

Lake geochemistry—a low sample density technique for reconnaissance geochemical exploration and mapping of the Canadian Shield

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Synopsis

In order to test methods of geochemical exploration and mapping by use of lake sediments for large-scale reconnaissance surveys of the Canadian Shield 176 samples of inorganic lake sediment were collected from seven areas within the Bear and Slave geological provinces, at a sampling density of one per 10 square miles. Two of these areas—High Lake and Hackett River—contain Archaean massive sulphide ore deposits, and a third—Terra mine—contains Cu and Ag ores. In order to relate the chemistry of the lake sediments to that of the surrounding bedrock, 447 samples of various rock types were collected from five of the above areas. The rock powders and the —250-mesh fraction of the lake sediments were analysed for Si, Al, Fe, Mg, Ca, Ti, Na, K, Mn, Ba, Zn, Cu, Pb and Hg. The lake sediments were further analysed for Ni, Co and Ag, and the rocks for As.

The data obtained show that the —250-mesh fraction of the lake sediments is a particularly homogeneous sampling medium, which closely reflects the average composition of the surrounding bedrock. It provides a uniform material for the sorption of metal ions dispersed by the weathering of ore deposits and smaller, more abundant, sulphide masses contained in the rocks enclosing the ore deposits. Ore metal anomalies are readily distinguished at this sample density, and the presence of Mg alteration zones associated with the deposits and areas of favourable rock type can be outlined. It is suggested that this economical method of geochemical exploration and mapping may be applied over the 70% of the Canadian Shield which is likely to contain inorganic lake sediments.

Canada is the second largest country in the world. More than half of its area is underlain by the

complex Precambrian block of the Canadian Shield. Permafrost conditions affect more than two-thirds of the Shield. For more than one-third of Canada's land area there are, therefore, three dominant conditions: size, complex Precambrian geology, and permafrost. Any economical method of performing a reconnaissance geochemical assessment of trace-element variations within this area must accommodate these three conditions. An outstanding feature of the drainage map of the Canadian Shield, relative to most other parts of the world, is the prominence of lakes. These lakes are the key to reconnaissance geochemistry in this vast, flat, Precambrian Shield.

The frequency of lakes ranges up to more than 7000 in a 5000 square mile area of northern Saskatchewan. In nearly all parts of the Shield there are sufficient lakes that lake muds or waters may be sampled at a density of one sample per square mile or greater. The materials sampled from lakes for geochemical investigations have generally been surface waters and inorganic sediments. Trace-element variations in drainage basins of lakes are reflected in these media by processes depicted in a very simplified form in Fig. 1. Rock types are normally characterized by certain trace-element concentration ranges.⁴⁷ Oxidation and leaching of the bedrock and the overlying Quaternary deposits releases these trace elements into soils, streams and, finally, lakes.

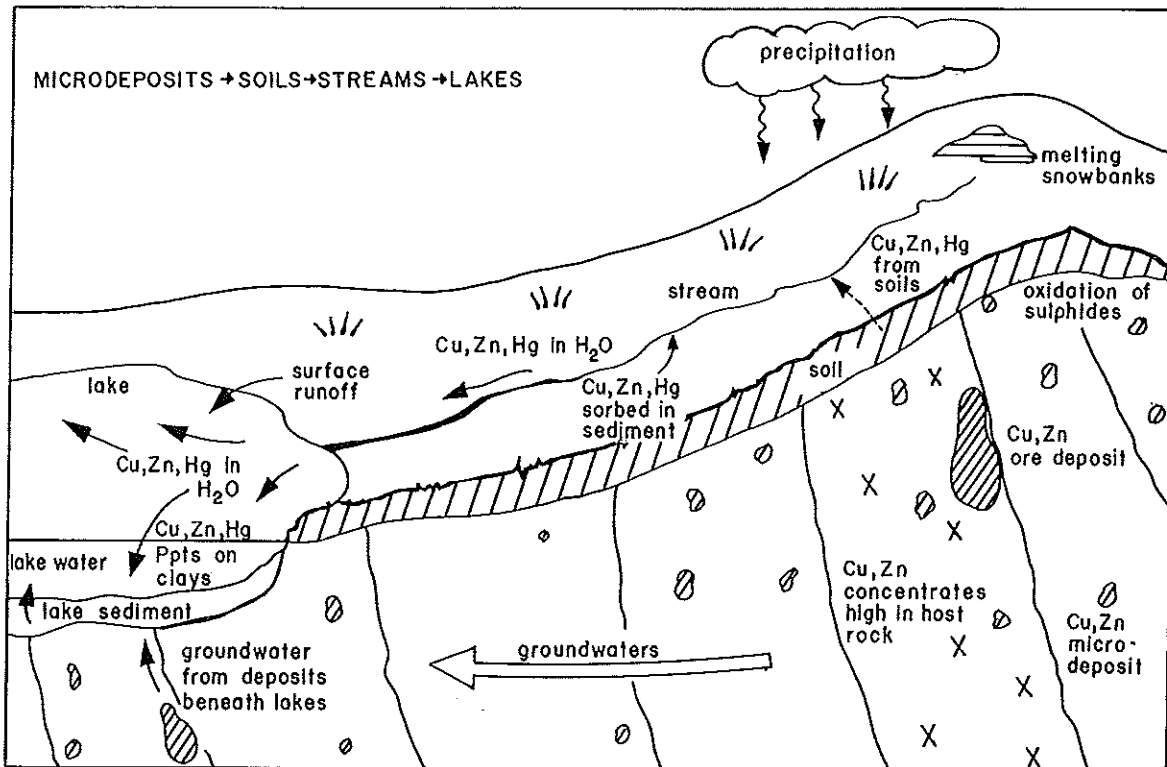


Fig. 1 Dispersion of metals from sulphides into lakes and lake sediments

Such geochemical dispersion in permafrost areas of Canada has only recently been described for Cu,² Zn and Ni^{4,5} and Hg.²⁴ In the U.S.S.R., however, documentation of geochemical dispersion due to chemical weathering processes in permafrost areas has been available for many years and appeared in major works on geochemical exploration methods,³⁷ hydrogeochemical methods,²² geochemistry of landscapes³³ and geochemical regionalization surveys.²³ Detailed studies on oxidation and dispersion processes for sulphides in permafrost zones are common in the Soviet literature.^{29, 31, 36, 44} Elements in permafrost zones are dispersed into drainage systems following migration through the overlying Quaternary deposits and soils.^{30, 34, 35} Groundwater, surface water and flash runoff in the spring are important factors in this dispersion process.^{26, 27, 28, 41, 42} Trace elements may also reach streams and then lakes in a sorbed form on the surface of clays or as included ions and complexes in the iron, manganese and organic coatings of fine sediment particles. Also, in rare cases where massive sulphide deposits are in the immediate vicinity, movement of sulphides in a particulate form may occur. These means of dispersion of trace elements into lakes have been more fully discussed elsewhere.³

A lake in the impeded and disorganized drain-

age system of the Shield normally has several small streams entering it from different points, but it has either no obvious exit stream or only one larger exit stream. Samples of sediment taken from such a lake either at the outflow stream bay, or at least away from any inflow bay, will reflect the trace-element content of the entire lake drainage basin. Through natural processes of mixing and averaging the lake sediment becomes a composite sample of the rocks within a drainage basin. The size of such drainage basins may commonly be one mile square or larger. In an area of the Shield where the rock type is uniformly basaltic it has been found that the variation in the bedrock trace-element content of Cu and Zn could be adequately shown at a lake sediment site density of one per 10 square miles.³ It appears that the averaging and smoothing effect on metal distribution produced by the drainage system will allow regional changes in bedrock trace-element geochemistry to be assessed at very low sample densities. Such an approach enables many of the problems of regional geochemistry in the Canadian Shield to be overcome.

The fact that lake sediments represent an average of the composition of the surrounding bedrock means that samples that are collected at wide—and therefore economic—intervals can adequately reflect the chemical composition of a

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wide area of rocks. Before such wide-interval sampling can be applied for mineral exploration, however, the effect of the distribution of elements within the rock mass must be assessed.

If anomalous concentrations of ore elements within a given area were confined to one or a few ore deposits, it is improbable that the resulting geochemical signal could be detected at a sample density of one per 10 square miles, for if the dispersion of elements from these deposits along the drainage system is restricted, it is unlikely that the small anomaly would be intersected. Alternatively, if these elements are widely dispersed, their signal will be too weak to be detected. Cameron and Baragar,¹⁰ however, have suggested that the condition is rare where ore-related mineralization within an area is confined to a few economic-size deposits. Instead, they have proposed that ore masses are distributed by size in a probabilistic fashion, and that orebodies are but the upper portion of more extensive populations of ore masses truncated by economic—not geological—considerations. These populations are continuous through non-economic 'showings' to very small masses and grains ('micro-deposits'). In terms of mass per cubic mile of rock these micro-deposits and showings probably exceed by many orders the mass of economic orebodies. It is these widely distributed showings and micro-deposits, as well as the ore deposit, that influence the composition of sediment in a lake with a drainage basin several miles in extent and allow anomalous areas to be detected at a wide sampling interval. By way of warning, it should be added that there must be many populations of micro-deposits that are truncated before the critically economic size is reached, thus leading to spurious anomalous results.

History of development and present status of low density lake geochemistry

The possible use of lake materials for geochemical exploration within Canada was first considered in the late 1950s.^{21,38} In the 1960s there were numerous investigations of the radon and uranium contents of surficial waters, including lake waters from various parts of Canada.^{14,18,45} Recently, lake waters were used with various degrees of success in regional exploration for base metals.^{2,5,24} Up to this time water had remained the principal lake sample medium. Only in rare cases were lake sediments collected—and then usually only over small areas and at high sample densities for uranium exploration.¹⁹ In 1970 the first regional lake sediment survey³ was conducted

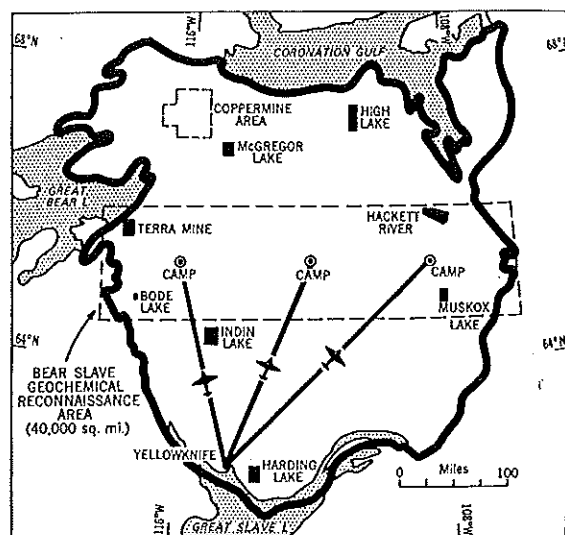


Fig. 2 Study areas within Bear and Slave geological provinces

for Cu in the Coppermine area (Fig. 2), lake sediments being shown to be a superior sample medium to lake waters. In part, this may have been attributable to analytical difficulties relating to the low element contents in waters. Lake sediments are, however, inherently closer to the original bedrock or surficial sediment compositions of the drainage area than waters. Weathering of rocks to sediments and sorption mechanisms on sediments are both complicated processes. Waters, which may have concentrations of trace elements dependent on environmental and other non-geological variations, are even more steps in the geochemical cycle away from the original rock material.

While the above methods were being tested at universities and by government agencies, many companies in Canada were using lake waters for uranium exploration, and a limited number had begun to use lake sediment in the late 1960s in detailed exploration for base metals. None of this work is currently available.

When the Geological Survey of Canada was carrying out the regional lake sediment survey in the Coppermine area, the Geology Division of the Saskatchewan Research Council was conducting detailed lake sediment and water sampling in the Cu-Ni-rich Flin Flon area,⁷ their conclusions confirming that sediment was the better sample medium. Also in the same year, one company which had conducted a regional gytja sampling programme outside the Shield recommended gytja as an excellent medium for mobile elements such as Mo. This raises the possibility of a third lake sample medium that could be used in certain organic-rich lake areas of the southern Shield. The use of organic gytjas has been proposed in the

U.S.S.R. as a means of prospecting in swamp regions.⁴²

What is planned in Canada for 1972? Government agencies will be involved in at least three regional lake sediment and water surveys. The Geological Survey of Canada will conduct a geochemical reconnaissance of a 40 000 square mile area of the Bear and Slave Provinces of the Shield at a site density of one per 10 square miles. The Department of Indian Affairs and Northern Development will cover several greenstone belts in the vicinity of Yellowknife at site densities of greater than one per square mile. The total area covered will be in the order of 1000 square miles. Lake sampling programmes will form part of more general geochemical surveys planned for parts of Newfoundland and Nova Scotia by the Department of Regional Economic Expansion. The newly formed Department of the Environment may carry out lake sampling in parts of Quebec to evaluate natural contamination by toxic elements. The Geological Survey renders technical advice on these programmes of other federal government departments. The Saskatchewan Research Council, Geology Division, will conduct a detailed geochemical sampling programme, including lake media, over a 1500 square mile area of the Canadian Shield in northern Saskatchewan. Several companies now use detailed lake sampling in base-metal exploration. Some of the larger companies will use this method in 1972 to assess numerous electromagnetic conductors outlined by airborne surveys. At least one Ph.D. thesis is planned on the subject of lake geochemical processes as they apply to mineral exploration. If successful, the 40 000 square mile survey (Fig. 2) to be carried out by the Geological Survey may eventually result in a geochemical reconnaissance of a large part of the Canadian Shield being conducted in this way.

Location and physiography of study areas

Eight study areas were selected on the basis that they are, or have been, sites for considerable prospecting activity. Five of the areas are in the Slave Province and three in the Bear Province. All eight areas contain rocks of possible economic potential, with the exception of the Harding Lake area, which is underlain by granitic rocks. Two of the areas contain proven ore deposits, as yet undeveloped. One area contains several small operating silver mines and another area contains abandoned gold mines.

One-third of the Bear Province and two-thirds of the Slave Province lie above the treeline in the

so-called Barrens. The treeline runs approximately from the northeast corner of the Great Bear Lake to the northeast corner of the Great Slave Lake (Fig. 2). The treeline also very closely approximates the boundary of the discontinuous and continuous permafrost zones. Bode Lake, Indin Lake and Harding Lake are regions of low hills with a relief of a few hundred feet, forested mainly by black spruce and underlain by discontinuous permafrost. The remaining five areas have very low relief, a tundra vegetation predominantly of mosses and lichens, and they are affected by continuous permafrost conditions.

Geology and metallogeny of study areas

Slave Province, 75 000 square miles in area, shares with the much larger Superior Province to the south the distinction of being the oldest portion of the Canadian Shield. Except for Proterozoic sediments and volcanic rocks along the margins of the province, it is composed of rocks of Archaean (>2400 m.y.) age. The Archaean rocks comprise a 'matrix' of granitic and high-grade metamorphic rocks enclosing north-trending belts of volcanic and sedimentary rocks metamorphosed to lower greenschist to amphibolite grade. The most common sequence found in the latter belts are mafic lavas, succeeded by much less abundant intermediate and acid volcanic and pyroclastic rocks. The volcanic sequences are up to 40 000 ft thick and generally occur along the margins of the belts. They are overlain, often conformably, by typical flysch-facies greywacke-shale sediments that occupy the axial zone of the belts. Sedimentary rocks are volumetrically much more abundant (4:1) than the volcanic rocks—a feature which is the converse of that in the volcanic-sedimentary belts of the Superior Province and which has an important bearing on the relative mineral potential of the two areas.

Very few ore-grade deposits have been located in the Slave Province. The mineral showings have been classified by Thorpe⁴⁶ into 11 types. Of these the massive sulphide Zn-Cu and Zn-Pb-Ag-Cu deposits of volcanic origin are by far the most economically attractive. Efforts in the Slave Province have, therefore, been very largely devoted to developing a low sample density technique to locate this type of deposit. The massive sulphide Archaean deposits do not in themselves provide a large target for surficial geochemical methods. It is believed, therefore, that if the methods described here are successful in locating these deposits, they

will certainly be effective for a number of other, larger, lower-grade deposits.

The massive sulphide ores of the Canadian Shield are generally considered to have formed subaqueously by the precipitation of metals brought in to the sea by fumarolic solutions. These solutions were released around centres of acidic volcanism. The deposits are thus associated with acid, often fragmental, volcanic rocks and with sediments of exhalative origin, such as chert, sulphide-facies iron formation and carbonate sediments. The deposits are often found at the interface between the intermediate and acid volcanic rocks or near the contact of the acidic rocks at the top of a volcanic pile and the overlying sediments. Unpublished studies by Cameron and others of the chemistry of the rocks associated with the massive sulphide deposits show that mineralization with ore elements is largely confined to the feeder pipe, to the deposit itself, and to a thin stratigraphic horizon in which the deposit lies.

The areas sampled within the Slave Province for this study are noted below.

High Lake

The High Lake Cu-Zn deposit is situated within a north-trending belt of intermediate and acid volcanic rocks near to their contact with apparently conformable tuffaceous sediments. It contains 5 200 000 tons of 3.5% Cu and 9.0% Zn, and is composed of pyrite, sphalerite, chalcopyrite and minor galena. Many details of the deposit are unknown because of insufficient drilling, but the character of the deposit and its host rocks clearly mark it as a typical Archaean exhalative sulphide occurrence. Gossans resulting from the oxidation of masses of pyrite, with minor pyrrhotite and arsenopyrite, are common within this belt of volcanic rocks.

Hackett River

The Hackett River Zn-Pb-Ag-Cu deposit is also a clear example of an Archaean massive sulphide deposit of exhalative origin, situated near to the contact of acid volcanic rocks with tuffaceous sediments.

The volcanic rocks around the deposit, although highly silicified and metamorphosed, indicate the presence of a vent structure or alteration pipe. One of the most interesting features of the deposit is the presence of limestone horizons of possible exhalative origin. Early drilling results indicated more than 10 000 000 tons of 8% Pb-Zn and 9 oz/ton Ag for the main zone, but it appears that there is more than one orebody in the general area.

Muskox Lake

This area is largely underlain by sedimentary and volcanic rocks of the Yellowknife Supergroup, although there are also a number of small intrusions of quartz diorite. No ore deposits have been discovered here, but there are a number of gossans resulting from the oxidation of sulphide bodies and there are lenses composed of pyrite with minor pyrrhotite and chalcopyrite. These occurrences are located in the centre of the sampled area in acid and intermediate volcanic rocks.

Harding Lake

The Harding Lake area is largely underlain by rocks of the granitic 'matrix' of Slave Province—chiefly biotite granites and muscovite granites. The granitic rocks are fringed to the northwest, north and east by Yellowknife Supergroup sediments that have been metamorphosed to knotted quartz-mica schists and hornfels near the intrusive granite contact. No significant sulphide mineralization has been noted in this area.

Indin Lake

The Indin Lake region was selected to represent a 'background' situation for both the rock and lake sampling because it contains all the rock types typical of the Archaean of Slave Province, but no known base-metal deposits. Basic, intermediate and acid volcanic rocks and sediments of the Yellowknife Supergroup underlie most of the area, and granitic rocks occur in the northwest portion. The sediments and volcanics have been metamorphosed to varying degrees up to granulite facies. The only important mineral occurrences are gold deposits, with some chalcopyrite and pyrite in quartz veins. These occur commonly in shear zones in the volcanics and sediments.

The three remaining areas sampled are in the Bear Geological Province. This province, to the west of Slave Province, is composed of rocks of Proterozoic age. In the southern part of the province miogeosynclinal sediments of Aphebian age occur in a zone flanking the margin of the Slave craton. To the west the eugeosynclinal facies of these sediments has been metamorphosed and migmatized. Farther to the west the lithology changes to a complex of andesitic to trachytic volcanic and pyroclastic rocks and molasse sediments which form the Echo Bay and Cameron Bay Groups. They are intruded by granites and are, in places, highly metamorphosed. North of Great Bear Lake these deformed rocks are overlain

by sandstones and dolomites of the Hornby Bay and Dismal Lakes Groups, and these, in turn, by the Coppermine River Group. The Coppermine River Group is a thick series of basalts overlain by red beds with intercalated flows, and these rocks are overlain by quartzites, dolomites and shales of the Rae Group.

In Bear Province there is a considerable variety of mineral deposits, although few are of economic importance. Their metallogeny has recently been summarized by Thorpe.⁴⁶ The most pertinent to this study are (1) native copper and chalcocite in the Coppermine basalts; (2) native silver associated with nickel-cobalt-iron arsenides and pitchblende in faults and fractures in the Echo Bay Group; (3) uranium and/or copper in fault-controlled massive quartz stockwork zones (these zones may be in excess of 1000 ft wide and 10 miles long); (4) fracture-controlled chalcopyrite mineralization in porphyritic lavas of the Echo Bay Group; and (5) stratiform copper mineralization in tuffaceous Echo Bay sediments.

Geochemical studies of the rocks and surficial materials associated with the Coppermine basalt ores have already been reported.^{3,10} Studies in other areas of the Shield^{14,18} indicated that lake geochemical methods are likely to be effective for delimiting uraniferous areas of Bear Province. The present studies have, therefore, been limited within Bear Province to two areas that contain deposits of types (2), (4) and (5) above and to one area that contains a distinctive (ultramafic) rock type.

Terra mine

Deposits of types (2) and (5) above are found at this mine, which has been operating since 1970. The rocks in the vicinity of the mine are mainly tuffaceous sediments and intermediate to acid volcanic rocks, dominantly porphyries, of the Echo Bay Group. Native silver, argentite, matildite, nickel-cobalt arsenides and sulphides, native bismuth, bismuthinite, chalcopyrite, bornite, pyrite, sphalerite and galena are found along faults and fractures. In the mine and outcropping on the adjacent hillside is a zone of chalcopyrite and pyrite with some galena and sphalerite. A further interesting feature of the mine area is a mass of magnetite-apatite.

Bode Lake

The rocks of the area sampled around Bode Lake are almost entirely porphyries: in the main, these appear to be lavas, but some may be intrusive. Chalcopyrite with pyrite and quartz is found in

fracture zones in these lavas a short distance north of Bode Lake.

McGregor Lake

The geological feature of greatest interest in this region is the Muskox Intrusion—a layered ultrabasic body of Neohelikian age. It is intruded into a basement complex of metamorphosed Aphebian sediments, migmatites, granite-gneiss and granodiorite. Non-economic concentrations of copper and nickel sulphides occur in the body and around its margin.

Sample collection, preparation and analysis

Bedrock sampling

Bedrock samples were collected at High Lake, Hackett River, Indin Lake, Terra mine and Bode Lake.

At High Lake 94 samples were taken along three traverses across the strike of the volcanic rocks and tuffaceous sediments (Fig. 3). Two of these traverses (C1, C2) are close to the sulphide deposit; the other (C3) is about two miles to the south. At Hackett River one traverse was made across the sequence of sediments and of volcanic rocks that lies 3-4 miles along strike from the main

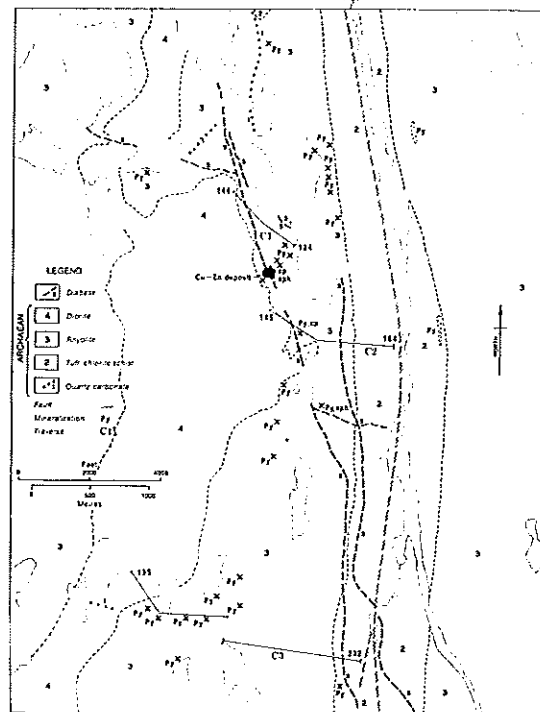


Fig. 3 Rock sampling traverses, High Lake, N.W.T. Geology after E. O. Dearden and B. A. Bradshaw, Kennarctic Explorations, Ltd.

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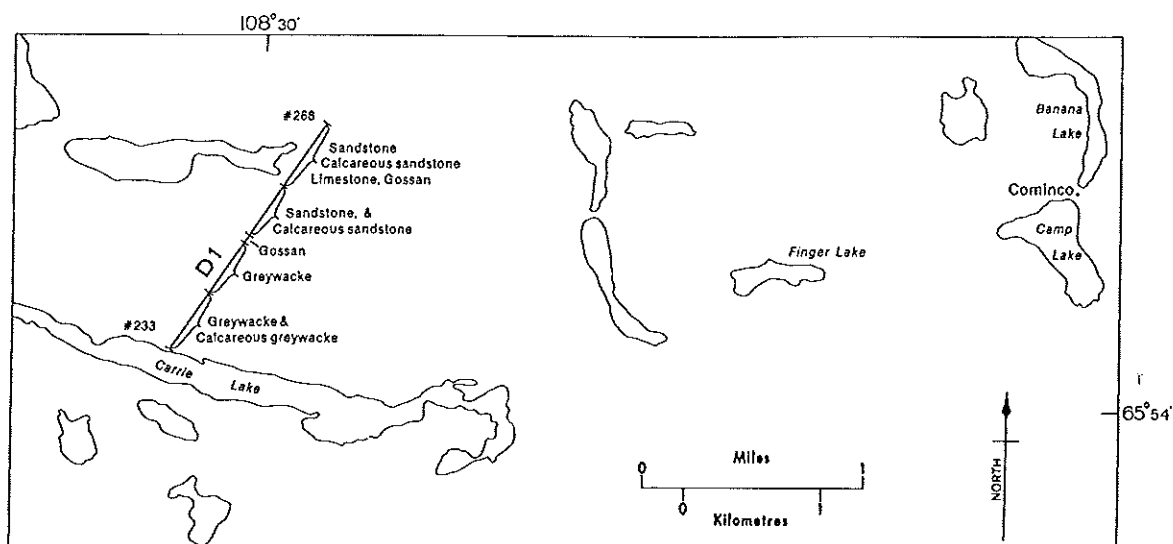


Fig. 4 Rock sampling traverse, Hackett River, N.W.T. Zn-Pb-Ag deposit is situated on north side of Camp Lake

ore deposit (Fig. 4). Here, 37 samples were collected. At Indin Lake 195 samples were taken along 12 traverses. These samples represent the basic, intermediate and acid volcanic rocks and the sediments of the Yellowknife Supergroup, and also the granitic rocks (Fig. 5). At Bode Lake three traverses were made across the feldspar porphyries, and 57 samples were collected (Fig. 6). One of the traverses passed over the mineralized zone. At Terra mine (Fig. 7) three traverses were made across the strike of the sedimentary-volcanic sequence that contains the two types of ore deposit referred to above. Some 40 samples were collected on these traverses. A further 25 samples were collected from porphyries that contain no obvious mineralization on the northeast bank of the Camsell River, opposite the mine. On most of these traverses fist-size samples were collected at 100-ft intervals. Outcrop is generally excellent. On the Hackett River traverse and on traverse C3 at High Lake samples were taken at 200-ft intervals.

Lake water and sediment sampling

Water and sediment samples were collected regionally at a density of approximately one per 10 square miles at the five locations where bedrock samples were collected and also at the McGregor Lake, Muskox Lake and Harding Lake areas. The lakes were reached by small fixed-wing aircraft and, because landing was only possible on large lakes, site distributions are uneven. By helicopter, a regular grid can be easily maintained.

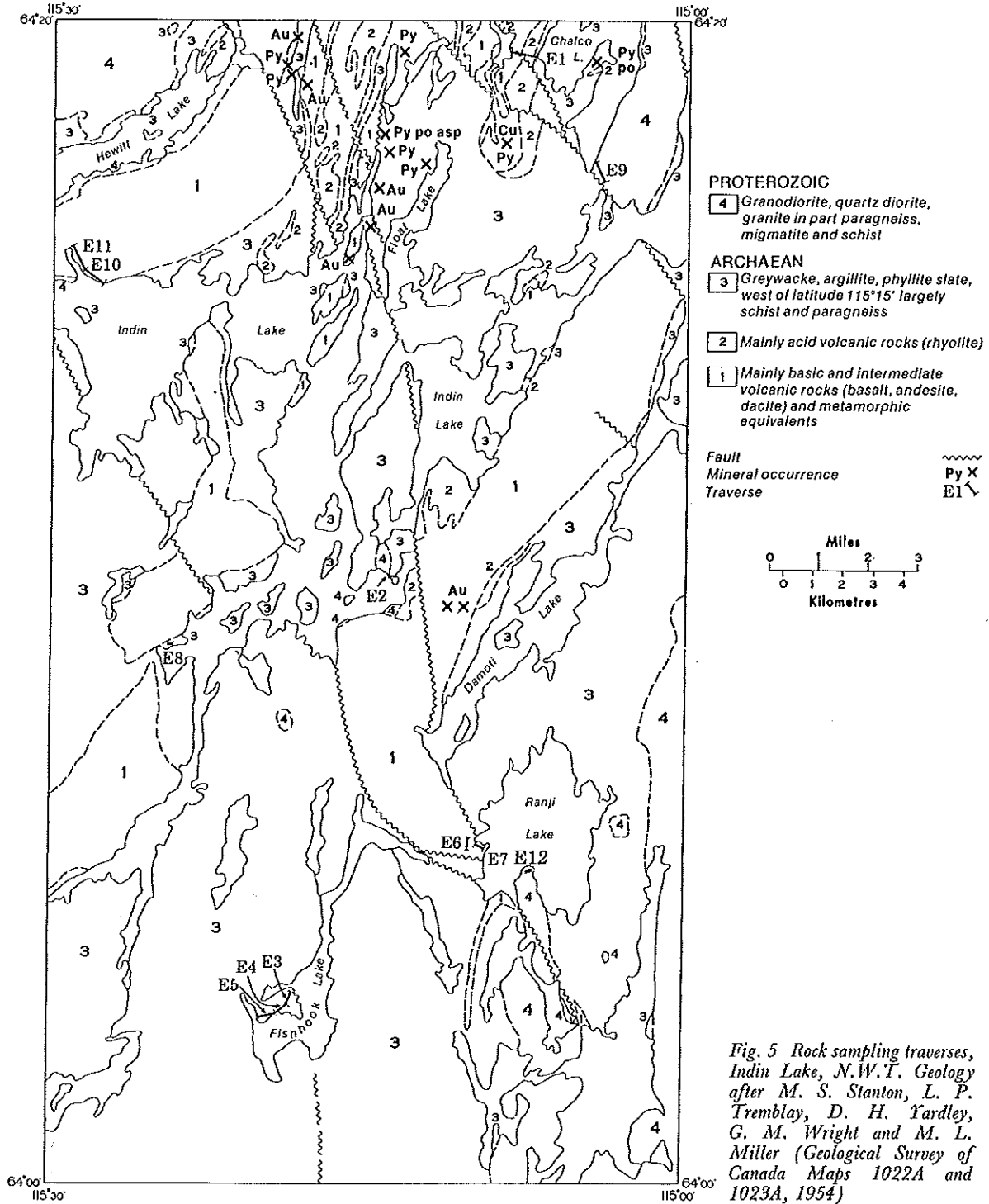
Water samples were always taken from just below the lake surface since this avoids layering effects in lake water related to redox changes.⁷ The organic and iron oxide coated sediments

found for 1 or 2 cm below the water-sediment interface were discarded as these are expected to show variations in trace-element content due to other than geological factors.^{39, 40} Sediment samples came from immediately below this discarded layer. Sediments came from near the lake shore in 3-8 ft of water.

Preparation of lake water and sediment samples

The sediments were air-dried and sieved to -250 mesh (63 μ m): this is the approximate boundary, in most surficial sediments, between the sand fraction, containing many rock fragments, and the silt fraction, that is largely composed of grains of individual minerals. In most surficial sediments from temperate and Arctic environments the dominant minerals in the silt fraction are quartz and feldspar.^{1, 9, 17} Although the quartz and feldspar may be derived from a variety of rocks, these components are often supplemented by other minerals, such as amphiboles and micas, that are more specific to certain rock types. This must be the case for the samples described here, for their major-element chemistry responds well to changes in the surrounding bedrock (see later).

Sediment less than 250 mesh was chosen because it has a relatively high surface area, which provides a fairly uniform absorbing medium.²⁵ Such a medium might be expected to reflect the chemical dispersion of elements carried in solution from surrounding mineral deposits. This has previously been discussed by Allan,³ who pointed out that the sorption capacity of lake sediments exceeds the amount of trace-element available in the drainage system. Major-element analysis (see



later) shows the sieved samples to be homogeneous, with variation from area to area and within areas that is largely the product of changes in the composition of the surrounding bedrock rather than variation in the silt/clay ratio. These sieved lake sediments may be compared to an enormous, flat, and relatively uniform resin bed that receives an input of various elements at differ-

ent places across its surface.

The quantity of trace elements removed from the drainage waters will mainly be dependent on both the concentration of the elements in the water and the available surface area of the sediment. Depending on these two major factors, an equilibrium amount of trace element will be removed by the sediment of the lakes. This process

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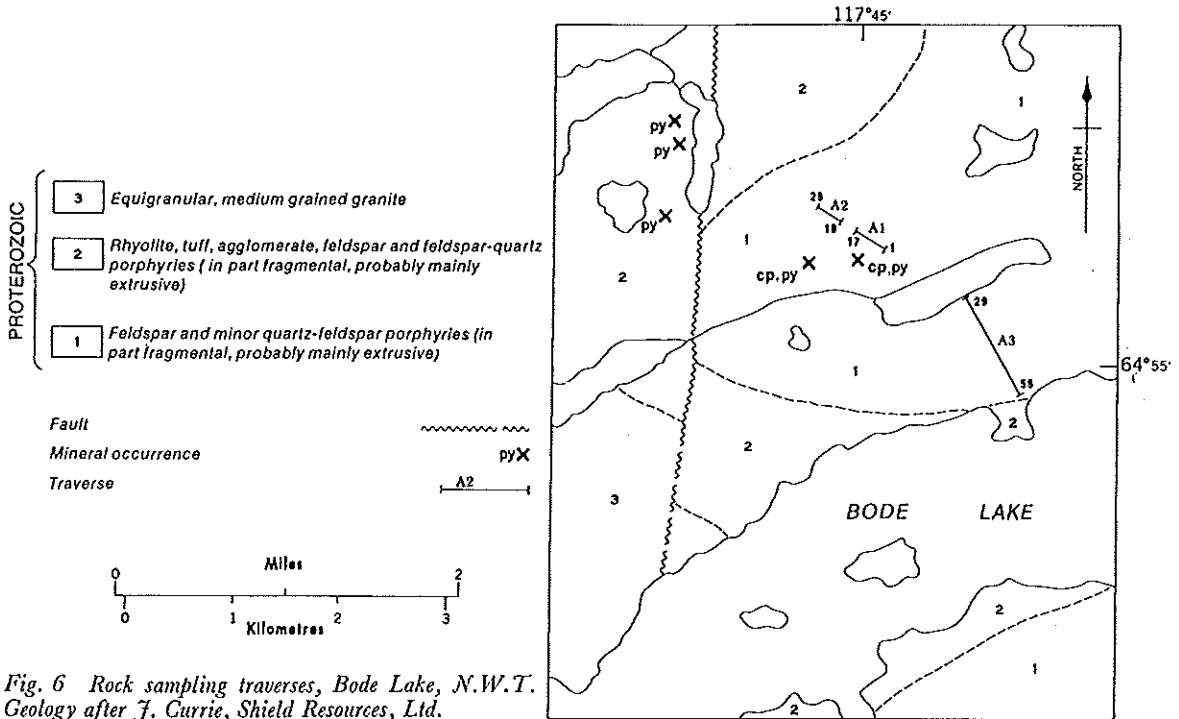


Fig. 6 Rock sampling traverses, Bode Lake, N.W.T. Geology after J. Currie, Shield Resources, Ltd.

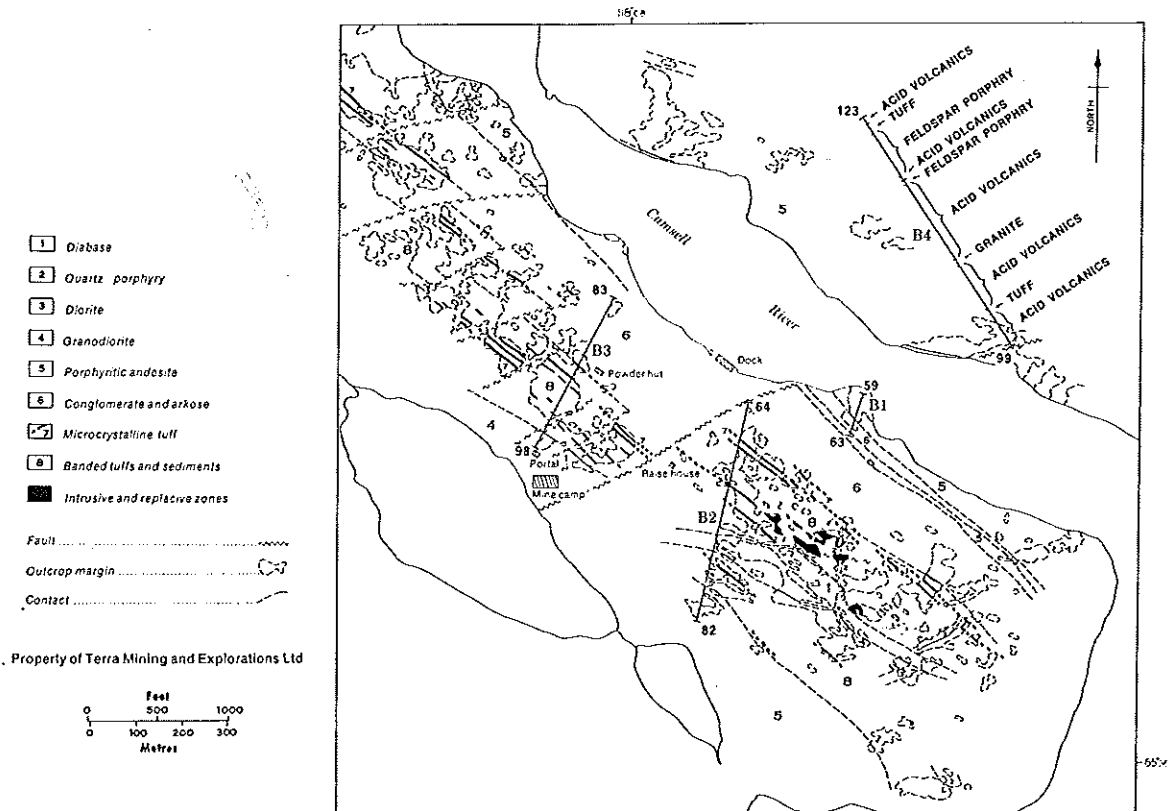


Fig. 7 Rock sampling traverses, Terra mine, N.W.T. Geology after N. Badham

is repeated at each lake in the drainage system until background levels are reached in both waters and sediments.

There are a number of variations which should be added to this rather simplistic explanation. A major one is that ions are probably sorbed on to

particles during transport of the latter in streams feeding the lakes. Another is that the analytical methods may leach not only the sorbed ions but also dissolve some of the ions that are bound within the structure of the mineral, and which have been carried in this form from the source rock.

Water samples were not filtered as there was no visible evidence of suspended loads.

The rock samples were reduced to $\frac{1}{4}$ -in chips between the steel jaws of a Chipmunk crusher, after which they were further reduced to about 20 mesh in a Braun pulverizer equipped with ceramic plates. 10 g of this material was sampled and ground to approximately -150 mesh in an alumina ceramic mill.

Analytical methods

The -250-mesh lake sediment samples and the rock samples were analysed for Si, Al, Fe, Mg, Ca, Ti, Mn and Ba by direct-reading optical emission spectrometer. After fusion of the sample with lithium tetraborate, containing cobalt oxide and strontium tetraborate as stabilizers and internal standards, the powder was sparked on a 'Tape Machine'. Na¹⁶ and K were analysed by adding 10 ml of 1 N HNO₃ to 210 mg of the above fused powder and heating until dissolved. 10 ml of 10 000 µg/ml Sr was added and the solution was made up to 100 ml, then being analysed by atomic absorption spectrometry. For Zn, Cu, Pb, Ni, Co and Ag 3 ml of 4 N HNO₃ and 3 drops of concentrated HCl were added to 0.2 g of the sample and heated to 95°C for 90 min. This was then diluted to 10 ml and analysed by atomic absorption spectrometry. For the Pb, Ni and Co a deuterium background correction was used. For the As determination the sample was fused with potassium pyrosulphate. The material was dissolved in 6 N HCl and the As was determined by the cold spot Gutzeit method. The cold vapour method for Hg has been described by Cameron and Jonasson.¹²

All of the water samples were acidified with concentrated HNO₃ on arrival in Ottawa. They were extracted with ammonium pyrrolidine-dithiocarbamate as chelating agent and methyl isobutyl ketone as solvent, and then analysed by atomic absorption spectrometry for Zn and Cu. The limit of detection for these two elements is 1 ppb.

At the time of writing most of the rock samples had not been analysed for Ni and Co, and none for Ag; none of the lake sediment samples had been analysed for As.

Presentation of results

The lake sediment and water results are presented

in the form of computer-drawn contour maps for each area. The contours are drawn from a regular grid computed from the original values. To compute this regular grid a uniform circular search radius is used: this is large enough to include several original values, which reduces the effect of an extremely high concentration. Because the search area is circular, and the original points are close to being on an even grid, any linear trends observed in the contours are due to trends in the bedrock or to other geological factors, and are independent of the contouring process.

For the various elements contour levels are:

Zn (Fig. 11) 20, 40, 60, 80, 100, 120, 160, 200 ppm

Cu (Fig. 12) 10, 20, 30, 40, 50, 60, 80, 100 ppm

Ni (Fig. 13) 10, 20, 30, 40, 50, 60, 80, 100 ppm

Co (Fig. 14) 5, 10, 15, 20, 25, 30, 40, 50 ppm

Ag (Fig. 15) 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.6, 2.0 ppm

Pb (Fig. 16) 5, 10, 15, 20, 25, 30, 40, 50 ppm

Hg (Fig. 17) 15, 20, 25, 30, 40, 50 ppb

In Figs. 11-17 the upper two contour levels are hachured; all numbers shown that are not labels for contour levels are actual sample values.

Bedrock geochemistry of sampled areas

As was demonstrated for the Coppermine area, the broad Cu anomalies in lake materials, miles in extent, are not the product of metal dispersion from ore deposits. Rather, they are the product of dispersion from 'micro-deposits' of copper minerals which are contained in the basalts, and which are genetically related to the orebodies. The objective of the rock sampling programme described here was to determine whether comparable occurrences of ore elements are associated with other important types of deposits in the Bear and Slave Provinces.

Areas in Slave Province

Where possible, the samples are classified into a number of groups. At Indin Lake they have been grouped into volcanic, sedimentary and granitic types. The volcanics have been further subdivided into basic (40.0-54.9% SiO₂), intermediate (55.0-67.9% SiO₂) and acid (>68% SiO₂). The grouping into sedimentary or volcanic has not been rigid; where a tuffaceous sediment is intercalated in an overwhelmingly volcanic sequence, it too is classified as a volcanic rock—conversely for a volcanic sample in a dominantly sedimentary sequence. In a number of cases assignment to one or other of these classes is difficult. At High Lake extrusive and pyroclastic rocks and tuffaceous sediments are intimately related. The samples have, therefore, not been subdivided into sediments and volcanics; neither

have those from Hackett River, where the succession sampled is dominantly sedimentary. At High Lake there are sufficient samples to make it practical to subdivide them into basic, intermediate and acid classes. It should be noted, however, that metasomatism of the rocks around the alteration pipe and ore deposit has modified their silica content, changing the 'classification' of some samples compared with that at the time of formation of the rocks.

Major elements

It would be inappropriate in a paper of this nature to make any extensive discussion of the major-element chemistry of the rocks; this will be done elsewhere. Much of this information is conveniently summarized by plotting the data for the different oxides in the different classes against SiO_2 . This is done in Fig. 8, where the three classes of volcanic rocks from Indin Lake and from High Lake are compared with data for average Canadian Shield volcanic rocks of Archaean age. These data are for Baragar and Goodwin's⁸ basalt (49.7% SiO_2) and salic fraction (66.8% SiO_2). The intermediate plot at 55.2% SiO_2 is a weighted average of their andesite, type *A* volcanic and type *B* volcanic in the abundance ratio 23:12:2:5:1 determined by Baragar and Goodwin. Major-element analyses for the different areas and rock types are shown in Table 1.

It may be seen from Fig. 8 that there is little difference for most elements in the plots for Baragar and Goodwin's data and those for Indin Lake. There is a definite enrichment, however, in alumina for the intermediate volcanic rocks at Indin Lake. Differences in the content of MnO and Ba may, at least in part, be due to analytical bias at this low concentration. The same degree of conformity does not apply to the data from High Lake. The plots for most of the oxides for this locality show what is believed to be the effects of Mg metasomatism of the rocks that surround the alteration pipe and ore deposit. MgO is more abundant in the rocks from High Lake than in rocks of equivalent silica content at Indin Lake or in those represented by the averages of Baragar and Goodwin. The plots in Fig. 8 suggest loss of Na_2O and Ba, particularly from the more acid varieties. Many of the plots of the other elements appear to have been displaced to the left as a result of a reduction in the SiO_2 content caused by the addition of Mg, and also possible loss of Si. The Al_2O_3 content of the acid volcanics at High Lake is very much lower than the general trend shown in Fig. 8.

The introduction of Mg into the rocks can also be readily detected by examining the sequence of

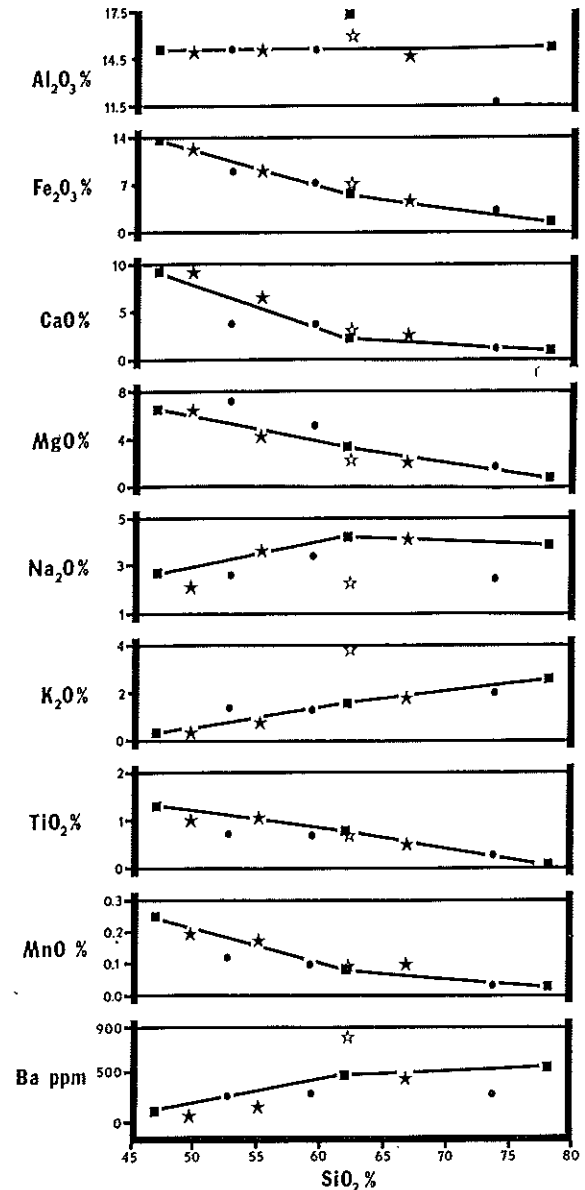


Fig. 8 Variation diagram: SiO_2 versus Al_2O_3 , total Fe as Fe_2O_3 , CaO , MgO , Na_2O , K_2O , TiO_2 , MnO and Ba: ■, basic, intermediate and acid volcanic rocks, Indin Lake; ●, basic, intermediate and acid volcanic rocks, High Lake; ▲, volcanic rocks, Bode Lake; ★, basalts, andesites (with type *A* and type *B*) and salic volcanic rocks from Archaean of the Canadian Shield. From Baragar and Goodwin⁸

analyses for individual samples. This introduction of Mg is accompanied by irregular loss of Na and Ba, and sometimes by K and Ca. Fe also seems to have been introduced or deposited with a number of the rocks sampled, mainly as sulphide. All of these metasomatic changes are largely confined to sampling traverses C1 and C2 in the area of the alteration pipe and ore deposit; traverse C3 (Fig. 3), some distance to the south, does not show these changes.

Table 1 Major-element composition, % (as arithmetic means), for rock types of study areas

Area and rock type	Number of samples	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃ * MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	MnO	Ba	
High Lake, all samples	94	59.8	14.6	7.11	4.98	3.29	2.78	1.42	0.60	0.091	0.028
High Lake, basic	22	52.7	15.2	9.41	7.41	3.83	2.50	1.27	0.69	0.118	0.025
High Lake, intermediate	54	59.4	15.2	7.08	4.70	3.75	3.39	1.31	0.67	0.096	0.029
High Lake, acid	16	73.6	11.5	3.29	1.76	1.06	1.42	2.01	0.25	0.031	0.028
High Lake, traverses	57	60.0	13.8	6.86	5.58	2.75	1.96	1.66	0.50	0.079	0.027
<i>C1-C2</i>											
High Lake, traverse <i>C3</i>	37	59.4	15.7	7.49	4.06	4.11	4.03	1.07	0.75	0.110	0.029
Hackett River, all samples	37	59.8	13.1	4.66	2.25	8.94	1.99	1.90	0.36	0.211	0.031
Indin Lake, all volcanics	109	58.5	15.5	9.01	4.18	5.67	3.24	1.21	0.89	0.156	0.030
Indin Lake, basic	55	47.0	15.1	13.92	6.35	9.51	2.59	0.36	1.33	0.254	0.014
Indin Lake, intermediate	21	62.1	17.2	6.62	3.40	2.46	4.18	1.61	0.79	0.084	0.044
Indin Lake, acid	31	77.9	15.2	1.48	0.89	0.94	3.83	2.50	0.16	0.025	0.050
Indin Lake, sediments	81	61.8	16.7	6.81	3.08	1.81	2.65	2.05	0.71	0.076	0.047
Indin Lake, granites	5	58.6	17.6	7.79	5.24	4.96	3.71	1.59	0.87	0.112	0.060
Bode Lake, all samples	57	62.2	15.9	6.13	2.35	3.00	2.22	3.80	0.62	0.097	0.082
Terra mine, all samples	65	56.1	15.4	9.56	3.25	3.95	3.09	3.31	0.60	0.215	0.076

*In this and all subsequent tables total Fe as Fe₂O₃.

The section sampled at Hackett River contains an abundance of limy beds and sediments with calcitic cement. The rock association in this area, and particularly the relation of these horizons to the alteration pipe near Camp Lake (Fig. 4), suggests that the carbonate material is of exhalative origin. This contention is supported by the manganese nature of the carbonate. The three samples with the highest amount of CaO, 48.4, 35.0 and 29.8%, contain, respectively, 1.23, 0.65 and 0.85% MnO.

The Indin Lake sediments are the chemically highly immature types so characteristic of the Archaean greenstone belts.⁶

Trace elements

Before the distribution of the trace elements in the Slave rocks is discussed, some mention should be

made of the degree of extraction of these metals from the samples during analysis. Zn, Cu and Pb were analysed by a partial leach in order that the component of the metal most subject to solution and dispersion within the drainage system would be analysed. In Table 2 there is a comparison of results for this attack and for a total leach of 10 representative samples from High Lake. These data indicate that the HNO₃-HCl attack has removed most of the Cu and Pb present in the rock, and less of the Zn. For As and Hg the extraction used is believed to remove virtually all of the metal in the majority of rock samples (J. J. Lynch, personal communication).

Zinc For Zn the area with the highest arithmetic mean content is High Lake (Table 3). There are two causes for this high level: first, the background level of abundance of Zn, shown by the geometric mean of 74 ppm and the median of 70 ppm, is

Table 2 Comparison of analytical data for Zn, Cu and Pb on 10 representative rock samples from High Lake (first column for each element gives results for total extraction (HF-HNO₃-HClO₄); second column is for the partial leach (HNO₃-HCl) method used to obtain data on Zn, Cu and Pb given in this paper)

Sample number	Zn, ppm (HF)	Zn, ppm (HNO ₃)	Ratio HF/HNO ₃	Cu, ppm (HF)	Cu, ppm (HNO ₃)	Ratio HF/HNO ₃	Pb, ppm (HF)	Pb, ppm (HNO ₃)	Ratio HF/HNO ₃
710124	144	142	0.99	29	32	1.10	<8	<8	—
710133	87	82	0.94	13	14	1.08	8	10	1.25
710143	157	102	0.65	37	37	1.00	20	22	1.10
710153	89	72	0.81	28	25	0.89	16	18	1.12
710163	74	61	0.82	23	18	0.78	<8	<8	—
710173	103	80	0.78	76	78	1.03	14	14	1.00
710183	29	24	0.83	57	61	1.07	<8	<8	—
710203	131	107	0.82	14	12	0.86	<8	<8	—
710213	86	43	0.50	71	66	0.93	<8	<8	—
710223	72	61	0.85	157	169	1.08	8	8	1.00
Mean ratio			0.80			0.98			~ 1.0

greater than for the other areas; secondly, the frequency distribution is skewed to high values, reflecting the presence of scattered mineralization along the two traverses, C1 and C2, close to the ore deposit. Because of this mineralization along C1 and C2, the arithmetic mean for these traverses is much higher than that for C3—which does, however, show a background level similar to that of the other two, with a geometric mean and median close to that for the whole area.

For the three classes of rock at High Lake the median value for Zn decreases from basic to acid, but there is a corresponding increase in the arithmetic mean. These features may be related to the generally higher background level of Zn within the major minerals composing basic rocks, and by the tendency for Archaean Zn sulphide mineralization to occur in acid volcanic rocks.

For the samples from the Hackett River traverse the background level, given by the geometric mean and median values of 42 and 43 ppm, respectively, is only slightly more than half the background at High Lake. The higher percentiles have values that are, however, similar for the two areas. This indicates the presence of scattered mineralization at both High Lake and Hackett River.

For the Indin Lake volcanics the background, shown by the median of 38 ppm and the geometric mean of 33 ppm, is even less than that found at Hackett River. There are no high Zn values at the higher percentile levels, confirming the general absence of mineralization along the sampled traverses. There is a general decrease in the arithmetic and geometric means and medians for Zn on passing over the sequence basic, intermediate and acid volcanic rocks.

The sedimentary rocks sampled within the

Indin Lake area have a quite different distribution of Zn. Background, shown by a geometric mean of 76 ppm and a median of 81 ppm, is higher than even the High Lake area. The statistical dispersion of the data is, however, very low, the highest value recorded being 112 ppm. These rocks, therefore, form a relatively high and uniform source of Zn. *Copper* The arithmetic mean of Cu (71 ppm) at High Lake is approximately double the geometric and median values of 33 and 37 ppm. This is caused by scattered mineralization along all three traverses skewing the frequency distribution. At 46 ppm the arithmetic mean of traverse C3, most distant from the ore deposit, is less than that of C1 and C2. As for Zn, however, the background level of Cu is relatively high along all three traverses.

Again, as for Zn, the geometric mean and median for Cu at Hackett River (17 and 23 ppm) are approximately half of those at High Lake. Cognizance should be paid to the facts that neither are the rock types in this area the same as for High Lake nor is the distance from the traverse to the most important deposit the same as at High Lake. Also, the main deposit at Hackett River contains little Cu. The Hackett River samples show Cu values at high percentile levels that are much smaller than those for High Lake.

The data for the Indin Lake volcanics reflect the very marked tendency for Cu to associate with basic rocks. The basic group have a median of 93 ppm Cu and very similar values for the arithmetic and geometric means. In contrast, the medians for the intermediate and acid classes are 16 and 4 ppm, respectively. Turning to High Lake, there is very little difference between the basic, intermediate and acid rocks there. There may be two reasons for this: first, originally acid and

lavas at either High Lake or Indin Lake. The most notable feature of the Pb distribution is a marked skewing to high values of Pb for the higher percentiles of the High Lake and Hackett River distributions, which reflects the presence of Pb mineralization, associated with ore deposits, in these samples. This is particularly marked for the acidic volcanics at High Lake.

Mercury Hg shows a rather uniform distribution, around the 10 ppb Hg level, in the rocks sampled from Slave Province (Table 3). The marked skewing to high values of Hg in the High Lake and Hackett River samples indicates the association of this element with sulphide mineralization.

Arsenic Arsenic also shows a uniform distribution. The determinations for most samples fall close to or below the detection limit of 3 ppm. In performing calculations this value is allocated to all samples showing some colour in the final solution. There is no marked association between the sulphide mineralization and the arsenic content of the rocks at either High Lake or Hackett River. The most interesting feature of the results is the much higher level of the values for the Indin Lake sediments. The median of 15 ppm is five times greater than that of any other group. The arithmetic mean of 16.9 ppm is three to four times that of the other groups. These differences would possibly be greater if this element could have been measured precisely at lower detection levels. If all samples assigned values of 3 ppm are, instead, assigned values of 0 ppm, the averages become: High Lake (94), 3.0 ppm; Hackett River (37), 2.0 ppm; Indin volcanic rocks (109), 1.0 ppm; Indin Lake sediments (81), 16.3 ppm. These values are in good agreement with Onishi's³² average for igneous rocks of 1.5 ppm As and for shales of 13 ppm.

Areas in Bear Province

Major elements

In Fig. 8 the major-element data for the 57 samples from Bode Lake are plotted. All of these samples fall within the limits 55–67.9% SiO₂ used above to define intermediate igneous rocks. The rocks at Terra mine are a rather heterogeneous mixture of sediments and volcanics, and are, therefore, not shown. The Bode Lake data for Al₂O₃, total Fe as Fe₂O₃, MgO, CaO, TiO₂ and MnO show no marked deviation from the Archaean trends. K₂O and Ba are, however, much higher in the Bode Lake rocks, and Na₂O is lower. Eade and Fahrig²⁰ have previously documented the higher level of K₂O in Proterozoic rocks of the

Shield in comparison with those of Archaean age. They did not note any significant difference for Ba.

Trace elements

Zinc For Zn the median and geometric mean for Bode Lake and Terra are at approximately the same levels (Table 3) as for High Lake. At higher percentile ranges the Bode Lake and Terra frequency distribution curves distinctly diverge from each other. The former is rather flat—indicative of a general absence of zinc mineralization along the traverses. The Terra data curves sharply up to higher Zn values in a similar fashion to the data from High Lake.

Copper The median values for Cu at Bode Lake and Terra (4 and 7 ppm, respectively) and the geometric means (5 and 11 ppm) are only a fraction of the same parameters at High Lake (37 and 33 ppm). The Bode Lake frequency distribution curve continues to be low up to the highest percentile levels. Only one sample, at 462 ppm, contains moderate Cu; the next highest is 36 ppm. This confirms the data for Zn on the very weakly mineralized nature of the rocks at Bode Lake. The mineral prospect at Bode Lake has not, to the present, been shown to be other than minor. The Terra distribution curve shows a rapid escalation in Cu values at higher percentile values. Thus, at Terra the zone containing the ore deposits contrasts much more sharply with the background level of Cu in rocks of the area than was the case with High Lake. Although this feature will be of assistance in making detailed geochemical surveys by use of soils, stream sediments or lake muds, it is not helpful for reconnaissance surveys. At Terra, more so than in the other areas, the anomalous results for Zn, Cu, Pb and As are mainly confined to a zone extending several hundred feet on either side of the stratiform copper ore horizon. Traverse B4 on the opposite side of the Camsell River from traverses B1–B3 shows few high results for any of these elements.

Lead The median Pb values for Bode Lake and Terra (14 and 13 ppm) and the geometric mean values (15 and 16 ppm) are slightly higher than the equivalent values for the Archaean areas. The distribution curve for the element at Terra resembles that at High Lake because of the effect of mineralization in the two areas. The Bode Lake curve shows moderate escalation.

Mercury For Hg the featureless nature of its distribution, noted for the Archaean areas, persists for the areas in Bear Province. The median values of 7 ppb at Terra and 6 ppb for Bode Lake are slightly smaller than those for the Archaean areas. At High Lake and Hackett River some high Hg values were associated with the mineralization;

at Bode Lake and Terra there are none. At Terra the highest Hg value is 17 ppb; at Bode Lake 10 ppb. For these two areas this element would appear to be of no value for either reconnaissance or detailed geochemical surveys.

Arsenic One sample from Bode Lake contains an As concentration greater than the detection limit of 3 ppm. At Terra there are a number of values greater than 3 ppm in the zone around the stratiform Cu horizon and silver arsenide veins. The arithmetic mean and geometric mean values and the distribution curves for As are very similar for the High Lake and Terra data.

Major-element composition of lake sediments

One of the more interesting aspects of this study is the major-element composition of the lake sediment samples. These data allow an assessment to be made of the effectiveness of lake sediments as a composite sample of the surrounding bedrock. The results obtained suggest that lake sampling may be useful for geological mapping as well as for

sediment data with that for bedrock all data given in Table 4 are corrected to 100% in terms of the oxides listed. This eliminates variation caused by changes in the moisture and organic content of the sediment samples.

The average of the five areas sampled for sediments within Slave Province is compared with Eade and Fahrig's²⁰ average of the Archaean for the Canadian Shield; and the average of the Terra and Bode Lake areas is compared with their average Proterozoic rock. The McGregor Lake area results have been excluded from the Bear Province average because these sediments were, in part, derived from an uncommon (ultramafic) rock type.

In comparison with the Archaean bedrock, the Slave Province lake sediments show a large percentage decrease in Ca, Na and Ba. The former two components are the major elements most readily lost during rock weathering.^{11,15} The apparent loss in Ba may be due to analytical bias between laboratories for this minor element. The next largest decrease is for Fe and Mn. It is possible that some of these components move to

Table 4 Comparison of major-element data for lake sediments

Area	Row	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	MnO	Ba
Indin Lake	1	69.0	15.5	4.23	2.39	2.29	3.19	2.62	0.66	0.072	0.062
High Lake	2	71.3	14.0	4.33	2.33	1.96	2.53	2.69	0.69	0.067	0.049
Muskox Lake	3	71.4	13.8	4.38	2.59	1.95	2.68	2.52	0.56	0.074	0.055
Harding Lake	4	70.6	15.8	3.89	1.93	1.42	2.72	3.07	0.46	0.055	0.060
Hackett River	5	78.2	11.7	2.84	1.33	1.05	2.37	1.99	0.40	0.044	0.037
Average R1-R5	6	72.1	14.2	3.93	2.11	1.73	2.70	2.58	0.55	0.062	0.053
Average Archaean (R6-R7) × 100	7	65.7	16.1	4.8	2.3	3.4	4.1	2.72	0.50	0.080	0.080
R7	8	+10%	-12%	-18%	-8%	-49%	-34%	-5%	+10%	-23%	-34%
Bode Lake	9	72.0	14.5	2.93	1.72	2.04	3.11	3.08	0.49	0.062	0.063
Terra mine	10	68.7	15.1	4.78	2.67	1.51	2.39	3.95	0.75	0.091	0.073
Average R9-R10	11	70.4	14.8	3.86	2.20	1.78	2.75	3.52	0.62	0.077	0.068
Average Proterozoic (R11-R12) × 100	12	65.5	16.1	5.0	2.1	3.3	3.5	3.54	0.62	0.091	0.082
R12	13	+7%	-8%	-23%	+5%	-46%	-21%	-1%	0%	-15%	-17%
(R11-R6) × 100	14	-2%	+4%	-2%	+4%	+3%	+2%	+36%	+13%	+24%	+28%
R6											
McGregor Lake	15	66.7	13.4	6.81	6.20	1.48	1.55	3.08	0.69	0.116	0.048

Data in rows 7 and 12 from Eade and Fahrig.²⁰ Row 8 is difference between Slave Province lake sediments and average Archaean rocks; row 13 is difference between Bear Province sediments and average Proterozoic rocks; row 14 is difference between lake sediments of Bear and Slave Provinces. All data converted to 100% in terms of oxides given above.

mineral exploration. In Table 4 are listed the average major- and minor-element compositions of the lake sediments for each area. A comparison is made of the means for different areas, of the means for Slave Province samples with those from the Bear, and of the sediment data with the estimated composition of the underlying bedrock. In order to provide a meaningful comparison of the

the surface of the sediment during diagenesis; the iron-rich layer seen at the sediment-water interface at many sample sites was excluded from all the samples taken. For all other elements the difference between the sediment and rock averages is quite small in proportion to the amount present. The largest absolute difference is for silica. The amount of silica and alumina in the samples

characterizes them as silty rather than argillaceous. The differences between the Bode Lake and Terra mine means and the average Proterozoic rock are almost precisely the same as for the Slave comparison.

Comparison of the Bear with the Slave lake sediment averages show that there are negligible differences for Si, Al, Fe, Mg, Ca and Na. There is a relative enrichment of 36% for K in the Proterozoic lake sediments and 13% for Ti, 24% for Mn and 28% for Ba. For K and Ti Eade and Fahrig²⁰ reported differences of this magnitude for the Archaean and Proterozoic crust of the Shield. They did not detect any marked difference for Mn or Ba.

Comparing individual areas, the most striking differences are observed for McGregor Lake. The sediments of this area reflect the contribution of ultramafic rocks in much higher amounts of Fe, Mg and Mn and a higher amount of Ti, with lower contents of Si, Al, Ca and Ba. Variation among the averages for other areas is much less. Indin Lake, High Lake and Muskox Lake—areas principally underlain by Archaean volcanic and sedimentary rocks, with some granitic material—are remarkably similar in their major- and minor-element composition. The Hackett River lake sediments are more siliceous: this is associated with the siliceous nature of the acid volcanics and sedimentary rocks of the area. If the calcitic component of the analyses is removed from the rock data for Hackett River, the sampled rocks are more siliceous than those from either High Lake or Indin Lake. The sediment data from

geology and geochemistry that will complement present types of mapping.

It is not proposed here to make any extensive discussion of the mapping of the major-element variations within the areas studied—this will be covered in a subsequent paper that will describe the multivariate statistical treatment of the major- and trace-element data. As an example of the variation that is obtained, however, contour maps for MgO in the lake sediments of the High Lake and Hackett River areas are shown in Fig. 9. In the discussion on the geochemistry of the rocks it was noted that there was Mg metasomatism of the rocks surrounding the vent and ore deposit at High Lake. The contoured plots for this area show an anomaly in the MgO content of the sediments near to the ore deposit. At Hackett River the MgO content of the sediments is low along the band of acid volcanics, because of their silicic character. There is, however, a MgO anomaly close to the known vent and ore deposit. In the typical geological environment of the Archaean massive sulphide ore deposit this pattern of low MgO values might be expected over the acid volcanic horizons, with anomalies outlining the metasomatized vent structures. There are at both High Lake and Hackett River other MgO anomalies, most of which can be eliminated as possible mineralized vents by comparing the trace-element levels of Zn and Ag at these locations. Nevertheless, at least one unexplained MgO anomaly exists at both locations.

Trace-element composition of lake sediments

Each trace element is discussed below separately. Variation between and within the areas can be considered in relation to their geology (Fig. 10) and to known or suspected mineralization. Because of space considerations, only seven of the eight sampled areas are shown as contour diagrams. *Not included in the contour diagrams are the data for the highly mineralized lakes adjacent to the High Lake and Hackett River ore deposits. These data are presented in Table 5.* Statistical data on the major- and trace-element content of sediments from all eight areas are given in Table 6. In comparing the sediment with the rock data median values have generally been used in order to avoid the untoward effects of a few mineralized samples.

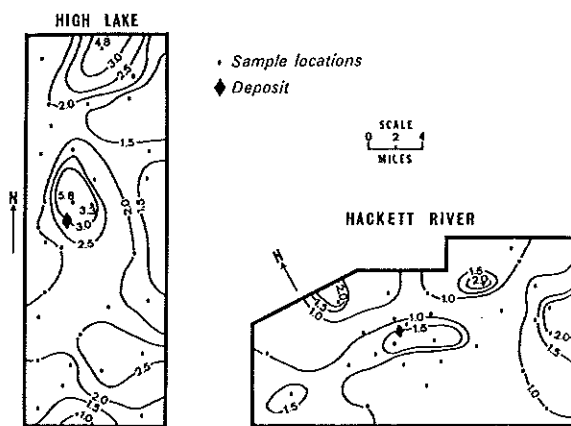


Fig. 9 Distribution of MgO, %, in lake sediments, High Lake and Hackett River areas

Harding Lake suggest that the underlying 'granitic' material is of granodioritic composition.

On the basis of the above information it can be suggested that major- and minor-element analyses of lake sediments can produce maps of the bedrock

Zinc

The area with the highest and most extensive Zn concentrations is High Lake (Fig. 11), with a median content of 124 ppm. The background

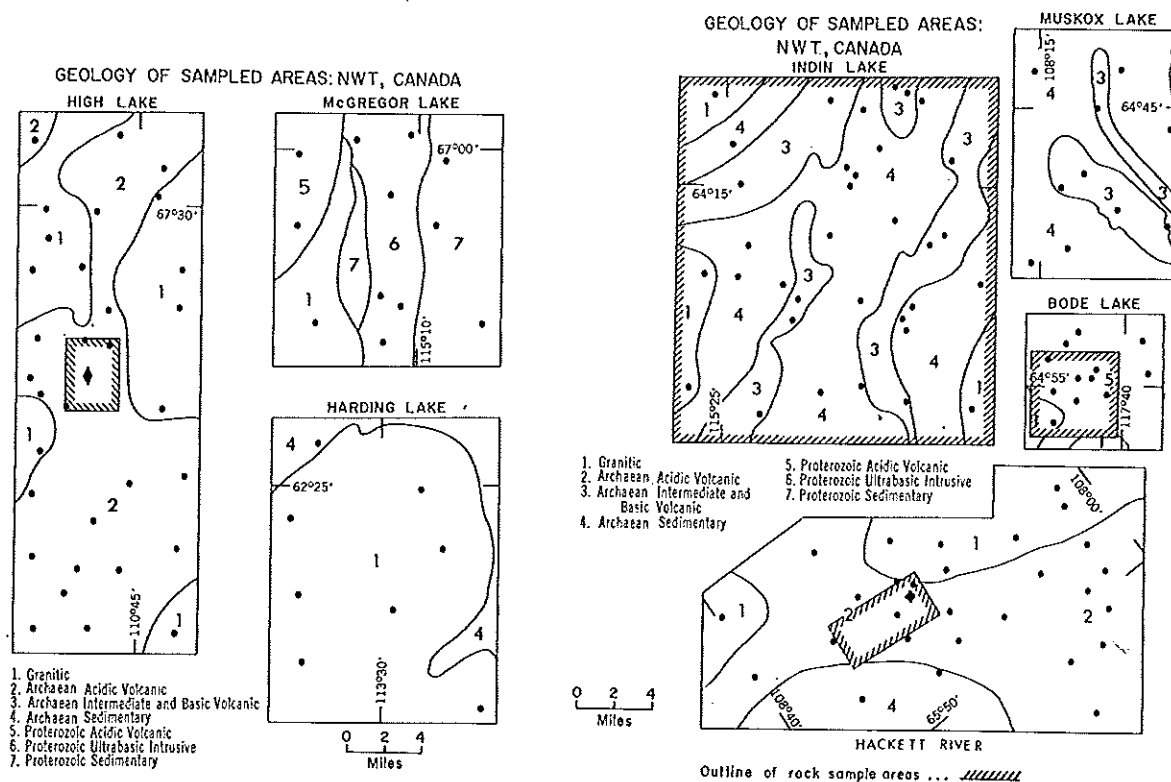


Fig. 10 Geology of areas sampled for lake sediments. Cu-Zn deposit located by diamond symbol at left centre of High Lake map; Pb-Zn-Ag deposit by diamond symbol at centre of Hackett River map; dots represent sample locations

level of abundance at Hackett River is much less, with a median of 44 ppm Zn. The Pb-Zn-Ag deposit at Hackett River, however, is clearly

ppm Zn contour); but much less for Hackett River.

It was shown above that there is a similar trend

Table 5 Major- and minor-element concentrations in -250-mesh sediments from lakes adjacent to Archaean massive sulphide deposits*

Sample type	Major elements: arithmetic means, %								Minor elements: arithmetic means, ppm									
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	MnO	Cu	Pb	Zn	Ag	Ni	Co	Hg	Ba	
High Lake†	62.9	14.0	5.00	2.49	1.54	2.43	2.29	0.67	0.07	3700	88	1791	1.1	47	50	0.042	40	
Camp Lake‡	69.1	12.1	3.00	1.66	1.12	2.02	1.69	0.50	0.03	624	140	1419	0.9	32	11	0.048	40	
Iron-rich sample§	41.5	32.5	26.5	0.99	0.00	0.54	2.77	0.83	0.01	278	319	213	25.6	6	5	0.075	40	

*The concentrations for High Lake and for Camp Lake given above were not used in any of the regional diagrams (Figs. 11-17). They are presented to show the great concentration difference between the regional trace-element levels and those in lakes adjacent to orebodies.

†Average of nine samples evenly distributed over High Lake which is the closest lake to the 5 000 000-ton Cu-Zn deposit in High Lake area (Fig. 3).

‡Average of three samples evenly distributed over Camp Lake which is the closest lake to the 10 000 000-ton Pb-Zn deposit in Hackett River area (Fig. 4). Compare with analysis of Hackett River ore given in text.

§This sample from the High Lake area is anomalous in Ag (25.6 ppm; Fig. 15) and is referred to in the text as the 'iron-rich sample'. It is not incorporated in the statistical treatments, but is included in Figs. 11-17. The values are for one sample.

defined by a sharp anomaly, which, at its peak, has Zn values as high as those at High Lake. From these two examples it can be seen that areas of ore potential may be outlined by broad areas of high values or by relatively less extensive and sharper anomalies in the lake sediment results. After a reconnaissance survey perhaps 50% of the area sampled at High Lake might have been selected for detailed follow-up survey (say, within the 160

in the background for Zn in the rocks of the two areas; the lake sediments in the High Lake area do, however, have a higher median value of Zn than the rocks that were sampled. At High Lake the 100 ppm contour very approximately marks the granite-greenstone contact.

All of the other areas sampled show median values rather higher than those at Hackett River; but only two, McGregor Lake and Indin Lake,

Table 6 Statistical data on major- and trace-element content of lake sediments

Area		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	MnO	Ba	Zn	Cu	Pb	Ni	Co	Ag	Hg
High Lake N=31	<i>X</i>	66.9	13.1	4.06	2.19	1.84	2.37	2.53	0.65	0.063	0.046	138.5	55.5	22.5	31.7	15.9	0.67	25.2
	<i>S</i>	5.2	1.1	1.47	0.96	0.67	0.36	0.48	0.16	0.021	0.008	75.7	28.2	43.2	16.3	10.3	0.18	14.2
	<i>G</i>	66.7	13.1	3.83	2.05	1.73	2.34	2.48	0.63	0.060	0.045	120.0	46.9	14.1	27.5	13.1	0.63	22.4
Hackett River N=28	<i>M</i>	68.5	13.0	3.53	1.99	1.82	2.45	2.55	0.65	0.061	0.050	124.0	51.0	11.0	28.0	14.0	0.70	20.0
	<i>X</i>	73.5	11.0	2.67	1.25	0.99	2.22	1.87	0.37	0.042	0.035	71.3	34.1	29.3	24.0	9.2	0.60	19.7
	<i>S</i>	7.5	2.0	1.36	0.55	0.36	0.67	0.55	0.11	0.016	0.013	71.5	32.5	95.1	27.4	11.6	1.16	11.7
Indin Lake N=35	<i>G</i>	73.2	10.8	2.37	1.15	0.91	2.14	1.81	0.35	0.039	0.033	50.5	24.7	11.9	16.8	6.3	0.30	17.4
	<i>M</i>	74.5	11.0	2.14	1.16	1.12	2.04	1.69	0.38	0.039	0.030	44.0	22.0	11.0	16.0	5.0	0.20	17.0
	<i>X</i>	65.7	14.7	4.03	2.28	2.17	3.04	2.49	0.63	0.068	0.059	75.8	37.7	12.1	35.1	15.2	0.37	14.3
Muskox Lake N=11	<i>S</i>	5.6	0.8	1.46	0.80	0.38	0.22	0.54	0.13	0.026	0.013	47.4	26.5	2.8	16.3	8.7	0.19	5.0
	<i>G</i>	65.4	14.7	3.79	2.17	2.14	3.03	2.43	0.62	0.065	0.057	66.5	31.5	11.7	32.3	13.3	0.33	13.8
	<i>M</i>	66.4	14.7	3.93	2.32	2.14	3.06	2.59	0.67	0.066	0.060	70.0	31.0	12.0	32.0	14.0	0.30	14.0
Harding Lake N=8	<i>X</i>	66.5	12.9	4.08	2.41	1.82	2.50	2.35	0.53	0.069	0.051	97.6	41.8	9.4	45.7	19.7	0.42	54.9
	<i>S</i>	7.9	1.2	1.01	0.69	0.30	0.20	0.37	0.14	0.017	0.009	33.4	16.5	2.4	13.0	6.3	0.43	16.4
	<i>G</i>	66.0	12.8	3.94	2.30	1.80	2.49	2.32	0.51	0.067	0.050	93.4	38.6	9.1	44.0	18.9	0.40	52.8
Bode Lake N=12	<i>M</i>	69.1	13.8	4.63	2.65	1.96	2.44	2.43	0.52	0.075	0.050	96.0	41.0	9.0	50.0	21.0	0.50	59.0
	<i>X</i>	63.7	14.3	3.51	1.74	1.28	2.46	2.77	0.41	0.049	0.054	55.2	25.4	9.8	27.7	10.9	0.50	24.0
	<i>S</i>	8.3	1.8	1.84	0.93	0.24	0.75	0.65	0.14	0.018	0.022	26.9	10.0	4.2	9.7	5.4	0.19	11.9
Terra Mine N=39	<i>G</i>	63.2	14.2	3.01	1.50	1.26	2.36	2.70	0.39	0.046	0.050	49.0	23.6	9.0	26.2	9.5	0.47	21.7
	<i>M</i>	63.8	14.7	4.46	2.16	1.26	2.43	3.16	0.45	0.050	0.060	56.0	27.0	11.0	29.0	12.0	0.50	17.0
	<i>X</i>	68.3	13.8	2.78	1.63	1.94	2.95	2.92	0.46	0.059	0.060	59.3	23.2	12.3	23.5	11.4	0.37	44.7
McGregor Lake N=12	<i>S</i>	5.7	1.3	1.59	0.79	0.35	0.34	0.58	0.16	0.021	0.009	32.5	12.6	6.5	15.6	8.5	0.24	17.3
	<i>G</i>	68.1	13.7	2.46	1.48	1.90	2.93	2.88	0.43	0.056	0.059	51.4	19.8	10.7	19.2	8.6	0.30	42.2
	<i>M</i>	69.6	13.4	2.43	1.33	1.96	3.10	2.81	0.45	0.052	0.060	61.0	30.0	13.0	18.0	9.0	0.30	37.0
Hackett River N=12	<i>X</i>	66.0	14.5	4.60	2.57	1.45	2.30	3.79	0.72	0.088	0.070	95.9	31.6	20.4	34.4	18.3	0.50	31.6
	<i>S</i>	7.4	1.9	1.81	1.09	0.36	0.26	0.48	0.14	0.036	0.012	31.8	11.1	6.2	17.2	10.5	0.24	19.7
	<i>G</i>	65.6	14.4	4.25	2.34	1.41	2.28	3.76	0.71	0.082	0.069	90.3	29.3	19.4	29.7	15.6	0.44	28.3
McGregor Lake N=12	<i>M</i>	67.2	14.4	4.82	2.65	1.40	2.29	3.92	0.75	0.076	0.070	95.0	34.0	21.0	34.0	18.0	0.50	31.0
	<i>X</i>	57.1	11.4	5.83	5.31	1.27	1.33	2.63	0.59	0.100	0.041	114.0	48.6	20.1	185.0	26.5	0.58	21.0
	<i>S</i>	9.0	2.6	2.02	3.38	0.87	0.37	0.71	0.14	0.036	0.010	48.6	23.3	7.6	236.0	23.6	0.17	6.6
Hackett River N=12	<i>G</i>	56.4	11.2	5.55	4.54	1.04	1.28	2.52	0.58	0.094	0.039	105.0	44.0	19.0	92.0	20.7	0.54	20.1
	<i>M</i>	56.9	11.7	5.29	4.31	0.84	1.35	2.72	0.57	0.093	0.040	129.0	43.0	18.0	132.0	18.0	0.60	20.0

X, arithmetic mean; *S*, standard deviation; *G*, geometric mean; *M*, median.
SiO₂ to MnO,%; Ba to Ag, ppm; Hg, ppb.

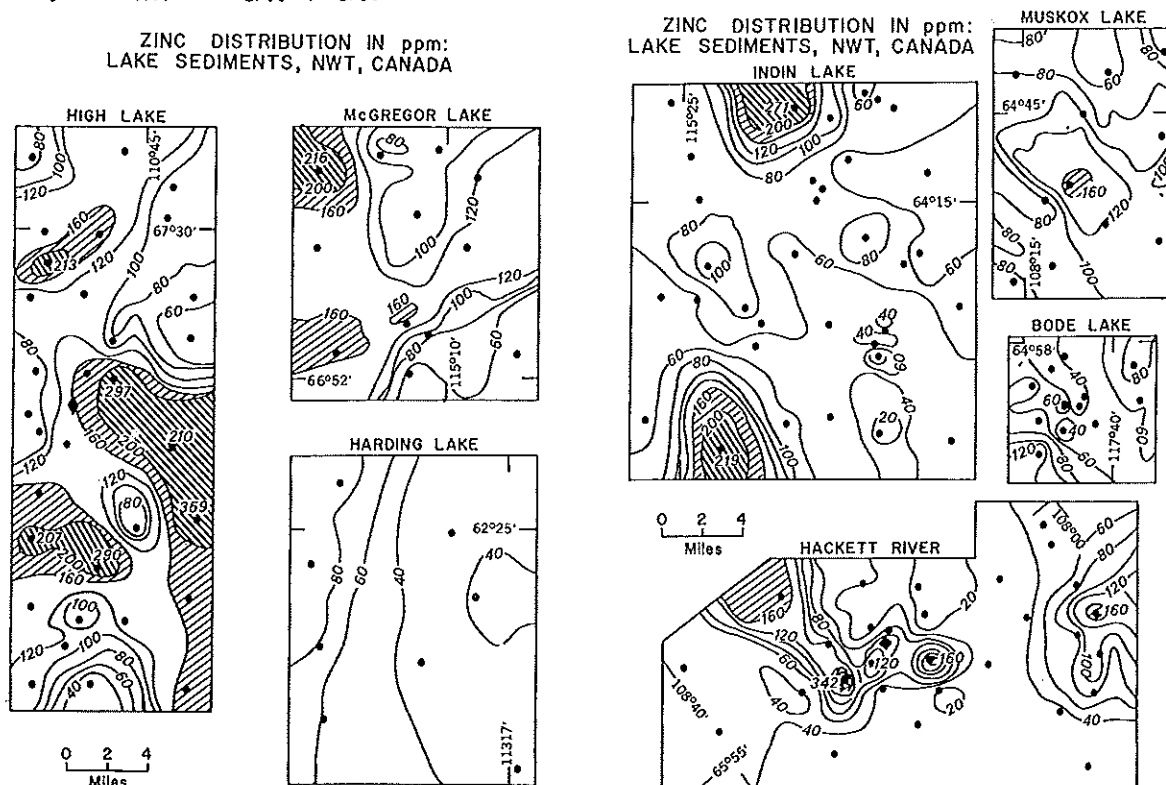


Fig. 11 Distribution of Zn in lake sediments of study areas

show sharp single sample anomalies. For all of these areas, apart from High Lake, the level of

abundance in the rocks and lake sediments is in broad agreement.

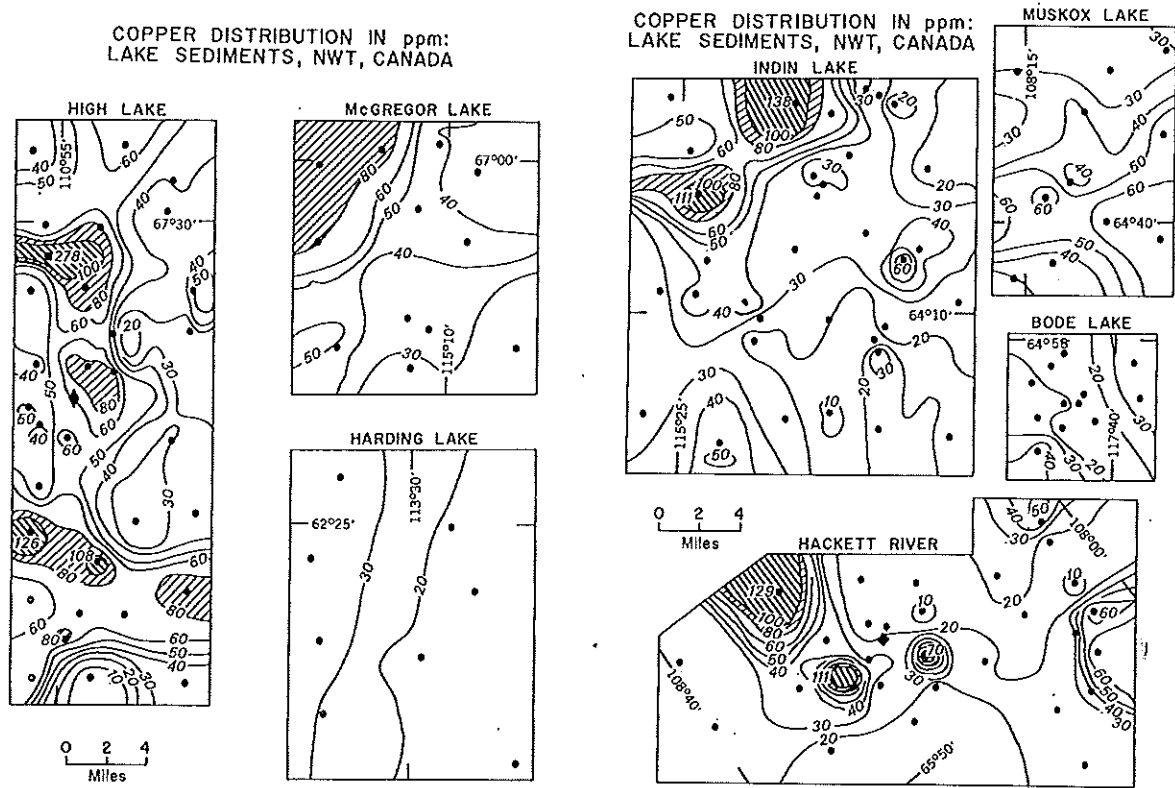


Fig. 12 Distribution of Cu in lake sediments of study areas

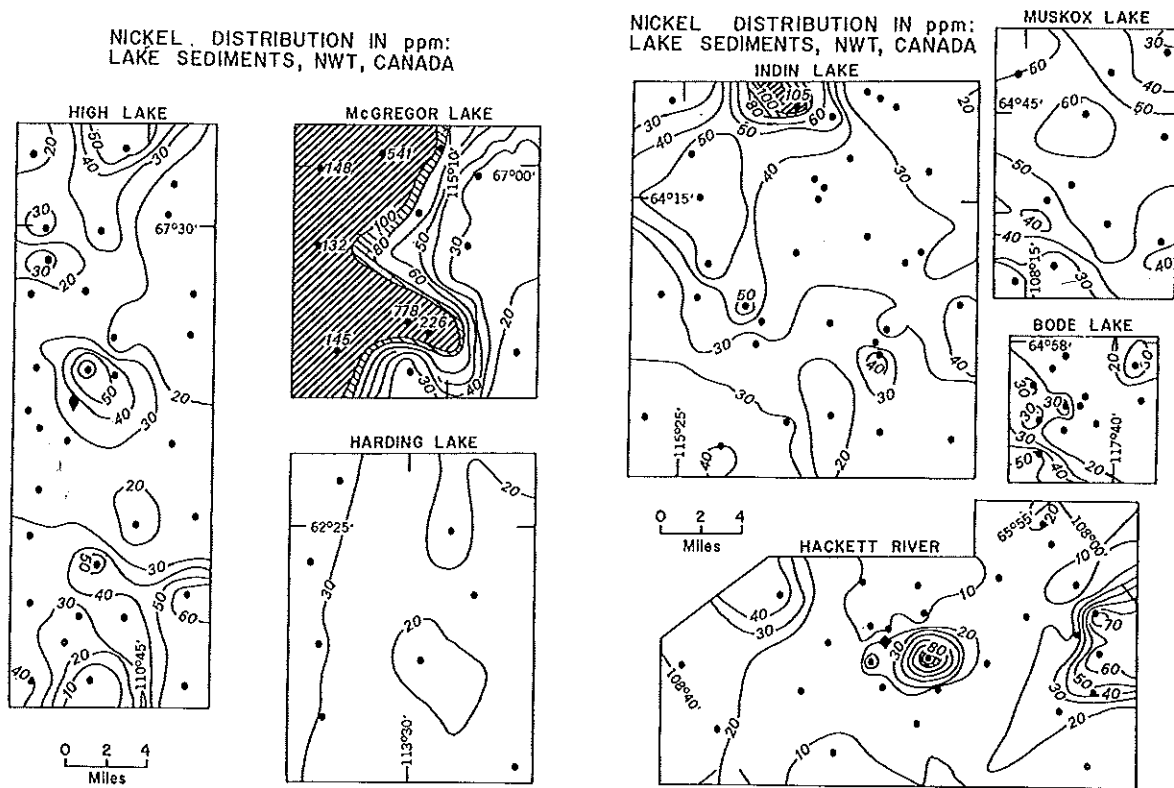


Fig. 13 Distribution of Ni in lake sediments of study areas

Copper

Concentrations of Cu in lake sediments (Fig. 12) produce somewhat similar results to those for Zn. The areas which appear to have the most favourable anomalies are High Lake, Indin Lake, Hackett River and McGregor Lake. High Lake again has the highest background level. Since this is the one area known to contain a large Cu-Zn deposit, this is an entirely satisfactory result. At Hackett River the higher Cu concentrations are found in the same area as the high Zn results. This may indicate the same type of ore association in this area as is present at High Lake. The anomalous Cu and Zn concentrations at Hackett River appear to lie along a zone in the acid volcanics.

At Indin Lake there is an interesting anomaly for Cu in the northwest corner of the area, where it coincides with a Zn anomaly. Airborne electromagnetic surveys in the Indin Lake area have been confined to the eastern volcanic belts. On the basis of the analyses, the northwestern volcanic belt might be more thoroughly investigated in order to explain the high Cu and Zn results.

Aside from these anomalous zones, the concentration of Cu in the lake sediments correlates well with the geology and the concentration of Cu in the different rock types. The 40 ppm contour at High Lake roughly parallels the granite-greenstone contact. The Hackett River area, the rocks of which are silicic, is low in Cu in the non-anomalous parts of the area. The area of granodiorites at Harding Lake is low and shows little contrast. Within the Indin Lake region the basic and intermediate volcanic areas are richer in Cu than those parts of the area underlain by acid volcanics. The low median Cu values of the rock samples from Bode Lake and Terra mine are also matched by similarly low results for the sediments, although in the former case the geometric mean Cu concentration in the sediment (Table 6) is unusually high relative to the rock mean Cu concentrations (Table 3). One area that has not been discussed so far is McGregor Lake. The Cu and Zn concentrations here are best reviewed with nickel.

Nickel

Lake sediments in the McGregor Lake area, especially where the sample sites lie within the Muskox Intrusion, have by far the highest Ni concentrations of any area sampled (Fig. 13), with up to 778 ppm. To the west of the intrusion, in country underlain by acidic volcanics and gneiss, there are moderately high Ni values in the range 132-148 ppm. These and the higher values over

the intrusion show a good correlation with the MgO content of the sediments; it therefore appears likely that the enhanced Ni content of these sediments has principally come from the Ni contained in the silicate minerals of the ultrabasic rock. The continental ice sheet, which moved from the southeast to the northwest in this region, may have carried ultrabasic rock detritus to the west of the Muskox Intrusion.

Nickel sulphide mineralization of the Shield, which is associated with ultrabasic rocks, is almost invariably accompanied by copper sulphides.¹³ In such areas as the Ungava nickel belt, where there are large Ni sulphide zones, the Cu concentrations in lake sediments substantiate this concept.⁴ Here, Ni concentrations of 100-200 ppm in lake sediment are accompanied by Cu concentrations of 80-100 ppm Cu, with a high value of 693 ppm Cu in the sediment closest to the ore zones of the Donaldson mine at the Raglan property. In many of the high Ni lake sediments from the Muskox Intrusion the Cu is not particularly high (40-50 ppm)—confirming the above interpretation of the origin of the high Ni values. In the northwest quadrant of the sampled area, however, relatively high Cu and Zn values accompany the enhanced Ni levels (Figs. 11 and 12). This region may merit further investigation.

Although no other areas have Ni concentrations approaching those at McGregor Lake, there are lower, but sharp, Ni anomalies at Hackett River, Indin Lake and High Lake. The latter is in the general area of the ore deposit and vent and coincides with the MgO anomaly (Fig. 9). Analyses of the High Lake rock samples for Ni that became available as this paper was being prepared show scattered (to 713 ppm) Ni mineralization in the metasomatized rocks around the vent. A similar explanation may also account for the Ni anomaly near the ore deposit at Hackett River. Analyses of the sediments from the lakes immediately adjacent to the ore deposits at High Lake and Hackett River, which have not been included in the contour diagrams for any element, do not show high levels of Ni (Table 5). The actual ore at Hackett River, however, also has a low Ni concentration (47 ppm). These Ni anomalies are thus associated with vent metasomatism rather than with the actual ore. (A sample of ore-grade material from Hackett River analysed 28% Zn, 210 ppm Cu, 97 ppm Pb, 21 ppm Ag, 47 ppm Ni and 103 ppm Co.)

The Ni levels in non-anomalous parts of the different areas correlate reasonably well with the geology; sediments overlying acidic rocks are generally low, those overlying basic rocks generally high. Thus, the median value for Hackett River (Table 6) is lowest of all, confirming that this area

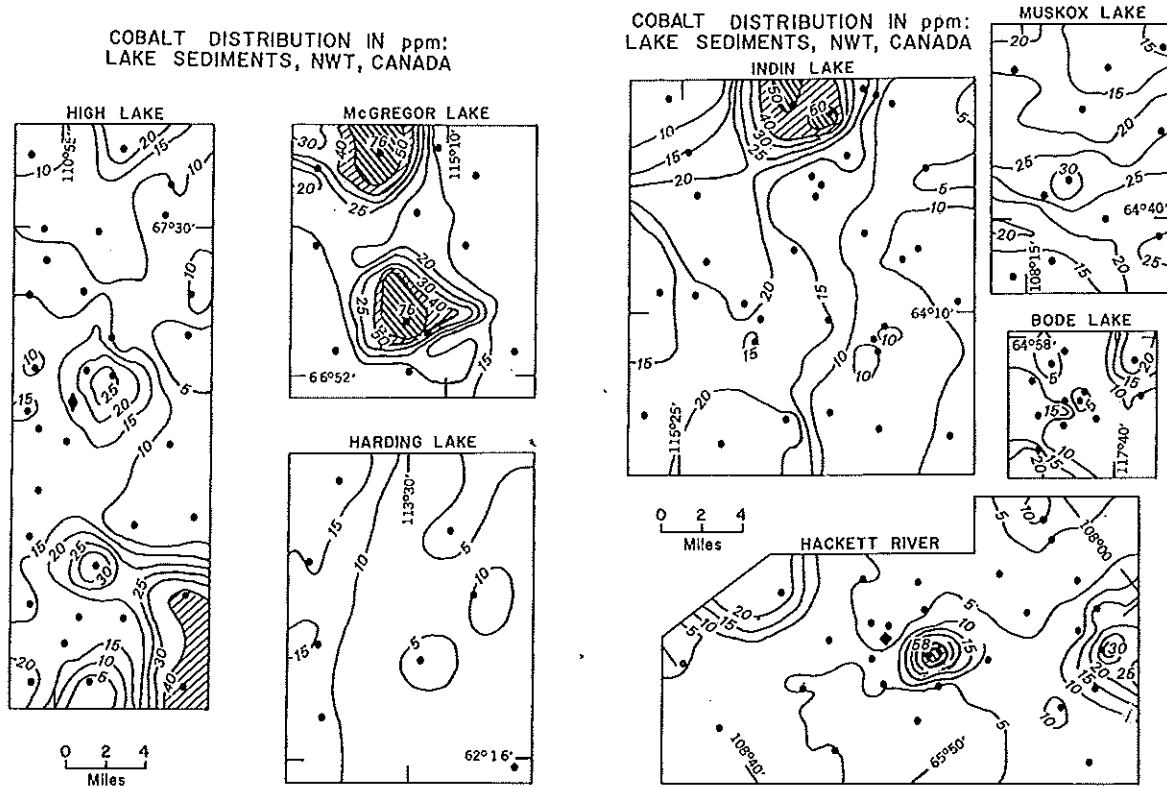


Fig. 14 Distribution of Co in lake sediments of study areas

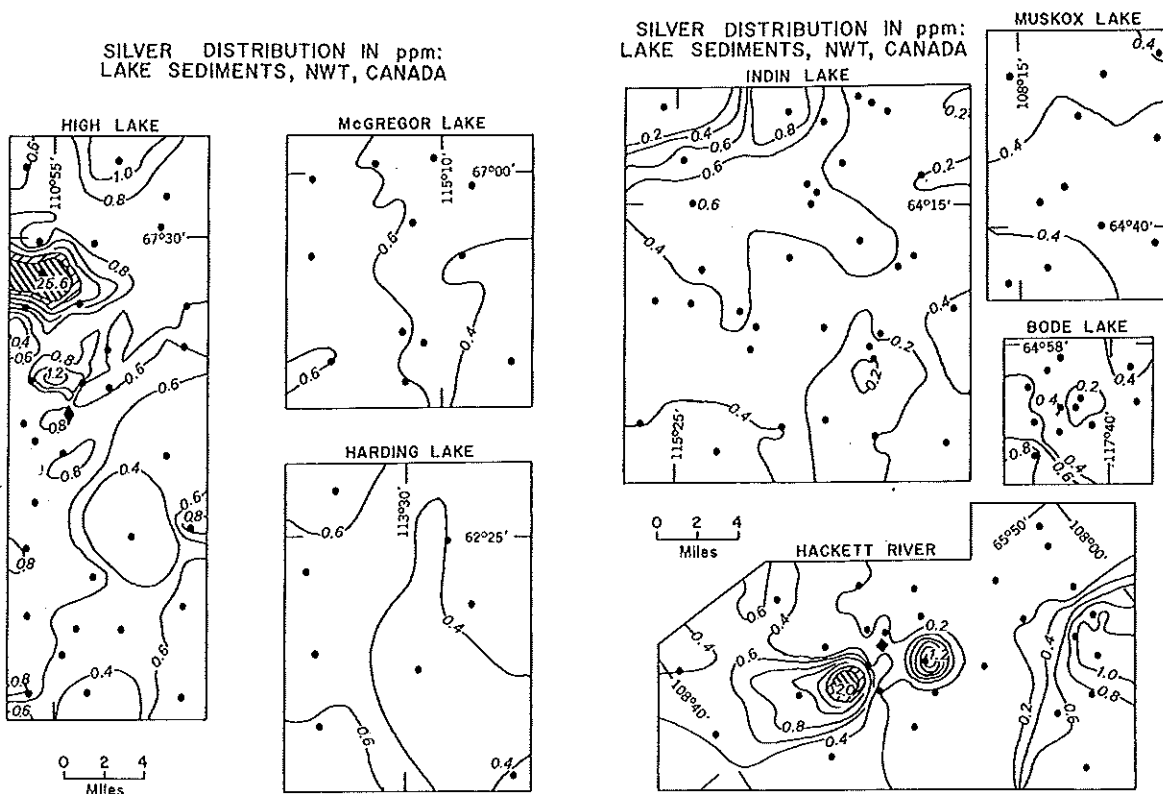


Fig. 15 Distribution of Ag in lake sediments of study areas

is largely underlain by silicic volcanic rocks and sediments that are poor in the base metals. The levels are also rather low at Harding Lake and Bode Lake, but higher at Muskox Lake, where there are a good deal of basic volcanic rocks. To what extent the moderately high Ni values at different points within the High Lake region are associated with sulphide mineralization is undecided, since the levels are rather higher than one might expect from the geology of the area.

Cobalt

The distribution patterns for Co (Fig. 14) are very similar to that for Ni. At McGregor Lake, however, the high Co values are more closely restricted to the area underlain by the ultrabasic Muskox Intrusion than are the high Ni values (Fig. 13). Again, at Hackett River, High Lake and Indin Lake the general pattern of Co anomalies parallels the Ni anomalies, and is presumably also caused by mineralization around a vent—at least for the first two examples. Away from the anomalous areas the distribution of Co closely follows that of Ni, being low in areas of acidic rocks and higher in areas of basic volcanics. Again, the Hackett River area has the lowest Co median, followed by Bode Lake and Harding Lake. As with Ni, the Muskox Lake area is intermediate in Co concentration.

Silver

The McGregor Lake, Harding Lake, Muskox Lake and Bode Lake areas have uniformly low Ag contents in their lake sediments (Fig. 15). In detail, such as at Indin Lake, the higher Ag values can be related to areas of basic rocks. There is no marked enhancement of Ag in lake sediments in the area of the Ag deposits at Terra mine (Table 6). The most striking areas in terms of Ag anomalies are Hackett River and High Lake. Two Ag values greater than 1 ppm were found in the former area. They are about five miles apart, straddling this Pb-Zn-Ag deposit. They stand out strongly against the low background of the silicic rocks of the surrounding area. These anomalies are clearly related to the massive sulphide mineralization of the Hackett River camp, and thus confirm the pattern given by the other elements. At High Lake there is an anomaly of the same magnitude immediately north of the location of the ore deposit. Farther north there is the unusually high value of 25.6 ppm Ag in iron-rich sediments taken from a lake that has a large gossan at its northern edge. This anomalous sample is listed in Table 5 rather than in the compilations given in Table 6. Zn and Cu are also

higher at this site, but not Ni and Co. Apart from these two anomalies, a number of other samples from High Lake have fairly high values in comparison with other areas. This is further evidence that this entire area is rather rich in base metals and, as such, is suitable for further prospecting.

Lead

The pattern of Pb distribution is very similar to that for Ag (Fig. 16). High Lake and Hackett River again provide most of the interest with a number of prominent anomalies. At High Lake the Fe- and Ag-rich sample is also enriched in Pb. There is a prominent Pb anomaly to the east of the deposit at High Lake and another in the south-east quadrant. At Hackett River there is a strong anomaly to the west of the deposit, in the same location as anomalies for Ag, Cu and Zn. Another, weaker, anomaly is close to the southeastern border of the area. This location contains anomalous levels of a number of other metals; it would appear to be worth further study. The background level of Pb in the lake sediments of the different areas corresponds well with the median values previously established for the rocks. Because there is very little difference in the Pb content of acid, intermediate or basic rocks, this element shows little contrast in its distribution across many areas, such as Indin Lake, Muskox Lake, McGregor Lake and Harding Lake.

Mercury

There are clear anomalies for Hg in the lake sediments from the Hackett River sites (Fig. 17). They flank either side of the ore deposit, and coincide with other base-metal anomalies. The higher value at the northwest site at Hackett River may be related to a rather higher content of free iron in this sample, which contains anomalous amounts of Cu, Zn, Co and Ni. At High Lake there are no Hg anomalies close to the ore deposit, but there are a number of others in different parts of the area, the origin of which is unknown. They are apparently close to the granite-greenstone contact (Figs. 10 and 17).

For the three areas in Slave Province where rock and lake sediment samples were collected there is good agreement in the background level of Hg measured in each material. For the Bode Lake and Terra mine areas the levels reached in the lake sediments are a good deal higher than those in the rocks. A possible explanation for this is that the rock sampling was restricted to igneous rocks or to tuffaceous sediments. Cameron and Jonasson¹² have shown that Aphebian shales from

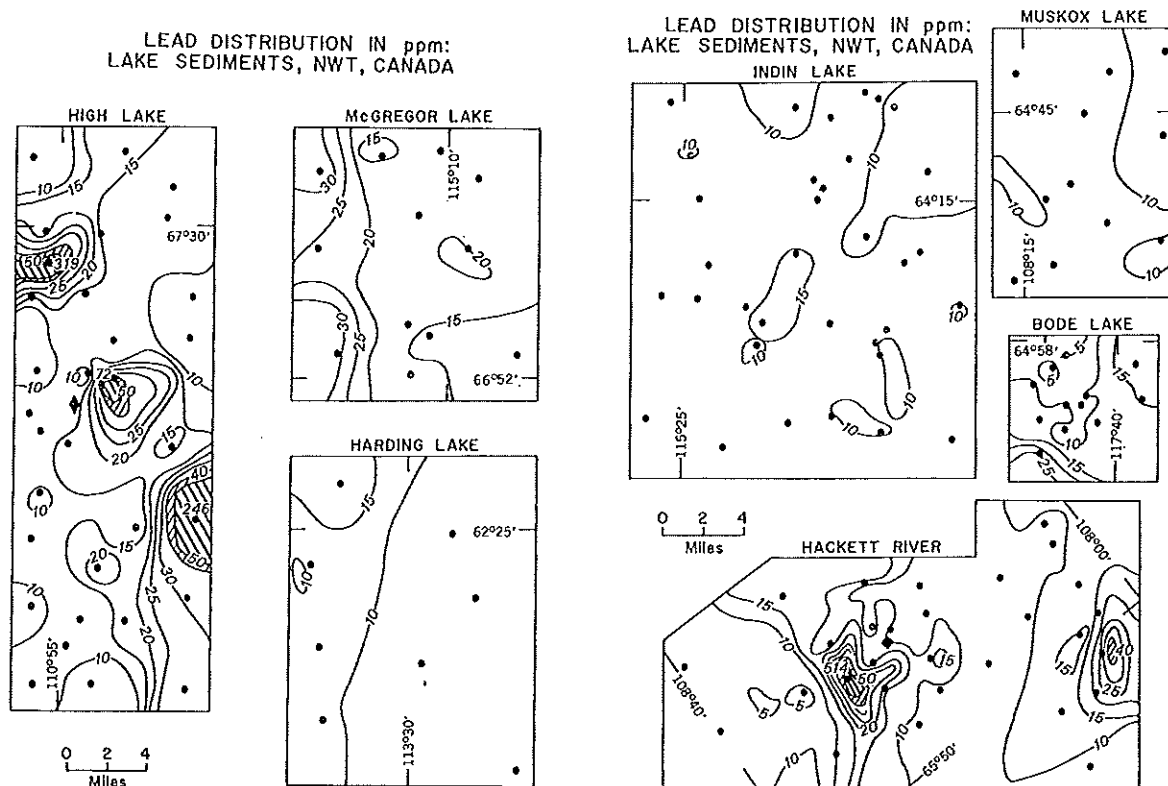


Fig. 16 Distribution of Pb in lake sediments of study areas

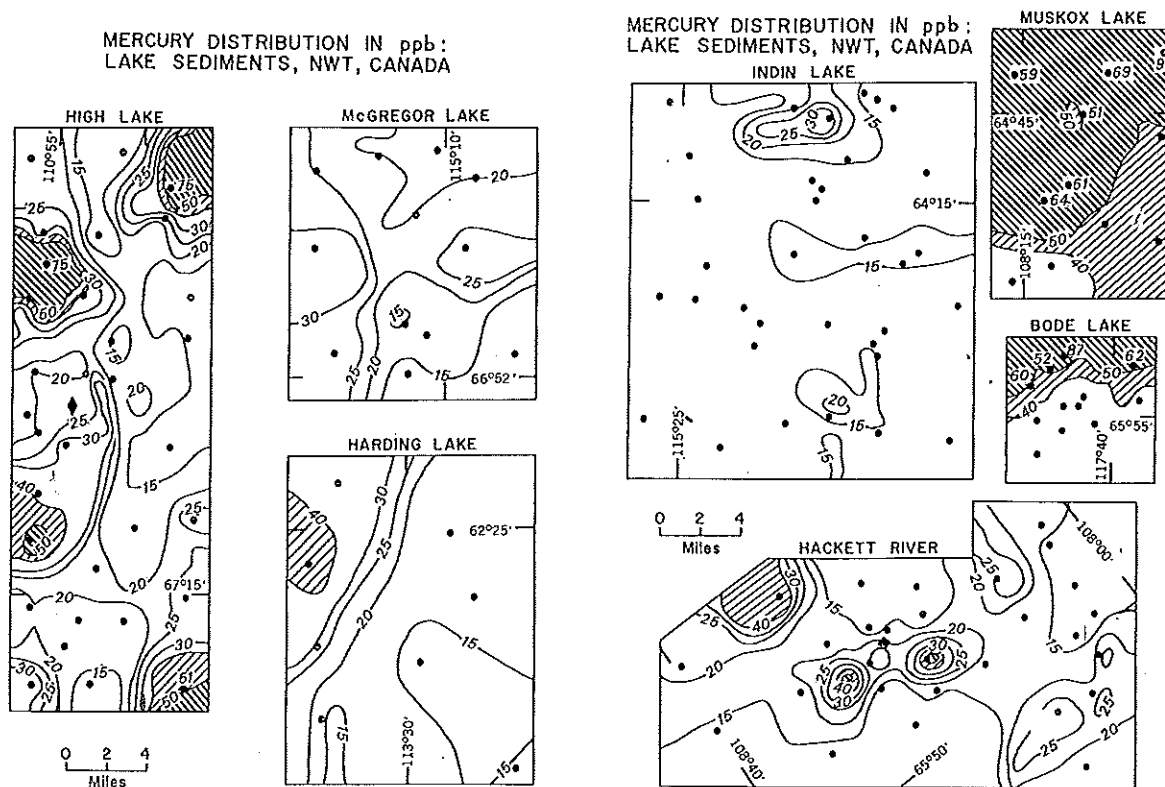


Fig. 17 Distribution of Hg in lake sediments of study areas

the southern part of the Shield have a notably higher level of Hg than do either Archaean or Phanerozoic shales and a very much higher content than igneous rocks; they attributed this to a greater degree of mantle degassing during the Proterozoic. It is possible that the Terra and Bode Lake areas contain Hg-rich sedimentary rocks of Aphebian age that contribute to the high content of this element in the lake sediments. The lake sediments at Muskox Lake have a uniformly higher level of Hg than those from any other part

of Zn. None of the waters from Bode Lake or from Harding Lake reaches these levels, and at Terra mine only four very scattered sites reached this minimum level, so these areas are not illustrated. The distribution patterns for Cu and Zn in the waters is quite similar to that of the lake sediments, although there are some obvious differences—the Hackett River deposit is very clearly outlined; the High Lake deposit rather less clearly at a lower level of metals. There are a number of other anomalies on the Hackett River (the one along

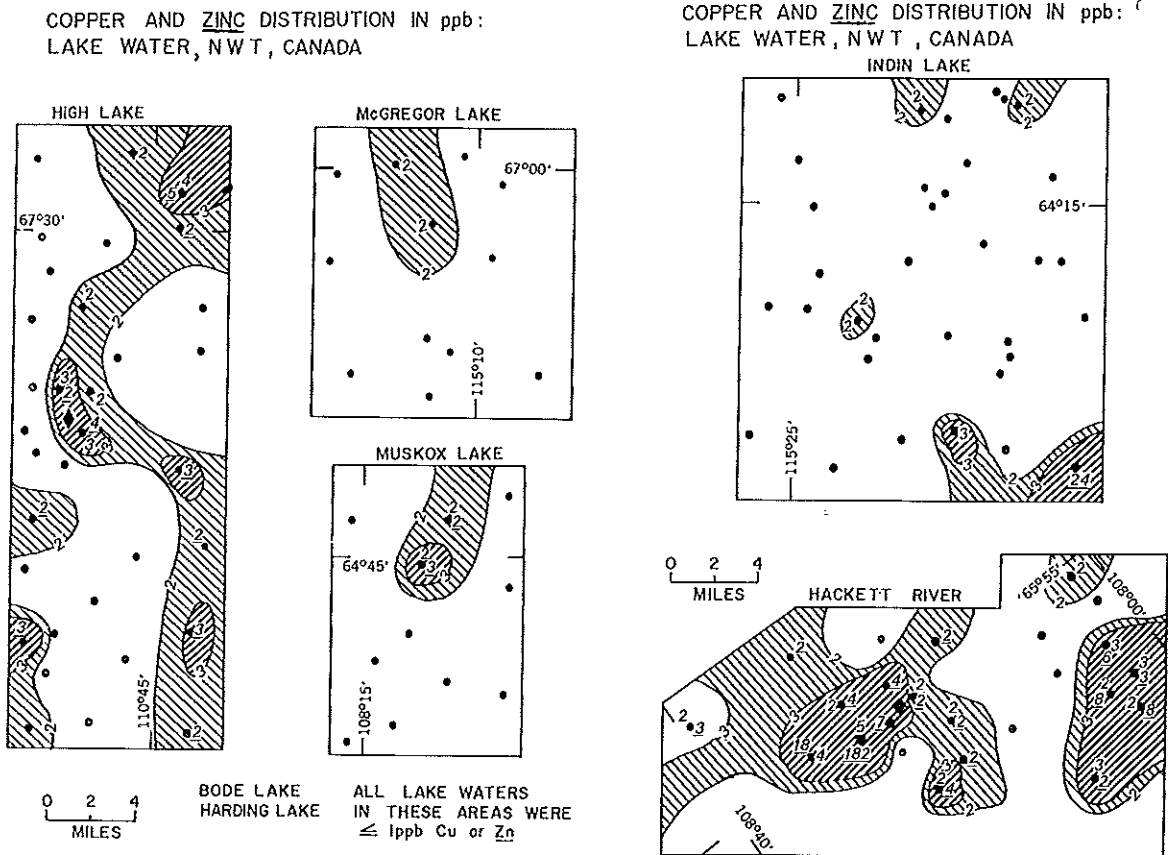


Fig. 18 Distribution of Cu and Zn in lake waters of study areas

of Slave Province. Presumably, this reflects a greater concentration of Hg in the Yellowknife Supergroup sedimentary rocks of this region than for the equivalent rocks in the other sampled areas, as the highest values are in the area underlain by such rocks (Fig. 10).

Trace-element composition of lake waters

Cu and Zn concentrations in lake waters from the sampled areas are shown in Fig. 18. Contours are drawn to enclose those areas where the waters contain 2 ppb and more of Cu or 3 ppb and more

the southeast margin of the map looks particularly interesting), High Lake, Muskox Lake and Indin Lake maps, where no deposits are known.

Water analyses give the promise of faster and cheaper geochemical surveys because it is much easier to obtain a water sample than it is to obtain a lake sediment sample. The ability to utilize waters as a sampling medium is, however, handicapped on two counts. First, present analytical methods have a limit of detection for the ore indicator elements that is close to or above the natural abundance of these metals in lake waters; more sensitive methods must be devised. Secondly, knowledge of the behaviour of trace metals in

lake waters of the Shield is virtually non-existent. Since it is believed that trace metals in waters are much more subject to seasonal and environmental influences than are the same metals within lake sediments, it is imperative that this information

Pb and Hg for the lake sediments and for the rock types of the different areas are compared. The geometric mean (and median) values are more stable to sampling imprecision than the arithmetic mean, particularly when the data are

Table 7 Comparison of geometric means for Zn, Cu, Pb and Hg in rocks and lake sediments

Area and sample material	Zn, ppm	Cu, ppm	Pb, ppm	Hg, ppb
<i>High Lake</i>				
Basic volcanics	80.1	40.6	12.7	8.5
Intermediate volcanics	65.8	31.6	10.3	9.3
Acid volcanics	80.5	25.0	11.7	10.2
Lake sediments	120.0	46.9	14.1	22.4
<i>Hackett River</i>				
Rocks	42.1	17.1	10.5	14.6
Lake sediments	50.5	24.7	11.9	17.4
<i>Indin Lake</i>				
Basic volcanics	39.8	80.8	7.6	7.4
Intermediate volcanics	38.4	10.3	7.1	11.1
Acid volcanics	21.4	5.0	6.5	13.0
Sedimentary rocks	76.4	34.8	12.9	9.8
Granites	65.5	21.1	10.3	3.3
Lake sediments	66.5	31.5	11.7	13.8
<i>Muskox Lake</i>				
Lake sediments	93.4	38.6	9.1	52.8
<i>Harding Lake</i>				
Lake sediments	49.0	23.6	9.0	21.7
<i>Bode Lake</i>				
Rocks	79.8	5.3	14.6	5.6
Lake sediments	51.4	19.8	10.7	42.2
<i>Terra mine</i>				
Rocks	74.0	10.7	15.7	6.9
Lake sediments	90.3	29.3	19.4	28.3
<i>McGregor Lake</i>				
Lake sediments	105.0	44.0	19.0	20.1

be available before lake water data can be properly interpreted. The cause of some of the anomalies shown in Fig. 18 must for the present remain unexplained; the more definite ones are probably related to mineralization, the others to environmental effects.

Summary of relationships between rocks and lake sediments for trace elements

Because the lake sediments have been shown to be relatively homogeneous within each area (Table 6), the samples obtained are probably representative of all lake sediments present within these areas. The same cannot be said for the rock data because of their relative inhomogeneity. In Table 7 the geometric mean values for Zn, Cu,

skewed, as they are for many of the rock populations.

Hg is consistently higher in the lake sediments than it is in the rocks. A possible explanation that might account, in part, for the enrichment of Hg in the sediments at Bode Lake and Terra mine has already been discussed, but it appears from the data in Table 7 that there may be a general tendency for Hg to be more abundant in lake sediments than in the surrounding rocks. Discounting possible analytical bias, which it is planned to investigate further, possible explanations for this difference are (1) that some of the Hg in the lake sediments did not come from the rocks but from the atmosphere, or through faults and fractures²⁶ in the crust; (2) that diagenetic or biological processes have concentrated the Hg near to the surface of the sediments of lakes; and (3) that

there is loss of Hg from near-surface rock samples.

Turning now to the other elements, Zn, Cu and Pb, for each of the areas containing significant mineral deposits—High Lake, Hackett River and Terra mine—the geometric mean content of each of these elements in the lake sediments is greater than that of any of the rock types measured in the same area. For the areas that are not known to contain large mineral deposits the reverse is more frequent: thus, at Indin Lake, one or more of the rock types contain a greater amount of these elements than do the lake sediments.

At Bode Lake, only Cu, perhaps significantly, has a higher geometric mean in lake sediments than in rocks. There are similar trends if the lake sediments of the Muskox Lake area are compared with the Indin Lake rocks, or if the Harding Lake sediment data are compared with the Indin Lake granitic rocks. Although the sampling methods have not been rigorous, and thus do not allow one to place statistical bounds of reliability on these differences, they do seem to be consistent. They are explained in the following terms.

In rocks intimately associated with mineral deposits there are at least two populations for each of the ore elements—the 'normal' rock population and the population due to micro-deposits of the ore minerals. This leads to a combined frequency distribution that is right skewed to a greater or lesser extent. The arithmetic mean of this population is often a good deal higher than the geometric mean or median. In the course of rock weathering and the processes of dispersion and, ultimately, sedimentation of these elements in lake bottoms, there is a general tendency to smooth the very irregular distribution that is characteristic of these elements in their host rock. In statistical terms there will be a tendency for the arithmetic mean and standard deviation of the ore element to decrease in a population of lake sediment samples and the median and geometric mean to increase relative to that of the original, unweathered rock population. The background level of abundance of an ore element, as defined by its geometric mean or median, will increase relative to the source rocks. All of these tendencies may be observed in the data presented here.

Even considering the above, the differences between the geometric means for Zn and Cu in the lake sediments at High Lake and the geometric means of these elements in the rocks are surprisingly high. Another general tendency should, therefore, be considered. This tendency is for the elements contained in sulphide masses to weather preferentially and be dispersed in the drainage system. At High Lake and Hackett River there are several visible gossans. It has been shown in permafrost areas of the U.S.S.R. that sulphide

zones are oxidized to considerable depth.^{29,31} In special cases this weathering may have been preglacial, as was proposed for the Norilsk deposit.⁴⁸ It is reported that in these areas of the U.S.S.R., due to the heat of the oxidation processes, these sulphides may form thawed zones in the permafrost, thus assisting in the processes of leaching and dispersing the elements of the sulphide masses. The presence of gossans, however, whether they be visible or concealed by vegetation or drift, is probably not critical to the development of anomalous metal values. Indeed, at Coppermine³ the area with the most visible gossans is not the area with the highest level of mineralization, as revealed by lake sediment analysis.

Conclusions

The -250-mesh fraction of inorganic sediments from lakes in the northern part of the Canadian Shield has been shown to be a homogeneous sampling medium that closely reflects the average composition of the surrounding bedrock. It provides a uniform material for the sorption of metal ions that are derived from ore deposits and from smaller, but more numerous, sulphide masses that are contained in the rocks around the ore deposits. By combining these two important characteristics of lake sediments it should be possible, in reconnaissance surveys, to outline simultaneously anomalies for the ore metals that are directly related to the ore deposits, together with other geochemical features associated with alteration zones and areas of favourable geology. Thus, for a typical Archaean massive sulphide ore deposit it may be possible to develop a hierarchical sequence of favourable geological-geochemical indicators on the basis of lake sediment analysis: (1) the occurrence of acid volcanic rocks; (2) within (1), zones underlain by exhalative facies rocks, such as carbonates and iron-rich sediments, that are related to the processes of ore deposition; (3) Mg or other alteration zones around the volcanic vent; and (4) anomalies of the ore metals.

The lake sediments are sufficiently homogeneous that the data derived from their analysis are eminently suitable for multivariate statistical treatment. In fact, the objective of geochemical mapping, as described in the preceding paragraph, is probably only completely attainable when such methods are employed. In a sequel to this paper an integrated statistical interpretation will be presented of the major- and trace-element data described here.

The methods of geochemical exploration and mapping described can probably be applied over

the 70% of the Shield that is underlain by continuous or discontinuous permafrost, and which, therefore, likely contains inorganic lake sediments. There remains 30% of the Shield that is outside the permafrost zone and is covered by thick forests. In this region trace metals in solution in the lakes may be scavenged by organic gyttjas and thus not reach the inorganic sediment. A programme of geochemical mapping and exploration over this region may require analysis of both organic and inorganic lake materials.

Analysis of lake waters provides a faster and cheaper method of geochemical exploration within the Shield than is possible with lake sediments. Before this can be realized, more sensitive analytical methods must be devised and a better understanding gained of the effects of seasonal and environmental influences on the trace-element contents of lake waters. Lake waters cannot, however, provide the broad range of opportunities provided by lake sediments for geochemical mapping of rock types.

One of the questions which remains largely unresolved is the optimum interval for lake sediment sampling within the Shield. The density of one sample per 10 square miles, which was used here and which will be again used in the survey of 40 000 square miles of the Bear and Slave geological provinces in the summer of 1972, is largely an arbitrary choice influenced by economic considerations. Previous studies of the lake sediment and bedrock chemistry of the Coppermine region showed that small ore masses and micro-deposits were so widely distributed and abundant in the rocks enclosing the Coppermine ores that a distinctive geochemical anomaly could be easily outlined at a sample density of one sample per 10 square miles. For the massive sulphide ore deposits at High Lake and Hackett River the distribution of micro-deposits and small sulphide masses is less widespread than at Coppermine. The evidence presented here has shown that this sample interval is still adequate for detecting areas of interest, and even the presence of massive sulphide ore deposits, in a greenstone belt. The sample density of one per 10 square miles is, however, no more than adequate, and where actual deposits are sought, rather than areas of interest, this density should be increased. Archaean massive sulphide deposits are probably one of the smallest base-metal targets in geochemical terms. For other types, particularly the large, low-grade, disseminated ores, a reconnaissance site density of one per 10 square miles should give very satisfactory results.

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