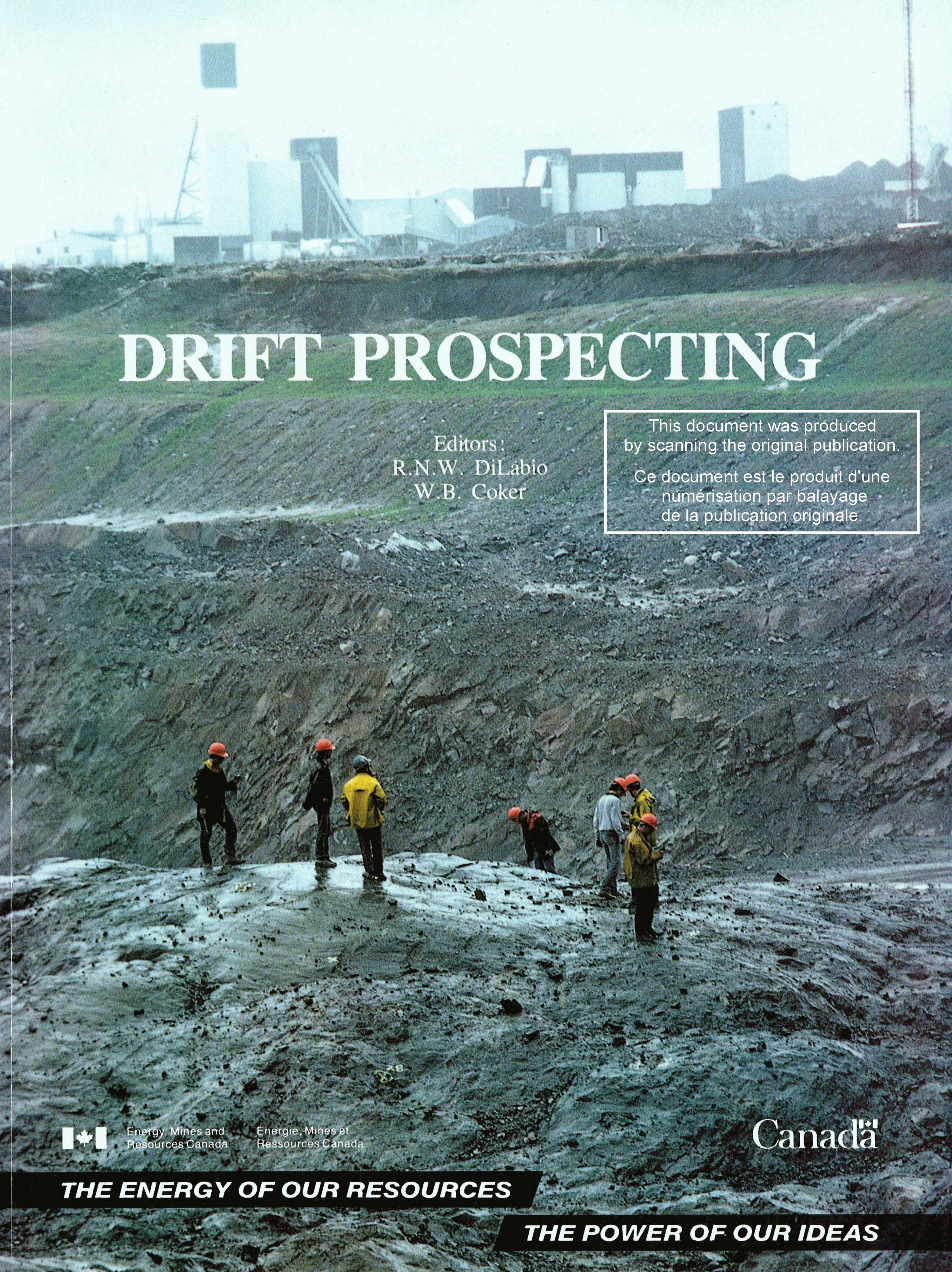


DRIFT PROSPECTING

Editors:
R.N.W. DiLabio
W.B. Coker

Energy, Mines and Resources Canada
Energie, Mines et Ressources Canada

Canada

THE ENERGY OF OUR RESOURCES

THE POWER OF OUR IDEAS

GEOLOGICAL SURVEY OF CANADA
PAPER 89-20

DRIFT PROSPECTING

Editors:
R.N.W. DiLabio
W.B. Coker

1989

Available in Canada through

authorized bookstore agents and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Ottawa, Canada K1A 0S9

and from

Geological Survey of Canada offices:

601 Booth Street
Ottawa, Canada K1A 0E8

3303-33rd Street N.W.,
Calgary, Alberta T2L 2A7

A deposit copy of this publication is also available for reference
in public libraries across Canada

Cat. No. M44-89/20E
ISBN 0-660-13361-X

Price subject to change without notice

Cover description

Glacially sculpted and striated
bedrock at the base of a thick
section of glacial sediments,
Selbaie Mine, Quebec

Original manuscript submitted: 1989 - 03 - 29
Final version approved for publication: 1989 - 06 - 02

CONTENTS

FOREWORD

This collection of papers is drawn largely from a special session "Mineral Exploration in Glaciated Terrain", which was part of the 12th International Congress of the International Union for Quaternary Research, held at Ottawa in 1987. These papers show the variety of types of research being carried out in different geological settings in Canada and Finland, where drift prospecting has been most widely and successfully used. The authors have emphasized the value of grassroots studies in glacial geology. They have shown how the basis for drift prospecting is a thorough understanding of the provenance, stratigraphy, and ice flow directions of glacial sequences, backed by data on the geochemistry, lithology, and mineralogy of glacial sediments.

We thank R.A. Klassen, Y.T. Maurice, E. Nielsen, B.T. Schreiner, W.W. Shilts, K.G. Steele, L.H. Thorleifson, and J.J. Veillette, who took the time to help in critical review of the manuscripts. K.A. MacInnis found many ways to improve the clarity of the manuscripts during her proofreading stint. The editors assume sole responsibility for any errors.

R.N.W. DiLabio
W.B. Coker

AVANT-PROPOS

La présente collection d'articles provient en grande mesure d'une séance spéciale intitulée "La prospection minérale en région glaciée", laquelle avait été organisée dans le cadre du XIIe Congrès international de l'Union internationale pour l'étude du Quaternaire, tenu à Ottawa en 1987. Ces articles se font le reflet des divers genres de travaux de recherche entrepris dans différents milieux géologiques au Canada et en Finlande, où les techniques de prospection des matériaux de transport glaciaires sont utilisées le plus couramment et avec le plus de succès. Les auteurs ont souligné la valeur d'études préliminaires en géologie des formations glaciaires. Ils ont ainsi démontré que la prospection des matériaux de transport glaciaires exige une connaissance approfondie de la provenance et de la stratigraphie des séquences glaciaires ainsi que de la direction de l'écoulement des glaces au sein de ces séquences, le tout étayé par des données sur la géochimie, la lithologie et la minéralogie des sédiments glaciaires.

Les rédacteurs remercient R.A. Klassen, Y.T. Maurice, E. Nielsen, B.T. Schreiner, W.W. Shilts, K.G. Steele, L.H. Thorleifson et J.J. Veillette pour le temps qu'ils ont consacré à faire une lecture critique des manuscrits. K.A. MacInnis a éclairci les manuscrits de maintes façons à l'étape de la correction d'épreuves. Ils assument en outre l'entière responsabilité de toute erreur dans les articles.

R.N.W. DiLabio
W.B. Coker

Application of glacial geological studies in prospecting in Finland

H. Hirvas[1]

Hirvas, H., Application of glacial geological studies in prospecting in Finland; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 1-6, 1989.

Abstract

The research group at the Geological Survey of Finland, established for applying glacial geological studies in prospecting, has developed the following research procedure. Exploration pits are dug at ore boulder sites. The till stratigraphy and directions of ice flow are established from these pits, the distance the boulders were transported is assessed, and samples for till lithology and geochemistry are taken. A probability sector for the source rock of the boulders is determined from the directions of ice flow. The study is continued by tracing ore boulders and unique heavy mineral contents through the till unit. The procedure has proved very useful in Finland, where the surficial deposits are shallow, the average thickness being a mere 6.7 m. During the last nine years, the source rocks for forty-five boulder trains or geochemical anomalies have been found.

Résumé

Le groupe de recherche de la Commission géologique de la Finlande, mis sur pied dans le but d'adapter des études de géologie glaciaire à la prospection, a mis au point la méthode de recherche suivante. Des puits d'exploration sont creusés à l'emplacement des blocs de minerai. La stratigraphie du till et les directions d'écoulement des glaces sont établies à partir de ces puits, la distance sur laquelle les blocs ont été transportés est évaluée et des échantillons sont prélevés pour établir la lithologie et la géochimie du till. Un secteur de probabilité pour la roche mére des blocs est déterminé à partir des directions d'écoulement des glaces. L'étude se poursuit par le dépistage du cheminement des blocs de minerai et l'identification des minéraux lourds uniques à l'unité de till. La méthode s'est avérée très utile en Finlande où les gisements de surface sont peu profonds, l'épaisseur moyenne atteignant à peine 6,7 m. Au cours des neuf dernières années, les roches mères de 45 trainées de blocs ou anomalies géochimiques ont été repérées.

[1] Geological Survey of Finland, Department of Quarternary Geology, SF-02150 Espoo, Finland.

INTRODUCTION

Finland is located in the centre of the Scandinavian glaciation area (Fig. 1). Finland has experienced multiple glaciations, each with minimal glacial erosion and deposition. The Quaternary cover of surficial deposits on the mostly Precambrian bedrock is thin, averaging only 6.7 m.

It is commonly thought that the surficial deposits only cover and hide the ore deposits. However, due to their origin, the surficial deposits and especially till, give excellent clues in exploration for ore deposits. Glacial erosion and deposition distributes minerals from a small ore subcrop over a large area, greatly increasing the likelihood of initial discovery.

The significance of the surficial deposits to ore prospecting in Finland becomes very evident when the following statistics are considered. Less than 3 % of the area of Finland is exposed bedrock, whereas 63 % is covered by till. More than half of the presently operating mines in Finland were discovered as the result of studies of ore boulders found in till. At present, the Geological Survey has information on about 7500 ore boulders found in till that have unknown source rocks. The systematic mapping of till geochemistry has revealed several hundred geochemical anomalies, which have to be checked for their significance in prospecting.

In Finland, an observation of great importance to boulder tracing and geochemical mapping has been made during the last decade. It is now known that in many areas in Finland there are at least two till beds of different ages (Fig. 2). Each till bed was deposited by ice moving in different directions (Hirvas 1981, Hirvas and Nenonen 1987). Boulders and finer grains of ore material found in till may have experienced multiple episodes of glacial and glaciofluvial transport. This has been termed ''complex transport'' by Hirvas et al. (1977).

A factor of equal importance is that the older till or sorted material may cover and protect the ore subcrop. In such cases, the youngest till bed has not received any ore material from the source rock, and any ore material it contains has been redeposited and diluted from the older till (Fig. 2 B) (Hirvas 1981).

In 1979, the Geological Survey set up a Quaternary research group to serve exploration in its Department of Quaternary Geology. The regular staff of the group comprises three geologists and one research assistant. For the field season, five geology students and an excavator are hired. The annual budget of the group is about $250 000

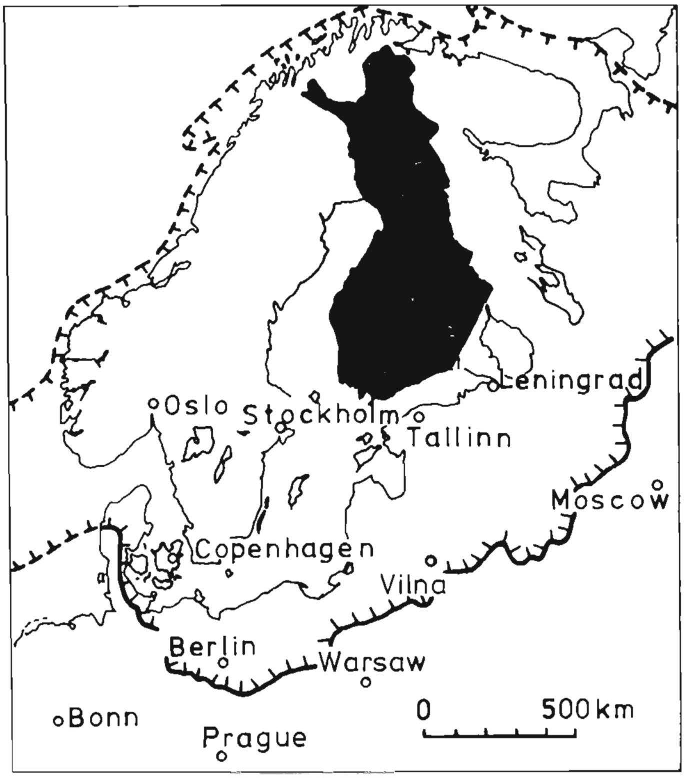


Figure 1. Finland within the area of the Scandinavian ice sheet. The maximum Weichselian boundary is also shown.

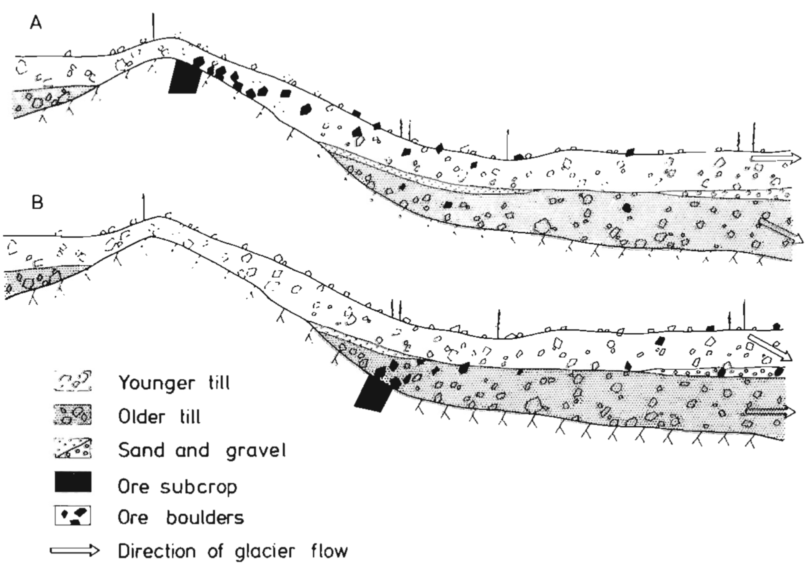


Figure 2. Schematic drawing of the topographic control of glacial erosion of an ore subcrop (A) and complex transport of ore boulders (B) (From Hirvas 1981, Fig. 1).

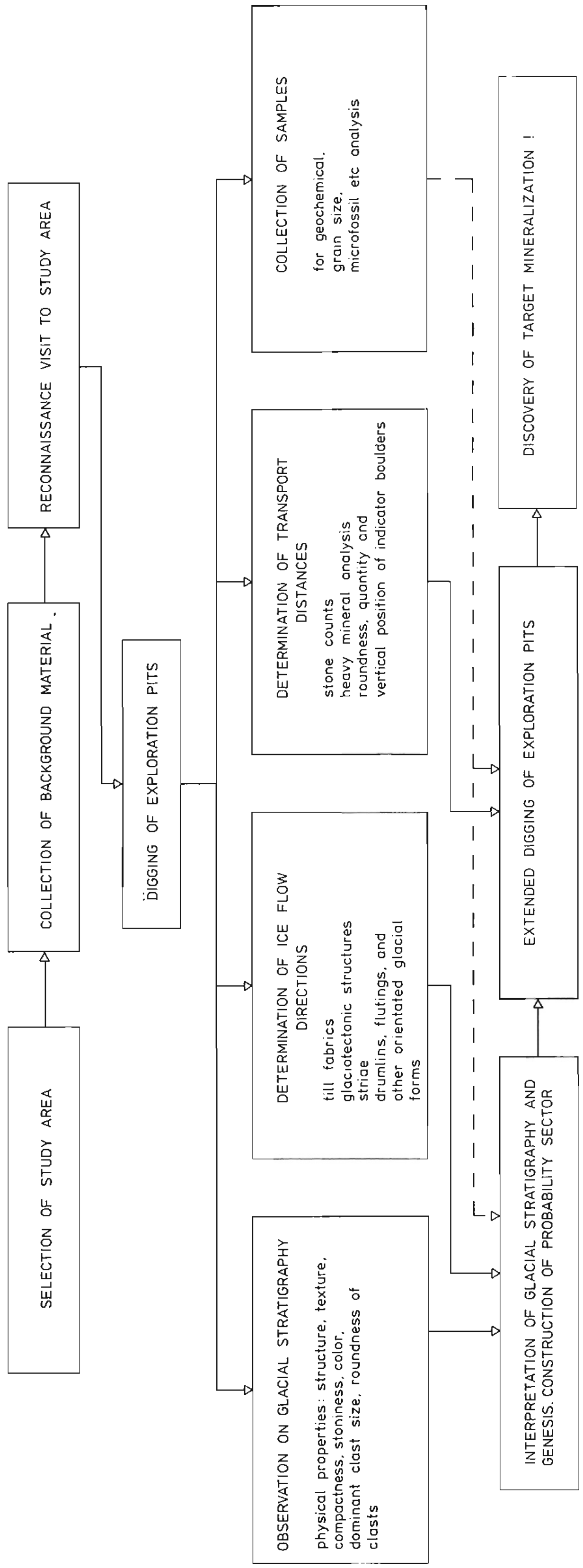


Figure 3. Flow chart for practical indicator tracing applied in Finland in an area of moderate or thin glacial sediment cover.

US, i.e. approximately 1 % of the amount of money spent annually for exploration in Finland. The group investigates the origin of ore boulders and geochemical anomalies by utilizing glacial geology. The group works in collaboration with the Exploration Department and the Geochemistry Department. The procedure used by the research group in exploration work is described below, and presented schematically in Figure 3.

METHODS OF STUDY

Field work begins by the digging of exploration pits at the sites where geochemical anomalies or ore boulders have been discovered. In each pit, the glacial stratigraphy and the directions of glacial flow are studied, and the transport distance of ore boulders is estimated. A typical exploration pit is four to five metres deep. If necessary, pits can be deepened to seven metres. To unravel the stratigraphy as much data as possible is gathered. For each till unit, physical properties such as colour, structure, and grain size distribution are noted. Compactness, stoniness, clast size, and average roundness of the clasts in the till, are noted on a scale from one to five, where one represents the lowest and five the highest degree of each property (Hirvas et al., 1976).

In each till unit, clast orientations are measured, pebble lithologies are identified, and heavy minerals are determined. Samples for trace metal and grain size analyses are taken. In this way we try to ascertain which of the till units in the stratigraphic sequence are only variations of the same till bed, and which are till beds of a different age, deposited during other glacial phases.

The directions of glacial flow are determined from till fabric analyses, striae, and streamlined landforms (Fig. 4). The distance of glacial transport of the ore boulders is estimated from pebble counts, and from the frequency of ore boulders, their number, size, roundness, and stratigraphic position (i.e., their vertical distribution) within the till bed.

Recent investigations have proven that the heavy mineral content of the till can be a very useful tool for estimating the distance of ore boulder transport. When the heavy mineral fraction of the till contains an abundance of the same ore minerals as the boulders that are being traced, the boulders proved to be from a short distance, i.e. between some tens of metres and some hundreds of metres away. On the contrary, when the heavy mineral fraction of the till was lacking the minerals of the ore boulders, the boulders came from far away, i.e. up to kilometres away.

BOULDER TRACING

With data on the genesis and transport direction of the till bed that contains ore boulders, the probability sector of glacial transport for the boulders is defined and drawn on the

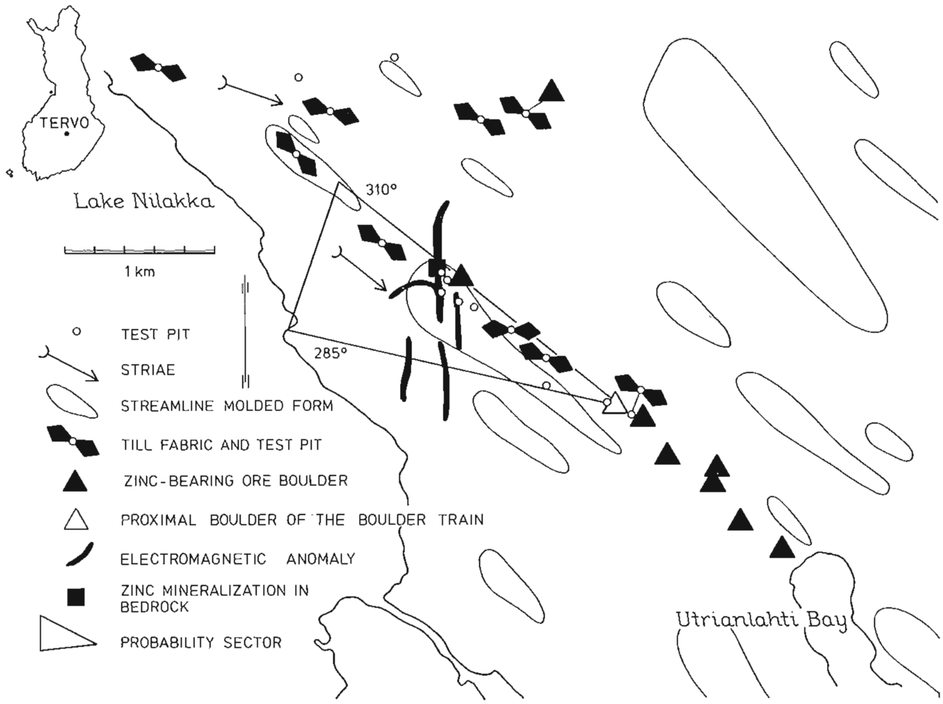


Figure 4. Zinc-bearing boulder train and the use of a probability sector in glacial geological studies serving exploration at Utrianlahti, Tervo. (Hirvas 1981, Fig. 2 and Nenonen 1984, Fig. 2).

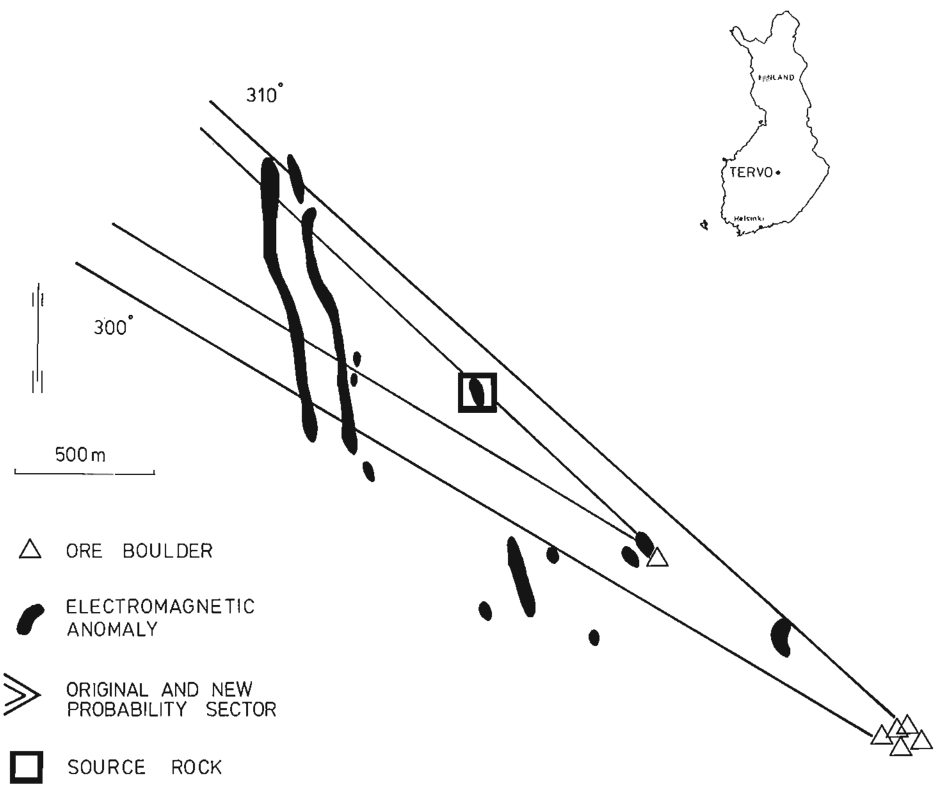


Figure 5. Original and new probability sectors and the use of geophysics at the nickel boulder tracing site of Utrianlahti, Tervo (Hirvas & Nenonen in press).

map (Fig. 4). The sector delimits the area where the source rock of the boulders is most likely to be found. This, of course, implies that the determinations of the direction of glacier flow are correct, and that the ore boulders were only transported by the glacier flow in question.

Since boulder trains and concentrations are often disconnected and of irregular shape, the probability sector is drawn from the so-called proximal boulder, which is the farthest up-ice boulder of the train. Often the back limit of the sector can also be defined, i.e. there are petrological or geophysical reasons why the boulders in question cannot originate from certain bedrock areas.

After delimiting the probability sector, further investigations are carried out inside the sector by digging exploration pits from the proximal boulder towards the direction from which the ice sheet advanced. If the boulder train or the probability sector is narrow or the boulders are assumed to be local, exploration trenches are dug completely across the probability sector. This is to make sure the boulder train is found, even if it is narrow, in which case it might not be discovered with the normal pattern and spacing of exploration pits.

Based on the distribution of ore boulders and heavy minerals in till, the test pits are systematically located towards the subcrop. Closer to the subcrop the boulders become more frequent, larger, and less rounded, and they are found progressively deeper in the till bed being traced. When there are no more boulders in the same till bed, digging has proceeded beyond the subcrop. At that stage, either a row of pits or a trench is dug in the direction of glacial transport, until the subcrop is found. The subcrop is usually found by digging, in areas of thin drift. In areas of thick surficial deposits, the subcrop is delimited to as small an area as possible, where it can be found by further investigations, such as drilling.

DETERMINATIONS OF HEAVY MINERALS IN TILL SERVES BOULDER TRACING

The use of heavy minerals in till for guiding tractor excavations has given very encouraging results. Frequently, glacial erosion of small ore subcrops produces only a limited number of boulders, which are hard to find. It is difficult, and sometimes impossible, to find ore boulders below the groundwater table where till is wet and liquefies when disturbed. This means that ore boulders may exist in some exploration pits but have simply not been found.

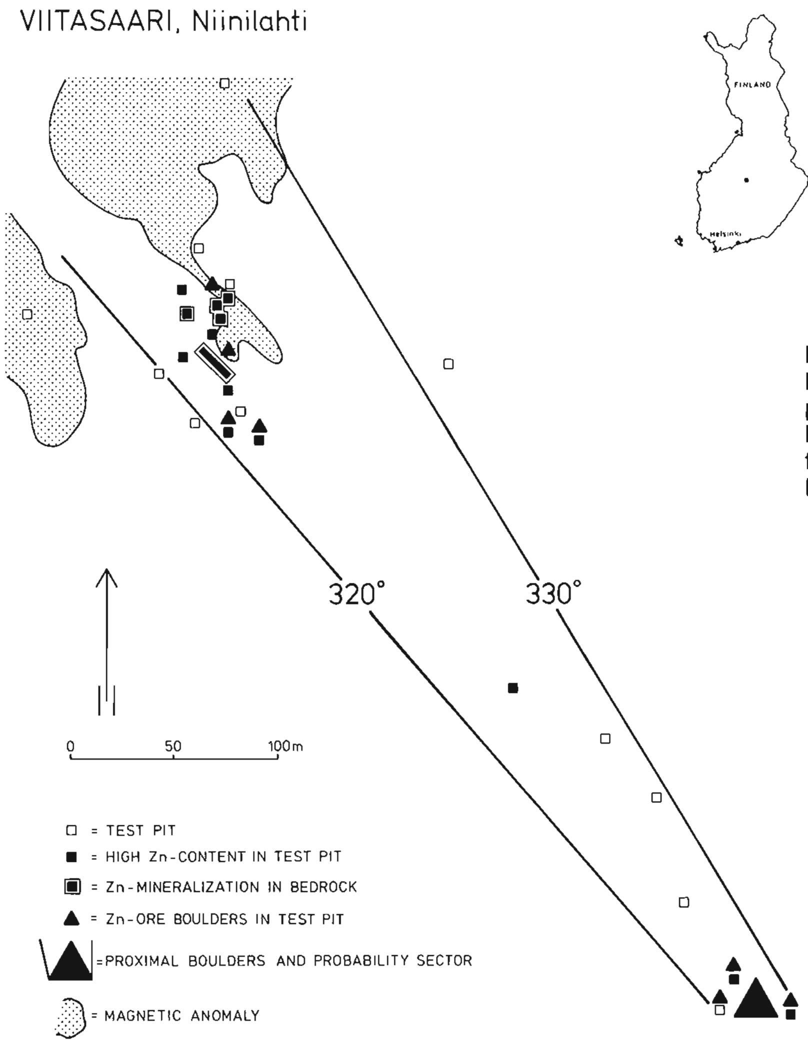


Figure 6. Typical example of the distance between proximal boulder and source rock. The proximal boulders of the zinc boulder train at Niinilahti, Viitasaari, have surfaced about 400 m from their source (From Hirvas & Nenonen 1985, Fig. 1).

On the other hand, the till matrix contains ore minerals from the subcrop, provided that they have not been weathered or dissolved completely. These so-called "mini boulders" are reliably obtained from the heavy mineral fraction of the till.

The method is suitable for the tracing of oxide ore minerals and native gold, as well as some sulfide minerals, such as galena and chalcopyrite.

The great advantage of the heavy mineral determinations compared with, for example, determinations of the trace metals in till, is that analyses can be done quickly in the field. The results are available only one or two hours after a pit is excavated. We can draw far-reaching conclusions regarding the distance to the source rock on the basis of the number, size, and roundness of the heavy mineral grains. In this way, heavy mineral determinations can be used immediately to guide the siting of exploration pits.

The concentration of heavy minerals from till is always done on a standard size sample (12 litres) in order to make the results comparable. In the past, the concentration was done manually by panning, but nowadays a mechanical spiral gold panner is used.

The study of the heavy mineral content in till is an important method in northern Finland. For vast areas of this region, the bedrock, in places 100 m below the ground surface (Virkkala, 1955), consists of completely loose, preglacially weathered rock. In such areas, the surfaces of ore subcrops are totally weathered, and as such no boulders can enter the till from them. Instead, the ore indications are traced in the finer fractions by heavy mineral determinations or by geochemical methods.

OTHER AIDS OF BOULDER TRACING

Inside the probability sector, it is possible to speed up and guide the pattern and locations of excavations. It is possible to draw a new sector, narrower than the former one, in order to delimit further investigations (Fig. 5).

Sometimes the petrophysical properties of the boulders, e.g. magnetism or electrical conductivity, are such that their source rock may be assumed to cause a definite geophysical anomaly. In such cases, pits may be dug directly over geophysical anomalies which occur inside the sector (Fig. 5).

Elevated bedrock areas in Finland typically have only one till bed, deposited by the youngest glacial flow. Older tills and sediments from ice-free intervals are found in bedrock depressions. There are cases where ore boulders are found only in the youngest till in areas where an older till bed is preserved in some bedrock lows. In these cases, the source of the boulders is probably located in an elevated bedrock area in the direction opposite to that of the most recent glacial advance, where only the youngest till bed covers the bedrock (Fig. 2A).

Evaluation of the topographgic position of the subcrop on the basis of the stratigraphic position of the boulders has proved to be a useful method. The method, called "topographic control" (Hirvas, 1981), has been applied with success at many boulder tracing sites.

CONCLUSIONS

The methods presented have been very useful in Finland. During the last nine years, investigations by these methods have been carried out at 57 sites. The source rocks of 45 boulder trains or geochemical anomalies have been located, a success rate of 79 %.

The distance from the proximal boulder on surface to its bedrock source was 0 to 1.4 km. In some areas with thin till cover, the proximal boulders were directly over their sources. In general, the proximal boulders have risen to the surface or upper part of the till at a distance of a few hundred metres, down-ice of the subcrop. For example, in a train of zinc boulders at Niinilahti, Viitasaari, the proximal boulder is 400 m away from the subcrop (Fig. 6).

In general, it takes the research group two or three weeks to investigate one distinct concentration of boulders. The unsuccessful cases are scattered single boulders on the surface or in the upper part of the till, where no others have been found by excavating. Even trace metal and heavy mineral analyses have shown nothing at these sites. Some of these isolated boulders have probably traveled to their place of discovery by complex glacial transport, perhaps over long distances. Some may have dropped onto the surface of the till from icebergs during deglaciation, when a great part of Finland was covered by the Baltic Sea.

The success of boulder tracing in Finland is due to a number of factors. First, the Quaternary cover is so thin that in most cases it may be penetrated by tractor excavator. Second, the bulk of the till, including the distinct concentrations of ore boulders, was transported only a short distance by the ice.

REFERENCES

Hirvas, H.
1981: Application of till stratigraphical studies in ore prospecting; in Glacial Deposits and Glacial History in Eastern Fennoscandia, Academy of Sciences of the USSR, Apatity, p. 48-54.

Hirvas, H., Kujansuu, R., and Tynni, R.
1976: Till Stratigraphy in Northern Finland; in Quaternary Glaciations in the Northern Hemisphere, eds. D.J. Easterbrook and V. Sibrava; IGCP Project 73/1/24, Report 3, Geological Survey, Prague, p. 256-273.

Hirvas, H., Alfthan, A., Pulkkinen, E., Puranen, R., and Tynni, R.
1977: A report on glacial drift investigations for ore prospecting purposes in Northern Finland 1972-1976; Geological Survey of Finland, Report of Investigation No. 19, 54 p.

Hirvas, H., and Nenonen, K.
1985: Niinilahti (Commune of Viitasaari): Case history of Zn ore boulder studies — Quaternary survey methods applied to ore prospecting; in INQUA Till Symposium. Excursion guide, ed. M. Saarnisto; Geological Survey of Finland, Department of Quaternary Geology, p. 72-74.
1987: The till stratigraphy of Finland; in INQUA Till Symposium, eds. R. Kujansuu and M. Saarnisto; Geological Survey of Finland, Special Paper 3, p. 49-63.
(in press): Field methods in glacial indicator tracing; in Handbook of Glacial Indicator Tracing, eds. R. Kujansuu, and M. Saarnisto; A.A. Balkema, Rotterdam.

Nenonen, K.
1984: Till stratigraphic studies as an aid to ore prospecting in Finland; Striae, v. 20, p. 101-105.

Virkkala, K.
1955: On glaciofluvial erosion and accumulation in the Tankavaara area, Finnish Lapland; Acta Geographica, No. 14, p. 393-412.

Tracing of uranium-rich boulders at Pahtavuoma, northern Finland

Heikki Hirvas[1] and Kalevi Mäkinen[2]

Hirvas, H., and Mäkinen, K., Tracing of uranium-rich boulders at Pahtavuoma, northern Finland; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 7-12, 1989.

Abstract

A great number of uranium-rich boulders located in a number of separate boulder trains have been found in Pahtavuoma area, northern Finland. The most extensive boulder train in the area lies to the northeast of the known uranium subcrop, and is composed of over 400 uranium-bearing surface boulders arranged in a broad but intermittent train following the youngest trend of glacial transport in the area. A second train similar boulders rich in molybdenum and copper has been identified to the south of the known mineralization. These are located in discharge sediments laid down as a result of an outflow from a glacial ice lake situated northwest of the mineralization. A futher 120 uranium-bearing surface boulders have been discovered about 700 m west from the known uranium subcrop. These differ in type from those described above having low molybdenum and copper contents, and are arranged in a boulder train which runs almost exactly north-south. The mineralization was found at the northern tip of this boulder train.

Résumé

Un grand nombre de blocs erratiques à forte teneur en uranium appartenant à des trainées de blocs distinctes ont été trouvés dans la région de Pahtavuoma dans le nord de la Finlande. La plus longue trainée de blocs se trouve au nord-est de l'affleurement d'uranium connu et se compose de plus de 400 blocs à teneur en uranium disposées à la surface en une trainée, large mais intermittente, suivant la tendance de transport glaciaire la plus récente dans la région. Une deuxième trainée de blocs semblables riches en molybdène et en cuivre a été repérée au sud de la minéralisation connue. Ces derniers gisent dans des sédiments de décharge d'un lac glaciaire situé au nord-ouest de la minéralisation. Une autre trainée de 120 blocs de surface riches en uranium a été découverte à environ 700 m à l'ouest de l'affleurement uranifère connu. Ces blocs diffèrent des blocs des trainées précitées par leur faible teneur en molybdène et en cuivre, et sont disposés en une trainée qui est orientée presque exactement dans l'axe nord-sud. On a détecté la présence de la minéralisation à la pointe nord de cette trainée de blocs.

[1] Geological Survey of Finland, Department of Quarternary Geology, SF-02150 Espoo, Finland.
[2] Geological Survey of Finland, Department of Quarternary Geology, P.O. Box 77, SF-96101 Rovaniemi, Finland.

INTRODUCTION

The Pahtavuoma site near Kittilä is located in central Lapland, in the center of the Scandinavian glaciation area, about 140 km north of the Arctic Circle (Fig.1). The area is located within the ice divide zone, where glacial erosion has been slight. This is reflected by the abundance of preglacial weathered bedrock and organic deposits underlying till (Hirvas et al., 1977). In the area there are generally two till beds of different age, deposited from different directions (Fig. 2). The older till was deposited from the northwest (320 to 340°) and the younger one from the south-southwest (200 to 220°). The till cover of the area is thin, generally only 0.5 to 3.0 m thick. During the last deglaciation there were glacial lakes in the region (Kujansuu, 1967) which discharged to the southeast and south as the ice receded to the southwest.

Ore prospecting in the Pahtavuoma area began with the search for copper ore by the Outokumpu company (Inkinen, 1979). In connection with that work, molybdenum- and copper-bearing uranium mineralization was found (Fig. 3). A low-altitude airborne survey carried out by the Geological Survey found a radiometric anomaly northeast of the mineralization. When it was checked, a great number of uranium-rich boulders were found in the investigation area (Fig. 4). They form several different boulder trains, whose source rocks all have now been located.

Figure 1. The location of Pahtavuoma and the greatest extension of the Scandinavian ice sheet during the Weichselian glaciation. The arrows show the directions of ice flow in the immediate vicinity of the study area during the late Weichselian.

BOULDER TRAINS

The most extensive boulder train in the area lies northeast of the known uranium mineralization (Fig. 4). The train consists of over 400 uranium-bearing surface boulders, which form a wide but intermittent boulder train. It is 1.9 km long and 500 m wide. The boulder train reaches its greatest boulder density at a distance of 900 to 1000 m from the known mineralization. After this point, the boulder density drops clearly and the form of the boulder train becomes scattered.

Because there were separate concentrations of boulders in this boulder train, it had to be clarified whether all the boulders of the train originated from the uranium mineralization already known, or from several different sources. For this purpose, 38 test pits were dug by tractor excavator into the boulder train, and about 70 new uranium-bearing boulders were found. All the boulders were found in the younger till, which was deposited from the south-southwest.

The direction of glacial flow according to the results of till fabric analyses and orientation of striae is south-southwest towards north-northeast, which supports the idea that the boulders originate from the known mineralization. Except for 20 boulders in the north-northeast part of the train, the boulders are of the same type (molybdenum- and copper-bearing) as the known mineralization. Because the boulders form a continuous train from the known mineralization, except in the peatlands, it is evident that the

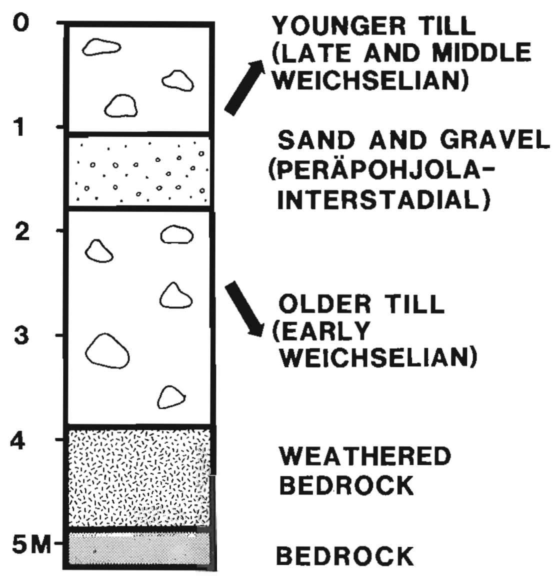


Figure 2. Typical till stratigraphy of the Pahtavuoma area.

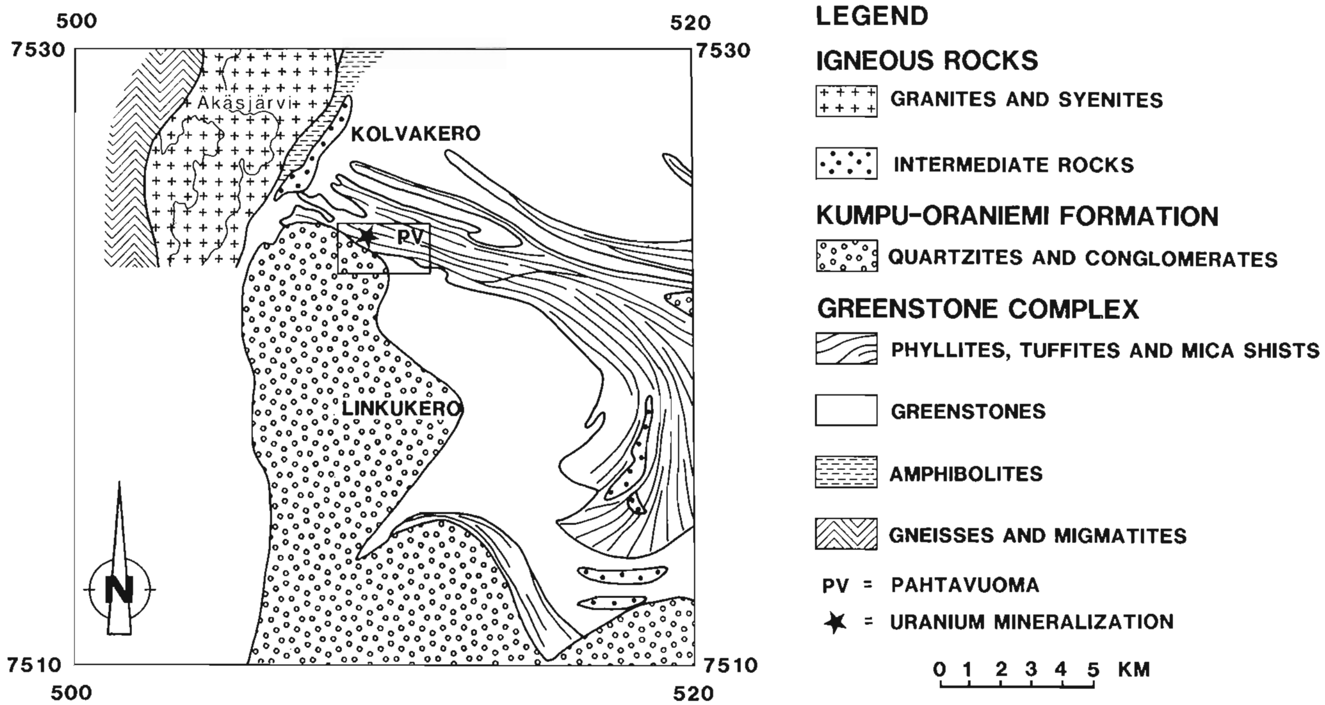


Figure 3. The uranium mineralization found by the Outokumpu company and the bedrock of the study area according to Inkinen (1979).

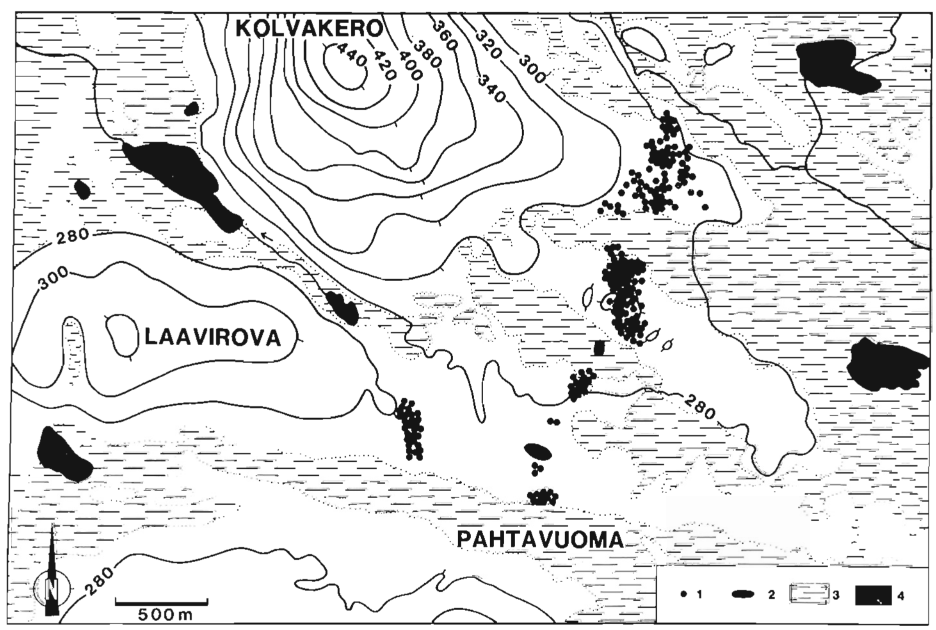


Figure 4. The uranium-rich boulders found in the area and the uranium mineralization found by the Outokumpu company. (1 = uranium-rich boulder, 2 = uranium mineralization, 3 = peatland, 4 = lake)

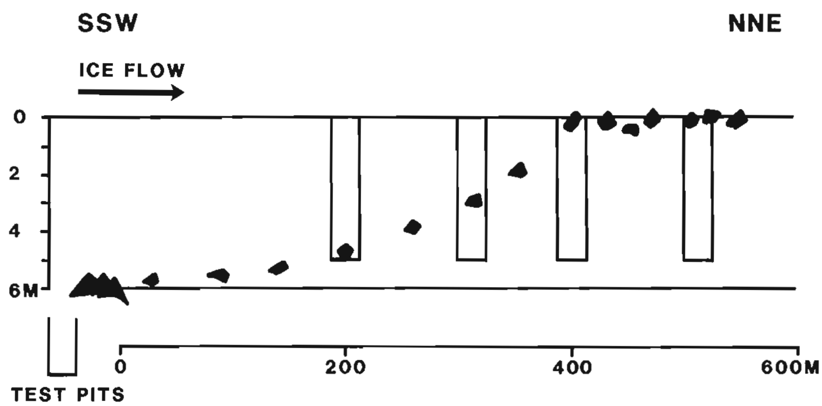


Figure 5. Schematic drawing of the stratigraphic position of the uranium-rich boulders in the younger till from the mineralization in the direction of glacial flow.

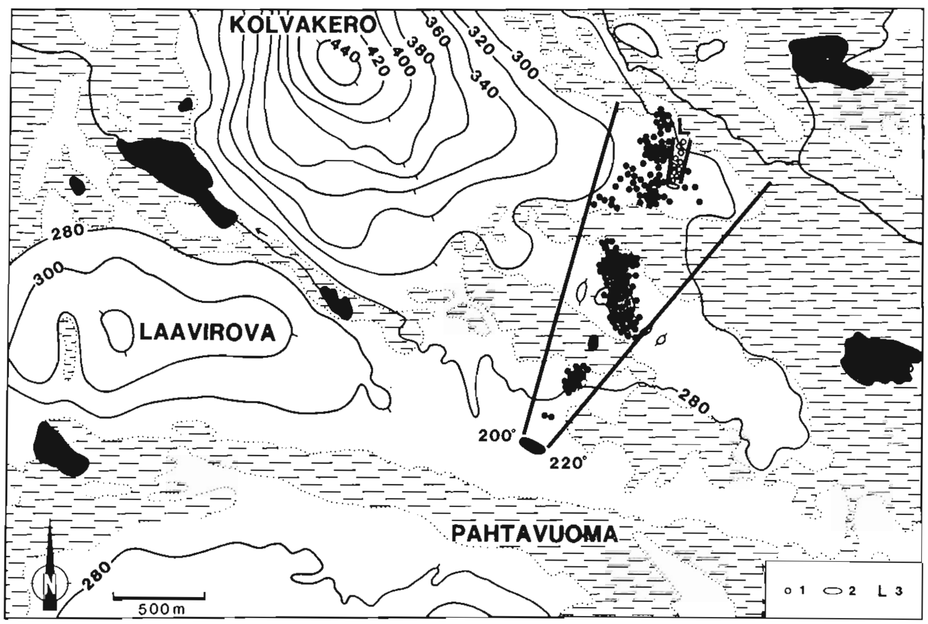


Figure 6. A small local boulder train (low in molybdenum and copper) within the large boulder train (high in molybdenum and copper). (1 = uranium-rich boulder from local mineralization, 2 = local mineralization, 3 = local boulder train. Other symbols explained in Fig. 4.)

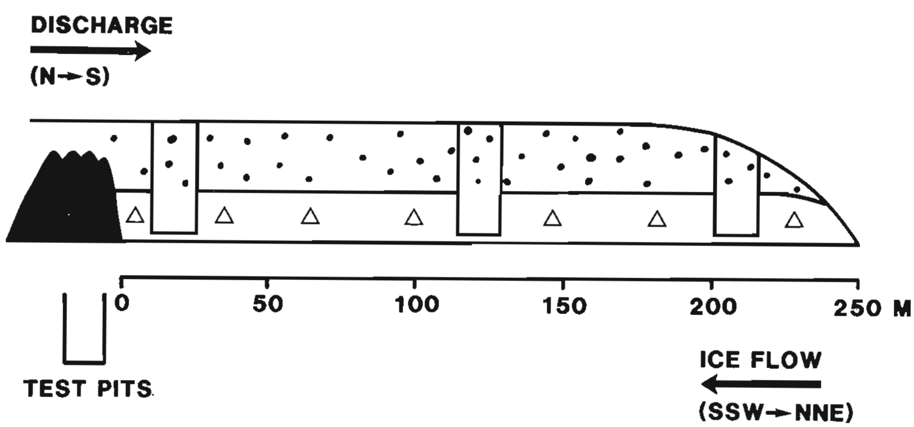


Figure 7. Schematic drawing of the stratigraphic position of uranium-rich boulders in discharge gravel south of the known mineralization. The discharge waters have eroded away the younger till from the mineralization (cf. Fig. 5).

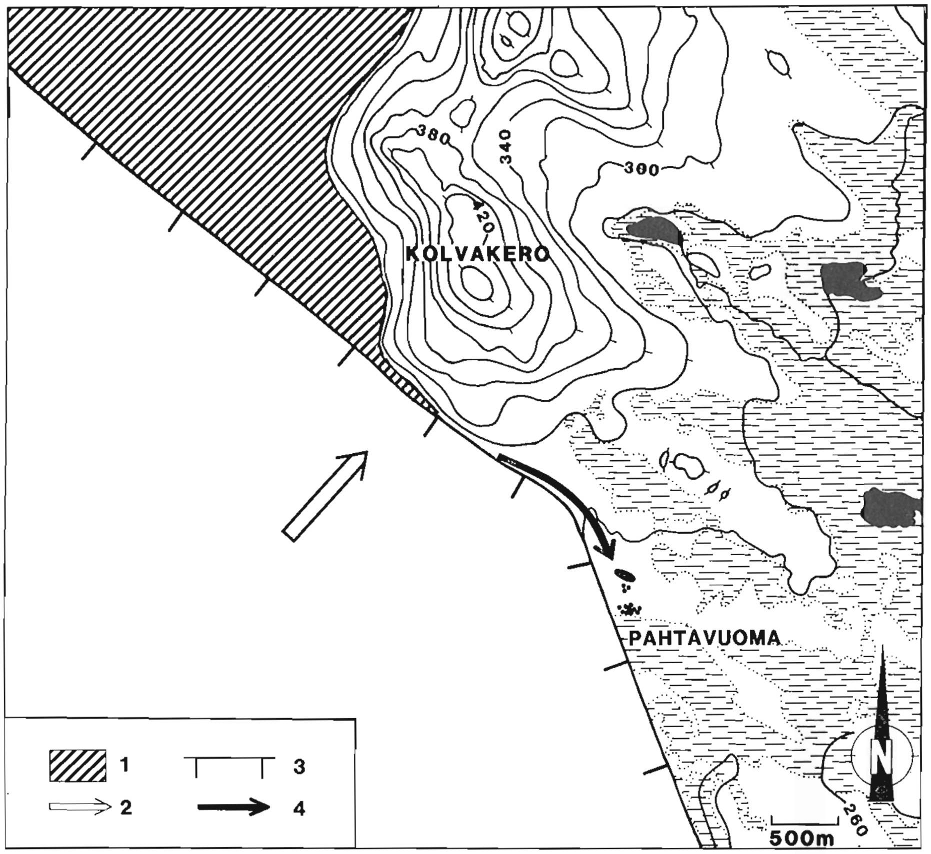


Figure 8. Transport of uranium-rich boulders, found south of the known mineralization, by discharge of the glacial lake (293 m asl) dammed west of Kolvakero. (1 = glacial lake, 2 = ice flow direction, 3 = ice margin, 4 = direction of discharge. Other symbols explained in Fig. 4.)

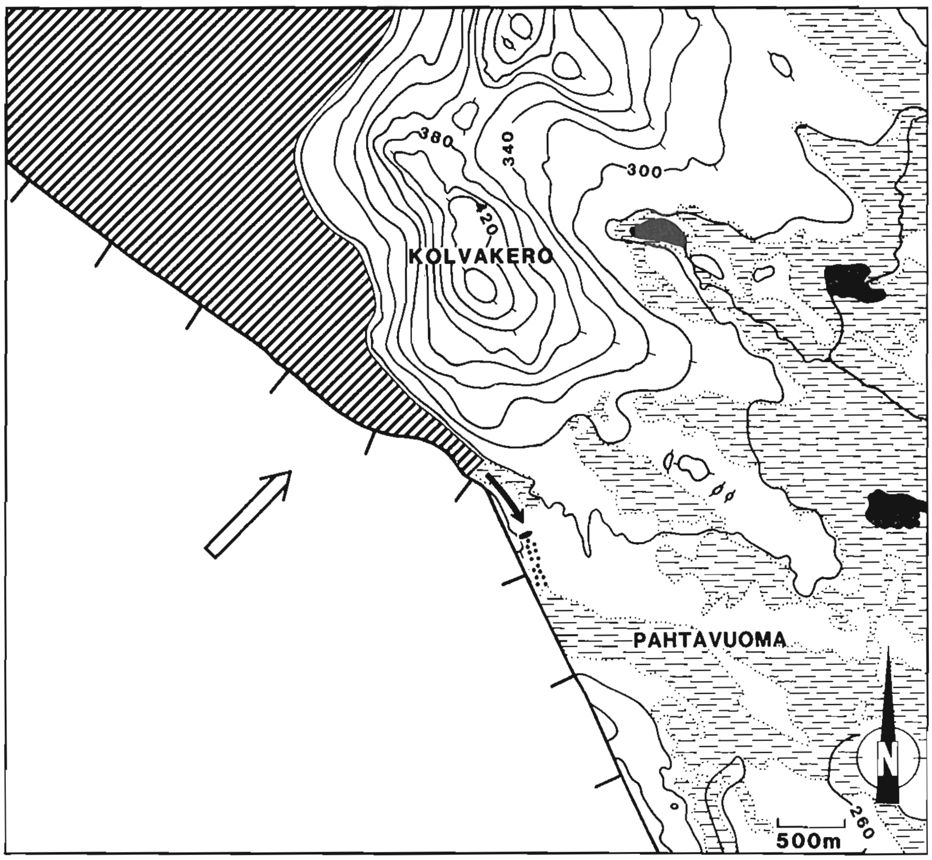


Figure 9. Transport of uranium-rich boulders found in the western part of the area by discharge of the glacial lake (276 m a.s.l.) dammed west of Kolvakero. (Symbols explained in Figures 4 and 8).

molybdenum- and copper-bearing boulders really originate from this mineralization. This conclusion is also favored by the stratigraphic position of the boulders. In the test pit closest to the mineralization, which is 200 m north-northeast of it, there are boulders only at the base of the younger till, and farther away, in the direction of glacial transport, there are boulders only in the surface part of the same till bed, which shows the shearing effect of the glacier (Fig. 5).

In the north-northeast part of the boulder train, there are twenty uranium-rich boulders with a low content of molybdenum and copper, differing from the main type of the train. Their source rocks were traced separately. Investigations showed these boulders to be quite local, and their source rock was only a few metres away in the up-ice direction. The difference in directions of glacial transport is probably due to the effect of Kolvakero hill (see Fig. 4) on the local direction of ice flow. Therefore, inside the large boulder train there is a small, local boulder train (Fig. 6), where the direction of ice flow according to striae observations is 190 to 195°, somewhat differing from the main direction.

South of the mineralization found by Outokumpu, there is another concentration of boulders, which are of the same type (with a high molybdenum and copper content) as in the large boulder train just described (Fig. 4). The boulders occur entirely within a deposit of sand and gravel on top of the till (Fig. 7). The boulders are not rounded, which means that the distance of transport was short. In the younger till bed underlying the deposit of sand and gravel, no uranium-rich boulders were found. The sand and gravel deposit was formed during the deglaciation phase, when the glacial lake west of Kolvakero was discharged (Fig. 8). The boulders of this train did not travel with the glacier, but the discharge waters from the glacial lake loosened the boulders directly from the fissured and weathered surface of the ore outcrop and deposited them in the discharge delta.

West of the main boulder train (Fig. 4), 120 uranium-bearing surface boulders were found. They represent a type that differs from the uranium-rich boulders of the trains mentioned before. The molybdenum and copper content of these boulders is low. The boulders form a train aligned almost north-south with a length of 450 m and a width of only 50 m. In the test pits that were made into the train, a great number of new uranium-rich boulders were found. All boulders are located in the discharge sediments of the ice-dammed lake. No uranium-rich boulders were found in the younger or in the older till bed found under the discharge deposit. The stratigraphic position and mode of transport of the new boulders correspond to those of the train in Figure 8, that is, the boulders have been transported only by the waters of the discharging glacial lake (Fig. 9). The northern end of the boulder train is on the mineralization that was found in connection with the boulder tracing. In the northern end of the boulder train, near the mineralization, the boulders are considerably larger and more angular than in the southern end.

SUMMARY

In the area of Pahtavuoma there are boulder trains and concentrations formed by both glacial transport and discharge waters. The glacial transport was towards the north-northeast, while the flowing water transported the boulders in an entirely different direction, from north to south.

The uranium mineralization located by Outokumpu has yielded two boulder trains, one of them formed by the younger glacial transport and the other by the waters discharged from the ice-dammed lake. In the distal part of the largest boulder train a small occurrence of uranium mineralization was found, which has yielded a small local boulder train inside the main train.

In the Pahtavuoma area, locating the source rock for the uranium-rich boulders was facilitated by different factors: thin Quaternary cover, the directions of glacial transport are clear, the distances of transport are short, and the boulders are easy to identify because of their radioactivity.

REFERENCES

Hirvas, H., Alfthan, A., Pulkkinen, E., Puranen, R., and Tynni, R.
1977: Raportti malminetsintää palvelevasta maaperätut-kimuksesta Pohjois-Suomessa vuosina 1972-1976. Summary: A report of glacial drift investigations for ore prospecting in northern Finland 1972-1976; Geological Survey of Finland, Report of Investigation 19, 53 pp.

Inkinen, O.
1979: Copper, zinc, and uranium occurrences at Pahtavuoma in the Kittilä Greenstone Complex, Northern Finland; Economic Geology, v. 74, pp. 1153-1165.

Kujansuu, R.
1967: On the deglaciation of western Finnish Lapland; Bulletin de la Commission Geologique de Finlande, no. 232, 98 pp.

Transportation of garnets in glaciofluvial deposits in southeastern Finland

Marjatta Perttunen[1]

Perttunen, M., Transportation of garnets in glaciofluvial deposits in southeastern Finland; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 13-20, 1989.

Abstract

The transportation distance and mode of deposition of garnets from known source rocks were studied in the 1-0.5 mm size range on nine traverses in the esker systems crossing the Salpausselkä I and II end moraines.

The highest garnet values were found within 8 km of the source area. The garnets can be traced over a distance of 79.5 km extending from the source area to the Gulf of Finland, where some garnets still remained in the last sample site, having been concentrated by littoral processes. The highs were registered in the Salpausselkä end moraines, especially Salpausselkä II, while low values occur 1 to 2 km up-esker from Salpausselkä II. The Salpausselkä end moraines and eskers differ in their behavior with respect to garnet concentrations. The high-low variation in the garnet content between sampling sites results from the rhythm of deglaciation.

Résumé

La distance de transport et le mode de mise en place des grenats provenant de roches mères connues ont été étudiés, dans la fraction granulométrique de 1 à 0,5 mm, le long de neuf cheminements dans les systèmes d'eskers qui recoupent les moraines de Salpausselkä I et II.

La plus forte concentration de grenats a été trouvée à moins de 8 km de la région mère. Les grenats peuventétre suivis sur une distance de 79,5 km depius la région mère jusqu'au golfe de Finlande où on a noté la présence de quelques grenats, concentrés dans la dernière zone d'échantillonnage sous l'action de processus littoraux. Les fortes concentrations ont été relevées dans les moraines de Salpausselkä, notamment Salpausselkä II, tandis que les très faibles concentrations se trouvent à 1 ou 2 km en amont des eskers, à partir de Salpausselkäa II. En ce qui a trait aux concentrations de grenats, les moraines et les eskers de Salpausselkä présentent des caractères fort différents. Les variations de fortes à faibles des concentrations de grenats d'un point d'échantillonnage à l'autre sont fonction du rythme de la déglaciation.

[1] Geological Survey of Finland SF-02150 Espoo, Finland.

INTRODUCTION

The purpose of the study was to determine the distances of glacial transportation and mode of deposition of garnets from known source rocks, in order to understand better the sedimentation of glaciofluvial deposits as well as to assist mineral exploration. Previous work in the same context had been done by Lee (1965) in Canada.

Garnet was chosen as the indicator mineral because it is hard, resistant to abrasion and easy to identify. A suitable area for the study was found in southeastern Finland (Fig. 1), where the rapakivi granite does not contain garnets but is surrounded by a large area of garnetiferous rocks. The rapakivi granite area in southeastern Finland is extensive.

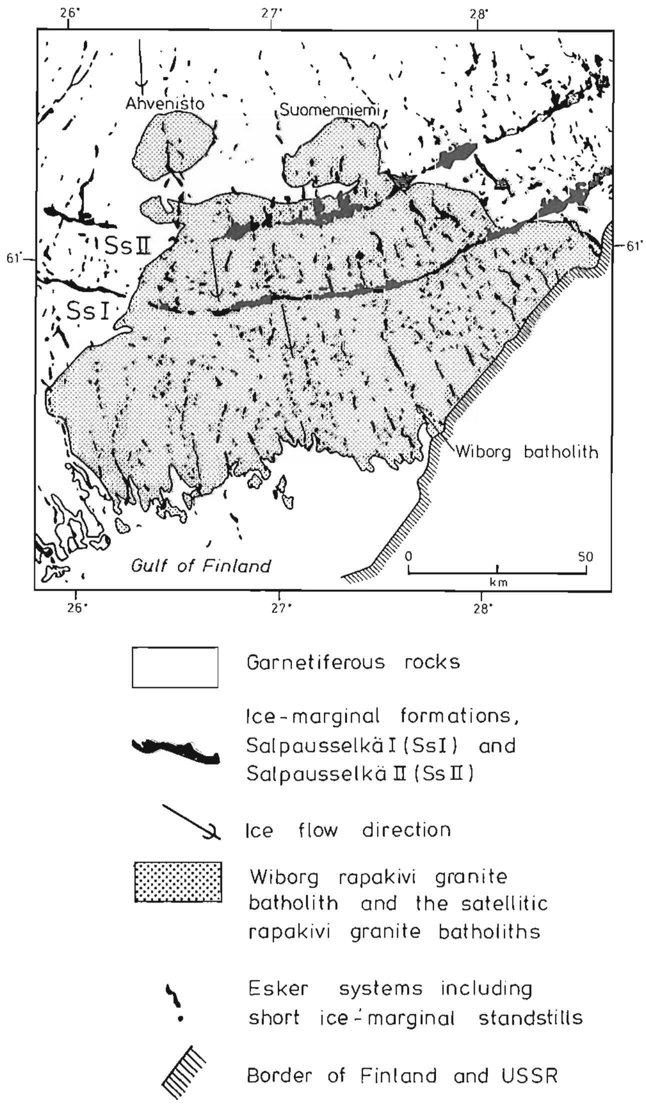


Figure 1. Generalized geological map showing bedrock (Simonen, 1980), (Salpausselkä I, Ss I, and Salpausselkä II, Ss II), esker systems including short ice-marginal stillstands (Kujansuu and Niemelä, 1984) and main ice-flow directions during the last Weichselian glaciation (Geological Survey of Finland, 1986).

The Wiborg batholith is about 18 000 km^2, the Ahvenisto batholith 242 km^2 and the Suomenniemi batholith is 365 km^2 (Vorma, 1976). Eskers of the Weichselian glaciation are abundant in the area, providing deposits that are easy to sample.

GLACIOFLUVIAL DEPOSITS AND THE SEDIMENTS

The most prominent landforms of Weichselian age are the Salpausselkä I and II (Ss I and Ss II) end moraines running west to east across the study area (Fig. 1). The eskers joining them have a roughly north-south trend, varying from southeast to southwest. In the Salpausselkä I foreland, the trend is the same. The eskers can be followed to the Gulf of Finland. Between Salpausselkä I and II, low-lying esker deltas indicate brief ice-marginal stillstands (Saarnisto, 1982). The eskers have some tributaries and contain ridges of different lengths and small separate hills. Salpausselkä I and II form ridges and marginal plains, sandur deltas and esker deltas. In the Salpausselkä I foreland, some separate hills of glaciofluvial deposits show brief ice-marginal stillstands; hence the eskers are not very uniform (Tynni, 1985).

Figure 2 shows nine traverses along the assumed flow directions of the glaciofluvial streams. Especially in the Ss I foreland, some of the traverses cross hills and ridges of two or three esker systems (J. Niemelä, pers. comm., Tynni 1985).

According to Saarnisto (1982), Salpausselkä II and most of the higher parts of Salpausselkä I are supra-aquatic, whereas many of the lower plains are shore terraces. The highest parts of the esker ridges in the Salpausselkä II hinterland and in the area between Salpausselkä I and II are supra-aquatic, but their slopes contain shore terraces

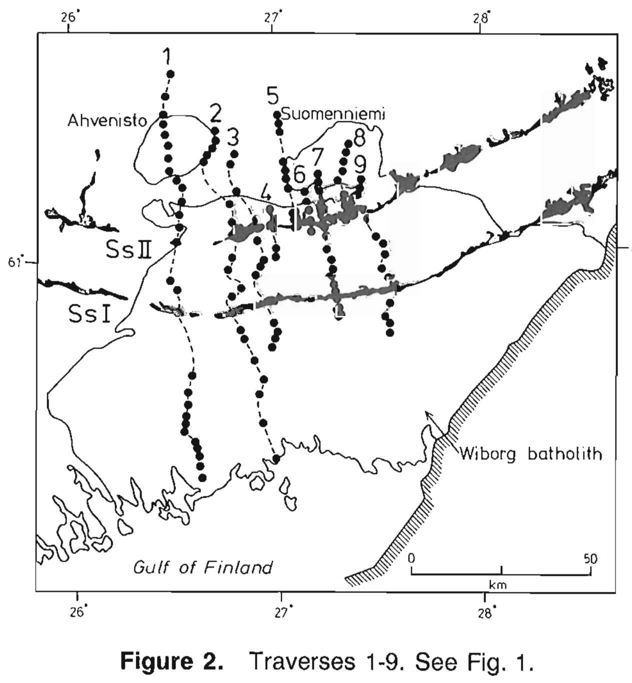


Figure 2. Traverses 1-9. See Fig. 1.

(H. Rainio, pers. comm.). In the Salpausselkä I foreland, widespread sandy-silty areas occur in the vicinity of eskers. Most likely they were originally glaciofluvial, but littoral forces have reworked them (Valovirta, 1972).

Typical sedimentary structures of eskers and esker deltas occur. The Salpausselkäs were formed during three stages in the glaciofluvial environment, by a readvancing ice sheet and by littoral processes (Hyyppä, 1951, cf., Saarnisto, 1982). The proximal glaciofluvial sediments of the ice-marginal formations of Salpausselkä I and II are in many cases till-covered, and the distal part regularly contains fine-grained sediments with cross-bedding and ripples.

The grain size of the sediments varies from cobbles, pebbles, gravel and sand to silt; usually there is a mixture of these grain sizes. According to the inventory of the gravel and sand resources of Finland done by Geological Survey of Finland (Kurkinen and Rainio, 1972, Koho, 1973), the glaciofluvial sediments in the study area are mainly fine-grained, especially in the Ss I foreland. Seismic soundings indicate the thickness of the deposits to vary in the eskers from a few metres to 20 m and in the Salpausselkäs up to 100 m.

The area lies between 0 and 159 m a.s.l. with a relief of 10 to 20 m. The land uplift in the area is at present 2 to 3 mm/y (Kakkuri, 1987). The elevations of the sample sites within the glaciofluvial deposits vary from 15 to 130 m a.s.l. for the eskers, from 80 to 115 m a.s.l. for Salpausselkä I and from 85 to 125 m a.s.l. for Salpausselkä II. The supra- aquatic area lies over 120 m a.s.l. in the hinterland of Salpausselkä I (Hyyppä, 1966).

BEDROCK GEOLOGY AND OCCURRENCE OF GARNETS

The study area is underlain by Precambrian bedrock, which belongs mainly to the postsvecokarelidic Wiborg rapakivi granite batholith, including the Ahvenisto and Suomenniemi rapakivi granites, with the gabbro-anorthosite surrounding the Ahvenisto rapakivi granite as a horseshoe arc (Fig. 1). These rocks are devoid of garnets. The surrounding rocks to the north, northwest and west of the rapakivi granite area belong to the so-called Savo schist area, of the Precambrian Svecokarelidic orogenic belt, which includes garnetiferous metapelitic rocks like granite, mica gneiss, cordierite gneiss and quartz-feldspar gneiss (Simonen and Lehijärvi, 1963, Simonen and Tyrväinen, 1965, 1981, Simonen, 1965, 1975, 1978, 1980, 1982, Lehijärvi and Tyrväinen, 1969 and Tyrväinen, 1986). The granites and mica gneisses are rich in garnets, with grains ranging in size from less than 0.5 mm to 2 cm in diameter. The garnet content in the rocks surrounding the Ahvenisto batholith varies between 1.1 and 4.2 % (Savolahti, 1956) while farther to the north, it varies between 0.7 and 4.1 % (Simonen, 1982).

The terrain is undulating. The bedrock is very well exposed in places, mainly in the Salpausselkä II hinterland. The well-exposed zone extends about 35 km north of this moraine (Kujansuu and Niemelä, 1984). According to Lundqvist (1987), this exposure area could be caused by glaciodynamic factors conducive to erosion. In other parts of the study area, good exposures are also common, except in the Salpausselkä end moraines.

METHODS

Field methods

Samples from 481 sites along nine traverses were collected over an area of 8 400 km^2 along the esker systems and the end moraines, Salpausselkä I and Salpausselkä II (Fig. 2). Gravel pits were used for sampling, where available; otherwise pits were dug and samples taken at a depth of one metre. Samples were collected from the cores of the eskers, avoiding slopes where shore accumulations commonly occur. Samples were collected from the upper or basal portion of the gravel pits above ground-water level. The material collected varies in grain size. The ''coarse material'' discussed in this paper consists predominantly of cobbles, pebbles and gravel, but the ''fine material'' contains a certain amount of gravel and/or sand (Figs. 3 and 4).

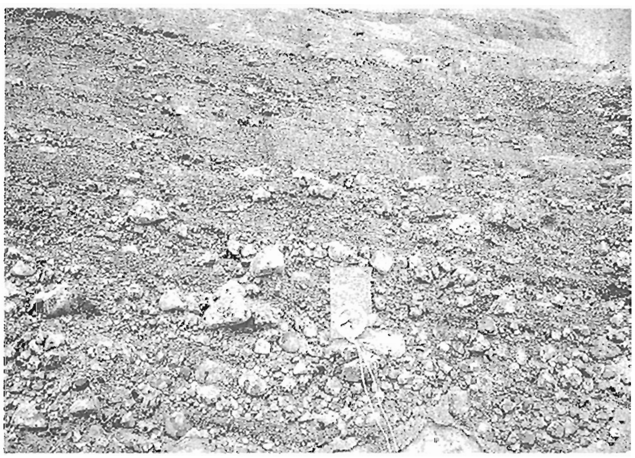


Figure 3. Coarse grained sediment, consisting of cobbles, pebbles and gravel. Compass 12 cm in length.

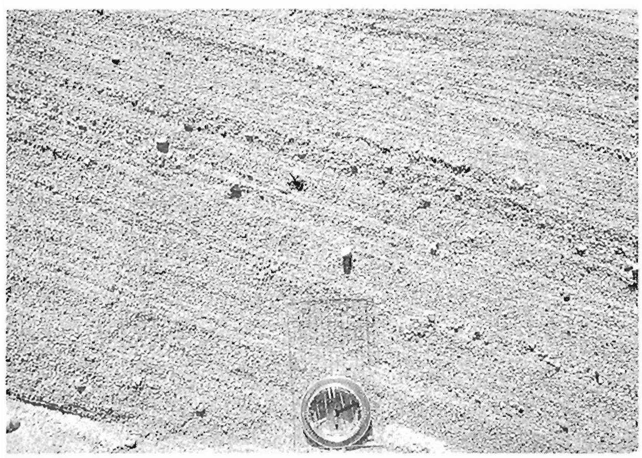


Figure 4. Fine-grained sediment, consisting of gravel and sand. Compass 12 cm in length.

Samples were sieved in the field to minus 4 mm; 10 litres of this material were then panned in the field in preparation for laboratory treatment. During sieving, 200 pebbles, ranging in size from 2 to 10 cm, were collected from 106 sampling sites for pebble counts. If the sample did not contain fragments over 2 cm, pebbles were collected elsewhere in the gravel pit, if available.

Laboratory methods

The minus 4 mm panned concentrates were dried at 80° C, and sieved into 4 to 2 mm, 2 to 1 mm, 1 to 0.5 mm and <0.5 mm fractions. The heavy minerals of the 1-0.5 mm fraction were further isolated with bromoform (s.g. = 2.810 to 2.830). The light and heavy fractions were then weighed. The magnetite was separated with a small hand magnet and the nonmagnetic heavy mineral fractions (hereafter "heavy mineral fraction"), were weighed.

Three hundred grains of heavy minerals, in the 1 to 0.5 mm size range, were split from each sample, the garnets were identified and counted using a binocular microscope, and the percentages calculated. Other fractions were kept for future studies.

GARNETS IN THE GLACIOFLUVIAL SEDIMENTS

In the 1 to 0.5 mm fraction, garnets occur as mineral grains or as grains in rock fragments. The most common garnet is an almandine (s.g. = 3.93 to 4.32, Deer et al., 1982, and Mineral Data of Finland, Geological Survey of Finland, Petrological Department). Its colour is mainly pink. Some red garnets have been found. Based on microprobe analyses (B. Johansson, Geological Survey of Finland), all the grains are almandine, with different chemical compositions. Near the contact with rapakivi granite, the range of MgO (5.0 to 5.3 %) and MnO (0.1 to 1.0 %) in the metapelitic garnets is significant (Korsman, 1977). The almandine grains are mostly angular and very angular, some being subangular and subrounded (Fig. 5). Some euhedral almandines as well as broken rounds have been found (Pettijohn, 1975).

DATA AND DISCUSSION

The transport and deposition of garnets in the 1 to 0.5 mm fraction have been studied along nine traverses in the esker systems, except in the Ss I foreland, where the gravel pits available for sampling may represent two or three different esker systems (Fig. 2). The traverses cross the Salpausselkä I and II end moraines. Along the longest traverse, the garnets can be traced over a distance of 79.5 km.

The transport and deposition of garnets from the source area into the non-garnetiferous rapakivi granite area will be discussed in detail for traverses 2, 3 and 7 (Figs 6, 8 and 9). A summary of all traverses will be given in the conclusions. As regards their behavior, the garnets can be divided into

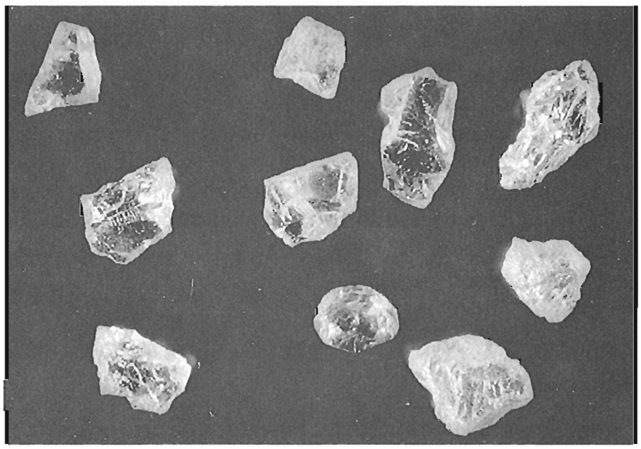


Figure 5. Garnet grains of almandine type in the size range of 1 to 0.5 mm. Colour is pink. Photo: J. Väätäinen.

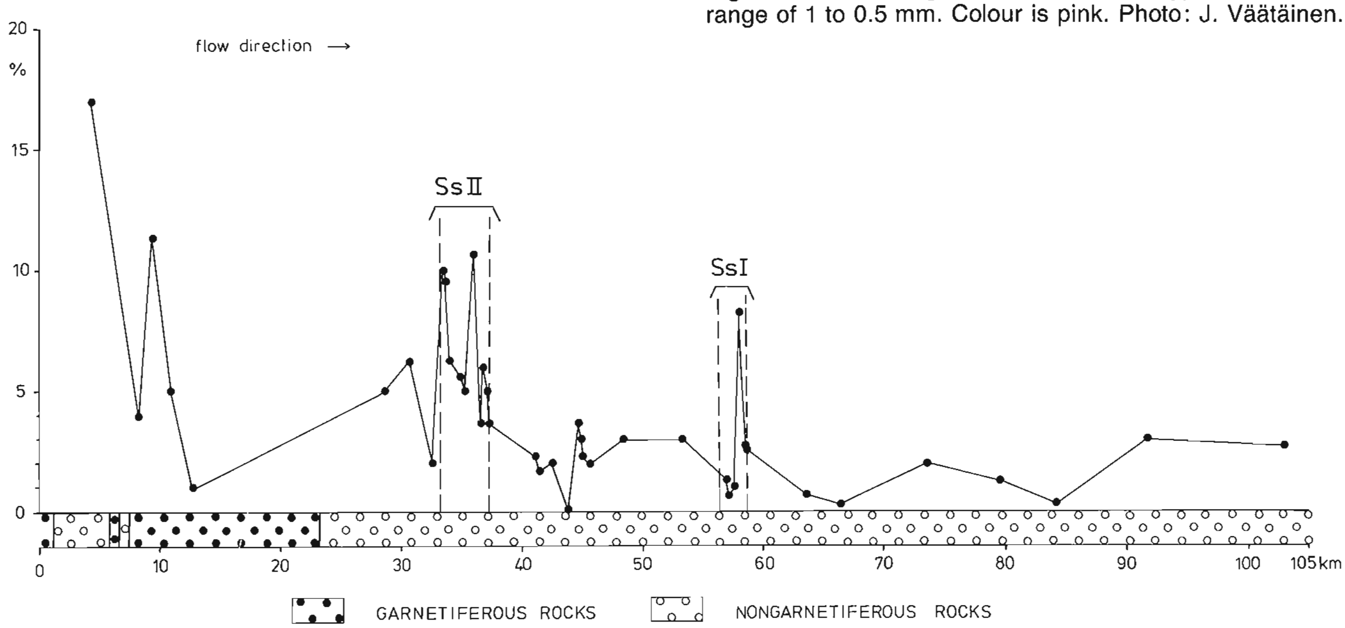


Figure 6. Transport of garnets along traverse 2.

five groups: 1) the glaciofluvial systems (mainly esker chains) in the Salpausselkä II hinterland; 2) Salpausselkä II (Ss II), 3) the glaciofluvial systems (mainly esker chains in the area between Salpausselkä II and I); 4) Salpausselkä I (Ss I); and 5) the glaciofluvial systems (mainly esker chains) in the foreland of Salpausselkä I.

The Traverses

Traverse 2

The garnet source area of traverse 2 (Fig. 6) is the large garnetiferous bedrock area, cut for a short distance by gabbro-anorthosite, which is devoid of garnets. The length of the traverse beyond the source area (from the contact of the rapakivi granite) is 79.5 km.

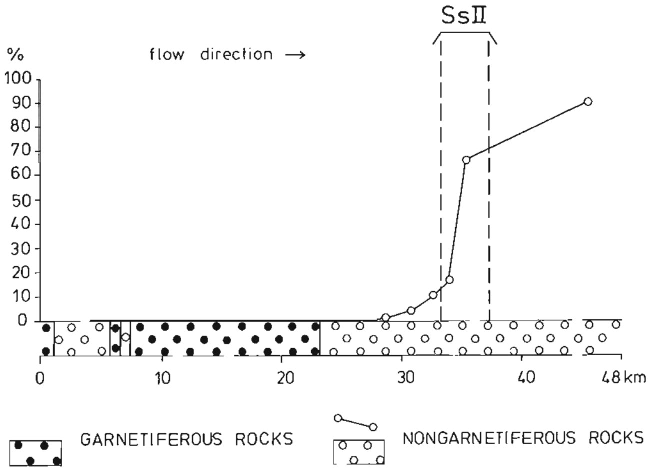


Figure 7. Transport of rocks along traverse 2.

As might be expected, the percentage of garnets in the glaciofluvial deposits in the garnetiferous bedrock area is high, up to 17 %, but values as low as 1 % were also found.

In the Ss II hinterland, 5.4 to 7.5 km down-esker from the source area, the percentage of garnets is 5 to 6.3 %. Within 1 km up-esker from Ss II, the garnet content has decreased to only 2 %. This is also the case along other traverses. In Ss II, the garnets show highs of 10 to 10.7 %, though values of 3.7 to 6.3 % were also found. Between Ss II and Ss I, the percentages have fallen to 0 to 3.7 %; Ss I has a high of 8.3 % and low values of 0.7 to 2.7 %.

Down-esker from Ss I, the garnets have decreased to constant low percentages, 0 to 3 %, though as far as 79.5 km from the source area, at the end of the traverse, a surprising high of 3 % occurs. The most probable explanation for this is that the area in the Ss I foreland, 15 to 65 m a.s.l., was covered by postglacial seas and lakes (Hyyppä, 1966, Valovirta, 1972). The concentrating influence of the littoral processes, although slight owing to their brevity (J. Donner, pers, comm.), may have affected the garnet percentage.

Pebble counts (Fig. 7) from the glaciofluvial deposits along the traverse show that non-garnetiferous rocks (rapakivi granite and gabbro-anorthosite) appear (6 %) in the eskers at a distance of 8 km from the contact of these rocks. At 10 km, the content of these pebbles increases to 66 %, and at 20 km they predominate (90 %). Whereas the non-garnetiferous rocks have increased, the garnetiferous rocks have decreased. These rocks were crushed and abraded faster than the garnets in the fine grain sizes, as is well known from till transport studies (Perttunen, 1977).

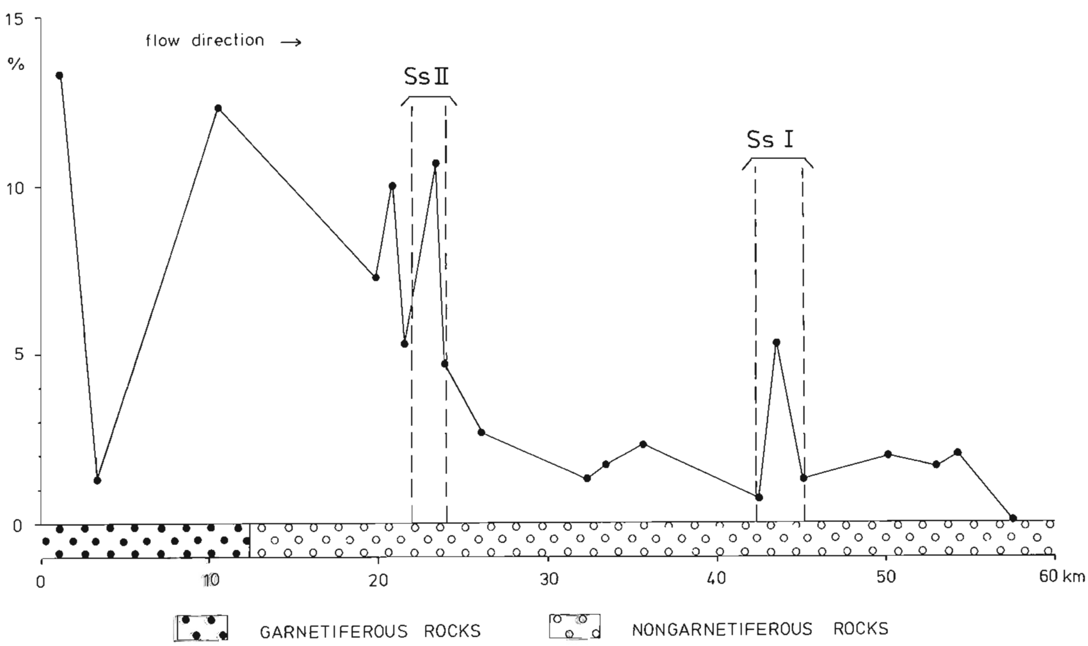


Figure 8. Transport of garnets along traverse 3.

Traverse 3

In the garnetiferous bedrock area, the garnets (Fig. 8) are abundant (12.3 to 33.3 %) in the glaciofluvial deposits, but a low value, 1.3 %, was also found. Down-esker from the source area, the lowest value (5.3 %) lies within 0.5 km of Ss II. Ss II has a high of 10.7 % as well as a lower percentage, 4.7 %, in the distal portion. Between Ss II and Ss I, the garnets have decreased to 1.7 to 2.7 %. Again, there is a high of 5.3 % in Ss I and low values of 0.7 to 1.3 %. Down-esker from Ss I, the garnets are 1.7 to 2 % and the traverse ends with the garnet content down to zero. Evidence from other traverses indicates that this does not represent final transport and deposition, but rather the normal high-low variation between sample sites.

Traverse 3 exhibits features similar to traverse 2 and they represent the western part of the area studied.

Traverse 7

The traverses (Fig. 9) of the eastern part of the area studied, differ from those in the western part. The first two sample sites on traverse 7 are situated in the distal portion of the Suomenniemi rapakivi granite batholith, 10.5 to 11.6 km from its contact. The garnets, having been transported at least 10.5 km, represent 3.7 to 11.3 % of the grains counted. In the following 4 km of garnetiferous bedrock, the garnets have increased to amounts of 18.7 % in a narrow esker. After a decrease to 5 % in the rapakivi granite area 1 km up-esker from Ss II, the high in Ss II is 17.7 %. This is almost the same content found in the eskers in the garnetiferous bedrock area. Ss II has one garnet content of only 1 %. Very low garnet percentages and a high-low variation between Ss II and Ss I can be noted along the traverse. In the middle of the traverse, between Ss II and Ss I, the behavior of the garnets is different from that observed along the traverses in the western part of the area. The garnet content increases, although the distance from the source area increases. An exceptional increase of garnets to 8 % occurs in a small ice-marginal esker delta and continues down-esker with amounts of 8 to 8.3 % in the Ss I foreland. According to the pebble counts, rapakivi granite (the non-garnetiferous rock) predominates at the site where the percentage of garnets has increased (Fig. 9). This shows the difference in the behaviour of the fractions in transport and deposition. The Ss I sample site on this traverse is not a high in garnets.

According to some researchers (Hyyppä, 1951, Rainio, 1985), the Weichselian ice sheet had retreated inland before readvancing and depositing Salpausselkä I. The eskers in the Ss I foreland and some in the hinterland were formed by the ice sheet that retreated inland before Ss I was deposited. This behaviour does not explain all the high garnet contents starting in the mid-hinterland of Ss I on the eastern traverses (Fig. 9). The explanation has to be found in the glacial geology — especially the glaciodynamics of the ice sheet (Drozdowski, 1985, Lundqvist, 1987), which has not yet been studied.

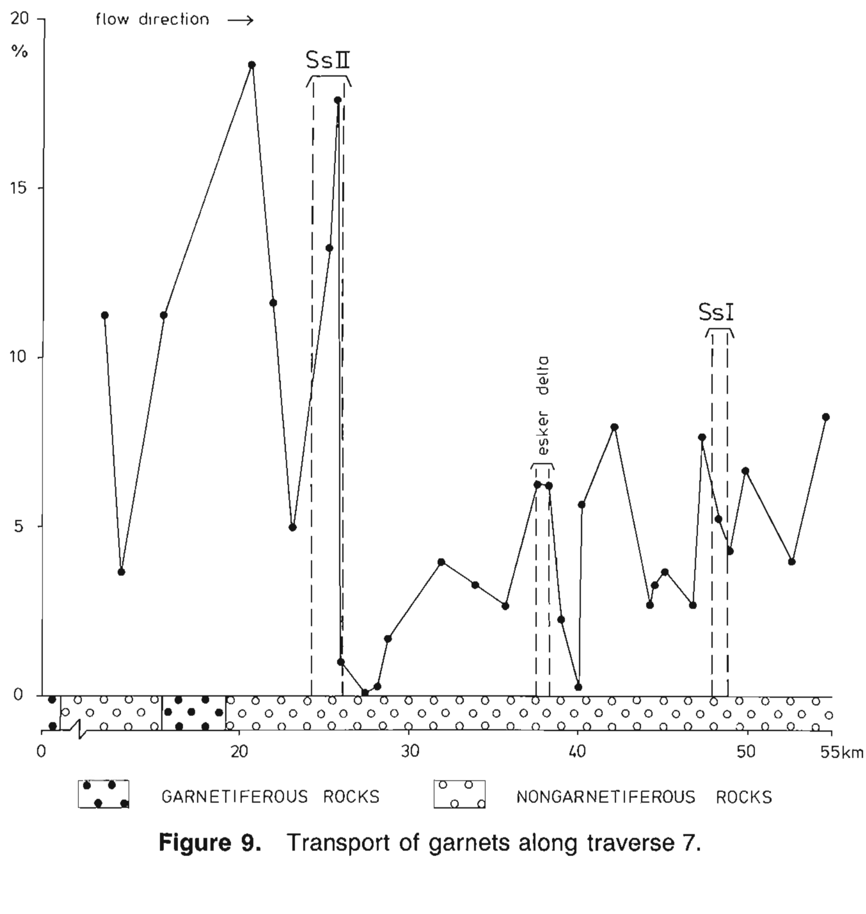


Figure 9. Transport of garnets along traverse 7.

CONCLUSIONS

The percentages of garnets in the samples from the nine traverses, in relation to the distance from source area, are shown on Fig. 10. They exhibit a distinct high, close to the source, and a stepwise decline away from it. A simple model of garnet transport has been derived from this diagram (Fig. 11), in which three levels of garnet abundance are identified and explained.

High garnet contents (11.0 to 40.0 percent) occur within 8 km of the source. At its widest, this zone extends to Ss II, which shows a high in every case. This shows the concentration of heavy minerals during stillstands of the ice sheet. The Salpausselkä moraines and eskers differ with respect to their garnet concentrations. Glaciofluvial sedimentation plays an important role, as shown by Shilts (1984). However, low contents are also common in the eskers and Salpausselkäs. This high-low variation in the garnet content between sample sites (Figs. 6, 8, 9) can be attributed to the fact that the amount of sediment transported and deposited varied greatly in accordance with the rhythm of deglaciation. There is a difference in the transport and deposition mechanism of the till and glaciofluvial deposits.

Intermediate garnet contents (highs in the range of 3.0 to 11.0 percent) occur between Ss II and I. From Ss II, in the high-abundance zone, the percentages drop steeply between 8 and 37 km from the source area. Low and zero contents are also common. Ss I, where this zone ends on western traverses 1 to 4, shows the lowest peaks for the most part. The intermediate level continues exceptionally on eastern traverses into the Ss I foreland.

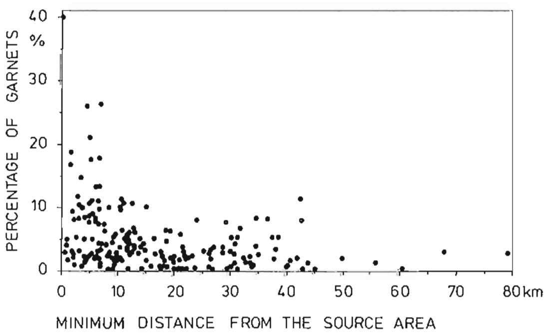


Figure 10. Transport distances of 1 to 0.5 mm garnets, all samples, shown from the source area. The distance from the source area is measured from the contact of the rapakivi granite areas.

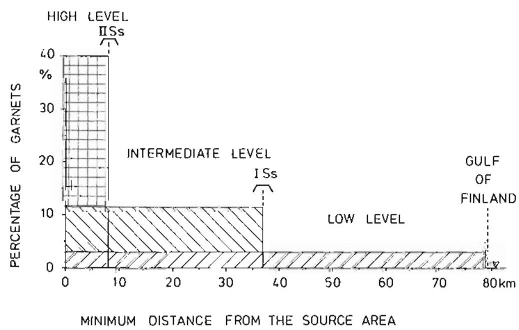


Figure 11. Simplified model of the transport and deposition of garnets from the source area, based on the diagram in Fig. 10.

Low garnet contents (3.0 to zero percent) are found between 37 and 79.5 km from the source area in the Ss I foreland.

The data gathered from this study permit some broad-scale applications to sedimentologic questions, in particular to variations in garnet contents with grain-size (in coarse sediments, 20 cm to 2 mm, vs. fine sediments 6 mm to 0.2 mm), as well as variations in the depth of deposits. The amounts of garnets 1.0 mm to 0.5 mm in diameter contained in coarse and fine surficial sediments in relation to distance from source area is shown in Figure 12. Close to the source area, the coarse sediments have higher garnet

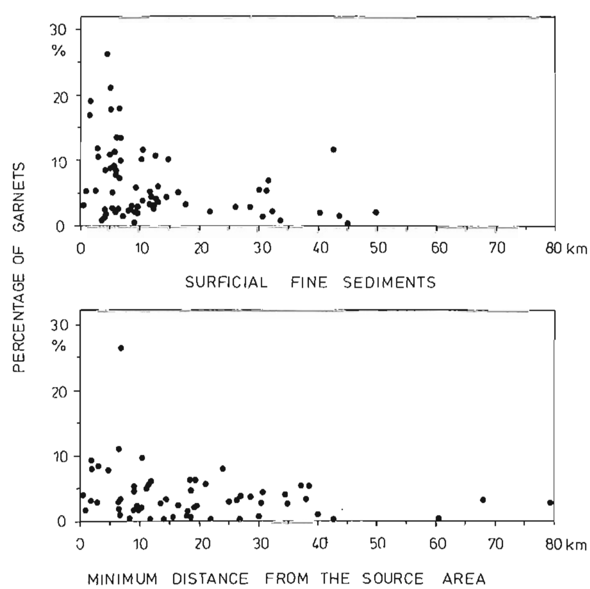


Figure 12. Percentage of 1 to 0.5 mm garnets versus distance from source area: a) in surficial coarse sediments, b) in surficial fine sediments.

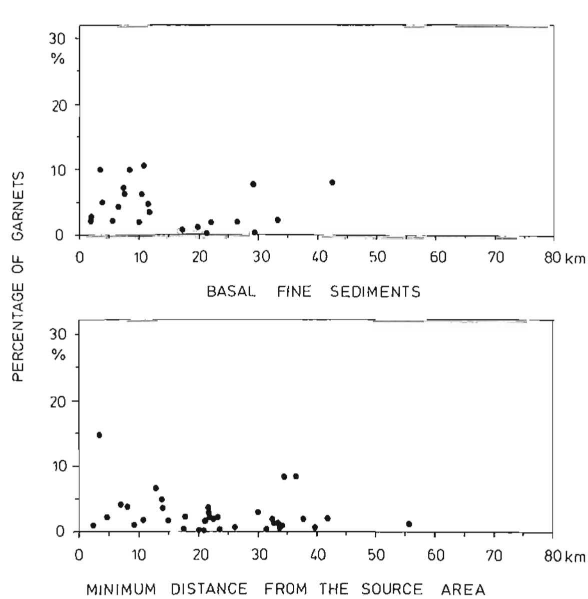


Figure 13. Percentage of 1 to 0.5 mm garnets versus distance from source area: a) in basal coarse sediments, b) in basal fine sediments.

contents than the fine ones (<26 per cent vs. <11 per cent). At intermediate distances, the contents are the same in coarse and fine sediments, whereas at >45 km garnets are sparse or non-existent in the coarse but sporadic in the fine sediments. This suggests a longer garnet transport distance in fine sediments.

In basal sediments, the amounts of garnet do not seem to differ markedly between coarse and fine sediments (Fig. 13), although somewhat higher contents appear in coarse sediments close to the source area.

Regarding the garnet content in the main eskers and a few small tributary eskers, no significant differences were found at similar distances from the source area.

Applied to practical exploration problems, this study shows that large amounts of garnets (or minerals with a similar specific gravity and hardness) indicate a close source area. This is an expected conclusion. The converse is not necessarily true; low contents are encountered close to the source as well as distant from it. Initial discovery of a low content should therefore be followed up by detailed studies to establish the broader pattern of distribution.

In the light of the encouraging results obtained from the study of garnet transportation, it is intended that further studies including other heavy minerals will be carried out in the future.

ACKNOWLEDGMENTS

I am most grateful to J. Kauhanen and R. Sivonen for panning of the samples.

REFERENCES

Deer, W.A., Howie, R.A., and Zussman, J.
1982: Rock-forming minerals. Vol. 1A. Orthosilicates; Longman Group Limited, USA. Second edition, 919 p.

Drozdowski, E.
1985: On the effects of bedrock protuberances upon the depositional and relief-forming processes in different marginal environments of Spitsbergen glaciers; Palaeogeography, Palaeoclimatology, Palaeoecology, v. 51, p. 397-413.

Geological Survey of Finland
1986: Striations, eskers and ice-marginal formations; unpublished map, 1:4 000 000 scale, Department of Quaternary Geology.

Hyyppä, E.
1951: Kuvia Salpausselän rakenteesta. On the Structure of the First Salpausselkä; Geologi, v. 3, no. 2-3, p. 5-7.

Hyyppä, E.
1966: The Late-Quaternary land uplift in the Baltic sphere and the relation diagrams of the raised and tilted shore levels; Annales Academiae Scientiarum Fennicae, Serie A III, v. 90, p. 153-168.

Kakkuri, J.
1987: Character of the Fennoscandian land uplift in the 20th century; in Fennoscandian Land Uplift, ed. Marjatta Perttunen; Geological Survey of Finland, Special Paper 2, p. 15-20.

Koho, S.
1973: Soravarojen arviointi TVL:n Kymen piirissä I — IV. (Gravel and sand resources of Finland; an inventory project 1971-78); Geological Survey of Finland, XIII, 247 p.

Korsman, K.
1977: Progressive metamorphism of the metapelites in the Rantasalmi Sulkava area, southeastern Finland; Geological Survey of Finland, Bulletin 290, 82 p.

Kujansuu, R. and Niemelä, J.
1984: Quaternary deposits of Finland; map 1:1 000 000 scale, Geological Survey of Finland.

Kurkinen, I. and Rainio, H.
1972: Soravarojen arviointi TVL:n Mikkelin piirin länsiosassa. (Gravel and sand resources of Finland; an inventory project 1971-78); Geological Survey of Finland, 94 p.

Lee, H.A.
1965: Investigation of eskers for mineral exploration; Geological Survey of Canada, Paper 65-14, p. 1-20.

Lehijärvi, M. and Tyrväinen, A.
1969: Pre-Quaternary rocks, sheet 3114, Vuohijärvi; Geological Map of Finland, 1:100 000, Geological Survey of Finland.

Lundqvist, J.
1987: Glaciodynamics of the Younger Dryas marginal zone in Scandinavia; Geografiska Annaler, Series A, v. 69 A, no. 2, p. 305-319.

Perttunen, M.
1977: The lithologic relation between till and bedrock in the region of Hämeenlinna, southern Finland; Geological Survey of Finland, Bulletin 291, 68 p.

Pettijohn, F.J.
1975: Sedimentary rocks; Harper & Row, Publishers, Inc. New York, Third edition, 628 p.

Rainio, H.
1985: Första Salpausselkä utgör randzonen för en landis som avancerat pä nytt; Geologi, v. 37, no. 4-5, p. 70-77.

Saarnisto, M.
1982: Ice retreat and Baltic ice lake in the Salpausselkä zone beween Lake Päijänne and Lake Saimaa; Annales Academiae Scientiarum Fennicae, Series A III, v. 134, 79 p.

Savolahti, A.
1956: The Ahvenisto massif in Finland. The age of the surrounding gabbro-anorthosite complex and the crystallization of rapakivi; Bulletin de la Commission géologique de Finlande, no. 174, 96 p.

Shilts, W.W.
1984: Esker sedimentation models, Deep Rose Lake map area, District of Keewatin; in Current Research, Part B, Geological Survey of Canada, Paper 84-1B, p. 217-222.

Simonen, A.
1965: Pre-Quaternary rocks, sheet 3024, Karhula; Geological Map of Finland, 1:100 000, Geological Survey of Finland.
1975: Pre-Quaternary rocks, sheet 3131, Luumäki; Geological Map of Finland, 1:100 000, Geological Survey of Finland.
1978: Pre-Quaternary rocks, sheet 3123, Mäntyharju; Geological Map of Finland, 1:100 000, Geological Survey of Finland.
1980: Pre-Quaternary rocks of Finland; map, 1:1 000 000 scale, Geological Survey of Finland.
1982: Mäntyharjun ja Mikkelin kartta-alueiden kallio- perä. Summary Pre-Quaternary rocks of the Mänty-harju and Mikkeli map-sheet areas, Sheets 3123 and 3142; Explanation of the maps of Pre-Quaternary rocks, 1:100 000, Geological Survey of Finland, 36 p.

Simonen, A. and Lehijärvi, M.
1963: Pre-Quaternary rocks, sheet 3113, Kouvola; Geological Map of Finland, 1:100 000, Geological Survey of Finland.

Simonen, A. and Tyrväinen, A.
1965: Pre-Quaternary rocks, sheet 3132, Savitaipale; Geological Map of Finland, 1:100 000, Geological Survey of Finland.
1981: Savitaipaleen kartta-alueen kallioperä. Summary: Pre-Quaternary rocks of the Savitaipale map-sheet area, Sheet 3132; Explanation of the maps of Pre-Quaternary rocks, 1:100 000, Geological Survey of Finland, 30 p.

Tynni, R.
1985: Lahden, Heinolan ja Kouvolan kartta-alueiden maaperä; (Manuscript), Geological Survey of Finland, 49 p.

Tyrväinen, A.
1986: Vuohijärven kartta-alueen kallioperä. Summary: Pre-Quaternary rocks of the Vuohijärvi map-sheet area, Sheet 3114; Explanation of the maps of Pre-Quaternary rocks, 1:100 000, Geological Survey of Finland, 35 p.

Valovirta, V.
1972: Kymen läänin maaperä. Summary Quaternary deposits in the coastal area of the Kymi district, Sheets 3023 + 3014, 3024, 3041 + 3043, 3042; Suomen geologinen kartta, 1:100 000, Maaperäkartan selitykset, Geological Survey of Finland, 46 p.

Vorma, A.
1976: On the petrochemistry of rapakivi granites with special reference to the Laitila massif, southwestern Finland; Geological Survey of Finland, Bulletin 285, 98 p.

Ice flow history and glacial dispersal patterns, Labrador[1]

R.A. Klassen[2] and F.J. Thompson[2]

Klassen, R.A., and Thompson, F.J., Ice flow history and glacial dispersal patterns, Labrador; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 21-29, 1989.

Abstract

Studies of drift composition and ice flow history in central Labrador demonstrate marked regional variations in the shape and orientation of glacial dispersal trains. Dispersal trains vary from simple 'ribbons' streamed down-ice from the bedrock source in the directions of last regional ice flow, to broad fans, to complex 'patches' centred about the source. The variations relate directly to the regional history of ice flow as recorded by streamlined glacial landforms and striae. Although drift composition may predominantly reflect transport during the 'last' phase of ice flow, 'older' flow trends can also be significant controls on dispersal patterns in surface drift. The record of 'older' phases of ice flow occurs on outcrop surfaces protected from erosion during later flow, and is most commonly preserved where buried by drift around the margins of bedrock exposures. The work emphasizes the need to develop programs of mineral exploration by drift prospecting within the broader context of the Laurentide Ice Sheet and regional ice flow history.

Résumé

L'étude de la composition des matériaux de transport glaciaires et de l'histoire de l'écoulement glaciaire dans la région centrale centre du Labrador démontre qu'il y a d'importantes variations régionales de forme et d'orientation au niveau des trainées de dispersion glaciaire. Ces dernières vont de simples "rubans" s'étendant dans le sens des glaciers depuis la roche mère dans les directions des écoulements glaciaires régionaux les plus récents, à de larges éventails et des zones complexes centrées sur la source. Les variations se rapportent directement à l'histoire régionale de l'écoulement glaciaire telle qu'en font foi la topographie et les stries du modelé glaciaire. Méme si la composition des matériaux de transport glaciaires peut essentiellement indiquer que le transport s'est effectué au cours de la "dernière" phase d'écoulement glaciaire, des écoulements "plus anciens" peuvent aussi influer considérablement sur la dispersion en surface des matériaux de transport glaciaires. L'empreinte des phases "plus anciennes" d'écoulement glaciaire se retrouve sur les surfaces d'affleurements «protégées» de l'érosion pendant une période d'écoulement plus récente et est en général mieux conservée sous les matériaux de transport glaciaires autour des marges des affleurements du socle rocheux. L'étude fait ressortir le besoin de mettre sur pied des programmes d'exploration minérale basés sur la prospection des matériaux de transport glaciaires dans le contexte plus large que présente l'histoire de l'inlandsis des Laurentides et l'évolution régionale de l'écoulement glaciaire.

---

[1] Contribution to the Canada-Newfoundland Mineral Development Agreement, 1984-1989.
Project carried by Geological Survey of Canada.
[2] Geological Survey of Canada 601 Booth St., Ottawa, Ontario, K1A 0E8.

INTRODUCTION

Prospecting in glaciated terrain requires knowledge of ice flow directions to trace indicators of mineralization to their bedrock source. For large areas of Canada, however, the history of ice movement is poorly known, particularly in remote regions of the Canadian Shield. Flow directions shown on the Glacial Map of Canada (Prest et al., 1968) are based primarily on airphoto interpretation of streamlined landforms, and portray late-glacial conditions that can differ markedly from older trends. Older flow trends can be important controls on drift composition and patterns of glacial dispersal (see Veillette, 1986; Bouchard and Marcotte, 1986) and they are, consequently, of significance to mineral exploration.

The Geological Survey of Canada has been developing a Quaternary geological basis for mineral exploration by drift prospecting in central Labrador as part of the Canada-Newfoundland Mineral Development Agreement. The work is designed to establish models of glacial dispersal that illustrate the relationship between drift composition and ice flow history. The models are based on dispersal trains derived from distinctive bedrock sources and on the record of striae on glacially polished bedrock surfaces. The area of investigation extends >600 km from the ice sheet margins along the Labrador coast to dispersal centres in central Labrador-Quebec. Consequently, the patterns of glacial dispersal presented here represent a wide range of glacial environments, and are well suited to illustrate the importance of glacial history to drift prospecting programs.

Previous work

Until aerial photographs became available during the late 1940's, knowledge of ice flow in Labrador was based on striae measured by Low (1896), who concluded that they were the product of a shifting dispersal centre in Quebec. More recently, the principal basis for interpretations of regional glacial history has been glacially streamlined landforms (Prest, 1984; Dyke and Prest, 1987), which are a record of the "last" imprint of the ice sheet. Collectively, the landforms describe regional flow trends that originate at a large "U-shaped" area centred about Ungava Bay with its base in the Schefferville region. Between the arms of the U, ice flow trends are convergent northwards towards the bay, and outside of it they are divergent outwards, trending east-northeast to east-southeast across central Labrador, and south to southwest across central Quebec. The U has been described both as the location of a major dispersal centre of the ice sheet that was active throughout a significant part of the last glaciation (Hillaire-Marcel, 1981), and of a residual centre developed only during late glacial conditions

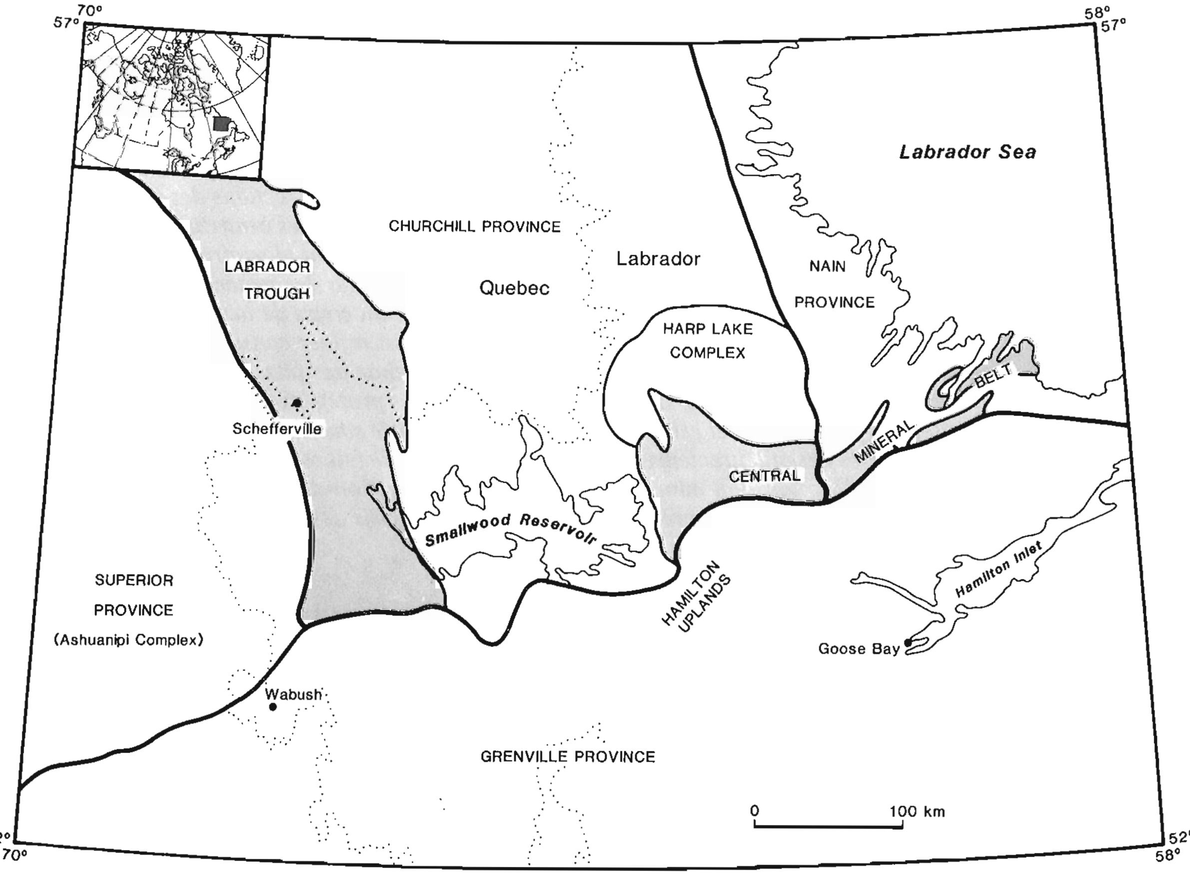


Figure 1. Index map of study area in central Labrador, and outline of the principal geological and physiographical divisions. (supracrustal sedimentary and volcanic rocks shaded).

(Ives et al., 1975). The Labradorean Sector of the Laurentide Ice Sheet is thought to have " ...consisted of a number of semi-autonomous dispersal centres which developed, shifted and disappeared during the late Wisconsinan." (Prest, 1984, p. 23; Dyke and Prest, 1987). Whatever the history of ice flow, Schefferville has been identified as the area occupied by the last remnants of the ice sheet in Labrador-New Quebec (Ives, 1960).

Detailed field studies have been concentrated in the Schefferville region, due in part to the logistical support available there (Henderson, 1959; Ives, 1960; Kirby, 1961,1966), and near Churchill Falls (Morrison, 1963). Quaternary geological maps of eastern and central Labrador illustrate the occurrence and orientation of streamlined landforms and serve as a guide to the "last" directions of glacial flow (Fulton et al., 1980 a,b,c; 1981, Fulton, 1986).

Detailed examination of striae has revealed a history of shifting ice flow across central Labrador that is far more complex than that recorded by the streamlined landforms and may represent flow during a significant part of the last glaciation (Klassen and Bolduc, 1984; Thompson and Klassen, 1986; Klassen and Thompson, 1987; 1988). The significance of that complex history to drift composition is the subject of this report.

Bedrock Geology and Physiography

The study area lies within the Canadian Shield, spanning parts of the Grenville, Nain, Superior, and Churchill structural provinces, and includes assemblages of supracrustal sedimentary and volcanic rocks (Fig. 1) (Greene, 1974). The supracrustal rocks comprise the Central Mineral Belt to the east, and the Labrador Trough to the west, and they have significant economic mineral potential (Ryan, 1984; Wardle, 1982). The crystalline basement is lithologically complex and includes quartzofeldspathic gneisses within the Grenville Province, gneisses within the Nain and Churchill provinces, and granites and gneisses within the Superior Province (Ashaunipi Complex). Helikian anorthosite and gabbro, and associated intrusive rocks, occur throughout the Churchill, Grenville and Nain provinces.

Figure 2. Striae associated with periods of 'older' ice flow are commonly found on surfaces that are protected from erosion during later periods of glacial flow. In Labrador, the older record, as shown on the near surface, was found to display striking consistencies in trend over large areas, and is considered to be the product of regional phases of ice flow (GSC Photo 203810C).

The region occupies parts of the Laurentian and James physiographic regions (Bostock, 1970), and is characterized by the rough, undulating topography that is typical of much of the Canadian Shield. Distinct physiographic characteristics, however, can be associated with the dominant geological features (Greene, 1974). Rugged highland plateaus are associated with the Ashaunipi Complex, west of the Labrador Trough, and with the Harp Lake Complex and other Helikian intrusives. Distinctive linear ridges and valleys, with relief of 100 to 200 m, characterize the Labrador Trough in the west and the Seal Lake Group in the central part of the study area.

METHODS

Ice flow trends are based on the orientations of both large-scale features, such as glacially streamlined landforms, and small-scale features, such as striae and grooves on bedrock surfaces. The sense of ice flow was determined from glacial streamlining and crag and tail features (e.g. abraded ledges; stoss and lee; rat tail striae) (Prest, 1983). The relative ages of striae having different trends are based on cross-cutting relations and the association of "older" striae with protected (lee) surfaces (Fig.2). Older striae occur rarely on exposed surfaces, and are considered to have been abraded from those surfaces during later periods of ice flow. Youngest striae, which occur on the most exposed outcrop surfaces, are generally parallel with streamlined landforms and reflect the same phase of ice movement. The relations used to establish relative ages are illustrated by Prest (1983, Fig. 17a,b; p. 32), and have been used by Bouchard and Martineau (1985) in west central Quebec, and by Veillette (1986) in the Timiskaming and Abitibi regions to determine ice flow history.

Evidence of older flow trends is widespread throughout central Labrador and can occur on surfaces that appear only slightly protected from later flow (Fig.2). The older record, however, is commonly buried on the flanks of outcrops and is easily overlooked. Within the study area, its recognition was facilitated by exposures created by road construction along the TransLabrador highway, and by mining activities in the Schefferville and Wabush areas. Elsewhere, digging around the margins of exposed bedrock was necessary to expose it.

The significance of striae in terms of ice flow history and transport of debris cannot be reliably established by the record on any one outcrop. Measurements obtained at hundreds of sites, however, have demonstrated striking consistencies in striae trends and relative age relations from site to site over large areas. Despite the small size of the features measured, they are considered to reliably represent large-scale movements within the ice sheet in central Labrador and to have a close linkage to drift composition and the development of dispersal trains.

DRIFT COMPOSITION

At more than 3,000 sites, till was collected for analysis of lithological and geochemical characteristics, and a field record was made of the occurrence and relative abundance of erratics. The distribution of distinctive 'indicator' erratics was mapped to establish distances and directions of glacial transport, and to map glacial dispersal trains as predictive models for mineral exploration. The term "indicator" is used to describe erratics derived from bedrock that is distinctive, either lithologically or geochemically, and is well-defined in areal extent. Indicator erratics constitute an important geological basis for mapping glacial dispersal trains and identifying glacial transport directions because they can be recognized at extremely low levels of abundance (<0.1 % by volume) and are readily traced in the field. Estimates of relative abundance derived both from qualitative field observation and from quantitative determinations have proven useful in defining dispersal patterns. Quantitative analysis of lithology is based on the examination of the 4 to 5.6 mm size fraction (pebbles), and the proportions of lithological categories are recorded as weight per cent.

Bedrock Sources of Indicator Erratics

Four distinct sources of indicator erratics, which are described below, are presented to portray models of glacial dispersal in Labrador (Fig. 3). The sources are areally large (10-100 km^2) and have contributed significant volumes of debris to the ice. They are well suited to characterize dispersal patterns at scales of 10's to 100's of km. Mineral exploration targets, in contrast, are generally much smaller, and consequently the volumes of debris and recognizable distances of transport associated with them can be more restricted. However, the overall configurations of trains derived from smaller sources are expected to be similar to those derived from larger sources, in the absence of local topographic effects on ice flow.

Flowers River Igneous Suite

The Flowers River Suite (Fig. 4) comprises felsic volcanic rocks and peralkaline granite intrusive rocks at the boundary between the Nain and Churchill structural provinces, near the Labrador coast (Hill, 1982). The dominant volcanic

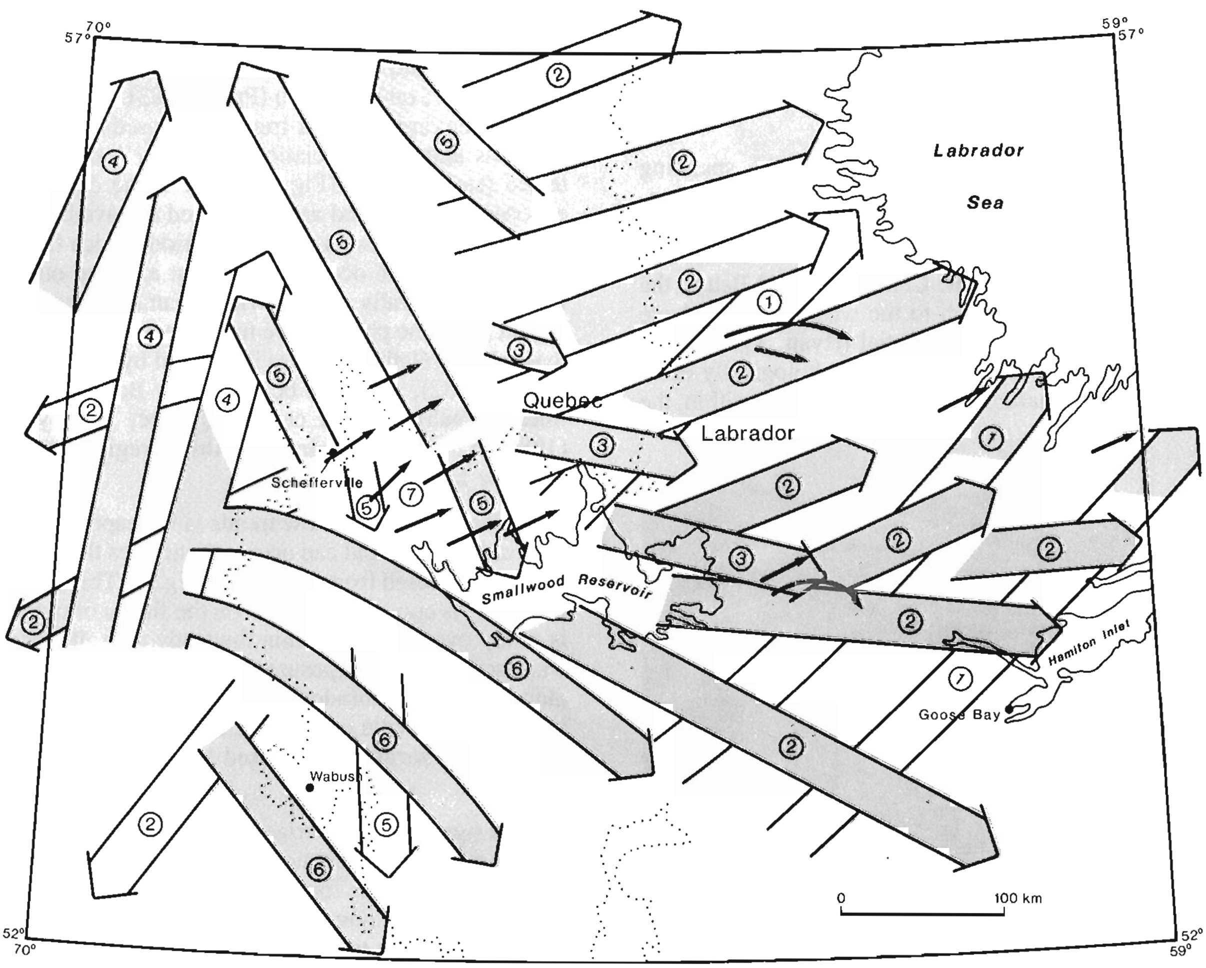


Figure 3. An interpretation of regional Phases of ice flow affecting central Labrador, based on striae and drift composition. Directions of ice flow are indicated by arrows, and their relative ages by numbers (oldest (1) to youngest (7)). Arrows are not shaded where later ice flow is superimposed on older. Solid, narrow arrows indicate late glacial, minor phases of ice flow.

lithology is a distinctive red to grey quartz feldspar porphyry characterized by deeply embayed phenocrysts, allowing it to be distinguished from similar porphyritic phases of the intrusive rocks. The porphyritic volcanic rock used as an indicator erratic underlies an elliptical area of 50 km^2.

Red Wine Complex

The Red Wine Complex (Fig. 4) underlies an arc 45 km by 15 km along the southern margin of the Central Mineral Belt, between sediments of the Seal Lake Group and gneisses of the Grenville Province. It comprises dismembered lenses of agpaitic alkaline rocks within peralkaline granitic rocks of the Arc Lake Suite (Curtis and Currie, 1981). The alkaline and peralkaline rocks are spatially associated with peralkaline volcanic rocks of the Letitia Lake Group (Thomas, 1981). The distinctive green and blue agpaitic alkaline rocks are compositionally and visually distinctive and are used to define glacial dispersal patterns from the Red Wine Complex.

Montagnais Intrusive Suite

Martin Lake Rhyolite (Fig. 4) of the Montagnais Intrusive Suite, a red feldspar porphyry, outcrops in the eastern part of the Labrador Trough. Although its sub-cropping distribution may be more extensive than presently mapped (6 km^2), unmapped occurrences would lie along the northwest- southeast strike of host rocks (R. Wardle, pers. comm., 1987). The Martin Lake Rhyolite is characterized by pink to white feldspar phenocrysts up to 0.5 cm in length in a very fine-grained red groundmass. The rock is visually distinctive, and easily identified against the dark coloured mafic volcanic and gabbroic rocks that are characteristic of drift in the eastern part of the Labrador Trough.

Nepheline Syenite

Three nepheline syenite plutons (Fig. 4), each of which is less than 10 km^2, outcrop in the Superior Province northwest of Schefferville (Fumerton and Barry, 1984). The plutons occur within an area 15 km by 15 km. The syenite is

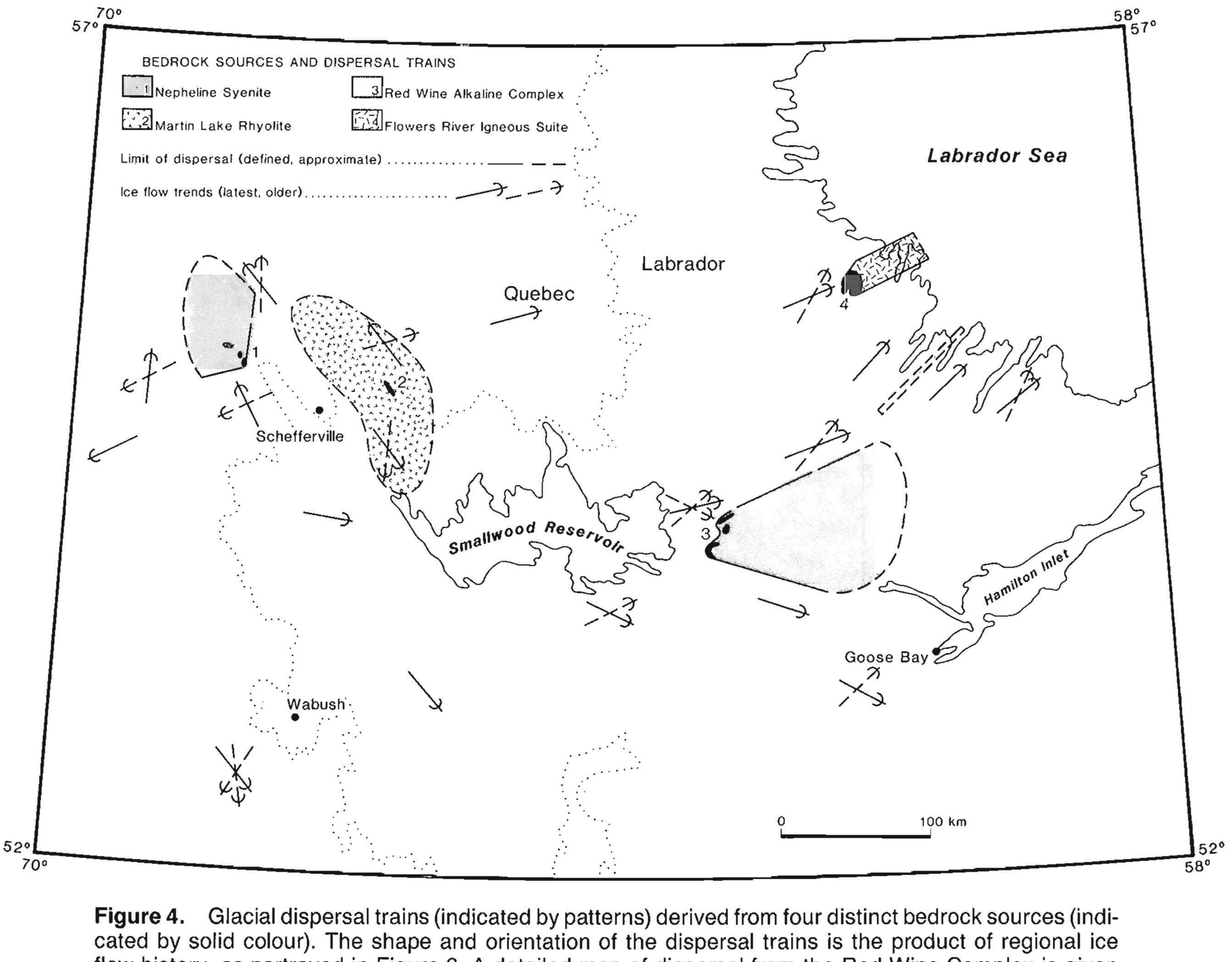


Figure 4. Glacial dispersal trains (indicated by patterns) derived from four distinct bedrock sources (indicated by solid colour). The shape and orientation of the dispersal trains is the product of regional ice flow history, as portrayed in Figure 3. A detailed map of dispersal from the Red Wine Complex is given in Figure 5.

coarse grained and contains nepheline, perthite and up to 15 % mafic minerals. Erratics of nepheline syenite exhibit a distinctive lumpy or etched appearance, with nepheline weathering recessively and perthite in relief.

ICE FLOW HISTORY

Glacial flow patterns demonstrated by the distribution of erratics and by striae have been used to unravel a sequence of events, referred to here as glacial "Phases", that represent large scale movement within the ice sheet, because of the large areas (> 10 000 km²) that they influenced and the glacial transport distances (> 100 km) associated with them.

No single outcrop or area can be used to characterize regional ice flow history across central Labrador and a summary (Fig.4) has been constructed by establishing relations among flow patterns characteristic of different subareas. The Phases are assumed to represent events within the course of the last glaciation (Wisconsin), although limited stratigraphic evidence near Wabush (Klassen and Thompson, 1988) indicates that the earliest Phases could be the product of glacial events prior to the last glaciation (Wisconsin).

Phases of ice flow that effected either all or large parts of Labrador are presented from oldest to youngest.

Phase 1

Ice flow towards the northeast across most of central and eastern Labrador originated from a dispersal centre southwest of the Churchill River. Erratics that can only have been transported during this Phase are rare, although debris from the Red Wine Complex occurring east of Harp Lake Complex represents an important exception. In that area, later phases of ice flow appear to have had limited effect.

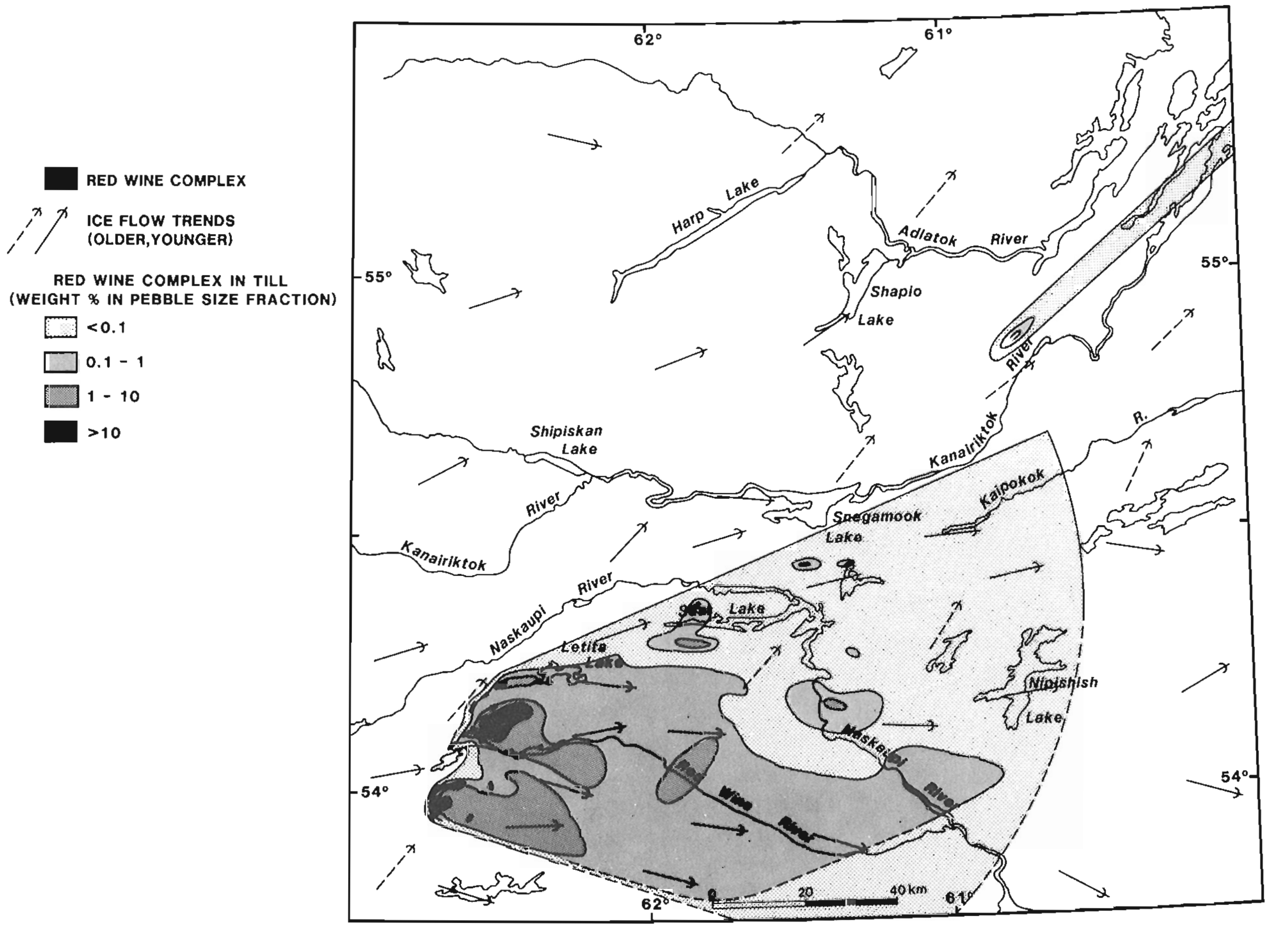


Figure 5. Glacial dispersal of agpaitic rocks originating from the Red Wine Complex include a broad 'fan', originating at the bedrock source and extending up to 100 km eastward, and a narrow 'ribbon' originating 150 km northeast of the source and extending a further 70 km northeast. Within the fan, elevated concentrations of indicator debris define a 'core zone' originated along the last direction of ice flow.

Phase 2

Ice flow toward the east-northeast, east-southeast and west-southwest originated from a dispersal centre located within or near the Labrador Trough. Phase 2 is considered to have been predominant during the last glaciation and to have extended across most of Labrador and eastern Quebec. The dispersal centre controlling Phase 2 was first recognized by the regional distribution of Labrador Trough debris within areas controlled by later Phases 4,5,and 6 (Ives, 1960; Peterson, 1965), and probably represents the southward extension of the Payne Centre in northern Ungava (Bouchard and Marcotte, 1986).

Phase 3

Flow was towards the east-southeast in the area north of Smallwood Reservoir. Although locally important, the regional significance of this phase is not clear for reconstruction of the ice sheet, and its effects on glacial transport cannot be distinguished reliably from either Phase 2 or late glacial, topographically-controlled flow around the northern margin of the Hamilton Uplands.

Phase 4

In eastern Quebec, flow was directed northwards off the Ashuanipi Complex. Trough debris transported during the earlier Phase 2 flow is an important component of till in the area where Phase 4 flow is recognized, despite erosion by ice during the latter event.

Phase 5

Flow was to the north-northwest, south, and south-southeast from the Schefferville region. Ice flow associated with Phases 4 and 5 defines regional patterns that are convergent northwards towards Ungava Bay and appears to have been initiated during late glacial time. South of Schefferville, northward flow of Phase 5 is matched by southward flow, and the zone between could define the location of a dispersal centre operating during late glacial time.

Phase 6

A locally dominant phase of eastward ice flow originated within highlands underlain by the Ashuanipi Complex and extended across the Labrador Trough. Although significant amounts of crystalline debris from the Complex were transported into the southern part of the Trough, some Trough debris transported westward during Phase 2 remains as a rare component of till on the highlands where Phase 6 originated. The eastward extent of this Phase is not clear and east-southeast flow identified south and east of the Smallwood Reservoir may be related to Phases 2, 3 or 6.

Phase 7

In the Labrador Trough, this last phase of ice flow was towards the northeast, in a direction more or less parallel with earlier flow during Phase 2. Based on the delicate character of striae, Phase 7 was a relatively minor phase of flow, likely operative during late glacial time and of limited duration.

All of the phases of ice flow portrayed are consistent with glacial transport directions demonstrated by indicator erratics (described below), and with striae. Detailed studies could reveal additional complexities to ice flow, such as may be related to topographic control on ice flow during the waning stages of glaciation. Evidence for such flow is known along the margins of highlands underlain by the Harp Lake Complex, and the northern end of the Hamilton Uplands (Fig. 1).

GLACIAL DISPERSAL PATTERNS

The configurations of glacial dispersal trains (Fig.3) vary markedly between the margin of the Laurentide Ice Sheet near the coast and its dispersal centres in the region of the Labrador Trough. In the Flowers River area near the Labrador coast, there has been a relatively simple history of ice flow comprising dominant flow to the east-northeast (Phase 2), with limited evidence of earlier flow to the northeast (Phase 1). Glacial transport from the Flowers River Igneous Suite is correspondingly simple, and erratics of volcanic porphyry define a ribbon-shaped dispersal train of outcrop width (30 km) streamed >50 km down-ice, in the direction of last regional ice flow. The northern margin of the train displays a slight ''dog leg'' that could reflect either northward transport during earlier flow or dispersal from an unmapped extension of the bedrock source.

Inland, away from the margin of the ice sheet, dispersal trains become more complex and assume a fan-like aspect, recording transport during more than one phase of ice flow. Indicator erratics from the Red Wine Complex, for example, form two distinct dispersal trains that are the net product of transport and erosion during several phases of ice flow (Phases 1, 2, 3), (Fig. 5). Further, the relative importance of those phases of flow on drift composition appears to vary. The trains comprise: 1) a broad 'fan' that originates at the bedrock source and 2) a 'ribbon' that originates 150 km northeast of the source.

The margins of the broad fan trend east-northeast and east-southeast, consistent with regional flow trends in Phases 2 and 3. The overall shape of the fan is based on the distribution of all known indicator erratics and represents net dispersal of all the regional phases of flow. Variations in the abundance of Red Wine debris, however, indicate that not all phases are equally recorded. Within the fan, for example, an elongate 'zone' characterized by 0.1 to 1 wt. % indicator erratics extends up to 80 km east and east-southeast from the source area (Fig. 5). That distribution suggests that regional flow to the east-southeast (Phase 2 or 3) is a more important control on drift composition than earlier flow to the east-northeast (Phase 2). The southern margin of the zone (0.1 to 1 wt. %) is linear and well-defined, lying directly across the northern end of the Hamilton Uplands, which extend northwards to the Red Wine River (Fig. 5). The northern margin of the zone curves generally around the Uplands, parallel with the youngest striae, and its form suggests that it has been modified by topographically controlled ice flow during late-glacial time. Within the central part of the zone, a 'core' containing 1 to 10 wt. % indicator erratics extends 30 km east-southeast from the two largest bedrock sources.

The ribbon-shaped dispersal train of the Red Wine Complex formed during the earliest period of flow towards the northeast (Phase 1). The train extends >70 km northeast from its point of origin, and maintains a width of about 5 km, which is narrower than the width of the bedrock source crossed by northeast-flowing ice. In the region between the up-ice 'head' of the train and its bedrock source, compositional evidence of Phase 1 dispersal to the northeast is presumed to have been eroded during later Phase 2. No clasts of indicator erratics were found in that intermediate area, despite intensive search. Within the ribbon train, however, indicator erratics occur at almost all sites, although they can be rare. An important exception occurs at a hilltop site at the up-ice 'head' of the train where erratics comprise >1 wt. % of the till. The large size of indicator erratics at that site, some of which were >10 cm, indicates little or no comminution of debris during glacial transport. The abundance and size of the debris is likely related to the dynamics of the ice sheet and the manner in which the debris was transported during glaciation. It appears likely to have been eroded from a bedrock source projecting into the ice and transported as a debris band within 'clean' ice above the base of the glacier. Deposition appears to have been initiated when the englacial debris encountered the topographic obstruction 150 km down-ice. In the area of the ribbon train, ice flow during Phase 2 does not appear to have been erosive, and striae associated with that phase are of delicate character, and are directly superimposed on striae of Phase 1. Consequently, the narrow ribbon shape of the train has been maintained despite the later ice flow.

The most complex ice flow history is in the region of the Labrador Trough, near the geographic centre of the Labradorean Sector of the Laurentide Ice Sheet. There, evidence for five distinct flow directions is recorded (Klassen and Thompson, 1987). Martin Lake Rhyolite (Fig. 4) has been dispersed in all directions from the bedrock source, defining a dispersal train shaped as a 'patch' rather than as a ribbon or fan. Although the net dispersal of erratics is in all directions about the source, the greatest concentration of debris extends north-northwest and south from the bedrock source, consistent with the last prominent flow trends (Phase 5).

Over the Ashuanipi Complex west of the Trough, the distribution of nepheline syenite (Fig. 4) describes a broad fan that originates at the bedrock source area and opens to the northwest. The margins of the fan trend west-southwest and north-northeast, and are aligned with Phases 2 and 4, respectively. The greatest concentrations of syenite in till occur northwest of the source and appear to be associated with transport during Phase 5, the last phase of ice flow in that area.

SUMMARY AND CONCLUSIONS

Glacial dispersal trains can display significant variation in size, shape and orientation as the direct result of ice flow history. Regional ice flow patterns, as portrayed on the Glacial Map of Canada, are essentially records of the 'last' flow directions and do not reliably indicate older phases of ice flow that can also be significant controls on drift composition and the shape of dispersal trains. Ice flow history can be revealed by field examination of striae on glacially polished bedrock surfaces. The record of 'older' flow is most commonly found on the flanks of outcrops and is easily overlooked, although it can be of great significance to establishing controls on the directions of glacial transport. Field studies based on the geological record, such as this one, provide a framework for establishing the transport directions of mineralized erratics and for developing effective exploration programs.

Along the Labrador coast, near the ice sheet margin, dispersal trains have a relatively simple configuration, and appear as ribbons streamed down-ice in the main direction of flow. Progressively toward the centre of the Ice Sheet, dispersal trains become increasingly complex and are the net product of glacial transport in different directions of ice flow. Depending on their location relative to former dispersal centres, glacial transport directions can have marked variation and dispersal trains correspondingly vary from narrow ribbons, to broad fans, to 'patches' centred more or less about the bedrock source. Although the work presented here is derived from Labrador, other large-scale dispersal centres existed within the Laurentide Ice Sheet, in the District of Keewatin for example, and complex patterns of ice flow and glacial transport may characterize large portions of the Canadian Shield elsewhere.

The dispersal patterns are derived from bedrock sources that are larger than typical exploration targets but are considered to represent models that can be applied to investigations at more detailed scales. They indicate that mineralized erratics or mineralized till found during the course of prospecting can have a relatively distant bedrock source and may have undergone transport in directions that are not obvious from examination of glacially streamlined landforms alone. Although streamlined landforms provide a useful guide to 'last' ice flow directions, they should not be uncritically used to establish directions of glacial transport and to trace the source of mineralized erratics. Glacial drift should be seen as the product of both bedrock and preexisting deposits, including components that have undergone transport during several phases of ice flow. Although the most important control on the shape and composition of dispersal trains may commonly be the 'last' phase of ice flow, that is not true everywhere. The northeast-trending ribbon associated with the Red Wine Complex, for example, further indicates that elevated concentrations of an indicator erratic do not necessarily indicate proximity to a bedrock source but could be the product of either topography or the manner in which debris was carried within the ice, or both, a conclusion also reached by Batterson (this volume) in the Strange Lake (Lac Brisson) area of northern Labrador.

The work in Labrador serves as a caution that no one particular dispersal model applies to drift prospecting, and that pre-conceived ideas on the configuration of dispersal trains can be misleading. It further emphasizes the need to consider an exploration area within the context of the Laurentide Ice Sheet, and the need for critical field studies of ice flow history at both local and regional scales during the course of exploration.

REFERENCES

Batterson, M.J.
1989: Glacial Dispersal from the Strange Lake Alkalic Complex in Northern Labrador; (This Volume).

Bouchard, M.A. and Marcotte, C.
1986: Regional glacial dispersal patterns in Ungava, Nouveau Quebec; in Current Research, Part B, Geological Survey of Canada, Paper 86-1B, p. 295-304.

Bouchard, M.A. and Martineau, G.
1985: Southeastward ice flow in central Quebec and its paleogeographic significance; Canadian Journal of Earth Sciences, v. 22, p. 1536-1541.

Bostock, H.S.
1970: Physiographic subdivisions of Canada; in Geology and Economic Minerals of Canada, ed. R.J.W.Douglas; Geological Survey of Canada, Economic Geology Report No. 1, p.10-30.

Curtis, L.W. and Currie, K.L.
1981: Geology and petrology of the Red Wine alkaline complex, central Labrador; Geological Survey of Canada, Bulletin 294, 61 p.

Dyke, A.S. and Prest, V.K.
1987: Late Wisconsinan and Holocene history of the Laurentide Ice Sheet; Geographie physique et Quaternaire, v. XLI, p. 237-263.

Fulton, R.J.
1986: Surficial geology, Red Wine River, Labrador, Newfoundland; Geological Survey of Canada, Map 1621A, Scale 1:500 000.

Fulton, R.J., Hodgson, D.A., Minning, G.V., and Thomas, R.D.
1980a: Surficial material, Kasheshibaw Lake; Geological Survey of Canada, Map 28-1979, scale 1:250 000.
1980b: Surficial materials, Snegamook Lake, Labrador; Geological Survey of Canada, Map 27-1979, scale 1:250 000.
1980c: Surficial materials, Goose Bay, Labrador; Geological Survey of Canada, Map 22-1979, scale 1:250 000.
1981: Surficial materials, Winokapau Lake; Geological Survey of Canada, Map 21- 1979, scale 1:250 000.

Fumerton, S.L. and Barry, A.P.
1984: Probable Archean nepheline syenite plutons in the Superior Province adjacent to the Labrador Trough; Canadian Journal of Earth Sciences, v. 21, p. 616-618.

Greene, B.A.
1974: Geological map of Labrador; Department of Mineral Development Division, Province of Newfoundland, Information Circular No. 15, 64 p.

Henderson, E.
1959: A glacial study of central Quebec-Labrador; Geological Survey of Canada, Paper 71-26, 37 p.

Hill, J.D
1982: Geology of the Flowers River-Notakwanon River area, Labrador; Department of Mines and Energy, Newfoundland, Report 82-6, 139 p.

Hillaire-Marcel, C.
1981: Continental ice complexes: distinction between centres of outflow and centres of loading of the crust — example of the eastern Laurentide Ice Sheet; Zeitschrift fur Geomorphologie, v.25, p.225-228.

Ives, J.D.
1960: The deglaciation of Labrador-Ungava — an outline, in Cahiers de Géographie de Québec, No. 8, pp. 323-43.

Ives, J.D., Andrews, J.T. and Barry, R.G.
1975: Growth and decay of the Laurentide Ice Sheet and comparison with Fenno- Scandinavia; Die Naturwissenschaften, v.62, p.118-125.

Kirby, R.P.
1961: Deglaciation in central Labrador-Ungava as interpreted from glacial deposits; Geographical Bulletin, no. 16, p. 4-23.
1966: Movements of ice in central Labrador-Ungava; in Ten years (1954-1964) of field research in Labrador-Ungava; McGill Sub-Arctic Research Paper no. 20, Department of Geography, McGill University, Montreal, p. 160-171.

Klassen, R.A. and Bolduc, A.M.
1984: Ice flow directions and drift composition, Churchill Falls, Labrador; in Current Research, Part A, Geological Survey of Canada, Paper 84-1A, p. 255-258.

Klassen, R.A. and Thompson, F.J.
1987: Ice flow history and glacial dispersal in Labrador Trough; in Current Research, Part A, Geological Survey of Canada, Paper 87-1A, p. 61-71.

Klassen, R.D.(sic) and Thompson, F.J
1988: Glacial studies in Labrador; in Current Research, Part C, Geological Survey of Canada, Paper 88-1C, p. 109-116.

Low, A.P.
1896: Report on explorations in the Labrador penninsula along the Eastmain, Koksoak, Hamilton, Manicuagan and portions of other rivers in 1892-93- 94-95; Geological Survey of Canada, Annual Report, v. 8, Part L, 387p.

Morrison, A.
1963: Landform studies in the middle Hamilton River area, Labrador; Arctic, v. 16, p. 272-275.

Peterson, J.A.
1965: Deglaciation of the Whitegull Lake area, Labrador-Ungava; Cahiers de Géographie de Quéebec, v.9, no.18, p.183-196.

Prest, V.K.
1983: Canada's heritage of glacial features; Geological Survey of Canada, Miscellaneous Report 28, 119p.
1984: The Late Wisconsinan glacier complex; in Quaternary Stratigraphy of Canada—A Canadian Contribution to IGCP Project 24, ed. R.J.Fulton; Geological Survey of Canada, Paper 84-10, p.21-36.

Prest, V.K., Grant, D.R., and Rampton, V.N.
1968: Glacial Map of Canada; Geological Survey of Canada, Map 1253A, scale 1:5 000 000.

Ryan, B.
1984: Regional geology of the central part of the Central Mineral Belt, Labrador; Mineral Development Division, Newfoundland Department of Mines and Energy, Memoir 3, 185 p.

Thomas, A.
1981: Geology along the southwestern margin of the Central Mineral Belt; Mineral Development Division, Newfoundland Department of Mines and Energy, Report 81-4, 40 p.

Thompson, F.J. and Klassen, R.A.
1986: Ice flow directions and drift composition, central Labrador; in Current Research, Part A, Geological Survey of Canada, Paper 86-1A, p. 713-717.

Veillette, J.J.
1986: Former southwesterly ice flows in the Abitibi-Temiskaming region: implications for the configuration of the late Wisconsinan ice sheet; Canadian Journal of Earth Sciences, v. 23, p. 1724-1741.

Wardle, R.J.
1982: Geology of the south-central Labrador Trough; Mineral Development Division, Newfoundland Department of Mines and Energy, Map 82-5.

Glacial dispersal from the Strange Lake alkalic complex, northern Labrador[1]

M.J. Batterson[2]

Batterson, M.J., Glacial dispersal from the Strange Lake alkalic complex, northern Labrador; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 31-40, 1989.

Abstract

A fortuitous combination of unique geology, topography, and an uncomplicated glacial history has led to the development of a well-defined glacial dispersal train from the Strange Lake alkalic complex.

Nine hundred and ninety one samples over a 1100 km² area were lithologically and geochemically analyzed. North-south lithological variation across the bedrock source is mirrored by pebble distributions in the dispersal train, which maintains a width comparable to the outcrop of the source rock along its length. Single-element geochemical patterns for ore-related elements (yttrium, zirconium, niobium, beryllium, lanthanum) define a ribbon-shaped dispersal train continuous for at least 40 km down-ice from the complex. Although dispersal follows a classical pattern of peak values close to source and declining values down-ice, several anomalous areas (both lithological and geochemical) were located. These anomalies correspond with topographic highs, notably crag and tail landforms. This suggests that topography acted to modify dispersal trends by intercepting material transported either englacially or high in the basal load.

This study suggests that regional till geochemistry should be conducted as part of detailed anomaly evaluation to determine if any anomalies are displaced ones within larger dispersal trains. In the Strange Lake dispersal train these anomalies correspond to topographically high areas on the underlying bedrock surface.

Résumé

Une combinaison fortuite de caractéristiques géologiques et topographiques uniques et une histoire glaciaire simple ont mené à la formation d'une trainée de dispersion glaciaire bien définie s'étendant depuis le complexe alcalin de Strange Lake.

Sur une superficie de plus de 1100 km², on a procédé à l'analyse lithologique et géochimique de 991 échantillons. La variation lithologique nord-sud en travers du socle est reflétée par des répartitions de galets dans la trainée de dispersion dont la largeur est comparable à celle de l'affleurement de la roche mère sur toute sa longueur. La répartition géochimique de chaque élément des minerais (Y, Zr, Nb, Be, La) définit une trainée de dispersion en forme de ruban, continue sur au moins 40 km en aval de la glace à partir du complexe. Même si la dispersion affiche une distribution classique allant des valeurs maximales près de la source à des valeurs décroissantes en aval de la glace, on a trouvé plusieurs anomalies (tant lithologiques que géochimiques). Ces anomalies correspondent à des crétes topographiques, notamment à des formes de terrain avec striage en amont et sédimentation en aval, et révélent que la topographie a contribué à modifier les tendances de dispersion en interceptant les matériaux transportés soit dans la masse de glace, soit dans la partie supérieure de la charge de fond.

L'auteur propose dans la présente étude que l'analyse géochimique du till à l'échelle régionale constitue une étape essentielle de toute étude d'évaluation détaillée des anomalies entreprise en vue d'établir si ces dernières sont des anomalies secondaires déplacées au sein de trainées de dispersion plus grandes. Dans le cas de la trainée de dispersion de Strange Lake, ces anomalies correspondent à des crêtes topographiques sur la surface du socle sous-jacent.

[1] Contribution to the Canada-Newfoundland Mineral Development Agreement, 1984-89.
Project carried by the Newfoundland Department of Mines.

[2] Geological Survey Branch, Newfoundland Department of Mines P.O. Box 4750, St. John's, NF A1C 5T7.

INTRODUCTION

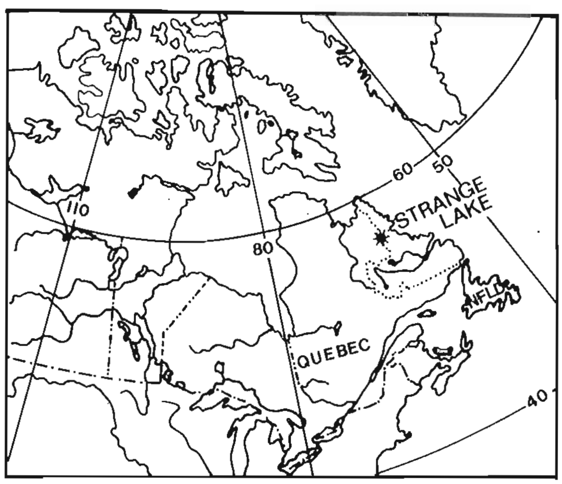
In Newfoundland and Labrador, and indeed over much of Canada, mineral exploration activity has traditionally outpaced Quaternary mapping. Numerous occurrences of mineralized float and geochemical anomalies exist that have not been traced to bedrock sources. This commonly results from a lack of detailed information on the glacial history and sediment genesis and the consequent inability to formulate a suitable exploration strategy. Quaternary mapping programs would greatly increase the number of explainable drift anomalies and the efficiency of mineral exploration in glaciated areas.

This paper details the effects of glacial dispersal from the Strange Lake alkalic complex in northern Labrador. The zirconium-niobium-yttrium-beryllium-rare earth element deposit has a unique geochemical and mineralogical assemblage and is distinct from surrounding bedrock, making it an ideal deposit for glacial dispersal studies.

Background

The Srange Lake alkalic complex (64°10'W, 56°20'N; Fig. 1) was discovered in 1979 through boulder tracing during follow-up of lake sediment anomalies found by the Canada — Newfoundland Uranium Reconnaissance Program (Geological Survey of Canada, 1979). The deposit is situated on a low-relief (150 m) topographic high on the Nain plateau, approximately 145 km west of Nain, Labrador and straddles the Atlantic-Ungava Bay watershed which delineates the Labrador — Quebec border. East of the complex is an elevated, dissected peneplain surface of Pliocene age (Cooke, 1929). The mean elevation is 500 m a.s.l, although individual highs may reach 600 m a.s.l. The climatic regime is insufficient to maintain a continuous tree coverage and vegetation is classified as 'low arctic tundra' (Rowe, 1972).

During the late Wisconsinan, the Strange Lake area was completely covered by eastward-flowing ice of the Laurentide Ice Sheet from a centre to the east of Hudson Bay (Shilts et al., 1979; Shilts, 1980; Hillaire-Marcel et al., 1980). Deglaciation began about 10,500 years B.P., and the study area was probably ice-free some time before 9,500 years B.P., based on a date of 8610±925 years B.P. on basal sediments from Kogaluk Plateau Lake, located about 30 km south of Strange Lake (Short, 1978).



INDEX MAP

Figure 1. Location of study area.

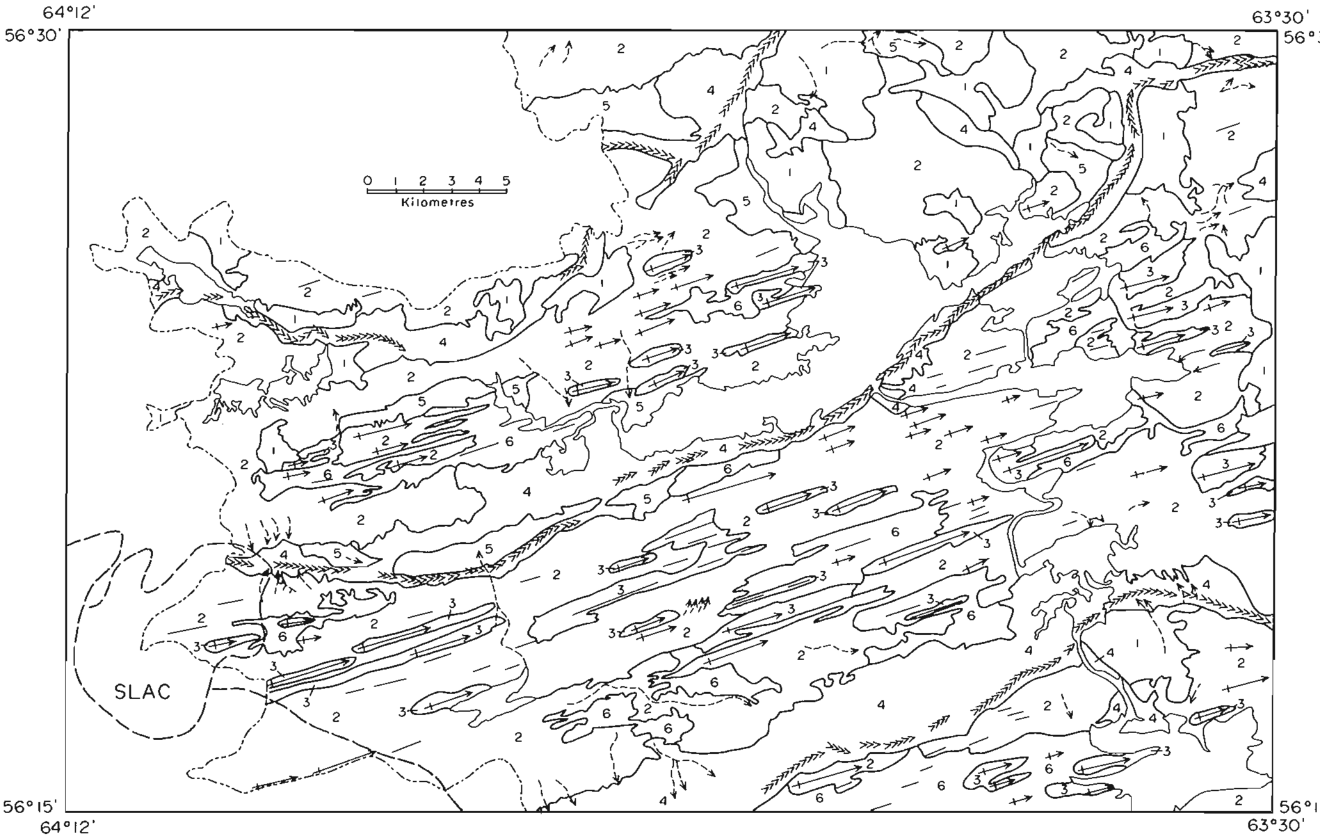
The Strange Lake region reveals evidence of only late Wisconsinan ice, which exhibited a remarkably consistent regional flow direction, with a mean trending 070° (Batterson et al., 1985). Till comprises 60% of the surficial deposits and underlies both organic materials and glaciofluvial sediments (Fig. 2). Till thickness is variable, ranging from a veneer (less than 2 m) to over 16 m in places. Glaciofluvial deposits occur as a veneer (less than 2 m) of well sorted sand or gravel over till, or as distinct esker ridges (up to 10 m high). Bedrock outcrops are rare and constitute less than 1% of the surficial terrain.

Two diamicton types were identified. A rarely exposed unit is thin (50-60 cm), massive and compact, with a silty to fine sandy matrix. Clasts are commonly subangular to subrounded, striated and of predominantly local origin. Together these characteristics suggest a subglacial (lodgment?) genesis (Boulton, 1976; Dreimanis, 1982; Ashley et al., 1985). Overlying this unit is a normally consolidated diamicton with a sandy to silty matrix. It has thin (less than 3 cm) ovoid inclusions of well sorted sand, and contains sub-angular to angular clasts of more distal origin than the underlying unit. These characteristics suggest a basal meltout till, which is defined as a till formed by "the slow release of debris from glacier ice that is not sliding or deforming internally" (Ashley et al., 1985, p. 38).

Geological Setting

The Strange Lake alkalic complex is a 1271±30 Ma (Zajac et al., 1984) peralkaline granite that intrudes rapakivi granite and gneissic rocks of Aphebian age. The margins of the complex are delineated by a ring fault. The complex is composed primarily of quartz, albite, potassium feldspar, riebeckite and aegerine. The deposit is 'strange' because it contains 'exotic' minerals, some of which are rare and currently unnamed, and it is enriched in incompatible elements (Miller, 1986).

The complex has been sub-divided into three units (Fig. 3): an exotic-poor phase containing less than 5% 'exotic' minerals and comprising about 70% of the complex, predominantly the outer margins; an exotic phase containing 5-10% and locally up to 15% 'exotic' minerals, occupying the central part of the complex; and an exotic-rich phase containing greater than 10% exotic minerals and the highest grade mineralization (Miller, 1986). The exotic-rich phase is the smallest in area (approximately 1 km^2) but contains 3.25% ZrO_2, 0.66% Y_2O_3, 0.56% Nb_2O_5, 0.12% BeO and 1.3% total rare earth elements (REE). The units can be further subdivided on the basis of grain size and the presence or absence of inclusions.



Legend

Post-glacial

[6] Organics: *Poorly drained bog of variable thickness. Commonly overlies till.*

Glacial

[5] Glaciofluvial Veneer: *Thin (< 1m) cover of fine to medium sand and associated gravels over till or bedrock.*

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

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

[2] Till: *Description as in 3. Surface may have gullied or featureless expression. Commonly greater than 2m thick.*

Pre-glacial

[1] Bedrock: *Area dominated by bedrock. Numerous pockets (< 1m thick) of glacigenic sediment common.*

Symbols

—— *Ridge parallel to flow*

'/'/ *Ridge transverse to flow*

+——> *Crag and tail hill*

>>>>> *Esker*

--↗ *Meltwater Channels*

Figure 2. Surficial geology of the Strange Lake area. The margins of the Strange Lake Alkalic Complex (SLAC) are shown by the dashed line. Adamellites are to the south of the complex and gneisses to the north and east.

SAMPLING METHODS AND ANALYSIS

Till was sampled from over 500 sites producing a total of 991 samples collected from an average depth of 40 to 60 cm below surface. This provided a nominal sample density of 1 site per 1.97 km^2 , although in the vicinity of the complex the sample density was increased to about 1 site per 0.5 km^2. Soil profile sampling of B, BC, and C horizons was completed where possible.

Samples were split and sieved, the 16 to 64 mm fraction being retained for lithological analysis. The silt/clay (finer than 0.063 mm) fraction was analyzed for beryllium, cadmium, cobalt, copper, iron, lithium, manganese, molybdenum, nickel, lead, and zinc by atomic absorption spectrophotometry after a nitric acid digestion and a hydrochloric acid leach; barium, cerium, chromium, gallium, lanthanum, niobium, rubidium, strontium, thorium, vanadium, yttrium, and zirconium were analysed by X-ray fluorescence; fluorine by ion-specific electrode, and uranium by delayed neutron activation.

DISTRIBUTION OF PEBBLE LITHOLOGIES

Adjacent to the complex, high concentrations (maximum 52 %) of Strange Lake Complex clasts occur. Generally, within 1 km down-ice of the complex, the percentage of mineralized clasts in till falls to below 10 %, and it continues to decline gradually down-ice. However, even at 40 km down-ice from the complex, 1-4 % of surface clasts were derived from the Strange Lake alkalic complex (Fig. 4).

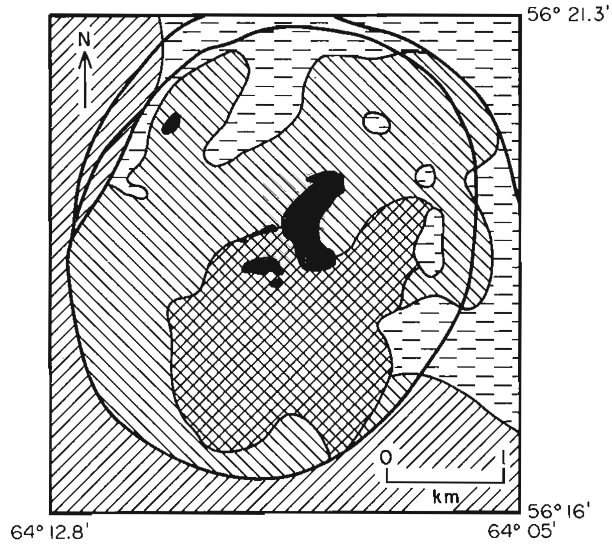


Figure 3. Bedrock geology of the Strange Lake Alkalic Complex (after Miller, 1986). Refer to Figure 2 for position of the complex within the study area.

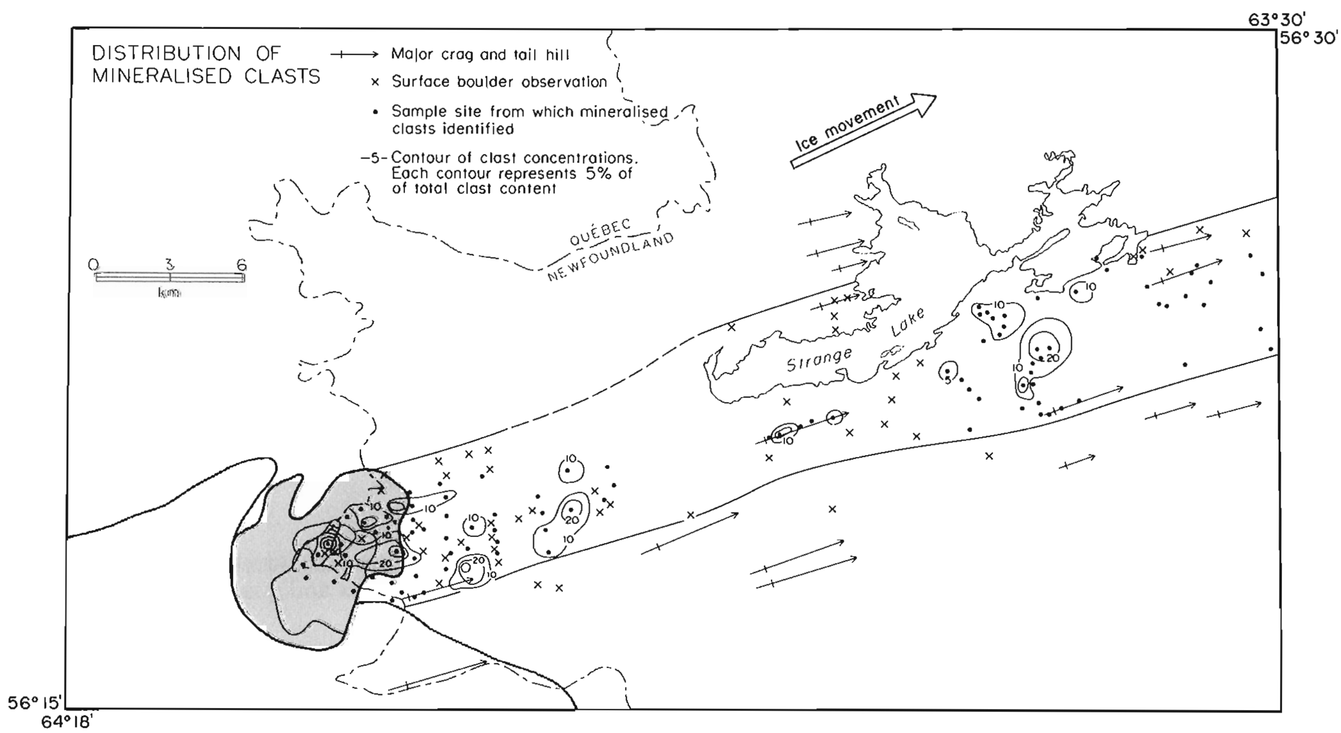


Figure 4. The distribution of mineralized clasts from the Strange Lake Alkalic Complex (shaded area).

Within the dispersal train are a series of inter-related and over-lapping boulder trains that originate from the sub-units identified by Miller (1986). A transect anywhere across the whole dispersal train, perpendicular to ice flow, reveals a sequence that mimics the outcrop distribution of the sub-units in the bedrock source (Fig. 5).

Exotic clasts have the broadest distribution pattern; they are found across the entire width of the boulder train, although dispersal from the northern part of the complex is not so clearly defined being covered by outwash sediments.

Clasts of exotic-rich debris occur up to 5 km down-ice and on hilltops 25 to 30 km down-ice. A number of exotic-rich boulders were observed south of the expected flow lines down-ice of mapped outcrop and may relate to dispersal from small, unmapped sources. The distribution of exotic-rich clasts overlaps the northern part of the dispersal train derived from exotic-poor bedrock which occupies the southern part of the complex. Exotic-poor clasts that occur north of the projected distribution are down-ice of a small inlier of exotic-poor bedrock within the exotic group. Anomalously high concentrations of exotic-poor clasts also occur 25 to 30 km down-ice of the complex.

GEOCHEMICAL PATTERNS

Geochemical patterns have been described in detail by McConnell and Batterson (1987). For consistency, data from near-surface C-horizon or mudboil samples have been considered. A total of 23 single-element maps were produced, with data arbitrarily divided into classes at the 50th, 70th, 85th and 95th percentiles. The geochemical patterns vary widely between different elements. The patterns for a group of elements including beryllium, lead, uranium, thorium, yttrium, and zirconium match the train delineated by mineralized clasts whereas the patterns for others (e.g. cobalt, nickel, and copper) reflect dispersal from the gneissic terrain to the north of the complex or the rapakivi granites to the south (McConnell and Batterson, 1987).

Several element associations are apparent in the data. A Pearson correlation coefficient matrix shows that elements with strong correlations (greater the 0.8) fall into two groups. The first association is cobalt-nickel-copper, which likely reflects a mafic component in the gneiss complex. The second is beryllium-lanthanum-niobium-lead-thorium-uranium-yttrium-zirconium, made up of lithophile elements associated with the ore minerals of the Strange Lake alkalic complex. Geochemical patterns of these lithophile elements are broadly similar (Figs. 6 and 7). The highest values occur over the peralkaline complex, particularly over the mineralized zone. The dispersal train extending down-ice from the source in the direction of ice movement, is ribbon-shaped, and is clearly delineated for at least 40 km down-ice from the complex. The geochemical contrast between the peralkaline-related dispersal train and local background over the gneissic terrain to the north is sharp. The difference between the peralkaline dispersal pattern and the one overlying and down-ice from the rapakivi granite is clear, although less pronounced. This is a reflection of more elevated ore-related element values within the rapakivi granite.

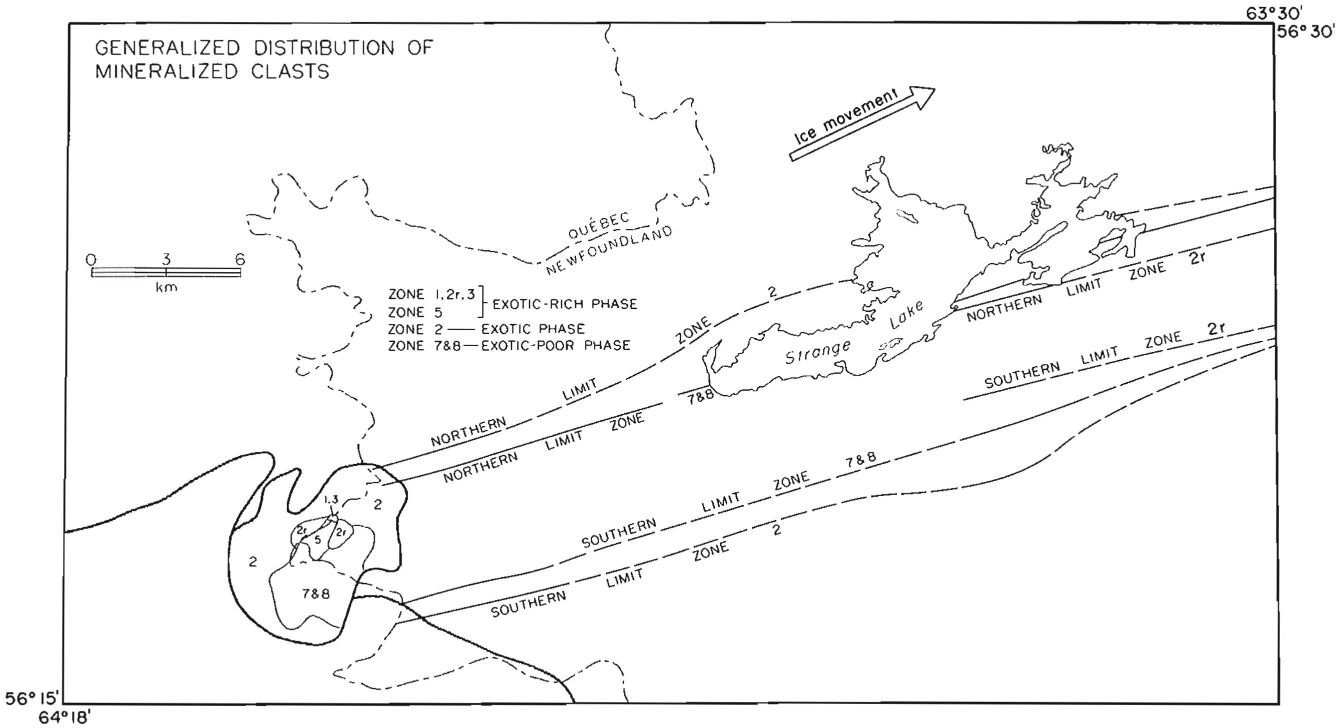


Figure 5. The distribution of mineralized clasts from sub-units of the Strange Lake Alkalic Complex.

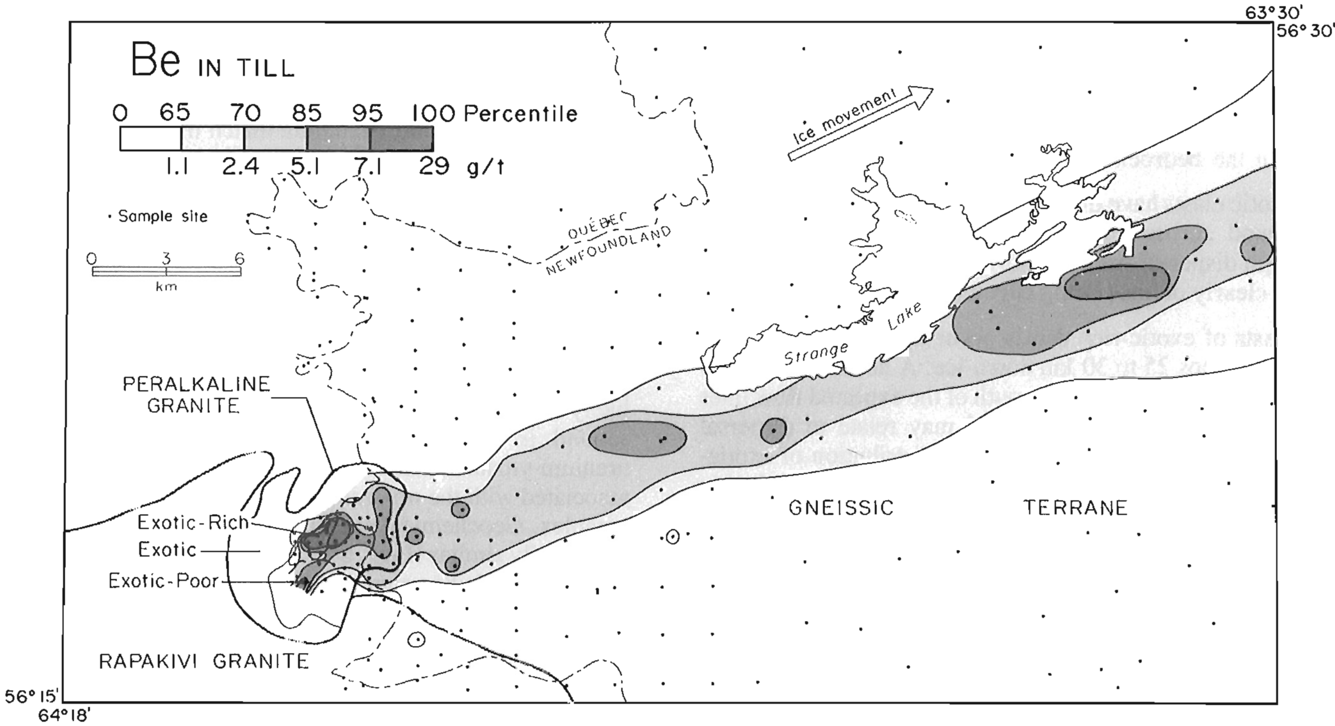


Figure 6: Beryllium in till.

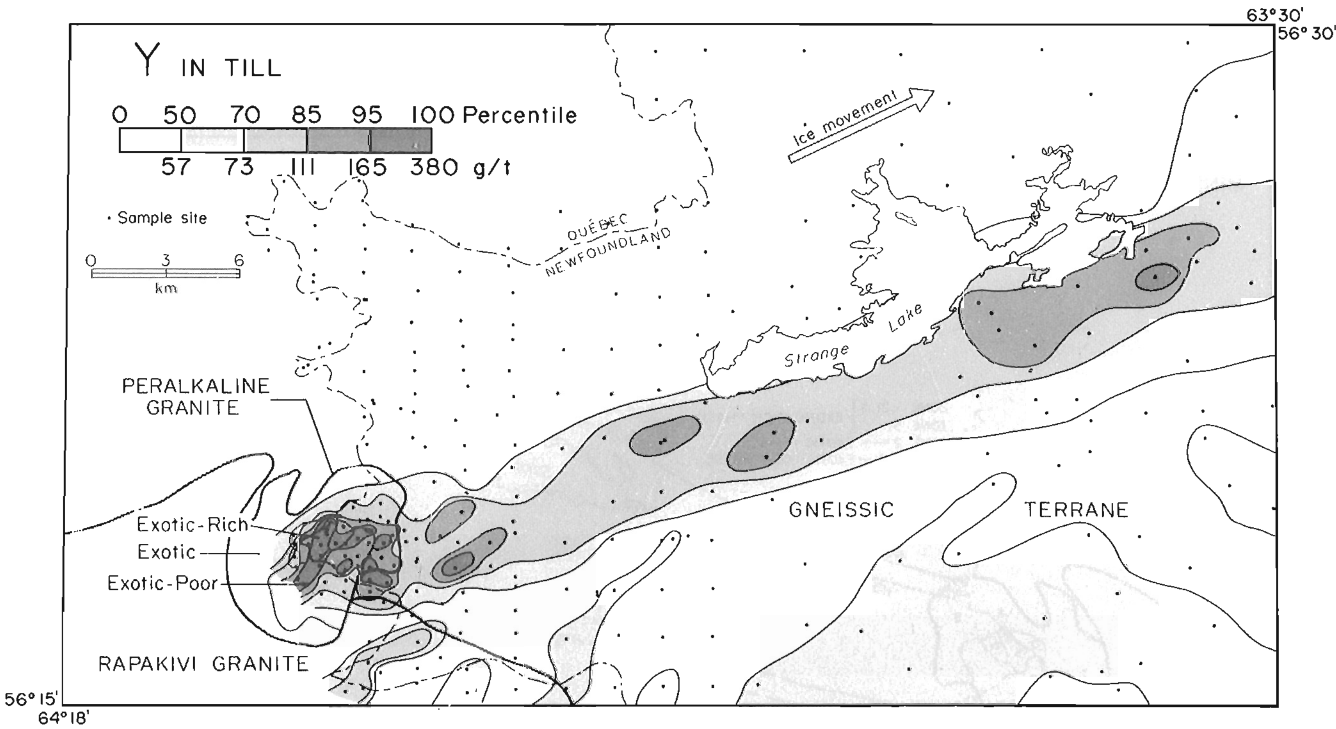


Figure 7. Yttrium in till.

DISCUSSION

Ribbon-shaped geochemical and lithological dispersal trains extending at least 40 km have been documented from the Strange Lake alkalic complex. Airborne spectrometry data (Geological Survey of Canada, 1985) suggest that the Strange Lake dispersal train may be traced to the vicinity of Anaktalik Brook, 55 km down-ice of the complex.

Ribbon-shaped trains have been described from a wide range of localities (DiLabio, 1979, 1981; DiLabio et al., 1982; Dreimanis, 1956; Holmes, 1966; Miller, 1984; Shilts, 1972, 1975). In other parts of Labrador, however, extensive fan-shaped dispersal trains are documented by Klassen and Thompson (1987) and Thompson and Klassen (1986). The form of a dispersal train is dependent on source rock characteristics (area, bedrock topography, resistance to erosion), down-ice topography, and the processes of glacial erosion, transportation and deposition of material (Minell, 1978; Shilts, 1982). A narrow, ribbon-shaped train may be expected from a single, prominent glacial event, assuming no topographic obstruction (e.g. river valleys or hills, Hyvarinen et al., 1973; Klassen and Shilts, 1977, DiLabio, 1979), whereas a fan-shaped train may result from more than one flow (Flint, 1971, Hyvarinen et al., 1973) or dissected topography. There are common characteristics to most dispersal trains. At the up-ice end (the head), the frequency or magnitude of a lithological or geochemical indicator increases rapidly to a peak and subsequently declines gradually (the tail) (Fig. 8; Shilts, 1976). Most material is transported a relatively short distance from its source. At greater distances down-ice, an indicator component becomes diluted by increasing amounts of local debris.

The Strange Lake dispersal train largely follows the classic pattern outlined above. One difference is the presence of well-defined areas of anomalously high geochemistry and lithological components within the dispersal train, especially at about 15 km and 25 km down-ice from the complex. It is considered unlikely that these highs relate to unknown sources of mineralization (R. Miller, personal communication, 1988). Throughout the Strange Lake area numerous crag and tail hills are evident, ranging from small features 5 m high at the crag with 100 m-long tails, to large ones 50 m high with 4 km-long tails. These anomalies coincide with these landforms.

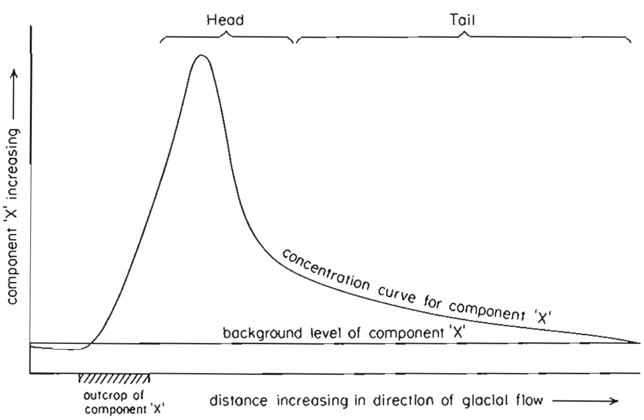


Figure 8. Idealized dispersal curve (after Shilts, 1976).

Crag and tail hills form through the deposition of sediment within a cavity or low pressure zone down-ice of a bedrock obstruction (Sugden and John, 1976). The shape and dimensions of the cavity and therefore the tail are determined by a series of factors including horizontal and vertical ice velocity, height of the bedrock obstruction and its length parallel to flow, and subglacial hydrostatic pressure (Boulton, 1982; Eyles, 1983). On the up-ice side, debris-rich ice stagnates or debris is lodged, as active ice shears over and around the obstruction (Eyles, 1983). Upon deglaciation a till ramp remains.

The crag and tail hills within the Strange Lake dispersal train have anomalously high geochemical and complex-related clast concentrations compared to the surrounding lowlands, irrespective of distance from source. At 40 km down-ice of the complex, geochemical values for beryllium and yttrium are in the 95th percentile of values (Figs. 6 and 7). This suggests that these topographic highs acted as "interceptors" of complex-derived sediment transported either englacially or high in the basal debris layer. In contrast, the topographically lower areas may have been zones of net erosion during periods of active ice movement, with deposition occurring only during deglaciation.

Near-surface sampling was conducted over seventeen crag and tail hills to determine if they can be sampled with confidence in regional drift exploration programs and to assess their significance within the Strange Lake dispersal train. At each feature, one C-horizon sample was taken from the ramp (up-ice of crag), one from the crag and between one and four samples from the tail, at sample intervals of 500 to 1000 m. Internal or stratigraphic variations and their potential effects on geochemistry and lithology are presently unknown. Within the train, crag and tail features have the greatest geochemical concentrations on the ramp or at the crag. Values are least, directly down-ice of crag, and increase farther down-ice (Fig. 9). Outside the train, there is no compositional variation along the length of the crag and tail.

Four major crag and tail features were selected for clast analysis, based on the tail length, which exceeded 1 km. The abundance of mineralized clasts along crag and tail features has the same longitudinal profile as the geochemistry. Within the crag and tail features, the content of Strange

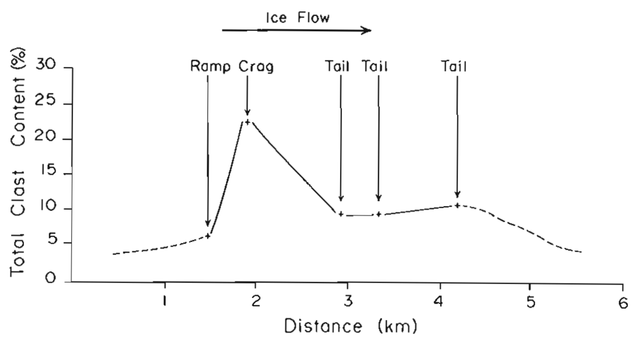


Figure 9. Typical mineralized clast distribution along a crag and tail hill located within the Strange Lake dispersal train.

Lake clasts increased down-ice within the tail from the low nearest the crag (within 1 km). In two cases, the site within 1 km down-ice of the crag revealed no mineralized clasts.

The distribution of clasts and the geochemistry suggests that dispersal along crag and tail hills represents two overlapping dispersal trains, one reflecting regional dispersal from the Strange Lake alkalic complex and the other reflecting local dispersal from the non-mineralized crag (Fig. 10). At point A, on the up-ice side of the crag, material derived from up-ice of and within the dispersal train contains mineralized material from the Strange Lake alkalic complex. The ramp is geochemically and lithologically enriched compared with till in adjacent areas at lower elevations.

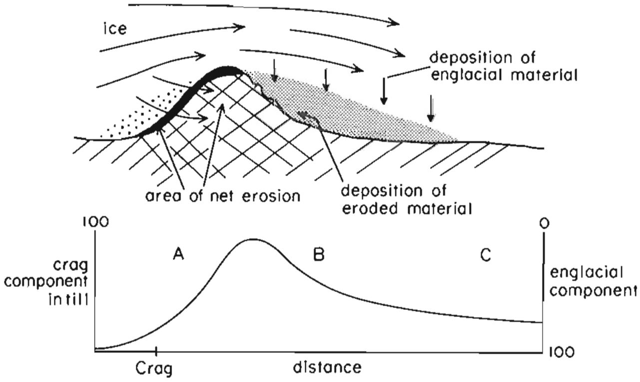


Figure 10. Model of the relationship of crag-related material and Strange Lake Complex-related sediment over a crag and tail hill within the Strange Lake dispersal train.

Bedrock erosion took place as ice flowed around the crag, as shown by numerous striae and grooves. Deposition of crag material occurred within a short distance of the source, the distance being a function of the source width along the ice flow path (Shilts, 1976). Strange Lake crags commonly have a source width of less than one hundred metres and the maximum concentration of material eroded from the crag is likely within several hundred metres of the crag (point B). Consequently, at point B, concentrations of peralkaline-related lithologies and geochemistry derived from englacial sources are diluted by the local material. Farther down the tail (point C), the proportion of local material diminishes with a consequent increase in complex-related sediment.

MINERAL EXPLORATION IMPLICATIONS

Although ice flow history and glacial dispersal are simple in the Strange Lake area, there are several aspects of the dispersal patterns that have important implications for mineral exploration in areas of glaciated terrain.

In many respects the Strange Lake dispersal train is a classic ribbon-shaped train. It is long and narrow, and it has a concentration of indicator components close to source, with values tailing-off down-ice. Description of the dispersal train is simplified by the known bedrock source of the mineralization. Case studies such as these are useful in describing glacial dispersal patterns, suggesting optimal sample spacing (e.g., 1 sample per 3 to 5 km given in McConnell and Batterson, 1987), and defining elements suitable for characterizing mineral deposits. However, in

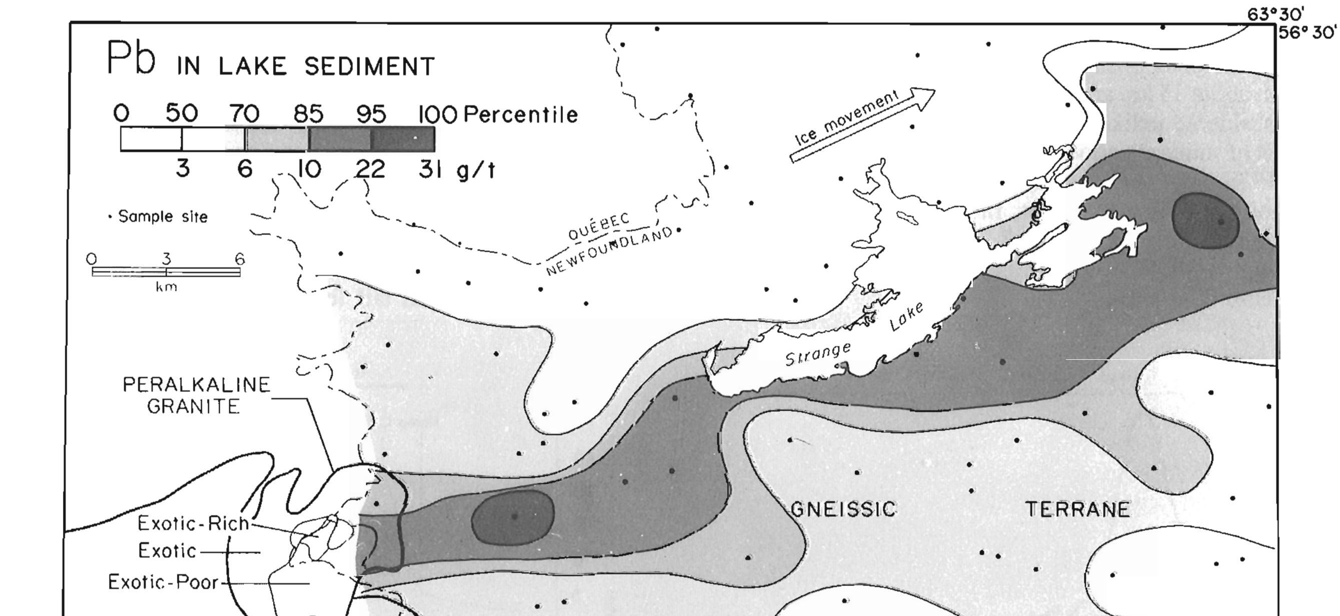


Figure 11. Lead in lake sediment.

the initial stages of exploration a regional till geochemistry database is not commonly available, and exploration companies may rely on regional lake geochemistry for the definition of anomalies. As an example from the Strange Lake area, in reconnaissance lake sediment geochemistry data, lead delineates an elongate anomaly that parallels the till geochemistry train with the highest lead value (31 ppm) occurring adjacent to the complex (Fig. 11). However, a significant lead anomaly occurs about 40 km down-ice. Follow-up till geochemistry would have produced a coincident till anomaly and a high concentration of mineralized clasts, and may have stimulated a search for local mineralization. Regional till geochemistry and mapping of surficial geology shows the anomaly to be coincident with a crag and tail hill and probably part of the long dispersal train originating at the Strange Lake alkalic complex.

In other areas of Labrador the glacial geology is more complex, the topography more diverse, and the vegetation dominated by boreal forest, which hampers exploration. Geochemical anomalies may therefore not be assigned easily to regional dispersal trains. However, if anomalies are associated with topographic highs, consideration should be given to potentially long distances of transport, and detailed surveys around anomalies should be supplemented by regional Quaternary mapping. Through this approach, erroneous conclusions concerning the source of anomalies may be avoided.

SUMMARY

1. Late Wisconsinan glaciation of the Strange Lake alkalic complex in Northern Labrador has produced a well defined ribbon-shaped dispersal train that extends at least 40 km down-ice from its source.
2. The extent of the dispersal train is attributed to a fortuitous combination of the unique geology of the source, topography that has the complex as an upland, a plateau surface down-ice, and unidirectional glacial flow patterns
3. High contrast, ribbon-shaped, multi-element geochemical dispersal patterns are well defined on single-element distribution maps. Beryllium, lead, uranium, thorium, yttrium and zirconium best delineate the complex.
4. A transect across the boulder train perpendicular to ice flow, has a sequence coincident with the outcrop distribution of the sub-units. This suggests glacial transport was along well-defined, persistent flow lines.
5. The dispersal train exhibits a series of well-defined geochemical and lithological highs. The suggestion that these anomalies are related to local, presently undiscovered sources of mineralization is rejected based on known bedrock geology and their coincidence with topography, notably crag and tail hills. It is likely that these topographic highs acted as 'interceptors' of complex-related sediment transported either englacially or high in the basal debris layer. Geochemical concentrations were generally elevated on constructional features compared to adjacent lowlands. This may be related to the continued deposition of sediment on crag and tail hills, whereas lowlands were zones of net erosion, where deposition of sediment occurred only during deglaciation.
6. Variations in the concentrations of complex-related components along crag and tail hills likely relates to their depositional history. In particular, a geochemical/lithological low within 1 km down-ice of crags is suggestive of two overlapping boulder trains, a regional train from the Strange Lake complex, and a local dispersal train from the non-mineralized crag. This latter train would have its maximum concentration close to source, thereby diluting the complex-related components. Farther down the tail, the dilution factor is less pronounced and an increase in complex-related components occurs.
7. Mineral exploration programs in areas of glaciated terrain should include a regional Quaternary mapping and till sampling component. In this way geochemical or lithological anomalies, especially if coincident with topographic highs, may be placed within a regional dispersal train rather than being considered local in origin.

ACKNOWLEDGMENTS

Field work was conducted in 1983-84 and thanks are extended to all those involved, both in field and support work. Geochemical analyses were conducted at the Department of Mines analytical laboratory. Drafting was completed by Tony Paltanavage and David Leonard in the Department of Mines drafting section, under the supervision of Ken Byrne. The manuscript was considerably improved by critical reviews from David Proudfoot and David Liverman (Newfoundland Department of Mines) and Rod Klassen (Geological Survey of Canada). This paper is a contribution to the 1984-89 Canada-Newfoundland Mineral Development Agreement and is printed with the approval of the Assistant Deputy Minister responsible for the Geological Survey Branch.

REFERENCES

Ashley, G.M., Shaw, J., and Smith, N.D. (editors)
1985: Glacial Sedimentary Environments; Society of Economic Paleontologists and Mineralogists, Short Course, Number 16, 246 p.

Batterson, M.J., Taylor, D.M., and Vatcher, S.V.
1985: Quaternary Mapping and Drift Exploration in the Strange Lake Areas, Labrador; in Current Research, Newfoundland Department of Mines and Energy, Mineral Development Division, Report 85-1, p. 4-10.

Boulton, G.S.
1976: A genetic classification of tills and criteria for distinguishing tills of different origin; Geografia, V. 12, p. 65-80.
1982: Subglacial processes and the development of glacial bedforms; in Research in Glacial, Glaciofluvial and Glacio-lacustrine systems, Proceedings of the Guelph Symposium on Geomorphology, eds. R. Davidson-Arnott, W. Mickling, and B.D. Fahey; Geo Books, Norwich, p. 1-32.

Cooke, H.C.
1929: Studies in the Physiography of the Canadian Shield, Part 1, The Mature Valleys of the Labrador Peninsula; Transactions of the Royal Society of Canada, V. 23, Section 4, p. 91-120.

DiLabio, R.N.W.
1979: Drift Prospecting in Uranium and base metal mineralization sites, District of Keewatin, Northwest Territories, Canada; in Prospecting in Areas of Glaciated Terrain, Institute of Mining and Metallurgy, London, p. 91-100.
1981: Glacial dispersal of rocks and minerals at the south end of Lac Mistassini, Quebec, with special reference to the Icon dispersal train; Geological Survey of Canada, Bulletin 323, 46 p.

DiLabio, R.N.W., Rencz, A.N., and Egginton, P.A.
1982: Biogeochemical expression of a classic dispersal train of metalliferous till near Hopetown, Ontario; Canadian Journal of Earth Sciences, v. 19, p. 2297-2305.

Dreimanis, A.
1956: Steep Rock Iron Ore Boulder Train; Geological Association of Canada, Proceedings 8, V. 1, p. 27-70.
1982: Work Group (1) — Genetic classifications of tills and criteria for their differentiation: Progress report on activities 1977-1982, and definitions on glacigenic terms; in INQUA Commission on genesis and lithology of Quarternary deposits, Report on activities 1977-1982, ed. Ch. Schluchter, ETH, Zurich, p. 12-31.

Eyles, N. (editor)
1983: Glacial Geology, An introduction for engineers and earth scientists; Pergamon Press, Oxford, 409 p.

Flint, R.F.
1971: Glacial and Quaternary Geology, Wiley and Sons, New York, 892 p.

Geological Survey of Canada
1979: Regional lake sediment and water geochemical reconnaissance data, Labrador; Geological Survey of Canada, Open File 559.
1985: Airborne spectrometry, NTS 14D/5; Geophysical Series, Map 35414(5).

Hillaire-Marcel, C., Grant, D.R., and Vincent, J.S.
1980: Comment and Reply on 'Keewatin Ice Sheet — Re-evaluation of the traditional concept of the Laurentide Ice Sheet' and 'Glacial erosion and ice sheet divides, northeastern Laurentide Ice Sheet, on the basis of the distribution of limestone erratics'; Geology, V. 8, p. 466-471.

Holmes, G.W.
1966: Early discoveries XXV, Stephen Reed, M.D., and the "celebrated" Richmond boulder train of Berkshire County, Massachusetts, U.S.A.; Journal of Glaciology, V. 6, p. 431-437.

Hyvarinen, L., Kauranne, K., and Yletyinen, V.
1973: Modern boulder tracing in prospecting; in Prospecting in Areas of Glaciated Terrain, ed. M.J. Jones; Institution of Mining and Metallurgy, London, p. 87-95.

Klassen, R.A. and Shilts, W.W.
1977: Glacial Dispersal of Uranium in the District of Keewatin, Canada; in Prospecting in Areas of Glaciated Terrain, Institution of Mining and Metallurgy, London, p. 80-88.

Klassen, R.A. and Thompson, F.J.
1987: Ice flow history and glacial dispersal in the Labrador Trough; in Current Research, Part A, Geological Survey of Canada, Paper 87-1A, p. 61-71.

McConnell, J.W. and Batterson, M.J.
1987: The Strange Lake Zr-Y-Nb-Be-REE deposit, Labrador: A Geochemical profile in till, lake and stream sediment and water; Journal of Geochemical Exploration, v. 29, p. 105-127.

Miller, J.K.
1984: Model for clastic indicator trains in till; in Prospecting in Areas of Glaciated Terrain, 1984, Institution of Mining and Metallurgy, London, p. 69-78.

Miller, R.R.
1986: Geology of the Strange Lake Alkalic Complex and the associated Zr-Y-Nb-Be-REE mineralization; in Current Research, Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, p. 11-20.

Minell, H.
1978: Glaciological interpretations of boulder trains for the purpose of prospecting in till; Sveriges Geologiska Undersokning, Series C, No. 743, 51 p.

Rowe, J.S.
1972: Forest Regions of Canada; Department of Environment, Canadian Forestry Service, Publication 1300.

Shilts, W.W.
1972: Drift prospecting; Geochemistry of eskers and till in permanently frozen terrain: District of Keewatin, Northwest Territories; Geological Survey of Canada, Paper 72-45, 34 p.
1975: Principles of Geochemical Exploration for sulphide deposits using shallow samples of glacial drift; Canadian Institute of Mining and Metallurgy, Bulletin, v. 68, no. 757, p. 73-80.
1976: Glacial till and mineral exploration; in Glacial Till: An interdisciplinary study, ed. R.F. Legget; Royal Society of Canada, Special Publication Number 12, pages 205-224.
1980: Flow patterns in the central North American ice sheet; Nature, v. 286, p. 213-218.
1982: Glacial dispersal: principles and practical applications; Geoscience Canada, v. 9, p. 42-48.

Shilts, W.W., Cunningham, C.M., and Kaszycki, C.A.
1979: Keewatin ice sheet — re-evaluation of the traditional concept of the Laurentide ice sheet; Geology, v. 7, p. 537-541.

Short, S.K.
1978: Palynology: A Holocene environmental perspective for archaeology in Labrador-Ungava; Arctic Anthropology, v. 15, p. 9-35.

Thompson, F.J and Klassen, R.A.
1986: Ice flow directions and drift composition, central Labrador; in Current Research, Part A, Geological Survey of Canada, Paper 86-1A, p. 713-717.

Sugden, D.R. and John, B.S.
1976: Glaciers and Landscape; Edward Arnold, London, 376 p.

Zajac, I.S., Miller, R., Birkett, T., and Mantel, S.
1984: The Strange Lake deposit, Quebec-Labrador; Paper presented at the Canadian Institute of Mining and Metallurgy Annual Meeting, Ottawa.

Drift prospecting in the Appalachians of Estrie-Beauce, Quebec

W.W. Shilts[1] and S.L. Smith[1]

Shilts, W.W., and Smith, S.L., Drift prospecting in the Appalachians of Estrie-Beauce, Quebec; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 41-59, 1989.

Abstract

Trace and minor element concentrations were determined in the < 63 μm fraction of over 1500 samples of till from the Estrie-Beauce region of the Quebec Appalachians. Till facies and weathering status of each sample, though locally important, were found to have little effect on the overall patterns of geochemical dispersal. This conclusion does not hold for fractions containing easily weathered minerals, such as sand-sized heavy minerals.

Glacial dispersal patterns reflect dominant southeastward transport direction of the last, Lennoxville, glaciation, in spite of earlier southwestward and late-glacial northward flow widely documented in stratigraphic sections and by striations. Large glacial dispersal trains of chromium and nickel from the ophiolite belts provide dispersal models with which smaller, less well-defined anomalies associated with various types of mineralization can be interpreted. For instance, the topographic setting of ophiolite outcrops bears a direct relationship to the strength and size of the train developed. Greatest erosion occurred where outcrops forming prominent massifs projected into the glacier and where channelling along valleys increased the velocity and resultant erosive power of glaciers.

In general, the trace element patterns from this regional till study reflect known mineralization and contain intriguing anomalies in areas underlain by bedrock with potential for mineralization.

Résumé

Les éléments en traces et accessoires ont été dosés dans la fraction < 63 μm de plus de 1500 échantillons de till de la région de l'Estrie et de la Beauce des Appalaches, au Québec. Le faciès du till et l'état d'altération de chaque échantillon, quoique marqués par endroits, auraient eu peu d'effet sur les configurations générales de dispersion géochimique. Cette conclusion ne vaut pas pour les fractions contenant des minéraux facilement altérés comme les minéraux lourds de la taille du sable.

Les trainées de dispersion glaciaire indiquent que la direction dominante de transport durant la derniére glaciation de Lennoxville a été vers le sud-est, même si des études de coupes stratigraphiques et de stries montrent que l'écoulement s'est fait d'abord vers le sud-ouest, puis vers le nord. De longues trainées de dispersion glaciaire de chrome et de nickel à partir des zones d'ophiolites constituent des modéles de dispersion permettant d'interpréter les anomalies moins bien définies associées à divers types de minéralisation. Par exemple, le cadre topographique des affleurements d'ophiolites influe directement sur la densité et la taille de la trainée formée. L'érosion est la plus marquée là où des affleurements formant des massifs proéminents s'avancent dans le glacier et où le ravinement le long des vallées a augmenté la vitesse et le pouvoir érosif résultant des glaciers.

En général, la répartition des éléments en traces de la fraction de < 63 μm dans cette étude régionale du till représente bien la minéralisation connue et renferme de curieuses anomalies dans des zones reposant sur un socle à fort potentiel de minéralisation.

[1] Geological Survey of Canada, 601 Booth St., Ottawa, Ottawa, Canada K1A 0E8.

INTRODUCTION

Studies of the physical and compositional characteristics of continental glacial sediments in the Appalachian region of southeastern Quebec have for some years provided models for the application of drift prospecting throughout the Appalachians and in other topographically rugged, geologically complex terrain. The Appalachians are underlain by complexly folded and lithologically diverse bedrock which forms an undulating, high-relief surface (Fig. 1) across which several continental glaciers flowed. This paper presents a summary of geochemical and sedimentological research based on mapping of surficial geology and on samples collected by various scientists, starting in 1963 and continuing through 1987. We emphasize copper and arsenic dispersal in this paper because of renewed interest in exploration for base metals and the well-known gold placer deposits of the region, but we also discuss data on elements associated with the extensive outcrops of ultramafic rock. Drift compositions influenced by ultramafic sources can be used to develop sedimentological models that pertain to general conditions of mineralization and glacial dispersal in the Appalachians.

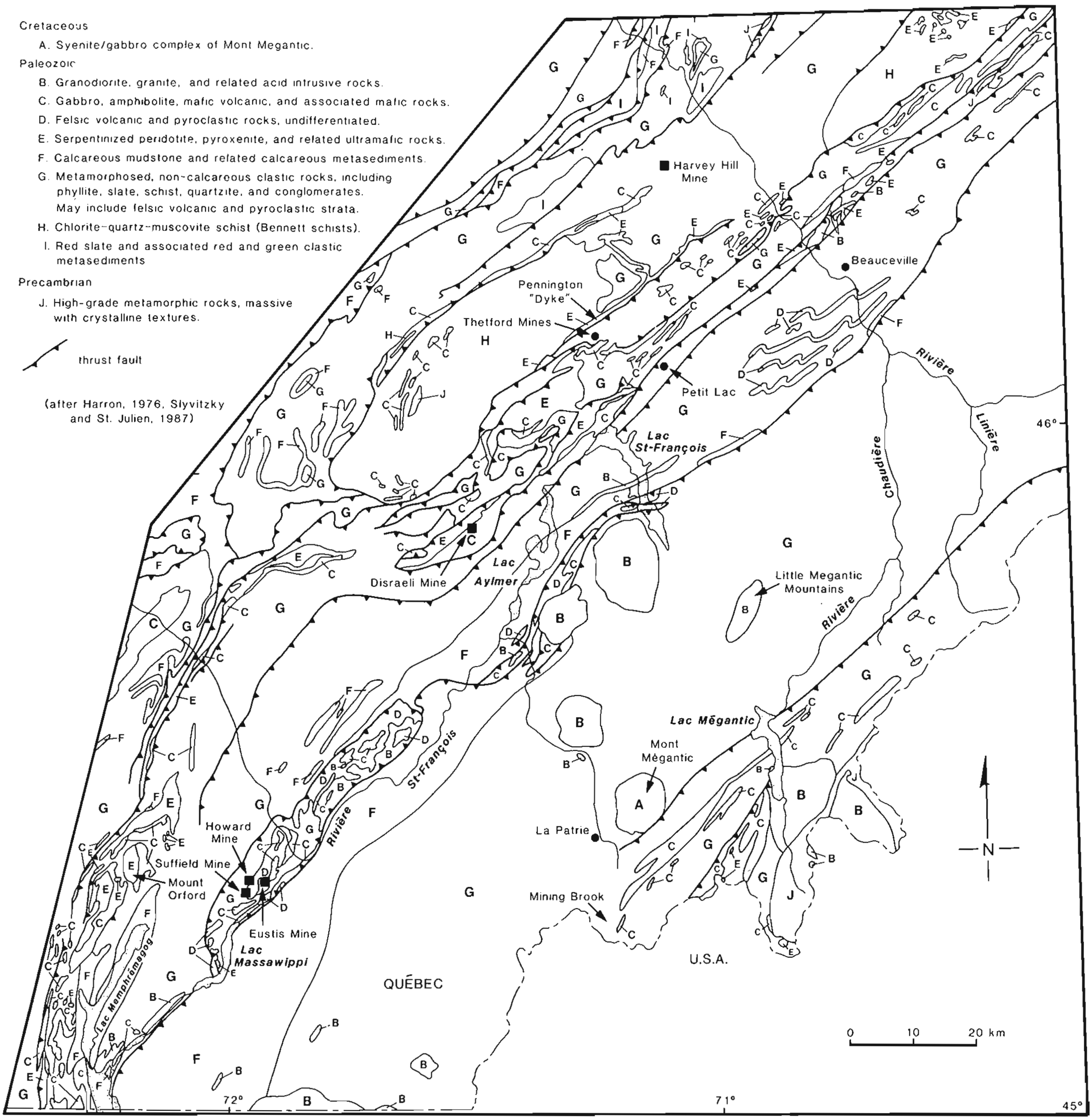


Figure 1. Bedrock geology of the Estrie-Beauce region (modified from maps in Slivitzky and St. Julien, 1987; Harron, 1976).

As a result of various mapping and thesis projects carried out in Estrie-Beauce[1] over the past two and a half decades, well documented till samples, collected from road cuts, natural river bank and man-made sections, and from nearly 50 boreholes to bedrock, has been assembled and curated at the Geological Survey of Canada.[2]

RELATIONSHIP OF SEDIMENTOLOGY TO GEOCHEMISTRY OF APPALACHIAN TILL

Geochemical data derived from the finer fractions of near-surface till samples theoretically should represent the glacial load of the last glacier to cross the region, regardless of facies sampled. However, experience gained in 20 years of working in the Quebec Appalachians and in adjacent New England dictates that the discussion of dispersal should begin with descriptions of: 1) the glacial sedimentological processes typical of this region of high bed relief; 2) late-glacial flow history; and, 3) postglacial alterations that weathering and ground-water processes have effected on the glacial sediments.

It should be borne in mind that the erosional and transportational history of glacial debris that eventually becomes till is often divorced from the mechanism by which the debris is ultimately released from ice. For example, clasts bearing facets and striations formed by differential movements within the dense basal load of a glacier can be deposited as or with supraglacial debris, if thrust to the surface by compressive flow, particularly in the terminal zone of a retreating, actively flowing glacier. Basal debris also can be thrust into the englacial position by being dragged upward over bed irregularities, to be released ultimately by meltout from a downwasting glacier surface. The geochemical composition, regardless of release mechanism, is usually a fair surrogate for the mineralogy of the load the glacier was carrying in the vicinity of the sample point. Thus, although there are several mechanisms of release, each of which produce distinctive facies of till, the mechanism and resulting facies is not as important as the position of the debris in the ice during transport. Whether a sample is properly assigned to one facies or another is not particularly important in interpreting compositional data from widely spaced sites in the Quebec Appalachians, but it may be important in the more rugged terrain of New England, where debris was entrained and transported over a wide range of levels in a continental glacier.

Our principal geochemical sample type in the Appalachian region has been till, and a discussion of its sedimentological characteristics is important if compositional parameters are to be interpreted correctly. It is first necessary to point out that the glacial bed beneath the continental glaciers that traversed the Appalachians had a total relief of about 1000 m, and it is not unusual to observe individual protuberances of the bed standing 500 m above the surrounding countryside (Fig. 2). These protuberances

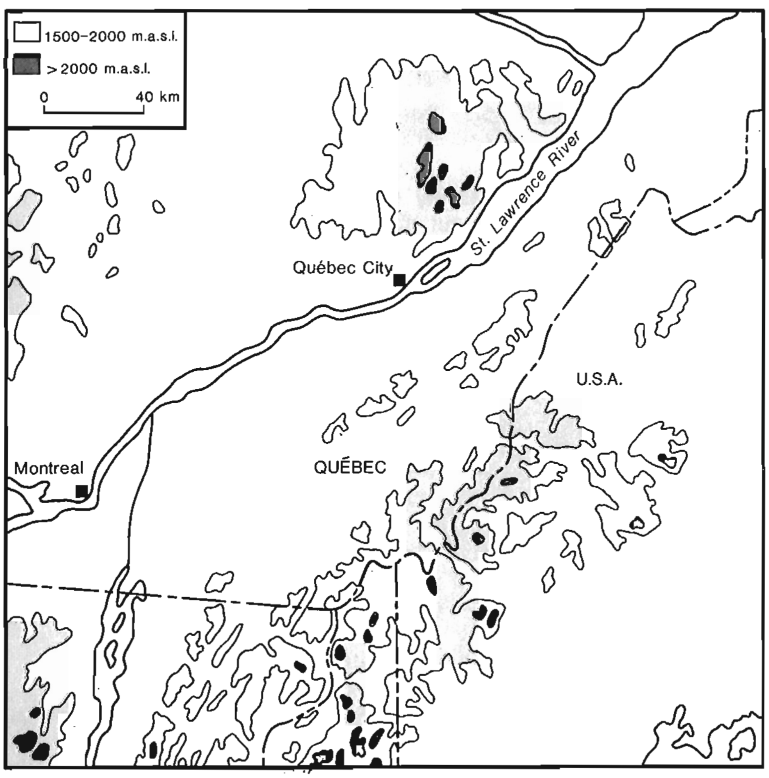


Figure 2. Simplified topographic map of Estrie-Beauce and adjacent regions.

[1] Estrie-Beauce will be used to describe the region of SE Quebec lying within the Appalachian mountains north of Vermont, New Hampshire, and northwest of Maine (USA), and south of Quebec City and Montreal. Estrie includes the Eastern Townships region of Quebec and Beauce includes Beauce County and adjacent areas south of Quebec City.

[2] Contributors to the collection include, in addition to the authors: A.P. Blais, S. Courtney, N.R. Gadd, C.A. Kaszycki, P. LaSalle, J. Locat, G. Lortie, B.C. McDonald, M. Parent, W. Podolak, and their assistants.

are commonly lithologically distinct, often being formed on harder igneous rocks, such as granites, gabbros, ultramafic rocks, or various types of mafic and felsic metavolcanic rocks. Glacial debris from these sources contrasts significantly with debris derived from the metasediments that generally, but not universally, form the lower parts of the landscape. Consequently, debris carried in and released from the higher parts of a glacier may be mineralogically and geochemically differentiated from more basal debris.

Lithologically differentiated debris was entrained at a wide range of levels within the lower 1000 m of glaciers that crossed the Appalachians. The debris eventually was melted out to form the till facies packages of each glacial advance and retreat cycle. The basal part of the facies packages represents a compressed cross-section of the sediment load of the lower one half or one third of the glacier. Sediment once dispersed vertically through 100's of metres of ice is now represented by beds less than five metres thick on the average. As in modern glaciers, the densest sediment load must have been concentrated in the basal 50 m of the glacier. This sediment would have been transported through the lower elements of the landscape, being blocked and deposited against or diverted by the numerous irregularities, massifs, and hills projecting above the Appalachian glacier bed (Shilts, 1976a).

BASAL FACIES

The basal load of Appalachian glaciers is represented by a dense, stony, matrix-supported diamicton with a matrix composed of subequal amounts of sand, silt, and clay (Fig. 3). It is commonly 2 to 3 m thick but can exceed 25 m in valleys, and is thin or absent over many highland areas. When unoxidized, it is typically olive grey, but it may have reddish hues either where the glacier incorporated red slates or volcanogenic erratics from the lower Chaudière valley, or where it reworked underlying proglacial sediments with red clay layers.

This basal till may be a lodgment facies, deposited from the glacier's sole; although it appears massive in excavations or natural exposures, where it is washed by running water it often can be seen to have well-developed and varied structures. Among the most common structures are subhorizontal, planar to undulating partings occurring at vertical intervals from a few centimetres to a metre or more (Fig. 4). The reason for their preferential etching by running water is difficult to establish but is thought to be caused by very thin (1 mm or less) layers of silt between massive stony till beds. Small stones are sometimes concentrated along these partings and at two sites the partings were observed to expand into metre-wide oval cavities filled with thin bands of laminated clayey silt interbedded with crudely cross-stratified and deformed gravel (Fig. 4). At several sites, the partings define massive till beds that seem to be draped over irregular underlying beds or bedrock (Fig. 5).

The structures described above are seen in basal tills of all ages in the Appalachians, but are only obvious where the till has been cleaned by strong water flow (river water, surface drainage, pumps, etc.). We feel that these structures are inherited from the glaciers themselves, that the partings

Figure 3. Typical cobbly, silty Lennoxville Till overlying vertically dipping slates of Connecticut Valley-Gaspé Synclinorium. (GSC #204411-H)

Figure 4. Closely spaced partings in Lennoxville Till. Cavity etched out above shovel is filled with alternating layers of laminated silt and gravel. Cavity is thought to be a conduit through which basal meltwater flowed. (GSC #204411-O)

Figure 5. Basal meltout till with structures typical of tills of Estrie-Beauce region. Note draping of till beds, thought to represent former debris bands, boundaries of which have been accentuated by washing during spring floods. (GSC #204411-C)

represent the boundaries of debris bands that were separated from each other by clean ice near the base of the glacier, a feature common in modern glaciers. The structures would have been preserved by slow melting of inactive basal ice so that meltwater was dissipated with almost no reworking of the sediment. The stony layers and gravel-filled cavities may represent conduits through which some of the meltwater was channelled. The draping of till layers over each other certainly suggests some such basal melt-out mechanism. If this model is correct and appropriate to generalize typical till depositional conditions in the Appalachians, true lodgment till is probably thin or rare, and the landscape is dominated by basal melt-out till lying directly on bedrock or on a thin lodgment facies. The melt-out till represents a "fossilized" glacier base with all the basal elements except ice. The original attitudes of glacial structures and fabric would have been altered significantly by removal of the ice.

It has been important to establish the validity of this model with respect to geochemical sampling, because if the partings define former debris bands, the till between them may change composition from band to band as noted in modern glaciers (DiLabio and Shilts, 1979). Although minor subhorizontal compositional variation has been noted in a detailed study of one of the basal till sheets in this region (Shilts, 1978) it is thought to be usually so slight as to constitute little problem in regional sampling of near-surface exposures.

In some sections and boreholes, we have noticed marked tectonization of unconsolidated deposits, presumably caused by drag of overriding glaciers. The form of tectonization varies from unidirectional deformation of laminated sediments by drag to stacking of one or more tills and associated waterlain sediment, thrust from their original beds into the ice, then melted out, one on top of the other (Shilts, 1981; Smith and Shilts, 1987). This phenomenon is particularly well illustrated at the base of a section on Rivière des Plante, where the two oldest tills are intercalated in a series of compositionally contrasting thrust plates (Fig. 6). Although confined to the older tills at this site, such thrusting and stacking can occur in youngest tills as well and should be considered when planning a sampling strategy or when interpreting sample data. At Rivière des Plante, the two older tills involved in stacking were formed by glaciers moving in radically different directions, with the result that their chemistry and mineralogy are markedly different (Poliquin, 1987; Shilts and Smith, 1986, p. 274).

ENGLACIAL FACIES

Above the debris-rich basal zone, the lower several hundred metres of the glaciers that crossed the Appalachians contained significant but comparatively less concentrated debris, contributed preferentially by the higher elements of the landscape that projected upward into the glacier (Shilts, 1973). The density of the englacial load was probably proportional to the texture of the relief— the isolated highlands and hills standing above the rolling Appalachian topography of Quebec contributing less englacial debris than the rugged, closely spaced hills of New England (Shilts, 1973; 1981).

Whatever the concentration of the load in the englacial position, this debris appears to have been "let down" on to the underlying basal facies as each glacier retreated. In Quebec the englacial debris consists of a layer of boulders with little identifiable matrix. The generally coarse size of blocks that form this surface mantle (ablation mantle of Shilts, 1973) reflects both the large initial size of joint-bounded blocks plucked from the highlands and the low frequency of clast-to-clast contact during transportation in ice with low debris concentrations. The boulders and associated minor fine-grained waterlain or diamictic sediment cap the underlying basal till facies, forming a regionally continuous surface mantle (Fig. 7). There is little chance of mistakenly sampling this facies for geochemical analysis, since it consists either of boulders alone, or of boulders with less than one metre of recognizable diamicton.

Figure 6. Tectonization of base of Rivière des Plante section. Dipping structures are traces of thrust faults bounding packages comprising Johnville and Chaudière Till and of interstadial fluvial and glaciolacustrine sediments. Fluvial sediments form gravelly lens just above water in right foreground. (GSC #204680-3)

Figure 7. Surface mantle of englacially transported, supraglacially released granitic blocks lying on basal till near St. Sébastien, Quebec. Called "ablation mantle" by Shilts (1973). (GSC #204411-A)

However, in the mountains along the U.S. border and in New England, this bouldery mantle thickens into a recognizable deposit of sandy, matrix-supported, bouldery diamicton that forms a blanket as much as 20 m thick over hard, silty, cobbly basal facies (Fig. 8). This deposit has been called ablation till by Stewart and MacClintock (1969; 1971) who cite its regional fabric as evidence of englacial transport. Although fabric cannot be measured confidently in the equivalent Quebec facies because of its thinness, it is thought to have been transported and released the same way. Although some of the englacial material ultimately may have been altered or reworked as a result of release by melting at a downwasting surface or may have been reworked by supraglacial or englacial meltwaters, it is generally thought to have been released by melt-out with minimal disturbance, just as for the basal facies. In these areas, virtually all near-surface exposures may be of this englacial facies and caution must be exercised in comparing geochemical analyses from different facies.

SUPRAGLACIAL PROCESSES

Both the basal and englacial sediment load potentially may reach the glacier's surface and be reworked by slumping and meltwaters. This is particularly probable where deglaciation has been effected by retreat of actively flowing ice. In this case the basal and englacial loads may be lifted to the surface along thrusts of active ice over stagnant ice in the terminal zone. The fact that such reworking seems to be rare in Quebec (and generally in northern New England, too) suggests that the glaciers were relatively inactive during the latter part of their retreat phases and that sediment release accompanied downwasting of relatively stagnant ice, a concept championed many years ago by Flint (1929, 1942), among others, and one that is quite reasonable for an ice sheet that thinned over a bed with relief one third to one half as great as its total thickness.

In summary, we recognize in the Appalachians two main sediment facies packages, both consisting of debris released directly from the ice with a minimum amount of reworking by englacial, subglacial or supraglacial meltwater. Where both are preserved, they usually consist of basal meltout till made up of vertically stacked diamicton layers representing former debris bands in the ice, which may or may not overlie lodgment till. The basal facies are overlain in much of Estrie-Beauce by a mantle of englacial boulders (with minor waterlain and diamictic sediment), which thickens in the more mountainous border region and in adjacent areas of New England into a mass of englacial or supraglacial meltout till, a sandy diamicton as much as several metres in average thickness. There is generally a strong compositional contrast between the basal and englacial/supraglacial facies packages, and both may show evidence of minor reworking by either internal or supraglacial meltwaters.

The significance of these two facies, basal and englacial, for mineral exploration in the Appalachians is profound. Since the higher debris reflects derivation from the higher elements of the glacier bed, and since these elements often owe their superior altitude to lithologies that contrast strongly with surrounding terrain, the englacial debris often has a sharply different composition from the immediately underlying basal facies (Shilts, 1973). In the Appalachians this means that ablation till can reflect composition of nearby as well as distant hills (i.e., it can be local) compared to basal facies that were carried longer distances through the lower elements of the landscape. In other words, no generalization can be made as to which facies represents the more distal provenance because local topographic factors influence provenance of any given sample. In any case, it is important to recognize the presence of these two facies groups because compositions derived from analysis of samples of one or the other can give significantly different dispersal patterns, as demonstrated by Shilts (1973; 1976a).

TILL WEATHERING

Unaltered Estrie-Beauce tills are typically blue grey to olive grey and commonly contain visible, mostly untarnished pyrite cubes. When these tills are subjected to postglacial oxidation, they assume a tan colour caused by precipitation of iron and manganese oxides/hydroxides derived from the breakdown of pyrite and other labile minerals, including sulphides that contain cations of economic significance. Oxidation and other weathering processes alter till to the depth of the water table, effectively removing sulphides and most carbonates above it. Removal or replacement of sulphides does not have a particularly severe effect on geochemical composition of silt and clay, partially because, as a result of their physical properties, some sulphides are not easily crushed to these sizes by glaciers and partially because many cations released by sulphide destruction have been reprecipitated in other forms or adsorbed by fine-grained till constituents. However, destruction of these components in the sand-sized fraction of till and of postglacial sediments derived from till can cause a severe distortion of the geochemistry of the

Figure 8. Typical "ablation till" in Vermont (Stewart and MacClintock, 1969). Note sandy, bouldery texture and sorted sandy beds representing supraglacial or englacial meltwater flow. Pick in right centre is 25 cm long. (GSC #204411-P)

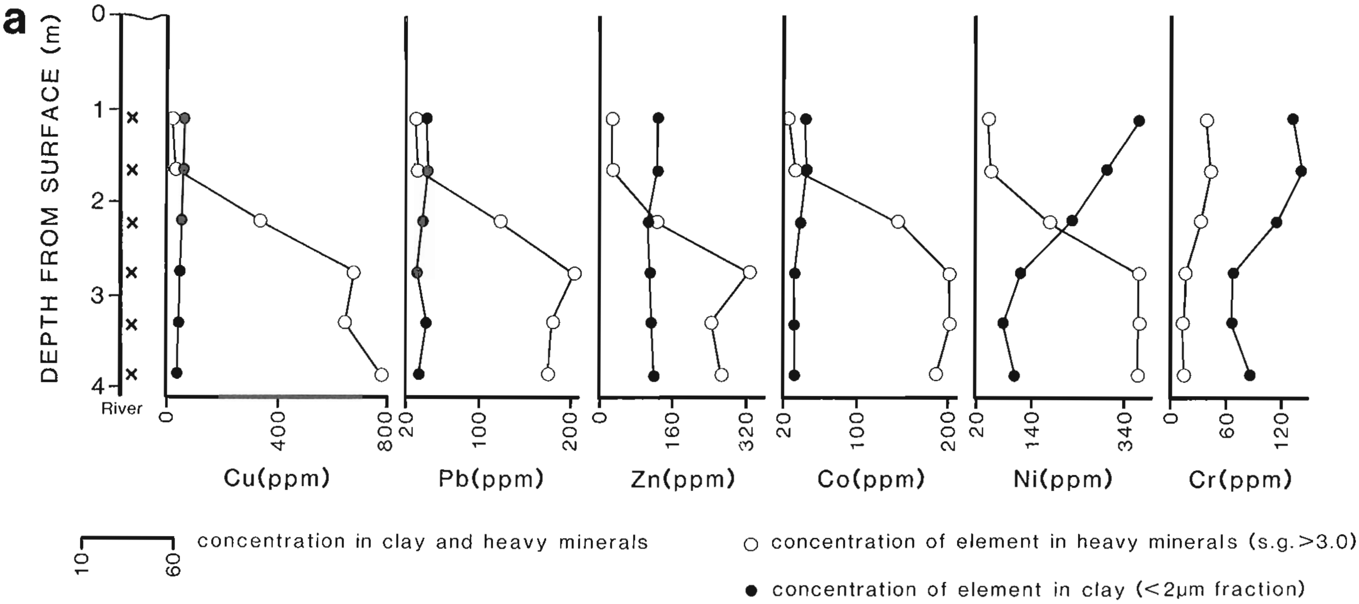


Figure 9a. Vertical profile showing effects of weathering on metal concentration in non-magnetic heavy mineral (s.g. >3.3) suites. Enrichment of nickel and chromium in clay fractions is provenance-related, resulting from redirection of southeastwardly dispersed Lennoxville glacier debris northward during the late Lennoxville reversal of flow. (from section 40 located at Petit Lac). **b.** Photo of section 40 being sampled near Petit Lac, Quebec. (GSC #204411-G)

Table 1. Concentrations of chalcophile elements in oxidized (OX) and unoxidized (UN) till samples.

SITE	Cu		Pb		Zn		Co		Ni		Cr	
	OX	UN	OX	UN	OX	UN	OX	UN	OX	UN	OX	UN
U 13	16	580	19	88	23	226	10	92	16	107	14	10
PL 60 66	29	455	39	147	41	219	34	195	65	438	94	18
U 28	18	465	16	73	33	169	24	92	25	86	19	13
U 103	33	512	17	58	52	263	29	133	40	132	27	16
U 531	142	600	24	176	36	360	26	235	30	200		

sand-sized heavy mineral (s.g. >3.3) fraction, which commonly contains, in unaltered Appalachian tills, more than 10% pyrite and small amounts of other sulphides. Sand-sized non-magnetic heavy minerals from oxidized till show severe depletion of both background and anomalous concentrations of such chalcophile elements as zinc, lead, copper, cobalt, iron, etc. (Fig. 9a,b; Table 1). Because of the volume of minerals destroyed by oxidation, even comparing concentrations of stable heavy minerals, such as gold and tin, among oxidized and unoxidized samples can be misleading, particularly where pyrite made up a large proportion of the original sediment. Removal of pyrite can cause the stable minerals to be over-represented in the heavy mineral suite.

To deal with these weathering problems, a simple procedure was developed to allow even inexperienced samplers to make judgements about oxidation state in the field, thereby reducing considerably the chances for sample error. Because the colour contrast between oxidized and unoxidized till is generally so striking in Estrie-Beauce, it was chosen as the main basis for assigning tills descriptors according to a "class" system.

Class I till samples are calcareous, hard, compact, various shades of grey (rarely maroon or mauve in northern Beauce County) basal till with, in most cases, visible, untarnished pyrite grains or rock clasts with unaltered pyrite inclusions. This class constitutes unaltered till and is generally found below the water table, which may be as deep as 4 or 5 m in high stream sections to less than 1 m beneath poorly drained areas, such as bogs or floodplains. For assessing the exploration implications of geochemistry or mineralogy of sand-sized heavy mineral concentrates, only this class of sample should be used, particularly for chalcophile elements.

Class II till is grey basal till that has been gleyed by being submerged beneath the water table after exposure to oxidation (as in a floodplain where a stream may migrate over a previously well-drained area) or is collected from the narrow transition zone between oxidized till and unoxidized till. It is identified by inclusions of rust-coloured goethitic pseudomorphs after pyrite or by a brownish hue reflecting the first stages of oxidation. The sulphide weathering process is so fast that a grey class I till, freshly exposed by spring flood waters, may be already stained brown and show noticeable tarnish of its sulphides by the end of the summer. Geochemistry of heavy mineral samples from class II tills yields variable and unpredictable results.

Class III samples are of compact, thoroughly oxidized tills that, except for their tan colour are physically identical to class I tills from which they have been altered. Their sulphides have been thoroughly leached and they are generally devoid of carbonates with the exception of siderite. The lower contact between this zone and underlying unoxidized till is usually very sharp and marks a major geochemical break in the sand-sized heavy minerals (Fig. 9a,b). The chemistry of the silt-clay and clay-sized fractions, dominated as they are by silicates, is relatively unaffected. In rare cases where the class I till had reddish colour, the pigmentation provided by the secondary oxides does not provide enough contrast to judge the true depth of oxidation.

Class IV samples are of diamicton that is derived from till that has been disturbed or severely altered by mass-wasting, frost, or soil-forming processes. Till, in the exposures from which these samples were collected, often has structures and/or crude layering created by downslope creep, or is mottled brown and grey by interaction with the biomass or by other chemical processes. When possible, this type of sample is avoided, but in many areas, exposures are so rare and shallow that no other type is available. Analyses of these types of samples may yield geochemical results that are so dominated by the secondary effects of cation redistribution due to weathering, that the chemical signal of glacially dispersed minerals is obscured.

The analyses on which the dispersal maps are based are largely of class III till (80 %), since oxidation generally affects sediments a metre or more below the approximately one-metre-thick postglacial solum, with smaller numbers of class IV (10 %), class I (5 %), and class II (probably <5 %). In the maps discussed in this report, if samples representing more than one class were available at a site, the analysis of a class III sample is reported. Table 1 shows the contrasts in geochemistry among chalcophile elements for heavy mineral separates from oxidized and unoxidized samples (class I and III) collected at common sites.

APPALACHIAN STRATIGRAPHY-EROSIONAL AND DEPOSITIONAL

The major stratigraphic units and glacial events of the Quebec Appalachians have long been known, in their broadest expression at any rate. In the recently completed Asbestos Initiatives Program[1], the stratigraphy and origin of buried gold placers were investigated by continuous coring to bedrock or preglacial regolith. No new glacial stratigraphic units were recognized in the 45 holes drilled, suggesting that the stratigraphic model originally proposed in Vermont by Stewart and MacClintock (1964) and elaborated upon by McDonald and Shilts for Quebec (1971) is adequate to describe the glacial events affecting Estrie-Beauce.

From stratigraphic evidence, it has been postulated that one or more continental glaciers crossed the area southward or southeastward before or early in the Wisconsin Stage. Johnville Till was deposited during the first glaciation for which there is any evidence. Retreat of the Johnville glacier was followed by a period of weathering and unrestricted northward drainage to the St. Lawrence River.

The subsequent Chaudière glaciation was initiated by a glacier that flowed across the region from an eastern Appalachian source, probably in New Brunswick or northern Maine (Rappol, 1988). This glacier removed and reworked most of the older deposits, and its till generally rests directly on bedrock, except in several deep valleys where it rests on older, unconsolidated sediments. The early westward flow phase was superseded in the study area by flow from a Laurentide source, southeastward across the region. Even though much of the Chaudière Till was subsequently reworked by southeastward-flowing ice of the later Lennoxville glaciation, it was an important event with respect to the composition of surface till. Components transported southwestward during its early, but main erosive phase, were retransported southeastward during its Laurentide phase and during the main phase of the later Lennoxville glaciation. Although greatly diluted by sediment produced by later glacial erosion, southwestwardly transported erratics can still be found southwest of their original sources (McDonald, 1966a; Elson, 1987). The possibility that multiple vectors of transport may distort compositional anomalies in Lennoxville Till must be considered when evaluating geochemical maps.

The front of the glacier representing the Laurentide phase of Chaudière glaciation retreated northwestward only to the northwestern edge of the Appalachians, damming a large lake, Glacial Lake Gayhurst, in the Chaudière and St. François River valleys (Shilts, 1981). As this lake expanded down these valleys in contact with the retreating Chaudière ice, tremendous amounts of coarse proximal sediment were

[1] The Asbestos Initiatives Program was a federal government project, carried out from 1984-1986, in the Estrie-Beauce region. The phases carried out by the Geological Survey of Canada were designed to introduce new mineral exploration techniques and data into the region economically affected by decline in asbestos production since 1983.

deposited as subaqueous fans and substantial quantities of fine-grained sediment debouched into deep water from subglacial meltwater conduits. Closely spaced pulses of dense, cold, sediment-laden water formed density underflows which sought and filled the lowest depressions on the lake floor with laminated, fine grained sediment. Gayhurst Formation is thus a unit of extremely variable thickness, being thickest where depressions occurred proximal to sediment-laden basal meltwater tunnels. Thickness of Gayhurst Formation sediment varies from zero to more than 100 m, often over short distances. It is not draped over the landscape but occurs only in depressions, a distribution also typical of sediment deposited in late-glacial proglacial lakes.

Southeastward readvance of the Chaudière glacier from its maximum retreat position at the Appalachian front, was continuous across Quebec and New England. The readvance is called the Lennoxville glaciation and represents the major late Wisconsin glacial event in the region. It was formerly thought to have deposited a simple facies package of lodgment till overlain by a mantle of englacial or supraglacial boulders that were deposited during regular northwestward retreat (Shilts, 1970). The (re)discovery, in the early 1970's (Chalmers, 1898; Lamarche, 1971), of northward pointing striae, clearly inscribed *after* those formed by the southeastward, main Lennoxville flow (Fig. 10), caused a significant reevaluation of the possible interpretations of geochemical data. The northward striae were ultimately attributed to the formation of the Quebec Ice Divide (Gadd et al., 1972; Shilts, 1976b, 1981). The ice divide marks a northeast-trending linear axis of outflow of an ice mass stranded south of the St. Lawrence River as a result of northward drawdown toward a re-entrant caused by ice calving rapidly into eustatically rising marine water in the lower St. Lawrence estuary (Thomas, 1977).

After the reversal of ice flow late in the Lennoxville glaciation, ice apparently readvanced southward against the Appalachians and several kilometres up the Chaudière and St. François valleys as long, low gradient, narrow tongues. This event was accompanied by ponding of ephemeral proglacial lakes in the major valleys, probably to altitudes of about 400 m above sea level, the lowest level of overflow eastward through Daquaam-Famine River valleys into the St. John River system. Sediments deposited in these late glacial lakes are thin and rare except near ice-contact subaqueous fans, such as the massive complex at Vallée Jonction.

Figure 10. Northward trending rat tail striae behind quartz veins through red slate, Beauce region, Quebec. (GSC #204411-I)

One perplexing problem associated with northward flow is that, although there is abundant and incontrovertible striation evidence for its occurrence late in the Lennoxville glaciation, there is almost no recognizable depositional evidence of it in the study area. Consequently, although the final flow direction north of the ice divide is northward, in this zone, as elsewhere, the glacial dispersal direction is overwhelmingly southeastward (Shilts 1973, 1976b). At this writing, only near Petit Lac, northeast of Thetford Mines, has till been found that bears a fabric and compositional evidence of northward flow (Shilts 1976a; Fig. 10). Even here, the high nickel concentrations seem to be displaced northward from a southeastward-trending dispersal train and not directly from an identifiable bedrock source.

This apparent lack of significant dispersal and lack of sediment (till) specifically related to the reversal of flow or to post-reversal southward readvance up the Chaudière and St. François valleys (Shilts, 1982; Bouchard et al., 1987) suggests that we may deduce glacial events from two types of "stratigraphy" in this region: 1) a (conventional) depositional stratigraphy, based on the number of till facies packages in sections; and, 2) an erosional stratigraphy based on comparing the superposition of striae on individual outcrops among several sites.

Erosional stratigraphy is an absolute indication of glacial events, and a fairly complete sequence of events can be ascertained by examination of hundreds of outcrops. However, not all glacial events are represented by recognizable striae, as later events may have eroded earlier striae from all but the most protected, and, therefore, inaccessible areas. Striae representing different glacial advances also may be indistinguishable because they were formed by ice flowing in the same general direction (i.e. Johnville and Lennoxville movements to the southeast).

Furthermore, depositional stratigraphy does not necessarily correspond to erosional stratigraphy, as some phases of glacial flow do not seem to have produced enough sediment to leave a recognizable deposit, the lack of sediment deposited during late-glacial northward flow being a case in point.

The above discussion highlights a real problem in both mineral exploration and reconstruction of glacial history: drift sheets do not necessarily exist or are not easily recognizable for every regional set of striations. This paradox is abundantly illustrated in this region and is very apparent in the geochemical maps discussed below. The relict dispersal effects of the penultimate, Chaudière glaciation are easier to discern within the general southeastward dispersal pattern in Lennoxville Till than are those of the latest northward and even younger southeastward phases of Lennoxville glacier flow, the latter being almost impossible to detect.

To summarize, the dispersal patterns reflected by near-surface till samples dominantly reflect the southeastward flow of the latest Lennoxville glacier. Nevertheless, coarser

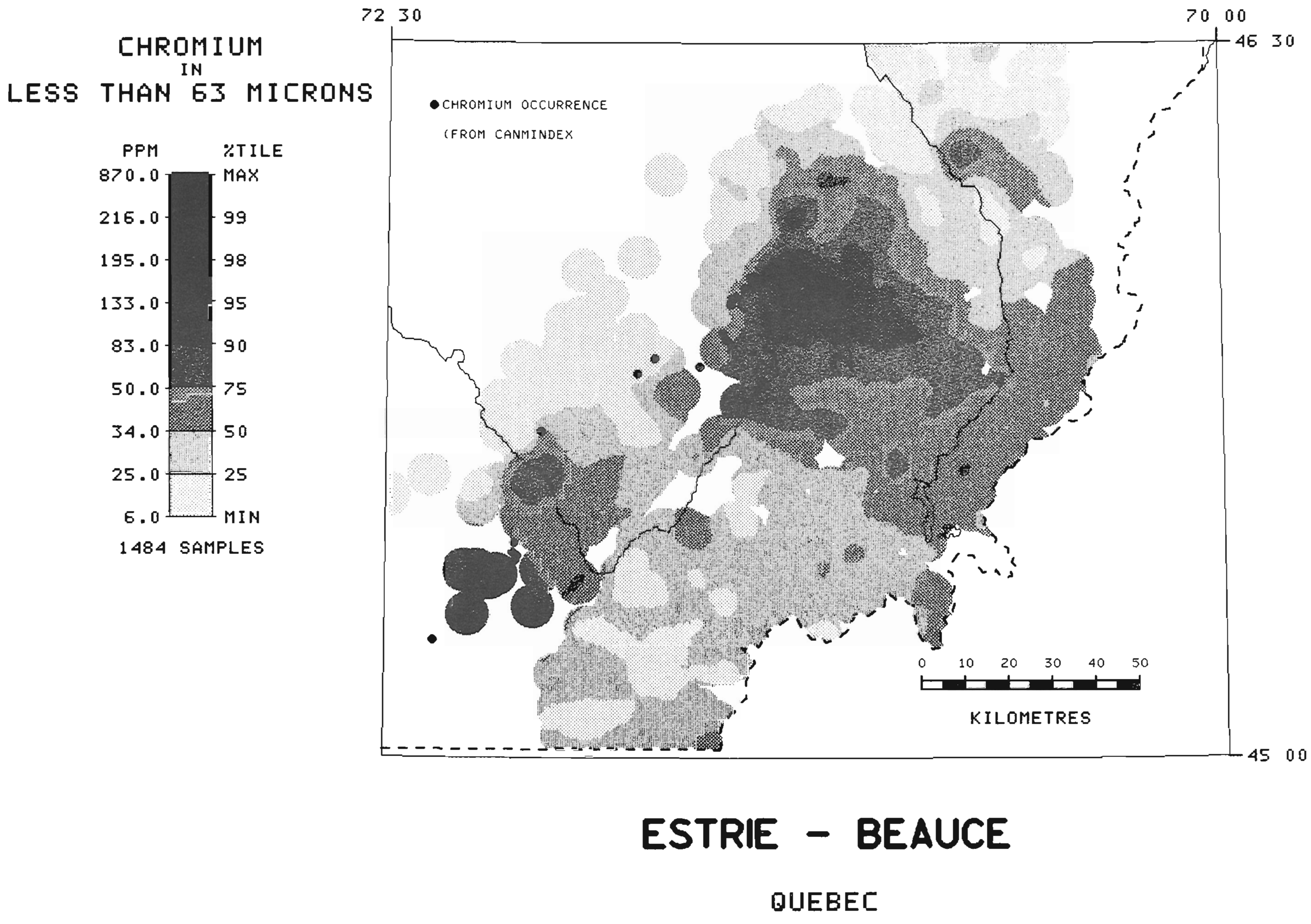


Figure 11. Chromium dispersal in <63 μm fraction of till.

erratics are found in locations west or north of their outcrops as a result of southwestward flow before and northward flow late in the Lennoxville glaciation. Shilts (1976a) and Parent (1987) describe geochemical evidence for northward displacement of fine-grained debris as well. All compositional patterns must be interpreted with these possible perturbations in mind.

GLACIAL DISPERSAL PATTERNS IN SURFICIAL SEDIMENTS

Introduction

Bearing in mind all of the possible ramifications of the sedimentological, weathering, and stratigraphic models discussed above, the authors selected a sample from each site and analyzed the silt-clay (<63 μm) fraction for several trace and minor elements. At the many sites where multiple samples were collected, we selected the uppermost class III (oxidized) sample or, if no class III was available, a class I or class IV. Thus, the bulk of the analyses on which these maps are based were performed on oxidized basal till, for the most part thought to have melted out of the ice rather than having been lodged beneath the sole of the glacier. The maps, therefore, reflect regional geochemical dispersal patterns for debris carried near the base of the Lennoxville glacier, regardless of how or when it was released from the ice.

Chromium and other ultramafic debris

The map of chromium dispersal (Fig. 11), updated from maps that were produced of this area in the early 1970's, demonstrates how a glacier dispersed debris from the lithologically distinctive Appalachian Ophiolite belt over a rough glacial bed (Shilts, 1973). Since that time, parts of these and accompanying nickel data (Fig. 12) have been highlighted in many publications (Shilts, 1975, 1976a, 1978, 1981; Rencz and Shilts, 1980) because they demonstrate so well the effects of topography and lithology on patterns of dispersal and permit discussion of the anatomy of dispersal trains.

From Figures 11 through 13 it can be seen that there are only four discrete trains of chromium and nickel-rich debris extending from the chromium/nickel-enriched serpentinized ultramafic lithologies of the ophiolite belt, even though the belt itself is relatively continuous along strike. Whether a train has been developed or not depends largely on three factors.

First, if the ultramafic outcrops stand high and were exposed to the full force of glacial erosion, without protection of surrounding hills, trains were formed. Although not thoroughly sampled, one such train extends southeastward from Mount Orford and nearby hills, which are cored by ultramafic rocks that stand several hundred metres above the surrounding terrain.

Second, the size of the outcrop is important. The narrow, serpentinized peridotite outcrop of the Pennington "dyke", extending northeastward from Thetford Mines, is less than 100 m wide and has shed relatively little debris through glacial erosion. Thus, dilution by high sediment concentrations from surrounding chromium and nickel-poor rocks has all but obliterated its geochemical signature. The large (10 km x 5 km) outcrop of various types of serpentinized ultramafic rock that strikes southwestward from Thetford Mines, on the other hand, has presented ample area for glacial erosion, which probably was enhanced by its higher altitude. The huge ultramafic train trailing southeastward from these outcrops can be traced geochemically for over 80 km and has been discussed at length in the publications cited above. Its effect on composition of modern (stream) sediments is discussed by Shilts (1976a) and Maurice (1988).

A smaller, prominent dispersal train has been developed where the ophiolite suite widens along strike just east of Chaudière River. This train, which can be traced geochemically over 15 km down-ice, is probably distinctive because of the relatively large size of outcrops, but also may have been enhanced by higher flow velocities and accompanying higher rates of erosion in ice moving up the Chaudière Valley, a major trough across the topographic grain of the Appalachians. A similar but less well developed train extends up the St. François River valley from the narrow ultramafic outcrops that cross it downstream from Sherbrooke. It was likely enhanced by high ice flow velocities with accompanying augmented erosion in the valley.

Third, trains are not well developed down-ice from parts of the ophiolite belt that occur in or form depressions that preferentially served as sites of glacial or interglacial/interstadial deposition. Such is the case for the ultramafic complex at Asbestos where more than 70 m of glaciofluvial and glaciolacustrine sediment covers the ultramafic outcrops. This sediment was presumably deposited as a subaqueous fan complex when the Chaudière glacier margin stood along the northernmost range of the Appalachian foothills, just before readvancing through Glacial Lake Gayhurst at the onset of Lennoxville glaciation. As a result of the protection afforded by the thick blanket of waterlain sediment, this relatively wide part of the ophiolite belt provided virtually no geochemical signature for Lennoxville Till deposited down ice (southeast) from Asbestos.

These glaciological conditions and geological characteristics of source outcrops account for many of the details of chromium and nickel dispersal in this region. However, the shapes of dispersal trains were further modified by topography in the dispersal area. The granodiorite stock that underlies Little Megantic Mountains, for example, stands as much as 500 m above the surrounding terrain and has blocked part of the ultramafic train, splitting it into two lobes that pass around either end of the highest parts of the stock.

The dispersal patterns of chromium and nickel have one anomalous aspect with respect to the known ice flow history of the region. As described above, in the Thetford Mines region and along the Quebec Ice Divide, ice flow reversed at the end of the Lennoxville glaciation to flow northward toward the marine calving bay in the lower St. Lawrence estuary (Thomas, 1977; Shilts, 1981; Lortie and Martineau, 1987). The flow reversal, marked by striations trending north $\pm 20°$ on literally hundreds of outcrops in the

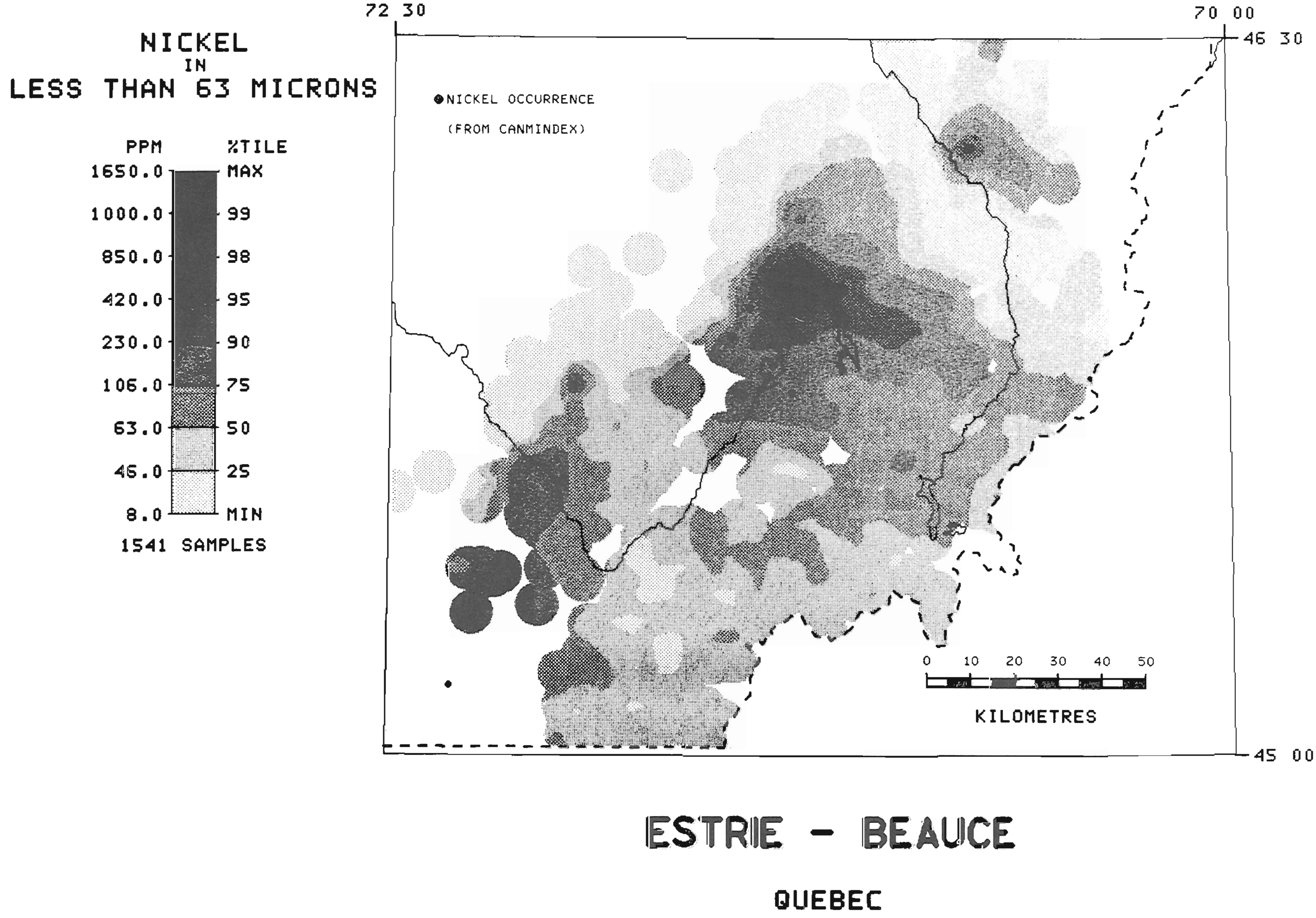


Figure 12. Nickel dispersal in <63 μm fraction of till.

region, has caused almost no distortion of the distinctive, southeast-trending geochemical pattern of ultramafic enrichment in the Thetford Mines and Beauceville areas. Although ultramafic surface erratics are found north of their outcrops, their concentrations are commonly low and the till on which they lie has background concentrations of chromium and nickel.

The reason for this apparent lack of dispersal northward is unknown, but a similar phenomenon has been noted also around the Keewatin Ice Divide (Shilts, 1984). Among the possible causes are:

1. The low ice-flow velocities associated with the ice divide. As with other flow systems, velocities increase exponentially away from the origin of flow (Boulton et al., 1977) so that erosion would have been slight, and displacement of entrained material would have been negligible after the ice divide came into existence. Prior to formation of the divide, however, ice in the vicinity of Thetford Mines would have been charged with basal and englacial debris during the phase of high velocity southeastward flow that existed when this area was far out on the limb of an eastern Laurentide Ice Sheet flow centre. Restricted transport away from other late glacial ice flow centres, such as those in Nova Scotia, relative to long-distance transport during earlier regional flow from distant ice dispersal centres likewise may be related to the low flow velocities characteristic of ice divides;
2. Debris might be eroded and entrained most efficiently during some particular phase of glaciation. Patterns of glacial dispersal may reflect transport (flow) directions during that phase. If this is true, glaciers would have accomplished most erosion and entrained debris most effectively early in the Lennoxville glaciation, when regional flow was southeastward. Once the easily eroded material that formed the glacier's substrate (i.e. frost shattered or weathered bedrock, previously deposited unconsolidated glacial or non-glacial sediments, etc.) was entrained, subsequent flow may have accomplished little beyond scratching rounded outcrops by dragging the entrained basal load across them in various directions. Lobes of chromium and nickel-rich drift projecting northward from the northern edge of the southeastward-trending dispersal train from Thetford Mines (Shilts, 1976b; Figs. 11, 12) suggest a >90° deflection of the southeastward transport vector of already entrained and displaced ultramafic debris.
3. The duration of flow in a northward direction may have been very short, so that little transport was effected, regardless of proximity to the ice divide. The fact that some ultramafic erratics do appear to have been transported several kilometres northward, as well as the several kilometre length of the documented northward projection of chromium and nickel-rich till from the main dispersal train suggests, however, that significant transport was possible.

Considering all of these characteristics of the ultramafic dispersal trains, the authors conclude that, although any one or all of these explanations may account for the restricted northward transport of debris, the second one seems to us to be the most important. This is because of the demonstrable northward transport of several kilometres of small amounts of ultramafic debris from sources virtually on the

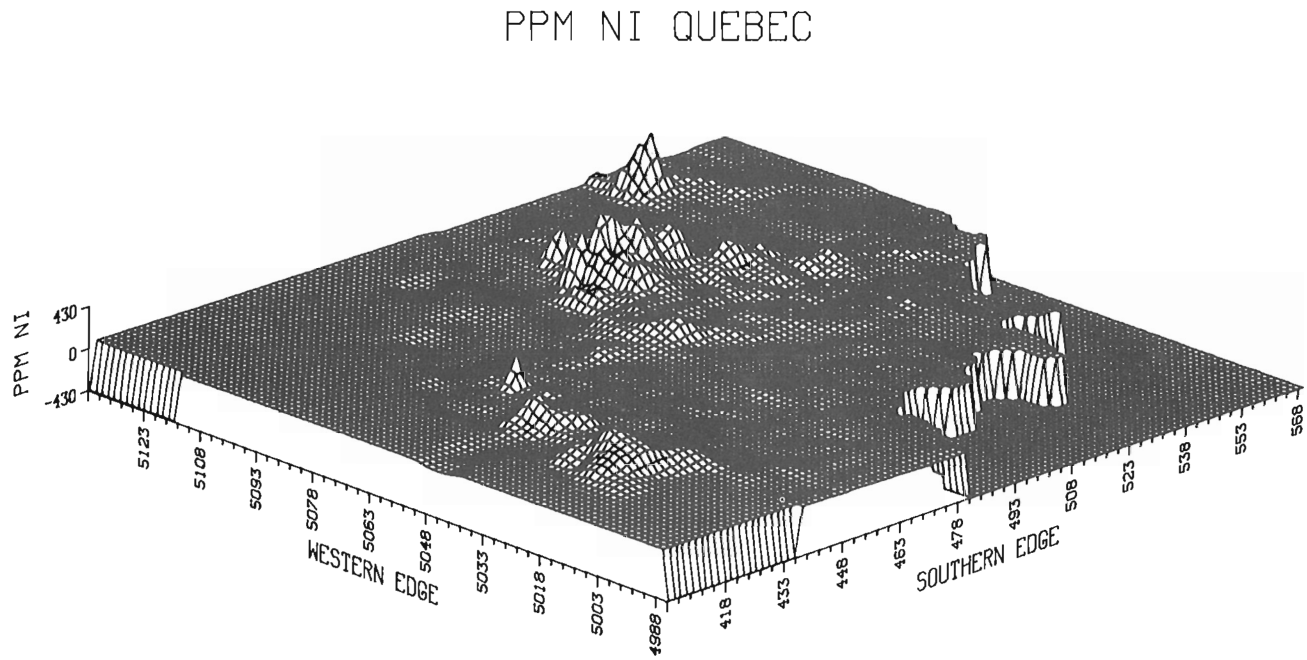


Figure 13. Three-dimensional representation of nickel dispersal in till. Irregular edge is U.S.A. border, relief is proportional to nickel concentration.

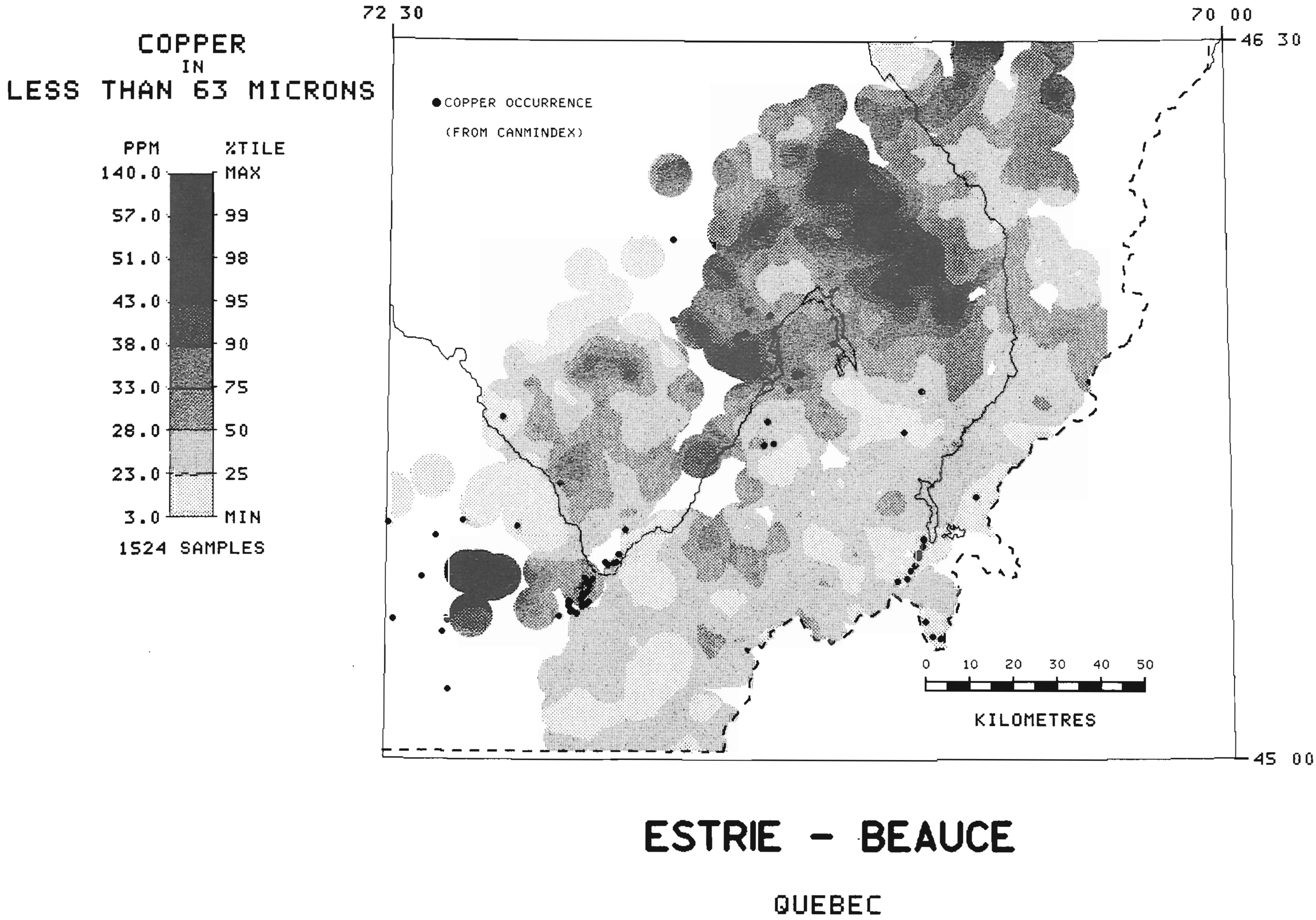


Figure 14. Copper mineralization and copper dispersal in <63 μm fraction of till.

ice divide[1]. In a related study, Shilts and Kaszycki (in press) note similar northward dispersal patterns for granodiorite from the northernmost plutons of the New Hampshire Plutonic Series.

Copper

The copper dispersal map (Fig. 14) shows two main features:

1. The range and magnitudes of copper concentrations are relatively low, probably as a function of rapid dilution of copper from its relatively small source outcrops by copper-poor silt and clay-sized detritus eroded from ''soft'' local rocks. A general depression of geochemical signatures of Appalachian bedrock is also indicated by regionally high carbonate concentrations in till ($4 \pm 2\,\%$). High carbonate concentrations suggest that significant amounts of metal-poor detritus were carried across the Appalachian terrain from sources within the Appalachians as well as from the unmetamorphosed Paleozoic platform strata underlying the St. Lawrence Lowlands. Nevertheless, several discrete areas of copper-enriched till can be differentiated on the maps, and of these, three are closely related to economic grades of copper mineralization. The association of copper-rich till with the Harvey Hill and Disraeli copper mines suggests that other anomalies on the map, not associated with presently known mineralization, should be followed up, particularly where located in areas of favourable geology. Most copper anomalies occur on or just down-ice from mafic to felsic volcanic outcrops. The effect of southeastward dispersal is not so pronounced as it is for chromium and associated elements. Some of the more diffuse zones of enhanced copper concentration appear to represent tails of dispersal trains, probably from bedrock terranes generally enriched in copper, but they cannot be tied to specific source outcrops at this low sampling density;
2. Down-ice from the Thetford Mines ultramafic outcrops, there is a pronounced depletion of copper in till. In fact, the pattern of this depletion is a mirror image of the pattern of ultramafic dispersal. Similar patterns have been noted for other base metals mapped-arsenic, lead, zinc, etc.

This dispersal-related phenomenon, called a ''negative dispersal train'' (Klassen and Shilts, 1978, p. 84; Shilts, 1984), is caused by dilution of the debris eroded from local bedrock by abundant debris eroded and transported from a distant source. In this case the diluting debris is the nickel-cobalt-chromium-magnesium-rich rock flour derived from easily eroded ultramafic outcrops. Debris of ultramafic affinity forms such a large proportion of the finest fractions of till, that it suppresses the background levels of non-ultramafic metals, and, presumably, any anomalous levels of metal that might exist in till that covers bedrock in the area of the ultramafic train.

In the same sense, surface till in the whole of Estrie-Beauce can be thought of as forming a negative train, diluted by fine-grained, metal-poor detritus from both the St. Lawrence Lowlands and the northwesternmost front of the Appalachians. This would account for what appear to be dampened contrasts between background and anomalous values for many metals.

The common occurrence of negative dispersal trains in geologically complex terranes, such as the Appalachians, makes application of conventional geochemical statistics to drift geochemical data sets risky. Even if sampling errors can be held to a minimum, the natural regional variations in degree of dilution, caused by differential erodability of the varied lithologies and topography of the substrate, will be reflected by shifts in local background values that exceed the background/anomaly contrast in the more distal parts (tails) of dispersal trains. The only way these variations can be handled effectively is to correct the maps, after production, by hand, or to transform the background variations through a high order trend surface analysis, contouring only the residuals on this surface. The concept of a statistically determined ''threshold'' value, even in an area as small as the one represented by these maps, is not particularly useful where various sampling and geological factors cause background variations so significant as to constitute a significant proportion of the background to anomalous signal in any given sector.

Arsenic

Much of the discussion of copper dispersal may be repeated for arsenic, but the overall dispersal pattern is quite different (Fig. 15). If arsenic concentrations are related in any way to gold potential, the strongest anomalies certainly would confirm such a relationship. Anomalies in the vicinity of Beauceville, southwest of Lac Mégantic near Mining Brook, and south of Sherbrooke are in areas either mined for buried preglacial placer gold (Beauceville, Mining Brook) or reported to have modern placers and auriferous till (McGerrigle 1936; McDonald, 1966b). However, in neither place has any indication of a bedrock source for the gold been confirmed, and the placer gold is not reported to be arsenical.

Arsenic anomalies south of Sherbrooke are in terrain where gold has been reported in modern alluvium and where Maurice (1986; 1988) has reported high concentrations of gold in heavy minerals from streams. Maurice suggested that the gold was reworked from till carrying auriferous components originally glacially dispersed southeastward from the massive sulphide deposits of the Eustis, Howard, and Suffield mines, southwest of Sherbrooke. If arsenic was associated with gold in those sulphide deposits, it does not seem to have formed a dispersal train, the strongest anomalies being isolated and apparently reflecting local arsenic sources in the Coaticook area. Although the high arsenic

[1] Gadd (1978) and Y.T. Maurice (1988 and pers. comm., 1988) show northward displacement of ultrafamic boulders and chromite, respectively, on uplands on either side of the Chaudière River Valley. While neither equated these patterns with northward flow, the present authors feel that they are a result of flow reversal. The lack of ultrafamic components in the valley, itself, is probably a result of reworking by the readvance lobe, discussed above. This lobe was confined to the Chaudière Valley and flowed southward up the valley.

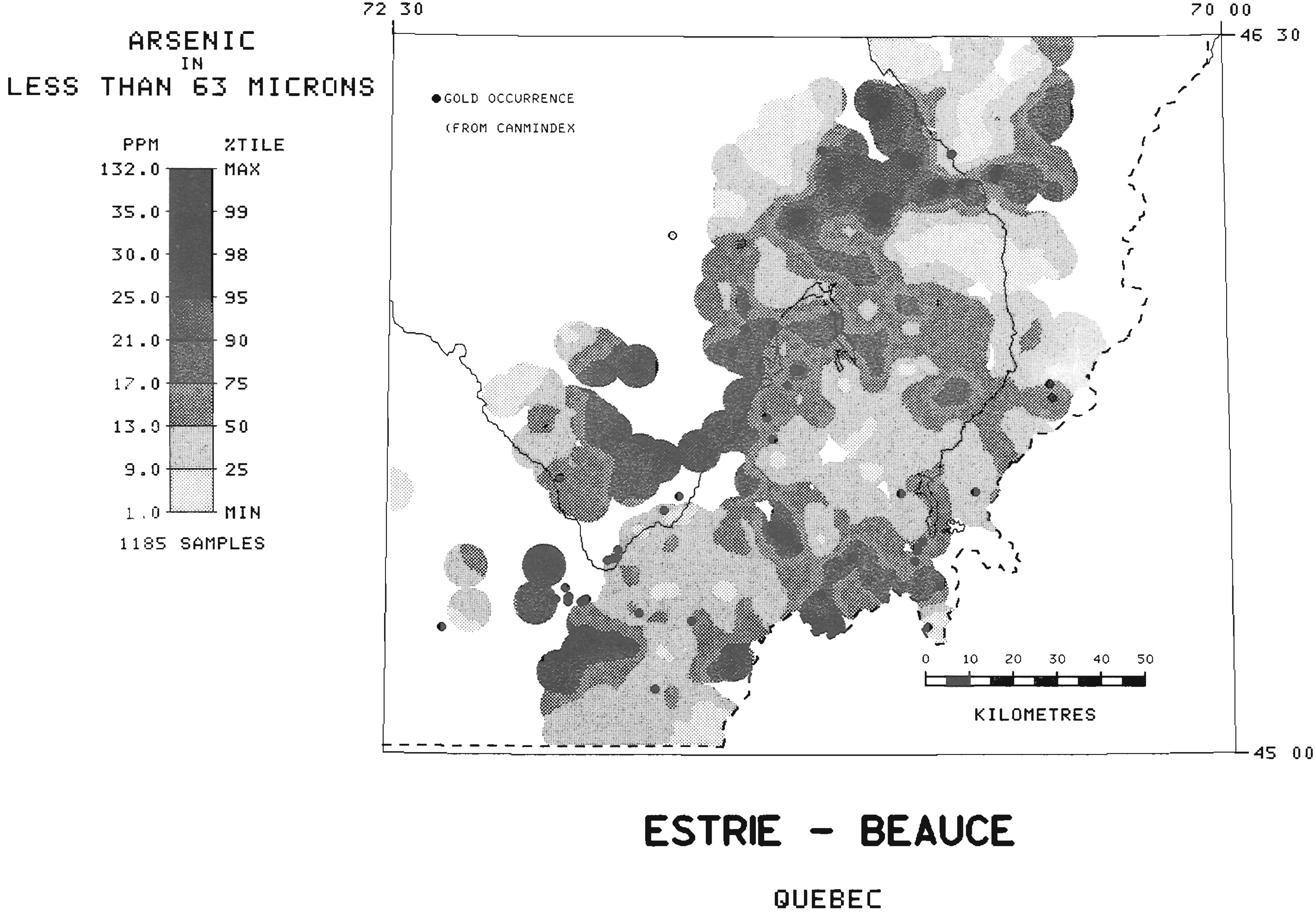


Figure 15. Gold mineralization and arsenic dispersal in <63 μm fraction of till.

concentrations in the vicinity of Coaticook correspond with a region of auriferous till mapped by McDonald (1966b), no visible gold was seen in heavy mineral separates from arsenic-enriched tills. Of over 100 samples collected in the Coaticook region, only two or three samples of arsenic-rich till yielded gold above the 10 ppb detection limit of geochemical anlayses of the <63 μm fractions. Unpublished reports by Terrain Analysis and Mapping Services, Ltd. indicate that gold is present in significant but uneconomic amounts in till at some sites in the Coaticook region.[1]

Arsenic from unknown sources has formed northwest-southeast trending belts of arsenic-enriched till in the northern part of the map area. These belts are presently thought to represent dispersal trains from sulphide sources within volcanic belts, but their economic significance is not known.

As with copper, arsenic displays a negative dispersal train southeastward from Thetford Mines. Any arsenic sources in bedrock beneath this train are not likely to provide enough of an imprint on the till to overcome the effects of dilution by ultramafic debris. In other words, if arsenic is related to gold mineralization in this region, the lack of arsenic anomalies in the area covered by the negative dispersal train does not rule out gold mineralization; it merely means that more sensitive statistical or analytical methods of determining background to anomaly contrast must be utilized.

Other elements

At the time of writing, geochemical data from this project are in the process of being plotted and evaluated, and only a few general comments can be made. Trace and minor elements particularly enriched in the ophiolitic complexes (cobalt, iron, magnesium, etc.) show dispersal patterns similar to those of chromium and nickel. Most chalcophile elements (zinc, lead) have dispersal patterns grossly similar to copper (zinc) and arsenic (lead). The negative train in the area of extreme ultramafic enrichment is well developed for these elements as well. Non-chalcophile elements, such as tin, tungsten and uranium have concentration patterns that resemble neither those of the above two groups nor those of each other. Uranium, for the most part, is enriched around granodiorite stocks and Mount Mégantic. Tin, possibly reworked from pre- or interglacial northward-flowing streams, is slightly enriched in till north of the granodiorite pluton on the Vermont/Quebec border, southeast of Coaticook. It is also rich in till east of Beauceville, for presently unknown reasons.

One more detail of the dispersal patterns in Lennoxville Till should be mentioned. As has been described previously (Shilts, 1973; 1981), the upper Chaudière valley, east of the Little Megantic Mountains, is covered by an extremely clay-rich till, the Drolet Lentil, composed almost wholly of reworked, laminated silty clay of the Gayhurst Formation. The St. François River valley between Lennoxville and Lac Aylmer, east of Stoke Mountains, is covered by a similar clay till, formed by reworking of underlying laminated silty clay (McDonald, 1967). Both of these units, stratigraphically equivalent to Lennoxville surface till, reflect only the geochemistry of the underlying silty clay and cannot be expected to represent regional or local geochemical trends. Like the area of the negative dispersal trains in the lee of the Thetford Mines ultramafic outcrops, these areas can be regarded as negative trains where geochemical signatures of underlying bedrock or mineralization are not likely to be expressed. Minor areas of similar clay till exist at various stratigraphic levels in drift throughout the Appalachians but these two regions are by far the largest and most important in interpreting regional geochemical patterns.

The same caveats about application of statistical manipulations in areas where significant negative dispersal trains are likely to occur should be considered where mapping reveals significant areas underlain by till reworked from older, unconsolidated, waterlain glacial sediments.

DISCUSSION AND CONCLUSIONS

Geochemical maps based on till sampling in the Appalachians reflect areas of known mineralization and areas where geological factors suggest that anomalies may represent as yet undiscovered mineralization. Nevertheless, other areas of known mineralization are not indicated. The reasons for this are complex, but understandable if the sampling is viewed in light of the Quaternary history and sedimentology of the region. One of the reasons for presenting these data is that the intense study of the glacial geology of the Estrie-Beauce region over the last 25 years has provided a sound conceptual and factual base with which to evaluate the apparent paradoxes in drift (and postglacial sediment) geochemical patterns.

First, the history of diverse ice flow directions in each of at least three glaciations must be recognized and the efficiency of the glaciers in eroding and transporting sediment during each flow event must be evaluated. For instance, it is known that ice flowed westward or southwestward during the earliest stages of the penultimate glaciation. To what extent did the westward-flowing glacier displace debris and how much of the westward dispersal pattern is reflected in the strong southeastward dispersal patterns of the following (Lennoxville) glaciation? How great an effect did the late-glacial northward flow of the Lennoxville glacier have on southeastward patterns developed during the Lennoxville maximum? Did the northward flow in Estrie-Beauce create significant thicknesses of surface till with northward fabrics and south-to-north provenance, as it did to the east in northern New Brunswick and adjacent Quebec? Although the

[1] Since writing this paper, large, class III till samples were collected from 2 sites where Terrain Analysis and Mapping Services personnel had identified high gold concentrations, but no visible gold, in heavy mineral separates. Preliminary processing of the till has yielded several <250 μm grains of gold from each site.

answers to these questions are important and still beg definitive discussion, it is possible to say from our data that the effects of Chaudière (westward phase) glaciation on geochemical patterns for surface till are minimal, and the reversal of flow to the north late in Lennoxville time moved already entrained debris northward but otherwise had little effect on geochemical patterns, in contrast to New Brunswick-Eastern Quebec, where the same or a similar event produced significant dispersal (M. Rappol, pers. comm. 1987).

Second, it is important to recognize that the till deposited during a single glaciation may be represented at or near the surface by several distinctive facies, and that the facies represent how the till was released from the ice, not how the debris of which they are composed was eroded and transported. For the purposes of this study, based on widely spaced samples, till composition can be assumed to be representative of till deposited for a distance of as much as a kilometre from the point of sampling. However, the bouldery mantle that litters the boulder-poor till of this region is often compositionally distinct as a result of its derivation preferentially from the higher parts of the landscape and its transportation in the higher englacial positions. If it is mixed with a finer matrix, geochemical analysis of this matrix could yield spurious results. Therefore, sampling should be carried out at as great a depth as possible and away from any structures that suggest meltwater reworking of the till during or after deposition.

Most of the basal till deposited during the last (Lennoxville) glaciation of Estrie-Beauce is thought to be composed of englacial debris, melted out from the basal part of the Lennoxville glacier. In some cases, this debris and the interstitial ice which formed the base of the glacier, was moved northward during the reversal of flow that followed its dispersal southeastward. Differential erosional etching, by water, of basal till exposures in this region, reveals tectonic structures that are thought to represent the boundaries of debris-rich and debris-poor bands, preserved by slow melting from the basal parts of the glacier. It has been shown that these bands can be compositionally differentiated (Shilts, 1978), and care must be taken to sample in such a way as to deal with such variation.

After deposition, tills in this region were subjected to oxidation by weathering to depths of up to 4 m. Samples must be classified according to their weathering state, easily done by noting whether the till has been stained brown in contrast to its normal olive grey colour. Heavy mineral separates from brown, oxidized samples will lack elements derived from non-resistate minerals, such as sulphides, which are destroyed readily under oxidizing conditions.

Dispersal patterns for the elements discussed in this report can be subdivided into three types: 1) The first type is dominated by trains of nickel, chromium and other elements preferentially enriched in the ultramafic components of the ophiolite belt that strikes northeastward through the map area; 2) The second type includes several anomalies for chalcophile elements (mainly arsenic, copper, lead, zinc) that correspond either to known mineralization or to parts of felsic to mafic volcanic belts that have high potential for mineralization. The concentrations of these elements are depressed in areas of strongest ultramafic dispersal because of dilution caused by erosion of large quantities of ultramafic debris from certain parts of the ophiolite belt; 3) Nonchalcophile elements (gold, uranium, tin, etc.) have patterns that are either indistinct, because of their relatively low concentrations relative to background (gold) or are related to late felsic intrusive bodies in the region (uranium, tin).

Finally, the geochemistry of the <250 mesh (<63 μm) fraction of tills of this region is a useful guide to potential mineralization, if a sampling protocol based on a firm understanding of glacial history, glacial sedimentation, and glacial sediment diagenesis/weathering is rigorously designed and followed.

ACKNOWLEDGMENTS

The authors wish to thank all of the scientists and their assistants who contributed samples to this project. The manuscript benefitted from a thoughtful review by Yvon Maurice, and his work on sediments derived from postglacial erosion of these tills should be compared to these data as it is published. The authors assume full responsibility for conclusions drawn. All geochemical analyses were carried out by Bondar-Clegg and Co. of Ottawa and Chimitec, Ltée. of Québec.

REFERENCES

Bouchard, M.A., Lortie, G., Turcotte, P., and Chauvin, L.

1987: The Thetford Mines-Asbestos area; in Pleistocene Stratigraphy in the St-Lawrence Lowland and the Appalachians of Southern Quebec: A Field Guide, ed. M. Lamothe; Collection Environnement et Géologie, v. 4, Université de Montréal, p. 140-159.

Boulton, G.S., Jones, A.S., Clayton, K.M., and Kenning, M.J.

1977: A British ice-sheet model and patterns of glacial erosion and deposition in Britain; in British Quaternary Studies, recent advances, ed. F.W. Shotton; Clarendon Press, Oxford, p. 231-246.

Chalmers, R.

1898: Report on the surface geology and auriferous deposits of southeastern Quebec; Geological Survey of Canada, Report of Activities, Part J, 161 p.

DiLabio, R.N.W. and Shilts, W.W.

1979: Composition and dispersal of debris by modern glaciers, Bylot Island, Canada; in Moraines and Varves, ed. C. Schlüchter; A.A. Balkema, Rotterdam, p. 145-155.

Elson, J.A.

1987: West-southwest dispersal of pillow-lava boulders, Philipsburg-Sutton region, Eastern Townships, Quebec; Canadian Journal of Earth Sciences, v. 24, p. 985-991.

Flint, R.F.

1929: The stagnation and dissipation of the last ice sheet; The Geographical Review; The American Geographical Society, v. XIX, p. 256-289.

1942: Glacier thinning during deglaciation — Pt. II, Glacier thinning inferred from geologic data; American Journal of Science, v. 240, p. 113-136.

Gadd, N.R.

1978: Surficial geology of Saint-Sylvestre map-area; Geological Survey of Canada, Paper 77-16, 9 p.

Gadd, N.R., McDonald, B.C., and Shilts, W.W.
1972: Deglaciation of southern Quebec; Geological Survey of Canada, Paper 71-47, 19 p.
Harron, G.A.
1976: Metallogeny of sulphide deposits in the Eastern Townships; Quebec Department of Natural Resources, ES-27, 42 p.
Klassen, R.A. and Shilts, W.W.
1978: Glacial dispersal of uranium in the District of Keewatin, Canada; in Prospecting in Areas of Glaciated Terrain — 1977, Institution of Mining and Metallurgy, London, p. 80-88.
Lamarche, R.Y.
1971: Northward moving ice in the Thetford Mines area of southern Quebec; American Journal of Science, v. 271, p. 383-388.
Lortie, G. and Martineau, G.
1987: Les systèmes de stries glaciaires dans les Appalaches du Québec; Ministère de l'Energie et des Ressources du Québec, DV 85-10.
Maurice, Y.T.
1986: Interpretation of a reconnaissance geochemical survey in the Eastern Townships of Quebec; in Current Research, Part A, Geological Survey of Canada, Paper 86-1A, p. 307-317.
1988: Regional alluvial heavy mineral geochemistry as a prospecting method in glaciated Appalachian terrain: a case history from the southern Quebec placer-gold belt; in Prospecting in Areas of Glaciated Terrain — 1988, ed. D.R. MacDonald and K.A. Mills;Canadian Institute of Mining and Metallurgy, p. 185-203.
McDonald, B.C.
1966a: Surficial geology, Richmond-Dudswell, Québec; Geological Survey of Canada, Map 4-1966.
1966b: Auriferous till in the Eastern Townships, southeastern Quebec; Geological Survey of Canada, Paper 66-2, p. 51-54.
1967: Surficial geology, Sherbrooke-Oxford-Memphrémagog, Québec; Geological Survey of Canada, Map 5-1966.
McDonald, B.C. and Shilts, W.W.
1971: Quaternary stratigraphy and events in southeastern Quebec; Geological Society of America Bulletin, v. 82, p. 683-698.
McGerrigle, H.W.
1936: Placer gold deposits of the Eastern Townships; Quebec Department of Mines, Annual Report for the year 1935, Part E, 65 p.
Parent, M.
1987: Late Pleistocene stratigraphy and events in the Asbestos-Valcourt region, southeastern Quebec; unpublished Ph.D. thesis, The University of Western Ontario, 316 p.
Poliquin, I.
1987: Stratigraphic and sedimentological studies of sections from Des Plante River, southeastern Quebec; unpublished B.Sc. thesis, University of Ottawa, 66 p.
Rappol, M.
1988: Glacial dispersal of Deboullie syenite, northern Maine, into western New Brunswick; in Current Research, Part B Geological Survey of Canada, Paper 88-1B, p. 49-54.
Rencz, A.N. and Shilts, W.W.
1980: Nickel in soils and vegetation of glaciated terrains; in Nickel in the Environment, ed. J.O. Nriagu; Wiley, New York, p. 151-188.
Shilts, W.W.
1970: Pleistocene geology of the Lac Mégantic region, southeastern Quebec, Canada; unpublished Ph.D. dissertation, Department of Geology, Syracuse University, 154 p.
1973: Glacial dispersal of rocks, minerals, and trace elements in Wisconsinan till, southeastern Québec, Canada; Geological Society of America, Memoir 136, p. 189-219.
1975: Principles of geochemical exploration for sulphide deposits using shallow samples of glacial drift; Canadian Institute of Mining and Metallurgy Bulletin, v. 18, p. 114-121.
1976a: Glacial Till and mineral exploration; in Glacial Till, ed. R.F. Legget; Royal Society of Canada, Special Publication no. 12, p. 205-224.
1976b: Glacial events in Quebec, northern New England; a reappraisal; Geological Society of America, Abstracts with Programs, v.. 8, p. 267.
1978: Detailed sedimentological study of till sheets in a stratigraphic section, Samson River, Quebec; Geological Survey of Canada, Bulletin 285, 30 p.
1981: Surficial geology of the Lac Mégantic area, Quebec; Geological Survey of Canada, Memoir 397, 102 p.
1982: The Highland Front Moraine Complex; in Guidebook of the 45th Annual Meeting of the Friends of the Pleistocene, Drummondville-Saint-Hyacinthe, Qu?ebec, Canada, eds. P. LaSalle, P.P. David, and M.A. Bouchard; Universit?e de Montréal, p. 47-51.
1984: Till geochemistry in Finland and Canada; Journal of Geochemical Exploration, v. 21, p. 95-117.
Shilts, W.W. and Smith, S.L.
1986: Stratigraphic setting of buried gold-bearing sediments, Beauceville area, Quebec; in Current Research, Part B, Geological Survey of Canada, Paper 86-1B, p. 271-278.
Shilts, W.W. and Kaszycki, C.
in press: Depth of glacial erosion; Atomic Energy of Canada, Ltd., Level 2 CAD report.
Slyvitzky, A. and St. Julien, P.
1987: Compilation géologique de la r?egion de l'Estrie-Beauce; Ministère de l'energie et des Ressources, Quebec, MM-85-04, carte no. 2030, 40 p.
Smith, S.L. and Shilts, W.W.
1987: Quaternary stratigraphy of Noire River cores, Beauceville area, Quebec; in Current Research, Part A, Geological Survey of Canada, Paper 87-1A, p. 159-164.
Stewart, D.P. and MacClintock, P.
1964: The Wisconsin stratigraphy of northern Vermont; American Journal of Science, v. 262, p. 1089-1097.
1969: The surficial geology and Pleistocene history of Vermont; Geological Survey of Vermont, Bulletin 31, 251 p.
1971: Ablation till in northwestern Vermont; in Till — a Symposium, ed. R.P. Goldthwait; Ohio State University Press, Columbus, p. 106-114.
Thomas, R.V.
1977: Calving Bay dynamics and ice sheet retreat up the St-Lawrence Valley system; Géographie physique et Quaternaire, v. 31, p. 347-356.

Gold in till: preliminary results from the Matheson area, Ontario

L.B. Bloom[1] and K.G. Steele[2]

Bloom, L.B., and Steele, K.G., Gold in till: preliminary results from the Matheson area, Ontario; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 61-70, 1989.

Abstract

The Ontario Geological Survey carried out a reconnaissance-scale overburden sampling project in the Matheson area of northeastern Ontario. In the period 1984-1985, a total of 643 till and 311 sand samples were analyzed for gold in three size fractions. Comparison of results indicates gold values for the heavy mineral concentrates, <250 mesh (<63 µm) and <10 mesh (<2.0 mm) fractions are not directly comparable. Gold values 'normalized' for the weight of the heavy mineral concentrate relative to the total weight of the sample, do not correspond directly with <250 mesh and <10 mesh results. Samples are ranked differently when the heavy mineral concentrate gold assay values or the 'normalized' gold values are considered. In general, the number and size of gold grains are indicative of the gold assay value of the heavy mineral concentrate. Occasionally, samples with abundant visible gold have low reported gold assays. Further studies are warranted to explain gold grain to gold assay value relationships.

Résumé

La Commission géologique de l'Ontario a mené un projet d'échantillonnage, à des fins de reconnaissance, des morts-terrains de la région de Matheson dans le nord-est de l'Ontario. En 1984-1985, on a dosé l'or dans trois fractions granulométriques dans un ensemble de 643 échantillons de till et 311 échantillons de sable. La comparaison des résultats indique que les titres d'or dans les concentrés de minéraux lourds et dans les fractions passées dans des tamis de calibre <250 mesh (<63 µm) et <10 (<2.0 mm) ne sont pas directement comparables. Les titres d'or, "corrigés" pour le rapport de la masse du concentré de minéraux lourds à la masse totale de l'échantillon, ne correspondent pas directement aux résultats des fractions passées aux tamis de calibre <250 et <10. Les échantillons sont cotés différemment selon qu'on considère les teneurs en or dosées dans des concentrés de minéraux lourds ou les teneurs "corrigées". En général, le nombre et la taille des granules d'or sont des indices de la teneur en or du concentré de minéraux lourds. On observe parfois des titres d'or faibles dans des échantillons où l'or visible abonde. Des études plus poussées des relations qui existent entre les granules d'or et les teneurs dosées sont justifiées.

[1] Analytical Solutions, 214-665 Roselawn Ave., Toronto, Ontario M5N 1L1
[2] Ontario Geological Survey, 704-77 Grenville St., Toronto, Ontario M7A 1W4

INTRODUCTION

The Ontario Geological Survey's Black River — Matheson (BRIM) reconnaissance scale overburden sampling project was designed to establish the regional Quaternary (glacial) stratigraphy and a till geochemistry database as an aid to mineral exploration.

The study area covers a 40 km-wide band from the Ontario-Quebec border 100 km west to the Timmins city limits (Fig. 1). The area, within the Abitibi Greenstone Belt, is underlain by geology similar to that in the mining camps of Timmins and Kirkland Lake, and is cut lengthwise by the Destor-Porcupine Fault Zone. Numerous gold occurrences are known, but most are concentrated in small areas of thin drift cover.

An extensive drift cover, up to 100 m thick, masks the geology and geophysical responses for a large portion of the study area. In areas with thick overburden, there has been limited exploration success for gold; with the exception of some recent discoveries such as the St. Andrew Goldfields' deposit and American Barrick's Holt-McDermott Mine.

Overburden sampling programs are an alternative exploration method for outlining zones of gold mineralization. Various factors, including sample collection procedures and analytical methods, contribute to the success of such programs. Preliminary conclusions, from the first two years (1984-1985) of the five-year BRIM project, on distribution of gold in three fractions of till samples are presented.

SAMPLE COLLECTION

This paper includes data from two drilling programs and two backhoe sampling programs performed in 1984 and 1985; additional sampling was carried out from 1986 through 1988. The distribution of the 1984 and 1985 sample sites is shown in Figure 2. A total of 243 till samples were collected from surface pits, usually dug by a backhoe, and 400 till and 311 sand samples were collected during the drilling programs.

The rotasonic drilling method was employed for this project. The rotasonic drill furnishes a continuous, relatively undisturbed, 88 mm diameter core from all formations including bedrock. The core provides large, complete samples for geochemical analyses. Some of the results of this study may not be directly comparable with surveys which use other sampling methods, such as reverse circulation drilling.

Sampling of drill core was done on a stratigraphic basis. Where possible, till units were sampled over a 1.5 m length, and sand units were sampled over intervals of 3 to 10 m. A 7 to 10 kg bulk sample and a separate 250 g sample were collected for each sample interval.

Till samples from surface pits were collected below a depth of 1.0 m whenever possible. Sampling depths ranged from 0.3 to 3.0 m with the average being 1.7 m. An attempt was made to collect samples within 0.5 m of the till-bedrock interface. The same sample sizes were collected as in the drill programs.

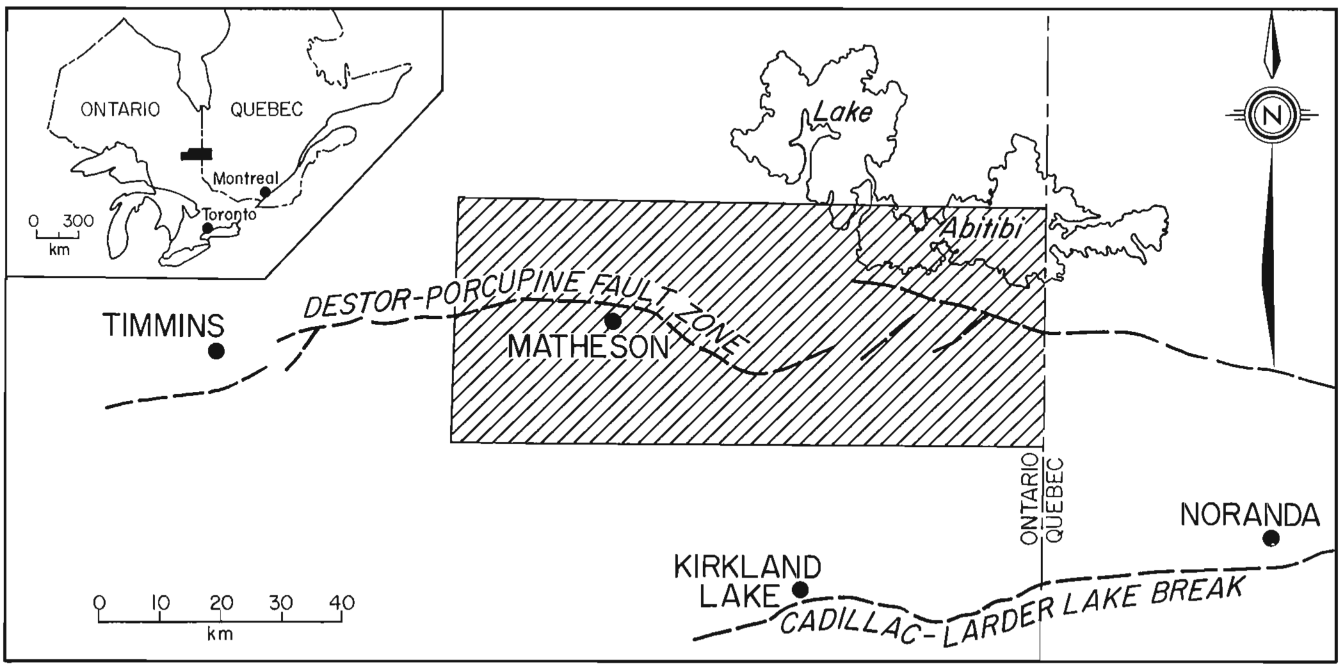


Figure 1. Matheson study area.

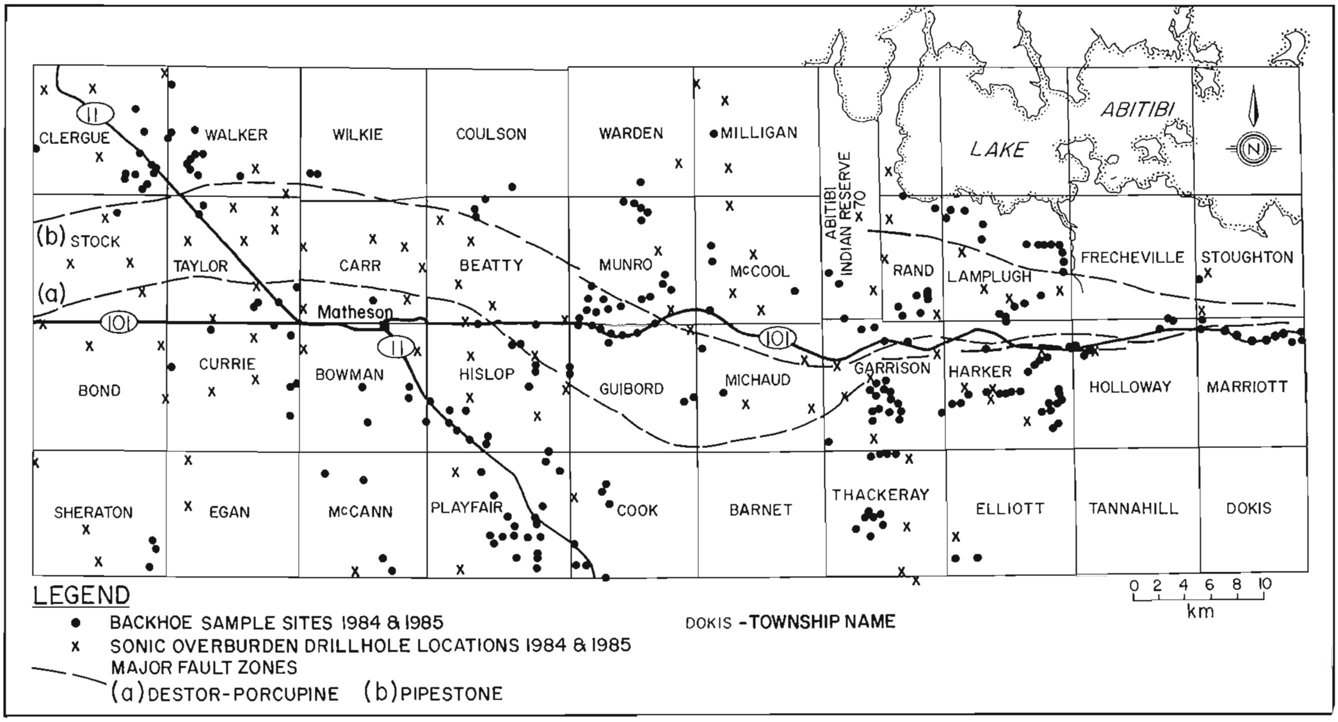


Figure 2. Some drillhole and backhoe trench locations.

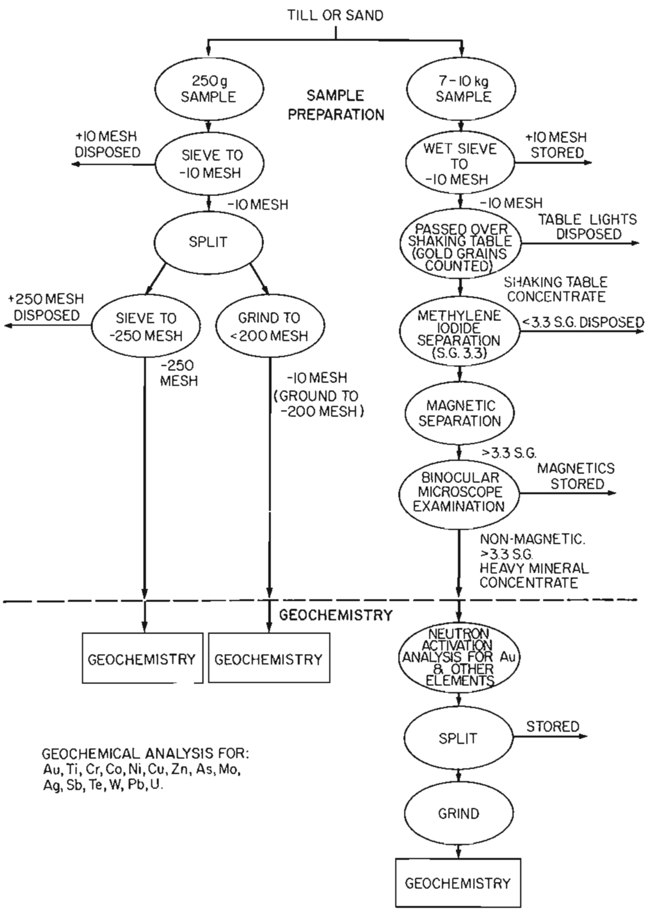


Figure 3. Sample preparation flow chart (after Baker et al., 1985).

SAMPLE PROCESSING AND ANALYSES

All samples were processed in the same manner. Three size fractions for each sample interval were prepared as shown on the sample preparation flow chart (Fig. 3). The 7 to 10 kg bulk samples were submitted for heavy mineral separation. The heavy mineral concentrates were prepared on a shaker table where the sample material is water-sluiced to remove lighter mineral grains. Samples with gold grains visible on the shaker table were further refined by a secondary panning procedure of the heavy mineral concentrate, to obtain the exact number, shape and size of gold grains. The entire non-magnetic heavy mineral (>3.3 s.g.) concentrate was analyzed for gold by instrumental neutron activation, as the method is non-destructive and the samples can be recovered for detailed examination.

The two other fractions, the pulverized <10 mesh material and <250 mesh material, were analyzed for gold by fire assay in combination with a direct current plasma finish. Each of the three fractions were also analyzed for a suite of 14 trace elements, many by emission spectrometric methods using a nitric-hydrochloric acid digestion.

THE DISTRIBUTION OF GOLD

The distribution of gold values in heavy mineral concentrates, for both till and sand units, is lognormal (Fig. 4). The geometric mean for all till samples is 118 ppb gold and 61 ppb gold for sand samples. The gold values range from below detection limit (2 ppb) to 96,000 ppb. The distributions of gold for tills collected from surface pits (oxidized) and by drilling (unoxidized) are also presented (Fig. 4).

The distinction between till samples from surface pits and drilling cannot be made based on histograms of gold in heavy mineral concentrates (Fig. 4). Some of the subtle variation may be due to the fact that near-surface and drill samples were collected from different locations.

Till collected by drilling was believed to be unoxidized, as most of the sampled intervals were from below 20 m. Several studies (Shilts 1975, 1984; DiLabio 1979, 1985) have demonstrated that the chemistry of unoxidized and oxidized till samples are different for many elements. The distribution of copper was studied to verify that the distinction between samples collected in surface pits and by drilling was synonymous with oxidized and unoxidized samples respectively, and that gold distributions were not effected.

For till samples collected by drilling, the copper value in the heavy mineral concentrate is greater than the value for the <250 mesh fraction for 95 % of the samples. Therefore, the ratio of copper in the heavy mineral concentrate to copper in the <250 mesh fraction is greater than one (Fig. 5). In contrast, almost 90 % of the till samples, collected from the near surface environment, have ratios of less than 1 (Fig. 5).

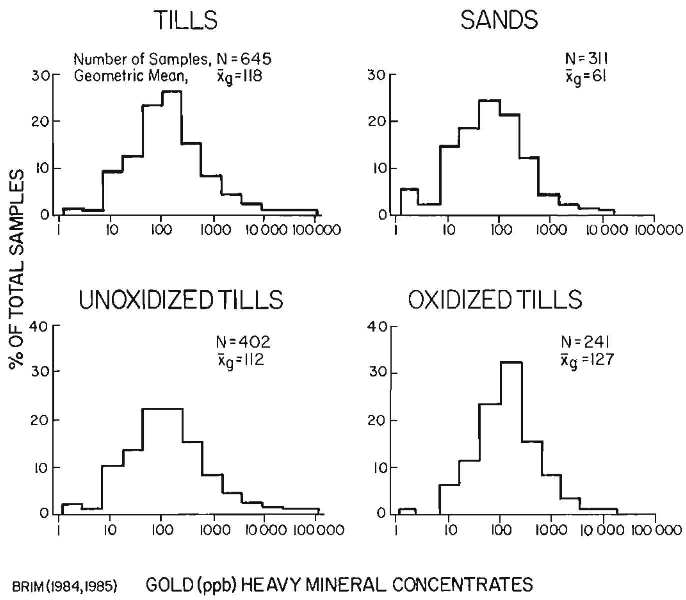


Figure 4. Distribution of gold in heavy mineral concentrates.

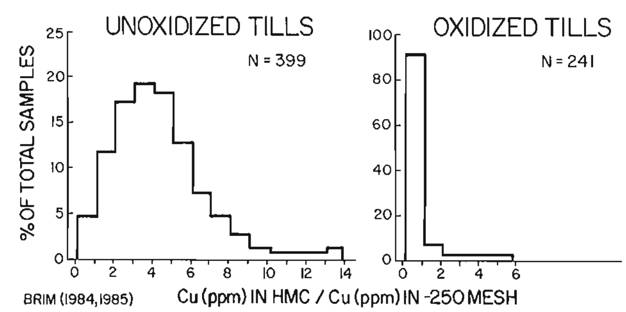


Figure 5. Distribution of copper between oxidized and unoxidized till samples.

The copper-rich minerals, such as sulphides, are decomposed in oxidized samples. Copper and other metal cations are released and then adsorbed on phyllosilicate and secondary minerals concentrated in the <250 mesh fraction. This process is also apparent for elements such as zinc, cobalt and nickel.

The distribution of gold in the <250 mesh fraction is different from that in the heavy mineral concentrates. In the <250 mesh fraction, the mean gold value for each of the

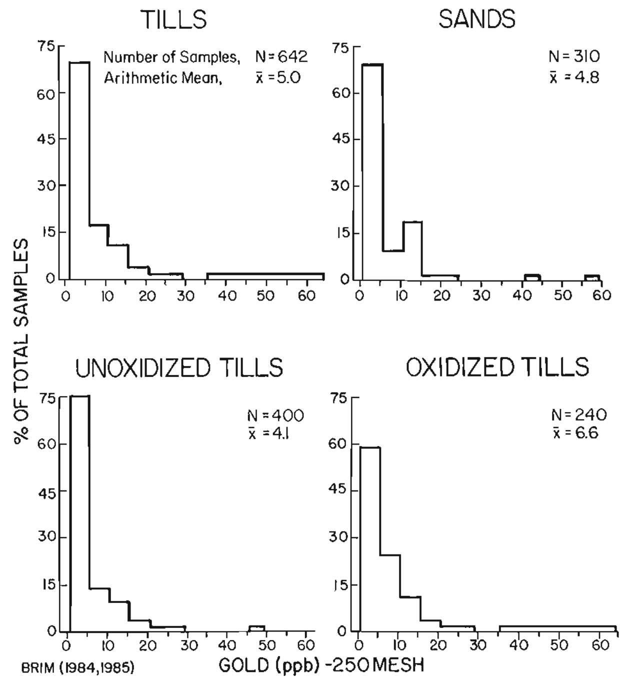


Figure 6. Distribution of gold in <250 mesh fraction.

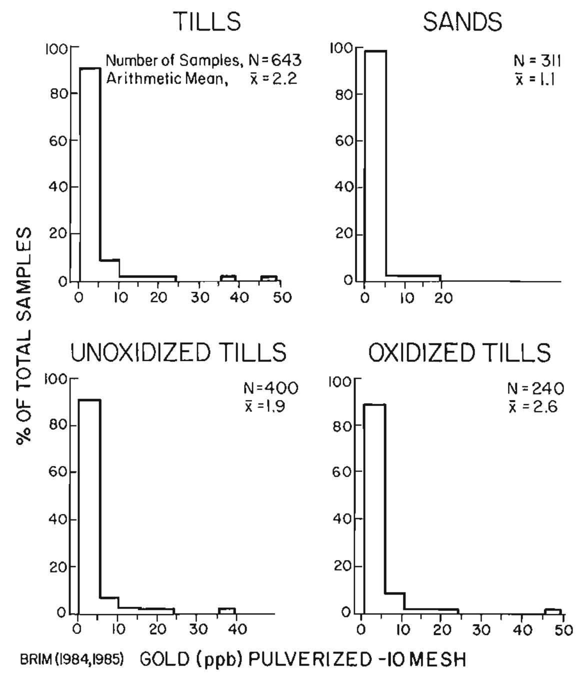


Figure 7. Distribution of gold in <10 mesh fraction.

four groups presented in Figure 4 is estimated to be <5 ppb (Fig. 6). All of the distributions are highly skewed. The majority of values occur at or near the detection limit of 2 ppb. The distributions of gold in the <10 mesh fraction are also skewed (Figure 7). The mean gold concentrations are at the detection limit.

The low gold values in the finer fractions of till and sand are consistent with the regional distribution of gold in bedrock. Bedrock samples were collected from 92 of the 102 rotasonic drill holes. The mean value for gold in these samples is 4.5 ppb, and 92 % of the values are less than 10 ppb. The highest value encountered was 1,700 ppb gold in a magnesium-rich tholeiitic basalt.

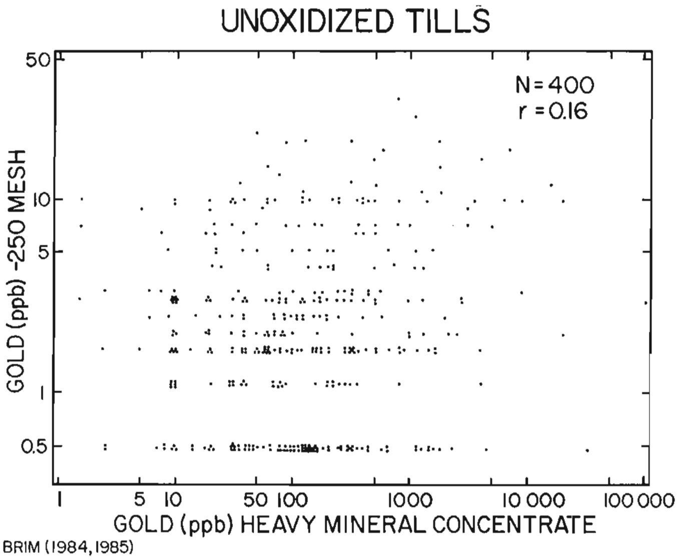


Figure 8. Comparison of gold in <250 mesh fraction and heavy mineral concentrate.

Comparison of the Distribution of Gold in Three Fractions

The type, size and residence sites of gold in till are different for each of the three fractions analyzed. The heavy mineral concentrates contain free gold (except those gold grains with a size or shape that results in their loss during shaker table processing), gold tied up in sulphide minerals, and gold tied up in oxide and silicate minerals if the mineral aggregates have a specific gravity greater than 3.3.

It is thought that the <250 mesh fraction gold assays reflect fine free gold, gold released from sulphides and any gold reprecipitated by postglacial processes. The <10 mesh fraction includes the gold types listed for the above two fractions. Assays of <10 mesh fraction material will yield reduced concentrations due to dilution by the large amount of common rock-forming (silicate-dominated) minerals.

As a result of the complex interactions of the type, size and residence sites of gold in till, there may or may not be an optimum fraction to analyze for gold in the BRIM area. In general, the analysis of heavy mineral concentrates for gold is a popular and effective means of developing mineral exploration targets. However, the analysis of heavy mineral concentrates is expensive and time-consuming. In order to test whether the <250 mesh and/or <10 mesh fractions of the till could be considered as less expensive alternative test media in the study area, gold results of the heavy mineral concentrates, the <250 mesh and the <10 mesh fractions were compared.

The plot of gold results from the <250 mesh and heavy mineral fractions demonstrates that there is no direct relationship between the values (Fig. 8). A comparison of the results for the <250 mesh and <10 mesh fractions shows poor correspondence between values, although it is true that for slightly more than half the samples, both results fall below the detection limit (Fig. 9).

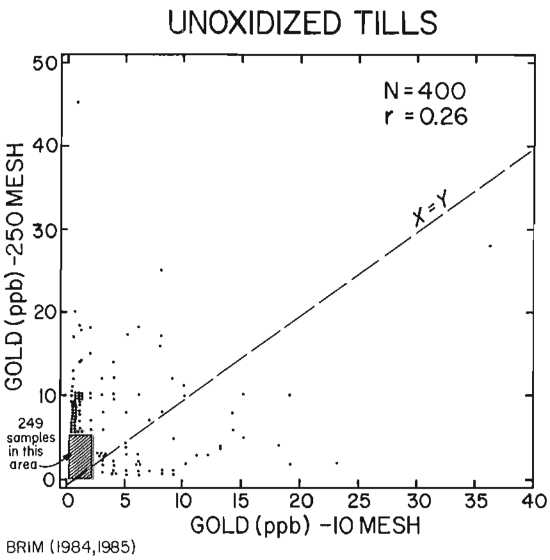


Figure 9. Comparison of gold in <10 and <250 mesh fractions.

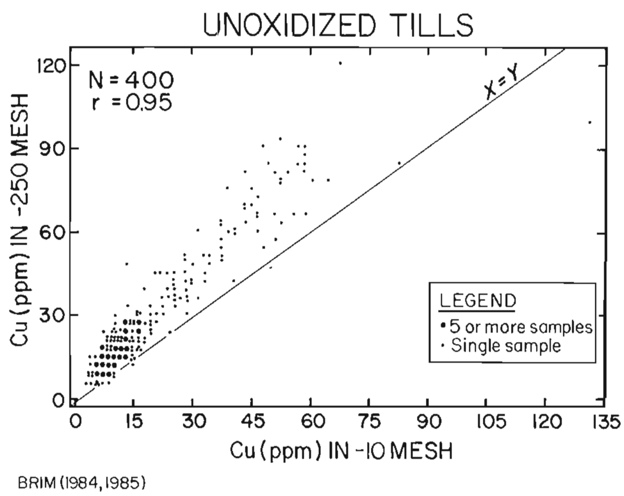


Figure 10. Comparison of copper in <10 and <250 mesh fractions.

Most elements other than gold, reflect a strong correlation between values in the <250 mesh and <10 mesh fractions. As an example, the copper values in the <10 mesh and <250 mesh fractions for unoxidized till samples show a strong correspondence (Fig. 10).

The lack of correlation when comparing gold values between fractions is primarily due to low concentrations of gold and the difficulty in preparing a "representative" sample. Only 10 g of material was assayed for the <250 mesh and <10 mesh fractions in this study, although sampling theory (Clifton et al., 1969; Harris, 1982) dictates that an adequate sample size would be 200 g of material.

Normalized Gold Values

The lack of correspondence between gold values in heavy mineral concentrates versus the other two fractions may be due to the variable proportion of heavy minerals in the bulk samples. As suggested by Sopuck et al. (1986) and Lavin et al. (1986), it may be necessary to "normalize" the weight of the heavy mineral concentrate relative to the total weight of the sample.

The weight of the <10 mesh material which was processed for heavy mineral concentrates varied from 2 to 12 kg and the weight of the non-magnetic heavy mineral concentrate varied from 1 to 50 g (Fig. 11). The majority of samples fall within the bounds of 0.1 % to 0.5 % non-magnetic heavy mineral concentrate by weight.

In a case where two heavy mineral concentrates contain the same weight of gold particles, say 1.0μg, but one weighs 2 g and the other sample weighs 50 g, then reported gold concentrations will be 500 ppb and 20 ppb respectively.

In order to smooth the effect of the weight of the heavy mineral concentrate it is possible to "normalize" the data. One method of normalizing the gold values is to multiply the gold result, reported in ppb or nanograms per gram, by the weight of the non-magnetic heavy mineral fraction. The result is the weight of gold in the sample in nanograms (Equation 1).

(1) Weight of gold in non-magnetic heavy mineral concentrate (ng) = Au (ng/g or ppb) × Weight of the non-magnetic heavy mineral concentrate (g)

The weight of gold is then redistributed over the total weight of the <10 mesh table feed (Equation 2).

(2) "Normalized" gold value (ng/g or ppb) = Weight of gold (ng) / Weight of the <10 mesh table feed (g)

The plot of "normalized" gold concentrations of the non-magnetic heavy mineral fraction indicates no clear relationship with the gold concentration of the <250 mesh fraction (Fig. 12). However, the "normalized" results are within the same range of values as the <250 mesh fraction results.

The lack of correspondence of the gold values may result from a variety of circumstances which include:

1. The gold is concentrated in the <250 mesh fraction and some of this fine material remains in suspension in the water and is lost when the sample is processed on a shaker table. This could account for samples where the gold value of the <250 mesh fraction is greater than the "normalized" gold values
2. The 10 g <250 mesh sample analyzed by fire assay is not representative of the sampled interval, as discussed previously.
3. The analysis by instrumental neutron activation of heavy mineral concentrates with large gold grains is prone to error caused by self-shielding effects.

Self-shielding is a phenomenon that for some elements including gold, may result in a large grain not being completely irradiated. Atoms on the outer edge of the grain will shield inner atoms from irradiation. Studies by Zweifel (1960) showed that reported gold results would be low by 13 % for gold wires of a 400 μm diameter, and reduced by

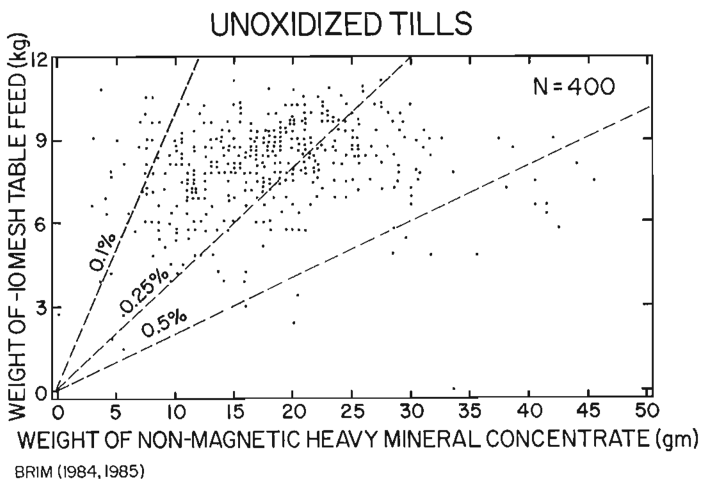


Figure 11. Weight of heavy mineral concentrates.

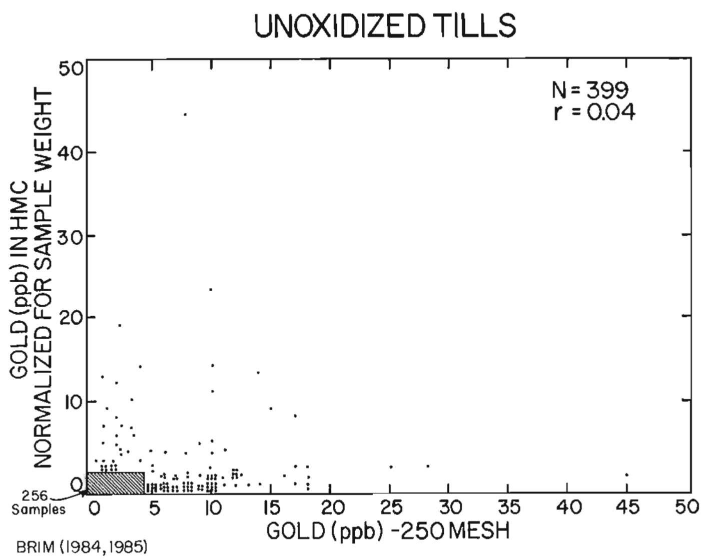


Figure 12. "Normalized" gold for heavy mineral concentrates.

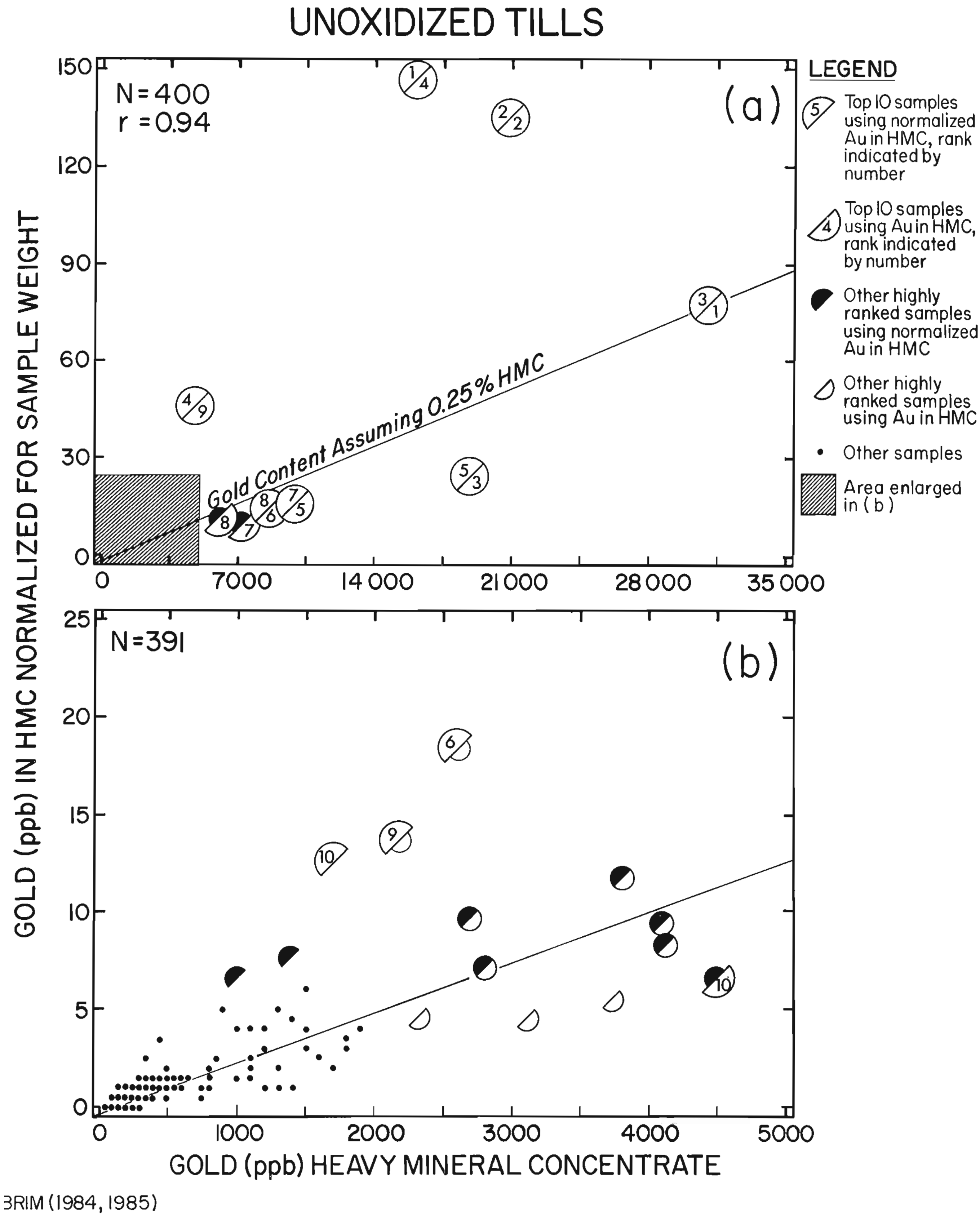


Figure 13. Gold in heavy mineral concentrates.

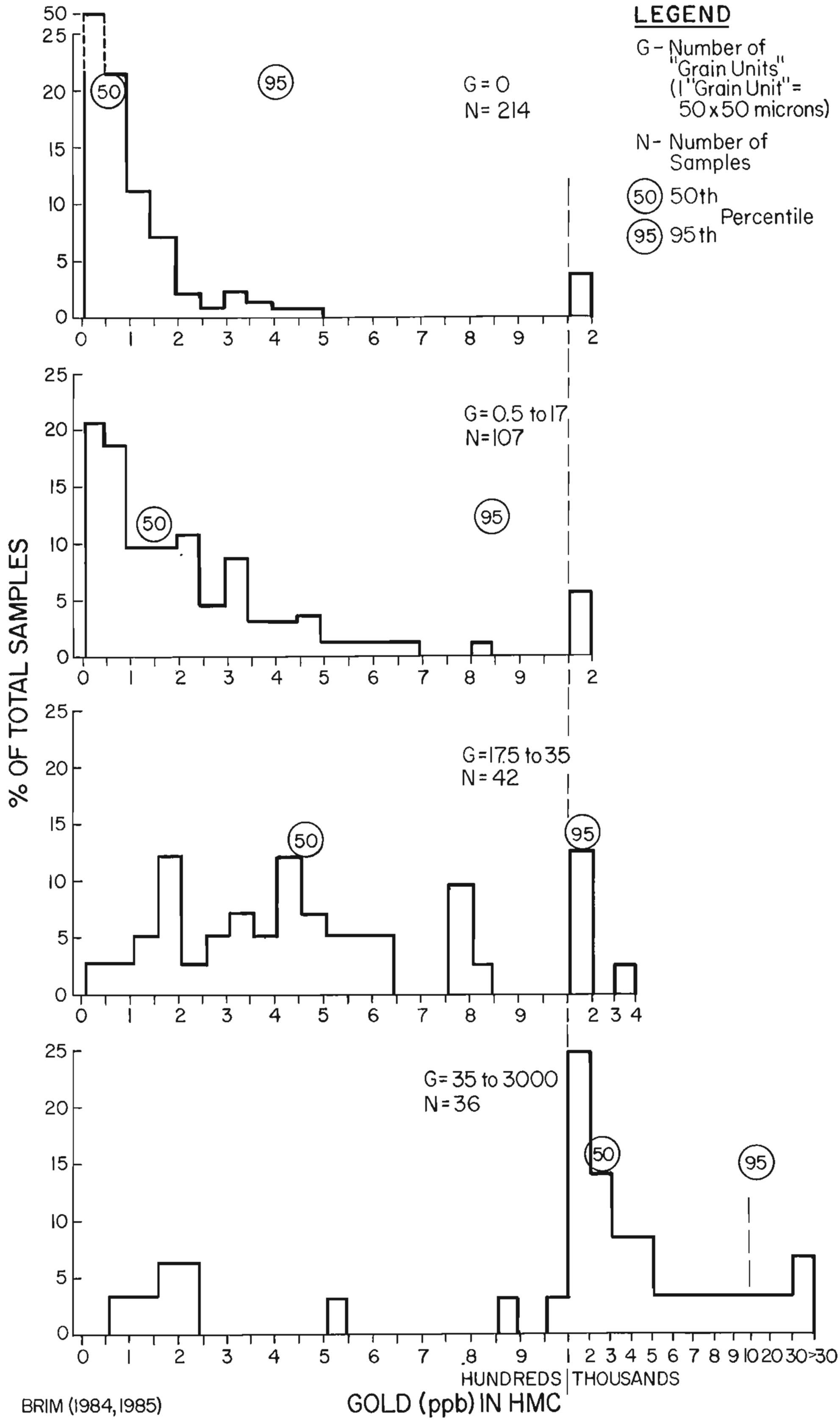


Figure 14. Distribution of gold assays based on number of gold grains in unoxidized till samples.

44 % for 2000 μm diameter wires. Another cause of inaccurate gold analyses by instrumental neutron activation analysis is the inconsistent geometry of large samples.

The "normalized" gold data are plotted against the original gold values for the heavy mineral concentrates (Fig. 13). There is good correlation between the two sets of values but there are interesting discrepancies on a sample-by-sample basis.

On ranking the till samples by high gold values, the same top 3 samples are selected from both data sets. However, for samples with less than 15,000 ppb gold in the heavy mineral concentrates, the significance of some samples over others between the two data sets is not uniform. This is apparent in Figure 13b, which is an expanded version of Figure 13a.

It has not been determined, at this time, which of these data sets demonstrates a clearer relationship to mineralization, but both the raw and calculated ("normalized") gold values may be useful in defining follow-up priorities.

THE DISTRIBUTION OF GOLD GRAINS

Another clue to the exploration significance of overburden samples is the number, size and shape of gold grains. In the study area gold grains up to 1575 μm × 925 μm have been recovered from till. In an effort to determine the relationship of the number and size of gold grains to assay results a crude "gold grain scale" was devised. Using a standard "grain unit" of 50 μm × 50 μm and ignoring the possible complications arising from varying thicknesses, all gold grains were converted to "grain units". As an example, a gold grain with reported dimensions of 100 μm × 100 μm is equivalent to four 50 μm × 50 μm "grain units".

The unoxidized till samples were separated into four groups based on the number of gold "grain units" in the sample. Histograms of assayed gold values (Fig. 14) were generated for the groups of samples with (a) no gold grains, (b) 0.5 to 17 "grain units", (c) 17.5 to 35 "grain units" and (d) greater than 35 "grain units". As expected, the 50th and 95th percentiles for gold assays rise as the number of "grain units" increase.

However, there are troubling details. The instrumental neutron activation gold analyses range up to 1800 ppb for samples with no gold grains The most likely explanation is that gold is present in forms other than free gold, such as contained in sulphides. A second explanation is that the gold is too fine grained to be visible on the shaker table during processing. At the other extreme, and perhaps of greater concern, six samples with greater than 35 "grain units" have less than 500 ppb gold reported. These samples contain at least one grain which is large enough to cause reduced gold assays due to self-shielding. The gold grain data for these six samples are presented in Table 1. However, other samples with equally large gold grains generate much higher gold values, as illustrated in Table 2. The size of the gold grains is certainly not the only determining factor. Further studies are warranted to explain this phenomenon.

Table 1. Samples with large gold grains and low gold assays

Sample Number	85-01-08	85-12-11	85-13-07	85-24-14	85-39-14	85-45-93
Gold Grains (number) & size [μm])	1 275×400 1 75×125	1 25×25 1 50×75 1 50×100 1 50×75 1 150×250 1 150×350	2 25×50 1 25×75 1 50×50 1 50×150 1 75×75 1 100×125 1 250×350	1 25×25 1 25×50 1 50×75 1 125×175 1 300×350	1 25×50 1 25×75 1 50×75 1 200×225 1 250×450	1 350×450
Gold Assay (ppb)	91	100	180	220	20 91	

Table 2. Samples with large gold grains and high assays

Sample Number	84-28-09	85-31-02
Gold Grains (number & size [μm])	1 50×100 1 100×100 1 100×150 1 100×200 1 250×350	2 25×25 2 25×50 1 50×50 1 50×75 1 50×100 1 150×150 1 150×350
Gold Assay (ppb)	8800	1600

CONCLUSIONS

In this preliminary examination of data collected during 1984 and 1985, several important points have been identified. These include:

1. The gold values for the heavy mineral concentrates, <250 mesh and <10 mesh fractions are not directly comparable.
2. The "normalized" gold data for heavy mineral concentrates does not correspond directly with <250 mesh and <10 mesh results.
3. Samples are ranked differently using the heavy mineral concentrate gold assay values or the "normalized" gold values.
4. Oxidized and unoxidized samples, as represented by samples collected from the near-surface environment (to 3.0 m depth) versus samples obtained by deep overburden drilling, respectively, have different chemical characteristics. However, the two groups cannot be distinguished on the basis of gold data.
5. The gold data for the <250 mesh and <10 mesh material using 10 g assay aliquots are not representative of the sampled interval.

ACKNOWLEDGMENTS

The authors acknowledge that field work by and discussions with C.L. Baker and M.B. McClenaghan were important contributions to the study. We thank A.M. Duic for the drafting of the figures. This study is part of the Operation Black River — Matheson (BRIM) project. This paper is published with permission of the Director, Ontario Geological Survey.

REFERENCES

Clifton, H.E., Hunter, R.E., Swanson, F.J., and Phillips, R.L.
1969: Sample size and meaningful gold analysis; United States Geological Survey, Professional Paper 625-C, 17 p.

Baker, C.L., Steele, K.G., and McClenaghan, M.B.
1985: Reconnaissance till sampling program, Matheson — Lake Abitibi area, Cochrane District; in Summary of Field Work and Other Activities 1985, Ontario Geological Survey, eds. J. Wood, O.L. White, R.B. Barlow and A.C. Colvine; Ontario Geological Survey Miscellaneous Paper 126, p.329-333.

DiLabio, R.N.W.
1979: Drift prospecting in uranium and base-metal mineralization sites, District of Keewatin, Northwest Territories, Canada; in Prospect ing in Areas of Glaciated Terrain-1979, Institution of Mining and Metallurgy, London, p. 91-100.
1985: Gold abundance vs. grain size in weathered and unweathered till; in Current Research, Part A, Geological Survey of Canada, Paper 85-1A, p.117-122.

Harris, J.F.
1982: Sampling and analytical requirements for effective use of geochemistry in exploration for gold; in Precious Metals in the Northern Cordilleran, ed. A.A. Levinson; p.53-67

Lavin, O.P., Grant, A., and Nichol, I.
1986: The optimization of geochemical exploration techniques for gold deposits in area covered by glacial till; Unpublished report prepared at Department of Geological Sciences, Queen's University, Kingston, Ontario, for Ontario Ministry of Colleges and Universities, University Research Incentive Fund, 64p.

Shilts, W.W.
1975: Principles of geochemical exploration for sulphide deposits using shallow samples of glacial drift; Canadian Institute of Mining and Metallurgy Bulletin, v.68, no 757, p. 73-80.
1984: Till geochemistry in Finland and Canada; Journal of Geochemical Exploration, v. 21, p. 95-117.

Sopuck, V., Schreiner, B., and Averill, S.
1986: Drift prospecting for gold in Saskatchewan, use of heavy mineral concentrates in till; in Gold in the Western Shield, ed. L. Clark; Canadian Institute of Mining and Metallurgy, Special Volume 38, p.435-469.

Zweifel, P.
1960: Neutron self-shielding; Nucleonics, p.174-175.

Effective mineral exploration for gold using geology, Quaternary geology and exploration geochemistry in areas of shallow till

C.F. Gleeson[1], V.N. Rampton[2], R.D. Thomas[2], and S. Paradis[2]

Gleeson, C.F., Rampton, V.N., Thomas, R.D., and Paradis, S., Effective mineral exploration for gold using geology, Quaternary geology and exploration geochemistry in areas of shallow till; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 71-96, 1989.

Abstract

Shallow surficial materials from a 180 km² area in eastern Ontario were systematically sampled at 1 km centres and two areas were sampled at 100 m centres. The object was to establish the most effective sampling techniques for regional and detailed geochemical exploration for gold in areas of shallow overburden. At each sample site a humus, a "B" soil and three till fractions were analyzed for gold. Heavy mineral identifications, pebble counts, and surficial and bedrock geology maps were used to determine the nature of the gold dispersal in the surficial deposits and to interpret the geochemical patterns.

The research area is underlain by a series of supracrustal rocks composed of mafic metavolcanics and intercalated carbonate metasediments with subordinate clastic metasediments which are flanked on the west by granite gneisses (Addington Gneiss) and on the east by the Lavant Gabbro Complex. Locally, small late stage granitic bodies intrude the gabbro complex and metasediments. The area is traversed by a major northeast-trending shear zone which encloses mylonitized and fractured gabbro, metavolcanic rocks, clastic metasediments and carbonates. Gold occurrences are hosted in altered rocks in the shear zone. They consist of quartz-carbonate veins and massive sulphide occurrences in mafic mylonite.

Most of the area is underlain by a loose relatively thin layer of sandy stony ablation till, deposited by glaciers moving in southerly directions, and rock rubble. Glaciofluvial complexes cross the central and eastern part of the area. A short-lived glacially dammed lake in the Clyde River Valley resulted in thin lacustrine sediments being deposited there.

The regional survey was effective in outlining the extent of the gold belt and in establishing promising targets for further exploration. Although all sample types are more or less effective on the regional scale some are more effective than others. For the detailed surveys all sample types are relatively useful in reflecting known gold mineralization. The results of this program indicate that regional shallow till sampling programs are not only cost-effective but technically effective in locating gold mineralization in areas that are covered with extensive but relatively thin glacial deposits.

Résumé

Des matériaux superficiels peu profonds provenant d'une zone de 180 km² dans l'est de l'Ontario ont été systématiquement échantillonnés à tous les kilomètres, et deux zones ont été échantillonnées de façon plus détaillée à tous les 100 m. Le but était d'établir le type de technique d'échantillonnage le plus efficace aux fins de recherche géochimique régionale et détaillée de l'or dans les zones de morts-terrains peu profonds. à chaque point d'échantillonnage, l'or a été dosé dans l'humus, le sol "B" et trois tranches granulométriques de till. Des relevés des minéraux lourds, des décomptes de galet, et des cartes géologiques des formations en surface et du socle rocheux ont été utilisés pour déterminer la nature de la dispersion de l'or dans les dépôts de surface et pour interpréter les résultats géochimiques.

[1] C.F. Gleeson & Associates Ltd., Lakeshore Drive, P.O. Box 10, Iroquois, Ontario, K0E 1L0

[2] Terrain Analysis & Mapping Services Ltd., P.O. Box 158, Carp, Ontario, K0A 1L0

La zone de recherche repose sur une série de roches supracrustales composées de roches métavolcaniques mafiques et de métasédiments carbonatés intercalaires accompagnés de métasédiments détritiques subordonnés qui sont flanqués à l'ouest par des gneiss à granite (gneiss d'Addington) et à l'est par le complexe de gabbros de Lavant. Par endroits, de petites masses granitiques récentes pénètrent le complexe de gabbros et les métasédiments. La région est traversée par une importante zone de cisaillement se dirigeant à l'est du nord et au sein de laquelle se manifestent du gabbro, des roches métavolcaniques, des sédiments détritiques et des roches carbonatées de nature mylonitisée et fracturée. Les manifestations d'or sont logées dans des roches altérées dans la zone de cisaillement. Elles se présentent sous forme de veines de quartz et carbonatées, et de masses sulfurées dans de la mylonite mafique.

La zone repose en grande partie sur une couche meuble et relativement mince de till d'ablation sableux et caillouteux, mise en place par des glaciers se déplaçant vers le sud, et de la blocaille. Les complexes glaciofluviaux traversent le centre et l'est de la zone. Un lac de barrage glaciaire de courte durée dans la vallée de la rivière Clyde a laissé une couche mince de sédiments lacustres à cet endroit.

L'étude régionale a permis de délimiter l'étendue de la zone aurifère et d'établir des cibles prometteuses pour de futures explorations. Certains types d'échantillons sont plus révélateurs que d'autres à l'échelle régionale. Aux fins des études détaillées, tous les types d'échantillons caractérisent assez bien la minéralisation d'or connue. Les résultats du présent programme indiquent que les programmes d'échantillonnage régional des tills peu profonds sont non seulement rentables, mais aussi techniquement efficaces lorsqu'il s'agit de repérer des minéralisations d'or dans des zones recouvertes d'une couche de sédiments glaciaires étendue, mais relativement mince.

INTRODUCTION

General

What sample media, sample density and sample fraction to use? This paper deals with these questions and the effectiveness of exploration geochemical techniques applied to the search for gold in an area of extensive, but relatively shallow overburden.

Location and Access

The area is located 82 km southwest of Ottawa and 50 km northwest of Perth (Fig. 1). Access is generally good from a series of gravel roads within the project area.

Past Investigations

Government- and industry-sponsored low density regional geochemical surveys in Canada have concentrated mainly on stream and lake sediment surveys. For precious metal exploration in glaciated areas, however, low density lake sediment surveys are not always adequate and stream sediment surveys may not be appropriate because of disjointed drainage.

Systematic regional shallow till sampling has been the practice for some years now in Sweden and Finland. In Canada the first integrated Quaternary-geochemical study on metals in tills was carried out in the mid 1950s in the Chibougamau area by Ermengen (1957). In more recent times, shallow till geochemical studies have been published for the Mt. Pleasant area, New Brunswick (Szabo et al., 1975), and for the Lac Mistassini area (Icon Mine), Quebec (DiLabio, 1981). In Ontario, Closs and Sado (1982a,b) have published studies on overburden geochemistry and Quaternary studies for base metal exploration and investigation of carbonatite complexes. Shilts (1976) has emphasized the importance of analyzing the clay fraction of near-surface tills for regional till surveys. Geochemical data on twelve trace elements in the clay fraction of tills from 1500 sites in southeastern Ontario (Kettles and Shilts, 1983) showed that several samples taken from the present research area contain anomalous amounts of copper, zinc, cobalt, nickel, silver, arsenic, cadmium and mercury.

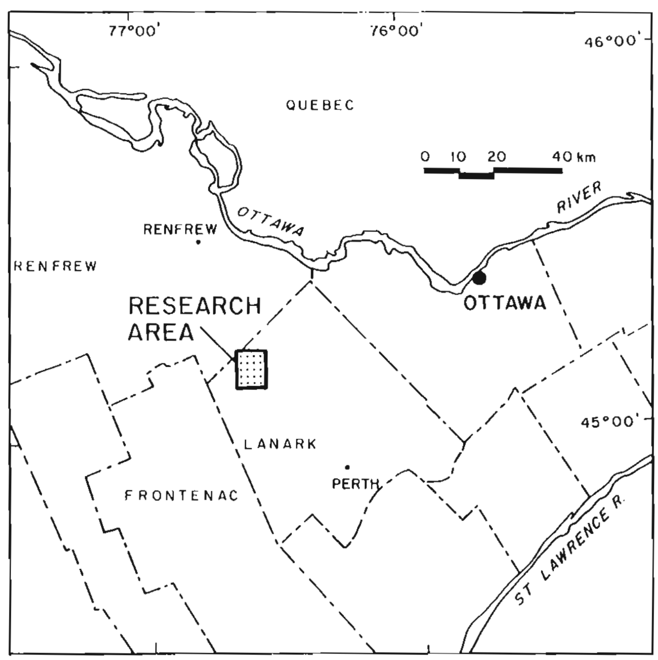


Figure 1. Location Map.

Publications dealing with till geochemical studies specifically related to gold exploration are not plentiful, although with the increased emphasis on gold more literature on this topic is appearing. Lee (1963) was one of the first in Canada to publish on the use of shallow till sampling in the search for gold. He was able to define dispersal trains down-ice from mines in the Kirkland Lake area by counting gold grains in heavy mineral concentrates from till. In the Beardmore-Geraldton area Closs and Sado (1981) found gold in ''B'' horizon of soils was effective only if the soils were developed on till. Where the bedrock source contained fine-grained gold, the gold in till anomalies were found in both heavy mineral and silt-clay fractions. However, where the bedrock source of gold was coarse-grained gold, anomalies were found only in the heavy mineral fraction.

Regional near-surface till studies, using a one per square kilometre sample density, over the St. George Batholith in southern New Brunswick (Thomas et al., 1983, 1987; Rampton et al., 1986) defined gold dispersal trains in heavy mineral concentrates up to 2 km in length. Cassiterite-bearing greisen zones were defined by anomalous tin values in the heavy mineral concentrates up to 14 km down-ice from the source area. Other Canadian examples of dispersal trains in near-surface till related to mineral occurrences include those in papers by Sinclair (1979), DiLabio (1981, 1982), Snow and Coker (1987) and McConnell and Batterson (1987).

One of the first applications of humus sampling to gold exploration in Canada was carried out in Duparquet area, Quebec (Gleeson and Boyle, 1979) in 1974. This work demonstrated that gold analyses of humus in areas underlain by permeable glacially transported overburden was effective in defining gold mineralization. Generally, soil samples of the ''B'' horizon over known occurrences gave poor or no gold anomalies. Earlier, a great deal of research had been completed by the USGS on the geochemistry of gold (Curtin et al., 1968, 1970,1971 and Lakin et al., 1974) in which they had established the effectiveness of humus sampling in defining gold mineralization.

Sampling of humus, soils and till for gold are now routinely used by exploration companies during exploration. However, much doubt about the proper application of these techniques still exists. Simple parameters such as the most effective sample density, the best media, and the proper size fraction to analyze in glaciated areas have not been established. This research project sets out to better define these parameters for geochemical exploration.

Present Investigation

The field work for this project was completed in 1983 and involved three phases: sampling of surficial materials, mapping of surficial geology and mapping of the bedrock geology (Gleeson et al., 1984, 1985, 1986; Rampton et al., 1986). In the regional sampling program, surficial material was systematically collected at one kilometre centers. In the vicinity of two gold occurrences more detailed sampling at 100 metre centers was completed. The detailed grids were designed to determine the most effective sample media and fraction for delineating gold mineralization, as well as to determine the optimum sampling pattern. At all sites, decomposed humus and ''B'' soil samples were taken. In addition, 0.5 to 1.0 m deep pits were dug to obtain samples of the parent material, generally till. In places where till was not present within a reasonable depth or distance from the desired location then glaciofluvial material was sampled. For the regional program 154 sites from 180 km^2 were sampled, and on the detailed grids 79 sites were sampled.

The surficial mapping program was designed to outline the distribution of the surficial deposits, to determine the ice flow or transport directions of the materials, and to determine the interrelationships of the surficial deposits. This information is required to properly interpret the geochemical data and to design follow-up programs. The bedrock mapping program was designed to up-date the geological data shown on maps by Peach (1948, 1958), Pauk (1983, 1984) and Carter (1981). Special emphasis was placed on differentiating between mylonitized gabbro and mafic volcanics and defining structure and alteration patterns that might be related to gold mineralization. Where possible, rock samples for gold analyses were obtained near each site sampled on the regional program. In addition, all mineral occurrences that could be found were sampled and analyzed for gold. For each sample site, 50 pebbles were identified and counted and a 2 g representative sample of heavy minerals was examined and the minerals were identified. Gold in all sample media, pebble counts and mineralogy were plotted. Basic statistical parameters were calculated for both the regional and detailed data. All data have been published by the Ontario Geological Survey (Gleeson et al., 1986).

PREVIOUS GEOLOGICAL INVESTIGATIONS AND MINERAL EXPLORATION

One of the earliest geological maps of the Lavant-Darling area was made by Vennor (1876) who outlined the Robertson Lake Shear Zone (RLSZ), and indicated several other probable shear zones and splays. He also commented on the economic geology of the area and noted a cupriferous belt in Lavant Township. Subsequent work concentrated on evaluating the magnetite, hematite and pyrite deposits of the area (Charleton et al., 1890; Ingall, 1901; Frechette, 1910). Ells (1904) completed a regional geological study of the region and reported several assays from Lavant and Darling townships ranging from 0.111 to 0.195 oz/ton gold and up to 5.2 oz/ton silver. In the 1940's, regional mapping of Darling and Lavant townships was completed by Peach (1948, 1958) and Smith (1958). Peach identified the RLSZ, which he extrapolated northward from Smith's area to Joes Lake. Sangster (1970) completed a regional metallogenic study which incorporated this area. A compilation by Gordon et al. (1979) lists the gold occurrences in Darling and Lavant townships as comprising the Ranworth (boulder) occurrence (1.5 oz/ton gold, 12 oz/ton silver) in the Little Green Lake area, and the Robertson occurrence (0.11 oz/ton gold over 5.6 feet of diamond drill core) in the Robertson Lake area some 10 km south of Joes Lake. The Ranworth boulder was found in 1962 on the Little Green Lake claims about 400 m south of the Little Green Lake gold occurrence (Northern Miner, 1962).

Jackson (1980) mapped mylonitic rocks lying adjacent to, and on both sides of the leucogranitic (Addington) gneiss in the White Mountain area adjoining the central west sector of the research area. Unlike Peach, she did not identify volcanic rocks to the east of the Addington gneiss but showed that they were mylonites derived from the gabbro with attendant retrograde metamorphism of the amphiboles to chlorite.

Carter studied the copper-antimony-gold-silver deposits of the Lavant-Darling area (Carter 1981, Carter et al., 1980), mapped part of the area and extended the RLSZ north of Joes Lake.

Pauk (1983) mapped the area south of the Clyde River and showed that the RLSZ lay between the Addington Gneiss and the Lavant Gabbro Complex.

Gleeson et al. (1984, 1985, 1986) produced surficial and bedrock maps of the area. The bedrock mapping showed the RLSZ north of the Clyde River to be much wider than shown by Carter (1981), extending northeast to Darling Long Lake.

Early records of base or precious metal exploration are sparse; however it appears that the Darling, Joes Lake and Robertson Lake occurrences were discovered prior to 1900. Vennor (1876) reported that a shaft was sunk on a copper occurrence on Lot 6, Conc. VII, Lavant Township.

Assessment reports have been filed for areas which include the Bradford, Darling and Little Green Lake gold showings (Robertson and Gleeson, 1981, Campbell, 1968, Hammerston, 1968 and Rankin, 1962).

South of Joes Lake, Taylor (1957) has reported the presence of trace amounts of chalcopyrite and tetrahedrite in drill core. Gleeson (1975) reported 0.45 oz/ton gold, 2.92 oz/ton silver, 1.85 % copper, 1405 ppm zinc and 0.83 % antimony from a grab sample of the Joes Lake occurrence.

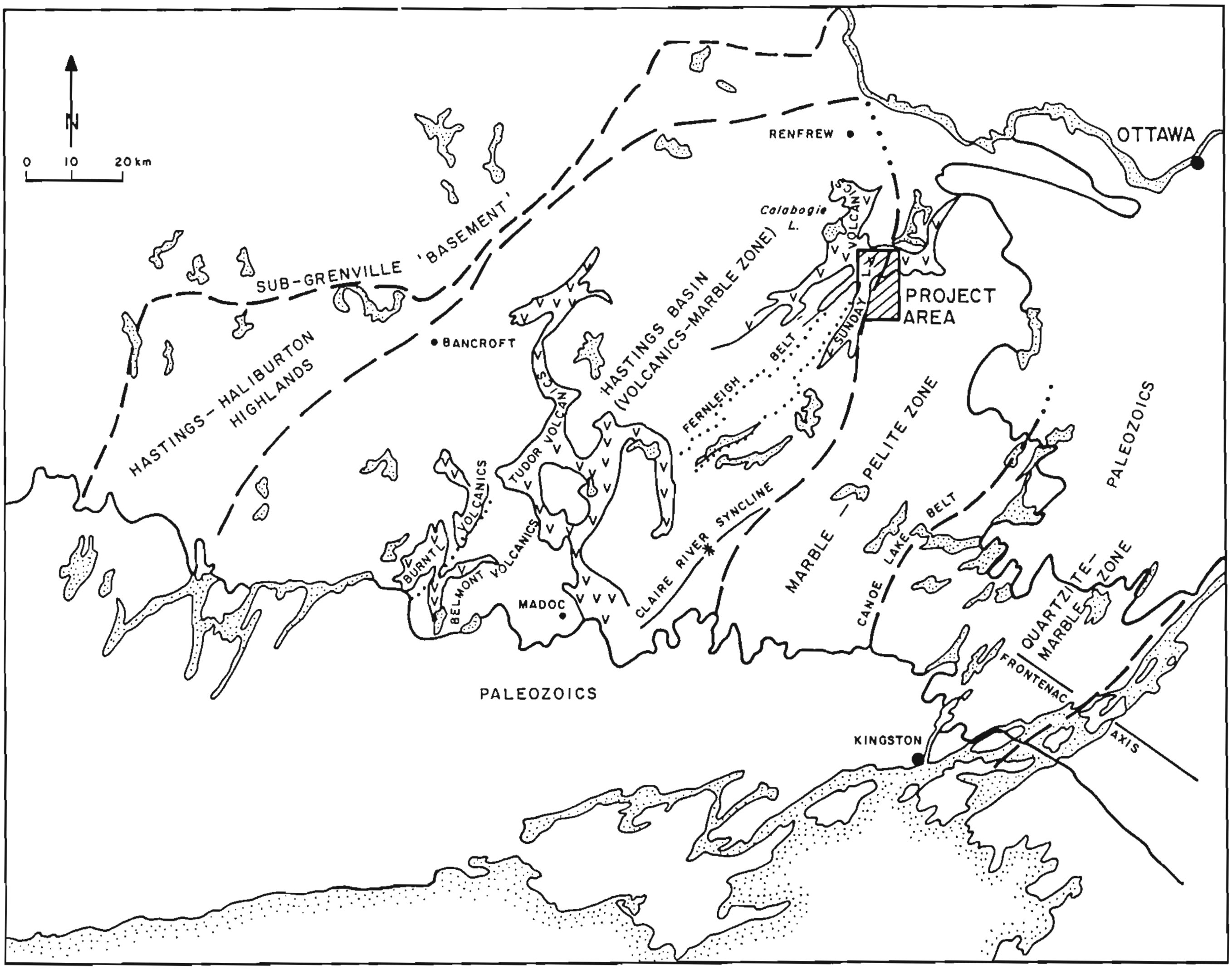


Figure 2. Sketch map of some principal geological elements of the southwest Grenville Province, Ontario.

I. Jonasson (pers. comm.) of the Geological Survey of Canada found that the tetrahedrite and pyrite from the Joes Lake gold occurrence contained 100 ppm (3 oz/ton) and 5.3 ppm (0.15 oz/ton) gold respectively. Selco completed VLF-EM, soil geochemistry (gold) and geological surveys prior to drilling three diamond drill holes at Joes Lake (Sinclair, 1978). One hole intersected 0.45 m of massive pyrite which assayed 5160 ppb gold, 5280 ppm copper, 475 ppb mercury and 1919 ppm antimony. Other analyses gave up to 0.02 oz/ton gold.

Most recently, Easton and DeKemp (1987) and Easton (1987a,b) have been investigating the geology of the area for the Ontario Geological Survey, and they have published geological maps at a variety of scales covering the area. The results of their investigations appear comparable to those reported herein.

GEOLOGY

The geology as herein described is primarily based on 1:10000 mapping (Gleeson et al., 1985) completed subsequent to the research work. The results of other workers have been synthesized and incorporated where possible; however as Easton and DeKemp's (1987) and Easton's (1987a,b) investigations were not available until after the completion of this paper, no attempt has been made to comment on or integrate their results with our observations and mapping.

Regional Setting

The area lies in the eastern portion of the Hastings Basin (Fig. 2), which forms part of the Central Metasedimentary Belt, a subdivision of the Grenville Province defined by Wynne-Edwards (1972). The Hastings Basin contains the thickest succession of supracrustal rock in the Grenville Province. The base of its stratigraphic section is characterized by a sequence of mafic volcanic rocks containing intercalated metatuffs and carbonate metasediments. The top of the section comprises an alternating sequence of carbonate and clastic metasedimentary rocks.

According to Sangster (1970) the basal volcanic rocks in the project area are a spilitized basaltic sequence with interbedded marble. These are overlain by carbonate metasedimentary rocks, which contain beds of clastic metasedimentary rocks. The clastic rocks have been interpreted as volcanic detritus eroded from adjacent volcanic highlands. According to Lumbers (1982) the carbonate facies was deposited both during and after volcanism, so that this facies is intercalated with most of the volcanic and volcaniclastic rocks. The supracrustal assemblages have been intruded by a variety of felsic to mafic syntectonic and late tectonic intrusive rock sequences.

Tectonism has affected all supracrustal rocks in the region; generally they have been folded around axes that trend northeast and north-northeast. One major fault zone, the RLSZ, can be traced from the project area southerly and southwesterly for 90 km to where it is covered by Paleozoic rocks. The northern sector of the region is cut by a series of late east-trending faults associated with the Ottawa-Bonnechere Graben.

Local Geology (Fig. 3)

Metavolcanic rocks (Map unit 1)

The intermediate to mafic metavolcanic rocks are found mainly along the west border of the area. They are fine- to medium-grained, dark grey hornblende, plagioclase (minor biotite and quartz) gneisses and amphibolites. Within the limits of the RLSZ, the rocks are highly sheared and difficult to distinguish from highly sheared gabbro. Mafic mylonites (map unit 7a) in the western part of the area may be derived in part from the metavolcanic rocks.

Metasedimentary rocks (Map unit 2)

Clastic metasediments underlie the extreme western side of the map area and occur also as small isolated shear slices within the RLSZ south of Joes Lake and north of Darling Long Lake. Generally, the metasediments are well banded, fine- to coarse-grained, medium to dark grey, biotite-muscovite-hornblende-quartz-plagioclase schists and gneisses.

Carbonate rocks (Map unit 3)

Major carbonate occurrences are southeast of Joes Lake, southwest of Peter White Lake and south and west of Darling Long Lake. Between these areas, carbonate units occur in a linear, northeast trending belt within the RLSZ.

Crystalline calcitic marble is the most common carbonate unit away from the shear zone. These rocks are medium- to coarse-grained, white to light grey, massive to well banded and locally they may include bands of graphite. Dolomitic marbles are fine- to medium-grained, grey and finely laminated. In places the dolomitic marbles contain fracture fillings and veinlets of iron-rich carbonates which host some of the gold occurrences in the area (eg. Darling Long Lake, Darling, Green Lake and Joes Lake occurrences).

The ferroan dolomites (map unit 3x) are restricted to the RLSZ and are quite variable in appearance. Visually they are microcrystalline to medium-grained and white to buff on fresh surfaces. They weather to an earthy rusty-brown colour. Within the RLSZ the ferroan dolomite is frequently associated with silicification (in the form of quartz), chloritization, sericitization and pyritization. The carbonated shear zones shown on Figure 3 are ferroan dolomite veins which occur mainly in gabbro. The ferroan dolomites are of hydrothermal origin and they are typical of the iron-carbonatization alteration that is frequently found associated with gold deposits in such gold camps as Timmins, Larder Lake and Red Lake.

Lavant Gabbro Complex (Map units 4 and 5)

In the map area the Lavant Gabbro Complex (LGC) is composed of late-stage intrusive bodies. Most range in composition from dioritic to ultramafic; the gabbroic phase being most prevalent (map unit 5). The LGC measures some 44 km long by 6 to 10 km wide. The western border of the complex is highly sheared (part of the RLSZ) and altered, and probably comprises the majority of the mafic mylonite

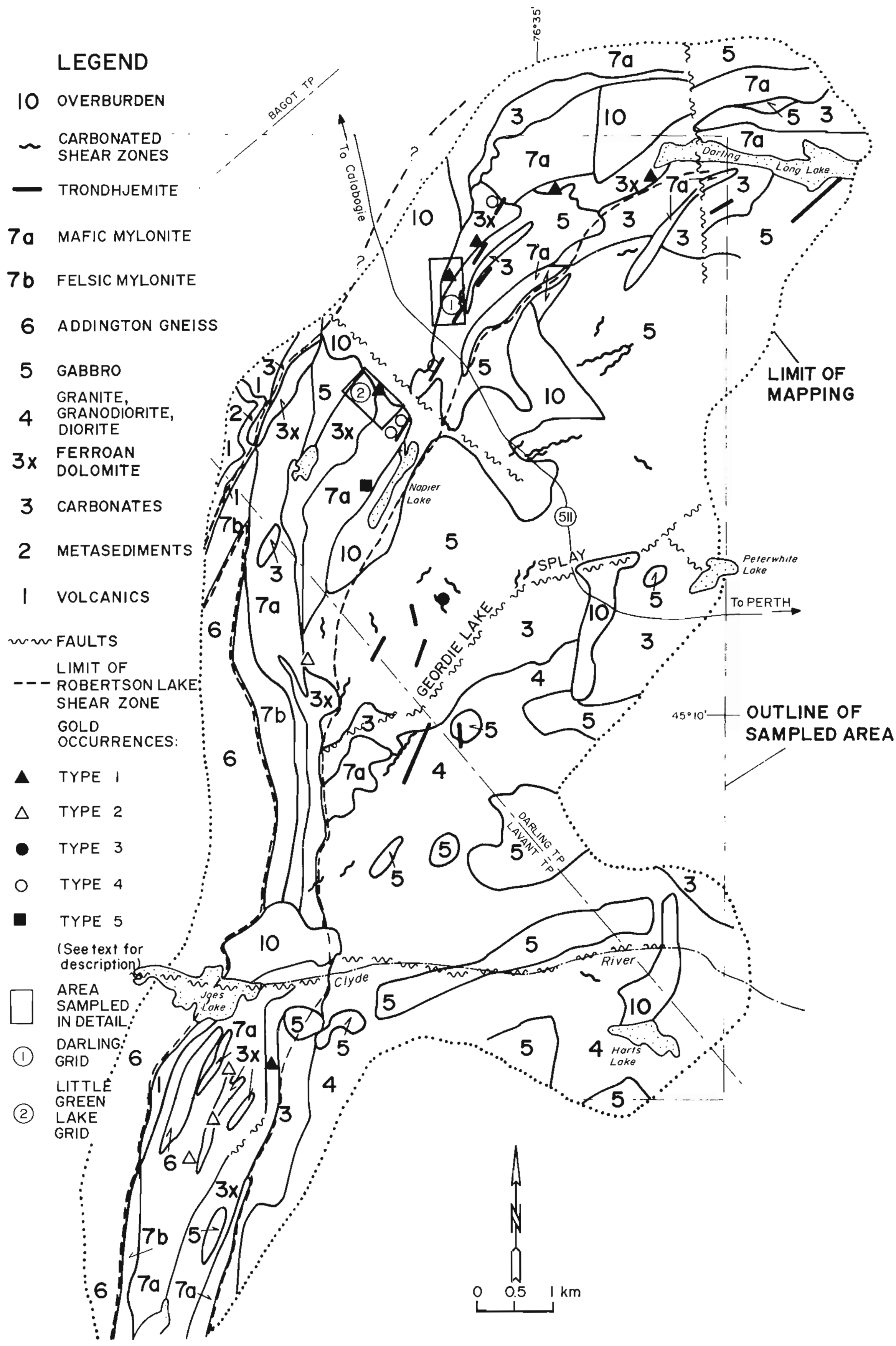


Figure 3. Geology of parts of Darling and Lavant Townships.

unit (map unit 7a). Mylonitized LGC rocks are fine grained, schistose and composed of chlorite as a metamorphic retrograde after hornblende, and andesine plagioclase, which frequently exhibits sericite overgrowths. Xenoliths and roof pendants of carbonate and metasedimentary rocks lie within the Complex, as do tectonically controlled ferroan dolomite zones and trondhjemite dykes and sills. Magnetite and disseminated pyrite (trace to 1 %) are common in the Complex.

Addington Gneiss (Map unit 6)

The Addington granitic gneiss complex forms a south-trending body in the western part of the area. The main body, 2 to 3 km wide, is bounded by two mylonite zones.

The Addington gneiss is a fine to medium grained, pink to greyish pink to red, granite and quartz monzonite. Along its sheared borders it becomes more gneissic (felsic mylonite) and may contain carbonate, chlorite and sericite as alteration products.

Mylonites (Map units 7a, 7b)

Rocks contained within the RLSZ and shown as map unit 7a have previously been mapped as mafic metavolcanic rocks. However field and petrographic studies from this project indicate that usually these rocks are intensely deformed and altered gabbroic rocks of the LGC. Shearing of the gabbro has produced mafic mylonite, whereas shearing of the more felsic rocks (eg. Addington gneiss) has produced felsic mylonite (map unit 7b).

Rocks in the mylonite zone have a layered appearance, ranging from gneissic to phyllitic. Mafic minerals have been retrograded to chlorite. Intense shearing and microbrecciation parallels the western contact of the LGC and the eastern contact of the Addington Gneiss Complex (Fig. 3). The mylonite zone extends the full length of the map area (21 km), varies in width from 1 to 3 km and dips 20 to 60° east. Dolomitic rocks and locally metasedimentary and metavolcanic rocks are also incorporated into the mylonite zone. Besides being mylonitized and brecciated the rocks in the RLSZ have been chloritized, carbonatized (ferroan dolomite), silicified, sericitized and pyritized. These alteration zones frequently host gold mineralization.

Trondhjemite

Trondhjemite dykes and sills are present in the RLSZ and in the LGC (Fig. 3). Where they occur in the mylonite zone they are oriented parallel to the schistosity and they are sheared to varying degrees. Commonly they are silicified (quartz veins and stockworks) and in places contain secondary carbonate and pyrite. Pyritized zones generally are auriferous.

Gold Occurrences

The gold occurrences in the area are shown on Figure 3. Five identified styles of gold mineralization, with some of their associated minerals, are listed below:

Type 1. quartz-carbonate veins in dolomitic marble (tetrahedrite, chalcopyrite, pyrite and gold)
2. quartz-ferroan dolomite zones in altered mafic mylonite (pyrite, chalcopyrite)
3. quartz-ferroan dolomite veins in gabbro (pyrite, arsenopyrite)
4. quartz veins in altered trondhjemite (pyrite, arsenopyrite, bismuthinite, gold, tourmaline)
5. conformable massive sulphide zones in altered mafic mylonite (pyrite,pyrrhotite, graphite, ?chalcopyrite, arsenopyrite).

Of the sixteen gold occurrences that have been identified in the map area, six (all of type 1) were previously known; the remainder have been found as a result of exploration (Gleeson et al., 1985) carried out subsequent to this research project.

QUATERNARY GEOLOGY

Regional striae patterns indicate that during the Late Wisconsinan the region was glaciated by ice moving in a southerly direction (Gadd, 1980). This is supported by the majority of striations observed in the map area (Fig. 4). Ice flow during part of the Late Wisconsinan may have been minimal, as the main components of regional ice flow were channelled down the St. Lawrence Lowlands to the east and across the Madawaska Highland to the west. During the waning stages of the Late Wisconsinan glaciation, glacial and subglacial tunnels developed in the ice, channels were eroded in the subglacial bedrock, and eskers, kames, and kame deltas were formed. Further ice wastage resulted in partial uncovering of the area and development of a glacial lake in the Clyde River valley as evidenced by deltas in the valley. This lake must have been short-lived because no significant amount of glaciolacustrine sediment was noted within the Clyde River Valley and the deltas show structures and morphology characteristic of the melting out of buried ice-blocks.

In the Ottawa Valley, glacial ice flow in a southeasterly direction may have persisted for a short period after deglaciation of the Madawaska Highland (Gadd, 1980). South-southeast trending striations in the northern part of the research area support this hypothesis. During this interval, ice-contact stratified deposits likely formed in a marginal zone parallel to the scarp marking the northern edge of the Madawaska Highland (Barnett and Clark, 1980); meltwater flowed in a general east-southeast direction.

The Champlain Sea did not directly affect the study area as its maximum elevation was only 175 m (Fransham and Gadd, 1977; Barnett and Clark, 1980).

Ablation till covers most of the area (Fig. 4). It is generally characterized by a light yellowish brown colour and is loose to compact. It varies in textural composition from sandy, with sand constituting 50 to 80 % of the till and clasts forming 10 to 20 % of the remainder, to stony with pebble-sized and larger clasts commonly constituting 15 to 35 % and sand forming 40 to 70 % of the till. The stony tills at a few localities may contain a significant portion of rock fragments dislodged by frost action from the underlying

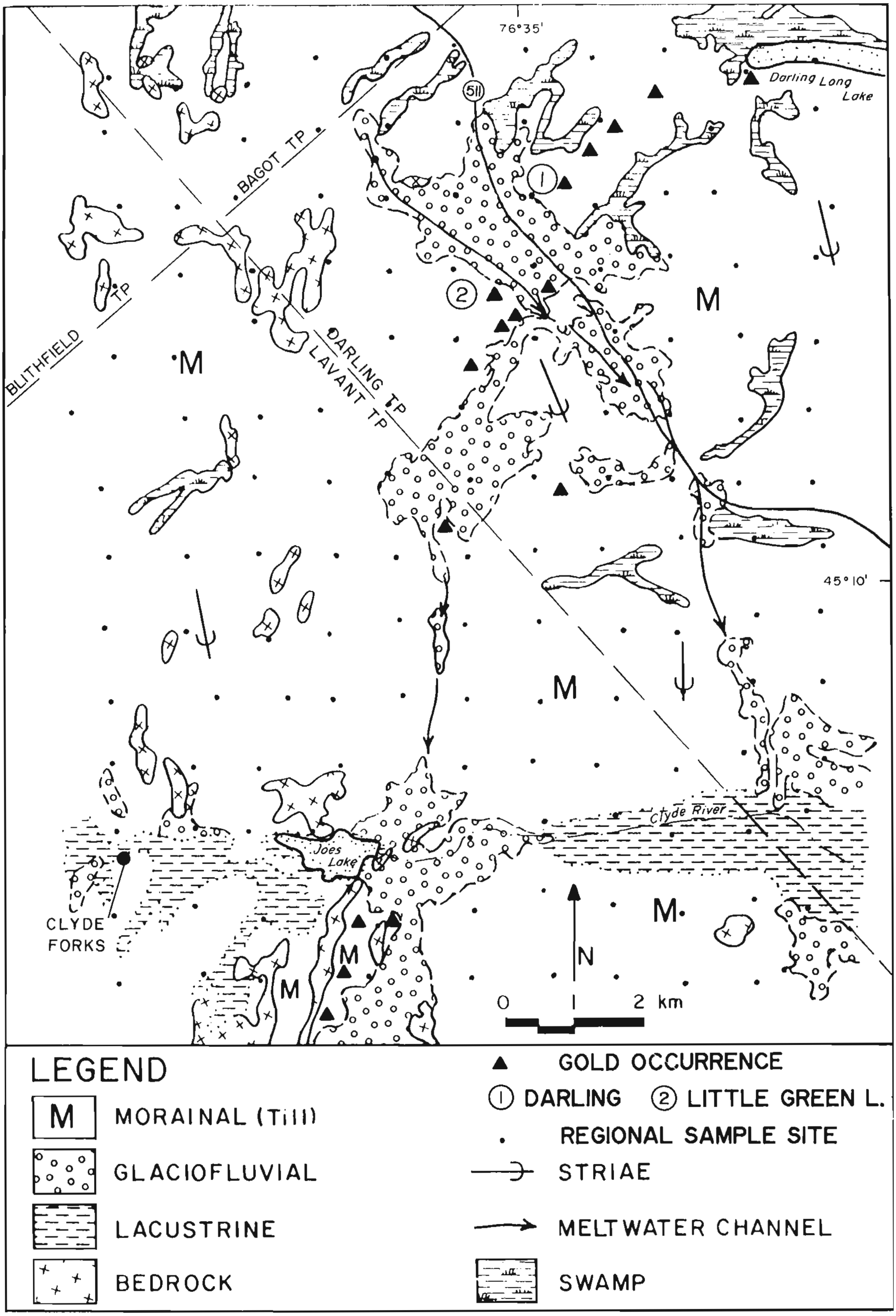


Figure 4. Quaternary Geology.

bedrock especially where the till is relatively thin. In addition, some of the ablation till at the base of slopes may have incorporated rock fragments that have moved downhill under the influence of mass wastage processes.

The ubiquitous distribution of the ablation till throughout the area has made it the prime sampling medium for this exploration program. Ablation till is generally believed to be much farther travelled than lodgment till, and thus a more difficult medium to utilize in the search for mineral deposits. However, it is clear from the results of this study that gold from known occurrences has been incorporated into the glacier, and a recognizable amount of it has been deposited with the ablation till. Generally, the dispersal trains of all media parallel the glacial flow directions determined from glacial striae.

Glaciofluvial deposits in the form of ice-contact stratified drift and outwash occur mainly in a belt in the north-central and southern parts of the area (Fig. 4). Glaciofluvial deposits include those sediments deposited by meltwater both ilders to stratified well sorted sand and gravel. Drill holes (Gorrell et al., 1985) indicate that the sand and gravel varies in thickness from 9 m to 32 m.

Care must be taken in interpreting geochemical anomalies found in glaciofluvial deposits because the down-ice distance from their source may be much greater than that for anomalies in till. In addition, the direction of transport by water depositing the glaciofluvial materials may also differ from the flow direction of glacier ice. For example, in the north-central part of the map area meltwater flow (according to the trend of esker segments and cross-bedding in these areas) appears to have been southeasterly (Fig. 4). Thus, anomalous gold values found in glaciofluvial deposits southeast of the gold occurrences in the north central part of the area could be interpreted as reflecting local bedrock sources of gold or as gold transported from the area surrounding the occurrences.

Within the study area, brown forest soils have developed on calcareous tills, whereas Podzols have developed on glaciofluvial deposits and noncalcareous tills. The "B" horizon generally extends to a depth of 0.2 to 0.4 m. The "C" horizon in parent materials shows evidence of oxidation due to groundwater percolation.

Regional Survey

Statistics

A statistical summary for gold in the various sample fractions and media from the 154 regional sites is shown in Table 1. Because of the lognormal nature of the data, the geometric mean will be used in this report. The humus is definitely enriched in gold relative to the mineral soils. Depletion of gold in the "B" soils relative to the tills is also apparent.

Gold in humus (Fig. 5)

Gold in humus generally increases to greater than 10 ppb over and near gold-bearing structures. The trends of the anomalies more or less follow the attitude of the underlying geological formations along the RLSZ. In the north-central part of the area the continuity of the gold trend along the RLSZ is broken over the area underlain by glaciofluvial deposits. In this area gold values decrease to less than 5 ppb. To the northeast, values increase again (11-119 ppb gold) over and near the gold occurrences. South of Joes Lake along the RLSZ there is relatively poor response for gold in humus. Presently known occurrences there are not reflected in the humus results.

Table 1. Statistical summary for gold (ppb) in regional samples.

Horizon	Arith. Mean	Std. Dev.	Geom. Mean	Log. Dev.	Range	
					Min	Max
Humus	7.4	14.9	4.2	2.6	<1	119
"B" soil (<80 mesh)	5.7	21.7	1.5	3.6	<1	223
Till (<5 mesh)	8.4	41.9	2.2	3.5	<1	506
Till (<250 mesh)	11.5	39.8	3.4	4.0	<1	460
Till (heavy minerals)	91.3	425.9	5.3	7.8	<	4358

A second southeasterly-trending anomaly follows from the east edge of the RLSZ, along Highway 511, to the Geordie Lake splay where mylonitized and altered gabbroic rocks predominate. The trend continues weakly southeastward over gabbroic rocks to the east boundary of the map area. An easterly-trending increase in gold also occurs over the LGC south of Clyde River.

Gold in <80 mesh "B" horizon soils (Fig. 6)

Values greater than 5 ppb gold in "B" horizon soils are clustered mainly over and near the gold occurrences. Continuity along the auriferous RLSZ is lacking. This is likely due to the "B" horizon soil in many places being developed in colluvium, loess or lacustrine materials, rather than till. Better anomaly definition is attained where the soil has developed on till. Little evidence of appreciable glacial dispersal of gold in the "B" horizon soils exists. Gold occurrences fall within circular anomalies that show little down-ice distortion.

Gold in total till (<5 mesh, Fig. 7)

Gold in the total till increases over most of the RLSZ and gold occurrences. The trend starts at the south edge of the project area and continues to Highway 511 where it comes to an abrupt end. The presence of glaciofluvial materials in this area may account in part for this interruption. The anomaly picks up again near Darling Long Lake where a value of 506 ppb gold occurs in the till and where subsequent work uncovered a gold occurrence of Type 1. A southeast trend to the high gold values on the west side of Highway 511 continues to the east edge of the project area. This anomaly may be related to the Geordie Lake Splay, which is underlain by altered gabbro and carbonate rocks. Other local increases in gold remain unexplained. The anomaly patterns around the gold occurrences indicate relatively short (less than 1 km) dispersal distances.

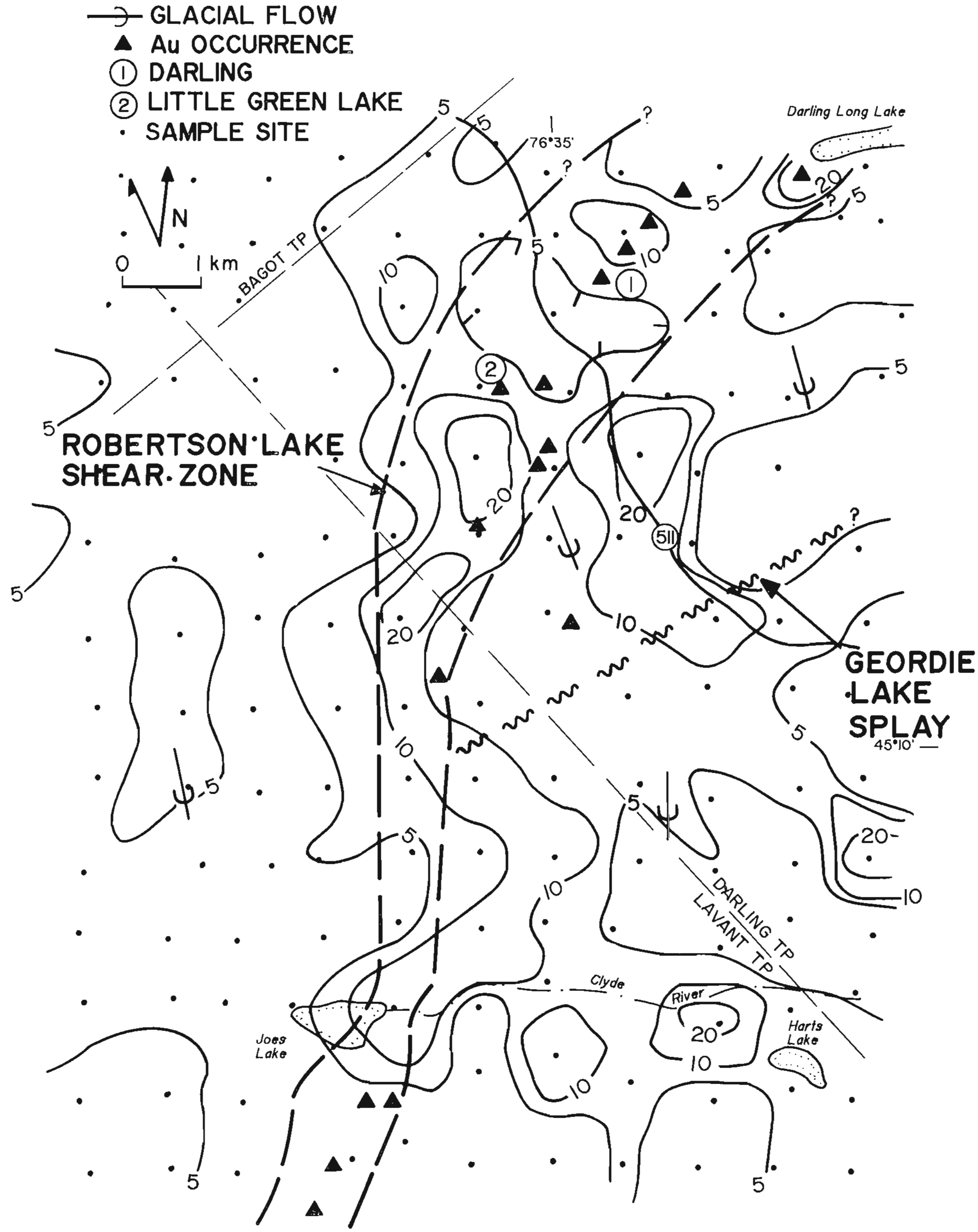


Figure 5. Gold (ppb) in humus.

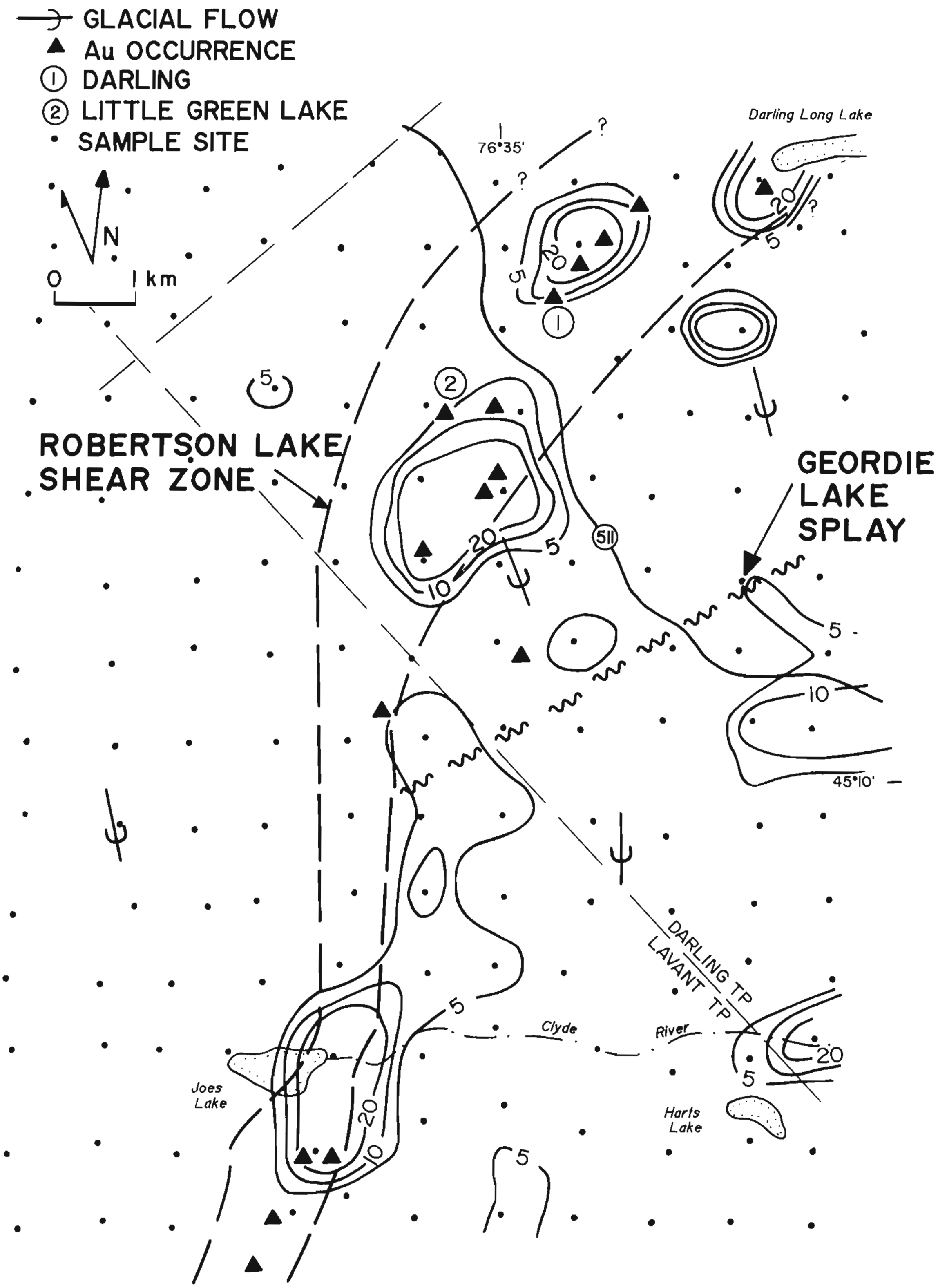


Figure 6. Gold (ppb) in <80 mesh "B" horizon soil.

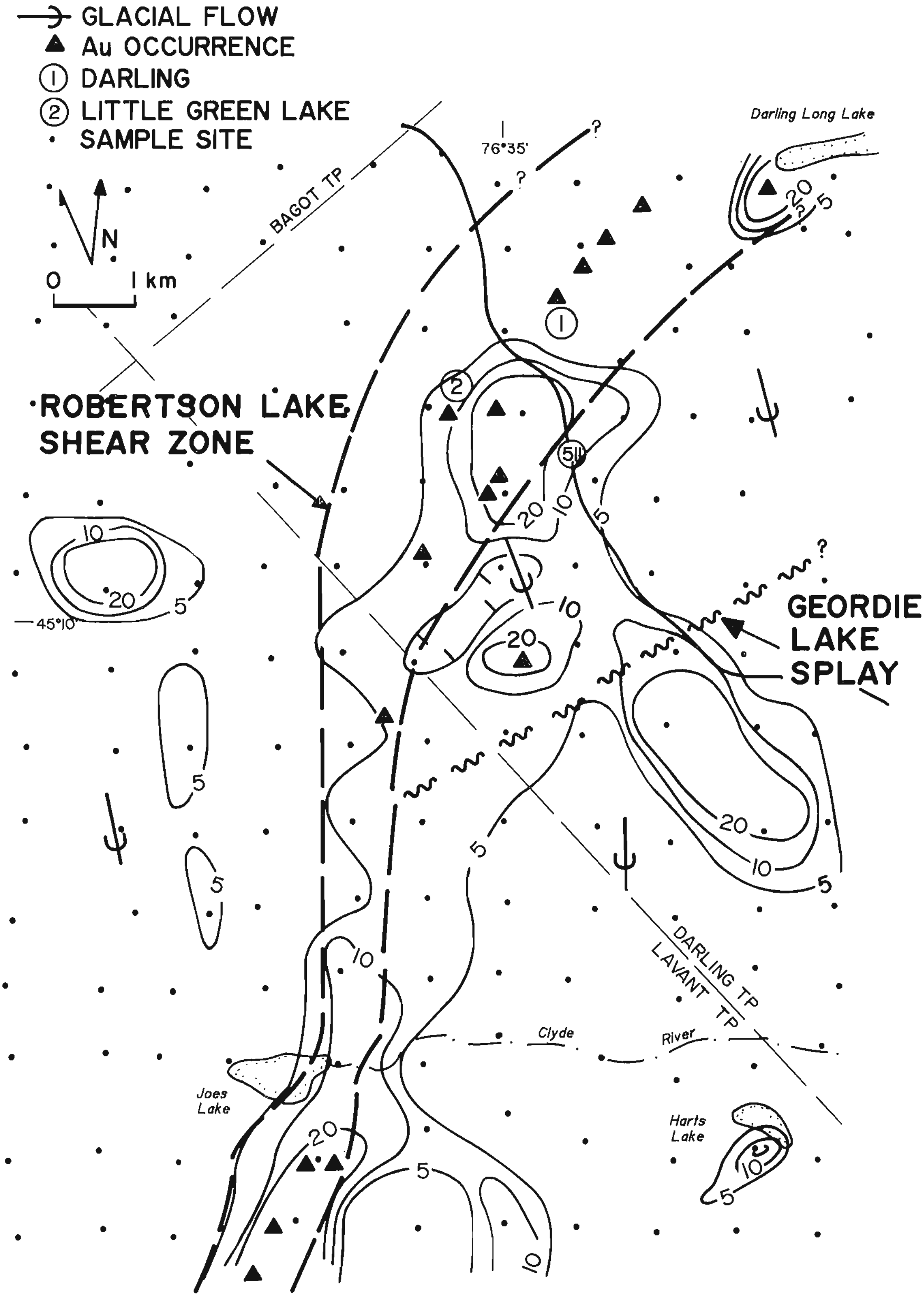


Figure 7. Gold (ppb) in till (<5 mesh fraction).

Gold in till (<250 mesh fraction, Fig. 8)

Anomalous gold patterns in the silt and clay fraction of the till over the RLSZ and gold occurrences are not markedly different from the total till anomaly patterns. Interruptions along the RLSZ are caused, in part, by the presence of glaciofluvial deposits in these areas. Other increases in gold values occur over and down-ice from the Geordie Lake Splay and west of the RLSZ where Addington gneiss is mylonitized. Maximum gold values (50-400 ppb) are related to gold occurrences. Anomalous patterns over and near the known gold occurrences suggest dispersal distances of 1 km or less. Isolated anomalies near Harts Lake and near the eastern and western borders of the area are unexplained.

Gold in Till (heavy mineral fraction s.g. >2.96, Fig. 9)

The distribution of gold in the heavy mineral fraction of the till samples shows a dominant north-northeast trend over the RLSZ and its associated gold occurrences. The central part of the anomaly (868 to 2276 ppb gold) between highway 511 and the west boundary of Darling Township proved to be caused by gold mineralization in a massive sulphide zone and quartz veining in altered trondhjemite. To the northeast near Darling-Long Lake, an anomaly (319 ppb) proved to be related to auriferous quartz-carbonate veining in dolomitic marble. A northeast trend enclosing a maximum value of 4358 ppb gold occurs along the Geordie Lake Splay. These results as well as high arsenic values in the heavy minerals (Gleeson et al., 1985) and the presence of altered mylonitized gabbro and carbonates along this splay suggest that gold mineralization is associated with this structure. Other anomalies in the southeast and western sectors of the area remain unexplored and unexplained. The gold results from the heavy mineral fraction of the till show limited dispersal distances (1 km or less) but better continuity, anomaly contrast and definition than other till fractions.

Clasts and heavy mineral dispersal

Relatively short glacial dispersal distances are also indicated by pebble counts of such distinctive lithologies as the Addington gneiss (Fig. 10) and Lavant gabbro (Fig. 11). The Addington gneiss pebbles constitute from 10 to 60 % of the total pebbles over its area of outcrop. Down-ice transport of pebbles from the main body of gneiss is about 1 km. Further dispersal is due to glaciofluvial transport.

Gabbro clasts over the unaltered gabbro constitute from 30 to 67 % of the total pebbles. The relationships between areas of gabbro outcrop and gabbro pebble counts in excess of 30 % are shown on Figure 11. The results indicate a down-ice glacial dispersal distance of 1 to 2 km. The low percentage of gabbro clasts within the northwest-central part of the area, underlain by gabbro, is caused by the presence of glaciofluvial deposits there (Fig. 3). The low counts within the western gabbro high, between highway 511 and the western boundary of Darling Township, is an area where many quartz-ferroan dolomite veins occupy shear zones in gabbro. Increases in gabbro pebbles north of the main gabbro body in the RLSZ are caused by "islands" of non-mylonitized gabbro within the shear zone. An area characterized by gabbro pebbles in excess of 10 % along the west edge of the gabbro outcrop and north of Joes Lake is related to glaciofluvial transport along the RLSZ (Figs. 3 and 4).

The heavy minerals show an abundance of chlorite (Fig. 12) and a relative depletion of amphibole (Fig. 13) over and near the RLSZ. These patterns reflect the zone of mylonitization and alteration which marks the RLSZ. As a result of shearing and retrograde metamorphism, the ferromagnesian minerals have reverted to chlorite in the shear zone. Again, dispersal distances, as best shown by the chlorite abundances, appear limited to 1 km or less. Similar increases in magnetic aggregates (i.e., magnetite enclosed in platy minerals, especially chlorite) and pyrite were also noted in the heavy mineral concentrates over and near the RLSZ. Non-aggregated magnetite ranges from less than 1 to 49 % of the heavy mineral concentrates. Samples containing greater than 20 % are closely related to magnetite occurrences in the area. In the west portion of the area, magnetite falls from 30 % near the magnetite occurrences to 20 % 1 km down-ice from the occurrences and to 9 % 2 km down-ice from the occurrences (Gleeson et al., 1986).

Discussion

The lowest background value for gold from the various materials sampled is 1.5 ppb for the "B" horizon soils. This value contrasts sharply with the humus material which averages 4.2 ppb gold. The tills are more auriferous than the "B" soils. One reason for the low values at many locations in the "B" soils may be that they are developed on colluvium, loess, or lacustrine materials, which have quite different compositions and origins than the underlying till. "B" soils developed directly on auriferous tills are generally not depleted in gold. Low values in "B" soils are generally not a problem when dealing with labile elements because they are transported hydromorphically from bedrock or underlying tills and enriched in the higher exchange capacity medium of the "B" soil. However, gold bypasses the "B" soil horizon because it is mainly taken up by the root systems of the overstory vegetation and returned to the surface when the leaves fall and decompose to form the humus. This phenomena has been reported by Gleeson and Boyle (1979) for the Duparquet area. Robertson and Gleeson (1981) sampled soil profiles in the Little Green Lake area; they also noted that the lowest gold values (5 ppb) occurred in the brown silty "B" horizon soil, versus 150 to 220 ppb in the underlying till and 10 to15 ppb in the humus.

The regional anomalous patterns for gold from the various sample media and sample fractions are in a general way similar, although gold appears more dispersed in humus samples than in the other fractions. Most humus samples from the east and central parts of the area contain 5 ppb or more gold, however, significant differences occur in detail. For instance, gold in humus does not reflect the presence of gold mineralization defined by all other sample media south of Joes Lake at this scale of sampling. Areas with gold occurrences frequently contain relatively low gold values in humus (slightly less than 10 ppb). However, in the central portion of the area, where gold in massive sulphides has been traced along strike for some 3.5 km, gold in humus ranges from 18 to 34 ppb. Similarly, over the gold occurrence near Darling Long Lake humus contains 119 ppb gold.

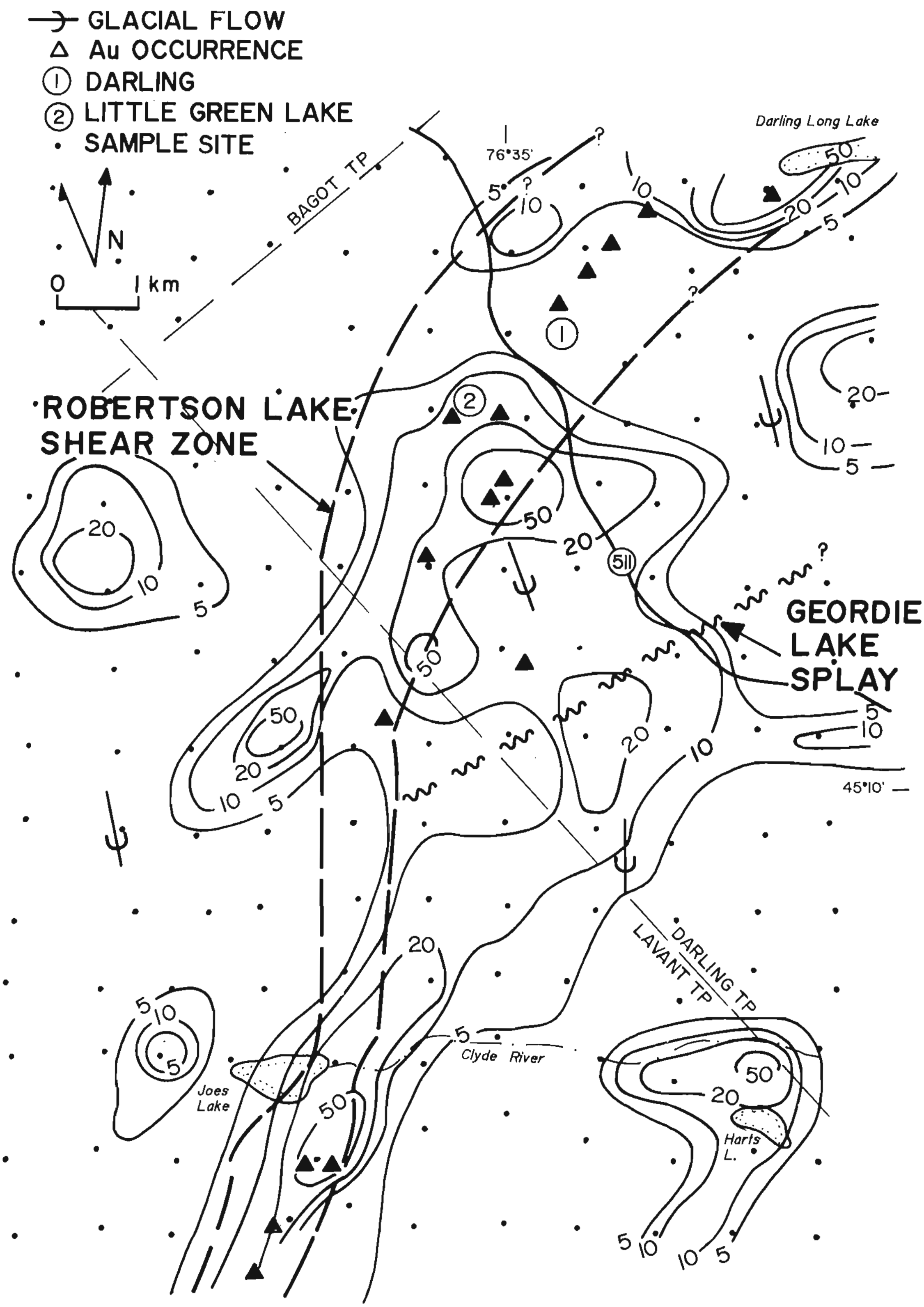


Figure 8. Gold (ppb) in till (<250 mesh fraction).

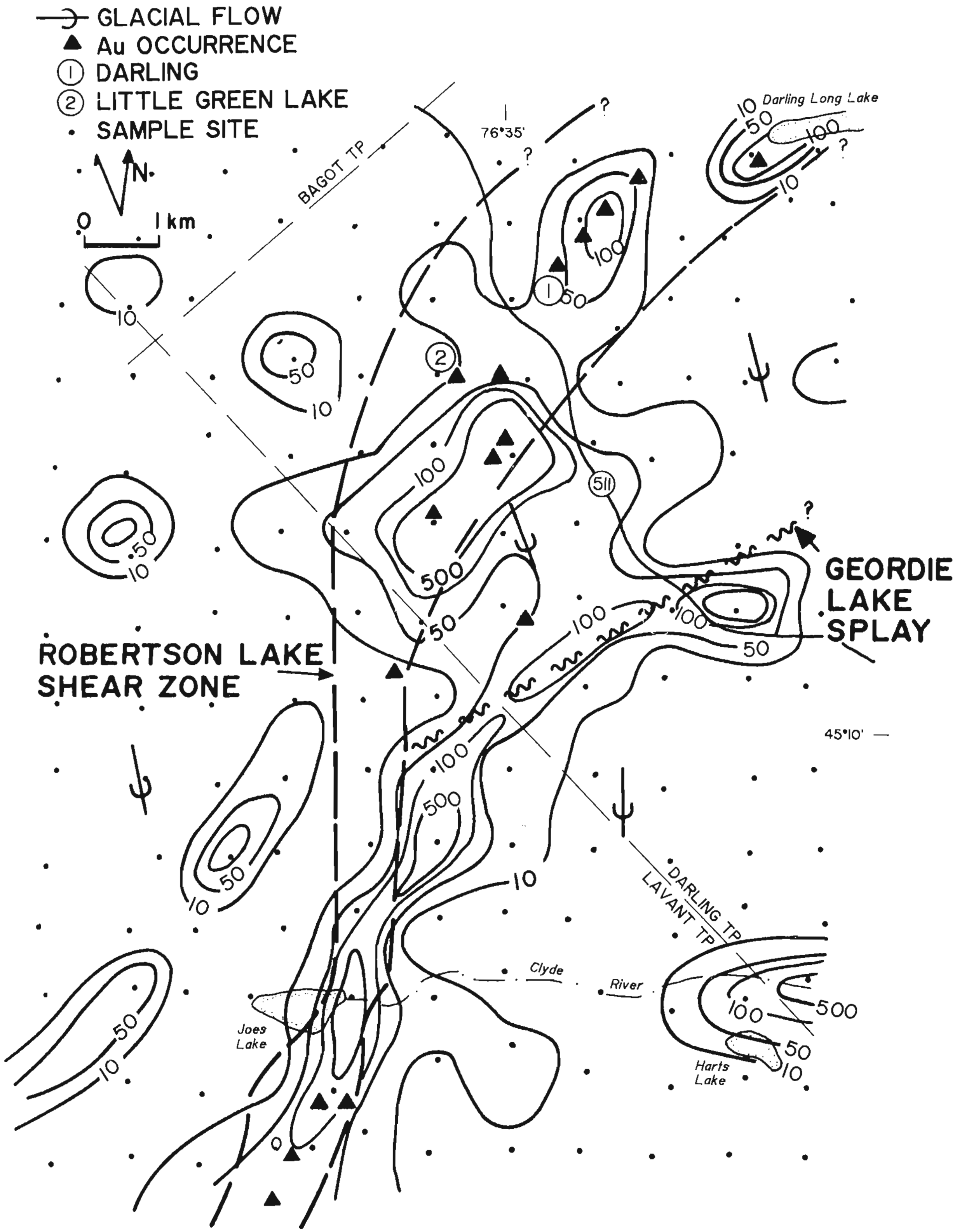


Figure 9. Gold (ppb) in till (heavy mineral fraction).

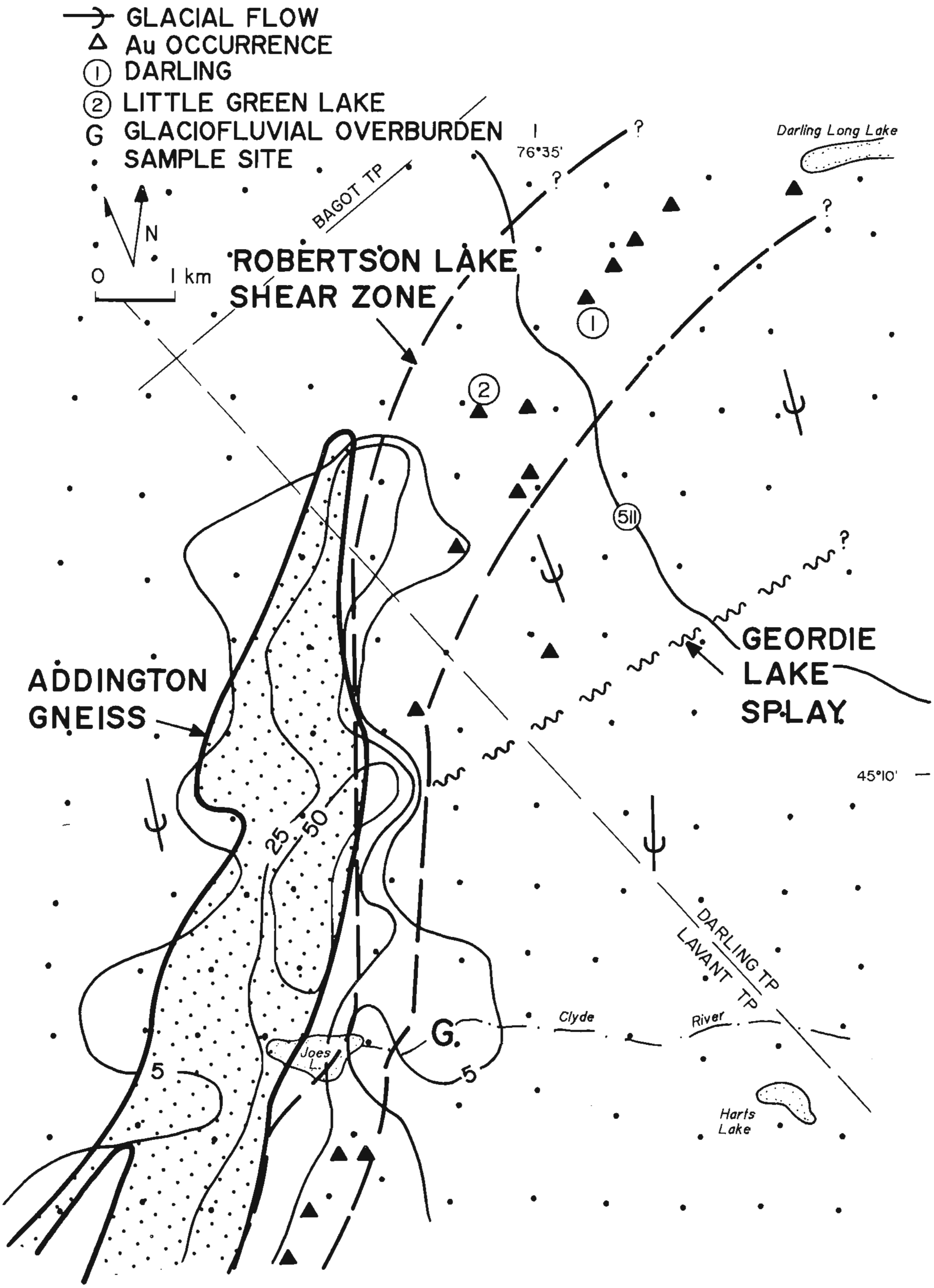


Figure 10. Percent Addington Gneiss pebbles.

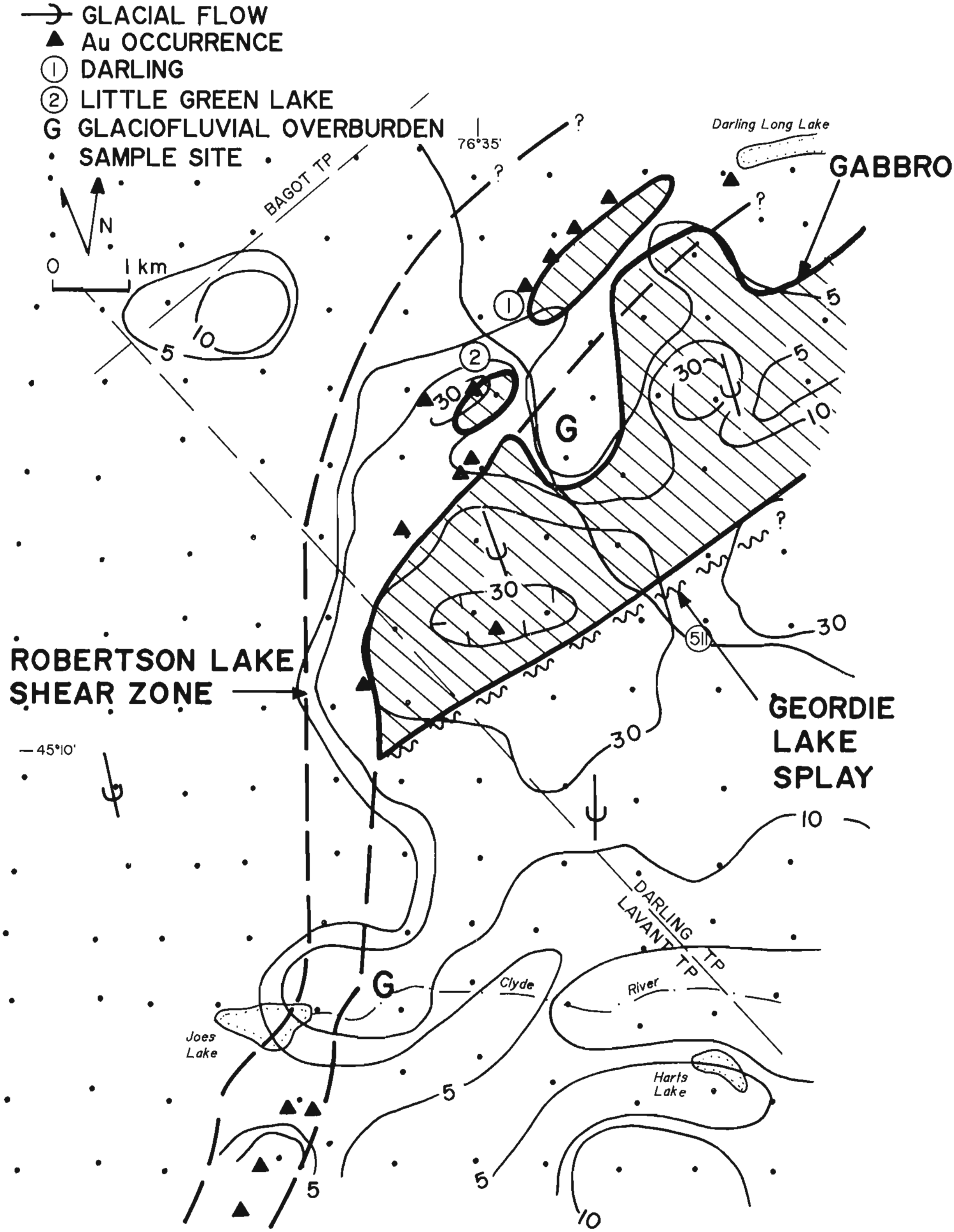


Figure 11. Percent Gabbro pebbles.

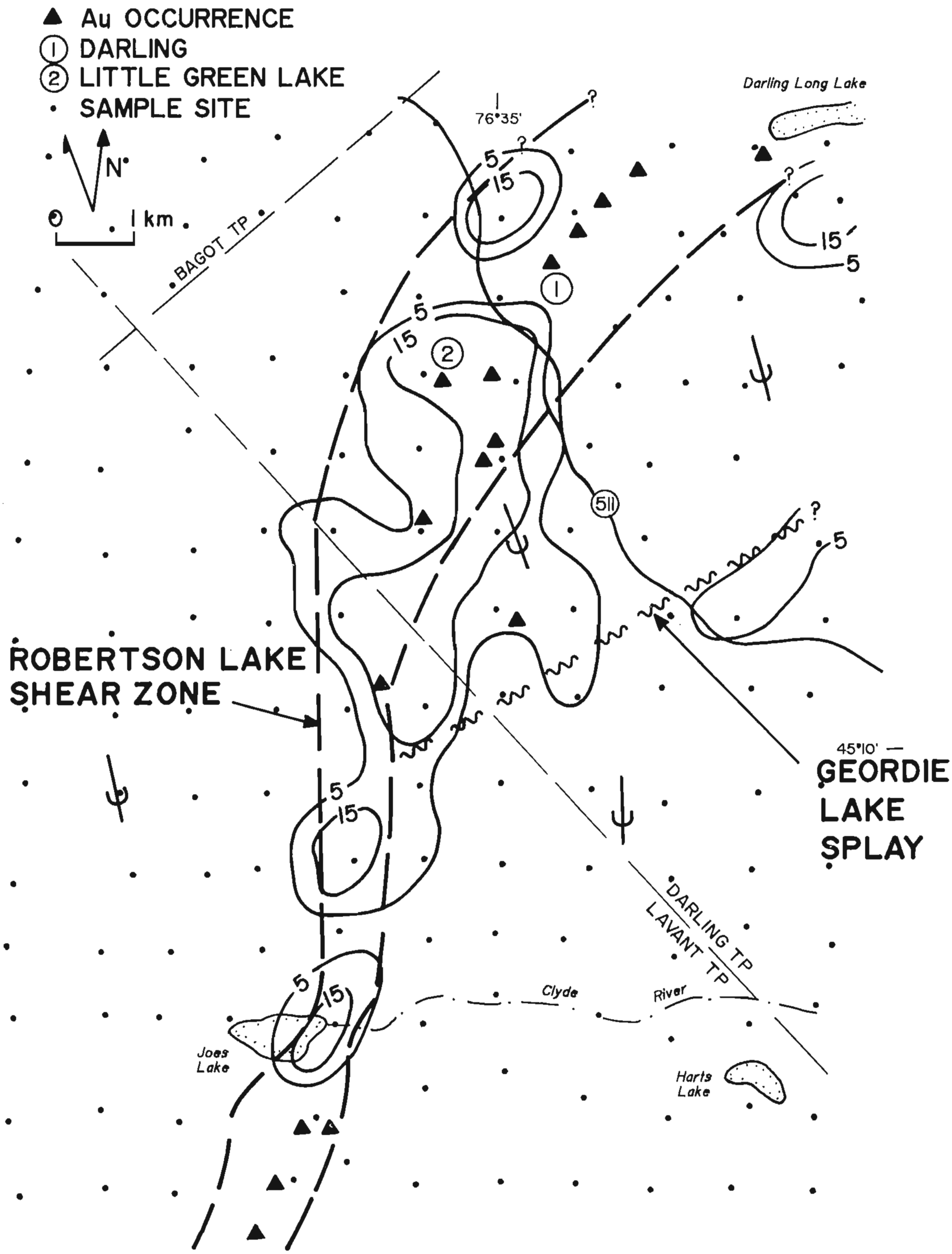


Figure 12. Percent chlorite in heavy mineral concentrates.

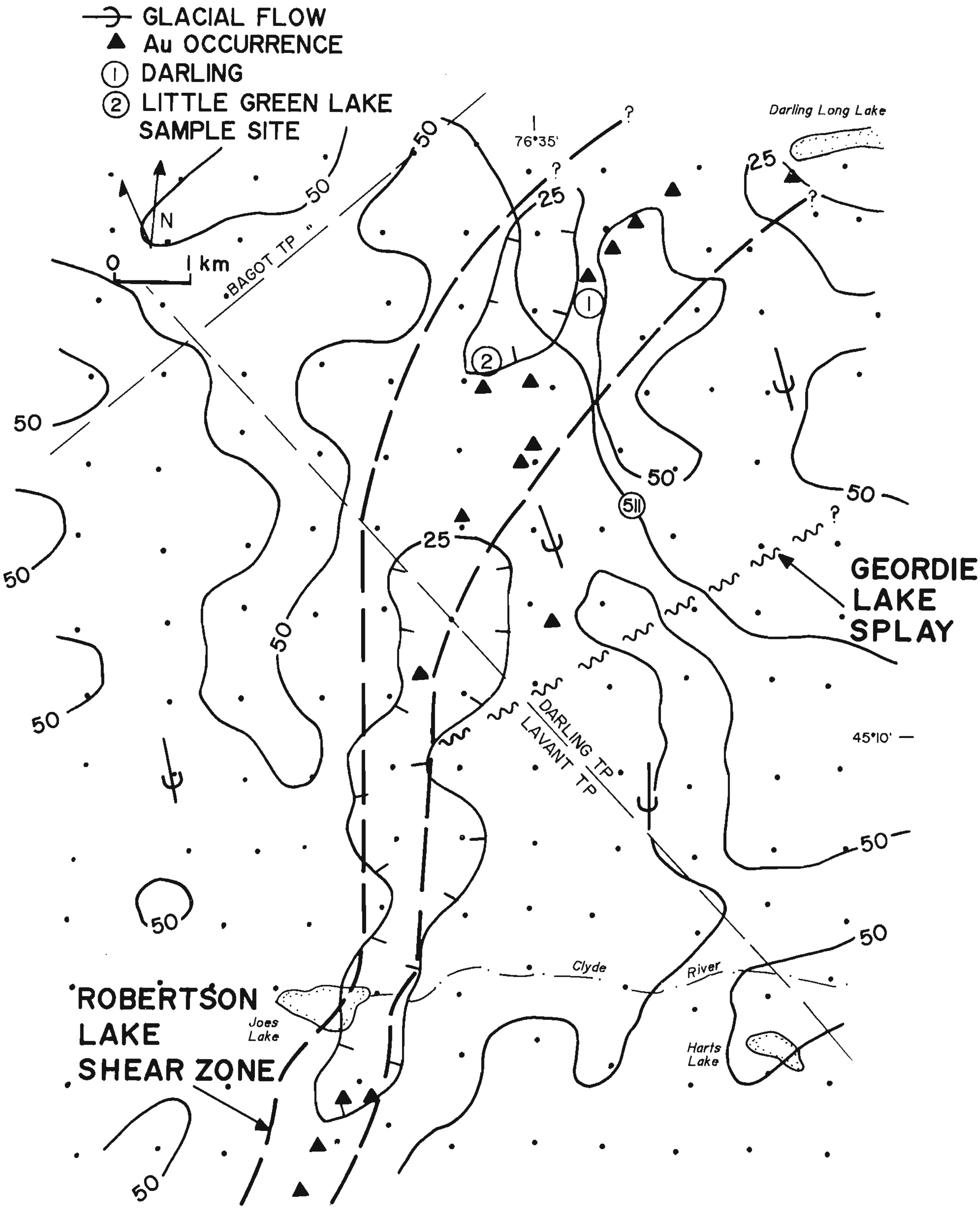


Figure 13. Percent amphibole in heavy mineral concentrates.

Gold in the "B" horizon soils defines gold occurrences in the central and northeast sectors of the area. The anomalies are limited to soils developed on till. Soils developed on other materials (e.g., loess or lacustrine deposits) are not anomalous.

In the till samples, the heavy mineral fraction gives the best anomaly definition (values greater than 50 ppb) and anomaly contrast for gold. The <250 mesh fraction also gives good anomaly contrast, but anomaly limits (10 ppb) are more diffused. This might be an expected feature for glacially dispersed fine grained gold. In some places the dispersal distance for gold in the silt-clay fraction appears considerably longer than for the heavy mineral fraction. For example, near Harts Lake the <250 mesh gold anomaly can be traced some 2 km down-ice, whereas the heavy mineral anomaly shows little down-ice dispersal. Similarly, the southeast edge of the <250 mesh anomaly associated with the RLSZ and Geordie Lake Splay northeast of Joes Lake is smeared about 1 km farther down-ice than the heavy mineral anomaly.

A sample density of one till sample per square kilometre is sufficient to define gold targets. The areas hosting gold mineralization are best defined by the heavy minerals, but sites of gold mineralization at Joes Lake, Darling Long Lake and in the central part of the area are defined by all till fractions. The effectiveness of this type of survey is illustrated by the fact that the majority of the gold occurrences (10 of 16) were found by subsequent exploration programs designed to follow up the regional geochemical results.

The distribution patterns based on pebble counts from till samples indicate limited down-ice movement of material. Most Addington gneiss and Lavant gabbro pebbles have been transported less than 1 km and 2 km respectively from their source areas. Short dispersal distances (1 km) also are indicated by heavy minerals that can be related to mineralization. Depletion of amphibole (due to chloritization) and increases in chlorite, pyrite and magnetic aggregates are common over gold-bearing rock units in the RLSZ. Peak magnetite values are associated with known iron occurrences. The examination of distinctive rock types and/or heavy minerals in tills aids in determining the location and character of mineralization. These procedures are also valid in areas of thicker glacial cover where overburden drilling is required to obtain till samples. In such situations, our experience has indicated similar transport distances for gold, heavy minerals and pebbles.

Detailed Investigations

Detailed sampling (100 m centres) was carried out in the vicinity of two known gold occurrences in Darling Township to test follow-up procedures. The Darling and Little Green Lake gold occurrences and grids are indicated on Figure 3. Both occurrences are quartz-dolomite veinlets hosted by fine grained dolomitic marble near the north contact of mafic mylonite. Fractures in the marble are filled with quartz-carbonate stringers containing blebs and disseminated grains of tetrahedrite, chalcopyrite, pyrite and occasionally native gold. In places, fine-grained sericite fills fractures in the dolomite. Both grids are primarily underlain by a blanket of relatively thin sandy till, although glaciofluvial deposits occur over portions of the grids.

Thirty-six sites were sampled on the Darling grid and 43 sites on the Little Green Lake Grid. Field and laboratory procedures were the same as those used in the regional study.

Statistics

A summary of the geometric means for gold in all sample fractions and media from regional and detailed samples is shown in Table 2. The means for gold are substantially higher for samples from the detailed areas than from the regional survey.

Table 2. Average gold content of surficial materials for regional and detailed areas.

Sample Type	Geometric Means for Gold (ppb)		
	Regional Samples	Darling Grid Samples	Little Green Lake Grid Samples
Humus	4.2	15.3	8.8
"B" soils	1.5	8.2	6.4
Till (<5 mesh)	2.2	13.0	13.0
Till (<250 mesh)	3.4	20.5	22.3
Till (heavy minerals)	5.3	81.7	105.6

Darling grid results

Gold in all sample types and fractions effectively defines the site of known gold mineralization (Figs. 14 and 15). Maximum gold values over the zone for each sample type are as follows: humus — 1795 ppb, "B" soil — 540 ppb, <5 mesh till — 373 ppb, <250 mesh till — 676 ppb, and heavy minerals in till — 5360 ppb. Values drop off very quickly down-ice. In the heavy mineral samples, gold drops to 14 ppb 150 m down-ice from the gold occurrence. All maps show second and third anomalous zones about 360 m and 670 m respectively south of the known gold showing. Gold values over the former are very high: humus — 30 to 516 ppb, "B" soils — 20 to 601 ppb, <5 mesh till — 18 to 1174 ppb, <250 mesh till — 72 to 807 ppb and heavy minerals — 617 to 12,158 ppb. The zone is open along strike to both the east and west. The third anomalous zone occurs at the south limit of the sampled grid. The sources of these last two anomalies have yet to be found.

All gold values in these anomalous zones are very high and in marked contrast to the regional results from this area. The only regionally sampled media that provided positive results near the Darling grid were the heavy minerals (Fig. 9). The Darling grid is located between one regional site to the west, which is in glaciofluvial material, and one to the east, which is over barren gabbro. This might explain the lack of anomalous results for other regional sample media.

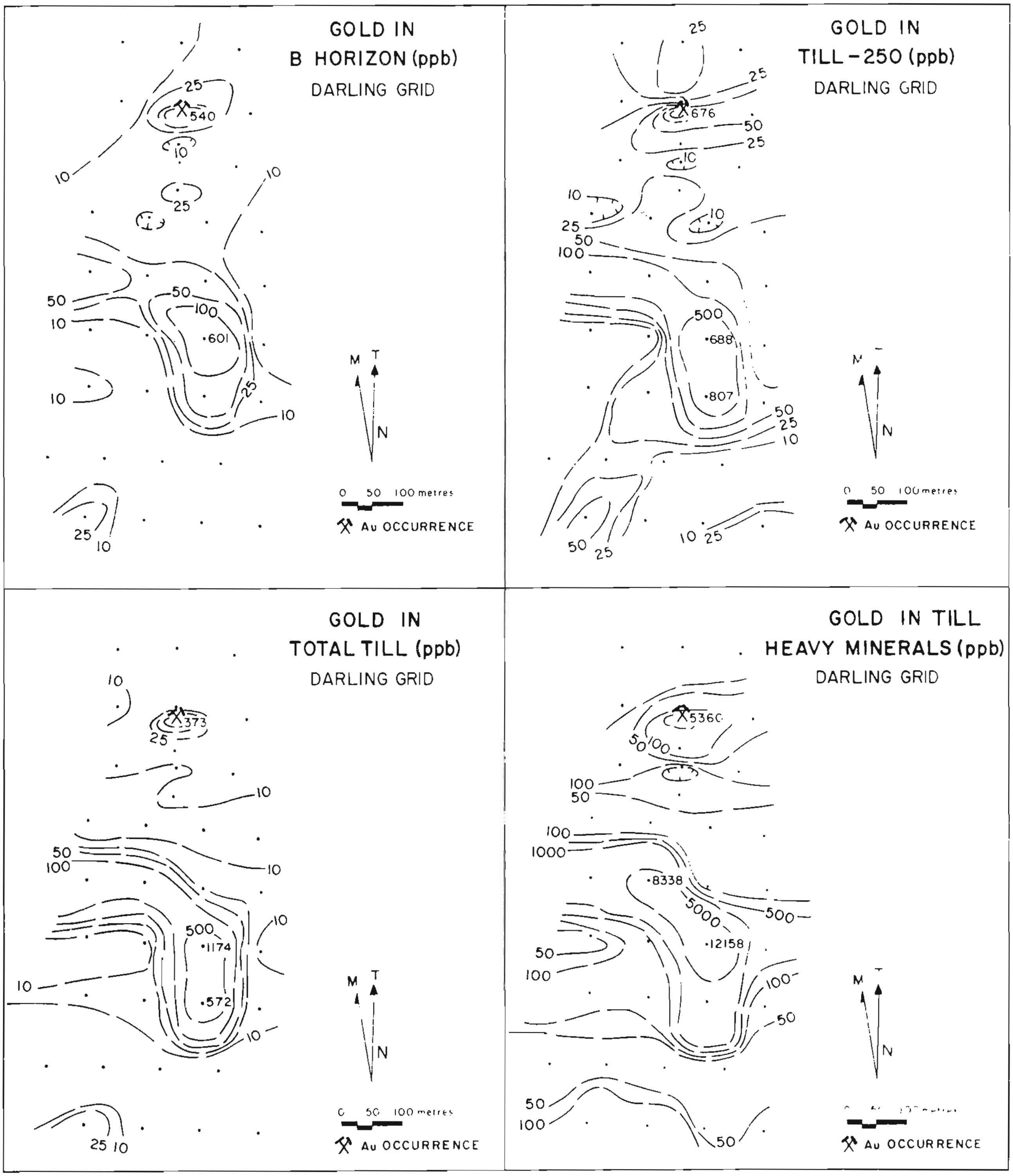


Figure 14. Gold in soil and till over the Darling Grid.

Pebble counts show an abundance of quartz (5-22 %) and carbonate (dolomite) pebbles (14 -60 %) over the two northern most anomalous geochemical gold zones on this grid (Gleeson et al., 1986). Heavy minerals such as sericite, pyrite, hematite and chlorite also are more abundant over these gold anomalies (Gleeson et al., 1986). An angular grain of gold (0.3 × 0.2 × 0.05 mm) was seen in the heavy mineral separate from the central anomaly which contains 12,158 ppb gold. Limited down-ice transport (100 m or less) from the known gold showing is evident for all indicators. Thus the source of gold in the central anomaly is interpreted to be locally derived from the underlying altered mafic mylonite.

Little Green Lake grid results

The Little Green Lake gold occurrence is not marked by large or intense gold anomalies in the surficial materials (Figures 15 and 16); however it does lie on the north flank of gold anomalies in all sample media. This small gold occurrence is not well pinpointed by sampling at 100 m centres. However, Robertson and Gleeson (1981) found values up to 2440 ppb and 225 ppb gold in humus and "B" soils respectively over the trenched showing at a more detailed scale of sampling (30 × 15 m).

Much stronger and more extensive anomalies in all sampled materials trend west-northwest across the north central portion of the grid. The zone is some 100 m wide and 500 m long and it is open to the west and east. Ranges of gold values enclosed by this anomalous zone are as follows: humus — 10 to 518 ppb; "B" soil — 14 to 113 ppb; <5 mesh till — 17 to 174 ppb; <250 mesh till — 35 to 231ppb; and, heavy minerals in till — 52 to 3448 ppb. At the southeast end of the grid the gold anomalies have a northeasterly trend and range as follows: humus — 17 to 35 ppb; "B" soils — 22 to 40 ppb; <5 mesh till — 32 to 63 ppb; <250 mesh till — 38 to 80 ppb; and, heavy minerals in till — 80 to 1071 ppb. In the central-southwest portion of the grid there is a strong northwest-trending humus gold anomaly (75 to 110 ppb) with associated weaker ones in "B" soils (6 to 22 ppb) and <250 mesh till (23 to 31 ppb).

The results would suggest that gold in the Little Green Lake area is controlled by northwesterly and northeasterly structures. This is compatible with the gold trends found in the regional study. The magnitude and extent of the gold anomalies further suggest that gold mineralization is more extensive in the Little Green Lake area than previously realized. The results also indicate that gold mineralization is not only within the dolomite, but is also within altered mafic mylonite.

Most pebble counts (Gleeson et al., 1986) showed no distinctive patterns with respect to the gold anomalies. However, there is an appreciable increase in quartz pebbles (2 to 52 %) over portions of the grid. The quartz is derived from quartz veins and quartz-ferroan dolomite zones in the underlying mafic mylonite. In fact, it was gold in quartz-ferroan dolomite boulders that first attracted the attention of

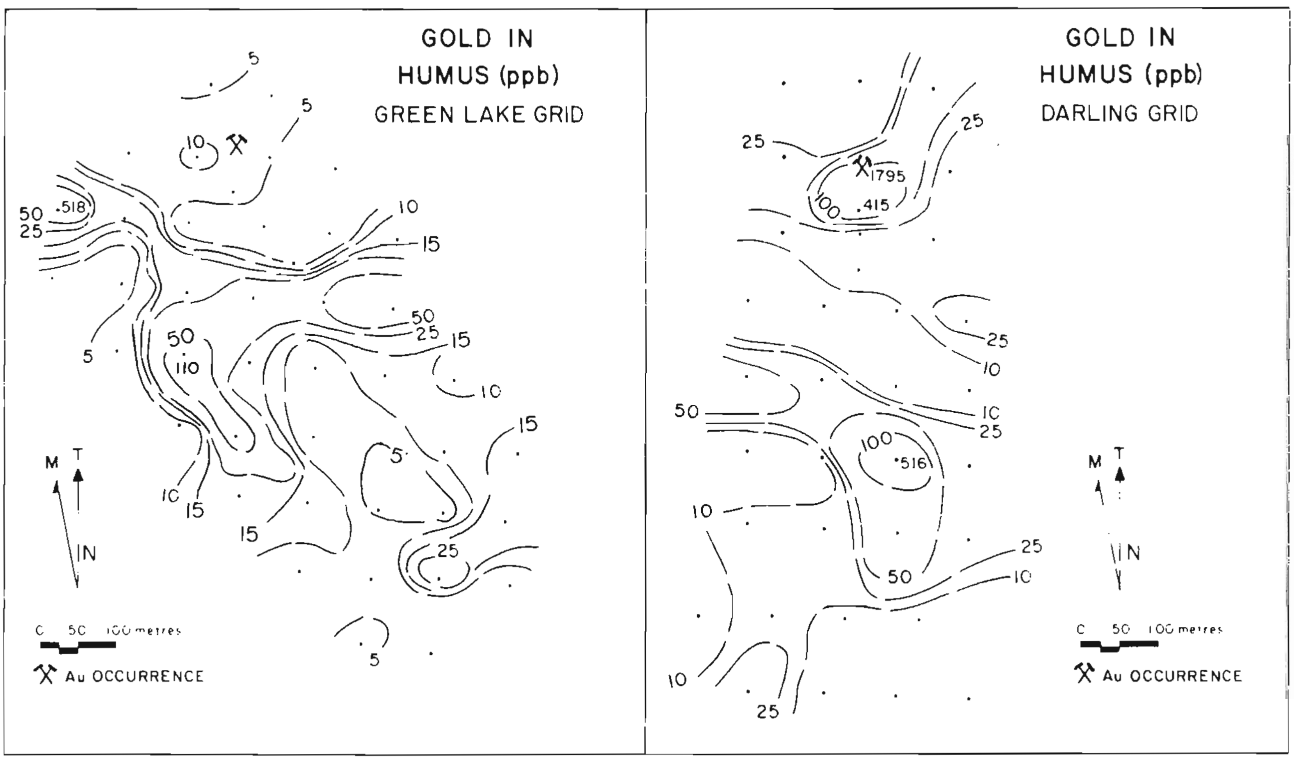


Figure 15. Gold in humus over the Darling and Little Green Lake Grids.

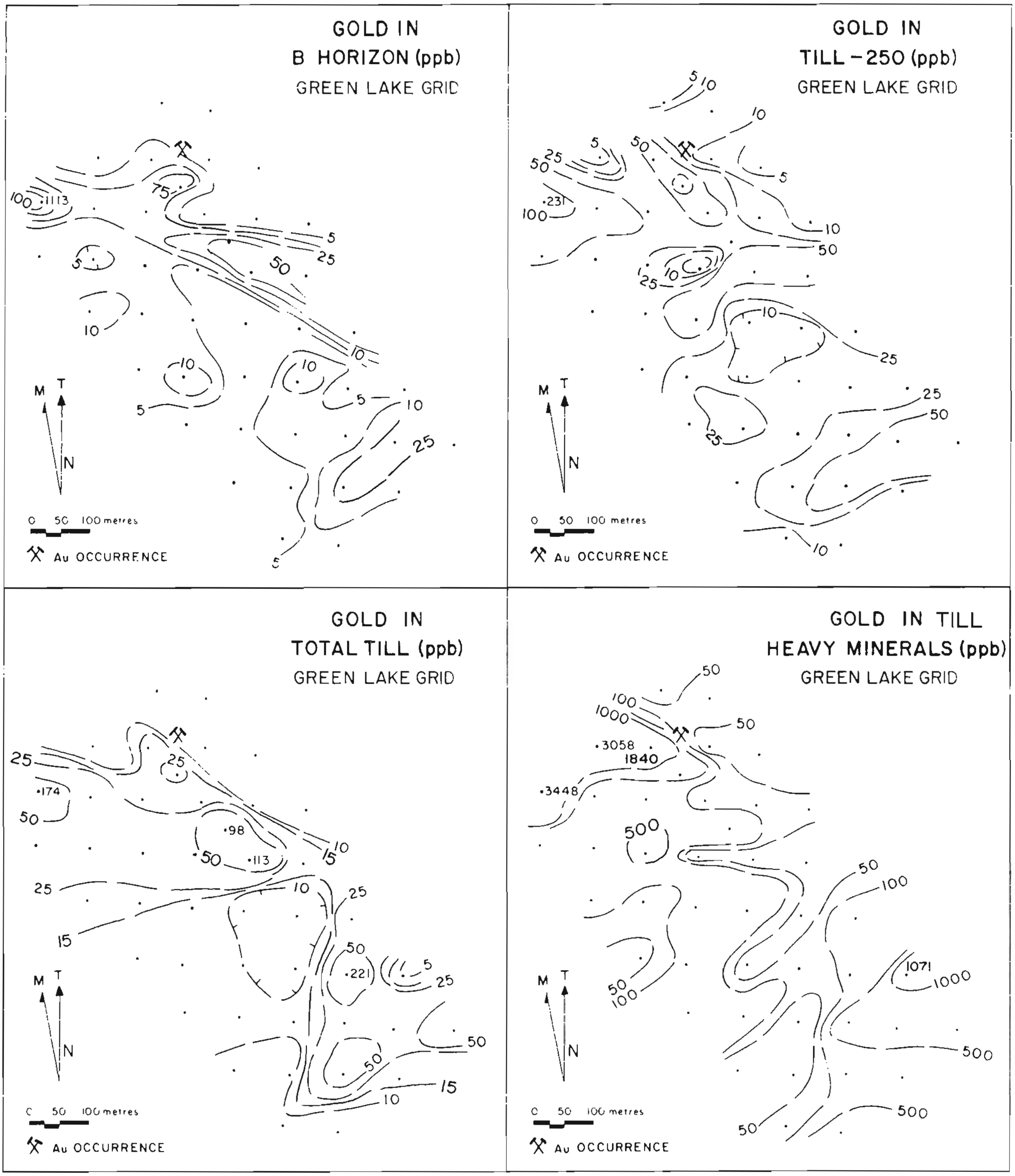


Figure 16. Gold in soil and till over the Little Green Lake Grid.

prospectors to this property in 1962. These boulders are located in the central-southwest part of the grid where they are enclosed by a northwest-trending anomaly of >50 ppb gold in humus (Fig. 15).

Heavy minerals that are more concentrated over the till anomalies include chlorite, sericite, magnetic aggregates, pyrite and limonite-goethite (Gleeson et al., 1986). All these minerals are known to be associated with gold mineralization in the area. In addition, two grains of angular gold (0.3 × 0.2 × 0.01 mm) have been found in a heavy mineral concentrate from about 50 m southwest of the Little Green Lake occurrence and one grain (0.08 × 0.05 × 0.05 mm) has been found within the gold anomaly in the southeast.

Discussion

The detailed geochemical study over and in the vicinity of the Darling gold occurrence shows that at 100 m centres, all sample media and fractions effectively define the known gold mineralization and outline two additional anomalous gold zones to the south. The distribution of pebble lithologies and heavy minerals in till associated with the gold occurrences suggest down ice transport of less than 50 m. The rather rapid down ice decrease in gold values in all till fractions over a distance of 100 to 150 m from the known gold showing and from the central anomalous belt at the Darling grid, confirms that down-ice transport of materials is confined to short distances. Glacial smearing seems most prevalent in the <250 mesh fraction.

The best heavy mineral indicators for gold on the Darling grid are sericite, pyrite, hematite and chlorite. Associated increases in quartz and carbonate pebbles over the geochemical anomalies reflect the style of gold mineralization causing the anomalies (i.e., quartz-carbonate veins in altered mafic mylonite or dolomite).

Geochemical results for gold from the Little Green Lake grid show a low intensity humus (6 ppb) anomaly and higher gold values in the other media 60 m down-ice from the known gold occurrence.

Other results from the Little Green Lake grid demonstrated that relatively intense and extensive gold anomalies occur in all sample media and fractions. These results define two major lineaments; one trending northwest in the north part of the grid and the second trending northeast in the southeast part of the grid. A northwesterly trending gold zone is defined by humus samples in the central-southwest sector of the grid where early prospectors found auriferous quartz-carbonate boulders. The linear character of the anomalies suggest structural controls for the gold mineralization. The anomalies are open both to the west and east of the grid.

Clasts containing quartz and heavy minerals such as pyrite and goethite-limonite (after pyrite) are more concentrated over the gold anomalies. Alteration patterns associated with the gold anomalies can be recognized by the increasing abundances of chlorite and sericite in the heavy mineral fraction of the till. Presence of visible gold in some of the heavy concentrates adds credibility to the gold anomalies in the north and southeast portions of the grid.

From the above geochemical patterns and data on the clasts and heavy minerals it is suggested that the gold mineralization in the detailed areas occurs in northwest- and northeast-trending, silicified, sericitized and pyritized shear or fault zones in mafic mylonite.

Analyses of the detailed grid samples have outlined new areas of probable gold mineralization, which require additional evaluation. These results effectively demonstrate that gold mineralization is more widespread in this area than previously realized, as was shown with the regional gold patterns.

SUMMARY AND CONCLUSIONS

The area covered by this investigation is underlain by supracrustal volcanic, volcaniclastic, calcareous and clastic sedimentary rocks of probably late Precambrian age. The sequence has been intruded by granitic and gabbroic complexes. Bounding the western edge of the gabbro complex is a major fault zone (RLSZ) that trends north and northeast through the area and is underlain mainly by mylonitized gabbroic and carbonate rocks with subordinate volcanic and granitic rocks. Along the RLSZ extensive areas of chloritization, carbonatization, sericitization, silicification and pyritization are present. Most known gold occurrences in the region are found within this structure. They are associated with quartz and quartz-carbonate filled fractures and veins in fine-grained grey dolomite; quartz-ferroan dolomite zones in mafic mylonite; quartz-ferroan dolomite veins in gabbro; quartz veins in trondhjemite sills and dykes intruding mafic mylonite; and massive sulphide zones in altered mafic mylonite. The associated metallic minerals include pyrite, chalcopyrite, tetrahedrite, arsenopyrite, pyrrhotite, bismuthinite and gold.

The surficial cover in the area is extensive but relatively thin. The deposits consist mainly of sandy to stony ablation tills with lesser amounts of glaciofluvial, lacustrine and organic deposits, mainly in the valleys. The dominant direction of ice advance was from the north, but glacial meltwater followed both southerly and southeasterly drainage directions.

The regional surveys were effective in outlining the extent of the gold belt and in establishing promising targets for further exploration. Although all sample types are more or less effective on the regional scale of sampling, some were more effective than others. Gold in the heavy mineral fraction of the till gave the best anomaly definition and contrast. Gold in the <5 and <250 mesh till fractions were relatively effective in providing exploration targets. Caution must be exercised when using the "B" soil horizon for gold geochemistry. The <250 mesh fraction is the most cost-effective of the three till fractions to use in geochemical till sampling for gold. Sampling and analysis of the <250 mesh till fraction at 0.5 km intervals would probably result in anomaly definition equal to or better than that obtained through sampling and analysis of the heavy mineral fraction at 1 km intervals, and could be completed at a lower cost. However, coarse grained gold mineralization could be missed by analyzing for gold only in the fine fraction of the till. Another advantage to using heavy mineral concentrates in regional till studies is that additional useful geological and mineralogical data can be obtained from examination of the heavy mineral separates. For instance in this study, heavy mineral separates indicated that a depletion of amphibole and increase in chlorite, pyrite, sericite and magnetic aggregates are indicators of the presence of mylonitized and altered rocks, which host the gold mineralization. In places tetrahedrite and gold have been identified in the heavy mineral separates. This helps to confirm the heavy mineral gold anomalies and to define the form in which gold may be present in the bedrock. The heavy mineral mineralogy is also useful in studying glacial dispersal patterns and thus assisting in interpretation of geochemical results. For instance, in this research program, dispersal distances in the order of one kilometre were determined by using such indicator minerals as magnetite, from magnetite iron formation, and chlorite, related to the RLSZ. Pebble counts can provide valuable data in determining direction and distance of glacial transport. In this study the indicated maximum glacial transport of significant amounts of Addington gneiss and gabbro pebbles was only 1 to 2 km.

In the detailed surveys, all sample types adequately reflect known gold mineralization. In this area, the use of humus for detailed surveys is relatively inexpensive as well as technically effective.

A better understanding of the geology and mineralization and a more complete evaluation of the geochemical data were obtained by mapping the bedrock geology and Quaternary deposits. For example: (1) multiple possibilities for the origin of certain geochemical anomalies were determined by delineating the extent of glaciofluvial materials and their direction of transport; (2) mapping of shearing and alteration along structures that coincided with linear geochemical anomalies confirmed that gold mineralization was concentrated along these features; and, (3) dispersal patterns were determined from analysis and comparison of the trend of contoured geochemical anomalies, from the distributions of pebbles and heavy minerals, from the location of different bedrock lithologies and from the direction of independently determined glacial flow patterns.

Shallow till sampling programs are not only cost-effective but technically effective. They would appear to be applicable to many areas of the Canadian Shield that are covered with extensive but relatively thin glacial deposits. Experience has shown that the techniques used here can also be effective in areas with thick overburden where samples have to be obtained by drilling. The key is systematic sampling.

REFERENCES

Barnett, P.J. and Clark, W.S.
1980: Quaternary geology of the Renfrew Area, Renfrew County; Ontario Geological Survey, Preliminary Map P. 2365.

Campbell, E.E.
1968: Report on Geology, Tetrahedrite Project, Darling Township, Ontario; Assessment Files, Ontario Geological Survey, Technical File No. 63A-530, 8 p.

Carter, T.R.
1981: Copper-antimony-gold-silver deposits of the Lavant-Darling area, southeastern Ontario: Geology, genesis, and metallogenetic significance; Unpublished MSc Thesis, University Toronto, Toronto, 210 p.

Carter, T.R., Colvine, A.C., and Meyn, H.D.
1980: Geology of base metal, precious metal, iron and molybdenum deposits in the Pembroke-Renfrew area; Ontario Geological Survey, Mineral Deposits Circular 20, 186 p.

Charleton, J., Bell, R., Coe, W., Merritt, W.H., and Blue, A.
1890: Report of the Royal Commission of the Mineral Resources of Ontario, p. 129-142.

Closs, L.G. and Sado, E.V.
1981: Geochemistry of soils and glacial sediments near gold mineralization in the Beardmore-Geralton area, District of Thunder Bay; Ontario Geological Survey, Study 22, 65 p.
1982a: Orientation overburden geochemistry and Quaternary geology investigations of carbonatite-alkalic complexes in the Prairie Lake and Killala Lake areas, District of Thunder Bay; Ontario Geological Survey, Study 23, 65 p.
1982b: Bedrock and overburden geochemistry investigations in the Midlothian Lake and Natal Lake areas, Districts of Sudbury and Timiskaming; Ontario Geological Survey, Study 24, 65 p.

Curtin, G.C., Lakin, H.W., Neuerbure, G.J., and Hubert, A.E.
1968: Utilization of humus-rich forest soil (mull); in Geochemical Exploration for Gold; United States Geological Survey, Circular 562, 11 p.

Curtin, G.C., Lakin, H.W., and Hubert, A.E.
1970: Mobility of gold in mull (forest humus layer); United States Geological Survey, Professional Paper 700C, p. 127-129.

Curtin, G.C., Lakin, H.W., Hubert, A.E., Mosier, E.L., and Watts, K.C.
1971: Utilization of mull (forest humus layer); in Geochemical Exploration in the Empire District, Clear Creek County, Colorado; United States Geological Survey, Bulletin 1278, 39 p.

DiLabio, R.N.W.
1981: Glacial dispersal of rocks and minerals at the south end of Lac Mistassini, Quebec, with special reference to the Icon Dispersal Train; Geological Survey of Canada, Bulletin 323, 46 p.
1982: Drift prospecting near gold occurrences at Onaman River and Oldham, Nova Scotia; in Geology of Canadian Gold Deposits, eds. R.W. Hodder and William Petruk; Canadian Institute of Mining and Metallurgy, Special Volume 24, p. 261-266.

Easton, R.M.
1987a: Geology of the Darling area, Lanark and Renfrew counties; Ontario Geological Survey, OFM94.
1987b: Geological compilation of the Clyde Forks area (NTS 31F/2); Ontario Geological Survey, OFM96.

Easton, R.M. and DeKemp, E.A.
1987: Darling area, Lanark and Renfrew counties; Ontario Geological Survey, Miscellaneous Paper 137, p. 220-228.

Ells, R.W.
1904: Report on the geology of a portion of Eastern Ontario; Geological Survey of Canada, Annual Report vxiv (new series) 1901, Pt. J, p.J1-J89.

Ermengen, S.V.
1957: Geochemical prospecting in Chibougamau; Canadian Mining Journal, v. 78, p. 99-104.

Fransham, P.B. and Gadd, N.R.
1977: Geological and geomorphological controls of landslides in Ottawa Valley, Ontario; Canadian Journal of Earth Sciences, v. 14, p. 531-539.

Frechette, H.
1910: On a number of iron ore properties in northeastern Ontario; Summary Report, Mines Branch, Department Mines (Canada), for 1909, Sessional Paper 26a, p. 82-85.

Gadd, N.R.
1980: Late-glacial regional ice-flow patterns in eastern Ontario; Canadian Journal of Earth Sciences, v. 11, p. 1439-1453.

Gleeson, C.F.
1975: Geological report on Pharaoh claims, Lavant Township, Ontario; Private report submitted to H. Pharaoh, 7 p.

Gleeson, C.F. and Boyle, R.W.
1979: Consider geochemistry when seeking gold; Northern Miner, March 8, 1979, p. C1 and C16.
Gleeson, C.F., Thomas, R.D., Paradis, S., and Rampton, V.N.
1984: Development and adaption of geochemical techniques to gold exploration in glacial drift; Ontario Department Natural Resources, Ontario Geological Survey, Miscellaneous Paper 120, p. 129-150.
1986: Exploration Technology Development Fund, Grant No. 065, Development and adaption of geochemical techniques to gold exploration in glacial drift (3 volumes); Ontario Geological Survey, Open File Report 5613, 123 p.
Gleeson, C.F., Thomas, R.D., Rampton, V.N., and Cordon, S.
1985: Summary of 1984 Exploration program: Gleeson-Rampton-Lac-Clyde project; Ontario Geological Survey, Assessment Files, 84 p.
Gordon, J.B., Lovell, H.L., deGrijs, J., and Davie, R.F.
1979: Gold deposits of Ontario, Part 2. Ontario Geological Survey, Mineral Deposits Circular 18, p. 45-46.
Gorrell, G.A., VanHooften, S., and Fletcher, T.W.
1985: Aggregate assessment for the County of Lanark, NTS 31B/NW, 31C/NE, 31F/SE and 31G/SW, Ontario; Ontario Geological Survey, Open File Report 5550, 27 p.
Hammerstrom, W.
1968: Diamond drilling by Siscoe Metals of Ontario Limited, Darling Township, Ontario; Ontario Geological Survey Assessment Files, Report No. 11, 13 p.
Ingall, E.D.
1901: Report on the iron ore deposits along the Kingston and Pembroke Railway, in Eastern Ontario; Geological Survey of Canada, Annual Report XII (new series), 1899 Pt. I, 91 p.
Jackson, V.A.
1980: Geologic setting of mylonitic rocks in the White Mountain area, Grenville Province, southeastern Ontario; BSc Thesis, Carleton University, Ottawa, 58 p.
Kettles, I.M. and Shilts, W.W.
1983: Reconnaissance geochemical data for till and other surficial sediments, Frontenac Arch and surrounding areas, Ontario; Geological Survey of Canada, Open File Report 947, 12 p.
Lakin, H.W., Curtin, G.C., and Hubert, A.E.
1974: Geochemistry of gold in the weathering cycle; United States Geological Survey, Bulletin 1330, 80 p.
Lee, H.A.
1963: Glacial fans in till from the Kirkland Lake fault — a method of gold exploration; Geological Survey of Canada, Paper 63-45, 36 p.
Lumbers, S.B.
1982: Summary of metallogeny-Renfrew County area; Ontario Geological Survey, Report 212, 58 p.
McConnell, J.W., and Batterson, M.J.
1987: The Strange Lake Zr-Y-Nb-Be-REE deposit, Labrador: A geochemical profile in till, lake and stream sediment, and water; Journal of Geochemical Exploration, v. 29, p. 105-127.
Northern Miner
1962: New Gold discovery made near Calabogie; Northern Miner, June 7, 1962, p. 9.
Pauk, L.
1983: Precambrian geology of the Lavant area, Frontenac and Lanark, Counties; Ontario Geological Survey, Map P. 2610.
1984: Geology of the Lavant area, Lanark and Frontenac Counties; Ontario Geological Survey, Open File Report 5519, 129p.
Peach P.A.
1948: Preliminary report of the geology of Darling Township and part of Lavant Township, Lanark County; Ontario Department Mines, Preliminary Report 1948-12, 4 p.
1958: The geology of Darling Township and part of Lavant Township; Ontario Department Mines, Annual Report, v. 65, pt. 7, p. 47-60.
Rampton, V.N., Gleeson, C.F., Thomas, R.D., and Paradis, S.
1986: Geochemical exploration in areas of shallow till: some case histories; Canadian Institute of Mining and Metallurgy, Bulletin v. 79, p. 67-74.
Rankin, J.
1962: Diamond drilling submitted by Siscoe Metals of Ontario Ltd., Darling Township, Ontario; Ontario Geological Survey, Assessment Files, Report No. 11, 20 p.
Robertson, D.M. and Gleeson, C.F.
1981: Geochemical orientation survey — Green Lake Gold Property, Darling Township, Lanark, Ontario; Assessment report submitted on behalf of Dungarvon Resources Ltd, 29 p.
Sangster, A.L.
1970: Metallogeny of base metal, gold and iron deposits of the Grenville Province of southeastern Ontario; Unpublished PhD Thesis, Queen's University, Kingston, 356 p.
Sinclair, I.G.L.
1978: Diamond drilling by Selco Mining Corporation Ltd.; Assessment Files (Diamond Drill File 13), Ontario Geological Survey, 7 p.
1979: Geochemical investigation of the Clyde River zinc property, Lanark County, Ontario; in Geochemical Exploration 1978, eds. J.R. Watterson and P.K. Theobald; Association of Exploration Geochemists, Toronto, p. 487-495.
Shilts, W.W.
1976: Glacial till and mineral exploration; in Glacial Till, an Interdisciplinary Study, ed. R.F. Legget; Royal Society of Canada, Special Publication no. 12, p. 205-224.
Smith, B.L.
1958: Geology of the Clarendon-Dalhousie area; Ontario Department Mines, Annual Report, v. 65 pt. 7, p. 1-46.
Snow, R.S. and Coker, W.B.
1987: Overburden geochemistry related to W-Cu-Mo mineralization at Sisson Brook, New Brunswick, Canada: An example of short-and long-distance glacial dispersal; Journal of Geochemical Exploration, v. 28, p. 353-368.
Szabo, N.K., Govett, G.J.S., and Lajtai, E.Z.
1975: Dispersion trends of elements and indicator pebbles in glacial till around Mt. Pleasant, New Brunswick: Canadian Journal of Earth Sciences, v. 12, p. 1534-1556.
Taylor, HF.
1957: Diamond drilling report; Ontario Department Mines, Geological Branch, Assessment File 61523, 9 p.
Thomas, R.D., Gleeson, C.F., Rampton, V.N., and Ruitenberg, A.A.
1983: Heavy mineral and soil geochemical survey of Eastern St. George Batholith; Department of Natural Resources, New Brunswick, Map Plates MP 83-16 to 83-28 inclusive.
1987: Geochemistry and geology of surficial materials overlying part of Eastern St. George Batholith, New Brunswick; Department of Natural Resources, New Brunswick, Report of Investigation 19, 26 p.
Vennor, H.G.
1876: Progress report of explorations and surveys in the rear portions of Frontenac and Lanark Counties; Geological Survey Canada, Report of Progress 1874-75, p. 105-165.
Wynne-Edwards, H.R.
1972: The Grenville Province; in Variations in Tectonic Styles in Canada, eds. R.A. Price and J.A. Douglas; Geological Association of Canada, Special Paper No. 11, p. 264-333.

Geochemistry of drift over the Precambrian Grenville Province, southeastern Ontario and southwestern Quebec

I.M. Kettles[1] and W.W. Shilts[1]

Kettles, I.M., and Shilts, W.W., Geochemistry of drift over the Precambrian Grenville Province, southeastern Ontario and southwestern Quebec; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 97-112, 1989.

Abstract

Approximately 2500 samples of till and related sediments have been collected over the Frontenac Arch and adjacent areas of southeastern Ontario and southwestern Quebec. Although the primary objective of the sampling was to map components in the overburden that might be related to sensitivity of the terrain to the effects of acid rain, the data can be applied also to mineral exploration in the area.

The <2µm fraction of the samples was analyzed for 14 trace and minor elements. Dispersal of these and other mineralogical components can be related to effects of glacial transport, composition of underlying bedrock, sediment facies sampled, or degree of weathering. Arsenic, for example, is enriched in an area where mining of arsenical gold was carried out in southeastern Ontario. The area of arsenic enrichment is larger than that underlain by arsenic-bearing bedrock as a result of glacial dispersal of arsenic-rich detritus. Concentrations of copper and chromium, for example, are consistently and uniformly low and high, respectively, in glaciomarine silty clay along the Ottawa and Gatineau valleys, compared to concentrations in the till cover in adjacent highland areas of southwestern Quebec. The mean concentrations in glaciofluvial and highly weathered till samples are markedly higher than those in unweathered to slightly weathered till. This likely reflects the presence of weathering products with high exchange capacities in the clay-sized fraction of these samples.

Carbonate analyses of till demonstrate that the physical nature of source outcrops significantly influences glacial erosion processes. Carbonate minerals derived from horizontal beds of unmetamorphosed Paleozoic limestone northeast of the Frontenac Arch, have been transported southwestward onto the Canadian Shield, effectively diluting the compositional signature of underlying bedrock for over 70 km down-ice from their source areas. In contrast, massive marble outcrops produced very small and weak dispersal trains.

Résumé

Environ 2500 échantillons de till et de sédiments connexes ont été prélevés dans l'arche de Frontenac et les zones adjacentes du sud-est de l'Ontario et du sud-ouest du Québec. Même si l'objectif premier de l'échantillonnage était de cartographier des éléments des morts-terrains qui pourraient être liés à la sensibilité du terrain aux effets des précipitations acides, les données peuvent aussi servir aux travaux d'exploration des minéraux dans la région.

Quatorze éléments accessoires et en traces ontété dosés dans la fraction <2µm des échantillons. Leur dispersion et celle d'autres éléments minéralogiques peuvent être associées aux effets du transport glaciaire, à la composition du socle sous-jacent, aux faciès sédimentaires échantillonnés ou au degré d'altération. Par exemple, l'arsenic est enrichi dans une zone du sud-est de l'Ontario où de l'or arsénical a été exploité. La zone d'enrichissement de l'arsenic est plus étendue que celle qui repose sur un socle arsénifère suite à la dispersion par les glaciers de détritus riches en arsenic. Par exemple, les concentrations de cuivre et de chrome sont systématiquement et uniformément faibles et élevées, respectivement,

[1] Geological Survey of Canada 601 Booth Street, Ottawa, Ontario, Canada

dans l'argile limoneuse d'origine glaciomarine, dans les vallées de l'Outaouais et de la Gatineau par rapport aux concentrations dans la couverture de till dans les hautes terres adjacentes du sud-ouest du Québec. Les concentrations moyennes dans les échantillons de till glaciofluvial et très altéré sont nettement plus élevées que celles du till légèrement ou aucunement altéré. Ce phénomène indique vraisemblablement la présence de produits d'altération à capacités d'échange élevées dans la fraction granulométrique argileuse de ceséchantillons.

Le dosage du contenu en carbonates des tills révèle que la nature physique des affleurements mères influe considérablement sur les processus d'érosion glaciaire. Les minéraux carbonatés provenant de couches horizontales de calcaire paléozoique non métamorphisé dans le nord-est de l'arche de Frontenac ont été transportés par les glaces vers le sud-ouest sur le Bouclier canadien, diluant la signature, en termes de composition, du socle sous-jacent sur plus de 70 km en amont de leurs sources. Par contre, des affleurements de marbre massif ont produit des trainées de dispersion très petites et très fragiles.

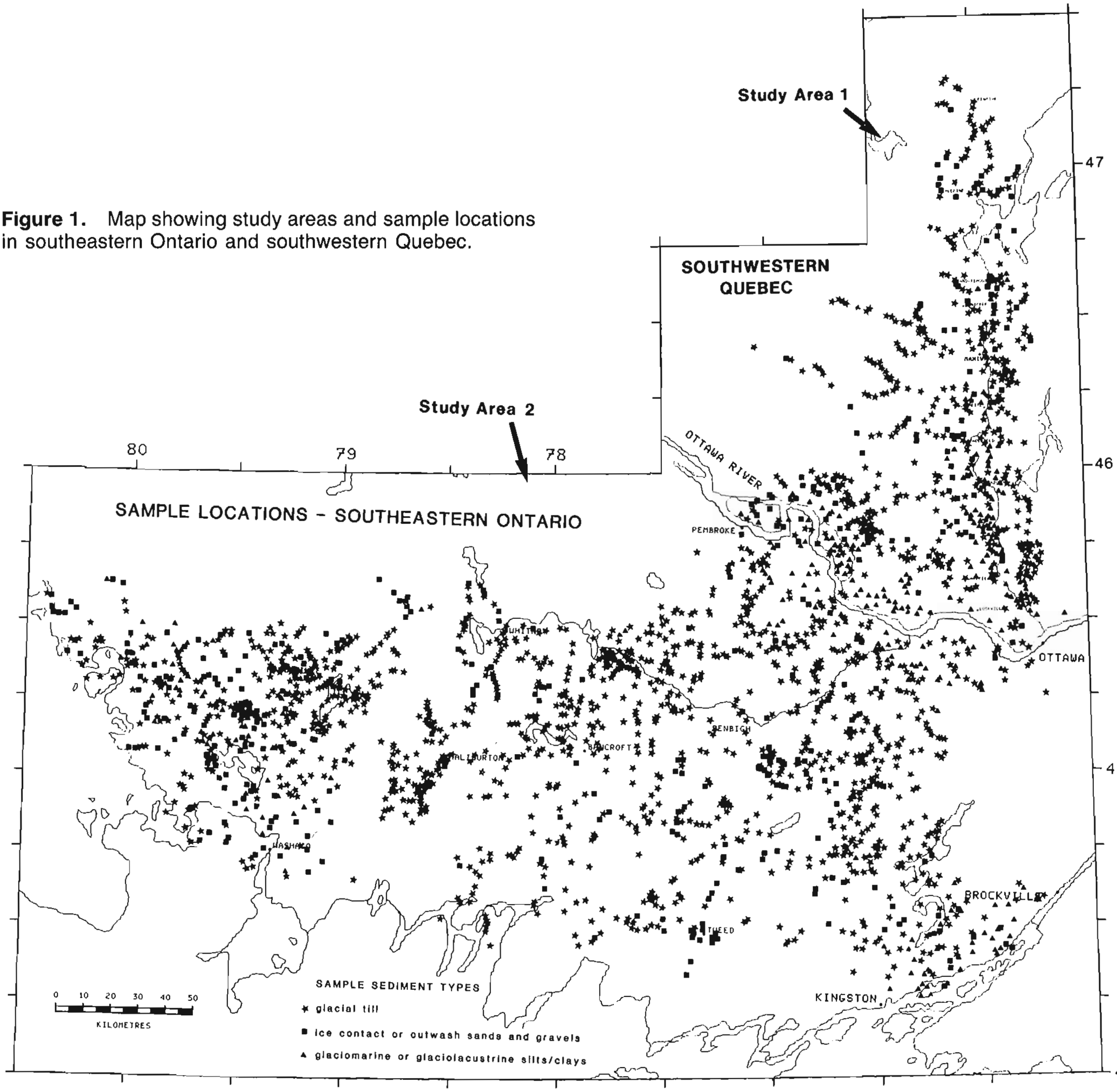


Figure 1. Map showing study areas and sample locations in southeastern Ontario and southwestern Quebec.

INTRODUCTION

In 1980, a sampling programme was initiated in the Frontenac Arch and surrounding areas in southeastern Ontario and in southwestern Quebec (Shilts, 1984a, Hornbrook et al., 1986). The main objective of the project was to quantify regional variation in drift composition in order to provide baseline data for use in assessing the sensitivity of the terrain to the effects of acid rain. For this purpose, two groups of compositional characteristics in till and derived sediments were determined: (1) texture and carbonate composition (the buffering components) and (2) concentrations of naturally occuring trace and minor elements (potential sources of environmental contamination if released by acid leaching or by exchange reactions with groundwaters). Geochemical and other information obtained from this project can also be used for mineral exploration using drift prospecting techniques.

Geochemical mapping was based on systematic sampling of glacial sediments (Fig. 1). Because the project was designed for environmental purposes, sampling strategies were different than they would have been, had the project been designed for drift prospecting purposes alone. The rationale behind the sampling plan was to collect, wherever possible, the surficial sediments most representative of the debris load carried by the last glacier to pass over the sample site, and, where true glacial sediments are covered by a mantle of late or postglacial sediments, to sample those sediments which have the greatest influence on the near-surface environment.

Because of this strategy, the database (over 2500 samples) generated during this study (Kettles and Shilts, 1983) is composed of information for disparate sample populations. Till, which has been transported only by ice, is considered most representative of the glacial load (Shilts, 1975). In upland areas, it was generally readily available for sampling, but where absent or inaccessible, glaciofluvial or outwash sands and gravels were collected. Glaciolacustrine and glaciomarine clayey silts were sampled at low altitudes, where they formed the predominant surface cover along major river valleys in the study area. Because each of the latter four types of sediment have undergone one or more cycles of fluvial transport before being deposited at the sample site, their physical and chemical characteristics are less representative of the glacial load than those of till.

In this paper, regional distribution patterns of carbonate minerals and selected trace elements in drift are examined. Possible causes of geochemical variation and their importance to drift prospecting are discussed. For ease of discussion, the two regions, one in southeastern Ontario and the other in southwestern Quebec, are treated separately although they are contiguous.

GEOLOGIC SETTING

Relatively flat-lying Paleozoic sedimentary rocks, dominated by carbonate lithologies, form flaggy outcrops in the Ottawa Valley and in the West St. Lawrence Lowland (Bostock, 1970) (Fig. 2 and 3). The remaining parts of both areas are underlain by Precambrian metasedimentary and igneous rocks (Baer et al., 1977), referred to collectively as "crystalline" bedrock, which are characterized by massive outcrops and sharp but low relief. Most Precambrian rocks are part of the Central Metasedimentary Belt of the Grenville Structural Province. The belt is dominated by extensive areas of carbonate-bearing metasedimentary rocks, felsic and mafic plutons, and metavolcanic and noncalcareous metasedimentary rocks. The Central Metasedimentary Belt includes the Frontenac Arch, a prominent geological structure that connects the main body of the Canadian Shield in the north to the Adirondack Mountains south of St. Lawrence River. The remainder of the crystalline terrain comprises medium to high grade metamorphic gneisses of the Ontario Gneiss Belt.

The dominant ice flow direction during the late Wisconsinan was southerly down the Gatineau valley in Quebec and south-southwest over southeastern Ontario. During the last stages of glaciation, one lobe of ice flowed southwestward, retreating from Lake Ontario towards the St. Lawrence Valley and another flowed south-southeastward and retreated up the Ottawa Valley (Richard, 1975; Gadd, 1980).

Stratigraphically, only one unit of till, which is associated with the last (Late Wisconsinan) glacial expansion of the Laurentide Ice Sheet, has been identified in the areas sampled (Gadd, 1980; Richard, 1975). This till was referred to as Fort Covington till in the Merrickville map area, (Sharpe, 1979) at the eastern edge of the area covered by this work. Till is the most widespread deposit, forming a thin cover (0 to 5 m thick) over both Precambrian and Paleozoic bedrock of the region but it can be thicker in depressions, along valley walls, and on the up-ice side of bedrock ridges.

Along the Ottawa, Gatineau, and St. Lawrence valleys and in low-lying areas near Georgian Bay, glaciomarine and glaciolacustrine sediments predominate. The Ottawa, lower St. Lawrence, and lower Gatineau valleys were inundated by the Champlain Sea and the upper part of the Gatineau valley by a late glacial lake; the limits and history of which are at present poorly understood (Dadswell, 1974). Low-lying areas in the southern and western parts of the Ontario study area were flooded by glacial Lakes Iroquois and Algonquin, respectively.

Field and Laboratory Methods

Samples were hand-dug from natural or man-made exposures along roads and streams as well as from sand and gravel pits. Sample locations and types are shown in Figure 1. Care was taken to collect materials from below the solum, except in the best exposures of till and other sediments, where samples were collected in profile over the entire sequence.

In this study, emphasis was put on studying the fine (silt plus clay ($<63\mu m$) and clay-sized ($<2\ \mu m$)) fractions of the sample matrix. Results of experiments undertaken to study chemical partitioning in till (Shilts, 1984b), indicate that there is a disproportionate amount of metal in clay-sized compared to the coarser parts of the till matrix. Because of the greater internal surface area than in coarser fractions, the fine component probably reacts preferentially with solutions passing through the drift; even small amounts of clay-sized detritus can have a major effect on the chemistry of ground or surface waters.

The clay-sized ($<2\mu m$) fraction of till, silty clay and some sand and gravel samples was separated by centrifugation and analyzed for selected trace and minor elements — copper, lead, zinc, cobalt, nickel, silver, chromium, molybdenum, manganese, iron, cadmium, mercury, uranium, and arsenic, after treatment with a hot nitric-hydrochloric acid leach. All elements were analyzed using atomic absorption techniques, except for uranium and arsenic, which were analyzed using fluorimetric and colorimetric methods, respectively.

The carbonate content of the silt plus clay-sized (<63 μm) and fine sand (63 to 250 μm), fractions was determined, after a method devised by Foscolos and Barefoot (1970), using a Leco carbon analyzer to measure carbon concentrations which were converted to percent calcium carbonate equivalent. Paleozoic limestone and dolomite erratics were separated from the granule-small pebble fraction (2 to 6 mm) and their weight percent of the total fraction was calculated. Grain size analyses were performed by standard methods.

Results of analyses along with sample locations and descriptions were stored on computer files. Geochemical data for a representative sample from each site were plotted and contoured using a computer package (APPMAP) developed by D.J. Ellwood of the Geological Survey of Canada.

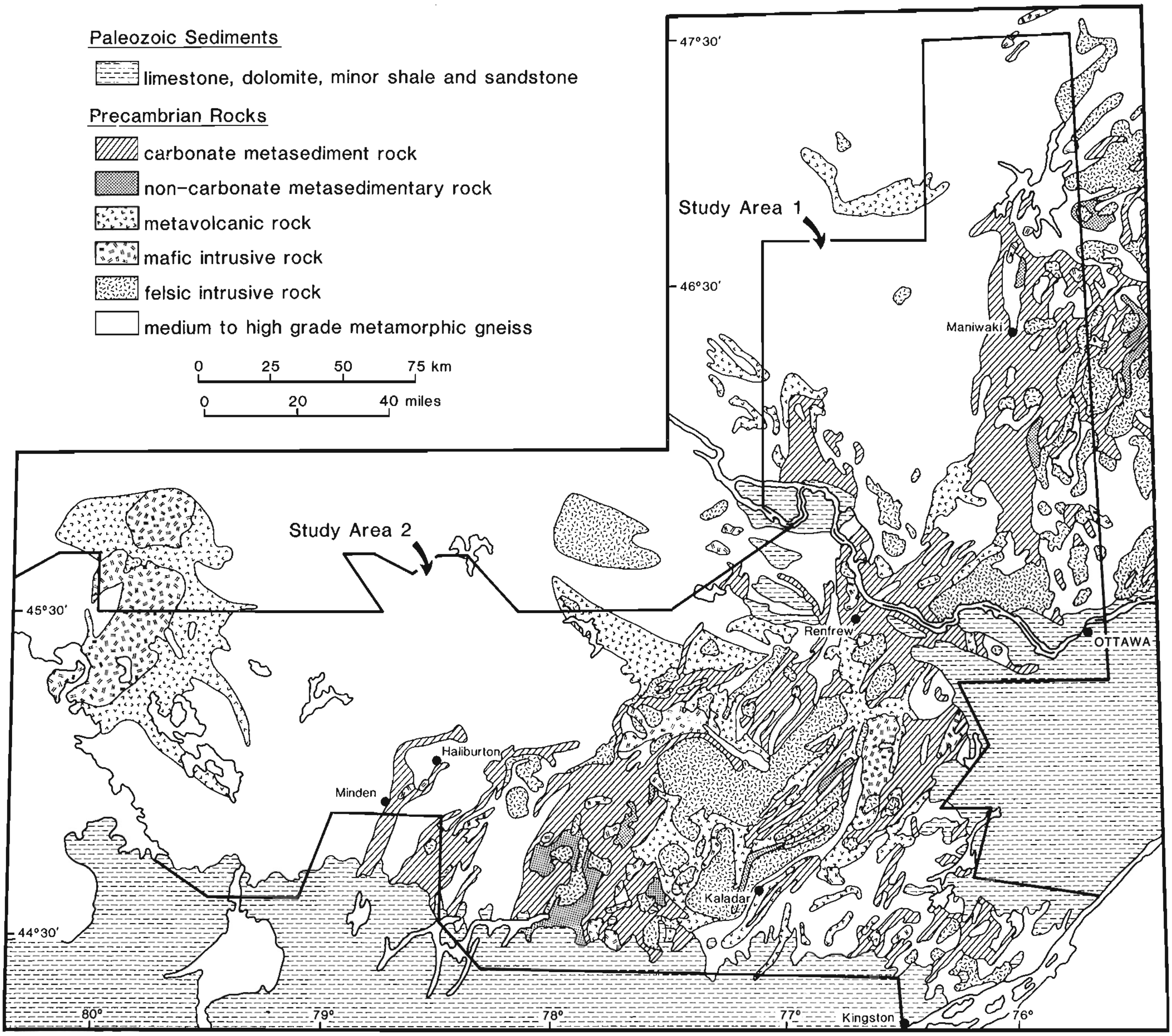


Figure 2. Map showing bedrock geology, southeastern Ontario and southwestern Quebec, modified after Baer et al. (1977).

DRIFT COMPOSITION

Data generated during this study confirm that drift composition is controlled by: (1) glacial transport processes; (2) composition of the underlying and up-ice bedrock; (3) sediment facies sampled; and, (4) degree of weathering. For individual samples, one or more of these factors affects composition; a fact well illustrated by some of the results of this study.

The distribution of carbonate minerals and changes in textural composition in drift in southeastern Ontario constrain interpretations of the processes of glacial erosion and transport. As would be expected, carbonate contents of silt plus clay (Fig. 4) and fine sand fractions (not shown) of drift are high (>10%) in areas underlain by Paleozoic rocks east and south of the Frontenac Arch. However, high concentrations also are found over all types of crystalline rocks in the eastern and southern parts of the Frontenac Arch itself. In contrast, concentrations of carbonate are low over the western part of the region, from Barry's Bay and Kaladar west to Georgian Bay, even where drift overlies marble. Weight percent Paleozoic limestone and dolomite erratics in the total granule fraction (not shown) produce regional patterns that have similar configurations.

The high frequency of Paleozoic erratics in carbonate-rich till overlying crystalline rocks and the widespread occurence of relatively carbonate-poor drift overlying marble suggest that carbonate components were more readily eroded from the flaggy, flat-lying unmetamorphosed rocks of Paleozoic basins than from the massive, little fractured Precambrian marble. This is reflected by dispersal of high

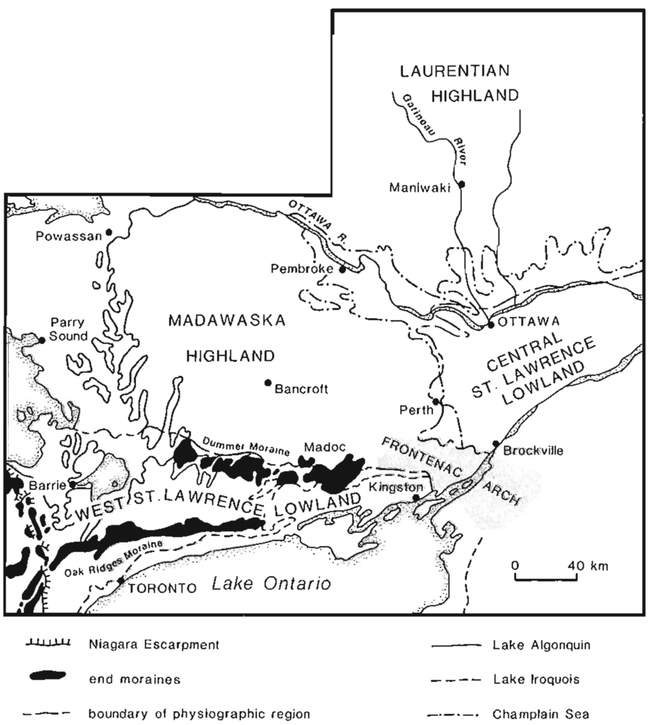


Figure 3. Map showing physiographic regions, southeastern Ontario and southwestern Quebec (modified after Freeman, 1979).

concentrations of erratics and finer carbonate debris derived from Paleozoic rocks more than 70 km southwestwards over the crystalline rock of the eastern Frontenac Arch. In contrast, in areas where crystalline material was carried from the Shield onto Paleozoic rocks, it was quickly diluted by glacial erosion of large quantities of Paleozoic debris. Carbonate concentrations in till increase dramatically directly on and down-ice from numerous Paleozoic outliers that occur near the southern edge of the Frontenac Arch. On and down-ice from marble outcrops of similar size, however, there is little enrichment of carbonate in the drift. The reason for the contrasting effects of these two mineralogically similar lithologies probably lies in the relative resistance to glacial erosion of the massive marble outcrops compared to the jointed, flaggy nature of the limestone outcrops.

Carbonate-poor till in southeastern Ontario generally has a smaller component of silt and clay-sized material than carbonate-rich till (Fig. 5). There appears to be little difference in texture between carbonate-rich till overling Paleozoic sedimentary rocks and carbonate-rich till overlying Precambrian crystalline rocks of the eastern Frontenac Arch.

Dispersal patterns of many trace elements reflect composition of the underlying bedrock. For example, the large areas of arsenic enrichment in southeastern Ontario (Fig. 6) broadly outline prominent belts of metavolcanic and metasedimentary rock. Two known sources of arsenic (Sangster, 1982) in these rocks are quartz vein-hosted sulphide deposits in metavolcanic and clastic metasedimentary rocks and arsenic-enriched pyrite in sulphide iron formation in clastic metasedimentary and carbonate rocks. These deposits are small, however, and the occurence of elevated arsenic concentrations over such a large area may indicate that there are high background concentrations of arsenic in the belts of metasedimentary and metavolcanic rocks themselves. Two detailed studies in the eastern Frontenac Arch area (Sinclair, 1979; DiLabio et al., 1982) indicate that dispersal from small sulphide occurrences in the marble is on the order of 1 km. In any case, enlargement of the area covered by arsenic-enriched drift to a size greater than the outcrop area of any of the known source rocks reflects processes of glacial erosion and transport of debris from the probable sources.

Distribution patterns of zinc and uranium in drift in southwestern Quebec also reflect underlying bedrock composition (Figs. 7 and 8). Almost all areas of zinc enrichment are underlain by marble, and the large area of uranium enrichment centered on and extending southeastward from 45°50'N and 76°35'E is underlain by granitic intrusive rocks. Marbles of the Central Metasedimentary Belt are known to be enriched in zinc (Sangster, 1982). The uranium enrichment likely represents high concentrations of this element in felsic accessory minerals such as apatite, zircon, or monazite, in granitic intrusive or pegmatic rocks. Alternatively, uranium may be associated with carbonatitic intrusive rocks which are known to occur in this part of southwestern Quebec (Hogarth, in Currie, 1976, p. 132).

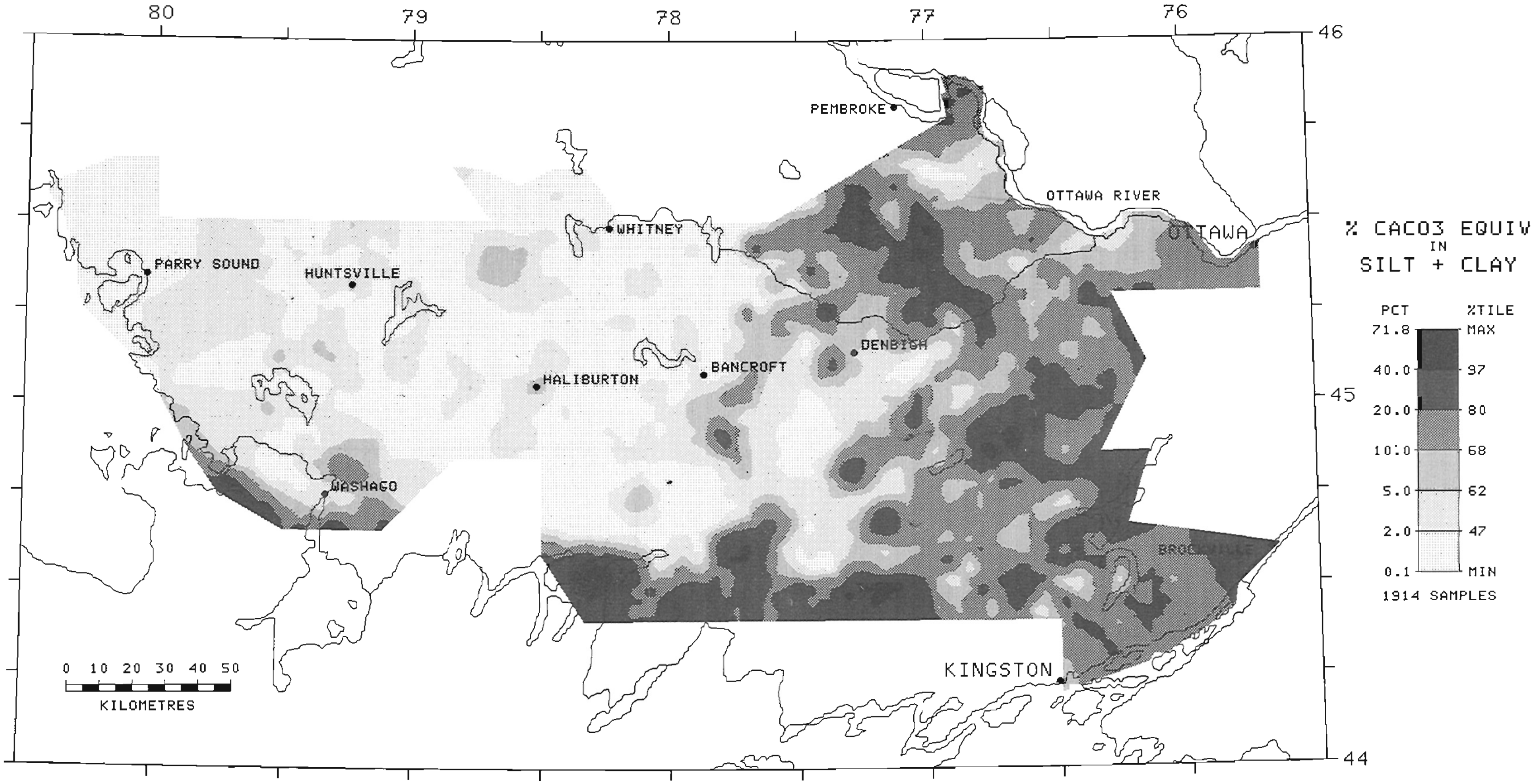


Figure 4. Map showing distribution of carbonate (% $CaCO_3$ equivalent) in silt plus clay-sized (<63 μm) fraction of glacial drift, southeastern Ontario.

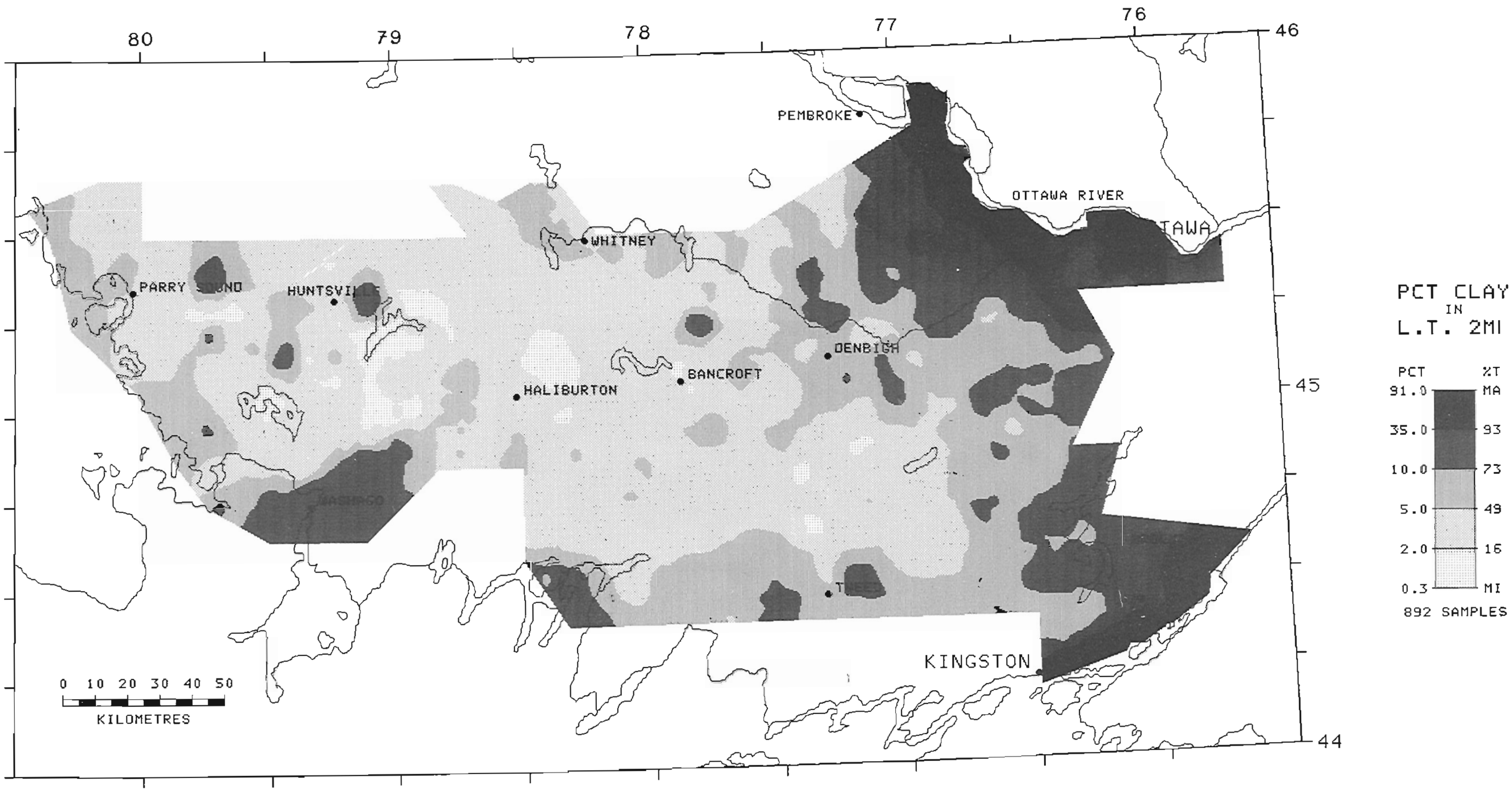


Figure 5. Map showing distribution of clay-sized detritus (<2 μm) in till and glaciomarine/glaciolacustrine silty clays, southeastern Ontario.

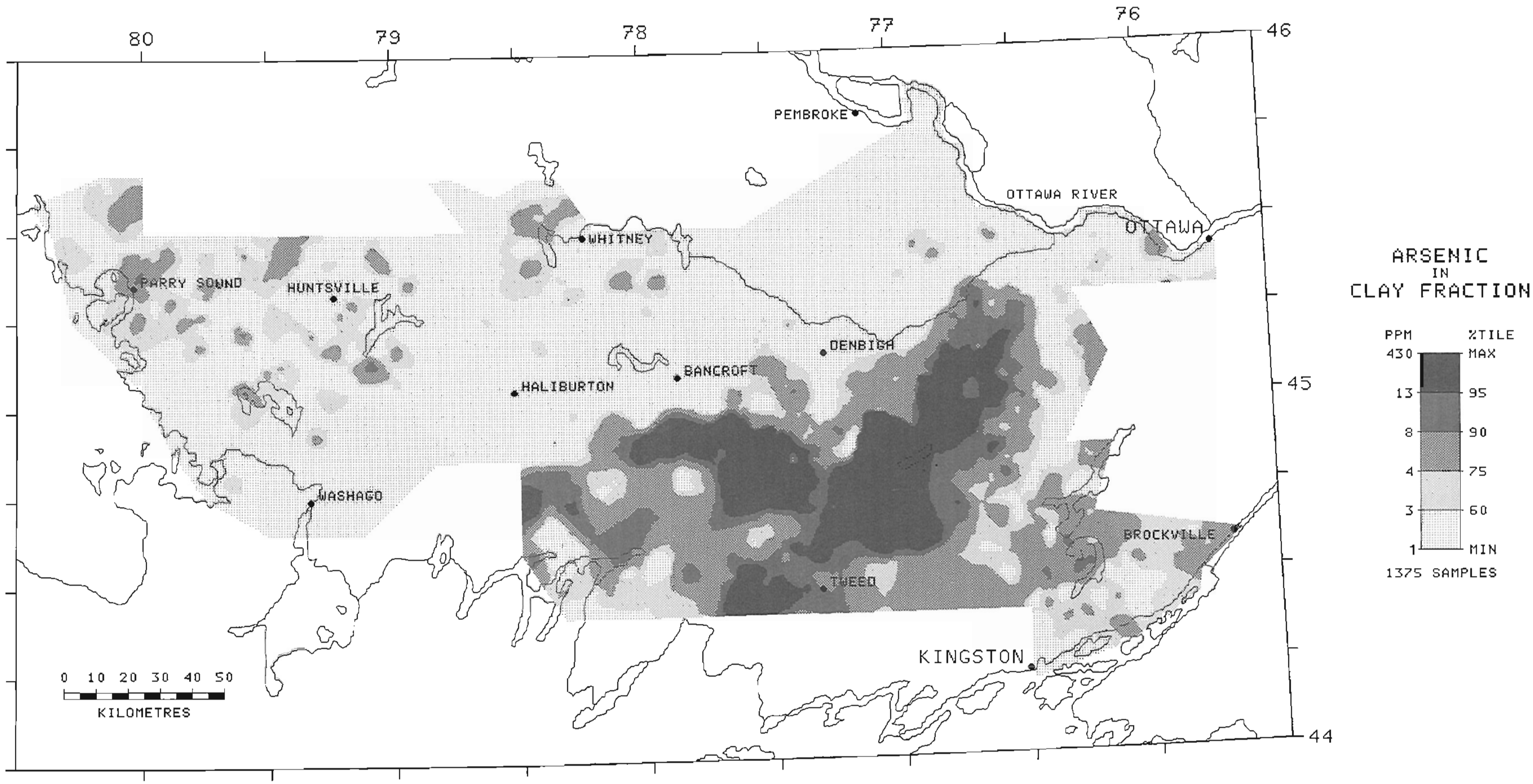


Figure 6. Map showing distribution of arsenic in clay (<2 μm) fraction in till and in glaciomarine/glaciolacustrine silty clays, southeastern Ontario.

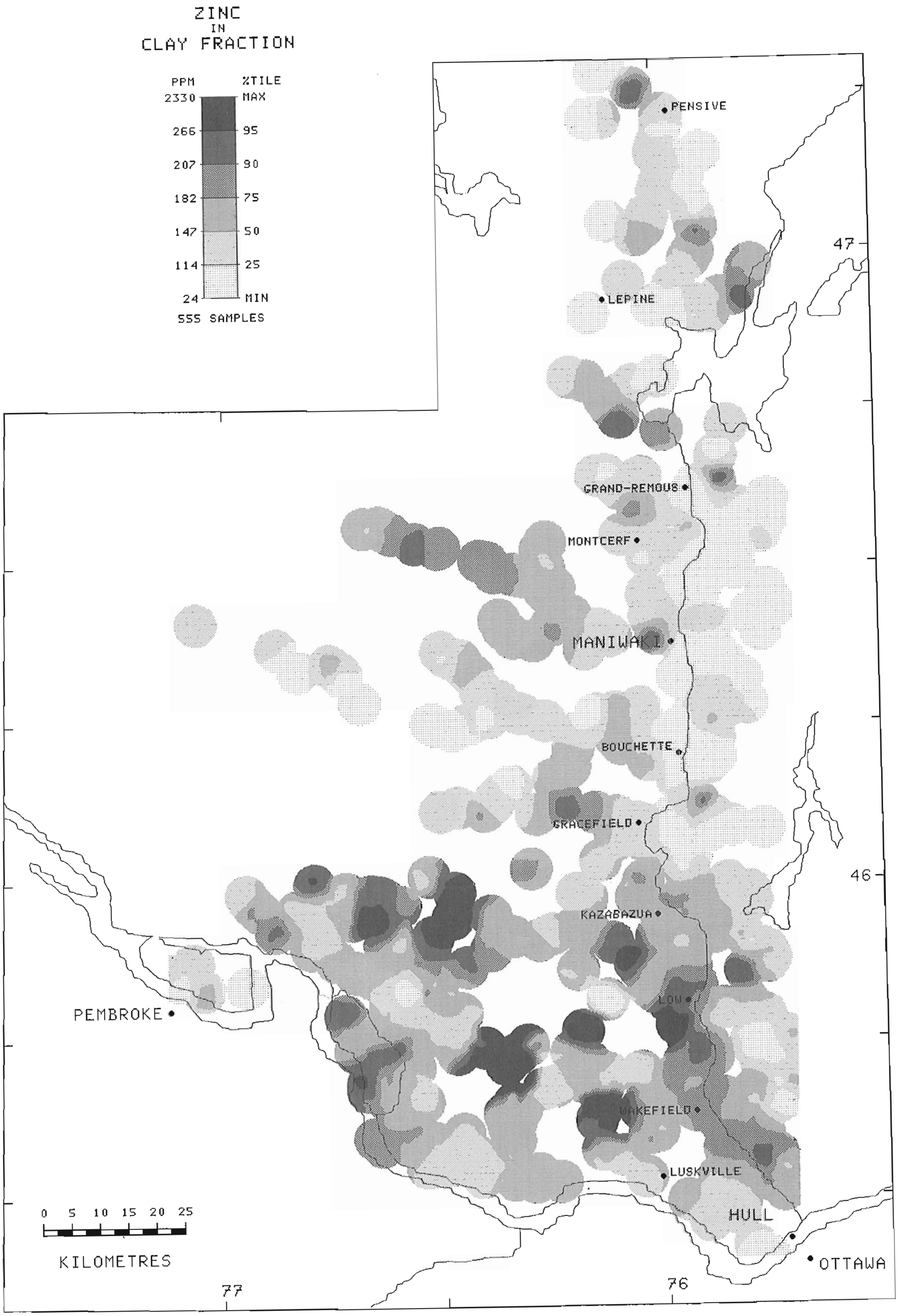


Figure 7. Map showing distribution of zinc in clay ($<2\ \mu m$) fraction of till and glaciolacustrine/glaciomarine silty clays, southwestern Quebec.

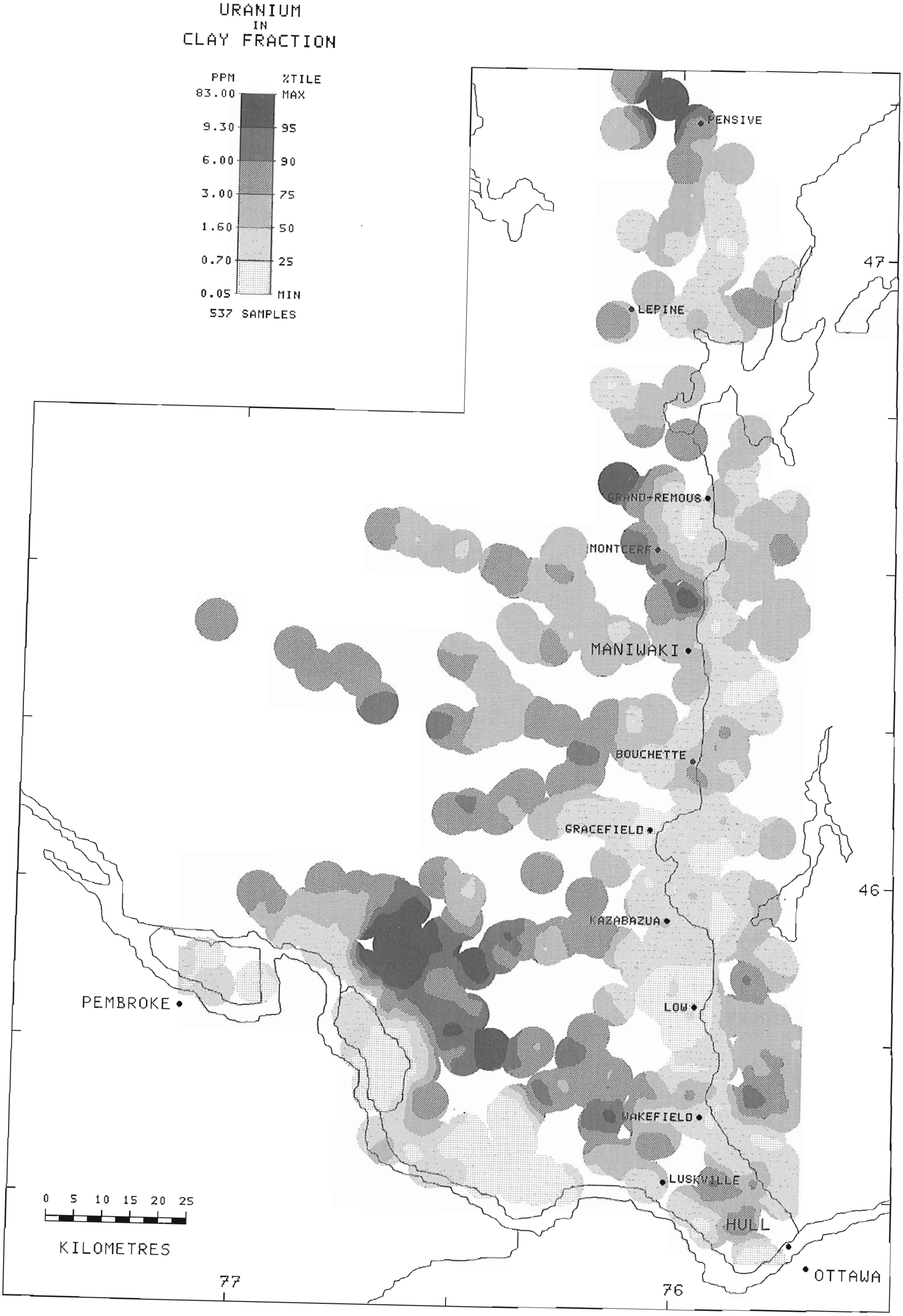


Figure 8. Map showing distribution of uranium in clay (<2 μm) fraction of till and glaciolacustrine/glaciomarine silty clays, southwestern Quebec.

Some chemical variation in glacial sediment composition may also be attributed to postglacial weathering. To investigate the effects of weathering on carbonate content, samples were collected in profile through the entire stratigraphic sequence, including the solum, in the best exposures of till. Table 1 summarizes results of carbonate measurements on some profiles collected in carbonate-rich drift in southeastern Ontario. Results indicate that at depths of one metre or less, severe leaching occurs regardless of the original carbonate content of the parent material. Below one metre, there is little or no depletion of carbonate, even in till which shows signs of weathering. Indications of weathering include colour changes from grey to grey brown, precipitation of oxides, and the presence of chemically disaggregated, coarsely crystalline clasts. In contrast, depths of leaching in carbonate-poor tills in the Thetford Mines area of Quebec, where weathering of the tills was studied in detail (Shilts and Kettles, in press), are much greater (over 2 m and often up to 4 m).

The degree to which weathering affects the carbonate content of drift appears to be controlled largely by the inherent provenance-related composition of the sediment. In the Thetford Mines area, which is part of the Appalachian Highlands, original carbonate contents in drift are low (4 % $CaCO_3$ equivalent) compared to the eastern part of the Frontenac Arch, where concentrations are frequently higher than 15 % $CaCO_3$ equivalent. In New York, Merritt and Muller (1959), studying leaching depths of tills, found that there are critical levels of carbonate in till, above which buffering capacity is disproportionately increased. In addition, in the Thetford Mines area, there are abundant pyrite fragments visible in the till matrix. Rates of leaching are thought to be further accelerated when sulphuric acid, produced from the breakdown of pyrite and other sulphides, reacts with any remaining sulphide and carbonate minerals in the soil (Levinson, 1974, p. 77). Thus, the low sulphide content and the high carbonate contents of the eastern part of the Ontario study area combine to keep leaching depths to a minimum, in spite of the coarse texture and permeable nature of the drift.

Concentrations of iron, sometimes of manganese, and frequently other trace elements, tend to be high in samples of till and other glacial sediments that were described in the field as being highly weathered. A large porportion of the clay-sized detritus of highly weathered samples is composed of secondary minerals consisting primarily of iron and manganese oxides and hydroxides, and probably some authigenic clay. These secondary minerals form as sulphide and silicate minerals break down (Shilts, 1973). Because these secondary clay-sized materials have high cation exchange capacity compared to the clay-size fraction of adjacent unweathered till, they scavenge cations from groundwater solutions. In this way, metal levels are built up in weathered sediment which are in excess of those in primary "glacial" clay fractions of adjacent deposits.

Another cause of variation in chemical composition of drift can be related to sediment facies sampled. Frequency distribution histograms were plotted using data for samples from each of four sediment groups — till, glaciofluvial or outwash sand and/or gravel, glaciolacustrine silty clay, and

Table 1. Carbonate measurements on sample profiles in areas of moderate to high carbonate drift in southeastern Ontario. Carbonate contents measured as $\%CaCO_3$ equivalent.

Profiles of $CaCO_3$ equivalent through oxidized and unoxidized till				
Till sample no.	Location, notes	% $CaCO_3$ (silt and clay)	% $CaCO_3$ (sand)	Sample depth (m)
SAR 0008 C	Packenham, Ontario;	1.3	3.8	1.0
8 B	8B and8C oxidized	14.3	12.6	2.0
8 A		23.3	13.3	2.3
8		24.1	13.9	3.0
SAR 0023 A	highly oxidized	1.4	0	0.5
SAR 0023	thin till on weathered marble	16.0	10.2	1.5
SAR 0027 K	section on	0.8	0	1.0
27 J	Madawaska River,	14.8	5.3	1.5
27 I	Burnstown, Ontario;	13.8	5.4	3.0
27 H	secondary carbonate	12.5	5.8	4.5
27 G	along roots in 27I,	13.3	5.9	6.5
27 F	27J; 27K highly	14.8	4.5	8.5
27 E	oxidized	13.8	5.8	10.5
27 D		14.2	5.3	13.0
27 C		14.9	7.9	15.0
27 B		13.3	5.5	18.0
27 A		14.3	4.5	19.7
27		14.8	5.3	21.0
SAR 0033	highly disturbed, oxidized till	13.4	2.3	1.0
SAR 0033 A	till	18.6	6.4	2.0
SAR 0036 B	oxidized till	0.4	0	1.0
SAR 0036 A	till	17.5	10.5	2.0
SAR 0036	till	20.3	10.3	3.0
AR 0001 A	oxidized till	15.9	5.9	1.0
AR 0001 B	till	26.6	6.7	2.0
AR 0001	till	26.3	7.3	2.0
AR 0013 C	oxidized till	13.1	9.1	1.5
AR-0013 B	unoxidized till	21.7	14.5	3.0
AR-0013 A	unoxidized till	21.1	13.1	3.0
AR-0013	unoxidized till	21.8	13.8	3.0
AR 0014 E	oxidized till in	18.9	8.3	2.0
AR-0014 D	marble quarry	16.3	6.9	3.0
AR 0014 C	till	16.8	8.3	4.0
AR 0014 B	till	15.1	6.9	6.0
AR 0014 B	till	17.3	9.3	7.0
AR 0014	till on marble	17.4	8.8	8.0
AR 0023 B	till	25.6	10.2	0.5
AR 0023	till	31.9	12.6	4.0

glaciomarine silty clay for each trace element. Histograms of copper and chromium, which typify results for the other trace elements, are shown in Figure 9 for each study area.

For each trace element, there is a narrow range of trace element concentrations in samples collected in glaciolacustrine and glaciomarine silty clay compared to till and glaciofluvial or outwash sand and/or gravel. The trace element levels in glaciomarine and glaciolacustrine sediments probably reflect the average composition of the clay fraction of rock flour suspended in the meltwater flowing into the lake or marine basin. The rock flour, in turn, was derived from many lithologically different source areas on the glacier's bed before being homogenized in the lake or sea and widely dispersed over the flooded areas. In contrast, the wide range of concentration levels for samples collected in till and glaciofluvial or outwash deposits, represents local variability in bedrock lithologies either at the sample site or just up-ice from it.

The compositional disparities among sediment types are clearly reflected by the regional distribution patterns of some trace elements. For example, concentrations of copper (Fig. 10), uranium (Fig. 8), and cobalt (not shown) in the clay-sized fraction are consistently and uniformly low, and chromium (Fig. 11) is consistently and uniformly high along the Ottawa and Gatineau valleys in southwestern Quebec, where glaciomarine and glaciolacustrine samples predominate. In the cases of copper (Fig. 9b), cobalt (not shown), and uranium (not shown), there is a wide range of concentrations in samples of till and glaciofluvial and outwash sediments, but the means, around which values for glaciomarine and glaciolacustrine samples also cluster, are low. In contrast, the mean concentration levels for chromium for samples from all sediment groups fall around the median, with samples of glaciomarine/glaciolacustrine sediments having a distinctly higher mean. The elevated levels of chromium in fine-grained sediments most likely reflect enrichment in chromium derived from the mafic rocks in the upper Gatineau valley. Similar chromium enrichment in marine clay was also found on the Boothia Penninsula, District of Keewatin (Shilts, 1980). In Keewatin, enrichment reflects the presence of debris in the glaciomarine sediment derived from fuschite-bearing supracrustal rocks which outcrop throughout the region, but a specific source in southwestern Quebec is presently unknown.

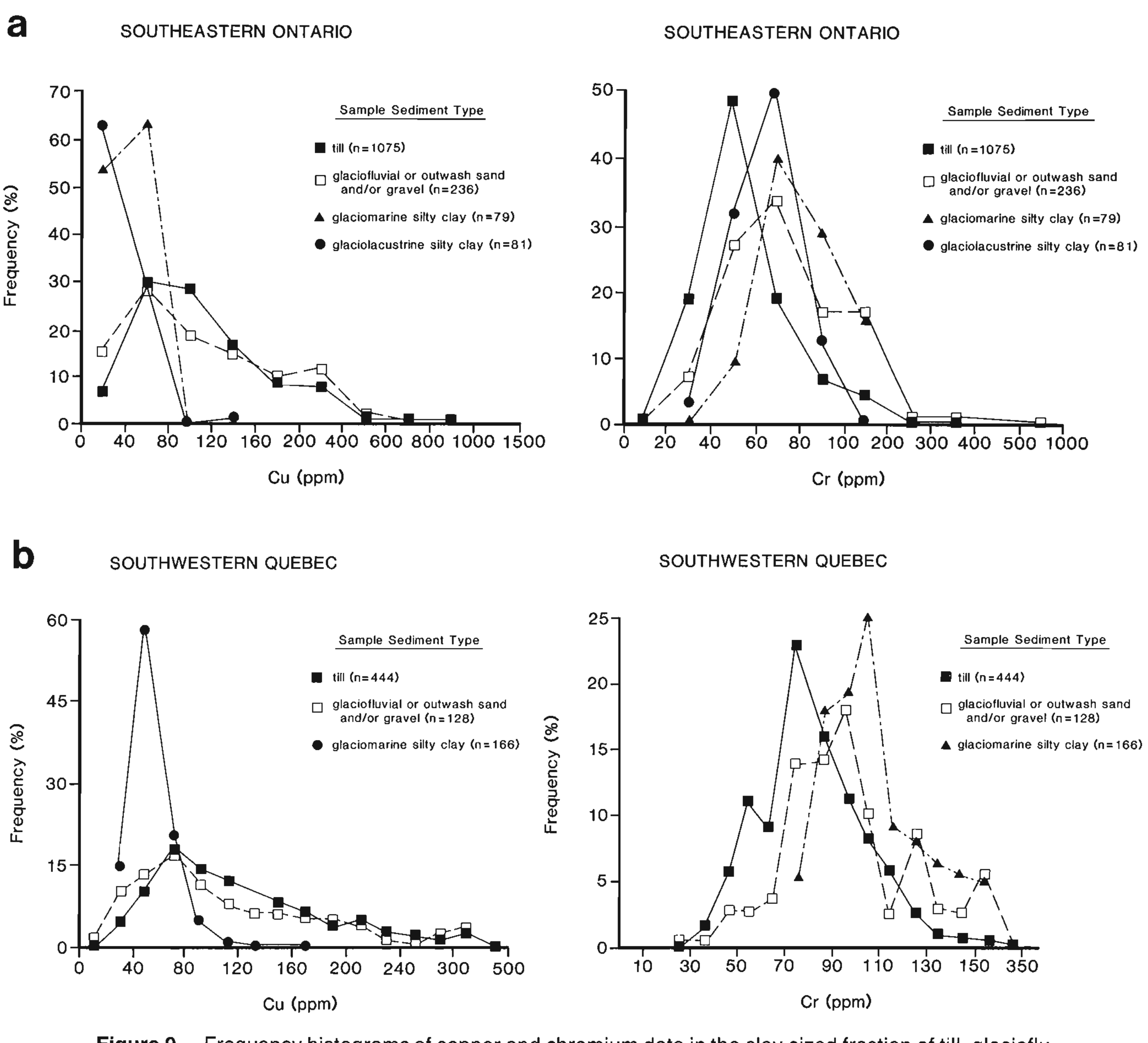


Figure 9. Frequency histograms of copper and chromium data in the clay-sized fraction of till, glaciofluvial or outwash sand and gravel, and glaciomarine and/or glaciolacustrine silty clay; (a) southeastern Ontario, (b) southwestern Quebec.

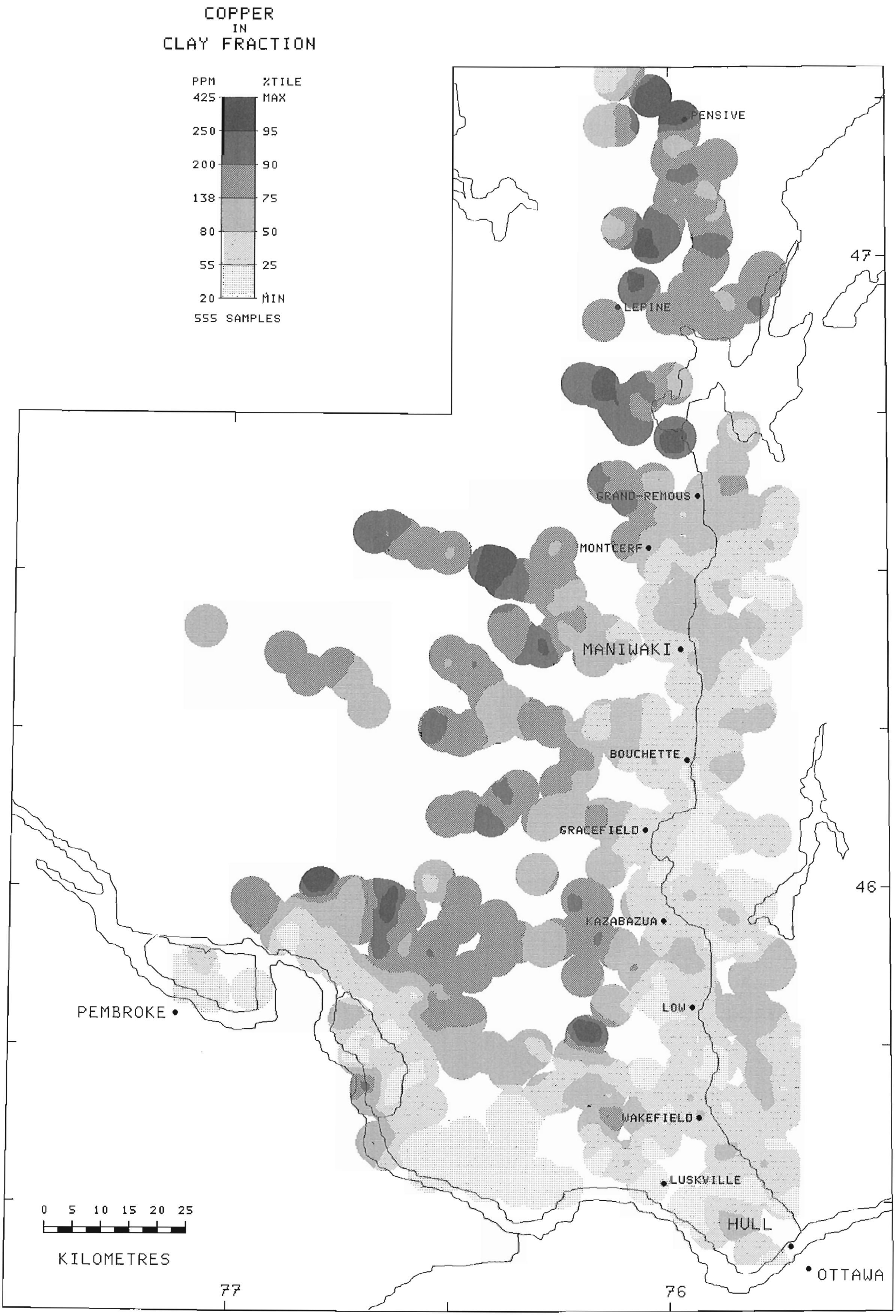


Figure 10. Map showing distribution of copper in clay (<2 μm) fraction of till and glaciolacustrine/glaciomarine silty clays, southwestern Quebec.

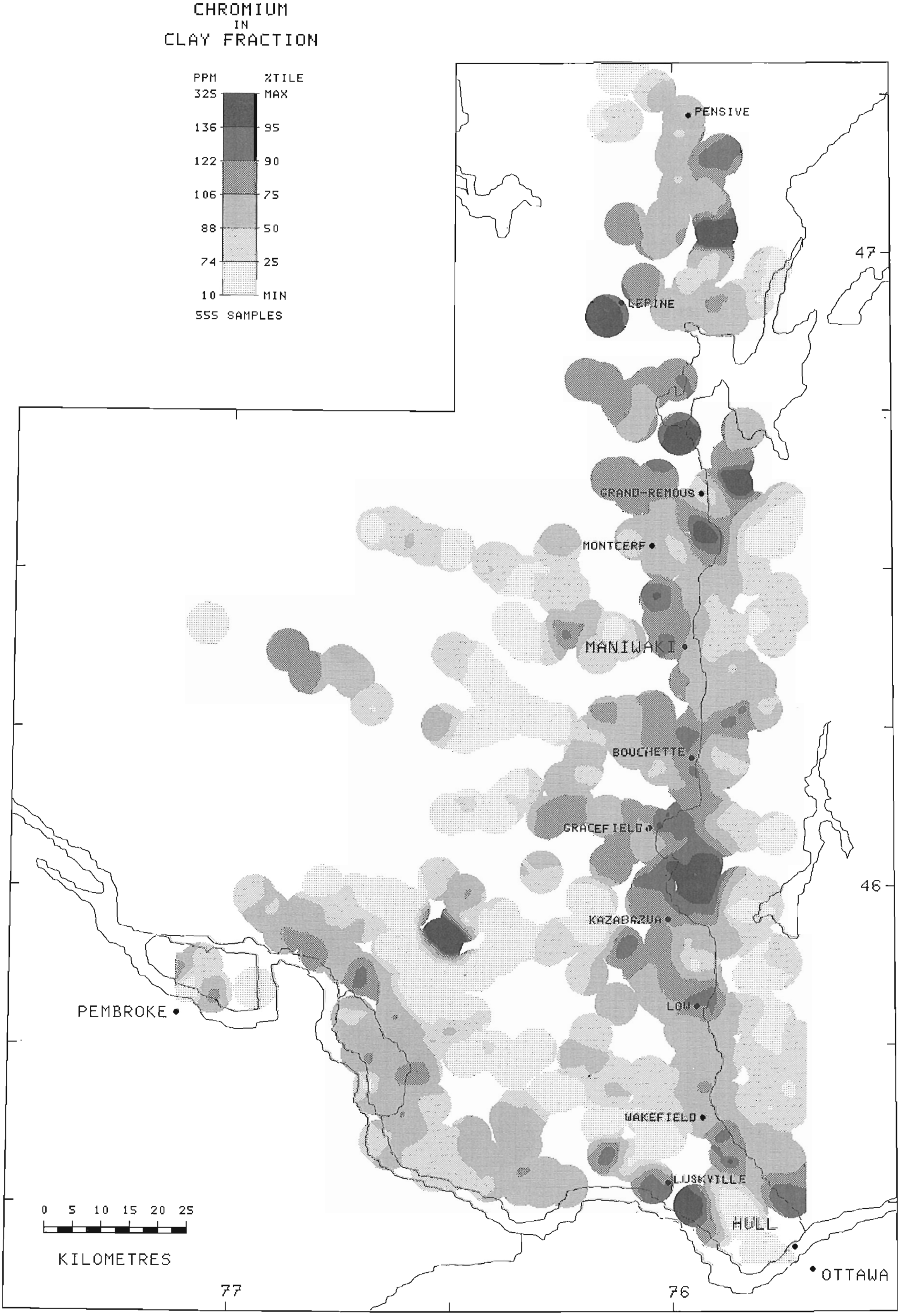


Figure 11. Map showing distribution of chromium in clay (<2 μm) fraction of till and glaciolacustrine/glaciomarine silty clays, southwestern Quebec.

In both study areas, the frequency curves for copper and chromium (Fig. 9), as well as for most other trace elements, exhibit similar relationships with respect to sediment type. The compositional disparities caused by changes in sediment facies sampled, however, are reflected much more strongly on the trace element maps for southwestern Quebec than for southeastern Ontario. Silty clay predominates along the Ottawa and Gatineau valleys in Quebec, as it does along the Ottawa and St. Lawrence valleys in southeastern Ontario. In Quebec, however, the silty clay cover makes up a much larger and more areally continuous part of the study area than it does in Ontario, and silty clay samples comprise over one third of the total sample population, compared to only one tenth in Ontario.

Figure 9 also shows that a larger number of glaciofluvial samples have higher trace element concentrations in clay, on average, than do samples of till. Because glaciofluvial and outwash deposit samples are generally more coarse-grained than till and other samples, a larger proportion of any clay-sized detritus present in their matrix is composed of secondary minerals, formed by weathering of labile minerals (Shilts, 1973). Because it is difficult to interpret which part of the geochemical signal for these samples represents provenance and which part the presence of weathering artifacts, data for these samples were not included among the samples from which the concentration maps were derived.

CONCLUSIONS

Distribution patterns of carbonate and trace and minor elements in drift over both study areas can be related to one or more of the following: (1) effects of glacial transport; (2) composition of the underlying and up-ice bedrock; (3) sediment facies sampled; and, (4) degree of weathering.

Regional distribution patterns of carbonate and different textural components in drift are influenced most strongly by glacial transport. In the area north of the St. Lawrence River in southeastern Ontario, the compositional influence of bedrock is partially masked by the exotic composition of glacially transported debris overlying it.This is reflected by high carbonate contents of till derived from Paleozoic terranes of the Ottawa valley. The carbonate-rich till lies on a variety of non-calcareous igneous rocks. Carbonate-poor till in southeastern Ontario and southwestern Quebec generally has a smaller component of silt and clay-sized material than the carbonate-rich till north of the St. Lawrence.

Because of the lack of dilution by Paleozoic debris, samples outside the areas of carbonate-rich drift are more likely to have trace element compositions that are more closely related to the average composition of the underlying bedrock than to the effects of glacial transport. Nevertheless, even in high carbonate areas, geochemical signatures of mineralized bedrock do stand out, albeit subdued in some cases. The fact that the distortion of underlying bedrock signatures by glacial processes is not so important outside the area of Paleozoic dispersal probably reflects low sediment production in the hard crystalline shield terrane.

In some cases, compositional changes reflect changes in the sediment facies sampled. Concentrations of copper, uranium, and cobalt were consistently and uniformly low, and chromium consistently and uniformly high in glaciomarine silt/clay samples collected over large areas along the Ottawa and Gatineau valleys. The geochemistry of these sediments reflects no more than the average composition of the clay fraction of rock flour suspended in the meltwater flowing into the basin in which they were deposited. As a result, their presence can, in a similar manner to that of Paleozoic carbonate debris in till in southeastern Ontario, effectively mask the composition of the underlying till and bedrock. Therefore, these sediments are of little value when used in mineral exploration studies.

In some areas, only sand, gravel or badly weathered till were available for sampling. When the clay fraction of these samples was analyzed, a disproportionate number were found to have high concentrations of one or more trace elements including most frequently iron and often manganese. High metal levels in these sediments are thought to reflect the high exchange capacities of postdepositional weathering products, rather than the original mineralogic composition of the sediment (see discussion in Shilts, 1973). As a result, interpretation of anomalies found in these sediments is difficult. Unless careful consideration is given to trace element and other data generated for these types of samples, they should be avoided as sampling media wherever possible.

The presence of chemical variations associated with changes in sediment facies and degree of weathering, demonstrates that in all drift geochemical studies carried out for the purpose of mineral exploration, particular emphasis should be put on careful selection or correct identification of glacial sediment type for sampling, and also on obtaining sample materials that are as unweathered as possible. This is especially important for detailed studies. By minimizing the amount of compositional variation caused by weathering and changes in sediment facies, those changes related to provenance can more readily be identified and properly understood.

ACKNOWLEDGMENTS

Many people have assisted with sample collection in both areas between 1980 and 1986, among whom P.H. Wyatt and A. Bolduc made considerable contributions. D. J. Ellwood and R.K. Burns offered much advice pertaining to the computer maps and files. J.R. Hill offered helpful discussions in the early stages of the manuscript.

REFERENCES

Baer, A.J., Poole, W.H., and Sanford, B.V.
1977: Riviere Gatineau Quebec — Ontario (Sheet 31), Geological Survey of Canada, Map 1334A.

Bostock,H.S.
1970: Physiographic subdivisons of Canada; in Geology and Economic Minerals of Canada, ed. R.J.W. Douglas; Geological Survey of Canada, Economic Geology Report No. 1, Chapter 2, p. 9-30, Map 1245A.

Currie, K.L.
1976: The alkaline rocks of Canada; Geological Survey of Canada, Bulletin 239, 228 p.

Dadswell, M.J.
1974: Distribution, ecology and postglacial dispersal of certain crustaceans and fishes in eastern North America; National Museum of Natural Sciences, Publication in Zoology, No. 11, 110 p.

DiLabio R.N.W., Rencz, A.N., and Egginton, P.A.
1982: Biogeochemical expression of a classic dispersal train of metalliferous till near Hopetown, Ontario; Canadian Journal of Earth Sciences, v. 19, p. 2297-2305.

Foscolos, A.E. and Barefoot, R.R.
1970: A rapid determination of total organic and inorganic carbon in shales and carbonates; Geological Survey of Canada, Paper 70-11, 14 p.

Freeman, E.B. (ed.)
1979: Geological highway map, southern Ontario; Ontario Geological Survey, Map 2441.

Gadd, N.R.
1980: Late-glacial regional ice-flow patterns in eastern Ontario; Canadian Journal of Earth Sciences, v. 17, p. 1439-1453.

Hornbrook, E.H.W., Kettles, I.M., and Shilts, W.W.
1986: Geochemistry of aquatic and terrestrial sediment, Precambrian Shield of southeastern Ontario; Water, Air, and Soil Pollution, v. 31, p. 969-979.

Kettles, I.M. and Shilts, W.W.
1983: Reconnaissance geochemical data for till and other surficial sediments, Frontenac Arch and surrounding areas, Ontario; Geological Survey of Canada, Open File 947.

Levinson, A.A.
1974: Introduction to exploration geochemistry; Applied Publishing Ltd., Calgary, 612 p.

Merritt, R.S. and Muller, E.H.
1959: Depth of leaching in relation to carbonate content of till in central New York state, American Journal of Science, v. 257, p. 465-480.

Richard, S.H.
1975: Surficial geology mapping; Ottawa Valley Lowlands (parts of 31G, B, F); in Report of Activities, Part B, Geological Survey of Canada, Paper 75-1B, p. 113-117.

Sangster, A.L.
1982: Geology of the Grenville Province and regional metallogenesis of the Grenville Supergroup; in Precambrian Sulphide Deposits, H.S. Robinson Memorial Volume, eds. R.W. Hutchinson, C.D. Spence and J.M. Franklin; Geological Association of Canada Special Paper 25, p. 91-125.

Sharpe, D.R.
1979: Quaternary geology of the Merrickville area; Ontario Geological Survey, Report 180, 54 p.

Shilts, W.W.
1973: Drift prospecting; geochemistry of eskers and till in permanently frozen terrain, District of Keewatin, Northwest Territories; Geological Survey of Canada, Paper 72-45, 34 p.
1975: Principles of geochemical exploration for sulphide deposits using shallow samples of glacial drift; Canadian Mining and Metallurgical Bulletin, v. 68, no. 757 p. 73-80.
1980: Geochemical profile of till from Longlac, Ontario to Somerset Island, Canadian Institute of Mining and Metallurgy Bulletin, v. 73, no. 822, p. 85-94.
1984a: Potential effects of acid rain on glaciated terrain; in Groundwater as a Geomorphic Agent, ed. R.G. LaFleur; Binghamton Symposia in Geomorphology, no. 13, Allen and Unwin, Boston, p. 135-156.
1984b: Till geochemistry in Finland and Canada, Journal of Geochemical Exploration, v. 21, p. 95-117.

Shilts, W.W. and Kettles, I.M.
in press: Weathering of sulphide-rich till; in Handbook of glacial Indicator Tracing, eds. R. Kujansuu and M. Saarnisto; A.A. Balkema, Rotterdam.

Sinclair, I.G.L.
1979: Geochemical investigation of the Clyde River zinc prospect, Lanark County, Ontario, in Geochemical Exploration 1978, eds. J.R. Watterson and P.K. Theobald; Association of Exploration Geochemists, p. 487-495.

Quaternary geology and its implications to gold exploration in the La Ronge and Flin Flon domains, Saskatchewan

J.E. Campbell[1] and B.T. Schreiner[1]

Campbell, J.E., and Schreiner, B.T., Quaternary geology and its implications to gold exploration in the La Ronge and Flin Flon domains, Saskatchewan; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 113-126, 1989.

Abstract

The general Quaternary stratigraphy for the La Ronge and Flin Flon domains is lower till, overlain by stratified sand and gravel and/or silt and clay, an upper till, and an upper stratified drift. Bedrock, glacial till and glaciolacustrine sediments are the predominant surface deposits. The main ice flow direction was towards 180° to 225°. A minor readvance occurred later with a direction of 215° to 240°.

The more extensive lower till is the preferred sampling medium whereas the thin, discontinuous upper till, deposited by the readvance, is unsuitable. Glacial Lake Agassiz covered much of the southeastern Precambrian Shield. The lake sediments occur below 427 m and are an impediment to surface geochemical and biogeochemical surveys. Till deposits within the lake were subjected to wave action and are often reworked, rendering them unsuitable for sampling.

In the Waddy Lake area, bedrock and till constitute 65 to 70% of the surface material and can be prospected using surface sampling methods. The major hindrance to drift prospecting is the presence of thick glaciolacustrine sediments particularly in the southeast.

The drift cover in the Sulphide Lake area is thinner and less extensive. Glacial lake sediments are not as prevalent. In places the tills have undergone extensive weathering and/or reworking, making them unsuitable for drift prospecting. Gold dispersal in the lower till generally reflects known gold occurrences in this area.

East of Amisk lake, glacial drift is less prevalent than in the La Ronge Domain. The most useful technique for drift prospecting is overburden drilling in topographic lows which are commonly muskeg-filled and underlain by stratified sediments.

Gold is its own best pathfinder in drift prospecting in these regions. The morphology and chemistry of the gold grains in till resemble known gold sources. Dispersal trains are best defined by heavy mineral analyses and gold grain counts from bulk till samples (> 4 kg). Analysis of the fine fraction (< 0.1 mm) of the bulk till samples is recommended to ensure detection of total gold content.

Résumé

La stratigraphie générale du Quaternaire pour les domaines de La Ronge et de Flin Flon comprend un till inférieur, recouvert de couches de sable et de gravier ou de limon et d'argile, ou les deux, un till supérieur, et des matériaux de transport glaciaires stratifiées au sommet. Le socle rocheux, le till glaciaire et les sédiments glaciolacustres sont les dépôts les plus répandus en surface. Les principales directions d'avancée glaciaire varient entre 180° et 225°. Une nouvelle avancée s'est produite plus tard dans une direction de 215° à 240°.

[1] Saskatchewan Research Council, 15 Innovation Blvd., Saskatoon, Saskatchewan S7N 2X8

Le till inférieur, plus étendu, est le milieu d'échantillonnage préféré tandis que la mince couche discontinue de till supérieur, mis en place lors de la nouvelle avancée, ne se prête pas à l'échantillonnage. Le lac glaciaire Agassiz couvrait la plus grande partie du bouclier précambrien au sud-est. Les sédiments lacustres gisent sous 427 m et nuisent aux levés géochimiques et biogéochimiques de surface. Les dépôts de till dans le lac ont été soumis à l'action des vagues et sont souvent remodelés, ce qui les rend non propices à l'échantillonnage.

Dans la région du lac Waddy, le socle rocheux et le till constituent de 65 à 70 % des matériaux de surface et se prêtent à la prospection par des méthodes d'échantillonnage de surface. Le principal empêchement à la prospection des matériaux de transport glaciaires est la présence de sédiments glaciolacustres épais, particulièrement dans le sud-est.

La couverture de matériaux de transport glaciaires dans la région du lac Sulphide est plus mince et moins étendue. Les sédiments de lac glaciaire eux sont moins répandus. Par endroits, les tills ont subi une altération ou un remodelage intense, les rendant non propices à la prospection des matériaux de transport glaciaires. La dispersion de l'or dans le till inférieur correspond en général aux manifestations connues dans cette région.

À l'est du lac Amisk, les matériaux de transport glaciaires sont moins répandus que dans le domaine de La Ronge. La technique de prospection de ces matériaux la plus utile est le sondage des morts-terrains dans les dépressions topographiques qui sont habituellement remplies par une fondrière et recouvertes de sédiments stratifiés.

L'or lui-même est le meilleur indicateur d'or dans la prospection des matériaux de transport glaciaires de ces régions. La morphologie et la composition chimique des granules d'or dans les tills ressemblent à celles des sources d'or connues. La meilleure façon de définir les trainées de dispersion des tills est de procéder au dosage des minéraux lourds et au décompte des granules d'or dans de gros échantillons de till (4 kg et plus). On recommande l'analyse de la fraction fine (moins de 0,1 mm) des gros échantillons de till si l'on veut s'assurer de repérer tout l'or présent.

INTRODUCTION

In recent years, there has been renewed interest in gold exploration in northern Saskatchewan. Much of the exploration activity has been centred in the southeastern part of the Precambrian Shield between La Ronge, Reindeer Lake and Flin Flon. This area comprises the La Ronge, Kisseynew, Glennie Lake and Flin Flon domains. (Fig. 1). Because more than 50 per cent of this area is covered with glacial drift, surface geochemical surveys, such as biogeochemical and overburden sampling have become an integral part of exploration programs. The selection and effectiveness of a geochemical survey method to be used depends to a large degree on the nature of the overburden cover. Therefore, a good understanding of the Quaternary geological conditions is an essential component of any surficial geochemical program.

Regional mapping of the Quaternary geology for the southeastern shield was done as part of the reconnaissance mapping and drilling program carried out by the Saskatchewan Research Council (SRC) for the whole Precambrian Shield region of Saskatchewan (Schreiner, 1984). This work, published at a 1:250,000 scale, provides the regional framework for ice movement direction, surface deposits, stratigraphy, glacial history and approximate extent of glacial Lake Agassiz, but is not detailed enough to provide all the needed information for exploration.

In order to assist mineral exploration, SRC has carried out site-specific investigations in three strategic locations (Fig. 2): Waddy Lake (Campbell, 1986), Sulphide Lake (Campbell, 1987a) and Amisk Lake (Campbell, 1987b). The former two are situated in the La Ronge Domain and the latter in the Flin Flon Domain. These sites were chosen as typical of the Quaternary geology of these regions as well as, providing specific information concerning the materials, stratigraphy, sampling media, nature of gold distribution and other factors critical to drift prospecting. In each area surficial mapping was carried out at a scale of 1:20 000. A till geochemical program involving bulk till (6 to 9 kg) sampling for geochemical analysis of the fine (< 0.1 mm) and heavy mineral fractions as well as gold grain documentation was conducted at the same time.

This information, combined with that from the regional mapping program, is used to compare the general Quaternary geology and till geochemistry of the study areas and to outline the implications for drift prospecting for gold.

REGIONAL QUATERNARY GEOLOGY

The thin drift and stratigraphy of the glacial sediments suggest that the last Wisconsinan glacial advance obliterated many of the features and eroded deposits of earlier glaciations. Therefore, glacial sediments and ice movement indicators are considered to be predominantly late Wisconsinan in age (Schreiner, 1984). The generalized distribution of surficial deposits of the southeastern portion of the Precambrian Shield is shown in Figure 3. Thin till and bedrock outcrops comprise 45 to 70 % of the surface, and 30 to 50 % comprise glaciolacustrine sediments related to glacial Lake Agassiz (Sopuck et al., 1986). Glaciofluvial material makes up less than 5 % of the surface deposits, and the remaining area is classed as organic terrain. Commonly, the drift is less than 5 m thick, except where glacial Lake Agassiz deposits occur. Thickness can exceed 20 m, particularly in the east where the lake deposits dominate. These values are based on augerholes drilled throughout the area (Schreiner, 1984; Campbell 1986, 1987a,b). Although glaciofluvial deposits account for less than 5 % of the surface materials, a thin patchy veneer of sand overlies till on a much broader scale.

Ice Movement Directions

The dominant ice flow was toward the southwest between 180° and 225°. At a few locations, finer, more weakly developed striae cut across an earlier set at directions of 215° to 245°. The origin of these striae is not clear but they are thought to be related to a minor readvance of a thin ice lobe into the glacial Lake Agassiz basin (Schreiner and Alley, 1975). Rare but notable occurrences of glacial striae trending west to northwest occur (Johnston, 1978) around Reindeer Lake and crossing striations trending east-west occur in the central La Ronge Domain (Schreiner, 1984). The relative age of these striae are unknown but Johnston suggests they are older than the southwesterly direction but still Wisconsinan in age. Local variations are attributed to ice flow deflections caused by the irregular bedrock topography.

In the La Ronge Domain the ice flow direction is generally parallel to sub-parallel to the regional structural fabric

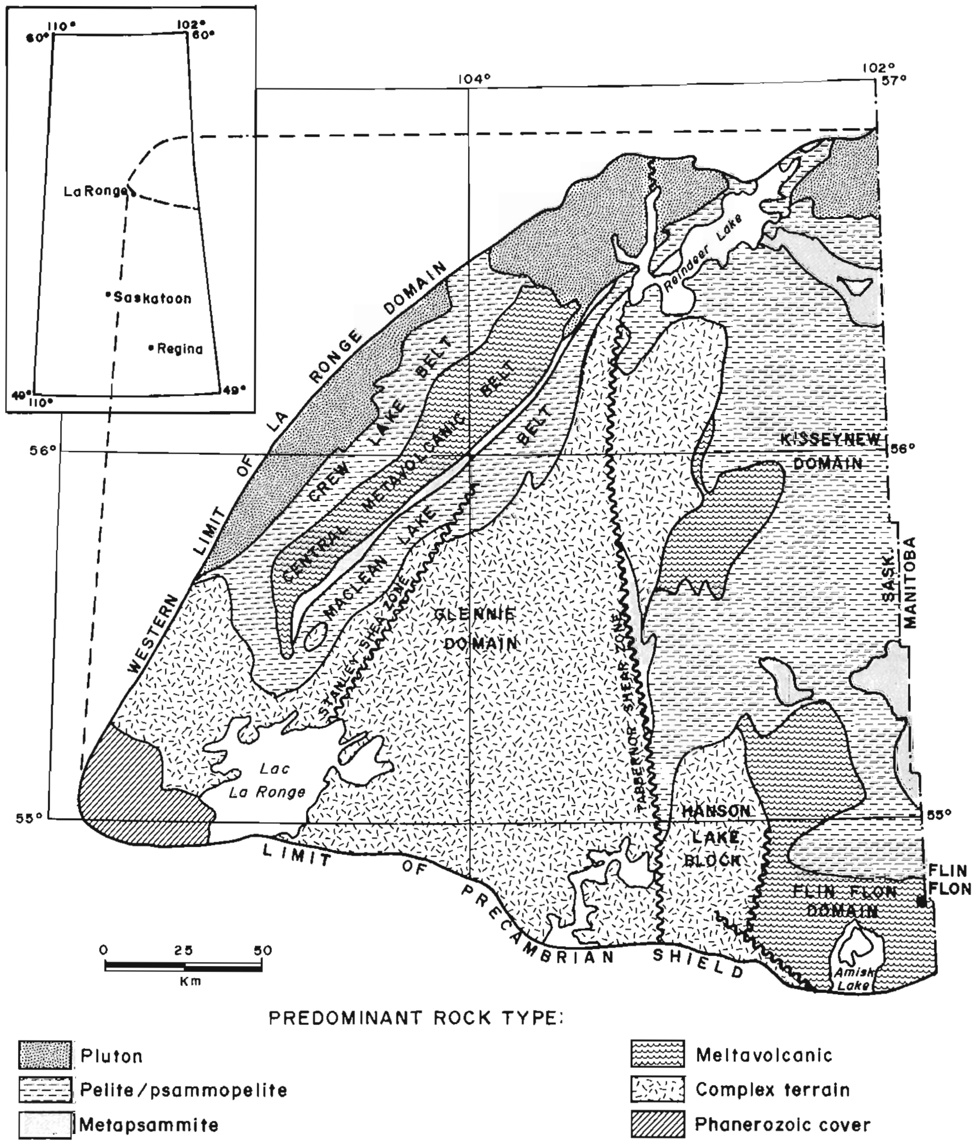


Figure 1. Location and generalized bedrock geology of the southeastern Precambrian Shield in Saskatchewan. The "complex terrains" include plutonic and supracrustal units. The Central Metavolcanic Belt contains about 40 percent plutons. The La Ronge Domain comprises all terrain west of the Stanley Shear Zone and its northerly extension (modified from Schreiner, 1986).

of the bedrock (Fig. 3). This has several implications for mineral exploration. Known glacial dispersal trains tend to be long and narrow following the ridge-and-valley topography that parallels the ice flow direction (Sopuck et al., 1986). This may lead to problems of overlapping dispersal trains complicating the task of identifying the source or sources of mineralization.

Proglacial Landforms

Proglacial Lake Agassiz covered much of the southeastern portion of the Precambrian Shield (Schreiner, 1983). As the ice retreated, Lake Agassiz inundated the low-lying areas as far north as Reindeer Lake and just west of the La Ronge Domain. The minimum area covered by the lake corresponds approximately to the area outlined by the extent of the glaciolacustrine sediments (Fig. 3). Glaciolacustrine sediments are also common under bogs and lakes, below the elevation of the highest beaches (commonly 427 m) and in topographic lows within areas mapped as dominantly till and bedrock.

Thick deposits of glaciolacustrine sediments are a major impediment to surface geochemical surveys. Till in the Lake Agassiz basin was subjected to wave action and reworked, rendering it largely unsuitable for drift prospecting.

Drift Stratigraphy

The generalized Quaternary stratigraphy sequence is based on information from 90 augerholes and 11 roto-sonic drill holes along roads in the area, roadside exposures, excavations and overburden geochemical surveys (Campbell 1986, 1987a,b; Schreiner, 1984): (1) lower till; (2) stratified sands and gravels and/or silt and clay; (3) upper till; (4) upper stratified drift. The lower till is widespread and commonly lies directly on bedrock. The upper till and stratified deposits were encountered only at a few locations but are widespread. The stratigraphy of the two type sections is shown in Figure 4 and the locations are shown in Figure 2. A more complete discussion of the stratigraphy is given by Schreiner (1984, 1986), and Sopuck et al. (1986).

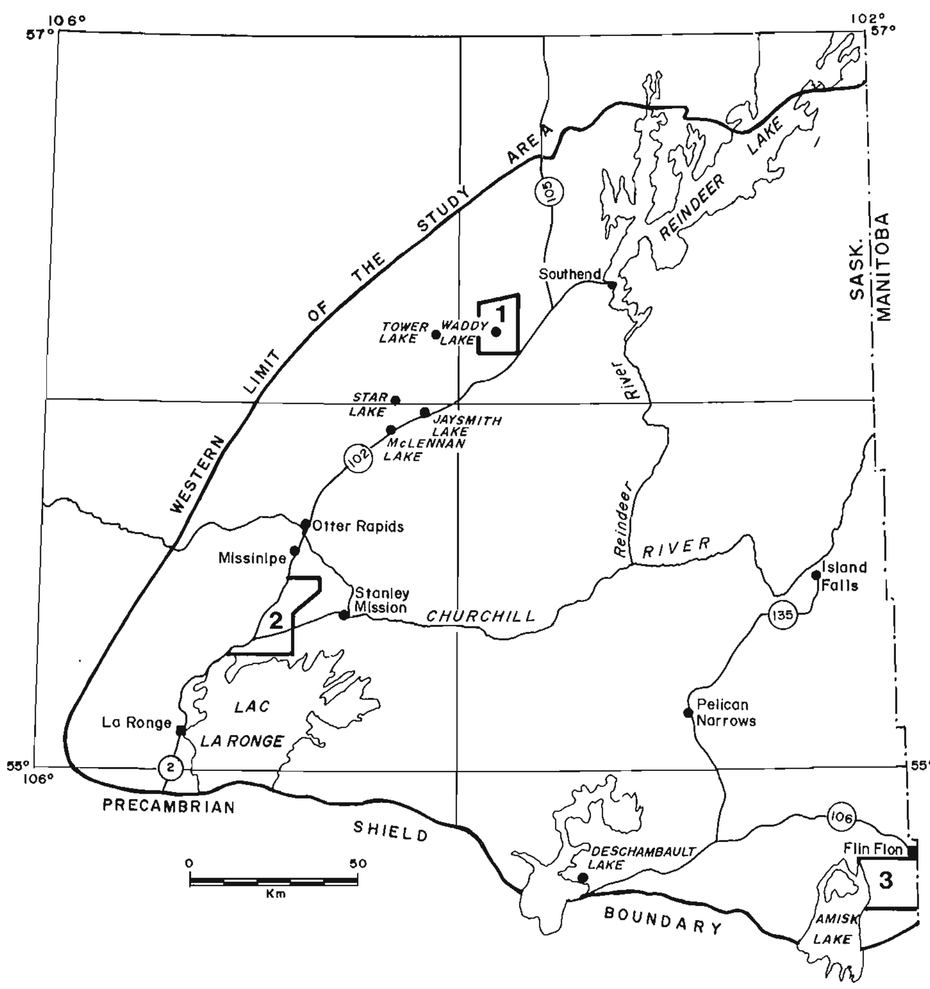


Figure 2. Location of study areas: Waddy Lake (1), Sulphide Lakes (2) and Amisk Lake (3). The location of the sections (Jaysmith Lake and Deschambault Lake) illustrated in Figure 4 are identified (Modified from Schreiner, 1986).

The lithologic composition of the lower till reflects the changes in local bedrock, making it the preferred sampling medium. The thin, discontinuous upper till, deposited by the readvance, reflects the incorporation of underlying sediments and is not representative of the local bedrock.

Soils

The more common soils found in the southeastern portion of the Shield are brunisolic, luvisolic, and to lesser extent, podzolic soils developed on well drained uplands (Canada Soil Survey Committee, 1978). Gleysoic and organic soils are restricted to poorly drained areas and are associated with peat deposits. Regosolic soils are related to unstable areas such as slumps or to recent deposits such as floodplains.

The following descriptions are modified from more detailed descriptions by Acton and Padbury in Schreiner (1986). Brunisols are the most widespread soils, which are developed primarily on the more permeable glaciofluvial and till deposits. The main characteristics of these soils are the presence of a weak to well developed Ae-horizon, depending on the degree of leaching and an underlying B horizon which shows no distinct accumulation of weathering products.

Luvisolic profiles are developed most commonly on glaciolacustrine silt and clay. The general characteristics of the soils are a well developed forest litter mat (L-H), a weak or absent organic (AH) layer and a (Bt) horizon of clay accumulation.

Podzolic soils are developed on well drained till and glaciofluvial parent material. These soils are characterized by a leaf-litter horizon (LH) underlain by a well developed, eluviated (Ae) horizon. The B-horizon shows an accumulation of iron and aluminum colloids with little organic matter. This soil type is rare in this part of the Shield.

WADDY LAKE AREA

Quaternary Geology

The distribution of surficial deposits in the Waddy Lake area is shown in Figure 5. The ice flow direction ranges from 188° to 205° with the most common direction ranging from 190° to 192°. Cross-cutting striae were not seen in this study area. With the exception of the Byers Fault, ice flow direction is nearly parallel to the regional bedrock trend. The drift is relatively thick and widespread, averaging five

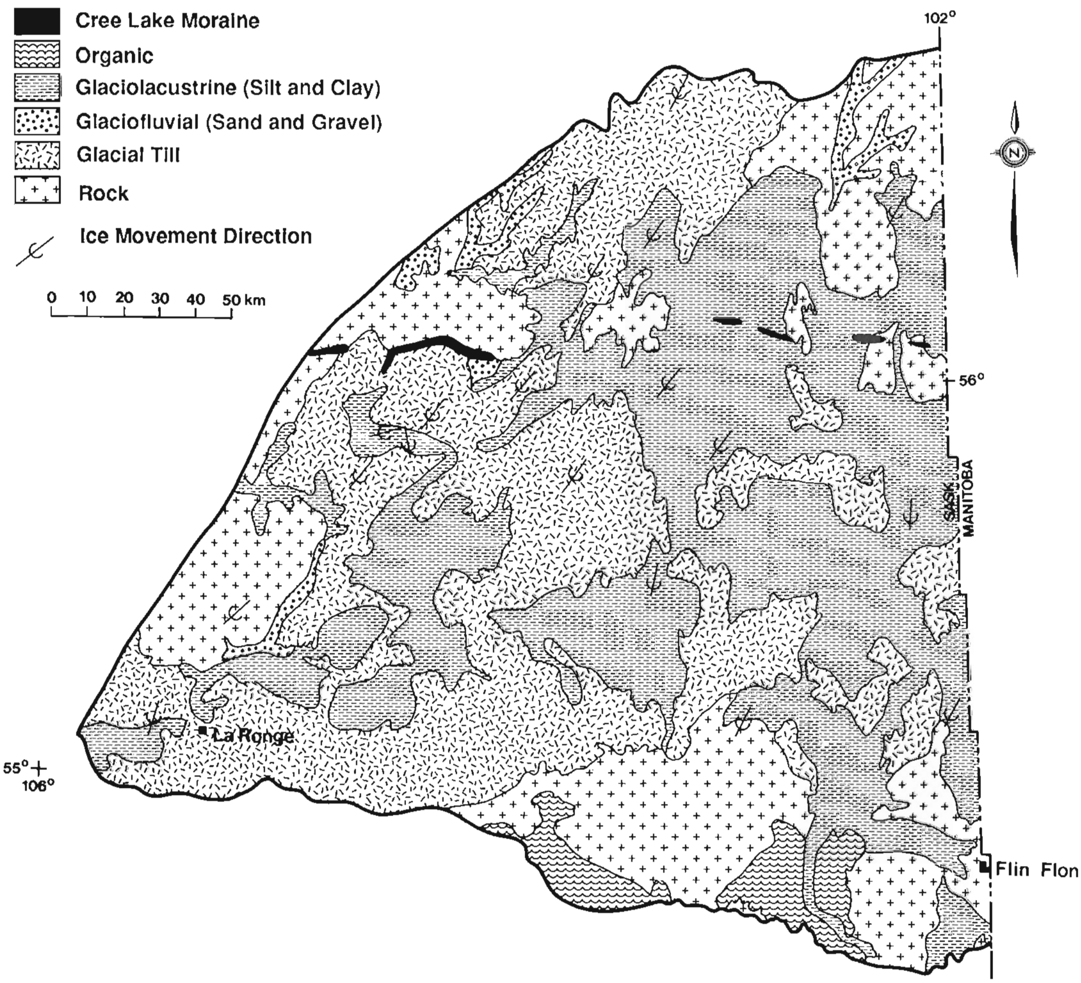


Figure 3. Surficial geology for the southeastern Precambrian Shield. Only the dominant surface materials are shown (Modified from Schreiner, 1986).

metres in thickness and covering approximately 70 % of the area. The composition of the deposits is glacial till 35 to 40 %, glaciolacustrine sediments 15 to 20 %, glaciofluvial sediments < 5 % and organic deposits < 10 %.

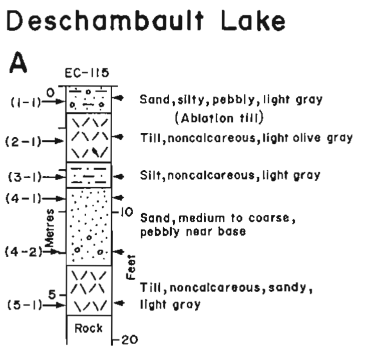
Two till units were identified in the Waddy Lake area. The upper till is thin (< 1 m) and discontinuous. This unit was identified at nine locations overlying lacustrine sediment. It is characteristically clay rich, brown, oxidized and clast-poor. The clasts are more rounded than those of the lower till, similar to the occurrence at Jaysmith Lake (Fig. 4). This till is the result of the minor readvance of ice into the Lake Agassiz basin as reflected by the incorporation of lake sediments into the till matrix.

The lower till is the most common till found in the area. Its thickness is generally less than four metres. This till is commonly greenish grey (due to the incorporation of intermediate to mafic volcanic bedrock) and dense. It contains abundant granules and has 30 to 50 per cent angular to subangular clasts in a silty-sand matrix (Fig. 6). The lower till, which was deposited subglacially, reflects the local bedrock lithology, and has undergone short transport distances of < 800 m (Campbell, 1986). Therefore, it is considered the best sampling medium for drift prospecting. A sandy ablation phase of this till was noted in several locations. Reworking of this till by wave action is restricted to lower slopes and the reworked part is generally thin (< 1 m) overlying undisturbed till.

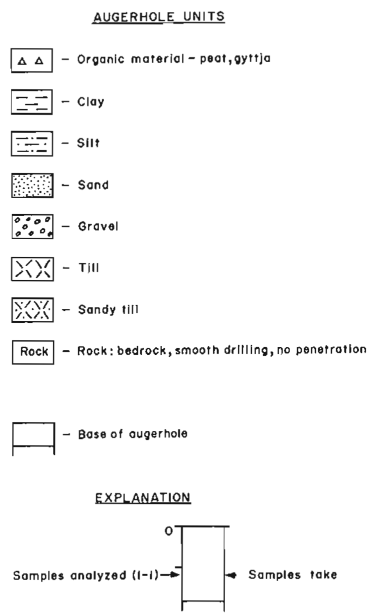
Clayey silt to sandy silt was the predominant glaciolacustrine material deposited in glacial Lake Agassiz (Schreiner, 1983). The Waddy Lake area coincides with the western limit of this lake. The glacial lake sediments are extensive but discontinuous and vary greatly in thickness (< 1 m to > 20 m) as indicated by surface mapping and subsurface drilling. The majority of lake sediments are found below the elevation of 427 m but have been found as high as 439 m. A cobble beach at approximately 457 ± 7 m is evidence of the highest lake level found to date. Thick lacustrine cover is restricted to the low-lying southeastern portion of the area and to topographic lows (Fig. 5).

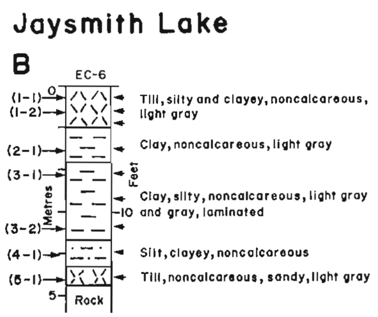
Gold Occurrence in Till

Gold has been known to occur in the till in the Waddy Lake area since the 1960's (Averill and Zimmerman, 1986). Geochemical and heavy mineral analyses of lower till samples reflect known gold occurrences and also indicate the presence of other previously undetected sources (Campbell, 1986). Forty-one per cent of the samples analyzed contained gold. Due to the presence of numerous gold showings, the threshold gold value for the lower till is high, 40 ppb (< 0.1 mm fraction) in the region just west of Waddy Lake. Excluding this anomalous population, the threshold gold value drops to 20 ppb (< 0.1 mm fraction). The gold grain counts varied from 0 to 300 with a threshold value of 10 gold



A. *Lithologic log from augerhole at Deschambault Lake.*





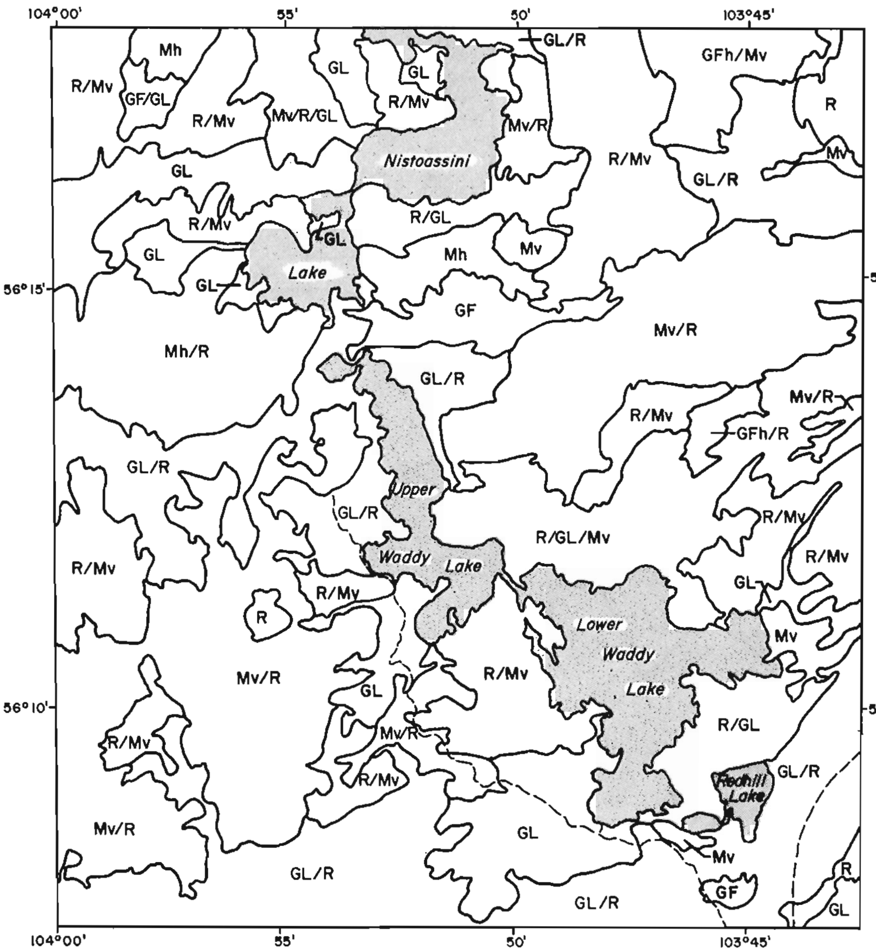
B. *Lithologic log from augerhole at Jaysmith Lake.*

Figure 4. Lithologic logs of till overlying lacustrine and fluvial sediments which are underlain by an older till deposit. Approximate locations are shown on Figure 2 (Modified from Schreiner, 1984).

grains per bulk till sample. Seventy-five per cent of the grains are irregular to delicate based on a classification scheme established by S.A. Averill, Overburden Drilling Management Ltd. The grain size of the gold grains ranges from $<50\mu m$ to $>1500\mu m$ with 70 % $<20\mu m$ and only 3 % $>500\mu m$. The gold appears to be associated with the fine sand-silt fraction of the till.

The size of the gold grains in the till reflects the fine-grained nature of gold mineralization in the area. Although there is only a weak correlation between gold in the fine and heavy mineral fractions, for many of the samples analysis of either fraction indicated the presence of gold in the till. However, a number of samples have anomalous values in only the fine fraction. This probably is due to the fine nature of the gold mineralization or the presence of gold occluded with other minerals and lost during heavy mineral separation (Sopuck et al., 1986). Based on present geochemical, mineralogical and lithological studies, gold itself is the best pathfinder (Averill and Zimmerman, 1986; Harper, 1984, 1985; Mellinger, 1986).

Examples of dispersal trains in the lower till in this region have been well documented. The EP gold zone was discovered by tracing the auriferous lower till of the Riddle train beneath lake sediments (Averill and Zimmerman, 1986). Bulk till surveys at Star and Tower Lakes outline distinctive surface dispersal trains extending down-ice from the known sources (Sopuck et al., 1986).



LEGEND

R - bedrock
M - moraine (till)
Mv - moraine veneer (<3m); mainly silty-sand till
Mh - hummocky moraine veneer; mainly sandy till
GL - glaciolacustrine sediments (silt and clay)
GLd - glaciolacustrine deltaic sediments (sand and silt)
GF - glaciofluvial (sand and gravel)
Op - muskeg (organics)

Explanation of terrain complexes

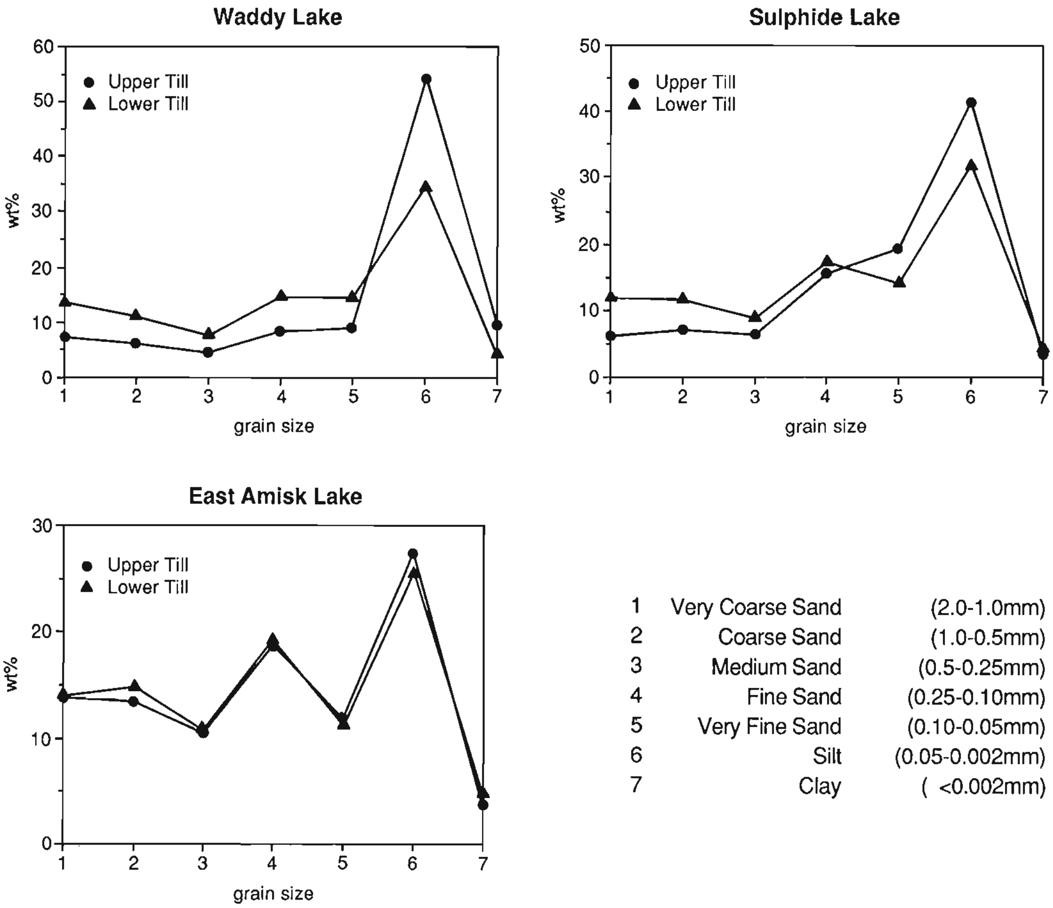
GL/R - Primary/Secondary

Figure 5. Generalized surficial geology of the Waddy Lake area.

Drift Prospecting Problems

Since 65 to 70 % of the surface material is bedrock or locally-derived till, surface sampling methods have been applied successfully in the Waddy Lake area. However, there are several problems. The narrow dispersal trains may overlap because the mineralization strikes parallel to the ice flow. These trains can be undetected if sampling stations are too far apart. The possibility of multiple sources must be considered when interpreting geochemical results.

The upper till and lacustrine material complicate surface sampling and interpretation of the geochemical results. Although the upper till is discontinuous, identification of the till, if present, is essential to proper sampling. In approximately 15 to 20 % of the area, surface exploration techniques will be affected by the glaciolacustrine silt and clay cover particularly in the area southeast of Waddy Lake, where this cover exceeds 20 m in thickness. The presence of lake sediments constitutes the major impediment to gold exploration in the area. Nearly all the gold prospects found to date are located above the 427 m elevation (Sopuck et al., 1986). The exception is the EP gold zone near Round Lake, which was discovered beneath the lacustrine cover (Averill and Zimmerman, 1986). A thin but discontinuous veneer of sand is present in the area. It is not related to the underlying till unit and has been found to be unsuitable for drift



1	Very Coarse Sand	(2.0-1.0mm)
2	Coarse Sand	(1.0-0.5mm)
3	Medium Sand	(0.5-0.25mm)
4	Fine Sand	(0.25-0.10mm)
5	Very Fine Sand	(0.10-0.05mm)
6	Silt	(0.05-0.002mm)
7	Clay	(<0.002mm)

		Waddy	Sulphide	East Amisk
Upper till	sand	36.2	54.8	68.6
	silt	54.3	41.7	27.7
	clay	9.5	3.5	3.7
Lower till	sand	61.5	63.8	69.5
	silt	34.5	31.9	25.7
	clay	4.0	4.3	4.8

Figure 6. Till textures: mean grain size distribution of till matrices in the study area shown as weight percent.

prospecting. This material has often been the main sampling medium for B-horizon soil surveys. Because there is good access in this area, both backhoe and overburden drilling are economical methods of subsurface sampling.

SULPHIDE LAKE AREA

Quaternary Geology

The distribution of surficial materials is shown in Figure 7. The areal distribution is: bedrock, 30 to 35 %; till, 30 to 35 %; glaciolacustrine sediments, 15 to 20 %; glaciofluvial sediments, <10 %; and organic materials, <10 %. Bedrock relief is high in this region, producing a rugged terrain which has influenced the local Quaternary geology. With the exception of low-lying areas, the drift is thin, and less extensive than in the Waddy Lake area. The average drift thickness is less than four metres but overburden drilling indicates thickness greater than 13 metres in topographic lows.

Crossing striae indicating two ice-flow directions were noted at four sites; an older set ranging in direction from 190° to 218° and the younger set from 212° to 240°. The most common ice-flow direction is 212° to 218° and represents the last major glacial advance in the late Wisconsinan. The ice-flow direction is sub-parallel to the regional bedrock geology (Campbell, 1987a).

Both the upper and lower till units found in the Waddy Lake area are present in the Sulphide Lake area. The tills vary considerably in texture, composition, colour and appearance throughout the study area reflecting the different source materials, modes of deposition, and postdepositional alteration. The till at the surface is generally weathered and/or reworked.

Althouth the upper till is thin (<1 m) and discontinuous, it is more prevalent than in the Waddy Lake area (Campbell, 1986, 1987a). In the field, it appears similar to the lower till. The upper till has a low clay content and a high silt to sand ratio (Fig. 6) reflecting the incorporation of the underlying sandy sediments. Generally, this till is completely oxidized.

Although the lower till is sandy (Fig. 6) and clast-rich, it is very similar to the lower till in the Waddy Lake area (Campbell, 1986). Variations in lithology reflect the changes in the local bedrock although the colour is commonly grey. This till was subglacially derived and has undergone short transport (<1 km). An ablation phase of this till has been noted in localized pockets throughout the study area.

A very sandy till, often associated with boulder lags, is also present in the area. It does not represent a separate till unit but rather the modification, primarily by wave action,

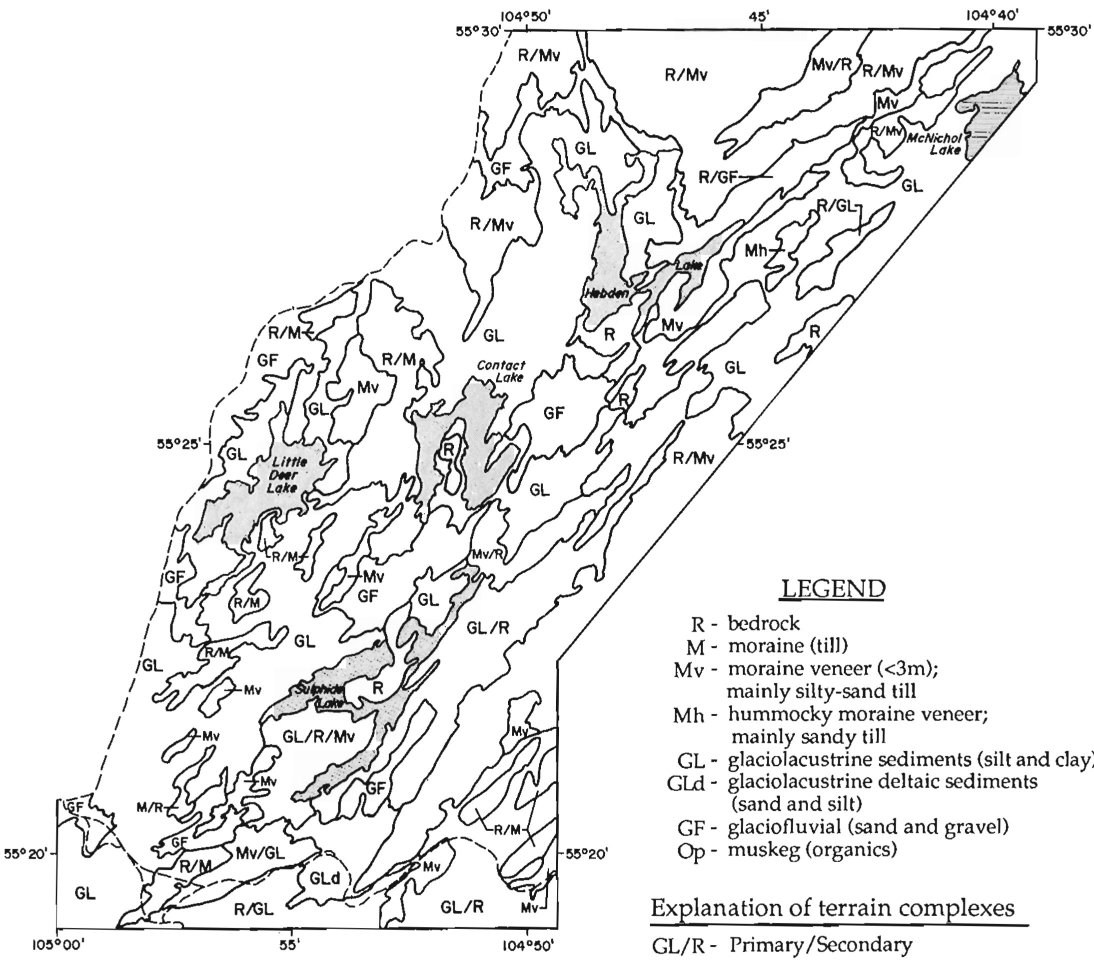


Figure 7. Generalizzed surficial geology of the Sulphide Lake area.

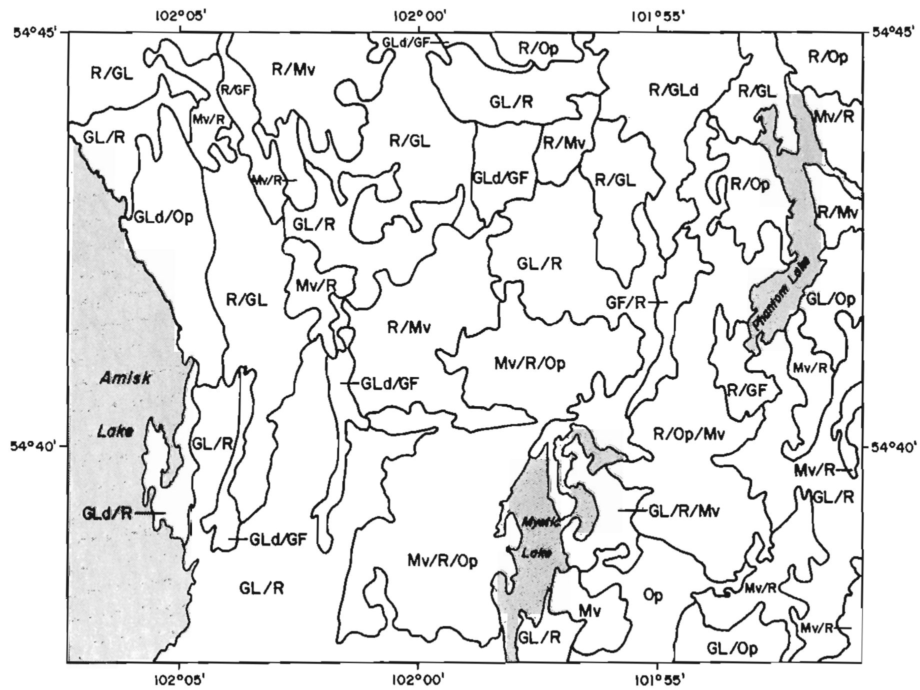
of existing till deposits, particularly the lower till. This till is relatively thin and patchy but widespread throughout the study area. In places it overlies undisturbed lower till.

Lake sediments comprising sandy-silt are found up to an elevation of 419 m but for the most part occur below 410 m. The highest evidence for Lake Agassiz are wave-cut terraces and a cobble beach at approximately 427 m. Due to the higher relief and rugged terrain, the effects of Lake Agassiz are much different than at Waddy Lake. Erosional features, indicative of a higher-energy environment, are common and wave-cut terraces and associated boulder lags commonly ring highlands. There is a widespread evidence of till that has been winnowed by wave action. Lacustrine sediments are restricted to the low-lying or gentle relief areas.

There are several significant deposits of glaciofluvial material in the Sulphide Lake area (Fig. 7). A broad belt of interlobate ice-contact deposits extends along the western edge of the study area (Schreiner, 1984). Several sandy sandur and fluviolacustrine plains occur throughout the study area. Overall, the surficial deposits are thinner and less extensive than in the Waddy Lake area (Campbell, 1986).

Gold Occurrence in Till

Gold dispersal in the lower till reflects known gold occurrences in this area. Regionally, the content of gold in the lower till is low in comparison to Waddy Lake (Campbell, 1986, 1987a). Regional geochemical threshold values for gold for the fine fraction (<0.1 mm) are 20 ppb and 1 visible gold grain in the heavy mineral fraction. Only 19 % of the samples analyzed contained visible gold. Gold grain counts varied from 0 to 100, and the grains ranged in size from <50 μm to 500 μm. The gold does not appear to be associated with any particular grain size. Sixty per cent of the gold grains are irregular to delicate. This suggests the nature of the primary gold varies with the type of mineralization, and with the size and form of the mineral deposit. The till geochemistry reflected a trend of bedrock enrichment in gold, arsenic and copper east of Contact and Hebden Lakes (Fig. 7). Otherwise, on a regional scale, gold is the best indicator of mineralization. Dispersal trains with known sources have not been located to date, although several anomalous areas have been delineated.



LEGEND

R - bedrock
M - moraine (till)
Mv - moraine veneer (<3m); mainly silty-sand till

GL - glaciolacustrine sediments (silt and clay)
GLd - glaciolacustrine deltaic sediments (sand and silt)
GF - glaciofluvial (sand and gravel)
Op - muskeg (organics)

Explanation of terrain complexes

GL/R - Primary/Secondary

Figure 8. Generalized surficial geology of the East Amisk Lake area.

Drift Prospecting Problems

In the La Ronge Domain, drift prospecting may be complicated by several factors: 1) drift that can be sampled effectively is less extensive; 2) topographic lows are commonly filled with stratified sediments; 3) the lower till is the preferred sampling media; however, the upper till is more prevalent in this area; 4) due to its similarity to the lower till, upper till is difficult to identify except where both tills occur at one site; and 5) the till is often weathered and/or reworked where exposed. The reliability of the gold content in this type of deposit depends on the degree of disturbance and on the transport distance of the material. Winnowing due to wave action will create anomalies that are more difficult to trace back to the source.

Glaciofluvial deposits inhibit surface sampling in several locations. The interlobate moraine along the western border of the study area is composed predominantly of sand and gravel with localized till pockets. Collection of both glaciofluvial and till samples would greatly complicate the interpretation of a geochemical survey conducted over this deposit. Extensive sandur plains occur in the central and southern portions of the area. Overburden drilling has shown that till deposits have been eroded from many of the topographic lows and the stratified sediments lie directly on bedrock.

Although glaciolacustrine sediment is not as widespread or thick as in the Waddy Lake area (Campbell, 1986, 1987a), it is still an impediment to surficial geochemical surveys. All organic deposits tested were underlain by lake sediments >1 m in thickness. The rugged terrain and limited access in the Sulphide Lake area limit the use of a backhoe or overburden drill for subsurface sampling.

EAST AMISK LAKE AREA

Quaternary Geology

The entire study area was inundated by glacial Lake Agassiz, yet bedrock and till are the dominant surface deposits. Lake sediments occur sporadically throughout the area and reworking of tills and other deposits is evident. As illustrated in Figure 8, the approximate proportions of the surficial materials are: 40 % bedrock, 25 to 30 % glacial till, 15 to 20 % glaciolacustrine silts and clays, 10 to 15 % organic material and <5 % glaciofluvial sand and gravel. Drift cover is thin, discontinuous, and highly variable in composition, in comparison to the areas in the La Ronge Belt (Campbell 1986, 1987a) with the exception of the south part of the East Amisk Lake area, where bedrock relief is lower. Based on hand-dug test pits and drillholes, the average drift thickness is <3 m but depths greater than 21.5 m have been recorded in topographic low areas (Campbell 1987b).

Glacial striae, grooves and roche moutonnées are prevalent throughout the study area. A set of crossing striae indicate an older ice movement direction ranging from 190° to 208° with a younger direction of 216°, suggesting a readvance in a slightly more southwesterly direction. The most common ice-flow direction noted ranged from 204° to 208°.

As in the La Ronge Domain, two till units are present in the Amisk Lake area. Both tills differ texturally from those found in the La Ronge Domain (Fig. 6). The lower till in the East Amisk Lake area is sandier than in the La Ronge area, has a higher sand to silt ratio but has similar clay content. The clast content is also higher. This till is locally derived and, for the most part, is a result of subglacial deposition. It is the most widespread till and often underlies the upper till or stratified sediments.

The upper till is thicker and more widespread in this region, although it is less than two metres thick and occurs only sporadically throughout the area. This till is typically brown, due to oxidation, with a silty-sand matrix and a low percentage of small rounded clasts. Its texture is similar to the lower till with only a slightly higher silt content (Fig. 6). The incorporation of bedrock, lower till and stratified sediments during the readvance may account for the coarseness of the upper till matrix in comparison to the upper till in the La Ronge Domain, where lake sediments are more prevalent. Two depositional phases of this till, ablation and subglacial meltout, were recognized in several exposures.

Glaciofluvial deposits occur predominantly in association with deltaic sediments and are interpretated as having been deposited in an ice-contact/glaciolacustrine environment at the ice sheet front during deglaciation. They may be associated with an ice-frontal position mapped to the northwest of the study area (Schreiner, 1984). Small kame-like gravelly deposits and channel fills are also associated with this ice-frontal environment. Till has been noted on topographic highs within these deposits.

The glaciolacustrine sediments are commonly restricted to gently sloped and low-lying areas, and predominate around Amisk Lake and in the south part of the area. Glaciolacustrine sediments extend to an elevation of 338 m but generally occur below 320 m. As the maximum level of glacial Lake Agassiz is estimated to have been 400 to 427 m, complete submergence of the study area is probable (Schreiner 1983, 1984).

Organic terrain constitutes a greater percentage of the surface deposits than in the other study areas. Muskeg occurs sporadically throughout the area. However, in the southeast portion of the area, the terrain is dominated by large organic deposits interspersed with outcrop ridges. Limited drilling of several large organic deposits indicates that they are commonly underlain by glaciolacustrine sediments. Often a thin till unit is encountered directly above bedrock.

Gold Occurrence in Till

Gold was found, by geochemical and visual analyses, in both the upper and lower tills. This is probably due to the greater amount of outcrop and associated mineralization exposed to erosion by the readvancing ice. The sporadic occurrence of the upper till makes it difficult to trace mineral dispersal in this unit. The results of geochemical analysis of the lower till reflected known mineral occurrences (gold, copper, zinc, tungsten, etc.) and outlined regionally anomalous areas such as Phantom Lake.

Regional threshold values for gold in the East Amisk area are 17 ppb in the fine fraction (<0.1 mm) and 5 gold grains for the heavy mineral fraction. There is no correlation between gold in the fine and heavy mineral fractions. Ninety-one per cent of the bulk till samples contained visible gold. The gold grain counts varied from 0 to 13 and the grains ranged from <50 μm to 800 μm in size. The gold is predominantly fine grained (94 % <200 μm) and appears to be associated with the silt and clay fractions. The gold grains are primarily irregular (46 %) to abraded (45 %) in shape. The large grains tend to be irregular to delicate.

Regionally, gold does not appear to be associated with any particular minerals which may be expected, because several types of gold mineralization occur in the area. However, the till geochemistry reflects the various mineralogical relationships down-ice from known gold occurrences. Although no glacial dispersal trains have been delineated in the East Amisk Lake area, the regional structural trends and ice movement direction would result in fan-shaped glacial dispersal trains. Preliminary geochemical results suggest bulk till sampling is more effective than soil sampling for regional geochemical surveys in this area.

Drift Prospecting Problems

Drift prospecting by surface sampling has limited application in the East Amisk Lake area. The major impediment to surface geochemical surveys in this area is the stratified drift cover and the organic material underlain by thick glaciolacustrine sediments. Backhoe trenching and overburden drilling would be necessary to obtain bulk till and bedrock samples for prospecting in these terrains. Because much of this area is accessible by road, these methods of exploration should be cost-effective.

Geochemical surveys are complicated by the presence of two till units and by the occurrence of gold in both tills. Proper identification of the upper and lower till as well as the various depositional facies is necessary to ensure effective sampling and accurate interpretation of the results. Soil surveys are not recommended in the area downwind from the stack in Creighton. Geochemical analyses have shown elevated values of sulphide elements in the B-horizon, because of contamination by stack emmissions.

IMPLICATIONS FOR GOLD EXPLORATION

Quaternary Geology

Because 60 to 70 % of the La Ronge and Flin Flon domains are covered with till, drift prospecting is becoming an increasingly popular method for mineral exploration. The Quaternary geology and gold occurrence in till for the study areas are summarized in Tables 1 and 2, respectively. Similarities among these three areas make regional extrapolations possible concerning Quaternary geology conditions and gold occurrence in till as well as concerning problems associated with drift prospecting. However, each study identified local variations illustrating the need to document the local Quaternary conditions prior to the commencement of geochemical surveys.

Information on the local ice flow directions is critical in determining the dispersal of trace mineralization. Various factors affecting ice movement, such as bedrock topography, the orientation of linear mineralized structures with respect to the ice flow direction, and the form of mineralization will create different dispersal patterns.

Throughout the southwestern portion of the Shield, bedrock and till are the dominant surface materials. As drift is generally thin, surface sampling can be done effectively and inexpensively.

The most widespread till in both domains is the lower, grey, silty sand till. The till was subglacially derived and has undergone relatively short transport distances. Lithological variations in this till reflect changes in the local bedrock source. Gold occurrences in the lower till can be traced to their origins.

Table 1. Comparison of the Quaternary geology in the Waddy Lake, Sulphide Lake, and East Amisk Lake areas

	Waddy Lake	Sulphide Lake	East Amisk Lake
• Ice direction	south	southwesterly	southwesterly
• Drift cover	70%	65%	55-60%
• Drift thickness	5 m	3 m	<3 m
• Upper till	clayey-silt	silty-sand	silty-sand
• Lower till	greenish	greyish	greyish
• Lake Agassiz	silty sediment lacustrine cover	sandy sediments reworking of till	clayey-silt sediments lacustrine cover
• Soils	moderate	well	moderate
• Weathering	moderate	intense	moderate

Table 2. Comparison of the gold occurrence in till in the Waddy Lake, Sulphide Lake, and East Amisk Lake Areas

	Waddy Lake	Sulphide Lake	East Amisk Lake
• Till	lower	lower	both
• Size	fine	fine to coarse	fine
• Shape	75% irregular to delicate	60% irregular to delicate	91% irregular to abraded
• Count (threshold value)	10 grains	1 grain	5 grains
• Geochemistry (threshold value)	20 ppb	20 ppb	17 ppb
• Trains	long and narrow (ribbon)	long and narrow (ribbon)	flame shaped?

The ablation phase of this till occurs in small localized deposits. It is characteristically a loose, gravelly, brown to grey, sandy till. The upper till, derived from a readvance into the Lake Agassiz basin, is prevalent but sporadic through the area. It is commonly a thin, brown, clayey silt to sandy silt till rarely found lying directly on bedrock. These deposits are not preferred sampling media as they are composed of material that has undergone long and/or multiple transport making it difficult to find their sources.

Glacial Lake Agassiz, as well as other minor glacial lakes, covered much of the southeastern portion of the Shield. Its deposits are extensive but discontinuous, generally occurring below 427 m in the La Ronge Domain and below 320 m in the Flin Flon area. The thickness of these sediments is highly variable, ranging from <1 m to >20 m. With the exception of the EP gold zone, all known gold occurrences are found above these lake deposits, illustrating the effectiveness of the silts and clays in inhibiting mineral exploration by sealing off anomalous bedrock and till from any surface expression. Areas covered by glaciolacustrine and fluvial deposits remain virtually unexplored. Recent use of improved backhoes and overburden drills have proved effective for drift prospecting in this type of terrain.

Boulders, cobbles, and pebbles are common in the silts, especially overlying till or bedrock. In areas with high concentrations of clasts, the silt may be misinterpreted as till.

Organic deposits, depending on their thickness and extent, can inhibit geochemical surveys. These deposits are commonly underlain by glaciolacustrine silts and clays. Humus samples can be effective in defining gold zones in bedrock if the lacustrine deposits are less than one metre thick (Rampton et al., 1984, and Sheehan and Gleeson, 1984). Where organic deposits are extensive, the most useful drift prospecting technique is overburden drilling.

Glaciofluvial sand and gravel are not very prominant but can complicate drift sampling programs locally. The largest deposit occurs in the La Ronge Domain in the form of an interlobate moraine. Although small till deposits occur within this moraine, surficial geochemical surveys are not recommended. In many areas, a thin sandy veneer (<1 m thick) is often present. It commonly forms the B-horizon of the soil and has been the sampling medium for soil surveys. This is not a suitable medium as anomalies may be due to concentrations of heavy minerals by water.

Soil Implications

There are several pedological factors which must be taken into account when conducting soil and bulk till surveys. Brunisolic soils are the most prominent soils sampled. Factors involved in the formation of this soil should be considered. The soil profiles are generally well developed. The leached Ae-horizon can be >30 cm deep and must be avoided when sampling. The B-horizon is often highly oxidized and greater than 100 cm deep. Elevated gold values due to the presence of hydromorphic gold may be encountered when using this soil horizon for sampling. This means bulk till sample pits commonly must be greater than one metre deep to obtain parent material (C-horizon). Silt and clay translocation from the upper part of soil profile to the lower part of the B-horizon and into the C-horizon by pedogenic processes have been noted in this region. This is manifested by fine sediment coatings on the upper side of pebbles. Work carried out in the SRC laboratory has shown that a significant amount of fine gold is tied up in these coatings. Therefore, care must be taken to include this material in any analyses.

Gold Occurrence in Tills

From detailed descriptions of known dispersal trains and gold grain characteristics in the La Ronge area (Averill and Zimmerman, 1986; Campbell, 1986, 1987a; Sopuck et al., 1986) the till geochemistry appears to reflect the nature of its mineralized source. Gold is its own best pathfinder in drift prospecting since it is rarely associated with other minerals. The morphology and chemistry of the gold grains in till resemble known gold sources. Heavy mineral concentrates and description of gold grains from bulk till samples have proven to be the most effective in depicting dispersal trains at greater distances from the source (Sopuck et al., 1986; Sopuck and Earle, 1987).

Results from the three study areas indicate that regionally there is no correlation between the gold content in the fine (<0.1 mm) and heavy mineral fractions. In some anomalous samples, the gold is found in only one of the fractions analyzed. This may be due to one or more reasons, such as; type of mineralization, size of gold grains, the presence of occluded gold, analytical error and/or sample contamination. Since the clay content of the lower till seldom exceeds 10%, loss of gold in clay is minimal (Sopuck et al., 1986). Therefore, in addition to heavy mineral concentration and analysis followed by gold grain documentation, analysis of the fine (<0.1 mm) fraction is recommended to ensure results that are representative of the total gold content of the till samples.

Concluding Statement

Studies in the La Ronge and Flin Flon domains have illustrated that the method and application of drift prospecting varies from area to area. Establishing both the regional Quaternary geological setting and local site characteristics are essential for geochemical drift sampling programs. This involves identifying the drift deposits, their characteristics, their origin and significance to prospecting. In conjunction with establishing the geological setting, the regional till geochemistry must also be determined to identify the nature of the gold and any associated minerals in the till. With this framework established, it is then possible to define the most dependable and productive sampling materials, and to choose the methods and analytical techniques to employ in the search for new gold deposits.

ACKNOWLEDGMENTS

The cooperation of the mining companies in allowing access to their properties is gratefully acknowledged. We thank the following people at the Saskatchewan Research Council for their assistance; Al Holstein for the geochemical analyses, W.C. Ross and Roy McKnight for the sedimentological analysis, and B. McIntosh for drafting and graphics work for the paper.

REFERENCES

Averill, S.A. and Zimmerman, J.R.
1986: The Riddle resolved: the discovery of the Partridge gold zone using sonic drilling in glacial overburden at Waddy Lake, Saskatchewan; Canadian Geological Journal of The Canadian Institute of Mining and Metallurgy, v. 1, no. 1, p. 14-20.

Campbell, J.E.
1986: Quaternary geology of the Waddy Lake area applied to prospecting for gold; Saskatchewan Research Council Report, R-842-1-E-86, 74 p.
1987a: Quaternary geology and till geochemistry of the Sulphide — Hebden lakes area; Saskatchewan Research Council Report, R-842-4-E-87, 74 p.
1987b: Quaternary geology of the East Amisk Lake area, applied to prospecting for gold; in Summary of Investigations 1987, Saskatchewan Geological Survey, Saskatchewan Energy and Mines, Miscellaneous Report 87-4, p. 148-150.

Canada Soil Survey Committee, Subcommittee on Soil Classification
1978: The Canadian System of Soil Classification; Canada Department of Agriculture, Publication 1646, 164 p.

Harper, C.T.
1984: Geological mapping, Waddy Lake area (Part of NTS 64D-4 and -5); in Summary of Investigations 1984, Saskatchewan Geological Survey, Miscellaneous Report 84-4, p. 6-20.
1985: Bedrock geological mapping, Waddy-Tower Lakes area (Part of NTS 64D-4 and 74A-1 and -8); in Summary of Investigations, 1985, Saskatchewan Geological Survey, Miscellaneous Report 85-4, p. 6-17.

Johnston, W.G.Q.
1978: Lake Agassiz's northernmost arm and other features of the Quaternary geology in the region around the southern part of Reindeer Lake, northern Saskatchewan; Musk-Ox, University of Saskatchewan, no. 21, p. 39-50.

Mellinger, M.
1986: Lithogeochemistry related to gold mineralization in Saskatchewan; in Gold in the Western Shield, ed. L.A. Clark; The Canadian Institute of Mining and Metallurgy; Special Volume 38, p. 253-271.

Rampton, V.N., Gleeson, C.F., Thomas, R.D., and Paradis, S.
1984: Geochemical exploration in areas of shallow tills; A paper presented at the Canadian Institute of Mining and Metallurgy? Ontario Geological Survey Till Tomorrow'84 Symposium, Kirkland Lake, Ontario, 1984.

Schreiner, B.T.
1983: Lake Agassiz in Saskatchewan; in Glacial Lake Agassiz, eds. J.T. Teller and L. Clayton; Geological Association of Canada Special Paper 26, p. 75-96.
1984: Quaternary geology of the Precambrian Shield, Saskatchewan; Saskatchewan Energy and Mines, Report 221, 106 p.
1986: Quaternary geology as a guide to mineral exploration in the southeastern Shield, Saskatchewan; Saskatchwan Research Council Report 189, 39 p.

Schreiner, B.T. and Alley, D.W.
1975: Quaternary geology, Lac La Ronge Area (73P), Saskatchewan; Saskatchewan Research Council, Geology Division, DREE Quaternary North Program, Preliminary Map 1.

Sheehan, D. and Gleeson, C.F.
1984: Case histories of till prospecting over the Doyon, Bousquet and Williams gold deposits; A paper presented at the Canadian Institute of Mining and Metallurgy? Ontario Geological Survey Till Tomorrow'84 Symposium, Kirkland Lake, Ontario, 1984.

Sopuck, V.J., Schreiner, B.T., and Averill, S.A.
1986: Drift prospecting for gold in Saskatchewan; in Gold in the Western Shield, ed. L.A. Clark; The Canadian Institute of Mining and Metallurgy Special Volume 38, p.435-469.

Sopuck, V.J. and Earle, S.A.M.
1987: Geochemical methods for gold exploration in northern Saskatchewan; Geological Association of Canada, Program with Abstacts, vol. 12, p. 90.

Models of glacial stratigraphy determined from drill core, Matheson area, northeastern Ontario

K.G. Steele[1], C.L. Baker[1] and M.B. McClenaghan[2]

Steele, K.G., Baker, C.L., and McClenaghan, M.B., Models of glacial stratigraphy determined from drill core, Matheson area, northeastern Ontario; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 127-138, 1989.

Abstract

An overburden drilling program in the Matheson area of northeastern Ontario has enabled the identification of six basic glacial (Quaternary) stratigraphic models. Stratigraphy and/or trace element chemical data were used to separate drift associated with different glacial events. One model contains drift from three glacial events and represents the composite stratigraphy of the Matheson area. Three models include Matheson drift and Middle drift, which are associated with ice advancing toward 170° and 240° respectively. Two models, representing approximately 70 % of the holes drilled, contain only Matheson drift. The composite stratigraphy of the Matheson area can be correlated with Quaternary stratigraphic sequences encountered in the Timmins area and in northeastern Quebec.

Résumé

Un programme de sondage des morts-terrains de la région de Matheson dans le nord-est de l'Ontario a permis de reconnaitre six modèles stratigraphiques glaciaires (Quaternaire) de base . Les données stratigraphiques et chimiques des éléments en traces ont été utilisées pour distinguer les matériaux de transport glaciaires associés à différents événements glaciaires. Un modèle renferme les matériaux de transport glaciaires de trois événements glaciaires et représente la stratigraphie composite de la région de Matheson. Trois modèles renferment les matériaux de transport glaciaires de Matheson et de Middle qui sont associés à des avancées glaciaires respectives en direction de 170° et 240°. Deux modèles, représentant environ 70 % des trous forés, contiennent seulement les matériaux de transport glaciaires de Matheson. La stratigraphie composite de la région de Matheson peut être corrélée avec les séquences stratigraphiques du Quaternaire observées dans la région de Timmins et dans le nord-est du Québec.

[1] Ontario Geological Survey, 77 Grenville St., Toronto, Ontario, Canada M7A 1W4
[2] Department of Geological Sciences, Queen's University, Kingston, Ontario, Canada K7L 3N6

INTRODUCTION

The Ontario Geological Survey has undertaken a reconnaissance-scale overburden drilling project in the Matheson area of northeastern Ontario. The object of the project is to establish the glacial stratigraphy and a till geochemical database as an aid to mineral exploration. Interpretations presented in this paper are based on drill logs and analytical data from 102 holes drilled during 1984 and 1985, and preliminary results from 72 holes drilled in 1987.

The study area is 40 km east of the Timmins-Porcupine mining centre and 20 km north of the Kirkland Lake gold camp. The study area of approximately 3700 km^2 is located between the Ontario-Quebec provincial boundary and the Timmins city limits (Fig. 1). The town of Matheson is situated in the west-central portion of the area.

PHYSIOGRAPHIC SETTING

The study area is immediately north of the Hudson Bay — St. Lawrence River drainage divide and is located in the Great Clay Belt physiographic region. The area contains three generalized physiographic sub-regions: bedrock upland, clay plain and sand plain. A bedrock upland associated with the drainage divide extends into the southern portion of the study area. Small bedrock uplands occur throughout the central and eastern portions of the area. A flat clay plain covers extensive portions of the west and central regions. Varved clay deposits reach a maximum elevation of 381 m (Baker et al., 1982), below which most areas between bedrock knobs are infilled with clay. Major north-south oriented esker complexes rise above both the clay plain and the bedrock uplands. Across the study area, there is, on average, approximately 5 percent outcrop, with some townships totally devoid of outcrop.

BEDROCK GEOLOGY

The study area is centrally located in the Abitibi Greenstone Belt of the Superior Province. The area is predominantly underlain by mafic volcanic and sedimentary rocks of low metamorphic grade (Fig. 2). All rocks in the study area, except diabase dikes, are Early Precambrian (Archean) in age. The northern half of the area is largely underlain by tholeiitic, komatiitic and calc-alkalic volcanic rocks of the Hunter Mine and Stoughton-Roquemaure Groups (Jensen and Langford, 1983). Two belts containing Porcupine Group sedimentary rocks, and various mafic and ultramafic layered sills are also found in the northern portion of the study area. Mafic and intermediate volcanic rocks of the tholeiitic Kinojevis Group and calc-alkalic Blake River Group (Jensen and Langford, 1983) underlie most of the southern half of the area. Isolated trondhjemite and granodiorite stocks and batholiths are found throughout the study area. All Early Precambrian rocks are cut by Late Precambrian diabase dikes.

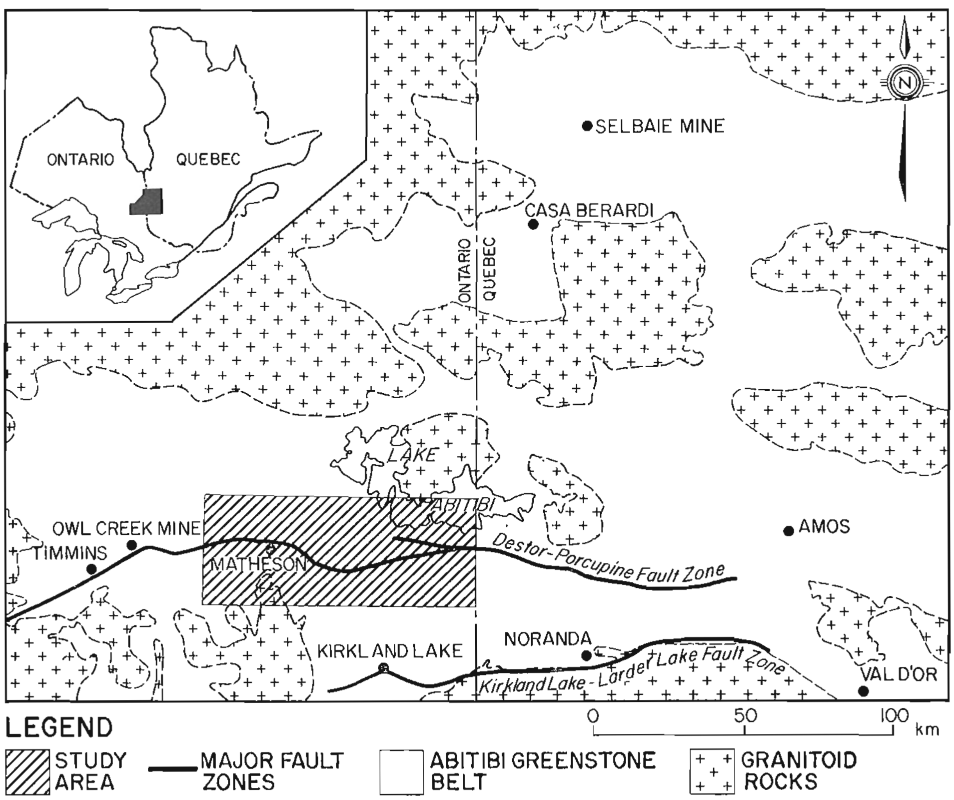


Figure 1. Location of the study area.

Structurally, the study area contains the northern limb of the Blake River Synclinorium, a large west-striking structure bounded by two major sub-vertical fault zones: 1) the Destor-Porcupine Fault Zone along the northern edge, and 2) the Kirkland Lake-Larder Lake Fault Zone to the south (Fig. 1). Both fault zones are important because of the numerous gold deposits and showings which are associated with them.

In the Matheson area, gold exploration has been successful along the Destor-Porcupine Fault Zone, but only where it outcrops or is covered by thin drift. Gold has been found within quartz or quartz-carbonate veins either along the fault zone or within faults related to it.

Away from areas with thin drift, there has been limited exploration success for gold in the study area. East-west oriented faults, the zones with the greatest potential for gold mineralization, tend to form bedrock valleys and are often covered by thick drift.

SURFICIAL GEOLOGY

The most recent ice mass to cross the study area is considered to be of Late Wisconsinan age. This advance is responsible for, or has directly influenced, the deposition of all Quaternary sediments exposed at surface. Overburden drilling has indicated that pockets of older material exist at depth.

The most recent ice advance produced striae and associated directional features indicating regional ice flow was to the southeast at approximately 170°. Older striae oriented at 240° have been noted on some bedrock faces protected from the most recent glacial advance. These ice flow directions are consistent with the findings of Veillette (1986) who completed an extensive study of striae and other ice flow indicators in the Abitibi region of northwestern Quebec. Veillette's work is discussed in the Regional Quaternary section of this paper.

The ice front receded northward through the region approximately 10 000 years B.P. (Prest, 1970; Baker, 1980). At that time the area was inundated by the waters of glacial lakes Barlow and Ojibway. Fine-grained sediments were deposited on the lake bottom (Fig. 3). Meltwater flowing from the ice mass into the glacial lakes deposited sand and gravel in the form of eskers and ice-contact deltas.

Surficial Deposits

Till

The uppermost till unit in the region has been informally referred to as the Matheson formation by Hughes (1959). On surface this till occurs as a thin, discontinuous veneer on the bedrock uplands. The till is highly oxidized and weathered to at least 1.0 m depth. In the subsurface, this till has been reported to exceed 30 m in thickness, although it more commonly ranges from 0.5 m to 6 m in thickness. Its distribution is influenced by the high relief of the bedrock surface. The thickest till sequences are located at stoss and lee positions of bedrock knobs and in steep-sided bedrock valleys. Unoxidized till is generally massive and compact, with a sandy silt to silty sand matrix. Clast content varies from 5 to 25 percent. Clast angularity ranges from extremely angular to subrounded. In general, volcanic and

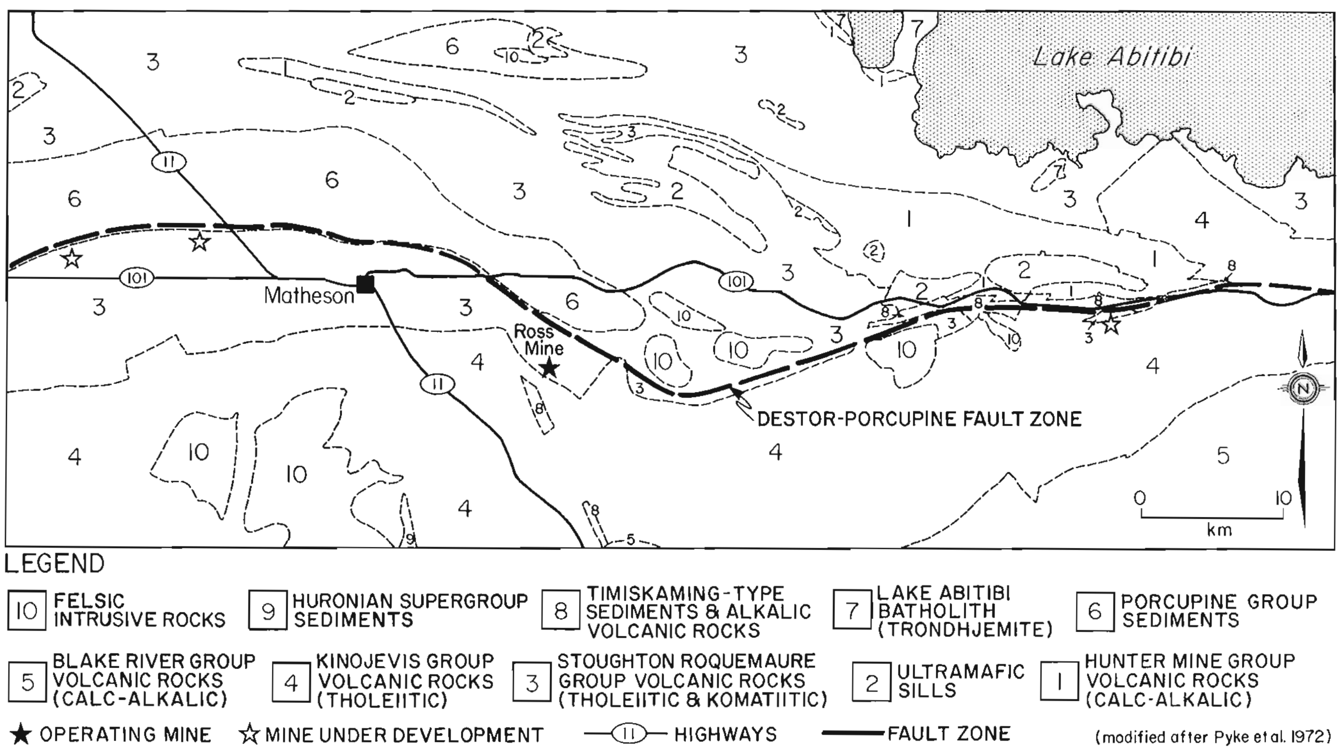


Figure 2. Bedrock geology of the study area.

sedimentary clasts are more angular than intrusive clasts. The majority of the till examined was interpreted to have been deposited subglacially by either lodgment or meltout processes. This was based on: 1) the abundance of locally derived clasts, 2) the overconsolidated nature of the till, and 3) clast shapes. In a number of locations stratified till was encountered. Most of this material is considered to represent flow till or debris flow deposition.

Ice-Contact Deposits

Esker systems contain the bulk of glaciofluvial deposits in the area. The orientation of most eskers follows bedrock lineaments and fault systems which trend to the north and northwest. The Munro Esker (Fig. 3) is by far the largest esker in the area; being 10 km wide and extending the 40 km width of the study area. Topography of the esker systems ranges from well defined crests flanked by kettles to flat plains mapped as sub-aqueous fans or deltas. The eskers are composed primarily of sand although layers of gravel are occasionally encountered. Ice-contact deposits not associated with eskers include small morainic ridges and kame deltas.

Glaciolacustrine Deposits

The deposits formed in glacial lakes Barlow and Ojibway have been formally named the Barlow-Ojibway Formation by Hughes (1965). The deposits can be divided into two units: 1) glaciolacustrine fine-grained sediments consisting of clay, varved clay and silt; and 2) coarse-grained material, primarily sand with minor gravel. Fine-grained deposits, mainly varved clay, form an extensive plain which onlaps bedrock uplands and esker complexes. In the study area, the average thickness of fine-grained materials is 17 m, although a maximum thickness of 75 m has been recorded.

The coarse-grained sediments have two principal origins: 1) a transitional facies from glaciofluvial sediments occurring along the sides of major esker complexes; and 2) reworking of glaciofluvial or till deposits in the high energy nearshore zone as the glacial lake level fell.

Swamp Deposits

Large areas of swamp are scattered throughout the region and usually occur on impermeable glaciolacustrine clay. Swamp deposits also occur in small bedrock basins in upland areas.

DRILL PROGRAM

The drill core data described in this paper were obtained from overburden drilling programs completed during 1984, 1985 and 1987. These programs were major components of a reconnaissance-scale till sampling project undertaken by the Ontario Geological Survey in the Matheson area. In areas of thick drift, a rotasonic overburden drill was used to recover cores for stratigraphic studies and geochemical sampling. During the period from 1984 to 1987, 174 holes were drilled (Fig. 4). Drilling was complemented by a program of till sampling by backhoe trenching in areas of shallow drift.

Drilling Method

The rotasonic drilling method utilizes both rotation and resonance on the drill string to obtain continuous, relatively undisturbed core from the ground surface into bedrock. No

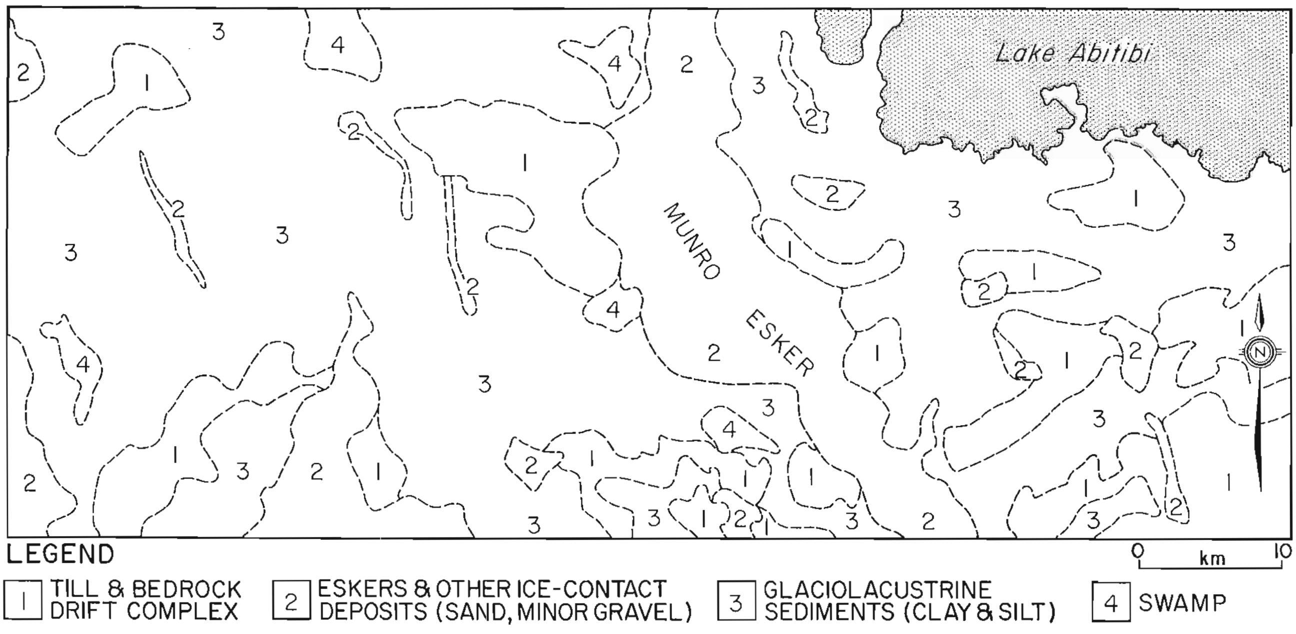


Figure 3. Surficial geology of the study area.

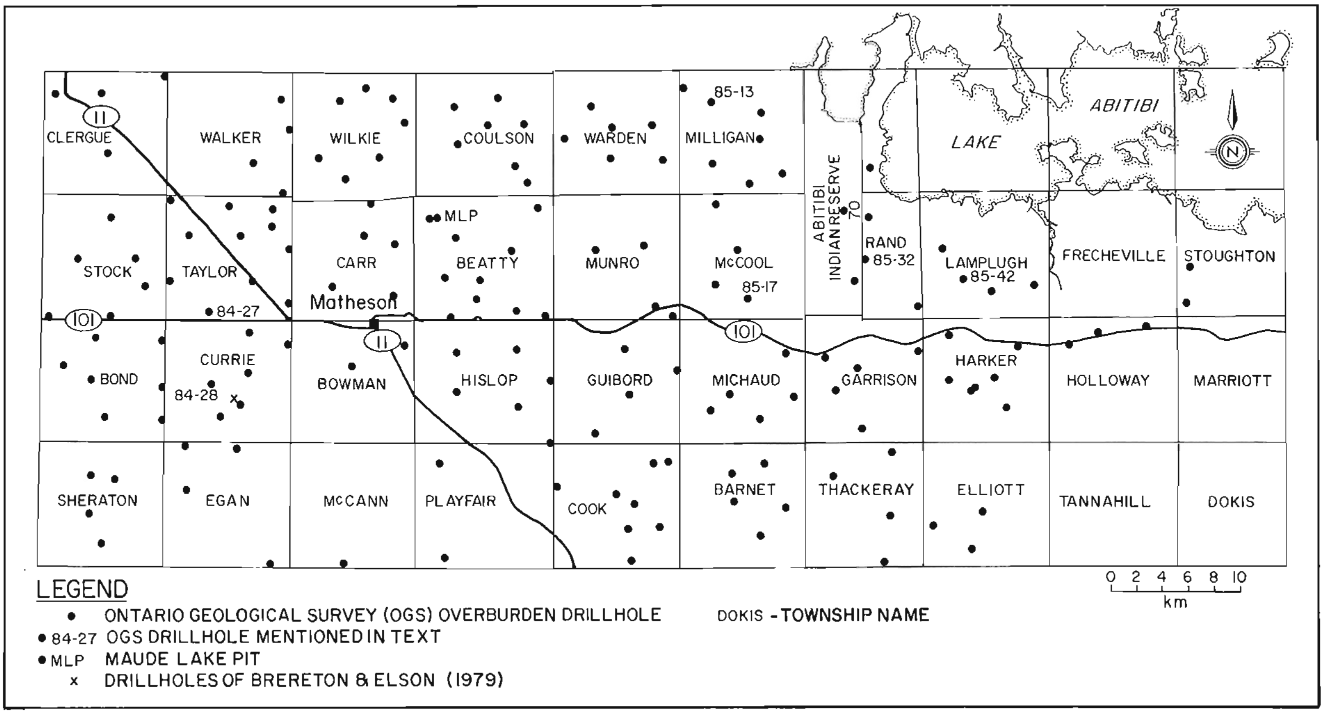


Figure 4. Drillhole locations and other data sites.

DATA AVAILABLE

DATA TYPE	FRACTION			CORE
	HMC	-63 µm	-2 mm	
	Geochemistry	Geochemistry	Geochemistry	Detailed Log
	Mineralogy	Carbonate	Major Oxides	Pebble Counts
	Gold Grain Counts		Texture	Weight Data

Figure 5. Data available.

drilling fluid is required, except when drilling bedrock and large boulders. The 88 mm diameter core allows interpretation of the stratigraphic record and depositional environments and the collection of large, complete samples for geochemical analyses. The rotasonic drilling methodology has been described in detail by Averill et al. (1986).

In order to recover the most "complete" glacial stratigraphic record present in the study area, many drillholes were sited over bedrock valleys oriented perpendicular to the most recent ice advance direction. These valleys were delineated through interpretation of airborne and ground electromagnetic geophysical data. Other drillholes were sited south of the Destor-Porcupine Fault Zone, in areas of complex or unknown geology, and in some areas to provide an even distribution of sample sites over the study area.

Sample Processing

All drill core was logged in detail, and till and glaciofluvial sand units were sampled. A 8 to 10 kg bulk sample and two 250 g samples were collected from each sample interval. The bulk samples were sent for heavy mineral separation. Processing steps are outlined on a flow chart presented in Baker et al. (1985). Mineralogical study of the heavy mineral (>3.3 s.g.) concentrates consisted of a 100-grain point count, plus a scan of the entire heavy mineral concentrate for indicator and accessory minerals. The nonmagnetic heavy mineral concentrates (HMC) were analyzed for: gold, arsenic, antimony, cobalt, chromium, uranium and tungsten by instrumental neutron activation analysis; silver, copper, lead, zinc, nickel and molybdenum by direct current plasma spectroscopy; and titanium and zirconium by X-ray fluorescence spectroscopy of a pressed disk.

From one of the 250 g samples, <63 µm and <2 mm subsamples were obtained. These fractions were analyzed for the same suite of trace elements as the HMCs. In addition, major oxide analyses were carried out on the <2 mm material. The second 250 g sample was submitted for till matrix (<2 mm) textural analysis and carbonate content determination on the <74 µm material (Dreimanis, 1962). A summary of the analytical data available for stratigraphic interpretations is presented in Figure 5.

GLACIAL STRATIGRAPHY

Six basic stratigraphic sequences have been identified from the drillhole data. These sequences differ in the number of till units, types of till as classified by depositional processes, and the amount and position of glaciolacustrine and glaciofluvial sediments. The six model sequences are presented and illustrated by field examples.

All drillholes encountered sediments deposited by, or associated with, the most recent southward flowing (170 degrees azimuth) glacial advance. Till deposited during this glacial event has been informally referred to as Matheson till. In this paper, Matheson till, overlying Barlow-Ojibway Formation sediments, and any intervening glaciofluvial sediments are referred to as Matheson drift. In approximately 30 % of the drillholes, sediments associated with an older glacial event or events were encountered. Sediments of these older glacial events have been informally termed Middle drift and Lowest drift.

Model 1 — Matheson drift — homogeneous till

The stratigraphic sequence of Model 1 contains only the Matheson drift consisting of Barlow-Ojibway Formation varved clay and silt overlying Matheson till on bedrock (Fig. 6). The till varies in thickness from 10 cm to greater than 30 m. In this model the complete till interval is homogeneous in appearance, texture, mineralogy and chemistry. At each drillhole for which this model is used, all till is believed to have been deposited by the same process.

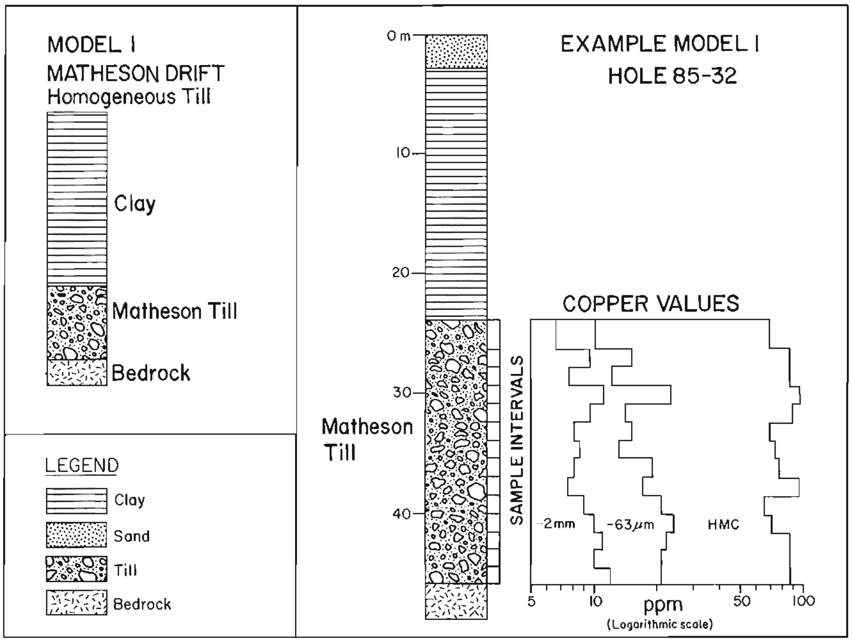


Figure 6. Model 1 — Matheson drift — homogeneous till

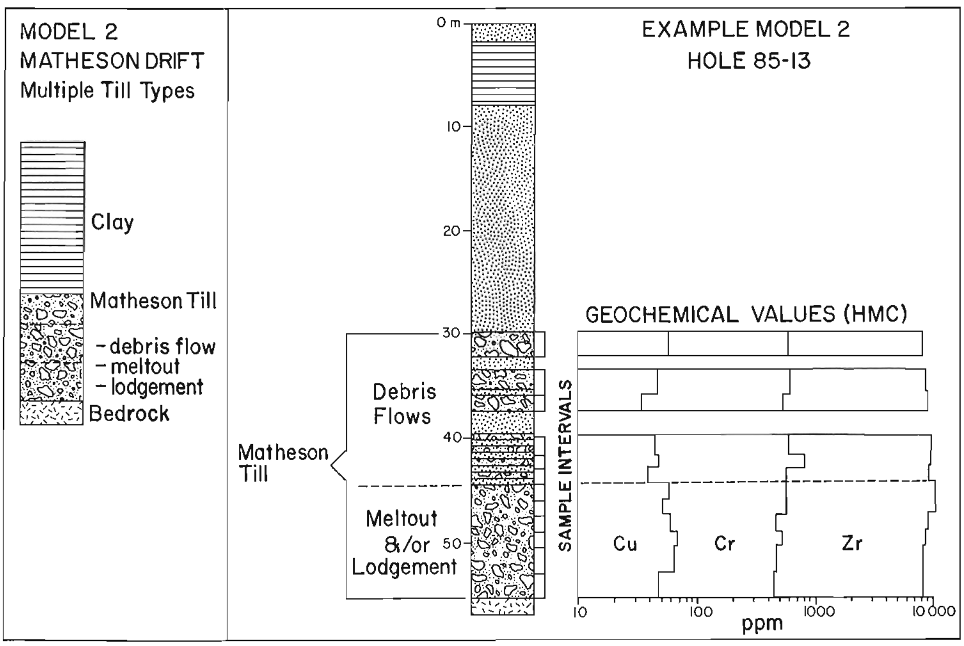


Figure 7. Model 2 — Matheson drift — multiple till types

Drillhole 85-32 is an example of Model 1 (Fig. 6). Copper values in each of the three sample fractions display relatively consistent downhole concentrations for the fourteen till samples. The spread of copper values within any fraction is attributable to the poor sorting of till. Most other elements determined are also relatively uniform in value for the fourteen till samples.

The logarithmic scale used in Figure 6 to present the copper values, emphasizes the different orders of magnitude of trace element values from the three sample fractions. Two generalizations can be made for all the data. For most elements in unoxidized samples, trace element values for the heavy mineral concentrates are 5 to 10 times larger than for the other two fractions. Secondly, values for <63 μm material are usually slightly larger than for the <2 mm material.

Model 2 — Matheson drift — multiple till types

Model 2 is similar to the first model in that only Matheson drift is present, however, Matheson till of Model 2 was deposited by two or more different processes (Fig. 7). During visual examination of the core, parameters such as matrix texture and sorting, structure, compactness, colour (particularly with respect to underlying bedrock colour), and clast lithologies and angularity, are combined to separate till units deposited by debris flow, meltout and lodgment processes. Usually, there are no, or only minor, geochemical and mineralogical differences between till intervals associated with the same glacial event but deposited by different processes.

In drillhole 85-13 (Fig. 7), till of the uppermost six samples is faintly laminated and interbedded with poorly sorted sand and occasional thin silt and clay layers. Till of this interval is interpreted to have been deposited as debris flows. The massive till below this interval was deposited by meltout and/or lodgment processes. All till samples, however, have similar chemical responses as illustrated by copper, chromium and zirconium values for the heavy mineral concentrates.

Model 3 — Drift from two glacial events

The stratigraphy of Model 3 consists of complete drift sequences from two glacial events (Fig. 8). The Matheson drift contains fine-grained glaciolacustrine sediments of the Barlow-Ojibway Formation overlying till. The older Middle drift has glaciolacustrine and/or glaciofluvial sediments overlying till, which usually rests on bedrock. In Model 3, there is an easily recognizable separation of the two drift sequences based on the stratigraphy. There is, in some instances, a significant corresponding discontinuity in the analytical data.

In drillhole 84-27, Matheson drift and Middle drift are well defined on the basis of stratigraphy (Fig. 8). Matheson drift occurs as interbedded till and sand overlain by clay. At the top of the Middle drift, a 1.2 m thick layer of alluvium containing shell fragments and organic material is present. The alluvium overlies 16 m of varved clay which was overconsolidated during a subsequent glacial advance. Chemical differences between till units of the two drifts are subtle. A major factor in the similar chemical values is that the ice sheets, from which these till units were deposited, advanced across the same bedrock lithologies up-ice of hole 84-27. If the till units were in contact, separating them on the basis of chemistry would be, at best, difficult. Plots of nickel, copper and chromium values for the heavy mineral concentrates illustrate these subtle differences (Fig. 8). In drillhole 84-27, the Matheson till has twice the clay content of the

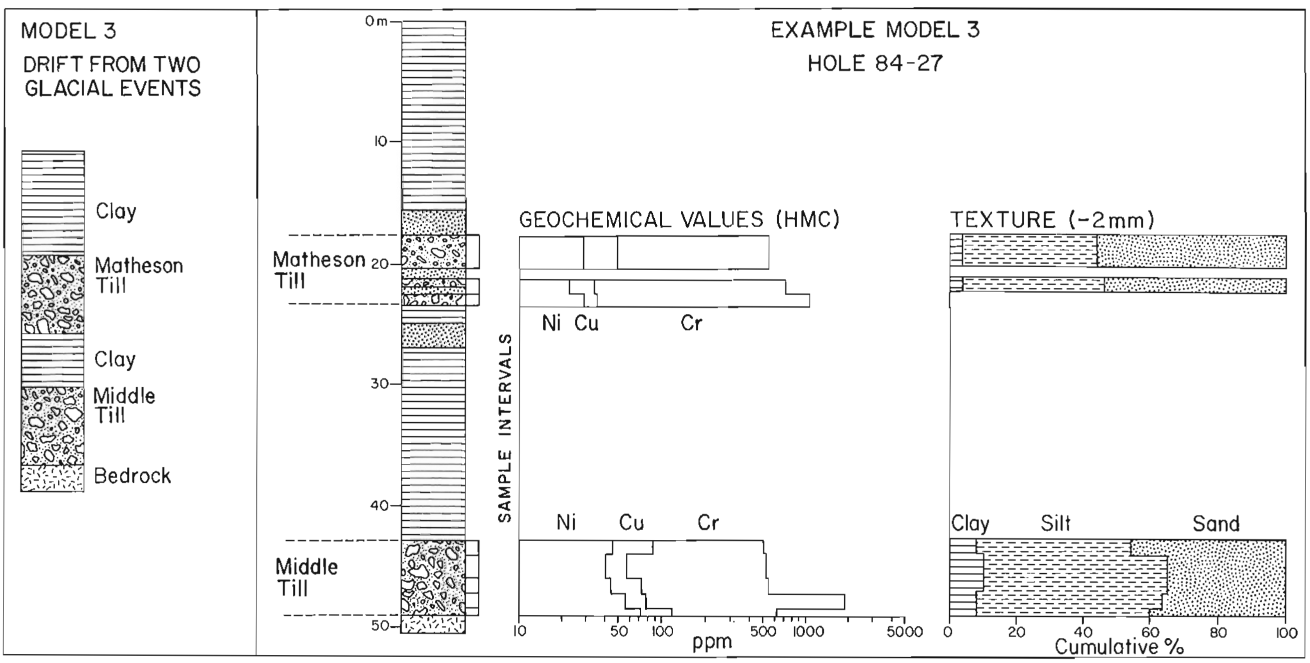


Figure 8. Model 3 — Drift from two glacial events

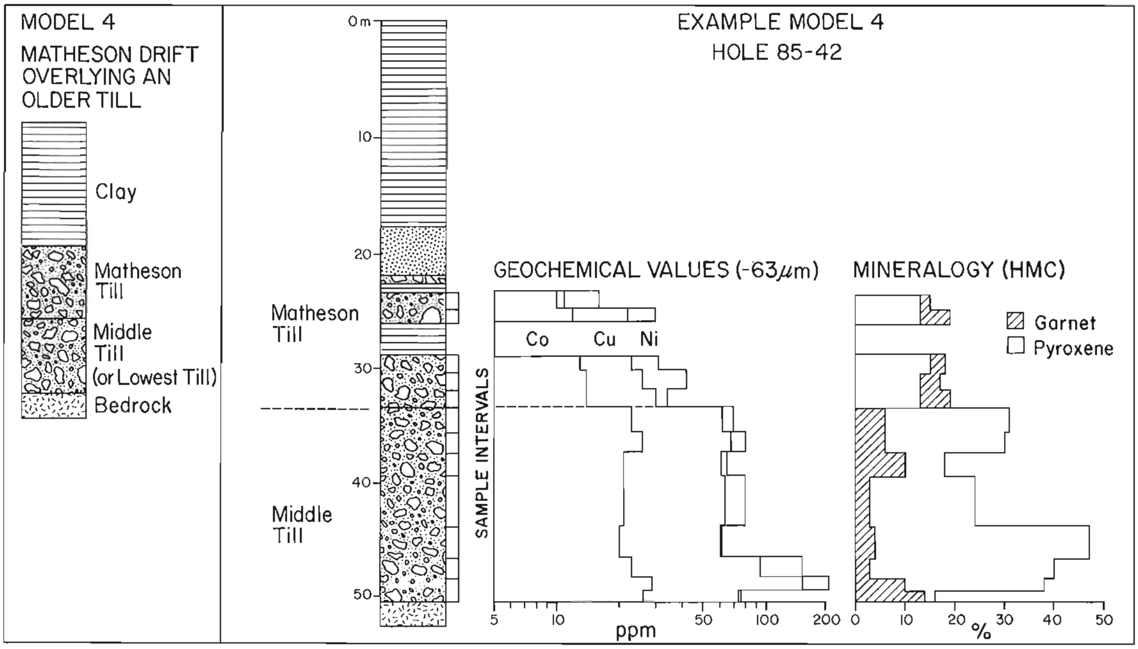


Figure 9. Model 4 — Matheson drift overlying an older till

Middle till, resulting from the incorporation of underlying glaciolacustrine sediments and from deposition by different processes. The textural data indicates distinct till units, though not necessarily associated with different glacial events. At this drillhole there are no discernible differences in the mineralogical data between the till units.

Model 4 — Matheson drift overlying an older till

In Model 4, the Matheson till and a till unit of an older glacial event are stratigraphically in contact with each other; no glaciolacustrine or glaciofluvial units separate the till units (Fig. 9). The till units can, in some instances, be differentiated by detailed visual examination of the drill core. Separation of a till interval, with mostly uniform physical properties, into multiple drift sequences is based on the identification of distinct statistical discontinuities in the analytical data. A zone of relatively consistent geochemical values within a till interval is cause to separate till units if these values are significantly different from values for overlying and/or underlying zones. The older till unit in this model is usually Middle drift.

In drillhole 85-42, two till units are in contact at a depth of 33.5 m. These units, the uppermost being the Matheson till, were initially differentiated during detailed logging of the core by an abrupt change in colour and density. Analytical data revealed that the five till samples above 33.5 m are geochemically and mineralogically distinct from those below, indicating different provenance. The most probable explanation is deposition from separate glacial advances. A less likely interpretation of the different provenance is varying distances of debris transport by the same ice sheet, probably due to subglacial versus englacial transport. The analytical discontinuity is well defined for several elements in the <63 μm fraction, including cobalt, copper and nickel (Fig. 9). In this drillhole, heavy mineral geochemistry, with

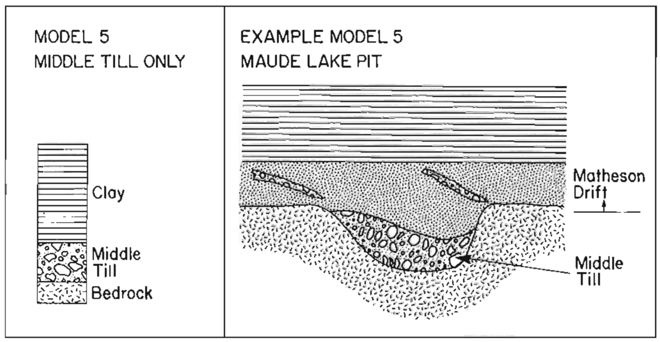


Figure 10. Model 5 — Middle till only

the possible exception of zirconium, cannot be used to separate the till units. However, garnet and pyroxene abundances in the heavy mineral concentrates can be used to confirm the separation of the till interval into two units, probably associated with separate glacial events.

Model 5 — Middle till only

The stratigraphy of Model 5 is glaciolacustrine sediments of the Barlow-Ojibway Formation overlying till deposited from ice of an earlier advance (Fig. 10). The stratigraphy of this model was recognized during field work at the Maude Lake pit, an exploration excavation located near the centre of the study area (see Fig. 4).

At the Maude Lake pit, an east-west trending bedrock valley contains pockets of Middle till resting on bedrock (Fig. 10). Beneath these till pockets, the bedrock is striated at 240° only; the long axes of pebbles in the till are likewise oriented at 240°. Elsewhere in the pit, the bedrock displays striae oriented at both 240° and 170°. The pockets of till are overlain by a unit of poorly sorted sand containing occasional diamict layers. The sand and overlying varved clay are interpreted to be associated with the most recent 170° (Matheson) glacial advance.

Although the stratigraphy of this model has yet to be recognized in drillcore, its existence must be acknowledged. Some drillholes interpreted to be Model 1 may actually have Model 5 stratigraphy.

It is probable that Model 5 stratigraphy would only be recognized in drill core if a distinctive bedrock lithology occurs up-ice to the northeast and glacial processes eroded that lithology and deposited the debris at the drillsite. Upon identification of that debris, it could then be reasoned that the till was deposited from ice advancing to the southwest (240°). The distinct lithology may be recognized through examination of clast lithologies or chemical results.

Model 6 — Drift from three glacial events

Model 6 has three drift sequences, each consisting of glaciolacustrine sediments overlying till (Fig. 11). Sediments of the Matheson drift and Middle drift overlie Lowest drift, about which little is known. Lowest drift has been recognized in less than 5 % of the drillholes and is very restricted in areal extent. Model 6 represents the composite glacial stratigraphy of the Matheson area.

Drillhole 84-28 is used to illustrate Model 6 (Fig. 11). The till interval of the Middle drift is thin and only one sample was collected from it. This presents problems firstly in recognizing the unit and its stratigraphic significance and, secondly, makes comparisons of analytical data with other till units suspect due to the poor sorting of till. The thin till unit at hole 84-28 is definitely separate and distinct from those above and below because it thickens and maintains its stratigraphic identity in nearby drillholes. This Middle till has a sandier matrix and slightly different density and colour from tills above and below. Geochemical data indicate the Matheson and Middle tills often have similar trace element concentrations compared to the Lowest till. This is illustrated in the plots for cobalt, nickel and zirconium values in the <63 μm material and chromium in the heavy mineral concentrates (Fig. 11). For some elements, Middle till geochemical values are intermediate between values for the Matheson and Lowest tills; as illustrated in plots of copper and nickel values in the heavy mineral concentrates (Fig. 11). In drillhole 84-28, the chemical differences between till units were subtle, therefore, separation of the till units into drift associated with three glacial events required the combined use of a detailed drill core log, textural data, and multi-element, multi-fraction geochemical data.

REGIONAL QUATERNARY STRATIGRAPHY

In the Matheson area, the composite glacial (Quaternary) stratigraphy as determined by this study is represented by Model 6. The three drift sequences identified correlate to some degree with the Quaternary stratigraphic sequences encountered at the Owl Creek Mine (Bird and Coker, 1987), Timmins area (DiLabio et al., 1988; Alcock, 1986; P.W. Alcock, personal communication, 1987) and in the Abitibi region of northeastern Quebec (Veillette, 1986) (Fig. 12). The proposed stratigraphy is consistent with the sediment record encountered at two overburden test holes drilled to bedrock in Currie Township, 11 km southwest of Matheson (Brereton and Elson, 1979).

Lowest drift

Sediments associated with the oldest glacial advance recorded in the Quaternary stratigraphic sequence are collectively and informally referred to as the Lowest drift. In the Matheson area, the Lowest drift has only been

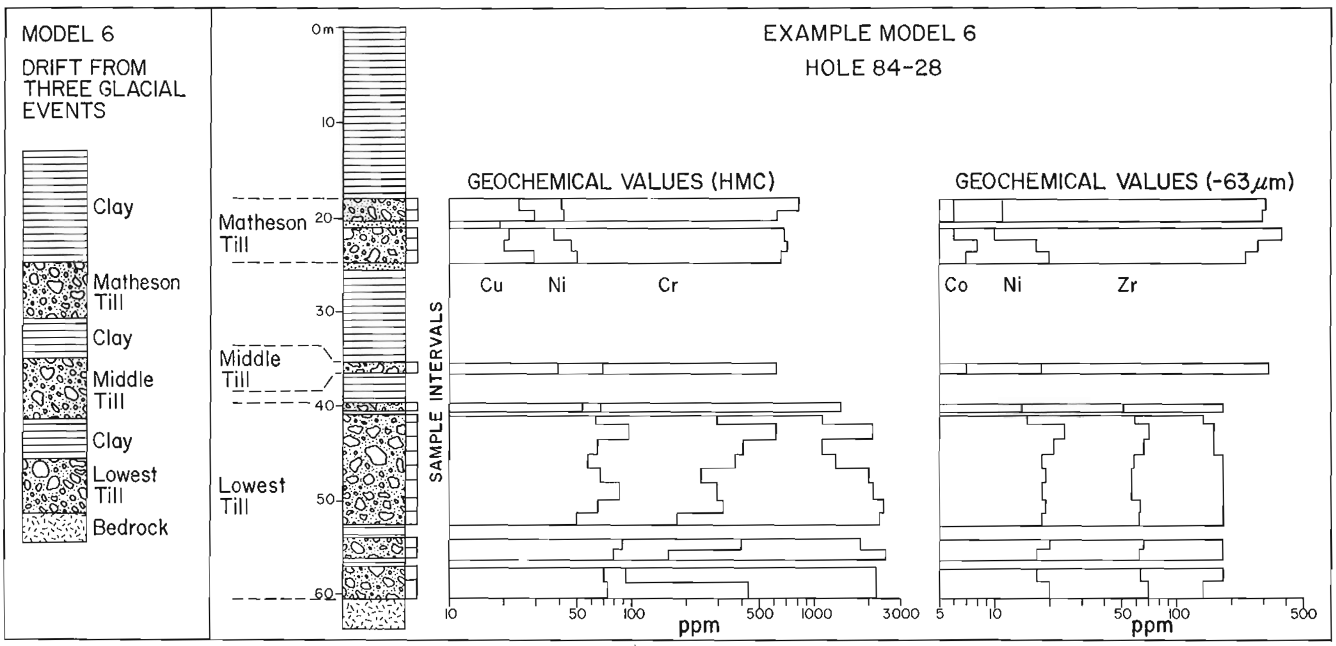


Figure 11. Model 6 — Drift from three glacial events

encountered in drill core. Sediments of this drift are areally restricted and preserved in isolated bedrock depressions. The Lowest drift has been encountered more often in the western portion of the study area, with the largest known subcrop located in central Currie Township. The most easterly known occurrence of this drift is McCool Township, 28 km east of Matheson. Sediments which correlate with the Lowest drift have not been reported in Quebec (Veillette, 1986).

Presently available analytical data from the Lowest drift provides no evidence to allow the direction of ice advance to be determined. In the future, it is possible that clast microfabric data or lithology and/or trace element dispersal patterns, may indicate the ice flow direction.

At the Owl Creek Mine, approximately 24 km west of the study area, a lowermost glacial stratigraphic package was tentatively correlated with an ice advance toward 240° (Fig. 12) based on striae and streamlined bedrock forms measured in the Timmins area (Bird and Coker, 1987). This package, informally referred to by Bird and Coker as the "Oldest", and the Lowest drift in the Matheson area can be correlated based on stratigraphic position. Bird and Coker (1987) indicated the ice flow directions associated with the two lowermost till units exposed at the Owl Creek Mine needed further investigation; and with new data the assigned directions may be changed.

Recent work in the Timmins area by Falconbridge Mines Ltd. (P.W. Alcock, personal communication, 1987) has found a stratigraphic sequence similar to that in the Matheson area. Drift resting on bedrock is tentatively correlated with ice which flowed toward 150°. Striae at this orientation are common on outcrops around Nighthawk Lake, which is situated between Timmins and Matheson.

In the Matheson area, the Lowest drift consists of either meltout and/or lodgment till overlain by glaciolacustrine and/or glaciofluvial sediments. Commonly the drift consists of till unconformably overlain by varved clay.

Middle drift

In approximately 30 percent of the holes drilled in the Matheson area, Matheson and Middle drift were encountered. Middle till is also exposed in the walls of the Maude Lake pit in Beatty Township (see Fig. 4). The subcrop of this drift is extensive enough to allow correlation between drillholes in small bedrock basins. Middle drift has been identified west of Harker and Lamplugh Townships. Glacial sediments at the same stratigraphic position are frequently encountered in drillholes in the Timmins (Bird and Coker, 1987), Selbaie (Bouchard et al., 1986), Casa-Berardi (Sauerbrei et al., 1987) and Amos (Veillette, 1986) areas of the Great Clay Belt and Abitibi Greenstone Belt.

A few striae and streamlined bedrock forms indicating an ice advance toward the southwest at 240° occur across the study area. Based on these striae and pebble fabric data from the Maude Lake pit, Middle drift is correlated with a 240° ice advance. Veillette (1986) completed an extensive study of ice flow indicators east and south of the Matheson area and concluded that the ice advance immediately preceding the Late Wisconsinan glacial maximum advance, flowed to the west-southwest (230° to 270°). This glacial advance is correlated with the Middle drift in the Matheson area (Fig. 12).

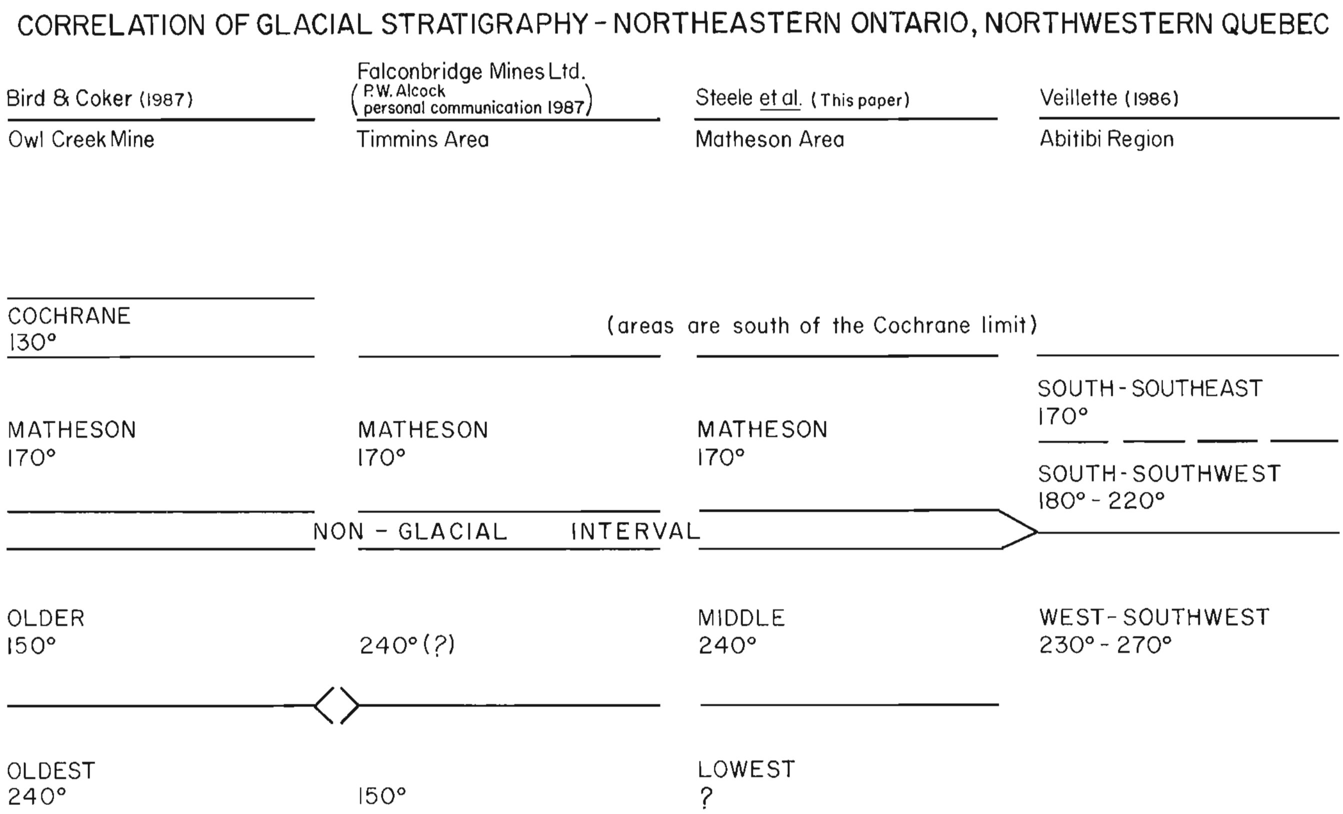


Figure 12. Correlation of glacial stratigraphy — Northeastern Ontario, Northwestern Quebec.

At the Owl Creek Mine, the glacial stratigraphic package below the Matheson has been tentatively correlated with a 150° ice advance based on clast fabric and dispersal patterns (Bird and Coker, 1987). This "Older" package (as referred to by Bird and Coker) consists of fluviolacustrine and glaciofluvial sediments overlying till. The "Older" package and the Middle drift of the Matheson area have the same stratigraphic position, separated from Matheson drift by a unit of nonglacial sediments. The Middle drift of the Matheson area consists of glaciolacustrine sediments, usually varved clay, overlying till. Occasionally glaciofluvial sand separates the clay and till. As mentioned previously, recent work in the Timmins area (P.W. Alcock, personal communication, 1987) has proposed that the glacial sediments immediately below the nonglacial interval can be correlated across the Timmins-Matheson area and assigned to a 240° ice flow direction. This interpretation will remain tentative until clast fabric data and stratigraphy differences between the "Older" and "Oldest" packages at the Owl Creek Mine and the Middle drift of the Matheson area are resolved.

A discontinuous layer of organic material separating the Matheson and underlying drift sequences has been identified in the Matheson-Timmins area. These nonglacial sediments have been informally named the "Owl Creek beds" by DiLabio et al. (1988). The layer is often developed on varved clay of the Middle drift. In this study, significant thicknesses of organic material at this stratigraphic position were encountered in drillholes 84-27 (Taylor Township) and 85-17 (McCool Township) (see Fig. 4). In drillhole 84-27, 1.2 m of horizontally bedded, alluvium containing small wood and shell fragments was encountered at the 23.8 m depth (Ontario Geological Survey, 1986a). This interval overlies 16 m of varved clay assigned to the Middle drift. In drillhole 85- 17, a 20 cm thick layer of peat at the 32.0 m depth separates the Matheson till from older drift (Ontario Geological Survey, 1986b).

Brereton and Elson (1979) have reported fossil plant detritus dated at >37,000 years BP (GSC-2148) from stratified beds beneath the Matheson till in two drillholes located in Currie Township, southwest of Matheson (see Fig. 4). In these drillholes, the organic-rich layers were underlain by 2 m and 9 m of clay. Occurrences of wood in drill core from the Timmins area have been reported by DiLabio (1982) and DiLabio et al. (1988). The wood fragments were found in and below the Matheson till. At the Owl Creek Mine, fluviolacustrine sand and silt containing twigs and leaves occurs at the top of the "Older" glacial stratigraphic package which lies immediately below the Matheson stratigraphic package (Bird and Coker, 1987).

The nonglacial interval (Owl Creek beds), immediately preceding the most recent ice advance, was long and warm enough to allow the growth of shrubs, trees and other vegetation (DiLabio et al., 1988). To date in the study area, there is insufficient data to determine if the interval should be considered of interglacial or interstadial rank. DiLabio et al. (1988) have suggested that the Owl Creek beds can be correlated with the Missinaibi Formation of the Moose River basin which is regarded as representing the Sangamon interglacial (Skinner, 1973).

Matheson Drift

The composite stratigraphy for the Matheson drift is Barlow-Ojibway Formation clay coarsening downward to sandy ice- proximal varves, overlying glaciofluvial sand with minor gravel, which in turn overlies Matheson till. Matheson till subtypes deposited by a variety of mechanisms, such as debris flow, meltout and lodgment, have been identified. Till deposited by the first two mechanisms is most common. Approximately 70 per cent of holes drilled away from esker complexes encountered Matheson till. Nearly all of these drillholes penetrated Barlow-Ojibway Formation clay. The Matheson drift can be correlated across the Great Clay Belt. In the Timmins area, including at the Owl Creek Mine, the Matheson drift has the same stratigraphy and flow direction as in the Matheson area (Bird and Coker, 1987; Richard, 1980; Richard and McClenaghan, 1985; Tucker and Sharpe, 1980).

In the Abitibi region of northwestern Quebec, Veillette (1986) has recorded evidence of a south-southwest (180 to 220°) ice flow direction which he assigned to the last glacial maximum. Veillette (1986) noted that the absence of differential weathering on cross-striated outcrops and the distance of transport of rock fragments from known sources suggest that this 180 to 220° flow and the last regional flow toward the south-southeast (170°) occurred within a single glacial episode during Late Wisconsinan time. All deposits associated with this glacial advance, independent of flow direction, are correlated with the Matheson drift (Fig. 12).

SUMMARY

A composite glacial (Quaternary) stratigraphy has been developed for the Great Clay Belt of northeastern Ontario and northwestern Quebec. Matheson drift, associated with the last ice advance, is correlated across the region. A nonglacial interval, marked by the deposition of glaciolacustrine clay and scattered organic material in the Matheson-Timmins area, occurred previous to this advance and provides a stratigraphic marker horizon. In Ontario two drift sequences occur below the Matheson till, whereas only one has yet been identified in adjacent Quebec. The younger of these drift sequences is associated with ice which advanced toward 240°. The lowest (and oldest) drift is poorly preserved. It has been tentatively assigned to a 150° ice flow direction, based on recent work in the Timmins area.

This stratigraphy was developed from: 1) drillhole data, and 2) detailed studies at excavations which exposed glacial sediments below the Matheson till. These studies provided data on ice flow directions through examination of striae, clast fabric and dispersal patterns.

DISCUSSION

In the Matheson area, the highly variable bedrock geology and topography makes it difficult to characterize till units on a regional scale. Data obtained from drill core logging and sample analyses should first be divided into separate and distinct units on a hole by hole basis. At an individual drillhole, all or some of the following data is used in the separation of till units: 1) stratigraphy from detailed logging of drill core (including pebble counts); 2) non- magnetic heavy mineral concentrate geochemistry; 3) <63 μm geochemistry; 4) mineralogy of heavy mineral concentrate; and 5) matrix texture. For individual drillholes, the concentrations of the following elements are useful to distinguish till units: copper, nickel, zinc, cobalt, chromium and zirconium. In some instances, where precious metals are present in significant amounts, gold, silver, arsenic, antimony, molybdenum and tellurium are also useful.

The identification of separate till units is relatively straightforward when all available data are combined. However, determining the stratigraphic significance of these units, such as separating and correlating drift sequences, is more difficult. At present, this task is best accomplished through a combination of stratigraphy and trace element data. In the future, dating of organic material and clay, clast microfabrics from oriented till cores and detailed statistical tests on trace element concentrations of till samples may make the assignment of units to their regional stratigraphic position almost routine. The models of glacial stratigraphy presented in this paper may be refined as more recent information becomes available.

ACKNOWLEDGMENTS

Discussions with and suggestions made by P.W. Alcock, R.N.W. DiLabio, W.B. Coker and J.J. Veillette were of valuable assistance to our work. The constructive criticism of an anonymous reviewer is gratefully acknowledged. L.B. Bloom aided in the interpretation of chemical data. We thank the many field assistants for their competent work during the drilling programs, and A.M. Duic for drafting the figures. This study is part of the Operation Black River-Matheson (BRIM) project. This paper is published with the permission of the Director, Ontario Geological Survey.

REFERENCES

Alcock, P.W.
1986: Quaternary stratigraphy and gold dispersion at Owl Creek Mine, Timmins, Ontario; Unpublished paper presented at Canadian Institute of Mining and Metallurgy District 4 Meeting, Winnipeg, Manitoba.

Averill, S.A., MacNeil, K.A., Huneault, R.G., and Baker, C.L.
1986: Rotasonic drilling operations (1984) and overburden heavy mineral studies, Matheson area, District of Cochrane; Ontario Geological Survey, Open File Report 5569, 61p.

Baker, C.L.
1980: Quaternary geology of the Kirkland Lake area, District of Timiskaming; Ontario Geological Survey, Preliminary Map P.2382, Geological Series, scale 1:50 000.

Baker, C.L., Steele, K.G., and Seaman, A.A.
1982: Quaternary geology of the Magusi River area, Cochrane and Timiskaming Districts; Ontario Geological Survey, Preliminary Map P.2483, Geological Series, scale 1:50 000.

Baker, C.L., Steele, K.G., and McClenaghan, M.B.
1985: Reconnaissance till sampling program, Matheson- Lake Abitibi area, Cochrane District; in Summary of Field Work and Other Activities 1985, Ontario Geological Survey, eds. J. Wood, O.L. White, R.B. Barlow and A.C. Colvine; Ontario Geological Survey, Miscellaneous Paper 126, p. 329-333.

Bird, D.J. and Coker, W.B.
1987: Quaternary stratigraphy and geochemistry at the Owl Creek Gold Mine, Timmins, Ontario, Canada; Journal of Geochemical Exploration, v. 28, p. 267- 284.

Bouchard, M.A., LaSalle, P., Lamothe, M., David, P.P., and Bouillon, J.J.
1986: Pleistocene stratigraphy of northwestern Abitibi from boreholes and excavations at Selbaie mine, Quebec; Geological Association of Canada, Annual Meeting, Program with Abstracts, v. 11, p. 47.

Brereton, W.E. and Elson, J.A.
1979: A late Pleistocene plant-bearing deposit in Currie Township, near Matheson, Ontario; Canadian Journal of Earth Sciences, v. 16, p. 1130-1136.

DiLabio, R.N.W.
1982: Wood in Quaternary sediments near Timmins, Ontario; in Current Research, Part A, Geological Survey of Canada, Paper 82-1A, p.433-434.

DiLabio, R.N.W., Miller, R.F., Mott, R.J., and Coker, W.B.
1988: The Quaternary stratigraphy of the Timmins area, Ontario, as an aid to mineral exploration by drift prospecting; in Current Research, Part C, Geological Survey of Canada, Paper 88-1C, p.61- 65.

Dreimanis, A.
1962: Quantitative gasometric determination of calcite and dolomite by using Chittick apparatus; Journal of Sedimentary Petrology, v. 32, p. 520-529.

Hughes, O.L.
1959: Surficial geology of Smooth Rock and Iroquois Falls map areas, Cochrane District, Ontario; unpublished Ph.D. thesis, University of Kansas, Lawrence, Kansas, 190p.
1965: Surficial geology of part of the Cochrane District, Ontario, Canada; in International Studies on the Quaternary, eds. H.E. Wright, and D.G. Frey; Geological Society of America Special Paper 84, p. 535-565.

Jensen, L.S. and Langford, F.F.
1983: Geology and petrogenesis of the Archean Abitibi Belt in the Kirkland Lake area, Ontario; Ontario Geological Survey, Miscellaneous Paper 123, 130p.

Ontario Geological Survey
1986a: Sonic drillholes 84-01 to 84-42, Cochrane District; Ontario Geological Survey, Maps 80759 to 80792, Geophysical/Geochemical Series.
1986b: Sonic drillholes 85-01 to 85-60, Cochrane District; Ontario Geological Survey, Maps 80845 to 80893, Geophysical/Geochemical Series.

Prest, V.K.
1970: Quaternary geology of Canada; in Geology and Economic Minerals of Canada, ed. R.J.W. Douglas; Geological Survey of Canada, Economic Geology Report Number 1, p. 676-764.

Pyke, D.R., Ayres, L.D., and Innes, D.G.
1972: Timmins-Kirkland Lake, Geological compilation series, Cochrane, Sudbury and Timiskaming Districts; Ontario Department of Mines, Map 2205, scale 1:253 400.

Richard, J.A.
1980: Quaternary geology of the Pamour-Kamiskotia Lake map area (NTS 42A/11 and 42A/12); Unpublished B.E.S. Thesis, Department of Geography, University of Waterloo, Waterloo, Ontario.

Richard, J.A. and McClenaghan, M.B.
1985: Quaternary geology of the Watabeag River area, District of Cochrane and Timiskaming; Ontario Geological Survey, Map P.2950, Geological Series — Preliminary Map, scale 1:50 000.

Sauerbrei, J.A., Pattison, E.F., and Averill, S.A.
1987: Till sampling in the Casa-Berardi gold area, Quebec: a case history in orientation and discovery; Journal of Geochemical Exploration, v. 28, p. 297-314.

Skinner, R.G.
1973: Quaternary stratigraphy of the Moose River basin, Ontario; Geological Survey of Canada, Bulletin 225, 77p.

Tucker, C.M. and Sharpe, D.
1980: Quaternary geology of the Timmins area, Districts of Cochrane and Timiskaming; Ontario Geological Survey, Map P.2360, Geological Series — Preliminary Map, Scale 1:50 000.

Veillette, J.J.
1986: Former southwesterly ice flow in the Abitibi- Timiskaming region: implications for the configuration of the late Wisconsinan ice sheet; Canadian Journal of Earth Sciences, v. 23, p.1724-1741.

Ice movements, till sheets and glacial transport in Abitibi-Timiskaming, Quebec and Ontario

J.J. Veillette[1]

Veillette, J.J., Ice movements, till sheets and glacial transport in Abitibi-Timiskaming, Quebec and Ontario; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 139-154, 1989.

Abstract

Recent and extensive overburden drilling for mineral exploration purposes has unveiled a complex glacial stratigraphy that constitutes a complementary new tool for the interpretation of the ice flow history of the Abitibi-Timiskaming region. From oldest to youngest, ignoring isolated occurrences of older, poorly known glacial sediments not discussed here, widespread till sheets consist of (1) a lowermost till associated with dominant west-southwestward and southwestward flows, (2) the Matheson till associated with both former west-southwestward and south-southwestward flows and a later south-southeastward flow and (3) the Cochrane till associated with southwestward, south, and southeastward flow directions. The change in flow direction that took place while the Matheson till was being deposited accounts for the lack of Paleozoic erratics from the James Bay Lowland in the easternmost and southernmost portions of the Matheson till. Deglaciation history inferred from bedrock-inscribed ice flow indicators and geomorphological indicators is supported by the distribution of 43 radiocarbon ages on basal postglacial organic materials.

Résumé

De nombreux forages dans le mort-terrain effectués récemment pour l'exploration minérale ont mis à jour une stratigraphie glaciaire complexe qui s'avère un nouvel outil complémentaire des plus utiles à l'interprétation des écoulements glaciaires dans la région d'Abitibi-Témiscamingue. Des plus anciennes aux plus récentes (si on écarte quelques cas isolés de sédiments glaciaires très anciens et mal connus), les nappes de till d'importance régional comprennent 1) un till inférieur associé aux écoulement WSW et SW dominants, 2) le till de Matheson associé d'abord aux écoulements WSW et SSW et subséquemment à un écoulement SSE et 3) le till de Cochrane associé aux directions d'écoulement SW, S et SE. Le changement de direction d'écoulement qui a eu lieu pendant la mise en place du till de Matheson explique l'absence de blocs erratiques paléozoéiques provenant des basses terres de la baie James aux limites est et sud du till de Matheson. Les modalités du retrait glaciare déduites à partir d'indices géomorphologiques de stries et autres marques gravées sur le socle rocheux sont confirmées par la distribution de 43 âges radiocarbones de la matière organique basale.

[1] Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8

INTRODUCTION

This paper presents a brief overview of the major glacial events and associated till sheets of part of the Abitibi-Timiskaming region of northwestern Quebec and northeastern Ontario (Fig. 1), with particular emphasis on glacial transport in the Matheson till. The reconstruction is based on five types of evidence: (1) sequence of events inferred from glacial deposits; (2) ice-flow indicators on bedrock; (3) lithological indicators of glacial transport; (4) deglaciation sequence from landform distribution; and, (5) from radiocarbon chronology. The existence of a major and rapid shift in ice-flow direction, from west-southwestward and southwestward to southeastward, that took place in the ice mass early in deglaciation is demonstrated. The shift has important implications in the interpretation of glacial transport data.

Extensive mineral exploration, mainly for gold, in Abitibi-Timiskaming during the last few years, has stimulated interest in the prospecting techniques applicable in glaciated terrain. The thick glaciolacustrine sediments of Lakes Barlow in Timiskaming, and Ojibway in Abitibi, masking till and bedrock over large areas of economic interest, are in part responsible for this situation. Drilling (reverse circulation method) in the vicinity and down-ice from geophysical anomalies, is used extensively by mineral exploration companies to study the dispersal of indicator minerals and gold grains in till. To interpret these drilling results and correctly explain transported anomalies in the drift, which locally exhibits a complex stratigraphy, requires a good knowledge of the broad regional ice-flow patterns and their chronological order.

MAJOR GLACIAL MOVEMENTS AND ASSOCIATED TILL SHEETS

Three major ice flows of different ages and directions (Fig. 2) have been identified in western Abitibi-Timiskaming (Veillette, 1986a). Striae from the two former flows? an oldest, rare, west-southwestward (230° to 270°) flow crossed by a younger, widespread flow, to the south-southwest (180° to 220°) — are crossed by ubiquitous striae from a last flow, to the south-southeast (130° to 170°). This chronology was established from measurements at over 2000 locations. Marks from the three flows occur together only west of the Lake McConnell-Harricana glaciofluvial complex (Fig. 2), a major interlobate moraine. It has been traced to the vicinity of North Bay, Ontario, and probably extends farther south (Veillette, 1986a). Hardy (1976) referred to the complex as the Harricana Moraine for that part south of James Bay where it marks a line of parting in the Late Wisconsinan ice sheet, with a lobe retreating, to the northwest, and another retreating to the northeast. These two lobes, resulting primarily from internal adjustments in the ice sheet at deglaciation, produced the last south-southeastward flow, west of the interlobate moraine, and the last south-southwestward flow east of it. Earlier, but still in Late Wisconsinan time, a single, major south-southwestward (180° to 220°) flow prevailed over the whole area (Fig. 2).

Natural exposures, showing more than one till sheet, are absent in the study area. However, overburden drilling in various parts of the region, has provided the basic information needed to construct a composite stratigraphy, characterized by several till sheets (Fig. 3). The relative ice flow chronology, obtained from erosional marks on bedrock, is here correlated tentatively with the uppermost two tills below the Cochrane Till.

Ancient glacial sediments at the very base of the stratigraphic column were encountered at the base of deep drill holes in the Casa Berardi area of western Quebec (Averill, 1986; D. Green, pers. comm., 1987; P. LaSalle, pers. comm., 1987), and in Ontario (Bird and Coker, 1987). Little is known about the direction of ice movement associated with these ancient diamictons, although Averill (1986) suggested a south to southwest trend.

A till of regional extent below the Matheson till

The presence of a distinct till sheet below the Matheson and separated from it by nonglacial or glaciolacustrine sediments (Sauerbrei et al., 1987) is now a common and well established occurrence in boreholes located north of the Kirkland Lake-Val d'Or axis (Fig. 3). Organic materials, present in the sediments below the Matheson till, both in Ontario (DiLabio, 1982; DiLabio et al., 1988), and Québec (D. Green, P. LaSalle, S.A. Averill, pers. comm., 1987), suggest a possible correlation with the pre-Missinaibi tills of Skinner (1973) in the James Bay area. The precise regional extent of this till and its physical properties remain poorly known, since most of the information available is from borehole data. A program aimed at mapping this till sheet from subsurface data has been undertaken by the author.

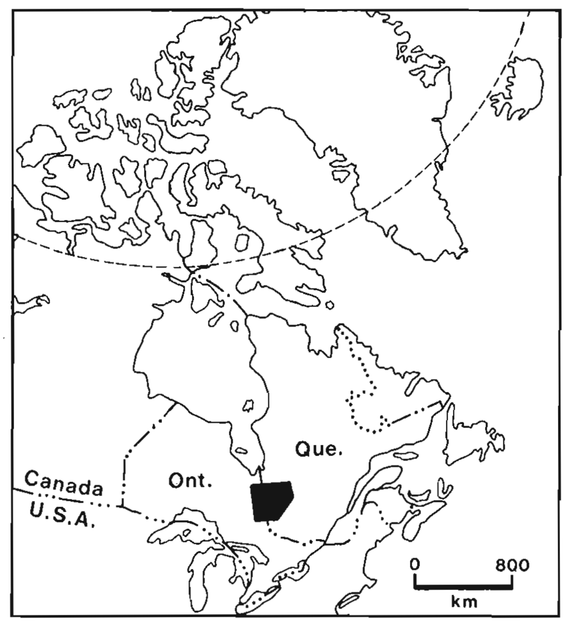


Figure 1. Location of study area.

In an open pit at the Selbaie Mine, Québec (Fig. 2), Bouchard et al. (1986) described a till below the Matheson till, and separated from it by sand containing gravel lenses. The underlying bedrock showed a stoss and lee topography to the southwest, which was found to match glacial transport in the same direction. The intertill sand gave a thermoluminescence age (Regen method) of about 100 000 years BP. Bouchard et al. (1986) concluded that the intertill sands mark an ice-free episode of interstadial or interglacial rank.

This lowermost till is perhaps the stratigraphic equivalent of the "Older Till" of Bird and Coker (1987) and Steele et al. (1986) in northwestern Ontario, and Averill (1986) in Québec and may be associated with the former west-southwestward (230° to 270°) flow of Veillette (1986a). Recent observations at the Selbaie site, however, suggest a cautious approach (see discussion) before inferring the presence of an older till at this site.

The Matheson till

The Matheson till (Hughes, 1955) is the regional surficial till commonly associated with the last major south-southeastward (130° to 170°) flow, south of the Cochrane readvance, in northeastern Ontario (Fig. 4). Hughes (1955) suggested that its southern limit may be as far south as the contact with the multi-till area of southern Ontario. In the western Abitibi-Timiskaming region of Québec, geologists engaged in overburden drilling commonly refer to the surficial till as Matheson. However, the easternmost limit of the

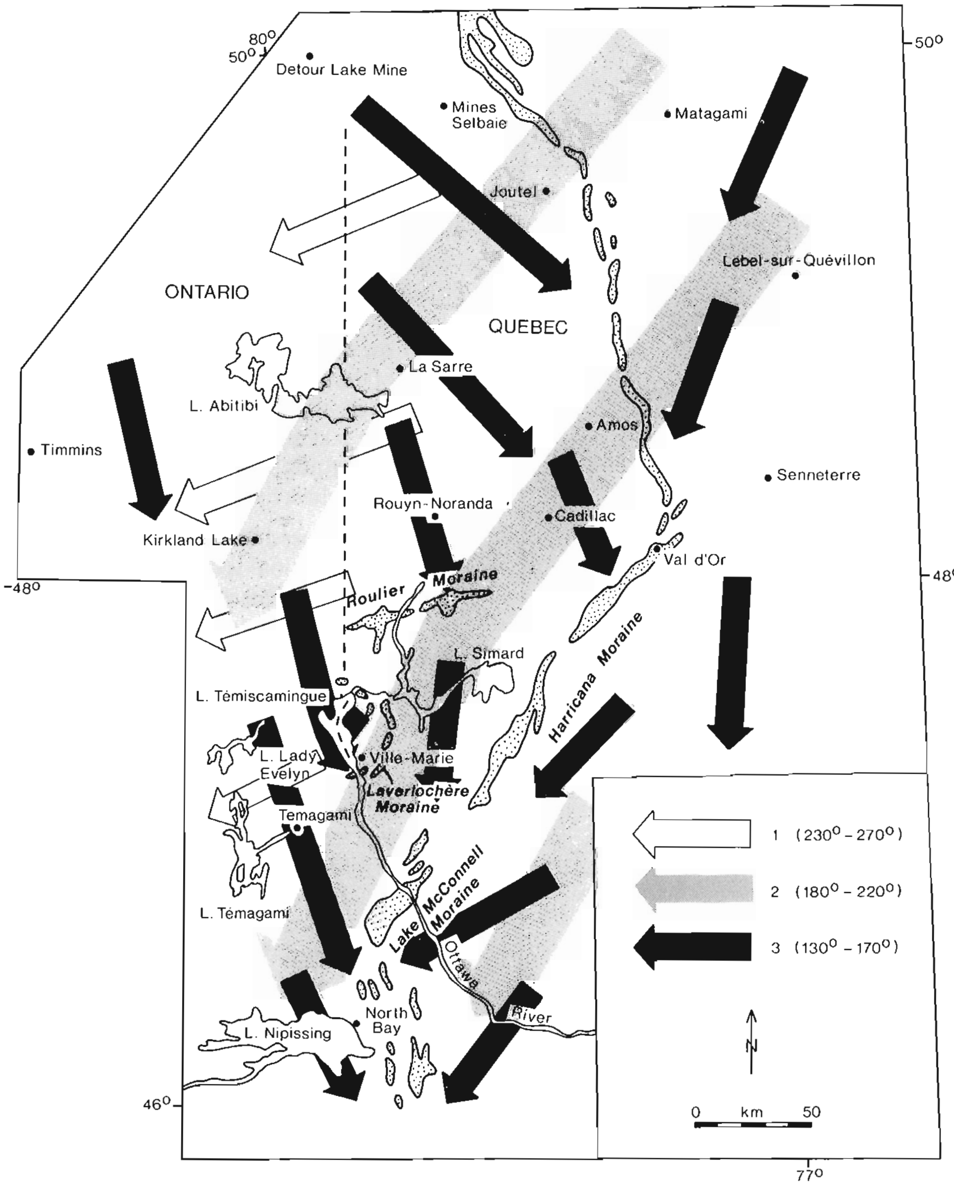


Figure 2. Chronology of ice flows in Abitibi-Timiskaming. Number 1 is oldest. Azimuths 130° to 170° refer to the area west of the Harricana Moraine.

Matheson till has not yet been established. It is proposed here to retain the name Matheson in Québec, but to consider the convenient natural limit formed by the Harricana and the Lake McConnell moraines as the easternmost and southernmost limits of the Matheson till. These limits in Quebec give the Matheson till sheet a common characteristic, i.e., a dominant south-southeastward direction of ice flow over most of its extent — up to the interlobate position. East of this position, the last dominant flow is to the south-southwest and southwest, from central Québec. In the north of the study area, the Matheson till is overlain by the Cochrane Till (Fig. 4) but its relationships to other tills farther north in the James Bay basin remain to be clarified. Stratigraphic position and ice-flow history suggest a probable correlation with the Adam Till (Skinner, 1973) in the Moose River Basin, Ontario.

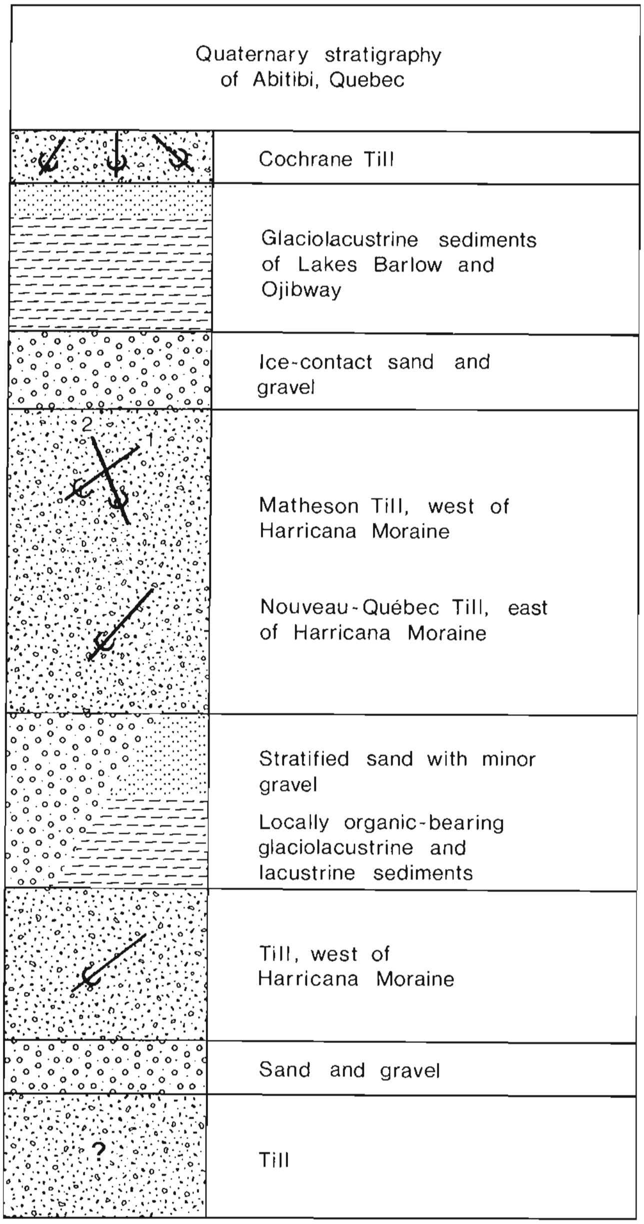


Figure 3. Simplified composite stratigraphy of northwestern Québec. Arrows indicate azimuths of ice flows commonly associated with the till sheets.

The Cochrane Till

The youngest unit is the Cochrane Till (Hughes, 1955) which overlies the glaciolacustrine deposits of Lake Ojibway (Figs. 3 and 4) and the Matheson till. It was formed by southward and southeastward readvances into Lake Ojibway between about 8500 years BP and 8000 years BP (Hardy, 1976; Hughes, 1955). Its southern limit has never been mapped, but thin cappings of the till occur in gravel pits in the Joutel and Matagami areas, Québec (Vincent et al., 1987). The till is found in low-lying areas, as far south as 30 km north of La Sarre, Québec. Its southern limit, in northwestern Québec, is now recognized 30 to 50 km farther south than that previously mapped (Prest et al., 1968; Hardy, 1976). The till appears to contain abundant Paleozoic carbonates right up to its distal margin.

A MAJOR SHIFT IN ICE-FLOW DIRECTION IN THE ICE THAT DEPOSITED THE MATHESON TILL

In northwestern Quebec and in northeastern Ontario, the Matheson till is normally associated with the last south-southeastward ice-flow direction on the basis of deglaciation landforms, striae, and direction of glacial transport. It seems, however, that at some locations, two superimposed ice movements of widespread regional extent have contributed to the formation of the till. Ice-flow history and glaciological models from several sources (see Veillette, 1986a), show, that in Late Wisconsinan time, the dominant ice-flow direction was towards the southwest, both east and west of the Harricana-Lake McConnell interlobate moraine. It follows that ice-flow indicators on bedrock associated with the last south-southeastward flow are strictly glacial retreat features which have nearly obliterated marks from an earlier direction of retreat within the same ice mass.

The proposed sequence of ice flow trends from early to final deglaciation is illustrated in Figure 5. In western Abitibi, ice flow directions changed by as much as 90°, west of the Harricana Moraine. Evidence for this major shift is provided by ice-flow indicators on bedrock, lithological indicators of glacial transport, landform distribution, and distribution of radiocarbon ages.

Ice-flow indicators on bedrock

This type of evidence has already been discussed in Veillette (1986a). Since then, additional fieldwork in central Abitibi, Quebec, has confirmed a dominant crossed-striae pattern consisting of a first south-southwestward (180° to 220°) flow crossed by a younger (deglaciation) south-southeastward (130° to 170°) flow, west of the Harricana Moraine (Fig. 2). None of the numerous (over 400) crossed-striae sites examined show evidence of differential weathering between the two striated planes. This observation, in conjunction with the other types of evidence described below, suggests that the shift occurred in the same ice mass, without an intervening ice- free period. At some sites, intermediate striae between earlier southwestward and final southeastward striae on the same outcrop, suggest that the shift was gradual.

Lithological indicators of glacial transport

Phanerozoic rocks, mainly carbonates from the Hudson Bay and James Bay Lowlands, deposited on the Precambrian substrate to the south, have been used in several studies of glacial transport in Ontario (see Karrow and Geddes, 1987) and in northwestern Quebec (Veillette, 1986a). In the Lake Timiskaming area of Quebec and Ontario, detailed mapping of carbonate content in the till matrix (less than 63 μm) and granule counts (Fig. 6) show that carbonate distribution is erratic and does not conform to the common negative exponential curve distribution typical of several indicator trains (Shilts, 1976). The carbonate limit obtained is farther south than the carbonate limit of Karrow and Geddes (1987), shown on Figure 7. These authors, adding to the observations and measurements of earlier workers in northern Ontario, produced a map showing the distribution of carbonate (presumably derived from Paleozoic rocks to the north) in the till matrix between upper Lake Superior and a north-south axis, roughly between Timmins and Sudbury, Ontario. In Timiskaming, carbonate in the till matrix and carbonate granules are believed to be derived mainly from the Paleozoic outlier of upper Lake Timiskaming (Lovell and Caine, 1970), since Paleozoic rock fragments are absent or rare immediately north and east of the outlier (Fig. 6). The dispersal pattern from this presumed source agrees with striae towards the southwest and south-southwest in the area, but also requires a south-southeastward component of flow to explain the presence of anomalous Paleozoic erratics in the stratified ice-contact deposits of the eastern portion of the Lake McConnell Moraine. Although Paleozoic clasts are rare in the moraine, it supports kettle lakes and ponds with high pH (up to 8.4) and total alkalinity values. Fossiliferous marl deposits up to 60 cm thick were measured at the base of a 8 m gyttja column at one location on the moraine. Paleozoic rock fragments are absent south of the moraine and the carbonate content of the till matrix is also very low (<1 %). Dispersal patterns from the Paleozoic outlier (Fig. 6) indicate that large areas of the till, down-ice from the source, and even at relatively short distances from it, do not contain Paleozoic granules or carbonate in the till matrix. On the other hand, large pockets of carbonate-rich till occur at random, south-southwest from the source, as is the case around Temagami, Ontario, and at specific locations (not shown on Fig. 6) in the lower Montreal River Valley. South of Montreal River, in Ontario, Paleozoic pebbles and cobbles are abundant at the surface in low-lying areas at several locations, but are absent in the till even below the weathered zone. Ice rafting associated with a late and shallow Post-Algonquin-Early Lake Barlow phase of glaciolacustrine submersion (Veillette, 1988), may be responsible for the distribution of these surface erratics (Fig. 8). The submerged area was reconstructed from washing limits and shoreline altitude measurements, and from the distribution of biological indicators of lacustrine submergence mapped by Martin and Chapman (1965) and Dadswell (1974).

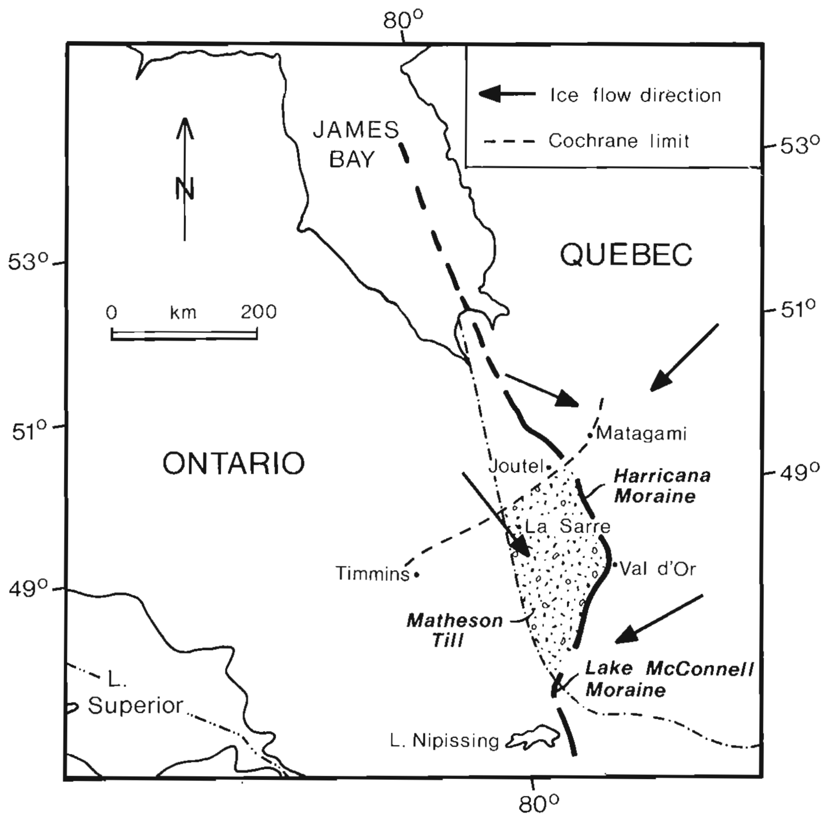


Figure 4. The Matheson till in Quebec and the approximate southern limit of the Cochrane Till in northwestern Quebec and northeastern Ontario.

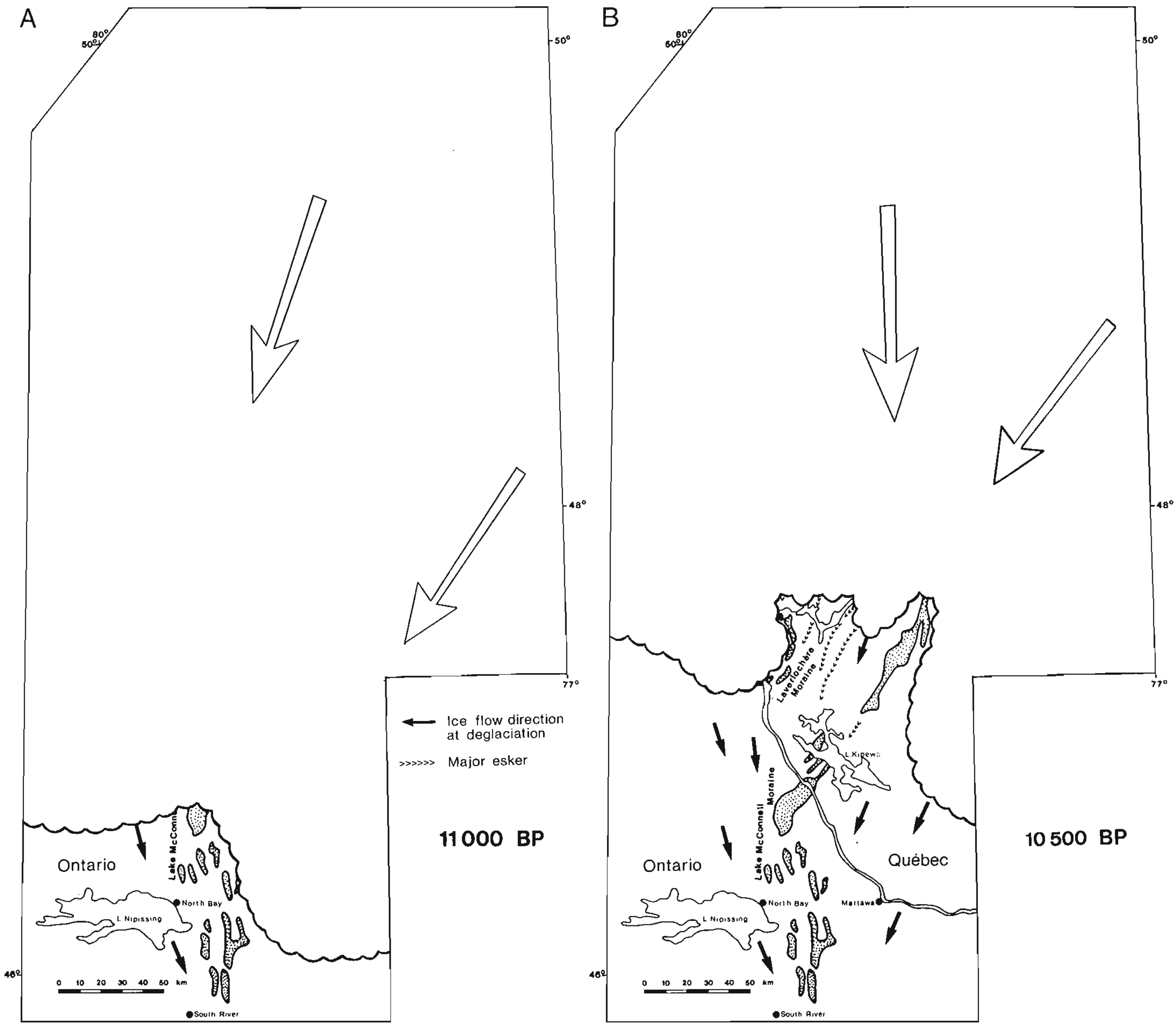
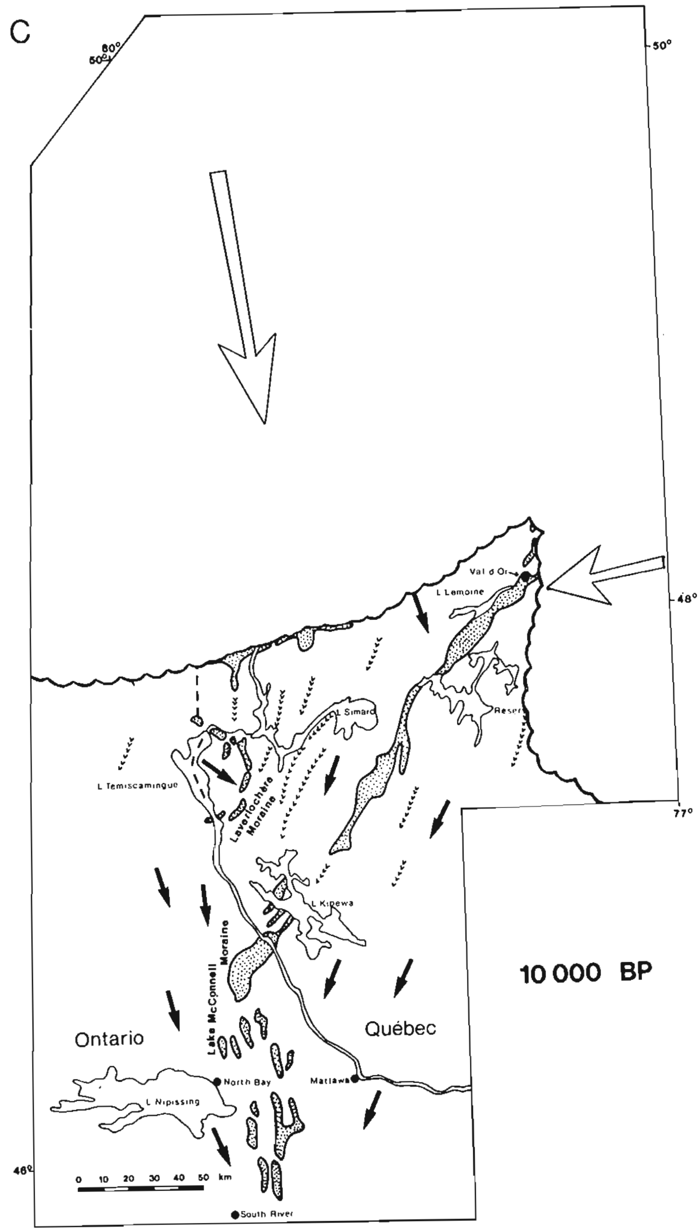
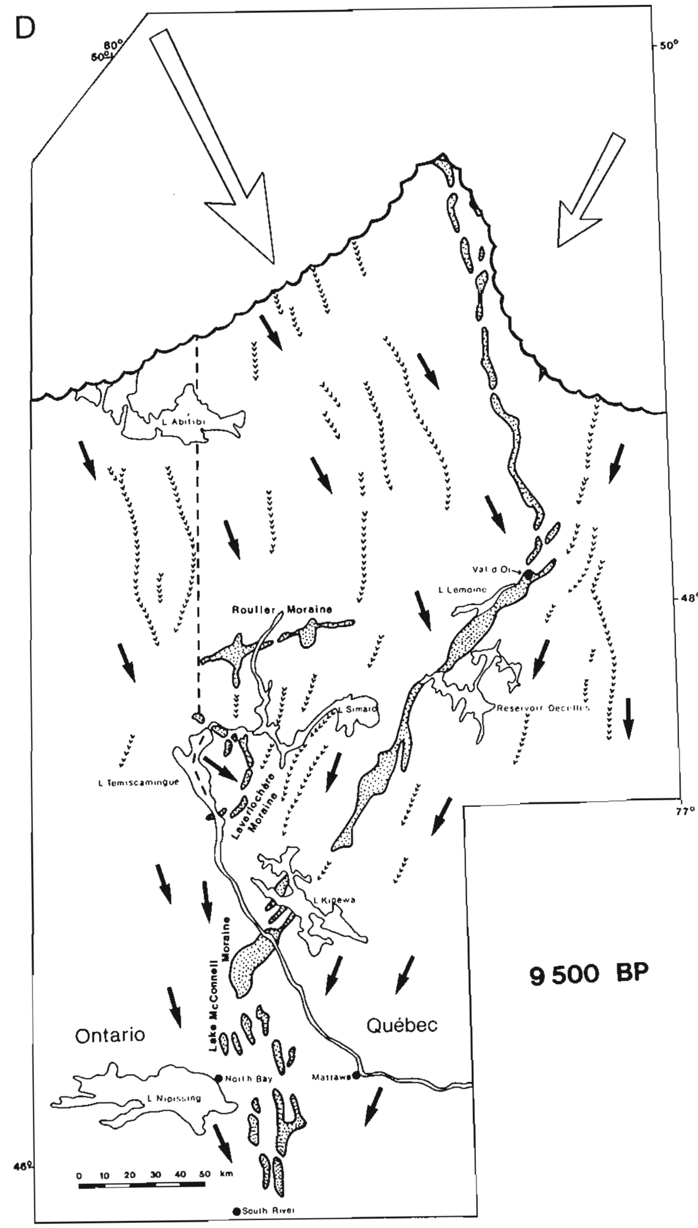


Figure 5. Gradual change in ice flow direction from early (A) to late (D) deglaciation; formation of two distinct ice lobes. Large arrows indicate dominant ice flow directions away from the ice margins.


C
10 000 BP
Ontario
Québec
Val d'Or
L Lemoine
L Simard
L Temiscamingue
Laverlochère Moraine
L Kipewa
Lake McConnell Moraine
North Bay
Mattawa
L Nipissing
South River
0 10 20 30 40 50 km
50°
80°
48°
77°
46°


D
9 500 BP
Ontario
Québec
L Abitibi
Roulier Moraine
Val d'Or
L Lemoine
L Simard
Reservoir Decelles
L Temiscamingue
Laverlochère Moraine
L Kipewa
Lake McConnell Moraine
North Bay
Mattawa
L Nipissing
South River
0 10 20 30 40 50 km
50°
80°
48°
77°
46°

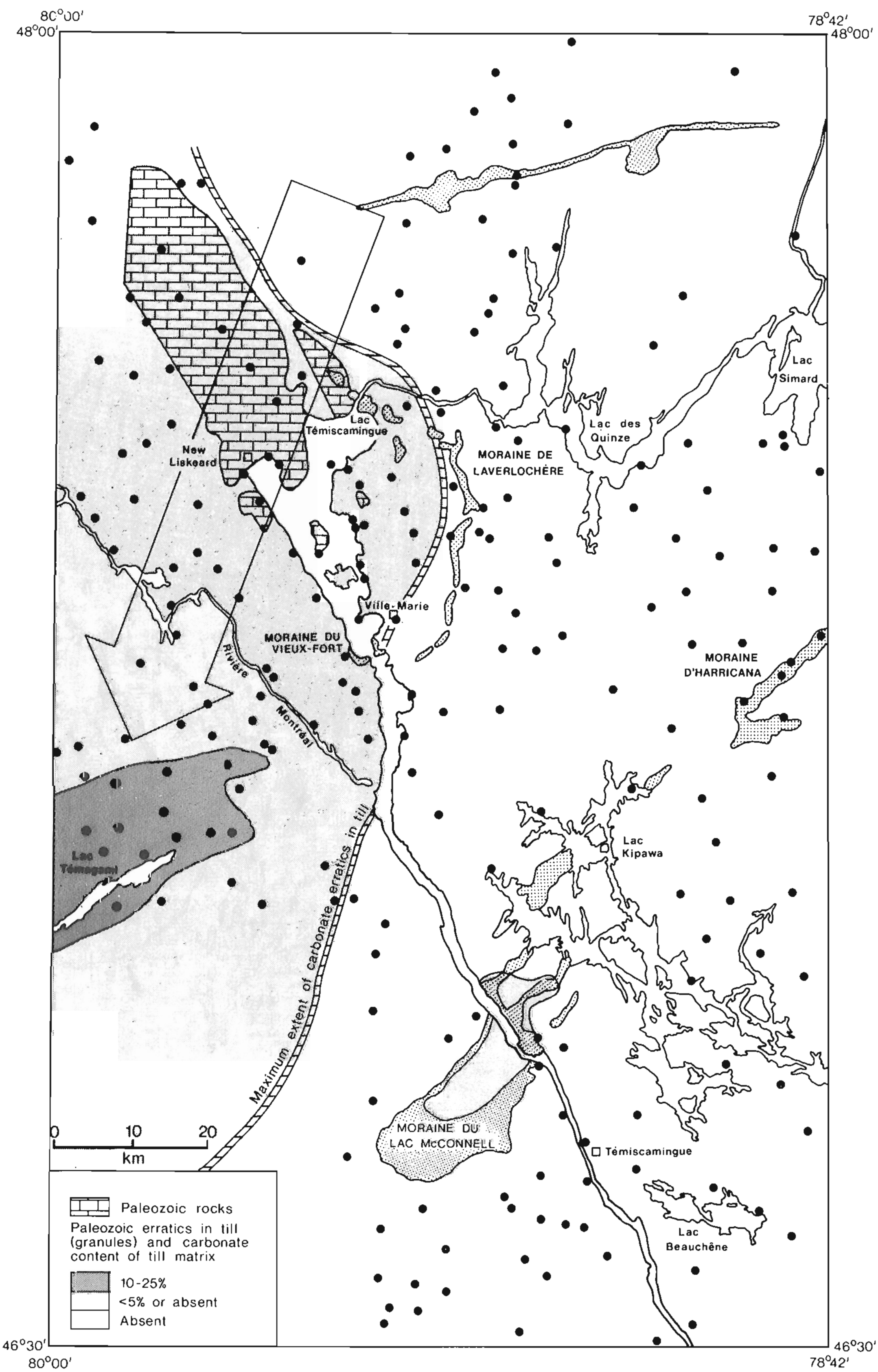


Figure 6. Dispersal of carbonates in the matrix (less than 63μm) and in the granules of the surficial till at 275 sampling sites (black dots) in Timiskaming, Québec and Ontario. The large arrow marks the dominant ice flow direction in Late Wisconsinan time.

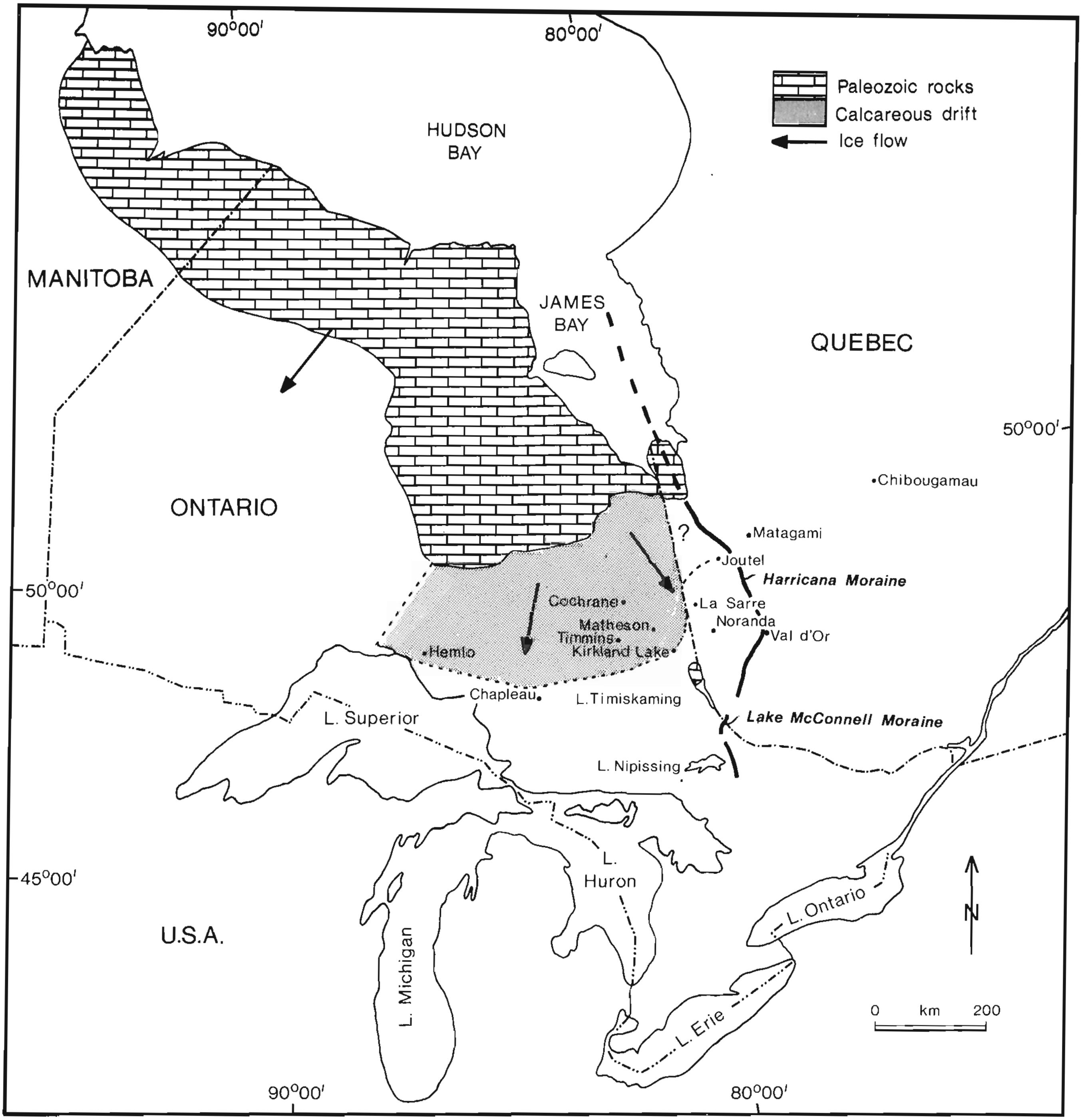


Figure 7. Carbonate dispersal from the James Bay Lowland in the surficial (pre-Cochrane) till of northwestern Quebec and northeastern Ontario. Sources of information in Ontario, Hughes (1955), Karrow and Geddes (1987), OGS (1986); and in Quebec, Veillette (1986a) and unpublished results, and, D. Green (pers. comm., 1987).

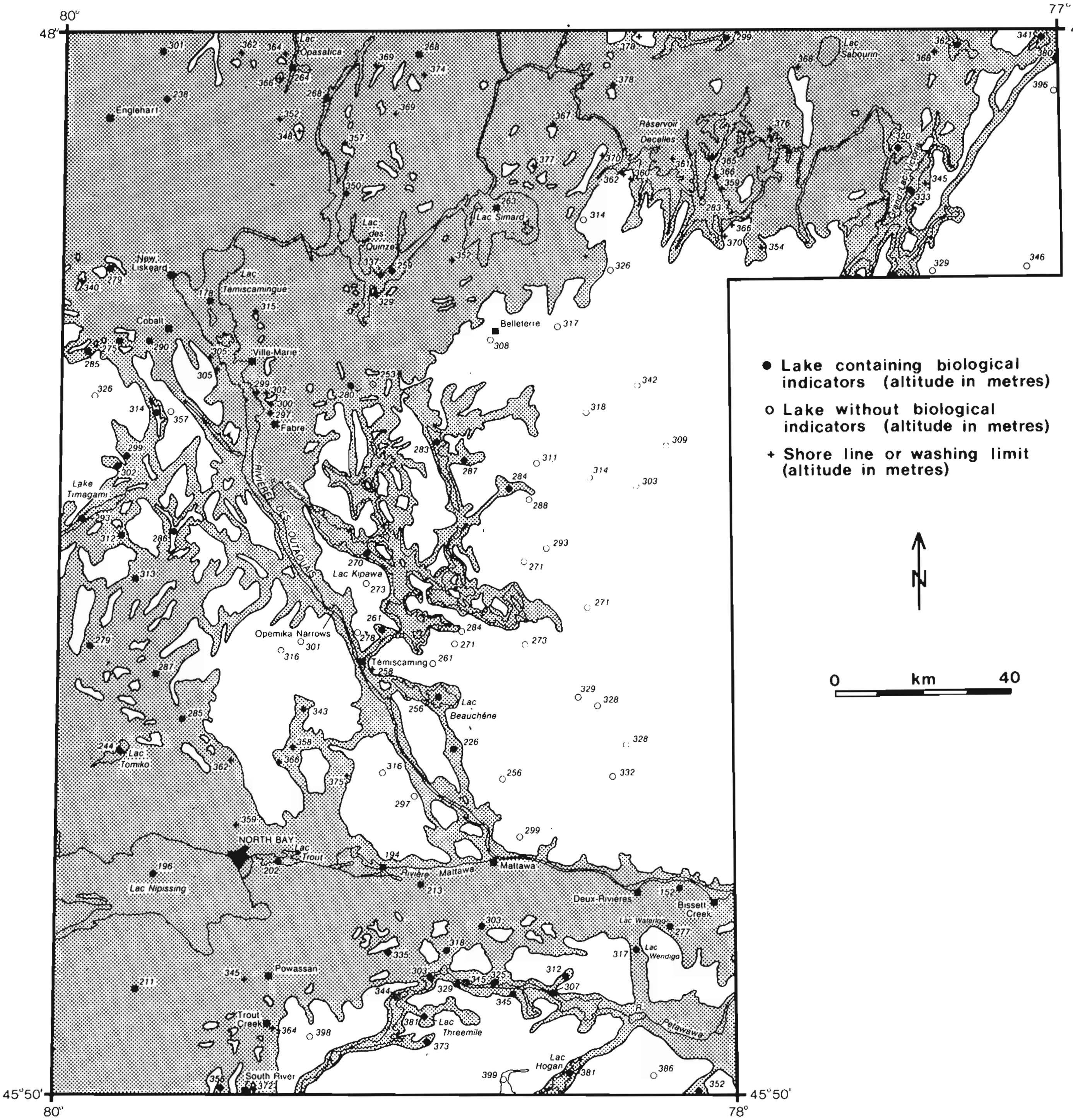


Figure 8. Maximum extent of proglacial lakes Post-Algonquin and Barlow south of 48°N. Black dots represent present lakes that were submerged and circles represent present lakes that were not submerged (from Veillette, 1988).

In the Abitibi region (Fig. 7) north and northeast of the Paleozoic outlier of Lake Timiskaming, carbonate content in the matrix of the Matheson till is abnormally low, and Paleozoic gravel-sized clasts are absent up to Joutel, Québec, where Paleozoic fragments occur in the Cochrane Till, but not in the Matheson till below it. A similar situation exists near the provincial boundary in Quebec (D. Green, pers. comm., 1987) at the latitude of Matagami. P. LaSalle (pers. comm., 1987), on the basis of a regional overburden drilling program, reports very rare occurrences of carbonates in the till for a large area of northwestern Quebec, west of Matagami and west of the Harricana Moraine. The scarcity of Paleozoic fragments in the Matheson till (below the carbonate-rich Cochrane Till) only 100 km down-ice (as inferred from surficial ice flow criteria) from its presumed source in Quebec, is in marked contrast with the highly calcareous till reported by Geddes (1984) at Hemlo, 200 km down-ice from the presumed source (Fig. 7). Hughes (1955), had reported a drop from a range of 10 to 32 % Paleozoic pebbles in the area west of Lake Abitibi in Ontario, to a range of 1 to 3 % west of Kirkland Lake. Similarly, carbonate content in the matrix of till samples from several boreholes in the Matheson area (Fig. 7) drops from about 15 to 30 % to a low of 5 to 8 % near the provincial boundary (Ontario Geological Survey, 1986).

It is thus apparent that an abrupt decrease in Paleozoic erratics occurs eastward, i.e., toward the Harricana Moraine, from Ontario. From Lake Timiskaming (Fig. 4) to the Joutel area, the Matheson till in Quebec appears to be devoid of Paleozoic fragments, in spite of abundant and obvious ice flow indicators to the south-southeast, down-ice from the source (Prest et al., 1968; Veillette, 1986a). These differences in dispersal patterns suggest a major difference in the behaviour of the Late Wisconsinan ice sheet between central Ontario and northwestern Quebec. It supports Skinner's (1973) suggestion of a northeastern provenance for the Adam Till, the stratigraphic equivalent of the Matheson till, farther north in James Bay. A study is in progress to test this assumption and to accurately map the dispersal of carbonate in the Matheson till towards James Bay.

Geomorphological Indicators

The orientation of the Harricana-Lake McConnell glaciofluvial system itself, and that of the large eskers of northeastern Ontario and northwestern Québec, constitute convincing evidence that a major shift in ice flow direction occurred during deglaciation of the region (Fig. 9). In the vicinity of Val d'Or, the directions of meltwater flow and ice flow shift from a general southwesterly direction (associated with the former south-southwestward (180° to 220°) flow) to a final south-southeastward flow (associated with the last south-southeastward (130° to 170°) flow). The Roulier Moraine, in Timiskaming (Veillette, 1986b) marks a frontal position of the ice lobe retreating to the northwest.

Evidence from absolute chronology

In the course of reconstructing the deglaciation chronology of the Timiskaming region, radiocarbon ages were obtained from cores of basal gyttja in small lakes and ponds at 32 locations (Veillette, 1983, 1988). An additional 11 dates from the work of earlier investigators, mainly in the North Bay area, were included for a total of 43 radiocarbon ages (Fig. 10) covering the entire upper Ottawa River area. Allowing for anomalous ages due to late melt-out conditions and old carbon contamination (Veillette, 1988; Richard et al., in prep.), the distribution of the ages shows an older zone with younger ones on each side. This corridor of older ages coincides with the longitudinal axis of the Lake McConnell-Harricana glaciofluvial system. The dates thus support the deglaciation history proposed on the basis of ice-flow indicators and glacial transport.

The problems associated with the interpretation of these minimum ages were discussed by Veillette (1988), and by Richard et al. (in prep.). A regional pollen zonation has been worked out from gyttja cores in the 32 basins and is in general agreement with the deglaciation sequence proposed (Richard et al., 1987). Because Lake Ojibway drained into the Tyrrell Sea at around 8000 BP (Hardy, 1976), ice retreated to the northwest for a period of about 1000 to 1500 years, from Val d'Or. It is during this short period that the glacial landscape of Abitibi was formed.

DISCUSSION

The occurrence of more than one regional, superimposed ice-flow direction in the Abitibi-Timiskaming region creates difficulties for the interpretation of glacial transport data. Till sheets, of limited extent and revealed only by drilling, as is the case for the till sheets below the Matheson till, cannot be associated with confidence with bedrock-inscribed ice flow indicators preserved at the surface. At this time, not enough is known about the oldest tills to make any valid inference about the regional flow directions of the glaciers responsible for their formation. These older sediments are not discussed in this paper.

In Abitibi, however, the youngest till below the Matheson till covers a substantial portion of the territory and shows an apparent correlation with a definite southwestward direction of ice movement observed on cross-striated sites at the surface. The term "apparent" must be stressed because of the speculative character attached to the correlation of erosional marks on bedrock with discrete till sheets. The presence of a distinct till sheet below the Matheson till, at first well documented in the Timmins area of Ontario (DiLabio, 1982; Bird and Coker, 1987; Steele et al., 1986, DiLabio et al., 1988) has now been verified (or suggested) at several locations in the mining districts of northwestern Quebec (Averill, 1986; Bouchard et al., 1986; D. Green, pers. comm., 1986, 1987; C.F. Gleeson, pers. comm., 1985, 1987; P. LaSalle and M.A. Bouchard, pers. comm., 1987), west of the Harricana Moraine. More direct observations from sections and large exposures are necessary before assigning firm glacial transport directions to this till.

Although the distribution and the directions of ice flow of the Matheson till are better known than that of the underlying till, the possibility that two major different directions of flow were responsible for its formation requires caution in interpreting glacial transport directions associated with it.

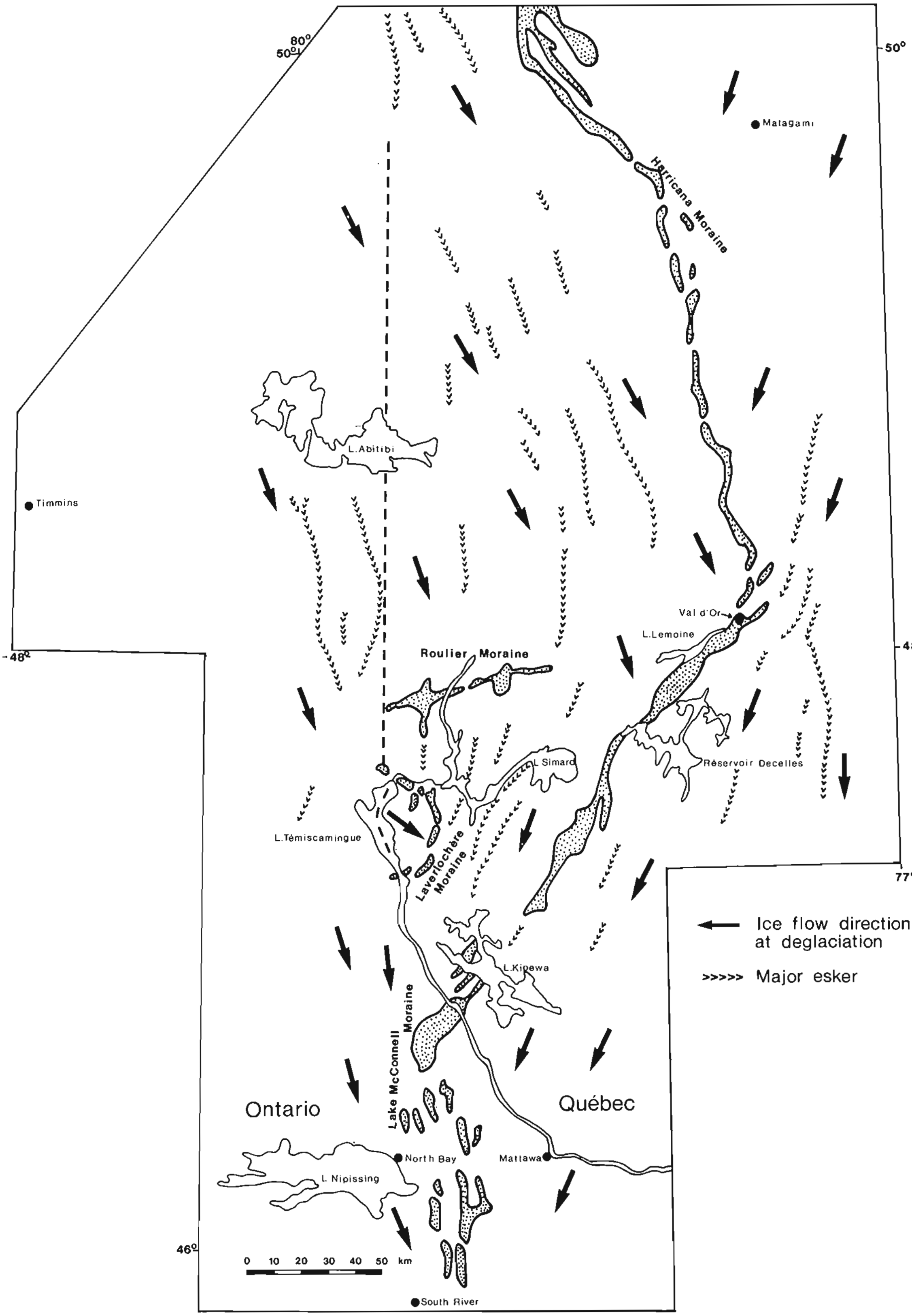


Figure 9. Ice flow and meltwater directions during the last retreat (after Veillette, 1986a).

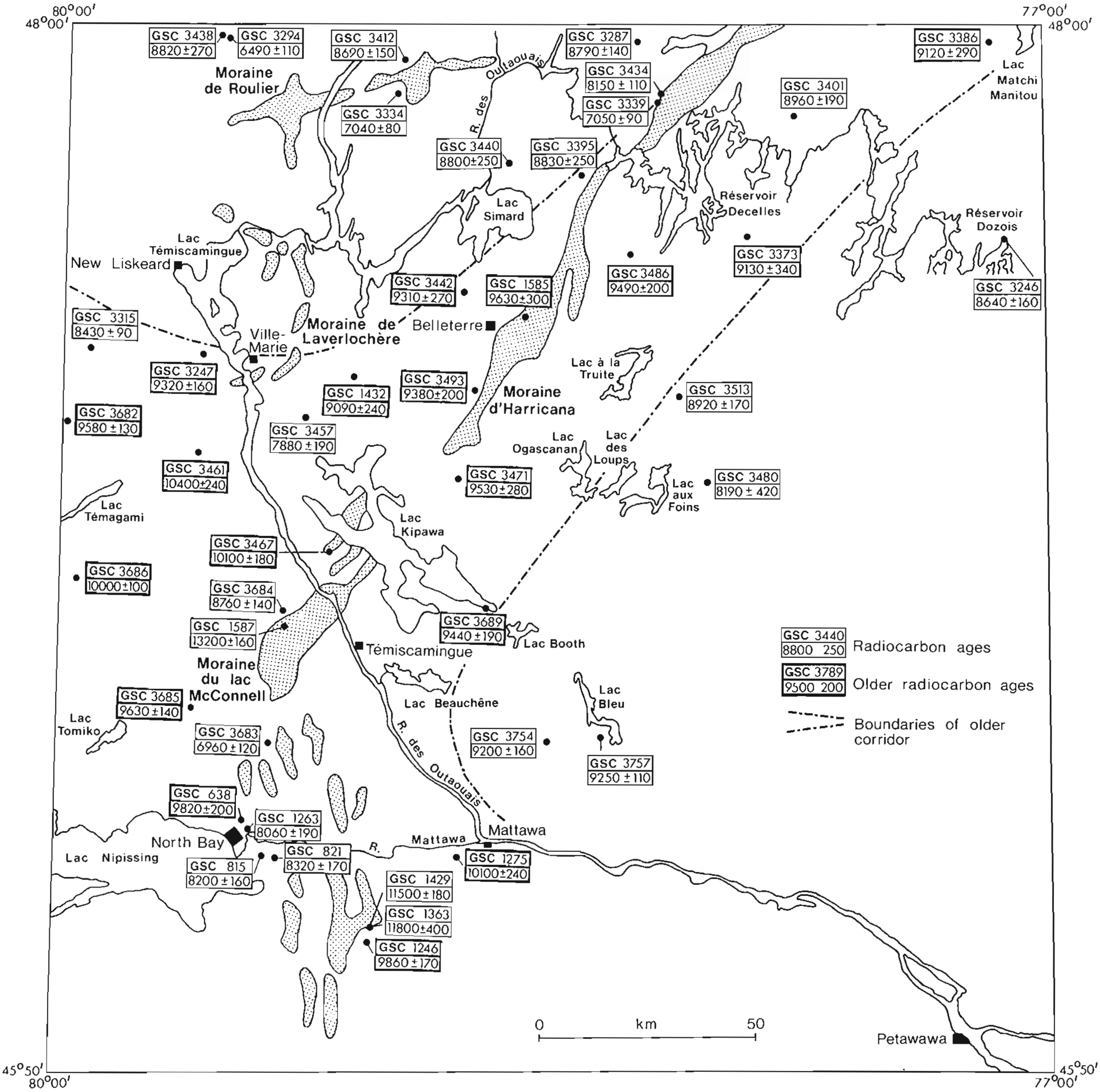


Figure 10. Distribution of 43 radiocarbon ages from basal organic materials in Upper Ottawa River, Quebec and Ontario (after Veillette, 1988).

This duality of provenance for the constituents of the till, is not to be automatically interpreted as a consistent and widespread characteristic throughout its whole area of occurrence. More detailed transport studies are required to assess the validity of this interpretation.

Two interesting case studies, conducted by Dreimanis (1958) in the Rouyn-Noranda area, illustrate the duality of provenance in this area. While studying the abundance of detrital minerals in indicator trains around sulphide ore bodies at Noranda, Québec, Dreimanis mapped an indicator train to the south-southwest of a large mineralized outcrop (Horne Mine) from striae and glacial transport data. He noted that megascopic ore fragments and even mineralized pebbles, were extremely rare in the train (less than 1 % at 0.1 to 4 km from the ore source). Similarly, the analysis of thousands of heavy mineral grains from till samples, showed an insignificant amount of sulphides (less than 0.01 %), at short distances down-ice from the outcrop of sulphides. To explain this unusual situation, Dreimanis speculated that many of the megascopic fragments may have been removed by the inhabitants of Rouyn-Noranda, which is built on the train, and that the finer sulphides in the thin sandy till could have been removed by oxidation. The trace metal levels were also found to be very low. A similar study in the vicinity of the MacDonald Mine (Dreimanis, 1958), only 9 km north-northeast of Noranda, showed an indicator train oriented to the south-southeast, but this train showed a higher proportion of megascopic fragments than at Noranda. The detailed study of the train was impaired by thick glaciolacustrine deposits.

The different orientations of the indicator trains at these two sites are believed to correspond with the two main directions of ice flow mapped in the area (Veillette, 1986a), as indicated by crossed-striae involving a former south-southwestward flow and a younger (deglaciation) south-southeastward flow. The Rouyn-Noranda area contains several striking examples of these two major flows (Veillette, 1986a). Comparison between the two sites suggests that glacial transport is the resultant of the two components of flow but that one may dominate locally. It would now be of interest to study the composition of the till south-southeast of the Horne deposit and compare glacial transport data with that found by Dreimanis to the south-southwest.

Another example illustrating the difficulties in attempting to match erosional stratigraphy to depositional stratigraphy is provided at the Selbaie mine open pit. Close inspection of the deposits and the bedrock exposed in the excavation during the summer of 1988 raised some questions regarding the occurrence of a distinct till sheet below the Matheson till at this site (Bouchard et al., 1986). All remnants of the original bedrock surface, which occur from 6 m to several tens of metres below the former ground surface within the perimeter of the excavation, bear marks of a unique, consistent, west-southwestward (240° to 270°) flow. Striae from a younger south-southeastward flow are, however, numerous in the general area outside the perimeter of the excavation. A till sheet (without intervening intertill deposits) covers bedrock with a stoss-and-lee topography streamlined to the west-southwest over most of the excavation. Till fabrics performed by M. Parent and myself point to a west-southwestward direction of movement near the base of the till sheet and a south-southeastward direction of movement near the top. The gravelly sands reported by Bouchard et al. (1986) as intertill sands may have a subglacial origin associated with early Matheson till deposition. Examination of large-scale detailed topographic maps of the excavation, updated monthly by Les Mines Selbaie, shows a topography of rock bosses favourable for the development of subglacial cavities on their down-ice sides. Thus, it remains to be demonstrated that a glacial event older than that responsible for the deposition of the Matheson till occurs at this location.

The most important implication of the results presented in this paper may be the relationship between the duration of a particular ice-flow event and its competence as an agent of glacial transport. In western Abitibi, the majority of the constituents of the Matheson till are probably derived from the northeast, due to the dominant southwestward direction of flow during Late Wisconsinan time. Later, the short-lived, superimposed southeastward and south-southeastward flows, resulting primarily from deglaciation processes, moulded the glacial landscape into its present-day shape, because they were the last ones to occur. This overprinting of one short glacial event on one of longer duration may lead to serious misinterpretation in glacial transport studies. In fact, the former southwestward flow was probably the main long-distance carrier of glacial debris in western Abitibi. Only detailed boulder tracing studies, conducted at a regional scale (Salonen, 1986) could help elucidate this problem. Recent observations by J-S. Vincent and myself in the lower reaches of the Nottaway River, in the James Bay basin, confirm the presence of a till deposited from the northeast, below the Cochrane Till. If this till correlates with the Matheson till to the south, and with the Adam Till to the west (Skinner, 1973), then it explains why the Matheson till in Québec is locally devoid of or contains only rare Paleozoic carbonates.

CONCLUSIONS

Extensive overburden drilling programs, carried out in recent years in Abitibi-Timiskaming, have unveiled a complex glacial stratigraphy. This new information, analyzed in conjunction with the relative chronology of ice flows determined from surficial indicators on bedrock, from landforms, and from long-distance lithological indicators of glacial transport has led to the following conclusions:

1. Three tills; from oldest to youngest, a regional unnamed till below the Matheson till, the Matheson and the Cochrane occur in the region. Older glacial and nonglacial sediments occur at depths below the regional unnamed till, but are poorly known at this time (Fig. 3).
2. The older till below the Matheson occurs throughout Abitibi, west of the Harricana Moraine, and has been associated with ice flowing to the southwest. Its extent is unknown. It may correlate with the pre-Missinaibi till(s) of Skinner (1973) in the Moose River basin of James Bay.

3. The Matheson till is the surficial till of northeastern Ontario and northwestern Québec, south of the Cochrane limit. In Québec, it is believed to have been deposited by ice flowing first to the southwest and south-southwest in Late Wisconsinan time, and to the southeast and south-southeast during deglaciation (Fig. 4). Its probable correlation with the Adam Till of Skinner (1973) in the Moose River basin of James Bay and with a till sheet along the Nottaway River, deposited by ice flowing from the northeast, is under study. In Québec, at least south of the Cochrane limit, the Matheson till does not contain Paleozoic erratics from the James Bay Lowland to the north.
4. The Cochrane Till is a thin, clayey, carbonate-rich till, deposited by surges in Lake Ojibway by Hudson Bay and James Bay ice before 8500 BP. It overlies the glaciolacustrine sediments of Lake Ojibway and the Matheson till. Detailed mapping of its southern limit in northwestern Québec is in progress, but preliminary work indicates that its southern extent is 30 to 50 km farther south than shown by previous work. In Ontario, Skinner (1973) has suggested a correlation with all or the upper part of the Kipling Till of the Moose River basin in James Bay.
5. A short-lived glacial flow in one direction, superimposed on another, larger glacial flow in a different direction, without an intervening ice-free period, presents difficulties in the analysis of transport data. Both erosional and depositional landforms from the younger flow have destroyed or masked those from the earlier flow. In the western Abitibi portion of Québec the existence of a major shift in the flow direction of the ice mass that deposited the Matheson till has been demonstrated. Provenance studies of till constituents support this model.

The primary mineralized belts of Abitibi are located, in part, in areas where complex ice flows have occurred (Fig. 11). This, rather than discouraging the application of drift prospecting techniques in the search for new ore deposits, should instead be a stimulus to attain a better understanding of ice sheet dynamics and, consequently, to improve our knowledge on the distribution of lithological indicators of ore sources. Glacial history of the Abitibi-Timiskaming area shows that the unveiling of the sequence of events that led to the identification of major ice flows and associated till sheets requires the use of several different methods of analysis. It follows that exploration surveys based on a quick, superficial assessment of the glacial history of a given restricted area, without the benefit of broader regional knowledge, may lead to disenchantment with exploration techniques normally used in glaciated terrain.

Much work remains to be done to assess some of the interpretations discussed in this paper. A detailed, three-dimensional reconstruction of the Quaternary sediments of Abitibi must be produced eventually, to maximize the usefulness of Quaternary sediments for mineral exploration purposes and to understand fully the regional glacial history.

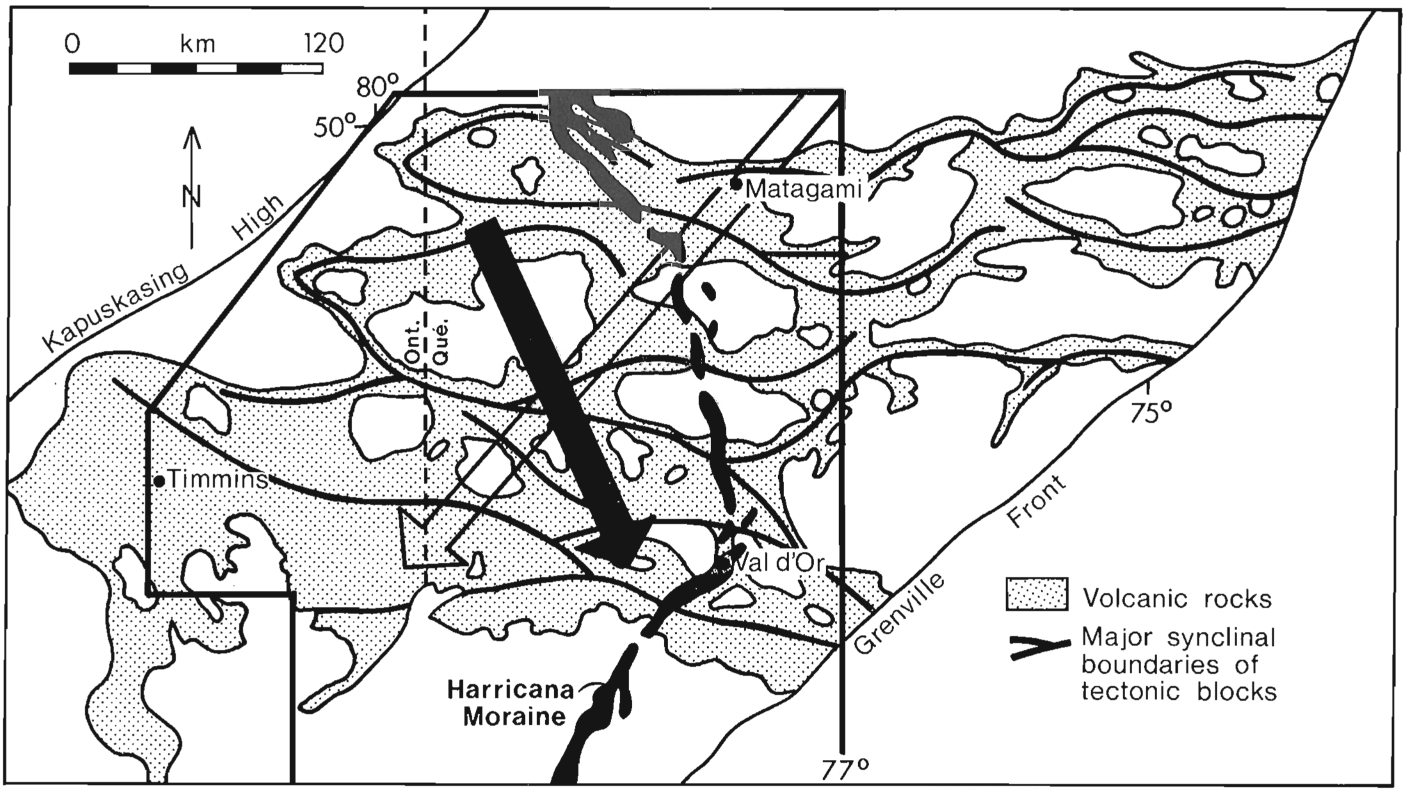


Figure 11. Relationships between mineralized areas and major axes of glacial transport in western Abitibi in Late Wisconsinan time. The two arrows illustrate the chronological order of the directions of glacial transport west of the interlobate moraine. Geology after Jolly (1978).

ACKNOWLEDGMENTS

Several mineral exploration geologists volunteered information that led to a better understanding of the regional glacial geology of the area. Special thanks are extended to C.F. Gleeson and R.D. Thomas (C.F.Gleeson & Associates), D. Green (Duration Mines), J.A. Dixon, C. Marcotte (Cogéma), J.A. Sauerbrei (INCO-Golden Pond) and S.A. Averill (Overburden Drilling Management). J.J. Bouillon from Les Mines Selbaie provided access to the open pit and pointed out areas of interest. Comments from M.A. Bouchard and V.-P. Salonen and discussions plus active fieldwork with M. Parent, GSC, proved most beneficial. H. Thorleifson critically read the manuscript, offered constructive suggestions and freely discussed his own results for areas to the west and northwest of Abitibi. Sincere thanks are extended to all.

REFERENCES

Averill, S.A.
1986: Heavy mineral anomaly interpretation, the importance of mineralogy and Quaternary stratigraphy, paper presented to the 1986 Prospectors and Developers Association, Toronto, Ontario, March 1986.

Bird, D.J. and Coker, W.B.
1987: Quaternary Stratigraphy and Geochemistry of the Owl Creek gold mine, Timmins, Ontario, Canada; Journal of Geochemical Exploration, v. 28, p. 267-284.

Bouchard, M.A., LaSalle, P., Lamothe, M., David, P.P., and Bouillon, J.J.
1986: Pleistocene stratigraphy of northwestern Abitibi from boreholes and excavations at Selbaie Mine, Québec; Geological Association of Canada, Program with Abstracts, v. 11, p. 47.

Dadswell, M.J.
1974: Distribution, ecology and postglacial dispersal of certain crustaceans and fishes in eastern North America; National Museums of Canada, Publications in Zoology, no. 11, 110 p.

DiLabio, R.N.W.
1982: Wood in Quaternary sediments near Timmins, Ontario; in Current Research Part A, Geological Survey of Canada, Paper 82-1A, p. 433-434.

DiLabio, R.N.W., Miller, R.F., Mott, R.J., and Coker W.B.
1988: The Quaternary Stratigraphy of the Timmins area, Ontario, as an aid to mineral exploration by drift prospecting; in Current Research, Part C, Geological Survey of Canada, Paper 88-1C, p. 61-65.

Dreimanis, A.
1958: Tracing Ore Boulders as a Prospecting Method in Canada; The Canadian Institute of Mining and Metallurgy, Bulletin, v. 51, p. 73-80.

Geddes, R.S.
1984: An exotic till in the Hemlo area, northern Ontario; Geological Association of Canada, Program with Abstracts, v. 9, p. 66.

Hardy, L.
1976: Contribution à l'étude géomorphologique de la partie québécoise des basses terres de la baie de James; Thèse de doctorat, Université McGill, Montréal, Québec, 264 p.

Hughes, O.L.
1955: Surficial geology of Smooth Rock and Iroquois Falls map areas, Cochrane District, Ontario, Ph.D. Thesis, University of Kansas, Lawrence, Kansas, 190 p.

Jolly, W.T.
1978: Metamorphic history of the Archean Abitibi Belt; Geological Survey of Canada, Paper 78-10, p. 63-83.

Karrow, P.F. and Geddes, R.S.
1987: Drift carbonate on the Canadian Shield; Canadian Journal of Earth Sciences, v. 24, p. 365-369.

Lovell, H.L. and Caine, T.W.
1970: Lake Temiskaming rift valley; Ontario Department of Mines, Miscellaneous Paper 39, 16 p.

Martin, N.V. and Chapman, L.J.
1965: Distribution of certain crustaceans and fishes in the region of Algonquin Park, Ontario; Journal of Fisheries Board of Canada, v. 22, p. 969-976.

Ontario Geological Survey
1986: Sonic Drill Holes 85-01 to 85-60; Ontario Geological Survey, Geophysical/Geochemical Series, Map 80845 to 80893.

Prest, V.K., Grant, D.R., and Rampton, V.N.
1968: Glacial Map of Canada; Geological Survey of Canada, Map 1253A, scale 1:500 000.

Richard, P.J.H., Larouche, A., and Veillette, J.J.
1987: Proglacial Lake Barlow vegetational environment: co-occurrence of tundra plants and temperate trees within spruce-dominated open forests; XII International Congress, International Union for Quaternary Research, Ottawa, Canada, July 1987, Program with Abstracts, p. 252.

Richard, P.J.H., Veillette, J.J., and Larouche, A.
in prep: Chronopalynostratigraphie et déglaciation durant l'épisode glacio- lacustre Barlow au Témiscamingue.

Salonen, V.-P.
1986: Glacial transport distance distributions of surface boulders in Finland; Geological Survey of Finland, Bulletin 338, 78 p.

Sauerbrei, J.A., Pattison, E.F., and Averill, S.A.
1987: Till sampling in the Casa-Berardi gold area, Québec: A Case History in orientation and discovery; Journal of Geochemical Exploration, v. 28, p. 297-314.

Shilts, W.W.
1976: Glacial till and mineral exploration; in Glacial Till, ed. Robert F. Leggett; Royal Society of Canada, Special Publication No. 12, p. 205- 224.

Skinner, R.G.
1973: Quaternary stratigraphy of the Moose River Basin, Ontario; Geological Survey of Canada, Bulletin 225, 77 p.

Steele, K.G., Baker, C.L., and McClenaghan, M.B.
1986: Reconnaissance till sampling program, Matheson-Lake Abitibi Area, District of Cochrane; in Summary of Fieldwork and other activities 1986, Ontario Geological Survey, Miscellaneous Paper 132, p. 398-403.

Veillette, J.J.
1983: Déglaciation de la vallée supérieure de l'Outaouais, le lac Barlow et le sud du lac Ojibway, Québec; Géographie physique et Quaternaire, v. 37, p. 67-84.
1986a: Former southwesterly ice flows in Abitibi-Temiskaming region: Implications for the configuration of the late Wisconsinan ice sheet; Canadian Journal of Earth Sciences, v. 23, p. 1724-1741.
1986b: Surficial geology, New Liskeard, Ontario-Quebec; Geological Survey of Canada, Map 1639A, scale 1:100 000.
1988: Déglaciation et évolution des lacs proglaciaires Post-Algonquin et Barlow au Témiscamingue, Québec et Ontario; Géographie physique et Quaternaire, vol. 42, p. 7-31.

Vincent, J-S., Veillette, J.J., Allard, M., Richard, P.J.H., Hardy, L., et Hillaire-Marcel, C.
1987: Dernier cycle glaciaire et retrait des glaces de la vallée supérieure de l'Outaouais jusqu'au sud-est de la baie d'Hudson, XIIe congrès de l'Union Internationale pour l'étude du Quaternaire, Ottawa 1987, Livret- guide excursion C-10, 87 p.

Glacial dispersal in Nova Scotia: a zonal concept[1]

R.R. Stea[2], R.G. Turner[2], P.W. Finck[2], and R.M. Graves[2]

Stea, R.R., Turner, R.G., Finck, P.W., and Graves, R.M., Glacial dispersal in Nova Scotia: a zonal concept; in Drift Prospecting, ed. R.N.W. DiLabio and W.B. Coker; Geological Survey of Canada, Paper 89-20, p. 155-169, 1989.

Abstract

A complex pattern of ice flows was imprinted on the landscape of Nova Scotia by the interplay of external and local ice divides. Four major Wisconsinan ice flow events (phases 1 to 4) have been defined. The shape and magnitude of dispersal trains in Nova Scotia are a result of the net effect of these ice flow events. The migration of ice divides during the Wisconsinan Stage from areas north of Nova Scotia to local areas produced a series of zones, areas with distinct dispersal trends defined by a pattern of mapped ice flow features. Dispersal studies in the zones confirm that the patterns of mapped ice flow features used to define the zones are mirrored by the shape of the dispersal trains. Topography and ice dynamics of the various glaciers controlled the deposition and composition of till units during the successive ice flow phases. Tills produced by the later phases (3 and 4) are characterized by dominance of clast over matrix modes and relatively local dispersal. Tills produced during the earlier phases (1 and 2) tend to be dominated by matrix modes and have greater percentages of far-travelled components.

Résumé

Un réseau complexe d'écoulements glaciaires a laissé son empreinte sur le paysage de la Nouvelle-Écosse suite à l'interaction des lignes de partage des glaces extérieures et locales. Quatre grands écoulements glaciaires du Wisconsinien (phases 1 à 4) ont été identifiés. La forme et l'importance des trainées de dispersion en Nouvelle-Écosse sont le résultat de l'effet net de ces écoulements glaciaires. La migration des lignes de partage des glaces pendant le Wisonsinien, depuis des régions au nord de la Nouvelle-Écosse jusque dans des régions locales, a produit une série de zones présentant des tendances de dispersion distinctes définies par un réseau de formes de relief façonnées par l'écoulement glaciaire que l'on a cartographiées. Les études de dispersion effectuées dans les zones confirment que ces réseaux, qui ont servi à définir les zones, correspondent à la forme des trainées de dispersion. La topographie et la dynamique des glaces des différents glaciers ont contrôlé la mise en place et la composition des unités de till durant les phases successives d'écoulement glaciaire. Les tills produits pendant les phases finales (3 et 4) sont caractérisés par la dominance des modes détritiques sur les modes matriciels et par une dispersion relativement locale. Les tills produits durant les phases initiales (1 et 2) tendent à être dominés par des modes matriciels et renferment des pourcentages plus élevés de constituants d'origine lointaine.

---

[1] Contribution to the Canada-Nova Scotia Mineral Development Agreement, 1984-89. Project carried by the Nova Scotia Department of Mines and Energy.
[2] Nova Scotia Department of Mines and Energy, P.O. Box 1087 Halifax, Nova Scotia, Canada B3J 2X1

INTRODUCTION

Continental ice sheets and local ice caps have imprinted a complex pattern of ice flows on the landscape of Nova Scotia. Quaternary mapping and till geochemistry programs (Stea and Fowler, 1979; Stea et al., 1985; Finck and Graves, 1987) in mainland Nova Scotia have led to the definition of four ice flow phases based on mapped ice flow features. Ice flow phases are defined as discrete, regionally mappable, trends of ice flow features. The sequence of ice flow phases is determined through correlation of superimposed striation sets and till sheets formed during these flows. Till sheets formed during separate ice flow phases in Nova Scotia generally have distinct provenance, geochemistry and dispersal patterns.

Mainland Nova Scotia is characterized by two juxtaposed tectonic terranes, each with distinct geology (Fig. 1). The Cobequid Fault system separates the Cobequid Terrane from Meguma Terrane (Donohoe and Wallace, 1982). The Cobequid Terrane consists of a highland massif of Precambrian to Carboniferous volcanic, metasedimentary and igneous rocks flanked by basinal sedimentary rocks of Carboniferous and Triassic age. The Meguma Terrane consists largely of Cambro-Ordovician metasedimentary rocks intruded by Devono-Carboniferous granitoid rocks. These rocks form a large part of the Southern Uplands physiographic province (Goldthwait, 1924). The bedrock terranes provide useful indicator erratics for the reconstruction of ice flow events.

Wisconsinan glaciations have produced distinct glaciated landscapes on upland and lowland regions of Nova Scotia. The lowland regions, underlain by Carboniferous and Triassic rocks, are characterized by thicker drift cover with occasional multiple- till sections exposed in coastal regions. The surface of the upland regions, however, are usually bare of drift, especially at elevations greater than 300 m. Glacial erosion features such as striations, reveal several discrete ice flow trends that can be traced consistently across the upland areas. These trends relate to specific glaciers that eroded and transported debris and deposited tills at different times on the lowlands.

Exploration companies in Nova Scotia have employed differing till prospecting techniques in the search for mineral deposits in these bedrock-physiographic terranes. Drilling has been used in thick drift areas of the lowland regions (Boyd, 1982); surface till and boulder sampling in the areas of till veneer (Felderhof, 1979).

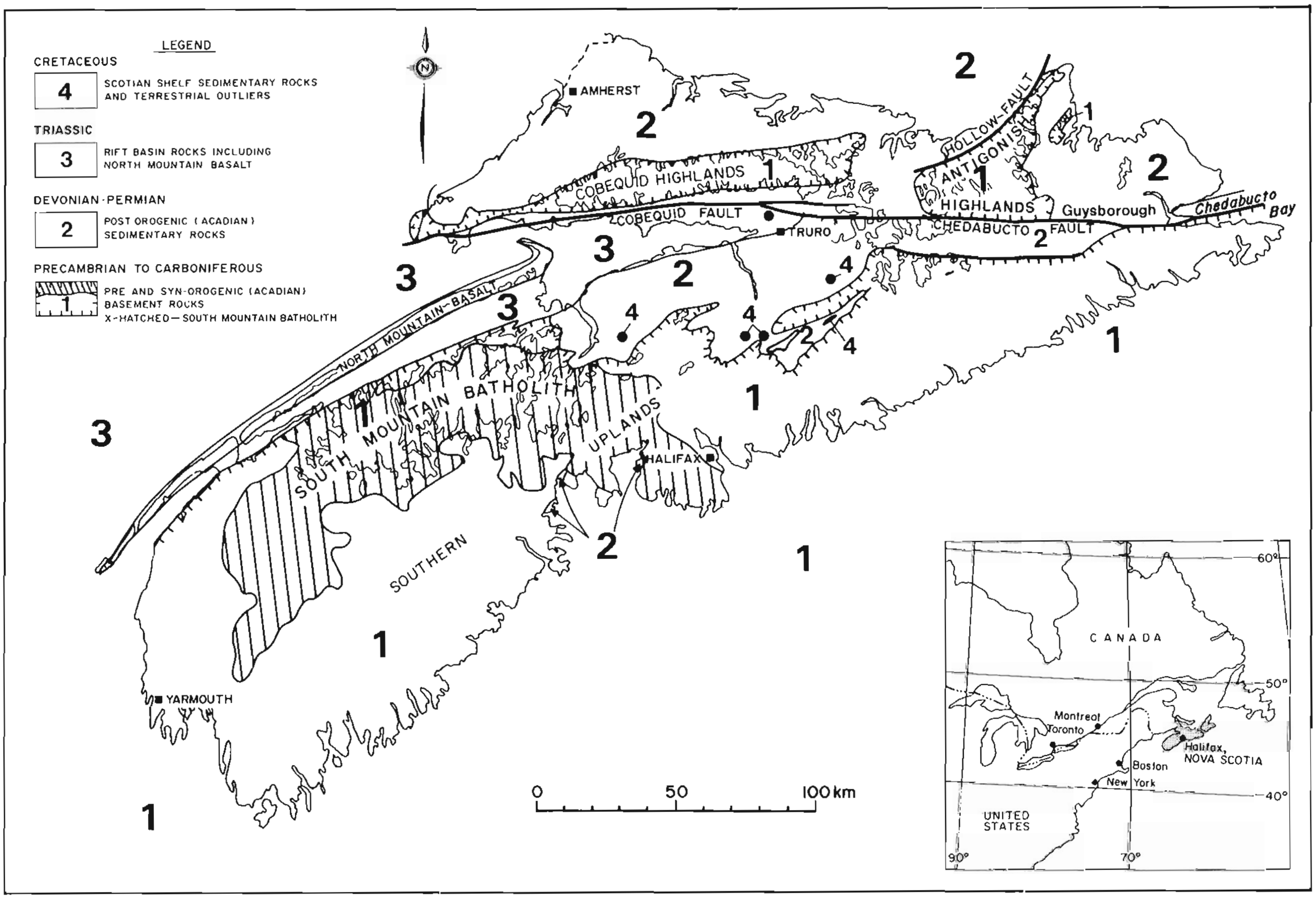


Figure 1. Generalized geology and physiography of mainland Nova Scotia.

This paper will present a model of glacial dispersal for the province. Dispersal patterns in different regions will be contrasted against ice flow phases based largely on striation patterns.

ICE FLOW PHASES

Striations were mapped as part of the till mapping programs. They provide detailed information on ice flow patterns. Because they provide a quick assessment of prevailing flow directions, they are a useful tool for exploration geologists. The patterns of ice flow mapped by striations are verified by the orientation of glacial landforms such as eskers and drumlins, and by till fabric and dispersal studies (Stea, 1984). The sequence of ice flow phases has been discerned from superimposed striation sites, and through correlation with stacked till sheets. (Stea, 1984). Each of the ice flow phases produced at least one recognizable till sheet, sometimes with genetic facies, such as lodgment and melt-out.

Phase 1

Striation patterns, distinctive erratics, till fabric, and striated boulder pavements suggest that the earliest, and most extensive ice flow was initially eastward then shifted to southeastward (Figure 2a). This flow is believed to be Early Wisconsinan in age (Grant and King, 1984; Stea, 1984; Stea et al., 1985). A till unit found at the base of many sections along the Nova Scotia coast and in the core of drumlins along the Atlantic shore (McCarron Brook Till; Stea et al., 1985; Hartlen Till of Stea and Fowler, 1979) was formed during this ice flow. It is generally a silty till with few clasts and numerous erratics and is characterized by homogeneity of composition and grain size over different geological terranes. Erratic trains of igneous rocks from the Cobequid Highlands and trains of basaltic rocks from the North Mountain are oriented southeastward and can be traced to the Atlantic Coast, up to 60 km down-ice (Nielsen, 1976). This phase may represent the main Laurentide ice flow. The

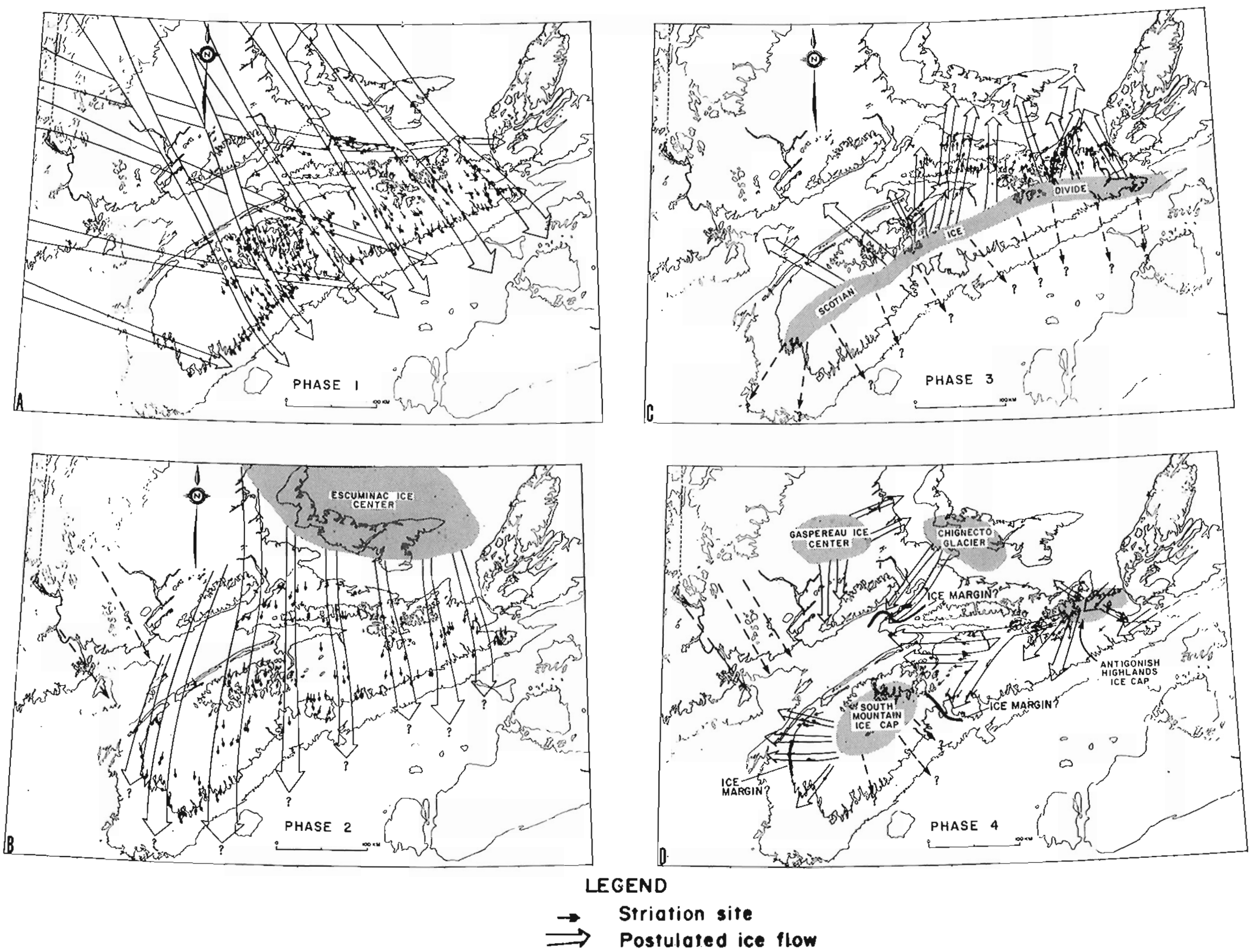


Figure 2. Compilation of striation sites and inferred ice flows in Nova Scotia during the Wisconsinan Stage.

Laurentide Ice Sheet may have crossed the Bay of Fundy but evidence of its passage has not been unequivocably traced across New Brunswick (Rampton et al., 1984). Anorthosite boulders in western Prince Edward Island of a presumed Canadian Shield source suggest that Laurentide ice did cross the region at some time (Prest and Nielsen, 1987).

Phase 2

The second major ice flow trend was southward and southwestward from the Escuminac Ice Center in the Prince Edward Island region (Rampton et al., 1984; Fig. 2b). This flow phase is analogous to the Acadian Bay Lobe of Goldthwait (1924) and the ''Fundian'' glacier of Shepard (1930). Goldthwait envisioned a southward flow from a Laurentide source across the Gulf of St. Lawrence. However, ice flow features in Prince Edward Island (Prest, 1973) and adjacent New Brunswick (Rampton et al., 1984) do not reflect a pervasive southward flow, but suggest radial flow from a local center. This event is recorded by southward striae crossing earlier southeastward trending striae at many localities on the upland regions. Material from the vast area of redbeds in the northern mainland and Carboniferous basins in the Prince Edward Island region was transported southward onto the metamorphic and igneous Cobequid and Meguma Terranes of mainland Nova Scotia. The distinctive reddish clay-rich till formed during this flow phase (Lawrencetown Till of Grant, 1975) is the surface till on drumlins and some areas of ground moraine along the Southern Uplands. Southward dispersal of distinctive Cobequid Highland erratics occurred with the dispersal of the red material (Grant, 1963; Fig. 3). Evidence of southward dispersal of red clastic material from the Bay of Fundy has also been noted in sediment cores in the Gulf of Maine (Schnikter, 1987).

Phase 3

During phase 3, granites from the South Mountain Batholith were transported northward onto the North Mountain basalt cuesta (Fig. 1; Hickox, 1962). Erratics from the Cobequid Highlands can be found throughout the Carboniferous lowlands to the north (Stea and Finck, 1984; Felderhof, 1979). A stony, autochthonous till was produced during this flow phase. The thickest deposits of this till unit are found along the Atlantic Coast away from the proposed ice divide (Fig. 2c). Northward-trending striations can be traced across the northern mainland of Nova Scotia (Fig. 2c). This well documented northward ice flow was clearly in response to the development of an ice divide in southern Nova Scotia (Fig. 2c). Ice flow was northward and southward from this divide across the axis of the Nova Scotia peninsula. This divide may have formed as a result of marine incursion into the Bay of Fundy (Prest and Grant, 1969) or a climatic event (MacNeill and Purdy, 1951; Hickox, 1962). Northward ice flow from the Scotian ice divide was probably synchronous with the Mid-Wisconsinan ice dome off Cape Breton Island proposed by Grant (1977). The divide can be traced from areas south of the Antigonish Highlands (Myers and Stea, 1986) offshore into Chedabucto Bay on the basis of northward ice flow features.

Phase 4

During this final phase remnant ice caps developed from the Scotian Ice Divide (Fig. 2d). Eskers and striations cut across features formed by earlier ice flows. The margins of ice caps or glaciers that formed over the Chignecto Peninsula and southern Nova Scotia are represented by moraines, ablation till, glaciofluvial deposits, and the pinch-out of till sheets

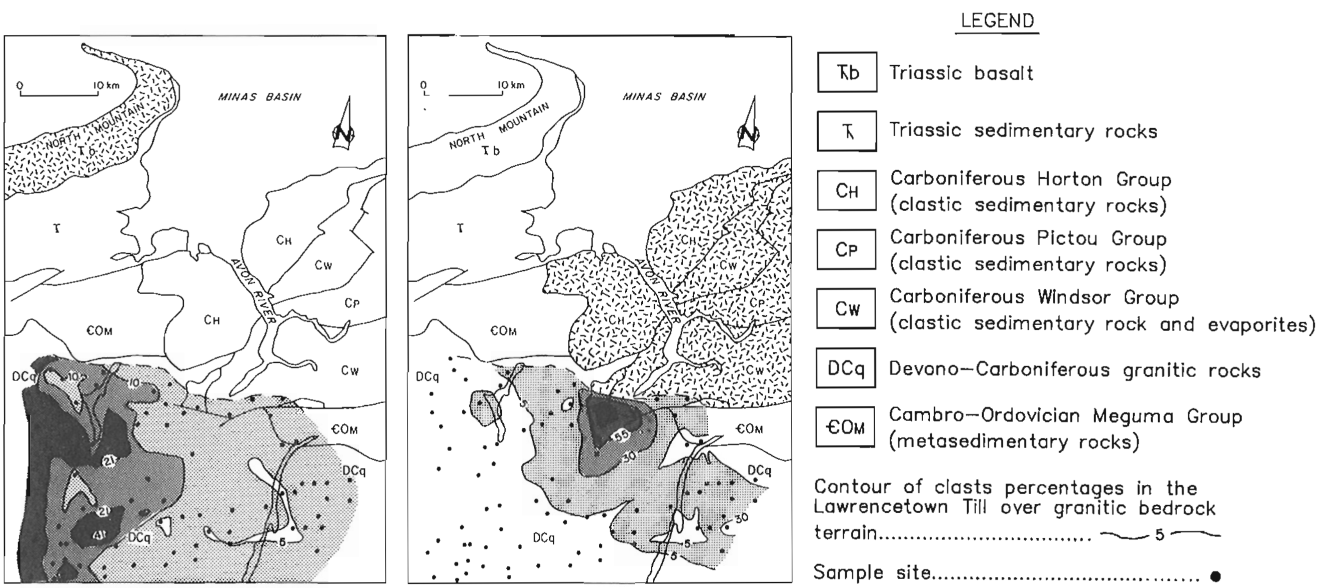


Figure 3. Dispersal of Carboniferous sedimentary bedrock and North Mountain basalt (stippled areas) in Lawrencetown till samples over granitic bedrock of the southern uplands.

(Fig. 2d). Ice flow during this last phase was strongly funnelled westward into the marine basins. Erosional features and deposits relating to these late-glacial ice caps are restricted to low- lying areas.

ZONAL CONCEPT OF GLACIAL DISPERSAL

The interplay of the regional ice sheets and local ice caps and the physiographic variation of Nova Scotia produced distinct zones of erosion and deposition, each of which is characterized by discrete transport histories (Fig. 4). These "zones" are a result of the migration of ice divides. The former ice divides and centers were defined by the patterns of ice flow indicated by striations and landform orientations and are the net result of the migration of these divides during ice flow phases 1 to 4. In Zone A the main flow trends are southeastward and southward. The erosional evidence for earlier ice flow phases (1 and 2) is dominant, while evidence for subsequent ice flow phases is lacking. Zone A was under the Scotian Ice Divide (Fig. 2c) where little erosion or deposition occurred after the earlier ice flow phases. In Zone A, older till units, such as the Hartlen and Lawrencetown Till outcrop on the surface, and deposits of residuum are often found, suggesting relatively little erosion or deposition during subsequent ice flow phases. In contrast, Zone B, which is located distal to the Scotian Ice Divide, shows ice flow trends and till deposits relating to the earlier ice flows as well as till formed during phase 3. It is assumed that flow from the Scotian ice divide was southward in this zone. In Zone C the earlier ice flows are represented, as well as late-stage southwestward ice flow (Phase 4). No evidence for ice flow during phase 3 is noted, however. Zone D records the earlier ice flows (phases 1 and 2) as well as the strong northward ice flow (Phase 3) from the Scotian ice divide. In Zones E and F, striations and till sheets relating to all four ice flow phases can be found, but Zone E lacks northward ice flow.

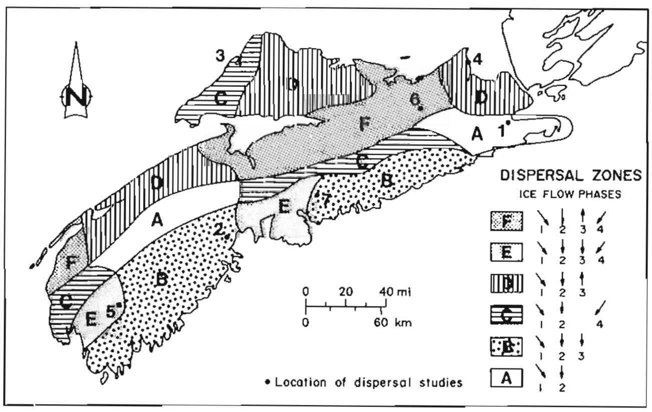


Figure 4. Map of the dispersal zones in mainland Nova Scotia related to the migration of external and local ice centers. Dispersal studies:

(1) Sangster Lake	(5) East Kemptville
(2) Gold River	(6) Garden of Eden
(3) Joggins	(7) Oldham
(4) Ballantynes Cove	

These zones are a result of the position of ice centers and divides over time. The position of the divides control the complexity of the ice flow patterns shown by striations and associated dispersal patterns. This is because little movement occurs near an ice divide (Denton and Hughes, 1981). Exploration geologists working within these various zones have contended with widely differing patterns of dispersal. Some areas show relatively simple patterns of southeastward dispersal whereas others are complicated by northward flow. Glacial dispersal trains originating from distinctive rock bodies and mineral deposits are described along with provenance studies of till sections to establish the validity of the zonal concept. These studies provide models of glacial dispersal within each of the zones shown on Figure 4.

DISPERSAL STUDIES

Sangster Lake (Zone A, No. 1)

Sangster Lake is located 20 km south of Guysborough in eastern mainland Nova Scotia (Fig. 4). This area is an example of dispersal from a geochemically specialized granite. It is in Zone A, a region where the dominant ice flow patterns are the two earlier phases (1 and 2; Fig. 2a,b). The Sangster Lake area has abundant surface boulders which are part of extensive areas of ablation till (Stea and Fowler, 1979). The ground moraine unit in this region was formed during the southeastward flow phase (Phase 1 ; MacEachern and Stea, 1985).

Figure 5 (adapted from Ford and O'Reilly ,1985) shows the geology of the Sangster Lake and Larry's River Plutons and their respective airborne radiometric signatures. Both plutons consist of various textural varieties of monzogranite. The Sangster Lake Pluton is distinct from the Larry's River Pluton being deformed, metasomatically altered, and enriched in uranium (G.A. O'Reilly, pers. comm., 1988). The anomalous equivalent uranium response correlates with the altered area of the pluton except for a lobe-shaped area of higher values southeast of the pluton. Boulders of the Sangster Lake granite are found within this area of higher radioactivity (G.A. O'Reilly, pers. comm., 1988) and therefore the lobe-shaped area probably represents a southeastward-oriented dispersal fan. There is no evidence of northward dispersal from the enriched granitic body, consistent with the striation evidence in the region. A study by MacEachern and Stea (1985) on the nearby Forest Hill gold district also showed that the dominant flow pattern and gold dispersal was southeastward during phase 1. The preservation of a Wisconsinan paleosol on the surface of the till unit formed by ice flow phase 1 (MacEachern and Stea, 1985) suggests that erosion during later flow phases had little effect on this till surface.

Gold River (Zone B, No. 2)

The Gold River area, located 60 km west of Halifax along the Atlantic coast, lies within Zone B, and has been affected by southeastward and southward ice flow of phases 1 and 2 (Fig. 2a,b). In Zone B, deposits of these earlier glacial phases are overlain by deposits related to the Scotian Ice

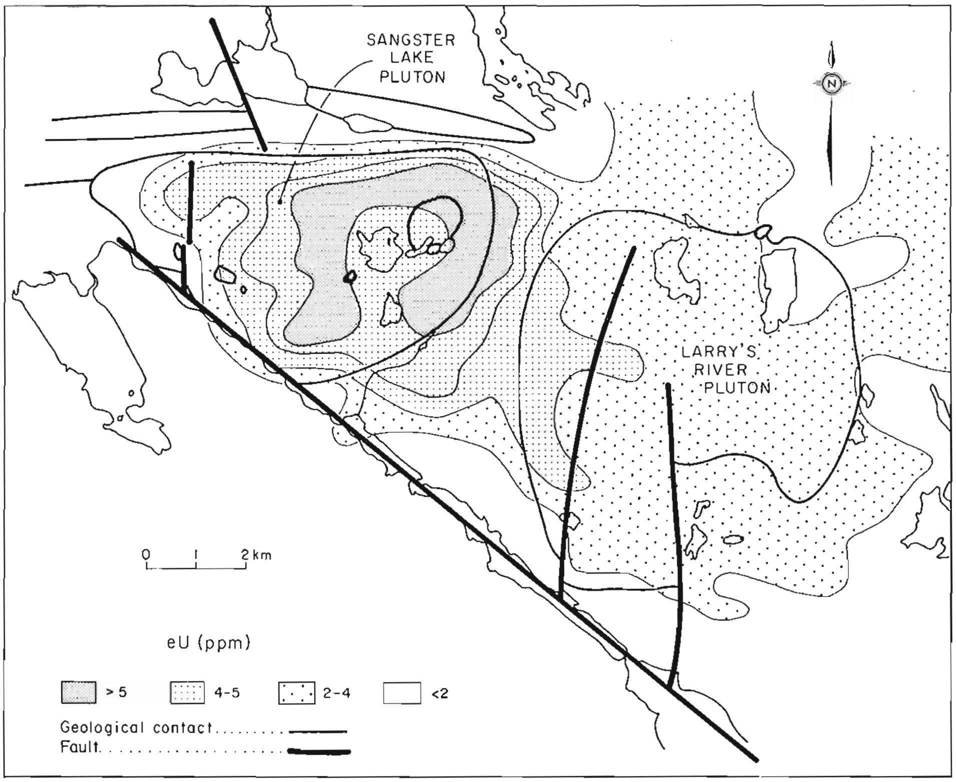


Figure 5. Airborne radiometric signatures of the Larry's River and Sangster Lake Plutons, Guysborough County, Nova Scotia.

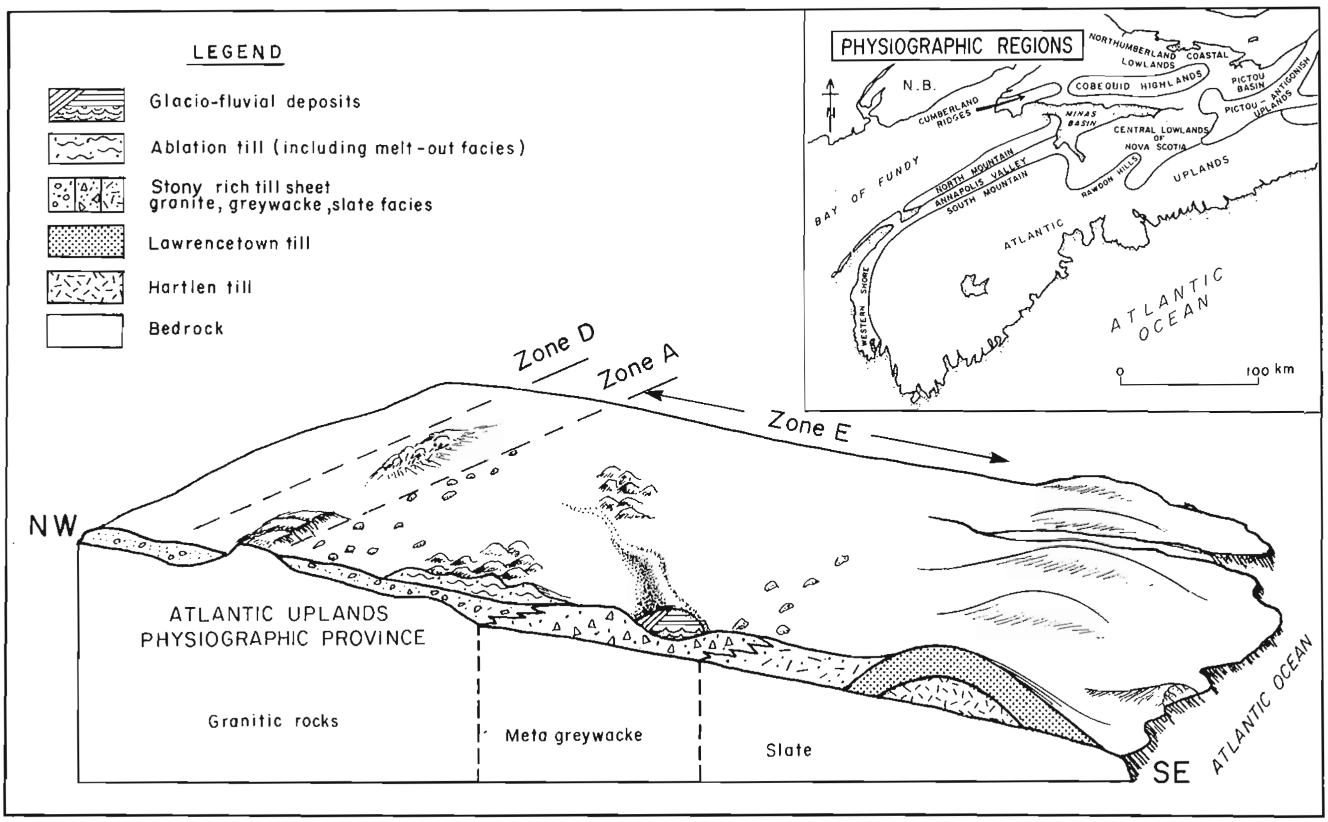


Figure 6. Schematic cross-section of the Quaternary stratigraphy of the Meguma Terrane in Zones A, D and E.

Divide (phase 3). The till stratigraphy and glacial landforms typical of the Meguma Terrane in this region are shown in Figure 6. Drumlins in the region are composed of the Lawrencetown and Hartlen Tills formed during phases 1 and 2. A stony, autochthonous till sheet overlies the drumlin tills and forms the surface ground moraine over most of the region. This surface till could have formed during either phases 3 or 4. It is characterized by poorly developed fabric and predominately local clast content. In Zone B the dispersal patterns of this till sheet are generally southward (Finck and Graves, 1987) but can vary widely from area to area. In Zone D the patterns trend northward (Fig. 4). The stony till sheet is characterized by "renewal-distance" values in the range of 100 to 200 m. This is the distance it takes for tills to take up 50 % of the new rock lithology down-ice of a contact (Peltoniemi, 1985). The Lawrencetown drumlin till on the other hand, has a renewal distance value between 1 and 10 km. A renewal distance value given by Peltoniemi (1985) for till formed by the Scandinavian ice sheet was 16 km. The extremely local nature of the stony till unit, and its relative immaturity (preponderance of clast over matrix fractions; Dreimanis and Vagners, 1971) suggest that the glaciers present in Nova Scotia, responsible for its formation had different dynamics than the regional ice sheets that formed the drumlin tills.

Figure 7 shows the distribution of clasts in the stony till sheet in the region of a granite-metasedimentary contact in the Meguma Terrane near Gold River, Nova Scotia. Dispersal ranges from southeastward to southwestward. It can be seen that granite clast attenuation is immediate, within a few hundred metres of the contact. Areas in Zone B either underlain by older till units or adjacent to drumlin fields will reveal more extensive southward and southeastward-oriented dispersal trains due to the mixing of clasts dispersed during earlier phases of ice flow. A study by DiLabio (1982) (Fig. 8) in the Oldham gold district in Zone B shows a southward-oriented dispersal train, although sampling may have not been sufficient to identify if any dispersal occurred during subsequent ice flow phases.

Joggins (Zone C, No. 3)

One of the most complete sections in Nova Scotia is at Joggins on the shore of Chignecto Bay (Stea, et al. 1985; Fig. 9). This section is located in Zone C, as it was influenced by phase 1, 2 and 4 glaciers (Fig. 4). This is an example of a depositional area where complex till stratigraphy produces three-dimensional patterns of dispersal. Surface till sampling only intersects the youngest dispersal fan.

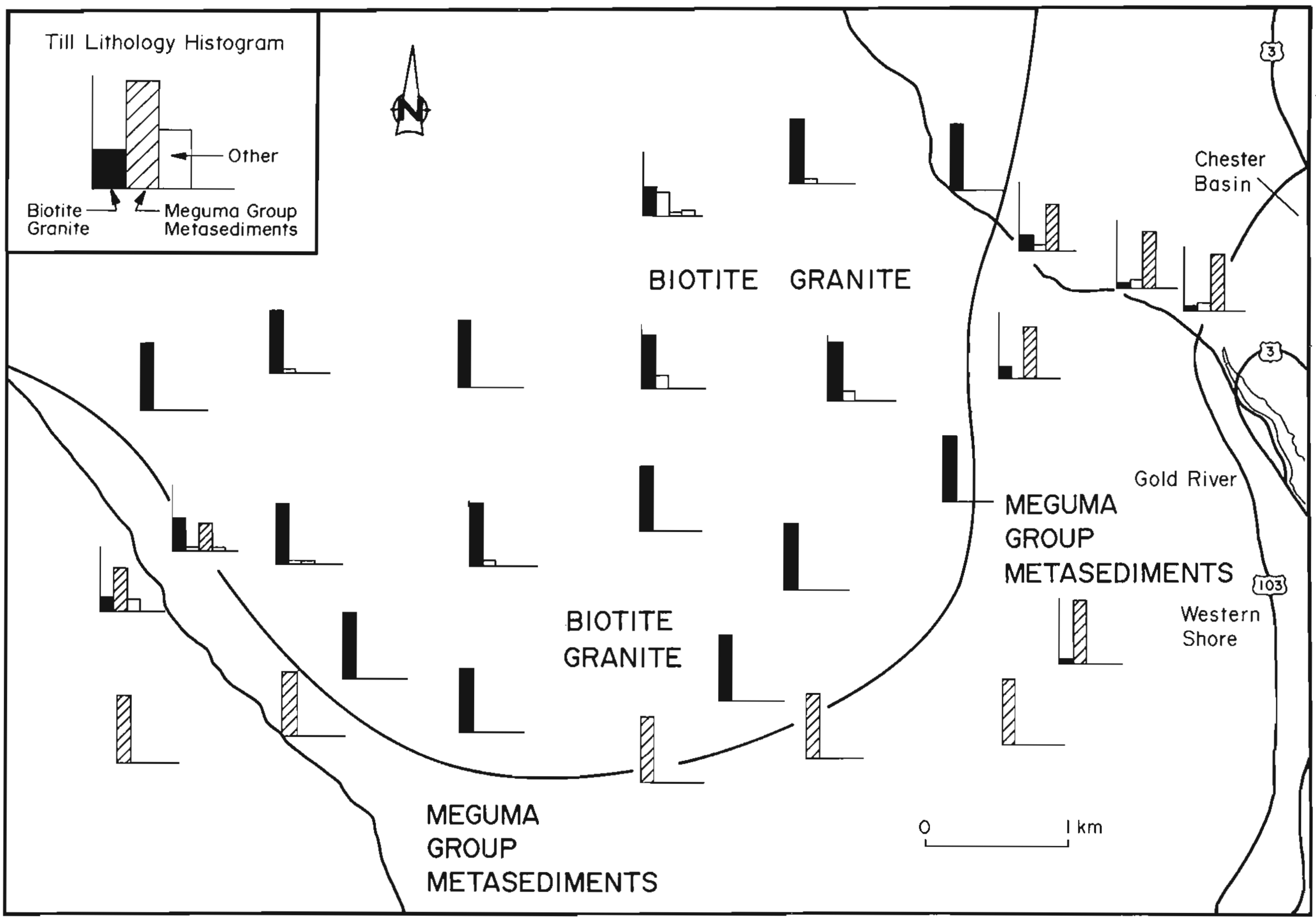


Figure 7. Pebble lithology of the stony till sheet in Zone B near Gold River, Nova Scotia.

Depositional areas in multi-phase zones (C, D, E, and F) will require more sophisticated mineral exploration methods. Three tills are exposed from the base to the top: a reddish-brown, compact silty till; a grey clay till; and a yellowish-brown, sandy till. The lowest till overlies a bedrock surface striated at 110° parallel to regional eastward striae (Fig. 2a) which correlate with ice flow phase 1.

The three till units have distinct lithological signatures suggesting differing source areas. Significant variations can also be seen within one till unit. The base of the McCarron Brook Till (lowest till) has a high percentage of igneous and volcanic erratics derived from the Caledonian Highlands to the west (lithologies I; Fig. 9). Concomitant increases in the percentages of calcareous red mudstone clasts (lithology H) and limestone (lithology F) upsection in the McCarron Brook Till suggest a change in ice flow to southeastward over Carboniferous evaporitic rocks and redbeds in New Brunswick (ECW; Fig. 9). The Joggins Till has distinctly higher percentages of coal and limestone clasts (lithologies B and C; Fig. 9) than the McCarron Brook Till. The ice flow direction inferred from the pebble data is southwestward, across coal measures which outcrop along the shore to the northeast of the section and curve to the southwest a short distance offshore (R. J. Ryan, pers. comm., 1987). The Joggins Till outcrops over much of the local area. The upper till can be differentiated from the lower two units by the preponderance of local feldspathic sandstone (lithology J; Fig. 9) which is derived from the Joggins Formation (lCj, Fig. 9).

Changing pebble assemblages in the lowest till record the eastward and southeastward ice flows during phase 1, while the middle and upper till record subsequent southwestward ice flows directed through Chignecto Bay (phases 2 and 4). The net effect of these dispersal events would be to produce a broad southeastward to southwestward dispersal fan in the three-dimensional sense, from an orebody buried by the three tills at Joggins.

Ballantynes Cove (Zone D, No. 4)

The lowland regions that flank the Cobequid Highlands and the Antigonish Highlands, where northward ice flow during phase 3 is pervasive, generally display two to three till units in stratigraphic section (Fig. 10). The type section is at Ballantynes Cove south of Cape George where 3 till units are exposed (Figs 4, 10). The lower till (unit 1) is red, matrix-rich and contains shell fragments derived from flow across the Northumberland Strait and can be correlated with shell-bearing basal units along the Northumberland Strait (Stea et al., 1987).

One of the distinguishing characteristics of the three till units at Ballantynes Cove is the stone content. The lowest till unit contains less than 10 % clasts, and exhibits little sample-to-sample variation. The middle till unit contains > 10 % clasts while the till unit above the boulder horizon has > 15 % clast-sized particles.

The abundances of red-brown coarse sandstone and conglomerate (lithology 1; Fig. 10) decrease towards the top of the lowest till unit (Unit 1) and grey feldspathic sandstones (lithology 2) remain fairly constant throughout. Black metasiltstone and shale clasts show a marked increase in abundance at the top of unit 1 and remain high to the top of the section. Green hard conglomerate and basalt (lithologies 7 and 8) increase markedly in abundance towards the top of unit 2 and in unit 3 near the boulder horizon. Diorite clasts are restricted to unit 2.

The relative abundance of reddish sandstone and conglomerate clasts, and the presence of well rounded plutonic clasts (lithology 6; Fig. 10) in till unit 1 are the result of southeastward ice flow across Devonian to Carboniferous conglomerates north of the section (Boucot et al., 1974; Fig. 10). Till fabric at the base of the section, shows a strong east-west orientation with a minor southeast mode. Shell fragments in the till and an overall low percentage of clasts confirm a correlation with till on the Northumberland Shore formed by southeastward ice flow.

The marked increase in the proportion of black metasiltstone clasts in unit 2 and the presence of dioritic clasts indicate erosion of Precambrian Georgeville rocks and a change in ice flow from southeastward to northeastward. The northeastward-striking till fabric in unit 2 confirms the change in ice flow direction.

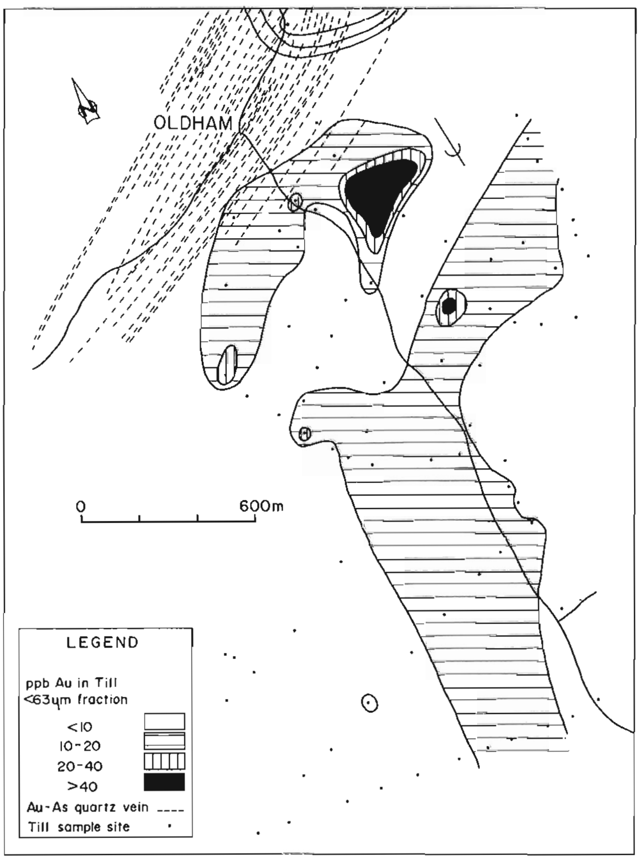


Figure 8. Dispersal of gold (< 230 mesh) levels in the Oldham Gold district (after DiLabio, 1982)

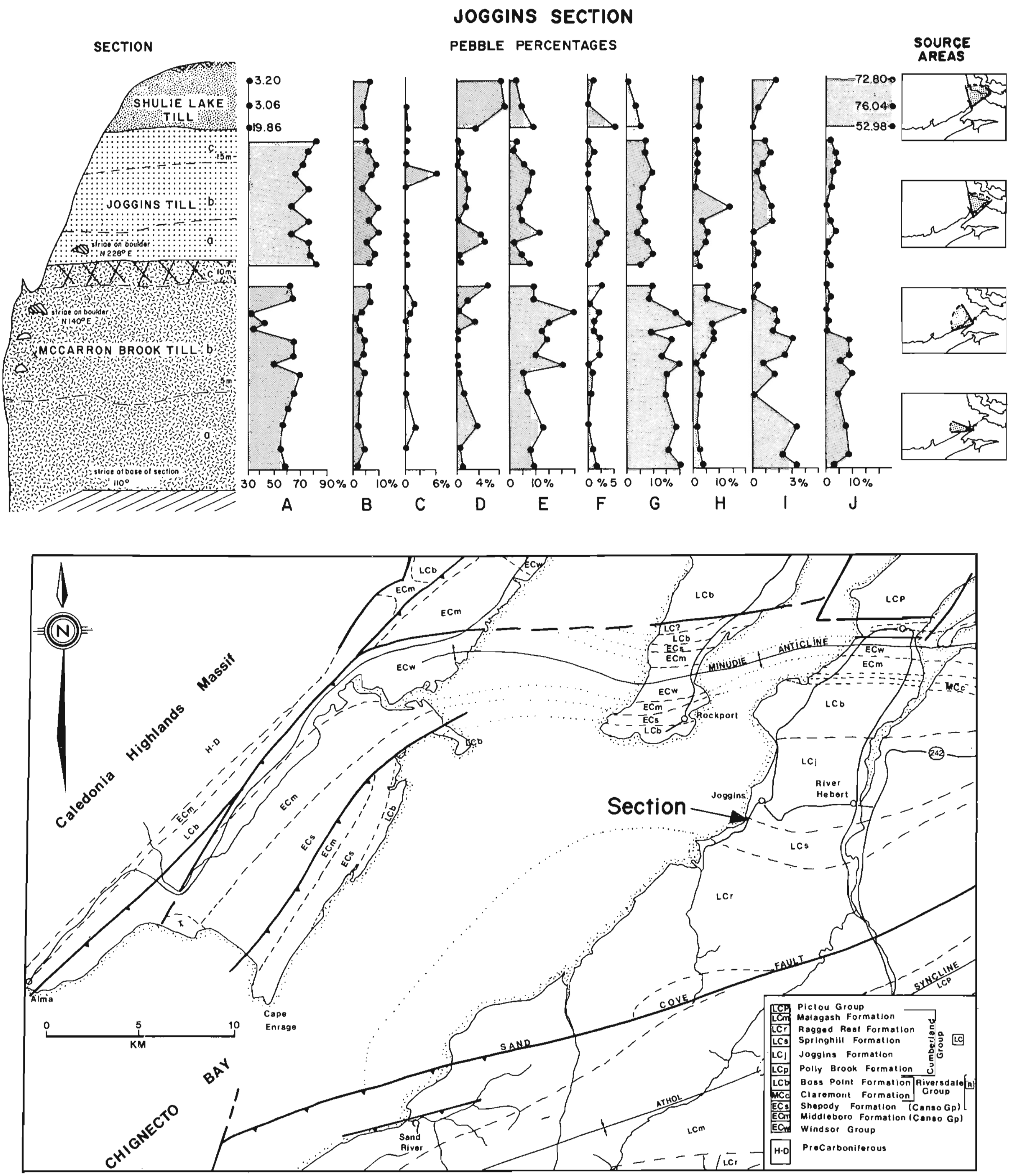
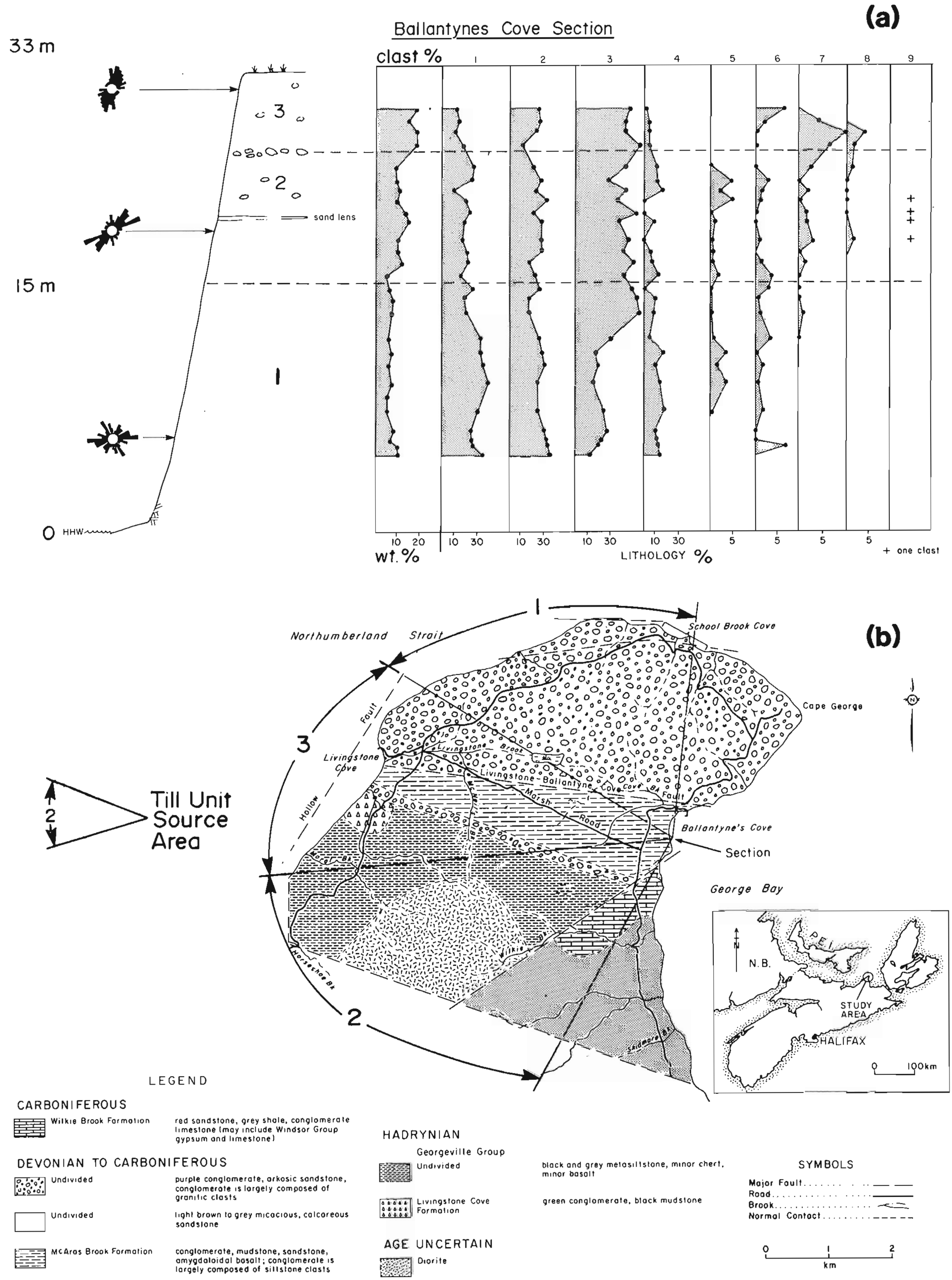


Figure 9. Stratigraphy and vertical variation in pebble lithology; Joggins Till section. Geology of the Joggins Area from R. J. Ryan (unpublished data)

Clast types: (A) grey sandstone, (B) coal, (C) pelecypod limestone, (D) sideritic sandstone, (E) coarse sandstone, (F) limestone, (G) brown argillite, (H) red-brown argillite, (I) igneous, metamorphic rocks, (J) weathered sandstone


(a)
Ballantynes Cove Section
33 m
15 m
0 HHW
3
2
1
sand lens
clast %
1 2 3 4 5 6 7 8 9
10 20
10 30
wt.%
LITHOLOGY %
+ one clast
(b)
Northumberland Strait
School Brook Cove
Cape George
Livingstone Cove
Fault
Hollow
Livingstone Brook
Livingstone - Ballantyne Cove Fault
Marsh Road
Ballantyne's Cove
Section
George Bay
Wilkie Bk
Horseshoe Bk
Skidmore Bk
Till Unit Source Area
N.B.
P.E.I.
STUDY AREA
HALIFAX
0 100km
LEGEND
CARBONIFEROUS
Wilkie Brook Formation
red sandstone, grey shale, conglomerate limestone (may include Windsor Group gypsum and limestone)
DEVONIAN TO CARBONIFEROUS
Undivided
purple conglomerate, arkosic sandstone, conglomerate is largely composed of granitic clasts
Undivided
light brown to grey micacious, calcareous sandstone
McAras Brook Formation
conglomerate, mudstone, sandstone, amygdaloidal basalt; conglomerate is largely composed of siltstone clasts
HADRYNIAN
Georgeville Group
Undivided
black and grey metasiltstone, minor chert, minor basalt
Livingstone Cove Formation
green conglomerate, black mudstone
AGE UNCERTAIN
Diorite
SYMBOLS
Major Fault
Road
Brook
Normal Contact
0 1 2
km

The upper till (unit 3) is differentiated from unit 2 by a higher percentage of stones and an increase in greenish, hard conglomerates and basalt clasts. Basalt is found in the McAras Brook Formation which underlies the section and outcrops in an east to west zone between the Georgeville and Devonian conglomerates. (Fig. 10) Their presence indicates a swing in ice flow either to the east or west. The till fabrics measured in unit 3 however, strike northeast to southwest. If the till fabric is parallel to ice flow, the only way to reconcile this contradictory evidence would be a 180° swing to southwestward ice flow or an unknown source of basalt. Striations along the Northumberland shore near Treen Bluff (Stea and Finck, 1984) attest to late southwestward ice flow although erosional evidence of this ice flow in Ballantynes Cove area is lacking.

The abundances of black metasiltstone clasts is directly correlated with the amounts of copper, lead, and zinc in the clay fraction. (Fig. 11). The black metasiltstones may have higher background copper, lead, and zinc values than the Carboniferous sedimentary rocks which are the source of the lower till. This plot illustrates the importance of defining till sheets when conducting till geochemical surveys. The higher copper, lead, and zinc background values in the upper till unit are controlled by the clast content of the till. This result has been supported in a synthesis of regional data (Stea, et al. 1986) as well as in other areas (Saarnisto and Taipale, 1985). The till sheets defined in this study each have a distinct lithogical character which translates into significant geochemical variation. This variation has to be assessed when conducting geochemical surveys (streams, soils, lake sediments) in till-covered regions.

East Kemptville (Zone E, No. 5)

The East Kemptville (Rio Algom) tin deposit is located in southwestern Nova Scotia 60 km northeast of Yarmouth (Fig. 1). It is the only primary tin producer in North America. It consists of mineralized greisens and greisen zones within a granite-metasedimentary rock contact (Chatterjee and Strong, 1984). The primary ore mineral is cassiterite with secondary chalcopyrite, wolframite and sphalerite. The discovery of the deposit was in large part due to the results of a regional till sampling program (McAuslan et al., 1980).

Figure 10a. Schematic diagram showing the stratigraphy, till fabric and vertical variation in pebble lithology of the Ballantynes Cove Section and **(b)** geology of the Cape George area.

Clast types:

(1) Reddish-brown and purplish sandstone and conglomerate
(2) Grey feldspathic sandstone
(3) Black-grey metasiltstone, shale
(4) Well-rounded sedimentary clasts
(5) Volcanic clasts
(6) Well-rounded igneous clasts
(7) Green hard conglomerate
(8) Amygdaloidal basalt
(9) Diorite

The area is blanketed by a thick, stony till unit composed primarily of the underlying bedrock unit. Ribbed and hummocky moraine areas are common in the area (Stea and Grant, 1982). This till unit overlaps several older till units in the coastal regions of Yarmouth County. The major ice flows mapped in the region are southeastward and southward (phases 1 and 2) and southwestward (phase 4) (Fig. 2). Evidence of northward ice flow or dispersal has not been documented in the region.

Various companies have run till geochemical surveys in the region and published their results as mineral assessment reports for the Nova Scotia Department of Mines and Energy (Wilson and Richardson, 1980). Figure 12 is a compilation of several of these surveys by Rogers and Garrett (1987) showing the patterns of tin levels around the ore body. Till within the area surrounding the Rio Algom deposit was sampled at a minimum spacing of 1 km x 3 km (McAuslan et al. 1980). A till matrix fraction termed the "whole till" fraction (< 10, > 100 mesh) was crushed and analyzed. The average grade of the orebody has been defined at 0.165 wt % tin, although locally levels of tin in the orebody can attain the percent range (D. Kontak, pers. comm., 1988).

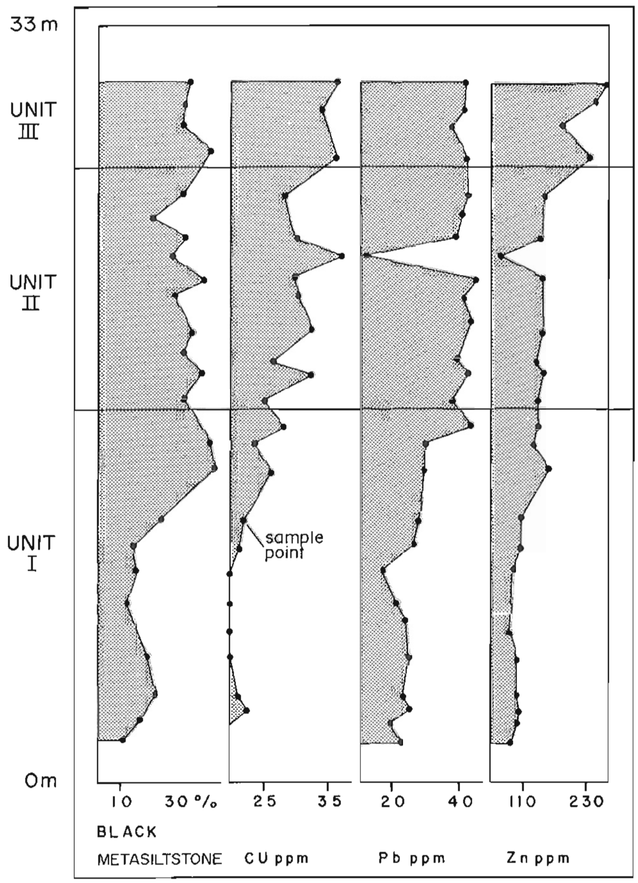


Figure 11. Vertical variation in percentages of black metasiltone, copper, lead, zinc, and silver, Ballantynes Cove Section.

Contoured "whole till" levels exhibit a fan of elevated levels extending 6 km in a southward to southwestward direction. The higher levels (200 to 300 ppm) appear to be displaced as much as 2 km from the orebody and there are "hot spots" 6 km down-fan. This dispersal train does not follow the classic linear train pattern with rapid down-ice depletion (DiLabio, 1987) . There may be several reasons for this:

1. A redistribution effect of local ice flow phases on an original southward-oriented train. The earlier ice flows trended southeastward and southward and were probably responsible for considerable erosion and transport in the region. Till units formed during these ice flows are exposed along the coast. It is likely that vestiges of older tills subcrop in the East Kemptville area.
2. Englacial transport; the area exhibits ribbed-disintegration moraine features (Stea and Grant, 1982) indicative of ice-marginal ablation areas. Some of the tin-bearing rock debris may have been transported for a distance higher in the ice mass, above the substrate in this marginal area.
3. Additional mineralized zones. It is possible that hot spots east and south of Davis Lake may relate to alternative sources of tin. (R. Mills, pers. comm., 1988). Alternative sources of tin may also be found in the region east of the mine site in the Meguma Group (D. Kontak, pers. comm., 1988). The general depletion of tin south of the mine, however suggests that the tin level patterns can be related to glacial dispersal from the mine area.

The dispersal fan falls within the range of ice flow as indicated by the local striations, which show three main ice flow directions (Fig. 12). Northward ice flow is not indicated either by dispersal or by erosional evidence and the lack of evidence does not support Gravenor's (1974) interpretation that the Yarmouth drumlin field south of the area formed by northward ice flow from an offshore ice dome.

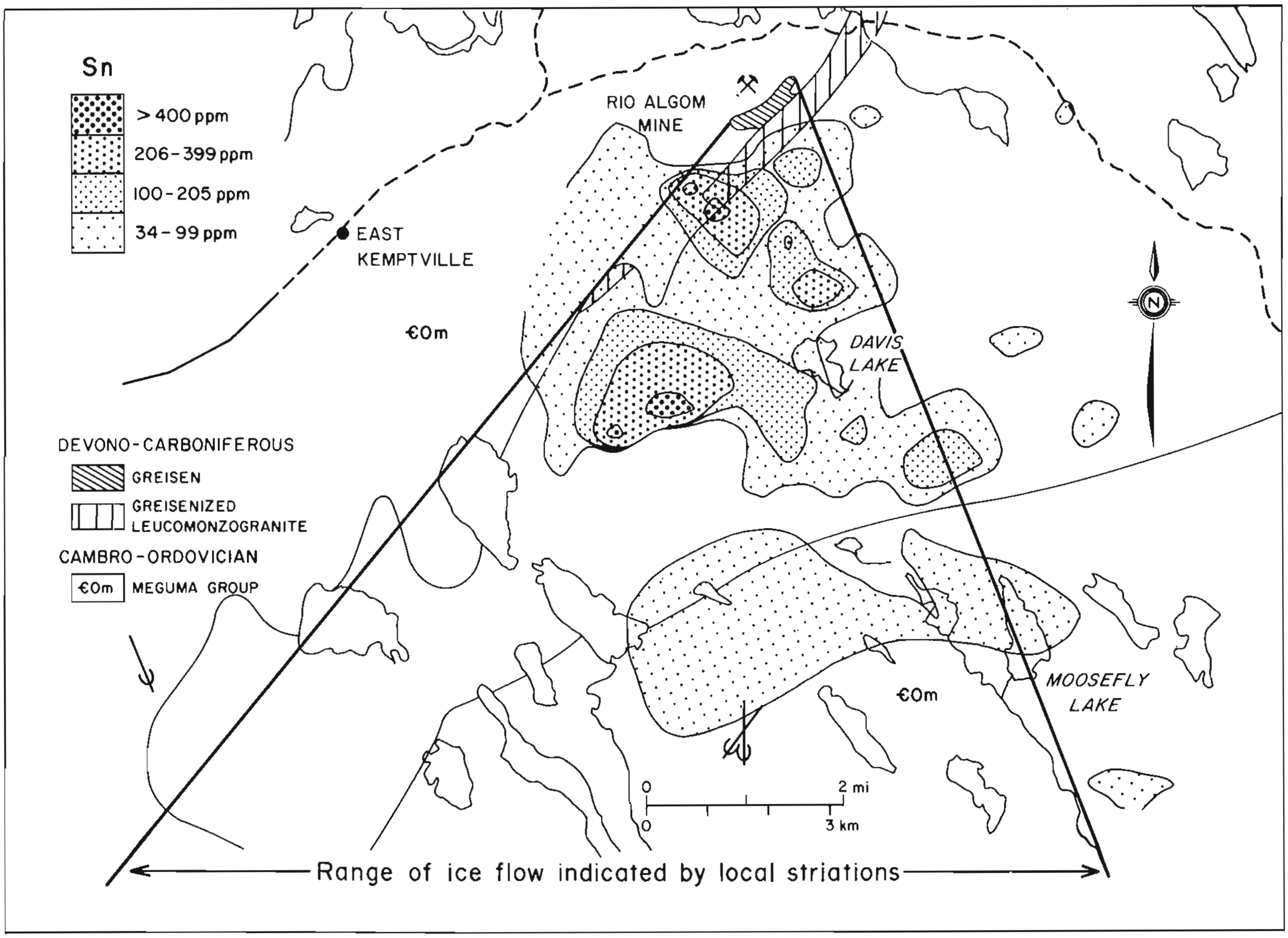


Figure 12. Computer plots of tin in "whole till" fraction of till (−10 +100 mesh) samples in regional and local surveys around the East Kemptville ore body (after Rogers and Garrett, 1987).

Garden of Eden (Zone F, No. 6)

Garden of Eden is located on the southern edge of the Antigonish Highlands (Fig. 1). Distinctive hornblende diorites (appinites) dispersed from a stock in the Garden of Eden area are easily recognized in the background of sedimentary and felsic volcanic rocks. The Eden Lake Complex is a late Precambrian rock suite composed of appinite, hornblende syenite, pegmatite, and microgranite (Murphy, 1985; Fig. 13). The Chedabucto Fault separates these rocks from the Carboniferous rocks to the south. The Moose River Shear Zone runs through Eden Lake and marks the eastern boundary of the appinite complexes to the west of the lake (Murphy, 1985).

Garden of Eden has been affected by four major ice flow events as illustrated in the modes on the rose diagram of striation trends in the region (Fig. 13). The relative ages of these ice flows have been recorded at two striation sites near Eden Lake. These sites reveal "mini" crag and tail features and striations relating to four ice flows. In each case crag and tail features from the earlier flow are cut by striations from a younger flow. A summary sequence of these flows from oldest to youngest is phase 1- 140°, phase 2- 165°, phase 3- 005°, and phase 4- 220°.

Two main till sheets are found in the region. A reddish silty till is associated with southeastward-trending drumlins south of Eden Lake. A stony, sandy till is associated with north-south trending ribbed moraine. The stony till overlies the reddish drumlin till. For the study, boulders (200 to 300) were counted at each site, taken largely from farmer's boulder fences and from deposits adjacent to major till sections. Till samples were also taken and counted where boulder piles were not available.

Figure 13 shows the dispersal pattern of boulder-sized appinite erratics from the Eden Lake Complex. The two long southeastward-trending dispersal trains are clearly the dominant pattern. The longest dispersal pattern is the 1 to 5 % contour trending 140° to 160°, which extends up to 20 km. This is parallel to drumlin trends of the region and

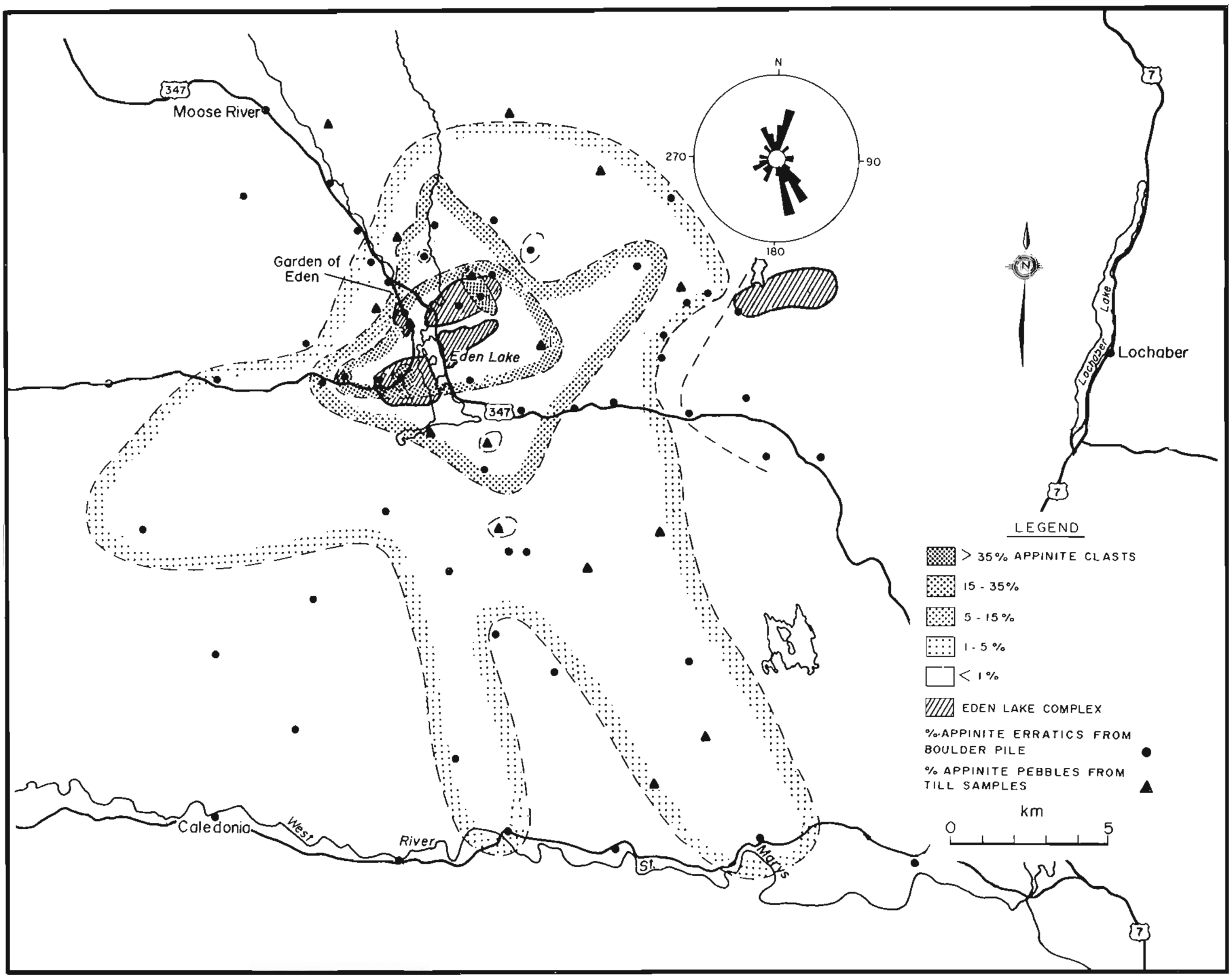


Figure 13. Plot of the dispersal of boulder sized Appinite clasts from the Eden Lake Complex based on counts from boulder piles and till sections. Rose diagram of striation trends in the 1:50 000 map sheet region.

represents dispersal during ice flow phase 1. The eastward extent of the 140° to 160° dispersal train is not known as it intersects with dispersal from the appinite complex east of Eden Lake. However, the 5 % to 15 % contour of appinite erratics extends about 5 km in this general direction. The 1 to 5 % contour also extends southward in lobate fashion between 170° and 180°. This southward-trending lobe may represent dispersal during phase 2. The 1 to 5 % contour of appinite boulders forms a broad fan extending up to 10 km northwest of Eden lake. This dispersal occurred during ice flow phase 3. The 5 to 15 % contour shows two distinct lobes, trending northward and northwestward, which parallel modes in the regional striation rose diagram (Fig. 13). This may be the result of changes in the ice direction during phase 3 (Fig. 13). Erosion and dispersal during phase 4 is represented by southwestward deflection of the 1 to 5 % appinite contour. One appinite boulder was found 40 km southwest of the Eden lake area. Two areas with greater than 40 % appinite clasts are located directly over Eden Lake Complex. These areas may be coincident with zones of appinite within the complex.

CONCLUSIONS

The mainland of Nova Scotia can be divided into "zones", each defined by a pattern of ice flows that represent from 2 to 4 discrete ice flow phases. Dispersal trains within each of these zones have differing trends and shapes. Dispersal trains in zones A and B can be linear and unidirectional, while dispersal in zone F takes on a more irregular form. The zones are a result of changes in the position of ice centers throughout the Wisconsinan Stage. The dynamics of these ice sheets controlled the erosion, entrainment and deposition of rock material, selectively forming tills and boulder trains and leaving other areas bare of drift. The shape and magnitude of dispersal trains in Nova Scotia were largely controlled by the location and dynamics of regional ice sheets and local ice caps and glaciers.

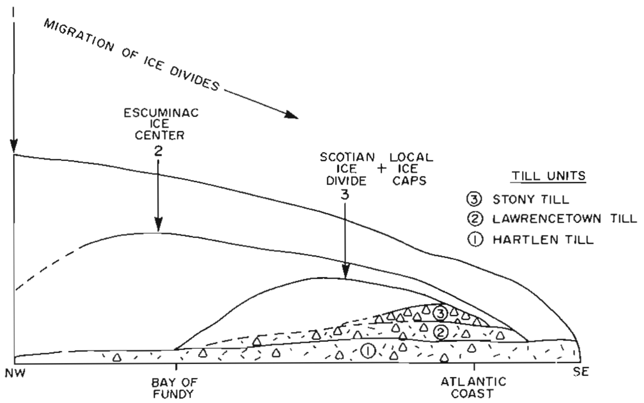


Figure 14. Shifting ice divides and the development of three compositionally and texturally distinct tills during Ice Flow Phases 1 to 4.

Dispersal studies confirm that the pattern of striations that were used to regionally define the zones are mirrored by the shape of the dispersal trains. In regions where topography or ice dynamics favoured till deposition during several ice flow phases, such as near Joggins and Ballantynes Cove, dispersal fans are three-dimensional in nature. When combined, the shape of these fans confirm the striation evidence of ice flow phases. In areas of drift veneer and bedrock exposure, surface dispersal fans can have irregular shapes, reflecting the net effect of several ice flow phases. Surface till and boulder dispersal studies in areas of variable till cover (East Kemptville; Garden of Eden) display this net effect. The Garden of Eden region is an area characterized by episodic deposition during the four ice flow phases, producing a patchwork of till units. Ablation boulders are samples of older as well as surface till units, either directly or by reworking. The net effect is a dispersal pattern confirming a multi-phase ice flow history.

Topography and ice dynamics of the various glaciers controlled the deposition and composition of till units during the successive ice flow phases. Tills produced by the later phases (3 and 4) are characterized by dominance of clast over matrix modes and relatively local dispersal. Tills produced during the earlier phases (1 and 2) tend to be dominated by matrix modes and have greater percentages of far-travelled components (Fig. 14). Clark (1987) suggests that basal ice velocity is a dominant factor controlling dispersal and till composition. The greater the velocity the less mixing of local basal debris with entrained allocthonous englacial debris. The shift in ice divides from external to local areas in Nova Scotia had the effect of reducing ice velocities and increasing mixing rates during the last phases of till formation (Fig. 14).

Mineral exploration companies can use the zonal concept along with surficial geology maps of the associated deposits in the development of strategies for mineral exploration based on sampling glacial sediments.

REFERENCES

Boucot, A.J., Dewer, J.F., Dineley, D.L., Fletcher, R., Fyson, W.K., Griffin, J.G., Hickox, C.F., McKerrow, W.S., and Zeigler, A.M.
1974: Geology of the Arisaig area, Geological Society of America Special Paper 139, Boulder, Colorado.

Boyd, R.T.
1982: Report on geology, overburden geochemistry and drilling; base metals, Walton, Hants County, Nova Scotia; Gulf Minerals Canada Limited; Nova Scotia Department of Mines and Energy, Assessment Report 11E/04C 07-I-51(02).

Chatterjee, A.K. and Strong, D.F.
1984: Rare earth and other element variations in greisens and granites associated with the East Kemptville tin deposit, Nova Scotia, Canada; Transactions of the Institute of Mining and Metallurgy, Section B, v. 93, p. B59-B70.

Clark, P.U.
1987: Subglacial sediment dispersal and till composition; Journal of Geology, v. 95, p. 527-541.

Denton, G.H., and Hughes, T.J.
1981: The last great ice sheets, John Wiley and Sons, Inc., New York, 484p.

DiLabio, R.N.W.
1982: Drift prospecting near gold occurrences at Onaman River, Ontario, and Oldham, Nova Scotia; in Geology of Canadian Gold Deposits, eds. R. W. Hodder and W. Petruk; Canadian Institute of Mining and Metallurgy, Special Volume 24, p. 261-266.
1987: The anatomy of dispersal trains; International Union of Quaternary Research, 12th International Congress, Programme and Abstracts, p. 156.

Donohoe, H.V., Jr. and Wallace, P.I.
1982: Geological maps of the Cobequid Highlands- Colchester, Cumberland, and Pictou counties, Nova Scotia; Nova Scotia Department of Mines and Energy, Maps 82-6 to 82-9.

Dreimanis, A., and Vagners, U.J.
1971: Bimodal distribution of rock and mineral fragments in basal tills; in Till — A Symposium, ed. R.P. Goldthwait; Ohio State University Press, Ohio, p. 237-250.

Felderhof, G.W.
1979: Report on geological, soil, well water, stream sediment and stream water geochemical surveys, ground VLF, radon and airborne and ground magnetic surveys, Earltown, Colchester County, Nova Scotia; Wyoming Mineral Corporation and Geoterrex Limited; Nova Scotia Department of Mines and Energy, Assessment Report, 11E/11A 54-D-67(01).

Finck, P.W. and Graves, R.M.
1987: Till clast and simplified glacial geology of the Halifax and Sambro map sheets (11D/12 and 11D/05); Nova Scotia Department of Mines and Energy, Published Map 87-4, scale 1:50 000.

Ford, K.L. and O'Reilly, G.A.
1985: Airborne gamma ray spectrometric surveys as an indicator of granophile element specialization and associated mineral deposits in the granitic rocks of the Meguma Zone of Nova Scotia; in High Heat Production (HHP) Granites, Hydrothermal Circulation and Ore Genesis; Institution of Mining and Metallurgy, St. Austell, Cornwall, England, 1985, p. 113-133.

Goldthwait, J.W.
1924: Physiography of Nova Scotia; Geological Survey of Canada, Memoir 140.

Grant, D.R.
1963: Pebble lithology of the tills of southeast Nova Scotia; M.Sc.Thesis, Dalhousie University, Halifax, Nova Scotia; Nova Scotia Department of Mines and Energy, Thesis 129, 235p.

Grant, D.R.
1975: Glacial style and the Quaternary stratigraphic record in the Atlantic Provinces, Canada; in Report of Activities, Part B; Geological Survey of Canada, Paper 75-1B, p. 109-110.
1977: Glacial style and ice limits, the Quaternary stratigraphic record, and changes of land and ocean level in the Atlantic Provinces, Canada; Geographie Physique et Quaternaire, v. xxxi, no. 3-4, p. 247-260.

Grant, D.R. and King, L.H.
1984: A stratigraphic framework for the Quaternary history of the Atlantic Provinces; in Quaternary Stratigraphy of Canada — A Canadian Contribution to IGCP Project 24, ed. R.J. Fulton; Geological Survey of Canada, Paper 84-10, p. 173-191.

Gravenor, C. P.
1974: The Yarmouth drumlin field, Nova Scotia; Journal of Glaciology, v. 13, p. 45-54.

Hickox, C.F., Jr.
1962: Pleistocene geology of the central Annapolis Valley, Nova Scotia; Nova Scotia Department of Mines, Memoir 5, 36 p.

MacEachern, I.J. and Stea, R.R.
1985: The dispersal of gold and related elements in tills and soils at the Forest Hill Gold District, Guysborough County, Nova Scotia; Geological Survey of Canada, Paper 85-18.

MacNeil, R.H. and Purdy, C.A.
1951: A local glacier in the Annapolis-Cornwallis Valley; abstract, Proceedings of the Nova Scotian Institute of Science, v. 23, pt. 1, p. 111.

McAuslan, D.A., Dickie, G.B., Sarkar, P.K, Sinclair, P.E., and Wilson, B.H.
1980: The history of discovery and the description of the East Kemptville Tin deposit, southwest Nova Scotia; abstract, 1982 Annual Meeting, Canadian Institute of Mining and Metallurgy.

Murphy, J.B.
1985: Geological Map of Central and Southern Antigonish Highlands; Geological Survey of Canada, Open File 1181, scale 1:50 000.

Myers, R.A. and Stea, R.R.
1986: Surficial Mapping results: Pictou, Guysborough, and Antigonish Counties, Nova Scotia; in Mines and Minerals Branch, Report of Activities 1985, ed. J.L. Bates; Nova Scotia Department of Mines and Energy, Report 86-1, p. 189-194.

Nielsen, E.
1976: The composition and origin of Wisconsinan tills in mainland Nova Scotia; Ph.D. thesis, Dalhousie University, Halifax, Nova Scotia; Nova Scotia Department of Mines and Energy, Thesis 277, 256 p.

Peltoniemi, H.
1985: Till lithology and glacial transport in Kuhmo, eastern Finland; Boreas, v. 14, p.67-74

Prest, V. K.
1973: Surficial deposits of Prince Edward Island; Geological Survey of Canada, Map 1366A.

Prest, V. K. and Grant, D. R.
1969: Retreat of the last ice sheet from the Maritime Provinces — Gulf of St. Lawrence region; Geological Survey of Canada, Paper 69-33, 15 p.

Prest, V. K. and Nielsen, E.
1987: The Laurentide ice sheet and long distance transport; in INQUA Till Symposium, Finland 1985, eds. R. Kujansuu and M. Saarnisto; Geological Survey of Finland, Special Paper 3, p. 91-102.

Rampton, V.N., Gauthier, R C., Thibault, J., and Seaman, A.A.
1984: Quaternary geology of New Brunswick; Geological Survey of Canada, Memoir 416, 77p.

Rogers, P.J. and Garrett, R.G.
1987: Lithophile elements and exploration using center lake bottom sediments from the East Kemptville Area, Southern Nova Scotia, Canada; Journal of Geochemical Exploration, v 28, p. 467-478.

Saarnisto, M. and Taipale, K.
1985: Lithology and trace-metal content in till in the Kuhmo granite-greenstone terrain, eastern Finland; Journal of Geochemical Exploration, v. 24, no.3, p. 317-336.

Schnikter, D.
1987: Late Glacial paleoceanography of the Gulf of Maine; International Union of Quaternary Research, 12th International Congress, Programme and Abstracts, p. 260.

Shepard, F.P.
1930: Fundian faults or Fundian glaciers; Geological Society of America Bulletin, v. 41, p. 659-674.

Stea, R.R.
1984: The sequence of glacier movements in Northern Mainland Nova Scotia determined through mapping and till provenance studies; in Correlation of Quaternary Chronologies, ed. W.C. Mahaney; Geo Books, Norwich, p. 279-297.

Stea, R.R. and Finck, P.W.
1984: Patterns of glacier movement in Cumberland, Colchester, Hants, and Pictou Counties, northern Nova Scotia; in Current Research, Part A; Geological Survey of Canada, Paper 84-1A, p. 477-484.

Stea, R.R., and Fowler, J.H.
1979: Minor and trace-element variations in Wisconsinan tills, Eastern Shore Region, Nova Scotia; Nova Scotia Department of Mines and Energy, Paper 79-4, 30 p.

Stea, R.R. and Grant, D.R.
1982: Pleistocene geology and till geochemistry of southwestern Nova Scotia (Sheets 7 and 8), scale 1:100 000; Nova Scotia Department of Mines and Energy, Map 82-10.

Stea, R.R. Day, T.E. and Ryan, R.J.
1986: Till and Bedrock Cu-Pb-Zn geochemistry in northern Nova Scotia and its metallogenic implications, in Prospecting in Areas of Glaciated Terrain, 1986, eds. W. J. Phillips and R. Salminen; The Institution of Mining and Metallurgy, pp. 241-160.

Stea, R.R., Finck, P.W. and Wightman, D.M.
1985: Quaternary geology and till geochemistry of the western part of Cumberland County, Nova Scotia (sheet 9); Geological Survey of Canada, Paper 85-17.

Stea, R.R., Scott, D.B., Kelley, J.T., Kelley, A.R., Wightman, D.M., Finck, P.W., Seaman, A., Nicks, L., Bleakney, S., Boyd, R., and Douma, M.
1987: Quaternary Glaciations, Geomorphology and Sea Level Changes: Bay of Fundy Region; NATO Advanced Course on Sea Level Correlations and Applications, Halifax, Nova Scotia, Field Trip Guidebook, 79p.

Wilson, B.H. and Richardson, J.
1980: Report on till and heavy minerals geochemical surveys; tin, East Kemptville, Yarmouth County, Nova Scotia; Shell Canada Resources Limited; Nova Scotia Department of Mines and Energy, Assessment Report 21A/04A 51-R-25(03).