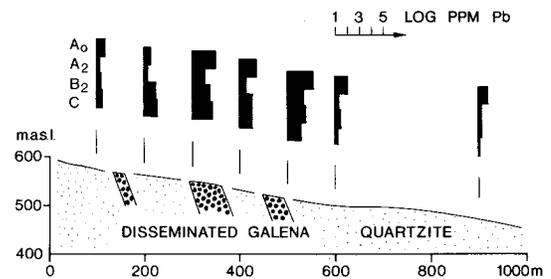


Figure 13.15. Lead values in different soil horizons at the Snertingdal lead deposit Norway, showing hydromorphic metal dispersion. General direction of glacial flow was towards the left (Sveian, 1979). Figure redrawn from Bølviken (1976).

In Figure 13.17, all the observed patches of natural lead poisoning at the Snertingdal lead deposit are plotted. Such a plot is equivalent to a geochemical map of the most intense hydromorphic anomalies in the root zone or humus containing part of the soil profile. It is based upon continuous visual observations, and is therefore fairly complete compared with ordinary geochemical map, showing results from samples taken at discrete sampling sites in a grid. A striking feature of Figure 13.17 is that the geochemical patterns of natural poisoning are very irregular and patchy, the poisoned areas being of varying sizes, elongated, fanshaped etc. This indicates that in searching for hydromorphic anomalies through soil sampling in glaciated terrain, instead of sampling, over a regular grid it may be more fruitful to sample sites where metals are likely to concentrate i.e. (1) sites selected on the basis of vegetation characteristics; (2) at places where the slope changes (3) in seepage areas; (4) in depressions, and (5) at the edges of bogs.

Electrochemical Dispersion

Based upon the existence of self-potential (SP) anomalies associated with ore deposits (see for example Sato and Mooney, 1960; Logn and Bølviken, 1974), an electrochemical model for element dispersion has been suggested (Bølviken and Logn, 1975). The redox potential (Eh) of groundwaters is high near the daylight surface and supposedly low at depth (Bølviken, 1978), therefore vertical Eh gradients must exist in the upper lithosphere. A good electrical conductor, such as an ore deposit penetrating such Eh gradients, will take on the character of a dipole electrode becoming an anode at depths and a cathode near the surface. The system ore deposit/country rock/groundwater consequently can be considered as a galvanic cell where natural electric currents flow carried by electrons in the orebody and by ions in the electrolyte formed by the groundwater. Positive current direction will be downwards in the orebody and upwards in the surroundings. Since overburden generally has better electrical conductivity than bedrock, the ionic current will flow more or less vertically in the country rock and horizontally in the overburden, the current density being highest in the overburden just above the subcrop of the hanging wall of the deposits (Fig. 13.18). Ions will move along the current paths and if during their migration they meet retaining agents like fine grained overburden, Fe-Mn hydroxides, or humus, they may be absorbed or complexed and interchanged for more mobile ions which in turn are released to the electrolyte.



Figure 13.16.

An area of naturally heavy-metal poisoned soil at the Mosbergvik lead zinc deposit, Balsfjord, Norway. Photo Arne Bjørlykke. GSC 203492-L

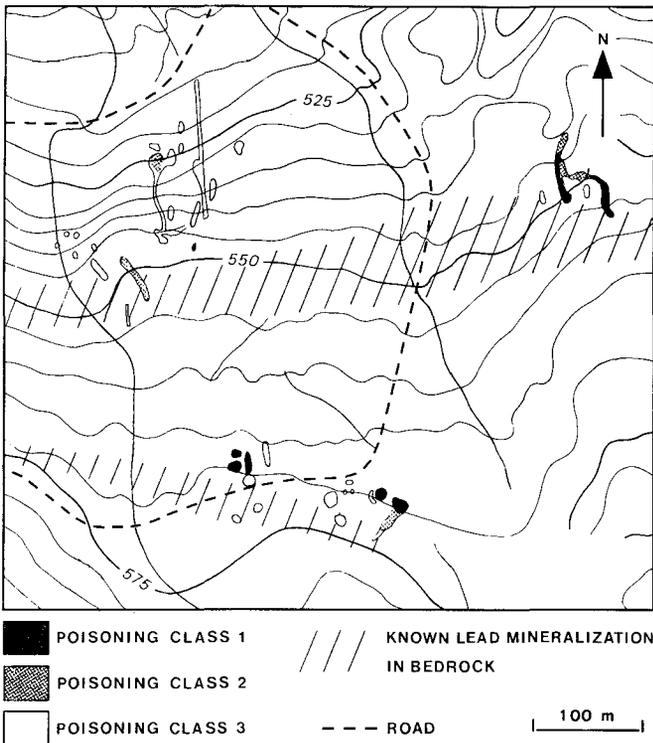


Figure 13.17. Patterns of naturally lead-poisoned soil and vegetation at the Snertingdal lead deposit, Norway. Increasing degrees of poisoning from class 3 to 1 corresponds to lead concentrations in the upper 5 cm of the soil of approximately 1-3 per cent. After Låg and Bølviken (1974).

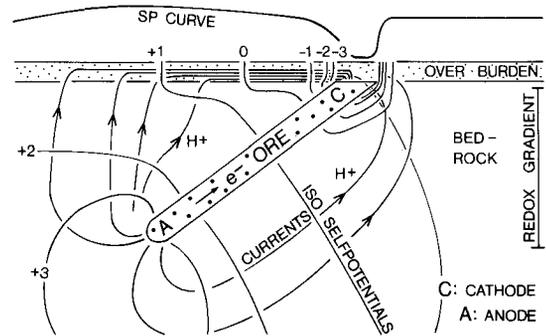


Figure 13.18. Principles of electrochemical dispersion. Due to vertical redox potential gradients in the upper lithosphere an electrically conducting orebody and its surroundings can be considered as a galvanic cell, with current flow carried by electrons in the orebody and ions in the groundwater.

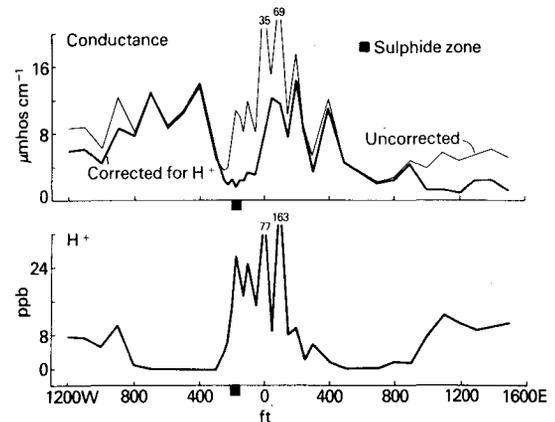


Figure 13.19. Distribution of H^+ and conductance in slurries of B-horizon soils in water (1 per cent strength) from a profile over the Armstrong A deposit, New Brunswick. After R.E. Uthe, quoted by Govett and Chorck (1977).

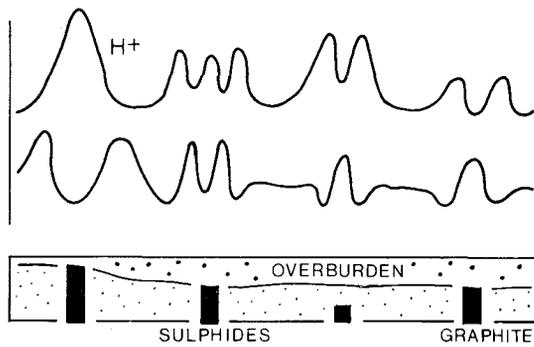


Figure 13.20. Schematic illustrations of H^+ and conductance in surface soils on glacial drift overlying sulphide and graphite conductors at various depths. After Govett (1976a).

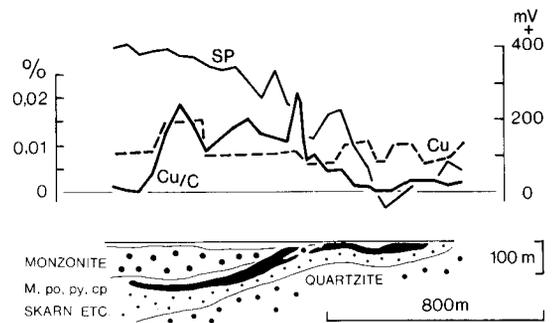


Figure 13.21. Values for copper and ratio copper-to-organic carbon in humus samples and self potentials from a profile over the Laurinoja copper-bearing iron deposit, Finland. After Nuutilainen and Peuraniemi (1977).

Field and laboratory data which seem to corroborate this model have been provided by a number of authors (Bølviken and Logn, 1975; Govett, 1973, 1974, 1975, 1976a; Govett and Chork, 1977; Govett and Whitehead, 1974; Govett et al., 1976; Juve, 1977; Kokkola, 1977; Nuutilainen and Peuraniemi, 1977; Sveshnikov, 1967; Shvartzev, 1976; Thorner 1975a, 1975b). In Canada Govett and Chork (1977), measured conductivity and H^+ in soils over several sulphide deposits and found that soil slurry conductivity seems to correlate with the content of organic carbon in the soils as well as with the localization of mineralization. Govett (1976a) suggested that deeply buried or blind sulphide deposits may be found by (1) a "rabbit ear" H^+ anomaly of two lateral peaks on the sides of a central trough (deep deposit), or an H^+ anomaly of three peaks separated by troughs (moderately deep deposit), (2) conductivity anomalies which are the inverse of the H^+ anomalies and (3) distribution patterns of metals generally similar to those of conductivity (moderately deep deposits) or similar to those of H^+ (very deep deposits) (Fig. 13.19, 13.20). Govett stated that wherever there is a detectable SP anomaly at the surface there will be an anomalous distribution pattern of H^+ in the soils. Nuutilainen and Peuraniemi (1977) also indicated that the content of organic carbon in the soil may possibly influence the development of electrochemical dispersion patterns. They collected humus samples from the A₀ soil horizon over known mineralization and analyzed the samples for sodium pyrophosphate soluble base metals and organic carbon following a method described by Antropova (1975). In a profile over the Laurinoja occurrence which is a skarn zone containing an average of 42 per cent Fe, 2.8 per cent S and 0.4 per cent Cu, the measured copper values in the humus show no anomalies over the mineralization. However, when the ratio copper/organic carbon is plotted, a distinct anomaly occurs over the deposit (Fig. 13.21). This anomaly has three outstanding features: (1) The anomaly occurs over the entire inclined part of the deposit, including its deepest extension which is covered by approximately 120 m of barren monzonite and 20 m of till; (2) there is no anomaly above the flat lying and Cu-poor part of the deposit; (3) a pronounced SP anomaly coinciding with the geochemical anomaly shows that the direction of the positive natural current dominantly is from the projection of the deepest part of the deposit towards the

outcrop area. Following an electrochemical interpretation (see Fig. 13.18), copper ions are suggested to move from the anodic area more or less vertically in the bedrock and into the overburden where the ions are trapped when they meet humus in the upper and presumably best conducting part of the soil. The flat lying part of the deposit does not produce an anomaly because (1) its copper content is low, and (2) it does not penetrate significant redox gradients.

Another observation indicating that electrochemical dispersion patterns develop in glacial drift above a sulphide deposit, is made by Juve (1977). In 1975, during the preparation for the open-pit mining of the Stekenjokk massive sulphide copper deposit in Sweden, the overburden was stripped off. In the till just above the subcrop of the ore, several tons of native copper were found occurring as a postglacial cement precipitated between the rock fragments and mineral grains of the till. One may wonder why native metals such as Cu, which is unstable under normal atmospheric conditions, can form in glacial drift above a sulphide deposit in an environment normally expected to be acidic and oxidizing. The primary mineralization at Stekenjokk consists of banded, massive to disseminated iron, zinc and copper sulphides lying conformably at the transition between acid pyroclastic rocks and black shales (Juve, 1974). Both ores and shales are highly conductive. The mineralization reaches great depths (700 m below surface), thus penetrating relatively large gradients of the earth's redox potential field. A well-defined surface SP anomaly was found above the deposit prior to the mining activity (Ø. Logn, pers. comm). Probably the cathodic potential of this long sulphide-carbon electrode was low enough to discharge copper ions from groundwater percolating in the zone of the subcrop of the ore during postglacial time. More recently native copper has also been discovered in till over the subcrop of the nearby Joma pyrite deposit in Norway (L.B. Løvås, pers. comm.). It appears that occurrences of native copper may be fairly common in glacial drift above the subcrops of certain massive sulphide copper deposits.

It should be noticed that the empirical data obtained up to now provide indications only and no proof of the existence of electrochemical dispersion patterns in the overburden above mineral deposits. This subject, geoelectrochemistry,

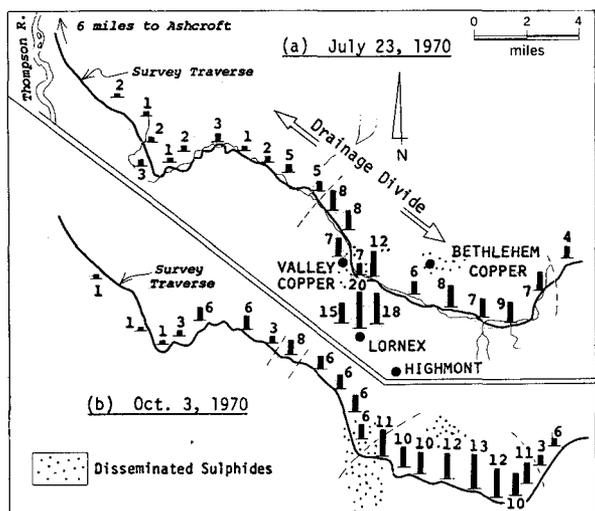


Figure 13.22. Results of SO₂ measurements (in ppb) in soil gas at two different dates from a traverse over the Lornex porphyry copper orebody, Highland valley, British Columbia. (Rouse and Stevens, written comm.).

warrants further research, especially in glaciated areas where conditions might have been such (low temperature, existence of clay layers etc.) as to inhibit the formation of significant geochemical anomalies in the soil by glaciation, oxidation or other commonly accepted processes. Under these circumstances glacial drift could be considered as a blanket of more or less neutral background material covering the bedrock source. Possible electrochemical patterns in such a neutral blanket would probably be easier to detect than analogous patterns in residual soil, where the effects of oxidation nearly always dominate over most other modes of dispersion.

Gaseous Dispersion

Release of vapours from metallic deposits does occur in nature largely due to: (1) some of the weathering products of sulphide minerals e.g. H₂S and SO₂ are gases; (2) mercury and several of its compounds have high vapour pressure at low temperatures and (3) two of the radioactive disintegration products of uranium – radon and helium – are gases. Vapour surveys are a relatively recent development in geochemical exploration. In glaciated areas they hold much promise in being able to define epigenetic geochemical anomalies over metal deposits covered by thick drift. They can also be used to trace glacial dispersion trains. The subject has been reviewed by Kravstov and Fridman (1965), Bristow and Jonasson (1972), McCarthy (1972), Ovchinnikov et al. (1973) and Dyck (1976). Most soil-gas surveys carried out to date in glaciated areas have involved analyses for sulphur compounds, mercury, and radon as well as the use of sniffing dogs.

Sulphur Compounds

Rouse and Stevens written comm. reported on the use of sulphur dioxide gas in the detection of sulphide deposits. In a case history study of the Guichon Batholith in the Highland Valley area of British Columbia, they noted that their highest readings from soil gas were obtained over the Lornex porphyry copper orebody which in places is covered by more

than 60 m of permeable till. Twelve months after Rouse and Stevens did their survey, Bethlehem Copper announced the discovery by diamond drilling of the J-H orebody just south of Bethlehem Copper's open pit. The new deposit is covered by up to 120 m of till. Background for SO₂ was about 2 ppb, and values over the copper deposits ranged from 7 to 20 ppb (Fig. 13.22).

Measurements of SO₂ in soil gas were made by Meyer and Peters (1973) over several sulphide zones covered by thin till in Newfoundland. They found that in this cool temperate climate there appears to be small but detectable soil-gas anomalies (1.9-7.4 ppb SO₂) over these deposits. The best responses were obtained in warm dry weather, the responses were considerably subdued when measurements were made on cool days.

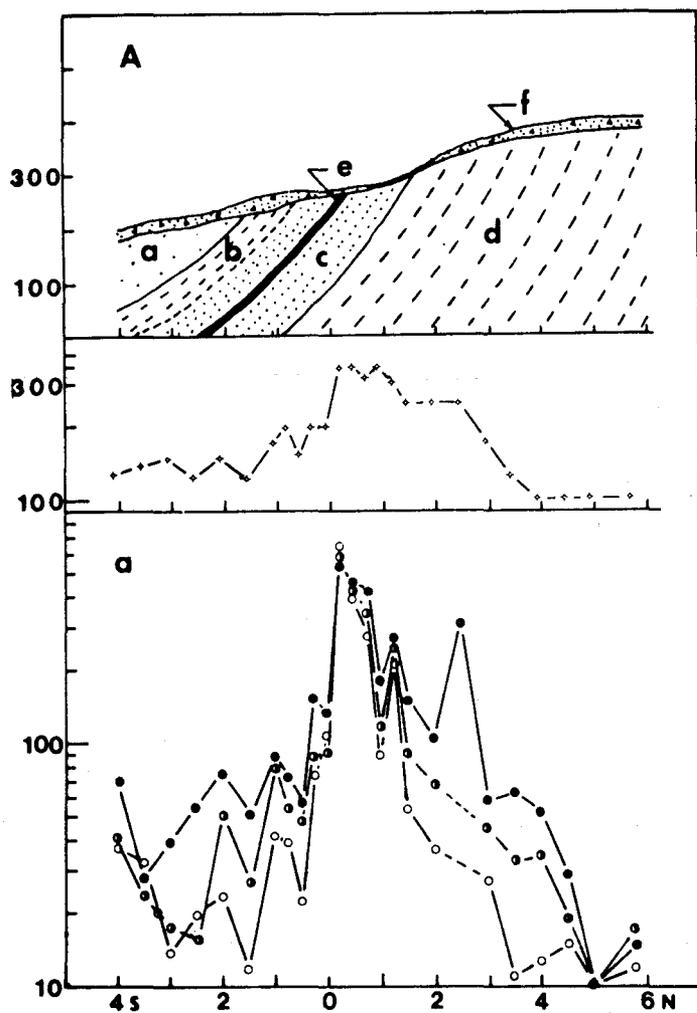


Figure 13.23. Geology (top), gamma-ray activity at the surface (middle) and alpha activity in soil gas (bottom), from a traverse across a subcrop of conglomerate ore at the Rio Algom Quirke mine, Elliot Lake, Ontario. Letter d denotes main conglomerate ore. Alpha activity in soil gas is given for three successive one minute counting intervals represented by dots, half-filled circles, and plain circles, respectively. After Dyck (1969).

Mercury

There are few published reports on soil-gas surveys for mercury in glaciated terrain. Most successful applications of this technique have been confined to arid areas (McNerney and Buseck, 1973). However, Boyle (1967) determined mercury in soil horizons over known mineralization at Cobalt, Ontario and Azzaria and Webber (1969) reported results from various soil traverses in British Columbia and Quebec. Preliminary work by Jonasson (1972) and Bristow (1972) over a Cu-Ag-Hg prospect near Clyde Forks, Ontario proved promising. Soil-gas mercury showed anomalous levels along the strike of mineralized veins.

Meyer and Evans (1973) completed exhaustive studies on mercury in glacial drift over a zinc-lead-cadmium deposit at Keel, Eire. They concluded that mercury levels in soil gas reflected the general pattern found for mercury in soil. The content of mercury vapour in soil gas was enhanced in warm, dry weather. Maximum mercury values in soil gas were found in 7 m thick well drained tills over mineralized faults and in 3 m thick poorly drained soil, over a preglacially decomposed zone of subeconomic sulphides.

Radon

Radon soil-gas surveys have been used successfully by several workers to help locate uranium mineralization under glacial cover. Dyck (1972) reviewed the use of radon methods in Canada. Wennerwirta and Kauranen (1960) reported on their work in Finland where radon soil-gas surveys were able to detect uranium mineralization covered by up to 1.5 m of till. Michie et al. (1973) found that alpha activity in soil-air was useful in the assessment of radioactive anomalies in northern Scotland, where bedrock is covered by several metres of glacial drift and 1 to 8 metres of peat. Dyck (1968, 1969) obtained positive results in his test work using soil-gas radon in sandy moraine over known uranium deposits in the Bancroft and Elliot Lake areas, Ontario (Fig. 13.23). Later in the Bancroft region Dyck et al. (1976) showed that meaningful results for radon could be obtained from snow cover over frozen ground. Morse (1976) worked in the same region and found that soil-gas radon is an effective exploration tool for uranium exploration in areas covered by relatively thin, permeable drift. Beck and Gingrich (1976) completed an alpha-track orientation survey over the "N" zone of the Cluff Lake uranium deposit in Saskatchewan; their results indicated that the survey was capable of outlining buried ore zones where till thickness ranged up to 20 m. Recently soil-gas radon surveys have been successful in delineating uranium mineralization covered by 5-15 m of permeable till in southwestern Quebec. (Pudifin, pers. comm.).

Dogs in Prospecting

The use of dogs to smell out sulphides was first tried by Kahma (1965) and his coworkers at the Geological Survey of Finland. The vapours detected by the dogs are sulphur dioxide, hydrogen sulphide and carbonylsulphide (Kahma et al., 1975). Brock (1972) reported the results of experiments with dogs in Canada and Orlov et al. (1969) have mentioned their use in the USSR. Alsatian dogs are most commonly used, and when trained properly they can detect sulphide-bearing boulders in till more than one metre below surface.

Nilsson (1971) described the training and use of prospecting dogs at the Geological Survey of Sweden. The dogs are bred and trained in the Kennel School of the Swedish Army. Male dogs are best fitted, but the individual qualities of different dogs vary greatly. Training begins at 1-2 years of age. Four months of basic training on snow in the winter is

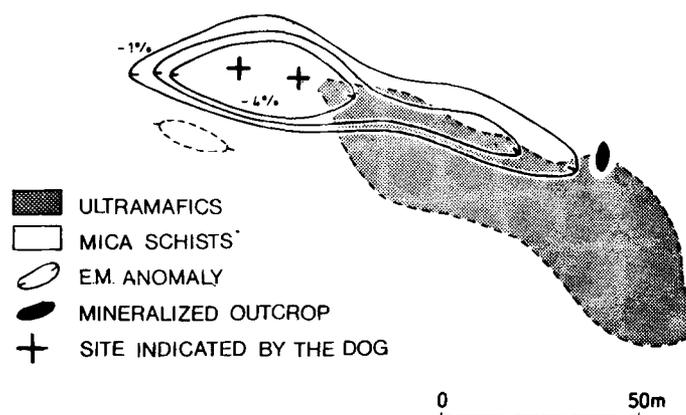


Figure 13.24. Sites where dog-indicated sulphide-mineralization occurs in bedrock under 2m deep overburden, Pielavesi, Finland. After Ekdahl (1976).

followed by about two months of practical field training on bare ground, at the end of which period the dog is normally working satisfactorily. Full effectiveness is generally achieved in the second summer of field work. A healthy well trained dog can work for about 8 hours a day with occasional rests.

Ekdahl (1976) has reported on a detailed investigation using a dog in an area where an outcrop of weakly sulphide-mineralized basic rock was known. On the southern side of this outcrop the dog displayed heightened interest in two places. Geophysical measurements revealed an electromagnetic anomaly over the same area (Fig. 13.24). Three trenches were dug to determine the cause. Disseminated pyrrhotite and chalcopyrite was found in a highly weathered horizon 1-2 m thick. The dog had discovered the mineralization through till 1 m thick overlain by sand and clay also 1 m thick.

COMBINED SYNGENETIC AND EPIGENETIC DISPERSION

Postglacial weathering of glacial drift, modifies original syngenetic dispersion patterns. The distribution of chemical elements presently found in the soil is, therefore, the result of a combination of syngenetic and epigenetic dispersion processes. Interpretation of such combined patterns requires an understanding of both types of processes leading to them.

Weathering of Glacial Drift

The most notable weathering process in the drift is soil formation, by which the upper part of the overburden is transformed into more or less horizontal layers that differ from each other in their properties and composition.

Five major factors govern soil formation (Jenny, 1941): (1) parent material; (2) relief; (3) climate; (4) biological activity, and (5) time. In glaciated areas the time available for the soil-forming processes has been short, and the climate generally cool. The chemical composition of the weathered part of the overburden of these areas is, therefore, often relatively closely related to the composition of the parent material. Depending on local conditions, various types of soil profiles may develop, of which podzols and tundra soils are the most important in glaciated areas (Robinson, 1949).

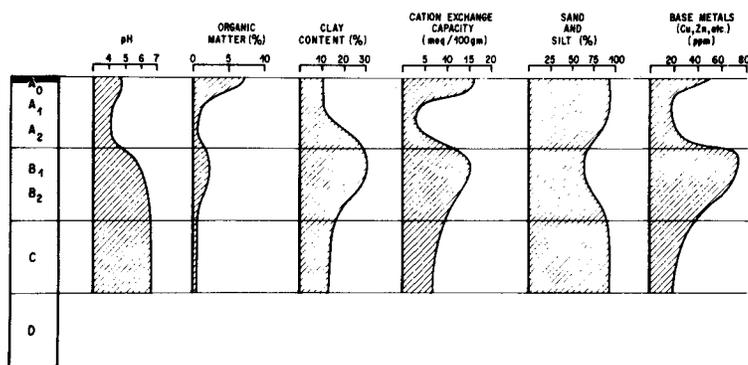


Figure 13.25. Variations in selected physical and chemical properties of different horizons of a generalized podzol profile. After Levinson (1974).

Characteristic features of the podzol profile are: (1) an upper zone rich in organic matter, (A₀-A₁); (2) a bleached layer leached of humus and black minerals, and (3) darker accumulation zones of sesquioxides (B₁-B₂). Variations in selected chemical and physical properties of a generalized podzol profile taken from Levinson (1974) are shown in Figure 13.25. Examples of heavy metal distribution are also given in Figure 13.15.

Shilts (1975a, b; 1976) stated that under Canadian conditions weathering has affected the upper 2-5 m of glacial drift in temperate areas and the active layer in areas of permafrost. In weathered drift, mineral grains derived from sulphide-type mineralization have largely been destroyed by oxidation. The soluble products of the oxidation are scavenged by other weathering products such as finely divided or precipitating hydrous oxides of Fe and Mn as well as clay minerals. If the composition and proportions of these scavenging phases do not change radically over an area, they should scavenge metal in proportion to the metal that was in the unweathered till in the form of sulphides. As a consequence, analysis of the clay fraction could be advantageous in delineating syngenetic geochemical dispersion patterns in till. Although combined syngenetic-epigenetic dispersion patterns are in fact obtained, they can, for interpretation purposes, be regarded as dominantly syngenetic. Many investigations indicate that combined syngenetic-epigenetic patterns are common in northern Europe (Kvalheim, 1967; Wennervirta, 1968; Jones, 1973, 1975, 1977; Kauranne, 1976a). Mehrtens et al. (1973) and Rice and Sharp (1976) reported on successful interpretations of combined syngenetic and epigenetic geochemical patterns in soils in Norway and north Wales. Nurmi (1976) used nitric and citric acid as extracting agents for heavy metals in anomalous and background till samples from Talluskanava Ni-Cu deposit, Tervo, central Finland, and calculated the percentage of syngenetic (glaciomorphic) metals using the formula:

$$\% \text{ Syngenetic Me} = \frac{\text{Me}_{(\text{HNO}_3)} - \text{Me}_{(\text{Cit. ac.})}}{\text{Me}_{(\text{HNO}_3)}}$$

He found that the Ni and Cu dispersions were mainly syngenetic, the hydromorphic component for both background and anomalous samples being of the order of 10 per cent,

while for Co the syngenetic component was approximately 45 per cent and 70 per cent in anomalous and background samples respectively.

A detailed study of the stability of various sulphide minerals in glacial drift at Fäboliden, northern Sweden has been carried out by Toverud (1977). Zn, Pb and to a lesser extent Cu were fairly easily extracted from the till (Table 13.1). Analysis of heavy and light fractions of the till revealed no general or marked differences between the metal content of the two fractions (Table 13.2). Pyrite and chalcopyrite were the only primary sulphide minerals preserved in the till, Zn, Pb and to some extent Cu occurred adsorbed to primary mineral grains or adsorbed in secondary minerals. Toverud concluded that the Cu anomalies in the area were dominantly clastic (syngenetic), while the Pb and Zn anomalies were mainly hydromorphically displaced i.e. combined epigenetic/syngenetic.

It should be remembered that the conclusions of Nurmi (1976) and Toverud (1977) are valid only for the particular environments in which the studies were conducted. These Finnish and Swedish investigations are from areas of dominantly intermediate and acid Precambrian rocks.

In the till over Carboniferous carbonate rocks in Ireland, base metals seem to form mainly syngenetic patterns, although some postglacial dissolution of sulphides apparently has occurred. Donovan and James (1967) studied the geochemical dispersion patterns in till overlying the Tynagh Pb-Zn-Ag-Cu-deposit in County Galway, Ireland. The distribution of high and low metal values in the till was found to be erratic and independent of depth and oxidation state of the till thus indicating a clastic (syngenetic) origin.

However, about 10-20 per cent of the total metals in the overburden was readily soluble, and each of the metals analyzed, (i.e. Cu, Zn, Pb, and Hg) was found to concentrate in the clay fraction, which also indicates a hydromorphic (epigenetic) origin for the metals. Postglacial oxidation processes were likewise indicated by the heavy metal contents of the solum, which were somewhat higher than those in the parent till material, the degree of variation within the solum generally being less than twofold. Under certain conditions, however, Cu, Zn, Pb and Hg were highly concentrated in peat near anomalous metal sources, concentrations being up to 0.19 per cent Cu, 7.8 per cent Zn, 0.42 per cent Pb and 0.42 per cent Hg. The areal distribution patterns of Pb, Zn and Cu in soils at a depth of 20-30 cm over the Tynagh deposit are narrow, elongated and stretch for a considerable distance from the orebody in the direction of the last ice movement. From Figure 13.26 it seems evident that the dominant component of the dispersion patterns of lead in soils at Tynagh is syngenetic. This is also the conclusion of Morrissey and Romer (1973), who have described the successful use of soil sampling in mineral exploration in glaciated regions of Ireland. Reconnaissance soil sampling is usually done at approximately 150 m centres on rhombic or square grids. Initial sampling depth generally varies between 23-46 cm. The minus 180 μm (80 mesh) fraction is normally analyzed for hot acid-soluble heavy metals. Any geochemical anomalies found by this procedure are followed up by ground investigation and by resampling on a tighter grid and/or at the maximum depth attainable manually. In promising areas, power augers are used for sampling overburden at depth.

Table 13.1
Cold extractable Cu, Pb and Zn in till fractions as
percentages of total content from section 2 at N. Fåbodliden. After Toverud (1977).

Sample No.	Depth m	Grain size mm	Total content, ppm Cu Pb Zn			Percentage extracted in cold																							
						8 M HNO ₃			4 M HNO ₃			1 M HNO ₃			0.50M Citr.acid			0.25M Citr.acid			0.05M Citr.acid			4M Am.acetate			1M Am.acetate		
			Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn			
103	0.5	0.06-0.20 <0.06	120 140	830 825	1555 1830	76 56	100 100	100 71	64 51	100 100	77 60	32 na	92 na	22 na	17 21	60 70	4 4	na 25	na 67	na 5	- 15	31 39	4 4	- -	51 52	3 3	- na	29 na	2 na
102	1.0	0.06-0.20 <0.06	45 70	340 560	530 655	100 97	100 100	100 93	84 70	92 100	79 73	53 50	97 100	32 32	- 33	71 71	7 10	- 32	65 68	9 10	- -	44 45	7 9	- -	44 41	5 5	- -	19 27	4 4
101	1.5	0.06-0.20 <0.06	75 100	300 650	930 1150	100 100	97 100	100 100	84 95	93 100	100 100	61 67	67 100	63 79	- -	53 60	15 17	- -	47 55	11 17	- -	37 40	7 11	na -	na 26	na 4	- -	20 17	4 2
100	2.0	0.06-0.20 <0.06	40 125	250 740	545 1400	na 80	na 100	na 100	na 71	na 100	na 100	na 59	na 93	na 86	- 26	64 57	33 26	- 23	56 57	28 24	- 18	44 38	18 17	- -	29 27	4 2	na -	na 16	na 3
099	2.5	0.06-0.20 <0.06	85 130	525 1315	770 1085	61 77	95 100	87 100	56 77	100 100	87 100	56 60	95 100	48 79	- 21	59 57	14 24	- 22	55 52	12 23	- -	34 30	9 16	- -	23 20	- 3	- -	18 14	- -
098	3.0	0.06-0.20 <0.06	115 195	805 1315	1065 1550	65 67	100 100	94 97	65 67	100 100	94 97	67 59	89 100	83 84	40 39	67 65	45 43	31 26	60 62	40 40	20 24	39 29	29 29	- -	39 37	4 3	- -	29 25	3 1
097	3.5	0.06-0.20 <0.06	195 205	615 880	1505 1655	62 68	98 100	100 100	56 63	98 100	93 100	49 49	89 95	54 57	23 21	60 50	21 18	21 20	57 52	19 18	22 18	44 41	15 15	- -	39 31	2 2	- -	31 23	- 2

Notes: na = not analyzed
- = below the detection limit

Results obtained from a zinc anomaly originally defined by manual sampling, were commented upon as follows:

"In most parts of the anomaly, including the area of greatest zinc concentration, power augering showed that zinc values in overburden diminished to background in the upper 1-2 m, but in a relatively restricted area near its centre and extending outside the geochemical anomaly delimited by shallow sampling, they were found to persist or increase with depth. At one point a value exceeding 50 000 ppm was recorded below 2 m of non-anomalous till, and a drillhole collared near this point intersected well-mineralized "suboutcrop".

Uranium seems to offer characteristic examples of combined syngenetic and epigenetic dispersion patterns in glacial drift. In Canada, Klassen and Shilts (1977) analyzed uranium in the clay fraction of till from perennially frozen terrain in the tundra. The till was sampled at a density of 0.5 samples per km². The resulting distribution patterns of uranium are of the order of hundreds of metres to hundreds of kilometres. A number of large bedrock source areas of uranium were detected, but the sample density was too small to disclose dispersion trains from some smaller zones of

potentially economic-grade mineralization. A more than 10 000 km² area of high uranium values appear north of Baker Lake (Fig. 13.27), parts of which are interpreted as being related to high background U values in the underlying volcanic rocks.

Bjørklund (1976a, b) found that the uranium content in till and stratified drift can be successfully used as a tool in the follow-up of U anomalies obtained by sampling lake sediments in Finland. His results suggest that the U anomalies in till are in part mechanical in origin and that the uranium in near surface samples has been partly leached out. Some observations leading to this conclusion are: (1) at the Paukkajanvaara area, the uranium content of the minus 0.06 mm fraction of the till did not coincide with the known fan of U-mineralized boulders (Fig. 13.28), (2) Strong U anomalies are present in the drift close to bedrock, but are generally lacking in the upper two metres of the till (Fig. 13.29), (3) Anomalous U values were found in stratified drift over U-mineralized bedrock (Fig. 13.29), (4) Good correlation exists between the U contents of the minus 0.06 mm fraction and that of the 0.06-0.25 mm fraction of drift sampled in a semiregional program.

Table 13.2

Contents of copper lead and zinc at various grain sites in light (<2.96 g/cm³) and heavy (>2.96 g/cm³) fractions of till. Section 2, N. Fäbodliden, Sweden. After Toverud (1977).

Sample No.	Depth (m)	Grain size (mm)	Sample weight (g)			*Light fraction (ppm)			**Heavy fraction (ppm)		
			Total	Light fraction	Heavy fraction	Cu	Pb	Zn	Cu	Pb	Zn
103	0.5	0.20-0.60	22.00	21.05	0.95	120	875	1370	100	1800	1600
		0.10-0.20	16.72	14.85	1.87	85	520	1140	100	1500	1300
		0.06-0.10	10.70	9.76	0.94	185	755	2030	70	1000	800
		<0.06	18.75	18.23	0.52	190	770	2025	80	1400	300
102	1.0	0.20-0.60	28.26	26.98	1.28	50	330	455	50	850	300
		0.10-0.20	13.68	11.93	1.75	30	200	285	40	1000	300
		0.06-0.10	5.78	4.90	0.88	25	170	215	40	800	300
		<0.06	2.54	2.22	0.32	30	205	275	50	850	300
101	1.5	0.20-0.60	26.94	25.93	1.01	35	225	400	120	1200	1200
		0.10-0.20	25.95	23.78	2.17	40	195	480	40	1100	300
		0.06-0.10	12.79	10.97	1.87	55	215	630	40	1100	300
		<0.06	11.84	11.31	0.53	110	385	1155	50	1400	300
100	2.0	0.20-0.60	33.45	32.00	1.45	25	205	315	60	900	790
		0.10-0.20	22.11	19.59	2.52	30	170	305	50	1100	300
		0.06-0.10	3.40	2.65	0.75	35	170	390	40	650	300
		<0.06	2.41	2.08	0.33	45	245	475	60	1100	300
099	2.5	0.20-0.60	28.74	27.68	1.06	40	425	430	250	1900	300
		0.10-0.20	28.43	25.88	2.55	40	240	370	60	1300	300
		0.06-0.10	17.19	15.85	1.34	65	625	550	50	2000	300
		<0.06	8.33	8.02	0.31	55	660	465	60	2000	300
098	3.0	0.20-0.60	25.17	23.79	1.38	95	735	1040	50	1000	490
		0.10-0.20	7.42	6.38	1.04	70	570	755	50	900	450
		0.06-0.10	2.47	1.76	0.71	65	515	650	50	1000	480
		<0.06	5.86	5.73	0.13	90	600	740	50	1300	300
097	3.5	0.20-0.60	15.06	12.27	2.79	160	535	1510	50	400	460
		0.10-0.20	4.76	3.72	1.04	120	405	1205	70	500	570
		0.06-0.10	2.25	1.76	0.49	105	425	920	70	700	520
		<0.06	0.67	0.60	0.07	140	950	1200	not analyzed		

Data obtained by optical emission spectrography,
 *direct reading spectrograph equipped with a tape machine,
 **registration on photo plate (Danielson 1968).

Humus as a Sampling Medium

Humus is dead organic matter, or more precisely is a decomposition product of organic origin that is fairly resistant to further bacterial decay. In glaciated regions, humus is a typical and almost ubiquitous constituent of the upper soil horizons. Where the climate is appropriate, organic deposits often accumulate in low lying or poorly drained areas forming bogs, swamps and muskegs due to a local low rate of plant decay in relation to plant production. Humus is capable of complexing practically all of the elements of the periodic table; in particular it forms strong compounds with heavy metals (Szalay and Szilagy, 1968; Szalay, 1974; Chowdhury and Bose, 1971 and Boyle, 1977). Therefore it is a geochemical sampling medium of great interest. In some cases the geochemical distribution patterns in humus are more or less purely epigenetic in relation to glaciation. Experience shows, however, that glacially dispersed minerals often are the source of those chemical elements presently found in humus, and geochemical dispersion patterns in humus can in many cases be classified as combined syngenetic/epigenetic.

The humus layer of soil profiles has been used as a sampling medium by several research workers (e.g. Boyle and Dass, 1967; Kauranne, 1967a, 1976b; Smith and Gallagher, 1975; Bølviken, 1967, 1976; Kokkola, 1977 and Nuutilainen and Peuraniemi, 1977). Results from soil surveys carried out by Boyle and Dass (1967) in the Cobalt area, Ontario show a greater concentration of Pb, Zn, Cu, As, Sb, Mo, Ag, Co, Mn and Hg in the humus horizons than in the B horizons. Anomalies in the A horizons over known veins gave much better contrast than those obtained from the B horizons. In certain cases, surveys over silver veins covered by 6 m or

more of till gave little response when the B horizons were sampled, whereas anomalies in the humus clearly marked the positions of the veins. Similar results for Au were obtained by one of the authors (C.F.G.) in the Duparquet area, Quebec and by Lakin et al. (1974) in the Empire district, Colorado.

Kauranne (1967a) sampled humus from an area containing Ni-bearing boulders and analyzed the samples for cold extractable heavy metals (CxHM). He found a weak anomaly which coincided with occurrences of the nickel boulders and the direction of ice movement. No continuous hydromorphic anomaly in the till was found under the anomaly in humus (Kauranne, 1976b). The apex of the humus anomaly terminated near a diabase dyke containing pentlandite-chalcopyrite mineralization.

It has long been known that some peat bogs are metalliferous, and may contain as much as several per cent of metal in the dry matter. Townsend (1824) remarked on recovery of copper from peat bogs in western Ireland, and Henwood (1857); Ramsay (1881) and Mehrrens et al. (1973) reported on a copper bog in north Wales, with which a new porphyry copper discovery (Rice and Sharp, 1976) was associated. Copper-bearing bogs have also been reported in Montana and Colorado, (Lovering, 1928; Forrester, 1942 and Eckel, 1949). A zinc-rich bog in New York State, has been described by Cannon (1955). In Canada, copper-rich bogs occur near Sackville, New Brunswick (Fraser, 1961a, 1961b and Boyle, 1977) near Bathurst, New Brunswick (Hawkes and Salmon, 1960) and at Highmont, British Columbia (Hornsnail, 1975). A bog high in zinc is found near Daniels Harbour,

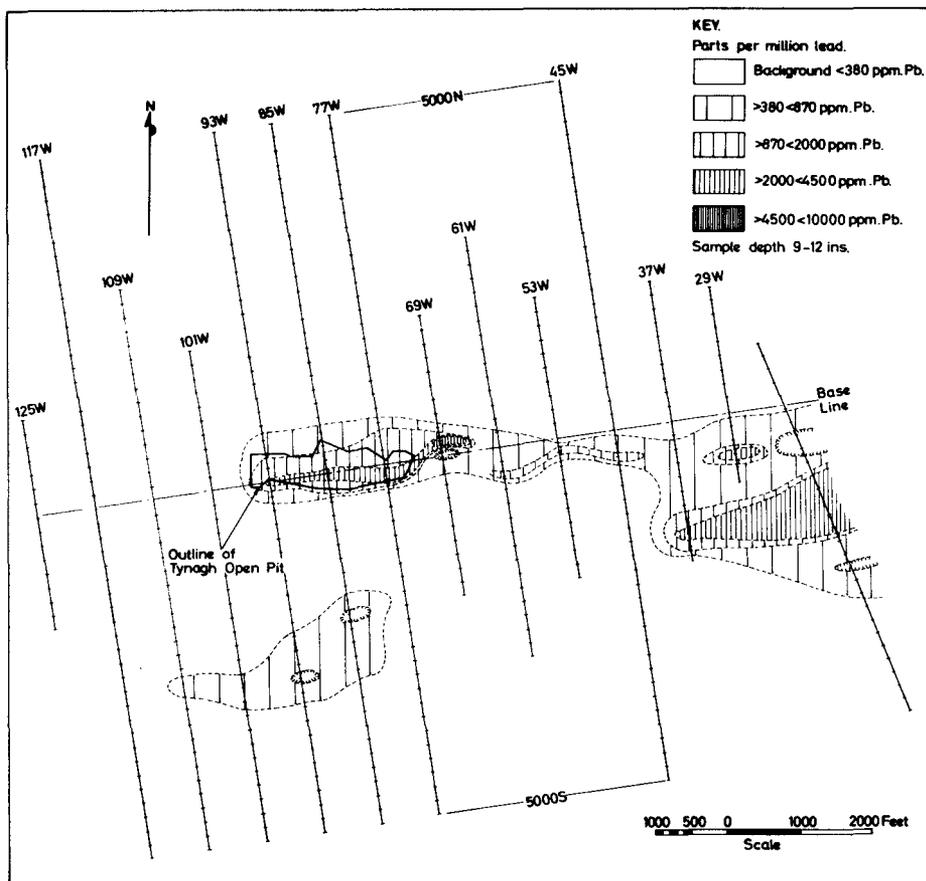


Figure 13.26.

Distribution of lead in minus 180 μm fraction of soil sampled at a depth of 24-30 cm over the Tynagh zinc lead deposit, Galway, Ireland. After Donovan and James (1967).

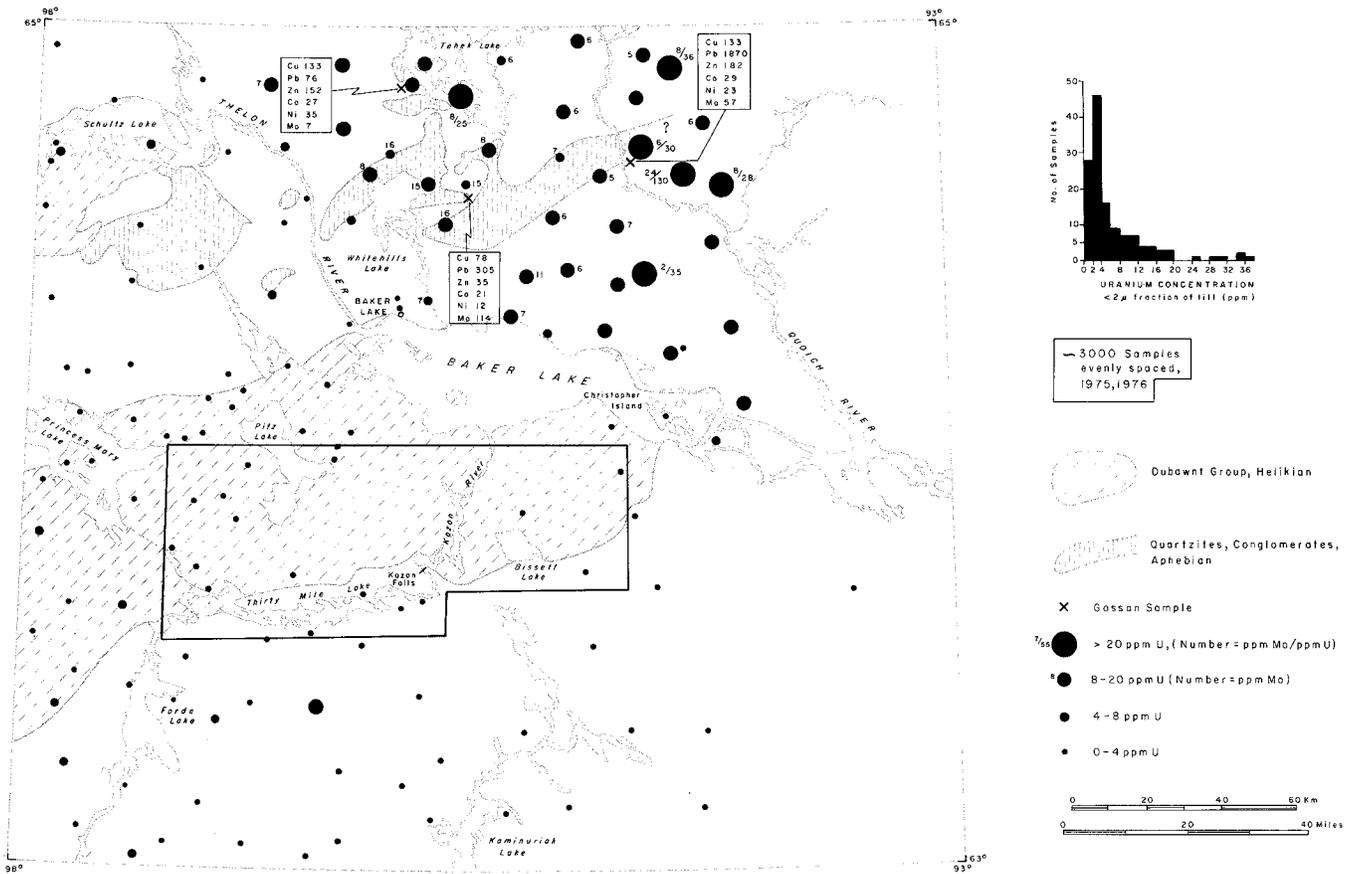


Figure 13.27. Uranium content in <0.002 mm fraction of till from Baker lake region, Canada. After Klassen and Shilts (1977).

Newfoundland (Gleeson and Coope, 1967). Donovan and James (1967) mentioned extreme zinc values in a bog near the Tynagh deposit, Co. Galway, Ireland. In Scandinavia, Armands (1967) reported on a uraniferous bog at Masungbyn, and Larsson (1976) on a cupriferous bog in the Pajalu district, both in northern Sweden. A related phenomenon of natural heavy-metal enrichment in humus was described in Norway (Låg et al., 1970; Låg and Bølviken, 1974 and Bølviken and Låg, 1977). In the USSR, metalliferous bogs have been reported by Moiseenko (1959), Manskaya and Drozdova (1964), Kochenov et al. (1966) and Albov and Kostariev (1968). Systematic sampling of peat as a prospecting method was pioneered in the 1950s by Salmi (1967), who found anomalous values for heavy metals over a variety of Finnish sulphide and iron deposits. An early review of the literature on geochemical prospecting in peat land has been given by Usik (1969).

Gleeson (1960), studied the distribution of metals in bogs of the Kenora area, Ontario and the Matagami area, Quebec, Canada. The zinc, copper and nickel content of the peat increased with depth and reached a maximum at the peat-clay interface. The bogs studied were underlain by 6-20 m of glacial lake sand, silt and clay. Test work over the Matagami Lake base metal mine proved negative; the dense,

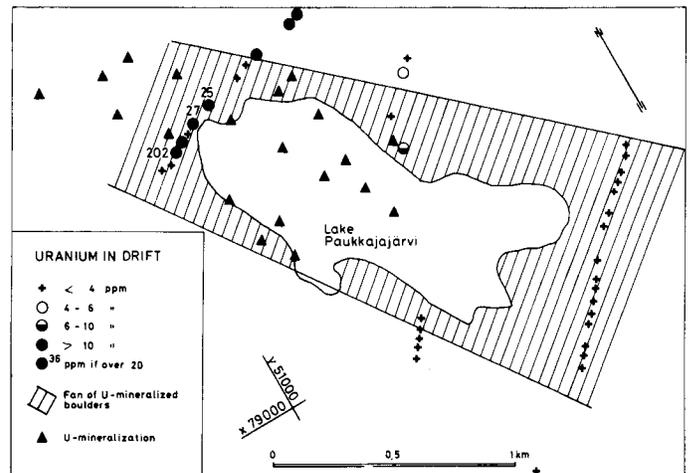


Figure 13.28. Uranium content in <0.06 mm fraction of glacial drift, Paukkajärvi, Karelia, Finland. After Björklund (1976).

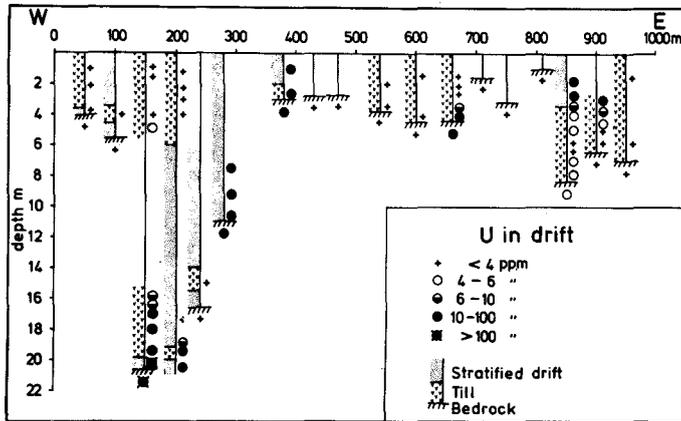


Figure 13.29. Uranium content in <0.06 mm fraction of glacial drift in a vertical section at Paukkajanvaara, Karelia, Finland. The section is located at the northernmost sampling line in Figure 13.28. After Björklund (1976).

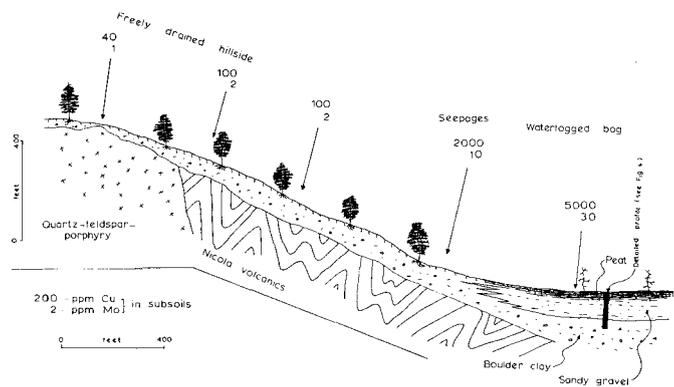


Figure 13.31. Molybdenum and copper in subsoils from a traverse in a study area in British Columbia. After Horsenail and Elliott (1971).

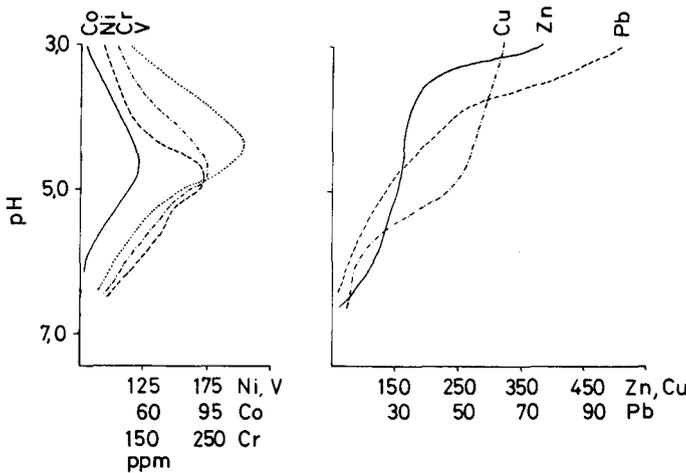


Figure 13.30. Generalized relationships between pH and metal content of 103 peat profiles from various parts of Lapland, Finland. After Tanskanen (1976a).

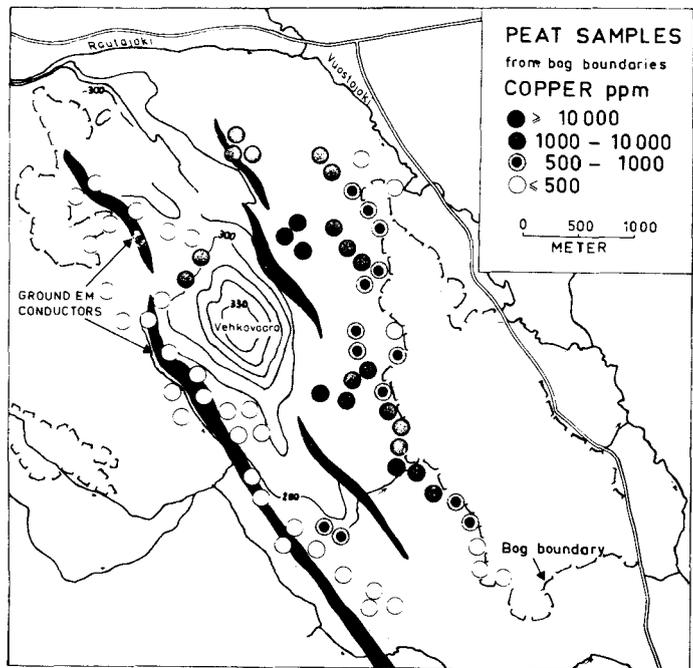


Figure 13.32. Copper content of peat samples in the Vehkavaara area, Pajala district, Sweden. After Larsson (1976).

impermeable glacial lake clays overlying the orebody effectively blocked movement downwards of oxygenated waters as well as the free movement of metal ions from bedrock to surface. When the subcrop of the ore zone was uncovered under about 6 m of clay, the surfaces of the sulphides were fresh and unoxidized.

More recent Canadian investigations including sampling of peat have been published by Fortescue and Hornbrook (1967, 1969), Hornsnail and Elliott (1971), Gunton and Nichol (1974), Bradshaw (1975b), Fortescue (1975) and Hornsnail (1975). Work in northern Europe has been reported by Erämetsä et al. (1969), Hvatum (1971), Erikson (1973, 1976b), Smith and

Gallagher (1975), Eriksson and Eriksson (1976a, b), Kokkola (1977), Nieminen and Yliruokanen (1976) and Tanskanen (1976a,b). A description of Russian work has been given by Borovitskii (1976). Tanskanen (1976a) investigated the variation of metal content versus such factors as pH, humification, ash content, and depth in 609 peat samples collected from 103 peat profiles in various parts of central Lapland, Finland. He found that each of the factors had different effects on the various elements: pairs of similarly-behaving elements were Pb-Zn, Cr-V, and Co-Ni. The relationship between pH and heavy metals is shown in Figure 13.30.

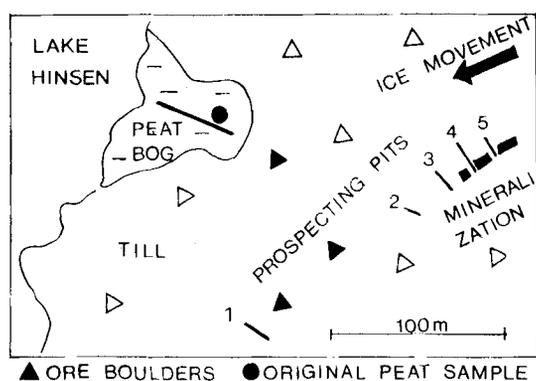


Figure 13.33. Cu-Zn anomalous peat bog, and prospecting trenches in the Lake Hinsén area, Sweden. After Eriksson and Eriksson (1976a).

The results of Hornsnail and Elliott (1971) (Fig. 13.31) are typical for many of those reported in both Canada and Scandinavia. Metals like Cu, Pb, Zn and Mo move hydromorphically down freely drained slopes, and are enriched in peat if the metal-rich groundwater reaches poorly drained bogs in the lowland. This phenomenon is utilized in a new exploration method "sampling of peat bog margins" which has become a routine prospecting technique in Sweden (Eriksson, 1976b and Larsson, 1976). The Geological Survey of Sweden samples peat bog margins at a depth of less than 0.5 m and at 50-100 m intervals; the method is used to follow-up results from reconnaissance geochemical drainage surveys, (see Fig. 13.32 after Larsson, 1976).

Eriksson (1976b) and Eriksson and Eriksson (1976b) have used peat as a sampling medium in reconnaissance surveys in central Sweden. The samples are taken at a density of approximately 7 per km² as close to the border of the bog as possible, and at a depth of about 2 m in the bottom of the organic layer close to the organic/inorganic interphase. Anomalous Zn and Cu values (1130 and 470 ppm Zn and Cu respectively) were found in a bog near Lake Hinsén. Boulder tracing in the vicinity of the anomalous bog led to the discovery of some rich base metal boulders at surface. After trenching and till sampling, Cu/Zn mineralization was found in the bedrock (Fig. 13.33). Later, detailed sampling of the bog revealed distribution patterns (Fig. 13.34) which show that the peat anomaly must be caused by percolating metal-rich groundwater, while the till anomalies most probably are of glacial origin. These interpretations indicate that both mineralized bedrock and till can be sources of high metal contents in bogs.

In another case history the same authors (Eriksson and Eriksson, 1976a) show that a train of boulders containing As, Cu, Pb and Zn was the only source of metals in groundwater creating metal anomalies in a peat bog. This case is an even clearer example of combined syngenetic-epigenetic dispersion. The anomalies, correctly interpreted, can be traced from the peat, through the till and back to the bedrock source. The source was subeconomic skarn-type mineralization containing arsenopyrite, pyrrhotite and chalcopyrite some 1.5 km north of the boulders.

Interpretation of Complex Patterns

In concluding this section two recently published case histories, one Canadian (Cameron, 1977) and one Finnish (Kokkola, 1977) are reported. They both demonstrate that syngenetic and epigenetic dispersion patterns can exist in the same area, and provide examples of how such patterns can be interpreted.

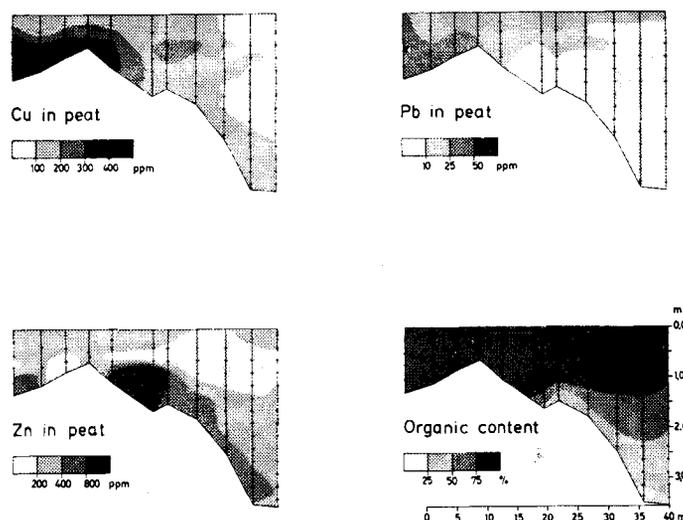


Figure 13.34. Distribution of Cu, Pb, Zn and organic material in a vertical section of a peat bog near Lake Hinsén, Sweden. For location see Figure 13.33. After Eriksson and Eriksson (1976a).

Cameron (1977) reported that in following up lake sediment anomalies in the Agricola Lake area in the eastern part of the District of Mackenzie, massive sulphide mineralization was found in metavolcanic rocks of Archean age. The sulphide zone occurs in a topographic depression (Fig. 13.35) in perennially frozen terrain. Soil samples were collected in a 30 by 30 m grid at a depth of 15-20 cm, and the minus 180 μ m (80 mesh) fraction was analyzed for 11 metals. Factor analysis was carried out to identify interelement relationships.

Factor 1 (Table 13.3) represents relatively immobile elements illustrated by the distribution of Au. A syngenetic dispersion train from the sulphide body upslope in the direction of the glacial movement was obtained (Fig. 13.36).

Factor 3 (Table 13.3) is related to elements of intermediate mobility exemplified by Cu. These are to some extent dispersed epigenetically from the mineralized area, and subsequently precipitated down the drainage channel, (Fig. 13.37).

Factor 5 is related to highly mobile elements like Zn, which are dissolved during postglacial time and carried away (Fig. 13.38). An illustration of the historical sequence of dispersion processes taken from Cameron (1977) is reproduced in Figure 13.39.

Kokkola (1977) sampled both till at the overburden bedrock interface and humus in a profile along the ice direction over the Pahtavuoma Cu-Zn deposit in northern Finland. The terrain is characterized by till and bogs, the thickness of the overburden varies from 0 to 6 m. Cu values in the till samples produced an intense, predominantly syngenetic anomaly approximately 2 km long in the down-ice direction from the deposit. In contrast, the Cu content in humus showed an epigenetic anomaly in the immediate vicinity of the mineralization, without any signs of being influenced by glacial movement (Fig. 13.40). Thus this latter dispersion pattern, which could possibly be hydromorphic and/or electrochemical, can be detected by surface sampling of humus, which is cheap compared to deep sampling of lodgment till.

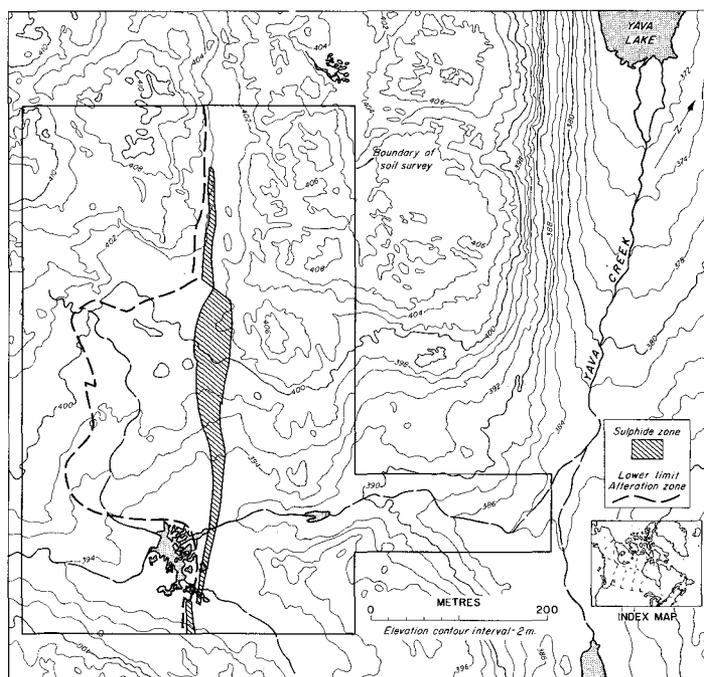


Figure 13.35. Location of a soil survey area in permafrost environments in the eastern part of the Slave Province, Canada. After Cameron (1977).

Table 13.3

Varimax factor matrix of logarithmically transformed soil data. Matrix accounts for 90.2 percent of variance of 284 samples. Only loadings of 0.25 or greater shown After Cameron (1977).

	Factor						
	1	2	3	4	5	6	7
Sum of squares	3.6	1.2	1.4	1.2	1.2	0.9	1.3
Mg		0.96					
Ca	-0.25		-0.77		0.40		
Mn		0.47	-0.30	0.46		-0.31	0.50
Fe	0.35			0.83		0.27	
Ni		0.26					0.92
Cu	0.48		0.63	0.29	0.36		
Zn					0.92		
As	0.45			0.29		0.77	
Ag	0.85		0.30	0.25			
Hg	0.83					0.33	
Pb	0.83		0.37				
Au	0.90						

SAMPLING METHODS AND COSTS

Geochemical soil-sampling methods at surface are well known and need no elaboration. However, methods of obtaining overburden samples at depth have been under development for some 20 years and a brief review of these developments will be presented.

The earliest geochemical sampling of till at depth was done in Scandinavia and Canada from hand-dug pits and by the use of hand-operated soil augers. Later Ermengen (1957) in his geochemical studies of the Chibougamau area, Quebec used a "pass-through" type of sampler for sampling till to depths of about 5 m. The sampling tool was designed so that the soil filling the head was continuously evacuated under the pressure of newly introduced material as the instrument was hand driven down with a sledge hammer. The sample recovered when the device was pulled out represented the bottom few centimetres of the traversed till. More recently a similar sampling device (Holman-type or Barymin Sampler) driven by small percussion drills has been used in Finland (Kauranne, 1975). Ermengen's studies were followed by those of Gleeson (1960), who used a hydraulic-powered drill mounted on a muskeg tractor and conveyor flight augers to profile to depths of 30 m. Van Tassel (1969) sampled tills in the Keno Hill area, Yukon Territory using an Atlas Copco overburden drill. The tract-mounted drill used a rotary action to penetrate the permanently frozen glacial overburden and compressed air forced the cuttings to surface. This program was successful in indicating a new high-grade silver deposit (Husky orebody) which is presently being mined.

In 1969, Gleeson and Cormier (1971) developed a light-weight percussion sampling system which proved effective in discovering the Louvem zinc deposit which has been exploited near Val d'Or, Quebec. This equipment was effective in sampling up to 30 m of till under glacial lake clays and silts which varied in thickness from 1 to 70 m.

As a result of extensive experimentation, Texasgulf Inc. and Bradley Brothers Diamond Drilling Limited developed a dual-tube rotary drill system which was mounted on a Nodwell tractor and first used in the Timmins area, Ontario. The system uses a dual-tube attached to a tri-cone bit (Skinner, 1972); by rotary action the bit breaks the material which is washed up to surface through the inside tube. This drill has been effective in sampling overburden up to depths of hundreds of metres. In Finland, percussion drills mounted on farm tractors have been used to sample tills at depths of 3 m or more. (Wennerwirta, 1973; Kokkola, 1976)

The costs of overburden sampling vary considerably depending on the type of equipment used, depth and type of overburden and density of the holes; Kokkola (1976) reported that the average cost per sample in Finland in 1974 was \$40(US). In Canada, costs (in 1977) using the small percussion drills vary from \$3-\$8 per metre, for tractor-mounted pneumatic drills they vary from \$4 to \$15 per metre and for the rotary dual-tube system costs may vary from \$10 to \$90 per metre. Hence to collect overburden samples at depth may cost from \$40 to \$300 each in contrast to surface soil samples which may cost from \$0.50 to \$20 each.

CHEMICAL ANALYSIS OF SOILS

A presentation of various methods for chemical analysis of glacial soils in geochemical exploration is outside the scope of this paper. It should be emphasized, however, that a

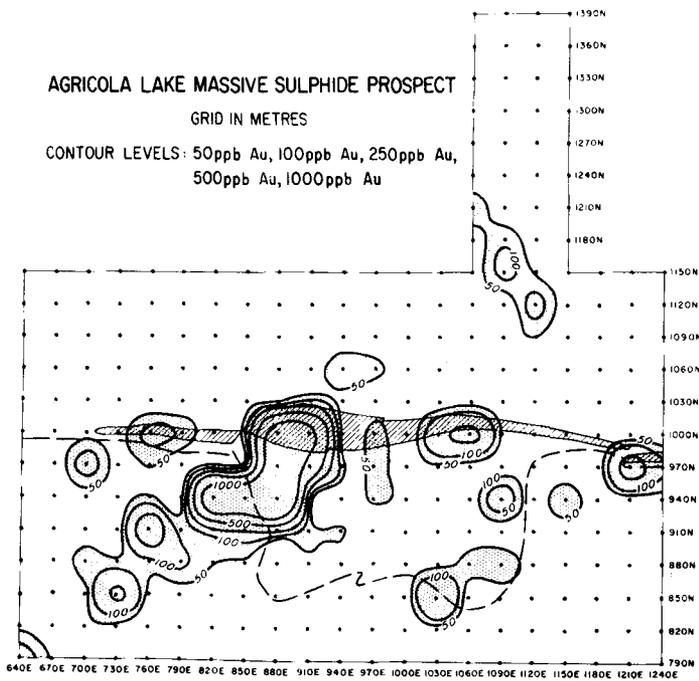


Figure 13.36. Distribution of gold in the minus 0.18 mm fraction of soils taken at a depth of 15-20 cm in a survey area in the eastern part of the Slave Province, Canada (see Fig. 13.35). After Cameron (1977).

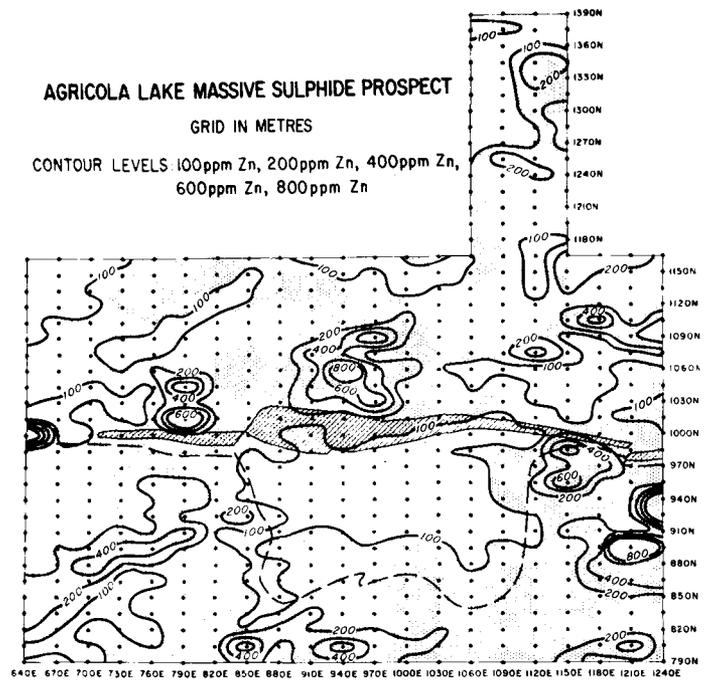


Figure 13.38. Distribution of zinc in the minus 0.18 mm fraction of soils taken at a depth of 15-20 cm in a survey area in the eastern part of the Slave Province, Canada (see Fig. 13.35). After Cameron (1977).

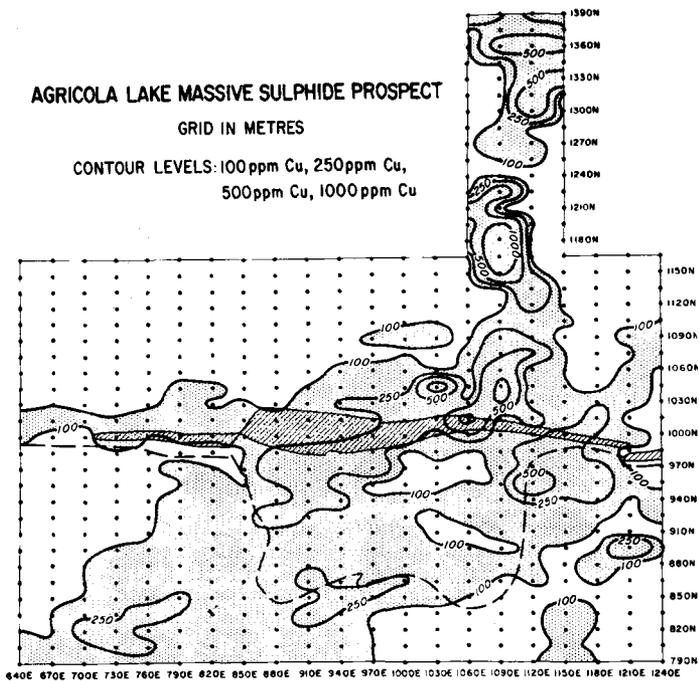


Figure 13.37. Distribution of copper in the minus 0.18 mm fraction of soils taken at a depth of 15-20 cm in a survey area in the eastern part of the Slave Province, Canada (see Fig. 13.35). After Cameron (1977).

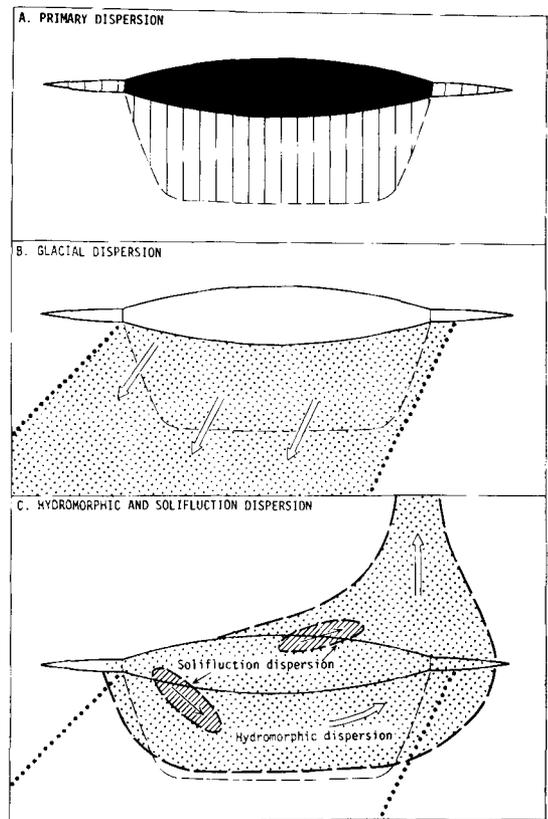


Figure 13.39. Generalized historical sequence of dispersion processes based on data from a study area in the eastern part of the Slave Province, Canada (see Fig. 13.35 to 13.38). After Cameron (1977).

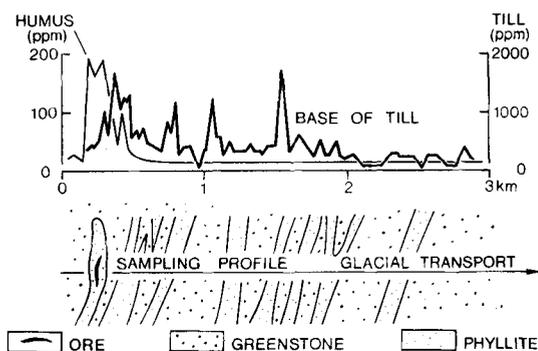


Figure 13.40. Copper in humus and copper at the base of till from a traverse along the direction of glacial transport across the Pahtavuoma copper deposit, Finland. Redrawn and somewhat generalized from Kokkola (1977).

meaningful interpretation of analytical data for soils requires knowledge about the mode in which the elements occur in the soil. A discussion of this problem leads to two practical questions (1) which chemical attack should be used on the soil samples, and (2) which grain sizes should be analyzed.

Mode of Occurrence of Trace Elements

Rose (1975) divided the modes of occurrence of trace elements in soils into four important groups: (1) as a major element in trace minerals; (2) as a trace constituent in a mineral of the parent material; (3) as a trace constituent in the lattice of a mineral formed during weathering; and (4) as a trace constituent adsorbed as a counter ion on the surface of an iron or manganese oxide, colloidal clay or organic particle, or in the exchange layer of a clay mineral.

In areas of glaciated terrane purely syngenetic geochemical dispersion patterns would normally comprise modes of occurrence of groups (1) and (2), while purely epigenetic patterns would mainly comprise groups (3) and (4). In complex syngenetic/epigenetic patterns the elements will occur as any possible combination of groups (1), (2), (3), and (4).

Chemical Digestion of Soil Samples

The disclosure of syngenetic dispersion patterns, requires a chemical digestion which is rigorous enough to attack primary minerals. Ideally, this would often require solid phase methods like X-ray fluorescence, and optical spectrography, or use of a perchloric-hydrofluoric acid digestion (Foster, 1971). However, in some cases, depending on the target, less rigorous acid attacks (Ellis et al., 1967; Lynch, 1971; Foster, 1971, 1973; Olade and Fletcher, 1974 and Peachey, 1976) or the simple potassium bisulphate fusion (Harden and Tooms, 1964) will suffice.

The disclosure of epigenetic dispersion patterns would normally not require a very strong chemical attack on the samples. In fact, the results of partial extraction techniques would in some cases give better contrast between anomaly and background than the totals. This was the case in a study of zinc in peats from several bogs in eastern Canada (Gleeson and Coope, 1967). However, Maynard and Fletcher (1973) arrived at the opposite conclusion for the analysis of copper in peat, stating that the greatest contrast was obtained using nitric acid-perchloric digestion. Bradshaw et al. (1974), nevertheless, found that the percentage of cold-extractable metals in mineral soil is increased where the anomalies are a result of hydromorphic accumulation, and increases very

dramatically in organic soils under the same conditions. These different results obtained by various workers clearly indicate that partial extractions of metals from soils to help define epigenetic dispersion patterns is a field which warrants further research. An ideal sample attack would be one that selectively dissolves trace elements of a certain mode of occurrence or a certain genesis. Interesting approaches to this problem are provided by: Meyer and Leen (1973) (evolution of metal vapours); Nurmi (1976), Toverud (1977) (results of partial and total extractions); Aleksandrova (1960), Antropova (1975) (organically bonded metals); Govett (1974, 1975), Nuutilainen and Peuraniemi (1977), Kokkola (1977) (extractants which disclose possible electrochemical dispersion patterns); Chao (1972), Chao and Sanzalone (1973) (dissolution of secondary iron and manganese oxides); Chao and Theobald (1976), Gatehouse et al. (1976) (sequential soil analysis).

Grain-size Fractions for Analysis

Shilts (1975a, b) discussed the mineralogical composition of various size fractions in till. Particles with a diameter of more than 0.25 mm consist mainly of mineral aggregates (rock fragments). Particles from about 0.060 mm to 0.25 mm consist mostly of quartz-feldspar mineral grains with varying amounts of carbonates, heavy minerals and rock fragments. From about 0.002 mm to 0.060 mm, the particles are mostly mineral grains consisting generally of over 90 per cent quartz, feldspars and carbonates, with minor percentages of heavy and phyllosilicate minerals. Particles finer than 0.002 mm consist predominantly of phyllosilicates (micas, clay minerals, chlorite etc.) and of easily crushed secondary oxides (limonite, hematite etc.), with varying accessory amounts of quartz, feldspar and carbonates. The proportions of these textural classes can vary over a limited area; apparently any analysis of till samples that combines two or more of these textural classes may be difficult to compare. In a successful study Shilts (1976) used the minus 0.002 mm fraction for analysis aiming at finding syngenetic dispersion patterns, utilizing the fact that some of the cations released locally from primary minerals in the coarser till fractions would be scavenged by a fairly constant proportion of scavengers in the fine fraction.

From a study of heavy metals in different till fractions in Sweden, Eriksson (1976a) concluded that the greatest contrast between anomalous and background values was obtained from the finest fractions when using HCl/HNO₃ extraction, and from the coarser fraction when analyzing the total metal content.

CONCLUSIONS AND FUTURE TRENDS

The processes and methods when carrying out geochemical soil studies in glaciated terrane are many and varied. An understanding of glacial as well as postglacial processes is paramount if proper interpretation of geochemical soil data is to be accomplished.

Bradshaw et al. (1974) introduced the use of conceptual models in exploration geochemistry. Application of such models based on Canadian case histories was done by Bradshaw (1975a) and later in Europe by Kauranne (1976).

Conceptual models (Fig. 13.41) represent a systematic way of visualizing the various factors that influence metal dispersion and provide a framework into which further data can be fitted. They are of particular importance in glaciated areas where the dispersion processes can be very complex. By expanding this type of presentation to include more and different situations for various elements, a clearer understanding of geochemical processes in relation to the

physical and chemical nature of the landscape can be attained. Such clarification will lead to a better interpretation of geochemical data as well as pointing out gaps in our knowledge.

An extensive program of systematic regional till sampling has been established in Finland (Kauranne, 1975; Stigzelius, 1976); large-scale regional till sampling is also being carried out in Canada (Klassen and Shilts, 1977). Such programs have already proved fruitful in evaluating the mineral potential of various areas and are particularly valuable where conventional reconnaissance stream and lake sediment surveys might not be applicable. One can expect that the vast amount of information obtained through this type of survey will greatly improve our knowledge about the use of soils for geochemical prospecting in glaciated areas. However, more studies into Quaternary geology, in particular into the three-dimensional configuration of indicator trains associated with mineral deposits are required, especially in areas covered by glaciolacustrine sediments; these basic studies are needed to help interpret regional till data.

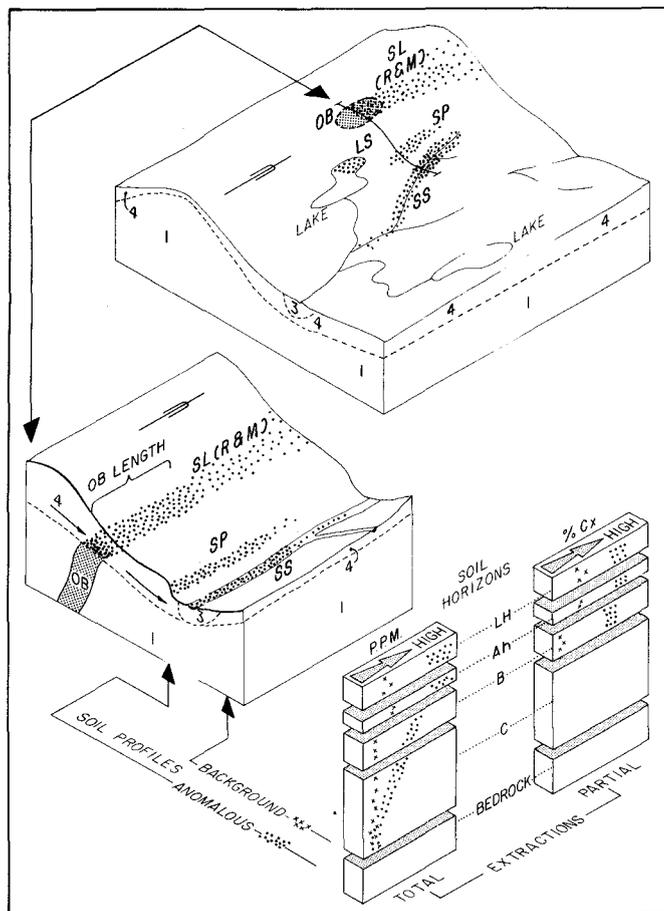
A better understanding of postglacial geochemical dispersion processes is also required if we are to advance the applicability of soil sampling in glaciated environments. Utilization of such processes may be beneficial even in areas where significant glacial dispersal trains are not detectable.

More research is needed in the use and understanding of gaseous dispersion in glaciated terrane. Airborne instruments for detection of gaseous or particulate anomalies caused by mineral deposits are today a real possibility (Barringer, see this volume, Paper 16 (abstract only)).

Studies into electrochemical processes and their role in the movement of ions through bedrock and glacial overburden will continue. The process is probably most important in areas of low relief, some data indicate that it might be operative even where sulphide deposits are covered by thick glaciolacustrine deposits (Govett and Chork, 1977).

A greater use of organic material as a sampling medium can be expected. Utilization of the enrichment of heavy metals by humus has great potential in geochemical prospecting, especially in areas with moderate or high relief where the anomalies formed in humus material can be so strong that the effects of most other dispersion mechanisms are overshadowed (Boyle, 1977) and where vegetation is strongly affected (Bølviken and Låg, 1977), sometimes to the extent that the naturally poisoned areas developed may be detectable by remote sensing techniques (Bølviken et al., 1977).

Very sensitive, rapid and reliable methods for determining chemical constituents of soils are now available to the geochemist. However, we lack knowledge concerning the most applicable extraction techniques that would best differentiate various types of syngenetic and epigenetic anomalies. Further research into this problem provides one of the promising avenues to a more efficient utilization of soils for geochemical prospecting in glaciated terrane.



- SL(R&M) = Residual (R) soil and anomaly
- SS = stream sediment anomaly
- LS = lake sediment anomaly
- SP = seepage anomaly
- OB = orebody

Figure 13.41. Idealized model for geochemical dispersion of mobile elements in well-drained and poorly-drained ground-till overburden. After Bradshaw (1975).

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