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Ontario Geological Survey
MAP 80 756
GEOCHEMICAL SERIES

Preliminary Studies of Lake Sediment Geochemistry in an Area Northeast of Sudbury

Sudbury and Temiskaming Districts

NTS References: 41 I/15; 41 P/2,7,10
ODM-GSC Aeromagnetic Maps: 284G, 1512G, 1513G, 1514G
ODM-OGS Geological Compilation Maps: 2221, 2419

"Much information on the distribution of chemical elements in rocks and their redistribution in the surface environment has been obtained as a result of progress in geochemistry, particularly during the last decade. Nevertheless, levels of trace elements and to a lesser extent those of major elements cannot be predicted reliably using geological maps."

J.A. Plant and R. Raiswell, *Applied Environmental Geochemistry*, p.36, edited by Ian Thornton, Academic Press, 1983.

INTRODUCTION

During the late 1970s the Ontario Geological Survey and the Geological Survey of Canada jointly completed a series of reconnaissance geochemical maps based on lake sediments and waters in the area along the northern shore of Lake Superior and further west. These maps (GSC-OGS 1978a, 1978b, 1979a, 1979b) included information on the pH of waters of some 4600 lakes.

In 1980 the Ontario Geological Survey commenced a research program aimed at the study of effects of "acid rain" on lakes to the north and east of Lake Superior with the general objective of relating the geochemical stratigraphy of deep basin lake sediments to the acid rain problem. This work was carried out by a team including a limnologist (M. Dickman, Professor, Brock University), a palynologist (J. Terasmae, Professor, Brock University) and geochemical staff of the Ontario Geological Survey (Fortescue *et al.* 1981, 1984). Briefly, by 1983 a method had been developed for the description of the pH history of lakes, which is based on detailed studies of the abundance of diatoms in the top 25 cm of lake sediment (Dickman and Fortescue 1984).

Prior to 1983, all of the studies by the team had been concerned with lakes located to the north and east of Lake Superior, especially around Wawa (Fortescue *et al.* 1981, 1984). In 1983 it was decided to test the methods that were developed around Wawa in a new area where different limnological and geochemical conditions were to be expected. The 1983 study was completed northeast of Sudbury where lakes known to have been affected by acid rain from the Sudbury smelters occur.

The team completed the field work during a 10-day period in late July and early August, 1983. Chemical analysis of the waters and lake sediment material were completed during the Winter of 1983/84. This broadsheet was compiled in the Summer of 1985.

OBJECTIVES

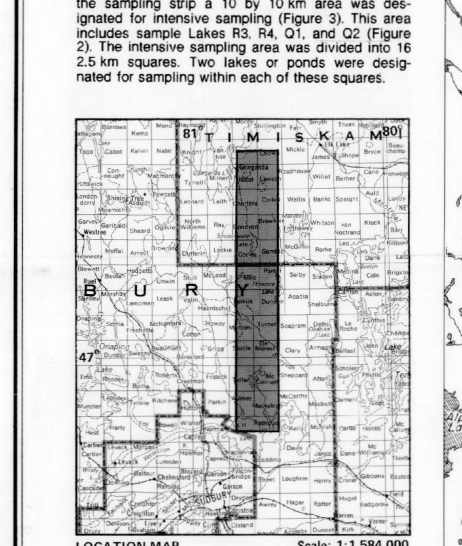
The project had the following objectives:

1. to complete a limnological/geochemical study of 40 lakes located in a 100 by 10 km sampling strip extending northward from Lake Wanapitei across the area affected by the fallout of chemicals from the plume from the Sudbury smelters in order to establish a working curve for future diatom-inferred pH measurements in the area and to establish the effects of the Sudbury smelter fallout on the geochemistry of surface midbasin lake sediments
2. to intensively study a 10 by 10 km area located within the sampling strip to establish a technique for regional geochemical sampling of lake sediments in the area affected by smelter fallout of trace elements
3. to draw conclusions from the limnological and geochemical studies concerning planning of future regional geochemical mapping in the area

METHODOLOGY

1. CHOICE OF STUDY AREA

The 10 km wide sampling strip extends 100 km north from the shore of Lake Wanapitei (Figure 1) and includes Frederick Lake, Solace Lake, Smoothwater Lake and across Highway 560 to Longpoint Lake (Figure 2). The area was located using the overprinted U.T.M. grid on 1:50 000 National Topographic Series maps and was subdivided into 10 by 10 km squares (i.e. micromodules, *see* Fortescue 1983). These were further subdivided into 5 by 5 km squares (micromodule quarters, *see* Fortescue 1984); within each micromodule quarter 1 lake was identified for study. The lakes are referred to by the code letters which are plotted on Figure 2. Within the sampling strip a 10 by 10 km area was designated for intensive sampling (Figure 3). This area includes sample Lakes R3, R4, Q1, and Q2 (Figure 2). The intensive sampling area was divided into 16 2.5 km squares. Two lakes or ponds were designated for sampling within each of these squares.



LOCATION MAP — Scale: 1:1 584 000 or 1 inch to 25 miles

Figure 1. Location of the area sampled. The extensive sampling area is highlighted.

Almost all of the sampling strip is underlain by the Gowganda Formation or the Lorrain Formation, both belonging to the Huronian Supergroup of Middle Precambrian age. The Gowganda Formation is a heterogeneous sequence of conglomerate, arkose, and wacke. The Lorrain Formation is a sandstone with local siltstone and quartz-pebble paraconglomerate beds (Dressler 1982). In general, the bedrock's contribution of elements to the lake sediments in the area was expected to be low. Consequently, if calcareous drift is absent in the area, then lakes that are low in nutrients (i.e. oligotrophic lakes) are likely to be common.

The area that was chosen for the intensive study is also within the Sudbury smelter plume. This should result in a lower pH of lakes due to acid rain fallout and which would also provide abnormal amounts of nickel and copper in the topmost lake sediment (i.e. Post-*Ambrosia*) material.

2. SAMPLING PROCEDURE

Similar limnological and geochemical sampling methods were applied to the sampling strip as a whole and to the lakes included in the area selected for detailed study. Within the sampling strip, field work was completed using a crew of 3 in a Bell 206 helicopter fitted with floats. Under favourable conditions, the team was able to sample up to 30 lakes per day.

At each lake sample point, the limnologist described the setting of the lake and the general nature of its waters. Observations of the pH, temperature, conductivity, and dissolved oxygen in the water column were made at 1 m intervals to the bottom of the lake using a special probe (Hydroprobe). Secchi disc depths were also taken. Sampling of the water was carried out using an integrating sampler to a depth of 5 m in deep lakes and from the surface in shallow lakes. One litre samples of water were collected from each lake. Lake sediment material was collected using an Ekman dredge to sample surface sediment.

The same procedure was used for the collection of samples and information from the area where detailed sampling was completed except that, instead of an Ekman sampler, a gravity sampler (developed by the Ontario Geological Survey) was used to obtain short cores (i.e. 30 to 50 cm long).

The pH of the water samples together with alkalinity was determined within 24 hours of collection in a laboratory set up at the base camp. After the intensive area sampling was completed, 2 long (about 50 cm) sediment cores were obtained from selected lakes for detailed diatom-inferred pH study.

3. SAMPLE PREPARATION

The remainder of the water sample was kept cool in a refrigerator and transported to the Geoscience Laboratories, Ontario Geological Survey, Toronto, where pH, sulphate, conductivity, calcium, and magnesium determinations were carried out. The Ekman dredge sediment samples were divided into 2 parts, one for diatom measurements and the other for geochemical analysis. The short core from the intensively studied area were kept cool and transported to Toronto for extrusion and sampling. In Toronto, the core was divided into a Pre-*Ambrosia* subsample (collected from a depth greater than 25 cm) and a Post-*Ambrosia* subsample (collected from a depth of 0 to 12 cm). The subsamples for chemical analysis were freeze-dried prior to being sent to the Geoscience Laboratories and other contracted laboratories.

4. CHEMICAL ANALYSIS

The Ekman samples were submitted to the Geoscience Laboratories, Ontario Geological Survey, Toronto, for trace element analysis for elements likely to be included in fallout from the smelters at Sudbury (i.e. nickel and copper) and other elements whose content in the sediment was expected to be normal (e.g. zirconium and niobium). The samples from the intensive study were sent for multielement analysis under contract by Barringer Magenta Limited, Toronto. In each case a reference standard mixture was prepared for quality control purposes. Subsamples of the mixture were submitted for analysis randomized within the batches of unknown samples and the data obtained from them tabulated to provide information on the performance of the analytical methods.

5. DATA PROCESSING

The results from the study of the diatoms in the Ekman samples were used by M. Dickman and his coworkers to prepare a working curve for the interpretation of diatom data. The curve was then used to interpret data from the 2 sediment cores from the area of detailed sampling.

The chemical data was tabulated. For comparative purposes relating to fallout from the smelter, nickel, copper, zirconium, and niobium data sets were transformed into Clarke Index-I units by a method described in detail elsewhere (Fortescue, in preparation). Briefly, the Clarke Index-I relates the content of an element in sediment to an estimate for the level of that element in the earth's crust as a whole. When geochemical data that is transformed in this way is plotted using a uniform format from element to element, *geochemical* comparisons can be made between element patterns based on the use of the Clarke Index-I as a datum. The use of the Clarke Index is of particular interest in geochemical mapping because it provides a datum for comparisons of patterns of elements (i.e. in lake sediments).

6. INTERPRETATION OF THE PATTERNS

The data obtained from limnology and geochemistry during the project are tabulated in full on this sheet for reference purposes. The results of the project that are pertinent to acid rain and geochemistry are written up under 2 headings; Limnology, and Geochemistry. At the end of this broadsheet some general conclusions are drawn regarding the planning of future regional geochemical surveys in the Sudbury area.

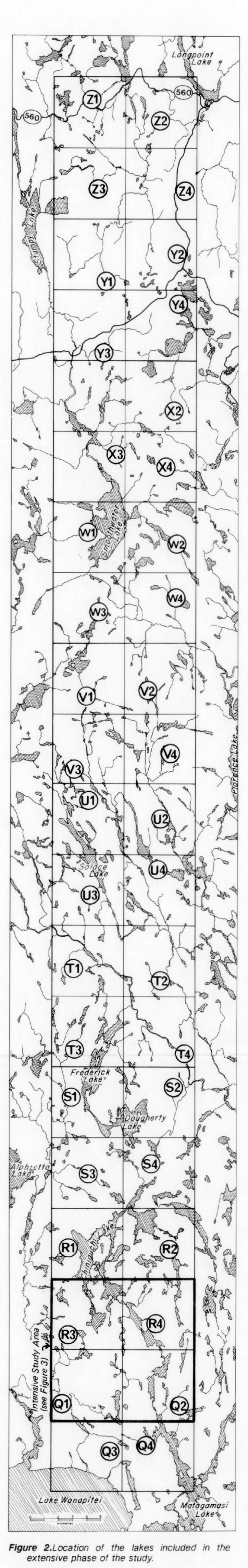


Figure 2. Location of the lakes included in the extensive phase of the study.

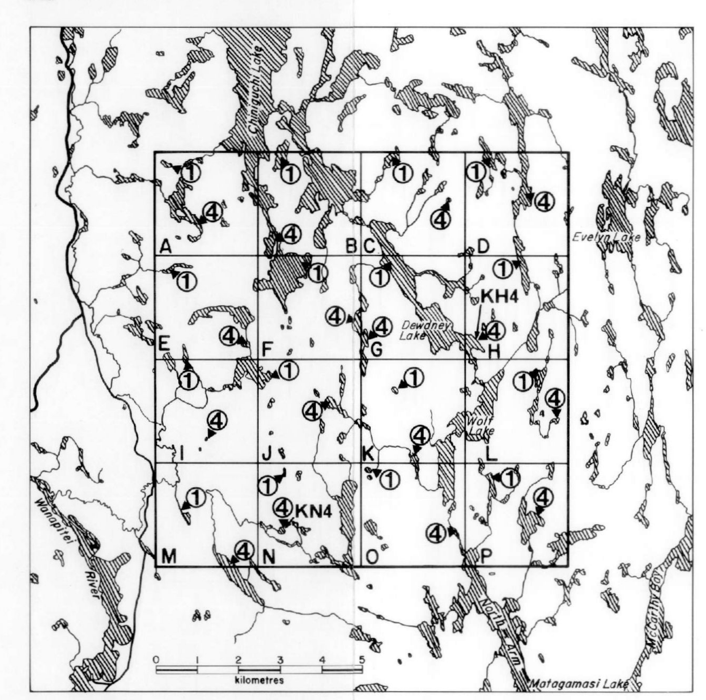


Figure 3. Location of the lakes and ponds included in the intensive phase of the study.

LIMNOLOGY

DIATOM-INFERRED pH

Section prepared by M. Dickman

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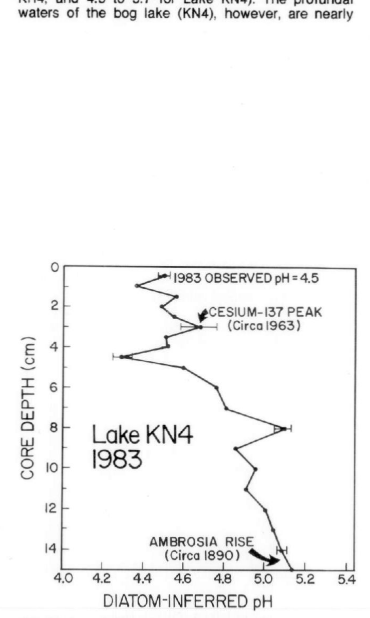

Figure 5. Downcore diatom-inferred pH for bog Lake KN4.

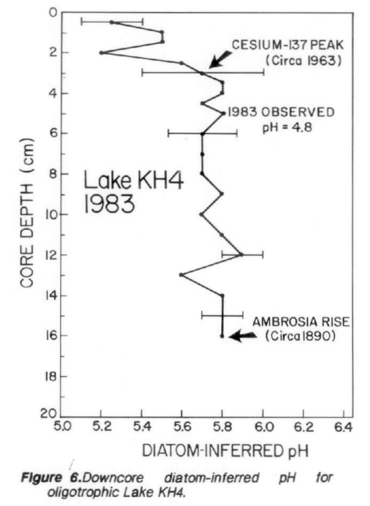

Figure 6. Downcore diatom-inferred pH for oligotrophic Lake KH4.

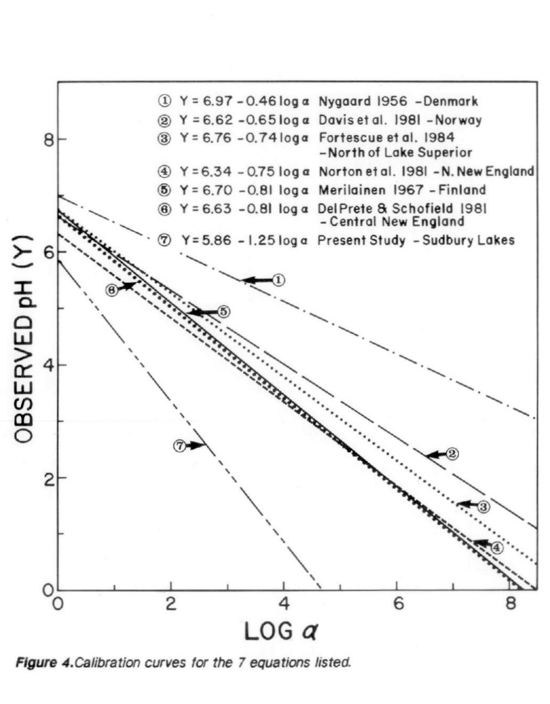

Figure 4. Calibration curves for the 7 equations listed.

Table 1. Data for the calibration of the Sudbury diatom-inferred pH curve for individual lakes along the sampling strip.

[illegible]

Table 2. List of diatom taxa identified in the surface sediments of Lakes KW1, KW2, KW3, and KW4.

[illegible]

Table 3. List of diatom taxa identified in the surface sediments of Lakes KS1, KS2, KS3, and KS4.

[illegible]

Table 4. Field data for 10 selected lakes, one in each micromodule sampling square.

[illegible]

GEOCHEMISTRY

LAKE WATERS

Data for the pH, sulphate, calcium, and magnesium content of the lake waters collected along the sampling strip are listed on Table 5. As expected, there is considerable variation in the pH of lake waters along the strip. The relatively high pH values for the Y and Z areas (Table 5) suggest that there has been a contribution of bases from the surficial material in this area. This is confirmed in the data for calcium and magnesium which are especially high in the waters of Lakes Y1 and Y2. Another indication of the effect of surficial material on pH and calcium/magnesium values occurs in areas S and T near the southern end of the sampling strip (Figure 2, Table 5). This example is more subtle than that described previously but shows up as mean values of 3.94 and 4.17 ppm for calcium in water compared with "background values" of around 2.5 ppm further north. Similarly, the magnesium for S and T lakes averages 1.01 and 1.11 ppm respectively which is also slightly higher than further north (Table 5). Although the method used for suphate determination in waters is close to the detection limit of 5 ppm, some patterns are observed in the data which suggest, but do not prove, that the effect of the smelters is at a maximum in areas U, V, and W (Figure 2, Table 5).

In summary, 19 of the 40 lakes sampled in the sampling strip were found to have a pH of less than 5.6 and are considered to be acid. A preliminary interpretation for the patterns of calcium and magnesium in the lake waters suggests that the overburden contributed these elements to the lake waters in significant amounts at the northern end of the strip where lush forest vegetation and glacial features were observed. In the south, a similar increase in calcium in Lake W1 is less well marked. The sulphate data suggests that the maximum input from fallout from the Sudbury smelter's plume is in the sampling strip from 45 to 65 km north of Lake Wanapitei.

Altogether 32 samples of lake water were collected from the intensive study area (Figure 3). For purposes of comparison, the data was divided into 2 subsets, (a) and (b) (Figure 7). The purpose of Figure 7 is to demonstrate to what extent data for pH of lakes collected in 2.5 km squares is reproducible. In the (a) series of sampling, 2 lakes with a pH greater than 4.9 are found in squares B4 and M1 (Figure 3). In the (b) series of lakes only 1 lake (B1) has a pH greater than 4.9. The lakes in the detailed study area are found to be very acid, which might be expected in an area where the bedrock is low in nutrients and there is a lack of calcareous surficial cover.

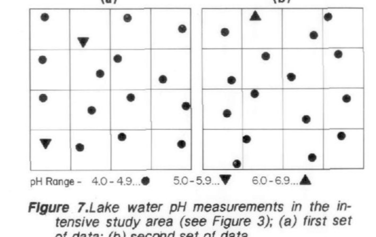

Figure 7. Lake water pH measurements in the intensive study area (see Figure 3); (a) first set of data, (b) second set of data.

[illegible]

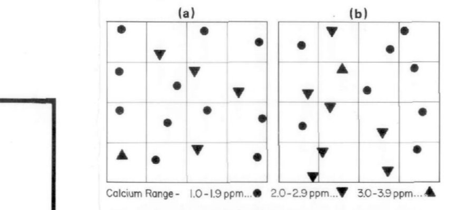

Figure 8. Lake water calcium content in the intensive study area (see Figure 3); (a) first set of data, (b) second set of data.

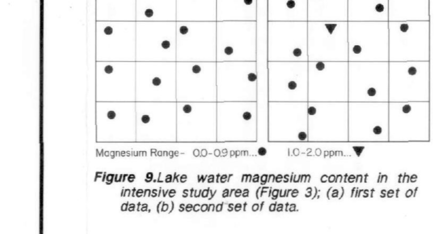

Figure 9. Lake water magnesium content in the intensive study area (see Figure 3); (a) first set of data, (b) second set of data.

Table 5. pH, sulphate, calcium, and magnesium of waters from the 40 lakes in the sampling strip. For an explanation of the code letters see Figure 2 (from Fortescue 1983).

Area	Distance From Lake Wanapitei (km)	Lake 1	Lake 2	Lake 3	Lake 4	Mean
		pH				
Q	5	6.1	4.5	4.6	5.8	5.3
R	15	4.3	4.3	4.5	4.4	4.4
S	25	6.4	6.0	4.7	6.5	5.9
T	35	5.7	5.9	5.3	6.4	5.8
U	45	5.7	5.7	4.7	5.7	5.5
V	55	4.6	5.0	5.4	4.3	4.8
W	65	5.7	4.8	6.1	4.9	5.4
X	75	5.4	4.6	5.8	4.5	5.1
Y	85	7.6	8.3	6.4	4.6	6.7
Z	95	6.8	6.3	6.6	6.6	6.6
		Sulphate (ppm)				
Q	5	8	7	9	9	8
R	15	7	7	10	9	8
S	25	8	11	9	6	9
T	35	11	8	10	5	9
U	45	7	11	13	10	10
V	55	10	11	12	8	10
W	65	10	N.D.*	10	9	10
X	75	9	8	8	8	8
Y	85	7	10	6	5	7
Z	95	10	8	10	9	9
		Calcium (ppm)				
Q	5	3.99	2.08	3.04	3.51	3.16
R	15	1.63	1.57	2.07	1.83	1.78
S	25	4.00	4.80	2.31	4.66	3.94
T	35	3.36	4.14	3.12	6.06	4.17
U	45	2.41	2.97	2.54	2.51	2.61
V	55	1.87	2.43	2.77	1.59	2.17
W	65	2.88	2.09	3.06	2.44	2.61
X	75	2.85	1.92	2.58	1.55	2.23
Y	85	15.02	17.26	3.16	1.34	9.20
Z	95	6.55	4.44	5.59	6.54	5.78
		Magnesium (ppm)				
Q	5	0.75	0.71	0.73	1.12	0.83
R	15	0.53	0.56	0.66	0.60	0.59
S	25	1.06	0.98	0.74	1.24	1.01
T	35	0.88	0.98	0.78	1.80	1.11
U	45	0.75	0.90	0.79	0.85	0.82
V	55	0.60	0.83	0.90	0.46	0.70
W	65	0.93	0.72	1.03	0.74	0.86
X	75	0.89	0.58	0.90	0.49	0.72
Y	85	3.71	3.14	0.88	0.40	2.03
Z	95	1.21	1.29	1.55	1.71	1.44

* = Not Detected

Table 6. The content of 20 elements in 10 replicates of a standard composite mixture of Ekman material included in the batch of unknowns for quality control (in ppm).

[illegible]

Table 7. Data for the 20 elements in Ekman dredge samples from the sampling strip (in ppm).

[illegible]

LAKE SEDIMENTS

The lake sediment collected with the Ekman dredge is considered to be material laid down in Post-*Ambrosia* time and, as a consequence, includes the natural level of elements plus material derived from atmospheric fallout from smelters. For this reason the multielement chemical analysis package chosen for these samples included elements such as copper and nickel likely to be enhanced in the samples due to atmospheric fallout as well as other elements (eg. zirconium, niobium, lanthanum, and yttrium) which are present in significant amounts in the lake sediment but not expected to increase significantly due to smelter fallout. The former group can be considered "signal elements" and the latter "control elements".

The performance of the analytical method used for the Ekman samples is summarized in Table 6 where data for 20 elements are listed. Because there is considerable noise in these data, it is believed that the mixture was inhomogeneous. For this reason these data should be considered as a first approximation only for the performance of the analytical methods employed. Note that the data for yttrium, niobium, and lanthanum in the mixture are relatively precise compared with other elements listed.

The data for the 20 elements in the Ekman samples taken from the sampling strip (Figure 2) are listed in full in Table 7. Data for selected elements (i.e. Ni, Cu, Nb, and Zr) are plotted on Figure 10 using the Clarke Index-I transform. Averaged pH data for the lakes of interest are also included in the figure.

The aim of Figure 10 is to focus attention on the enhancement of nickel and copper in the lake sediment collected relatively close to the Sudbury smelters compared with the level of these elements in normal sediment collected further north. The plot of the curves for the elements niobium and zirconium is used as a control. It is concluded that both nickel and copper decrease with increasing distance from the smelters, this effect being most marked in the first 35 km from the margin of Lake Wanapitei (Figure 10). Unlike nickel and copper, niobium and zirconium are relatively uniform in concentration in the lake sediment along the whole sampling strip. The pH curve for lake waters indicates no direct relationship between water pH and nickel and copper in the sediment although there is a pH high in the area of Lake Y2 associated with calcium in surficial material as discussed above. The full element data listing for the Ekman samples appear in Table 7 and are not further discussed here.

It is desirable to remove the effects of fallout of trace elements from the atmosphere from data collected for regional geochemical surveys. In order to accomplish this it is necessary to separate the "Pre-" (i.e. uncontaminated) *Ambrosia* sediment from the "Post-" (contaminated) *Ambrosia* sediment material. This is accomplished simply by using a sediment core sampler and extruding the cores obtained to a different depth for each sample type. Consequently, the sediment cores which were collected from the intensive study area were inverted and extruded in 2 stages. The first stage removed all material obtained deeper than 20 cm (i.e. Pre-*Ambrosia* material) and the second all material from 0 to 12 cm in depth (i.e. Post-*Ambrosia* material). The transitional material was combined and used for the quality control reference samples as described above. Samples of Pre- and Post-*Ambrosia* material, plus replicates of the quality control mixture, were analyzed under contract by Barringer Magenta Limited, Toronto, for 13 elements using a multielement technique of instrumental analysis. In this experiment special care was taken to mix the reference standard material well prior to sampling. Data for the quality control samples are listed in Table 8 and indicate that the performance of the analytical procedure for all elements is satisfactory.

The first experiment on the intensive study geochemical data was to determine if the Pre- and Post-*Ambrosia* data for nickel and copper was similar, or different, from that for elements not considered to be present in the atmospheric fallout (i.e. zirconium and titanium). Data for the Pre- and Post-*Ambrosia* levels in the samples collected during the intensive survey are plotted on Figure 11. If the same content of an element is present in the Pre-*Ambrosia* material as in the and Post-*Ambrosia* material, then the pattern for the elements would be like that for zirconium and titanium with the points clustered along the 45° slope line. In the case of nickel and copper there is a cluster of points at the upper left side of the graph which indicates that many samples are enriched in these elements in Post-*Ambrosia* material. [illegible]

[illegible] scan sheet (Fortescue 1970, in preparation) displays the geochemical patterns to advantage for comparative purposes. Consequently the plots for the detailed study area data have been set up using these criteria (Figure 12).

The scan sheet (Figure 12) provides detailed information on the distribution and concentration of 13 elements in 20 samples of Pre-*Ambrosia* lake sediment taken from the area selected for detailed study. The data are presented on a series of small squares, each representing the area, arranged in rows and columns. By reading across a row, one can see the distribution patterns for elements within the same range of Clarke Index-I values. By reading down a column, one can see the distribution patterns for the same element at different concentration levels.

The intensive study area (Figure 3) is underlain largely by rocks of the Gowganda and Lorrain Formations, which are known to be siliceous and generally low in most elements. An examination of the geochemical patterns on Figure 12 confirms that the Clarke Index-I levels of most elements in the sediments are low and exhibit a random nature to many of their patterns. This distribution of elements would be expected in lake sediments in an area of uniform bedrock geology with little surficial cover. This is in marked contrast to geochemical patterns observed in lake sediments obtained in other areas (*see* Fortescue, in preparation) where variations in the bedrock lithology and chemical composition of the surficial cover give rise to strong geochemical patterns in lake sediment data.

A close inspection of Figure 12 reveals some apparent development of geochemical gradients (Figure 13) for some elements. For example, magnesium increases from southwest to northeast and this trend may also be seen for titanium, zirconium, and chromium. The strontium pattern suggests that this element is relatively low in the western and southern margins of the area compared with the central portion. The copper patterns are interpreted to indicate that higher values occur in the southwest than in the northeast of the area. The patterns for other elements (including calcium, lead, nickel, manganese, zinc, cobalt, and iron) are generally random over the whole area.

In summary, two experiments were completed on the geochemical data from the area where the intensive study was made. The first experiment established that atmospheric fallout had, in fact, affected many of the lake sediments in the area. The results for nickel and copper to the southwest were particularly high when compared with the calcium and magnesium levels which were unaffected by the fallout. The second experiment was concerned with the geochemical patterns in the Pre-*Ambrosia* geochemical data. Owing to the uniformity of the bedrock conditions and the general lack of calcareous drift in the area there are few recognizable patterns of distribution for individual elements although a few weak patterns are identified and discussed.

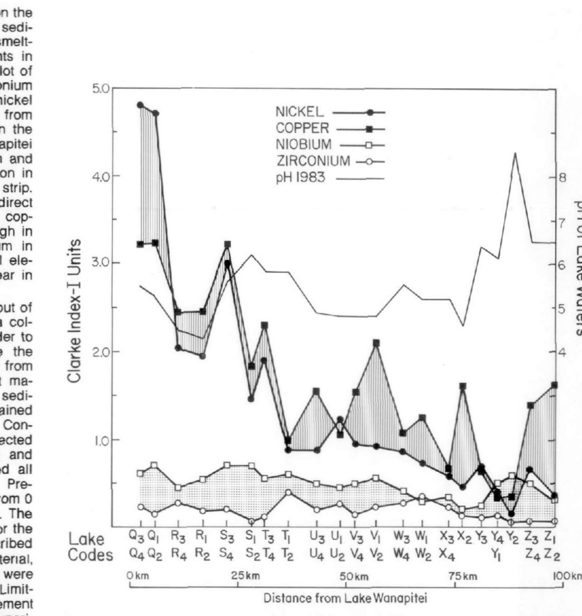

Figure 10. Graph of the level of 4 elements in Ekman (Post-Ambrosia) lake sediment collected from selected lakes along the sampling strip (see Figure 2).

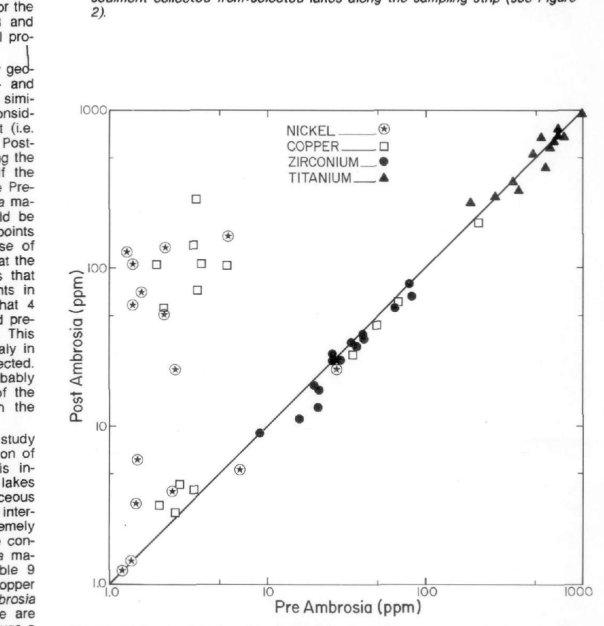

Figure 11. Graph showing the distribution of nickel, copper, titanium, and zirconium in Pre- and Post-Ambrosia lake sediment collected from the intensive study area (see Figure 3).

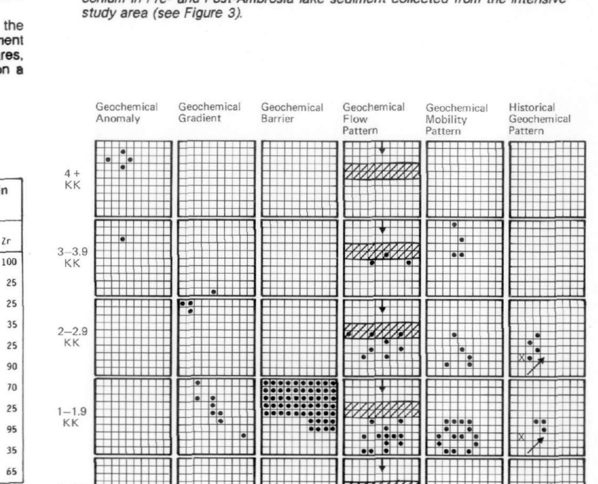

Figure 13. Conceptual models for 6 common regional geochemical patterns based on the concepts of landscape geochemistry.

Table 8. The content of 13 elements in 8 subsamples of a composite mixture of lake sediment randomized in the batch of unknowns from the detailed study area (in ppm).

Replicate	Ca	Mg	Fe	Mn	Ti	Zr	Sr	Ni	Cu	Pb	Cr	Co	Zn
[illegible]	9090	2430	14700	211	800	44	73.9	39	50.1	13	39	14	94
[illegible]	9310	2620	14000	223	920	49	66.1	38	49.5	10	37	14	86
[illegible]	9910	2740	14400	223	918	49	82.3	38	49.5	13	63	21	91
[illegible]	9400	2640	13800	213	911	48	74.8	35	47.6	12	36	14	97
[illegible]	9390	2670	14100	220	889	48	83.1	34	49.4	11	38	18	95
[illegible]	8820	2550	13500	215	884	46	69.4	38	48.6	13	36	11	90
[illegible]	8930	2650	13800	216	933	48	67.4	40	47.8	11	40	25	87
[illegible]	8890	2550	13200	215	890	46	79.0	37	47.8	11	37	21	79

Table 9. Data for 13 elements in samples from the intensive study area (in ppm). Note that samples preceded by a "P" (eg. PKA1) indicate Pre-Ambrosia material, while those without the P (eg. KA1) are Post-Ambrosia material.

Sample	Ca	Mg	Fe	Mn	Ti	Zr	Sr	Ni	Cu	Pb	Cr	Co	Zn
[illegible]	[illegible]	948	2180	30.9	530	26	35.3	22	20.3	5	26	7	71
[illegible]	[illegible]	1950	8760	174.0	911	53	62.4	15	21.2	4	37	12	43
[illegible]	[illegible]	1980	11400	169.0	685	40	60.1	14	20.5	1	30	7	65
[illegible]	[illegible]	2740	52600	281.0	1050	51	64.9	232	235	48	53	35	229
[illegible]	[illegible]	1440	7470	122.0	699	40	41.6	14	38.1	3	42	9	58
[illegible]	[illegible]	1270	8960	145.0	715	34	59.3	13	29.0	5	41	6	36
[illegible]	[illegible]	1470	9880	144.0	750	36	54.4	14	28.1	5	41	5	60
[illegible]	[illegible]	1040	8060	76.0	495	21	45.8	13	55.9	2	28	2	69
[illegible]	[illegible]	1210	4600	126.0	622	37	53.8	15	24.3	6	24	12	27
[illegible]	[illegible]	3550	17900	157.0	1380	88	124.0	59	62.0	30	42	37	49
[illegible]	[illegible]	2080	19300	248.0	996	63	65.5	25	35.4	2	46	14	90
[illegible]	[illegible]	3110	38400	430.0	1320	79	92.2	66	71.9	29	57	24	127
[illegible]	[illegible]	2200	17200	186.0	1040	67	90.0	36	31.1	7	51	13	74
[illegible]	[illegible]	3450	18000	197.0	1160	81	109.0	15	11.5	5	34	42	41
[illegible]	[illegible]	4040	26700	388.0	1610	96	119.0	17	14.4	2	53	19	55
[illegible]	[illegible]	629	1890	22.6	395	16	25.9	15	49.0	2	22	4	11
[illegible]	[illegible]	1140	13800	84.7	405	13	33.0	10	39.4	<1	16	2	220
[illegible]	[illegible]	1040	11000	157.0	607	27	54.7	18	40.5	4	38	8	121
[illegible]	[illegible]	1340	5650	96.1	597	21	54.3	12	35.1	1	18	6	98
[illegible]	[illegible]	1070	8220	50.4	531	25	36.2	127	113.0	30	23	28	61
[illegible]	[illegible]	1300	8050	88.8	628	28	52.1	273	225.0	72	33	22	113
[illegible]	[illegible]	1030	5830	47.1	565	24	34.7	172	177.0	50	28	19	204
[illegible]	[illegible]	630	2100	54.2	194	9	34.0	26	36.1	7	15	9	29
[illegible]	[illegible]	3230	23400	224.0	1430	77	98.5	279	215.0	51	51	73	174
[illegible]	[illegible]	651	1530	44.1	276	18	25.0	18	36.0	3	19	14	52
[illegible]	[illegible]	742	103000	870.0	253	14	23.0	18	34.3	<1	37	10	60
[illegible]	[illegible]	715	2180	50.0	364	18	33.8	22	38.4	2	22	9	27
[illegible]	[illegible]	5300	32800	267.0	1850	86	116.0	155	146.0	120	67	33	169
[illegible]	[illegible]	1350	11500	153.0	687	34	39.4	55	33.9	9	41	35	85
[illegible]	[illegible]	1210	16400	117.0	560	26	45.4	243	270.0	110	42	19	120
[illegible]	[illegible]	982	3830	51.1	669	28	49.0	133	105.0	38	36	12	59
[illegible]	[illegible]	1870	10300	148.0	867	49	63.2	34	25.7	6	35	17	58
[illegible]	[illegible]	1930	8200	112.0	633	38	70.8	59	32.6	5	27	10	104
[illegible]	[illegible]	1390	5990	75.0	757	36	36.2	104	107.0	29	36	11	117
[illegible]	[illegible]	1320	8550	167.0	683	32	63.9	14	26.6	8	37	7	32
[illegible]	[illegible]	872	16000	44.5	512	17	25.3	125	112.0	46	27	11	84
[illegible]	[illegible]	1350	6150	111.0	703	45	63.5	40	42.6	16	25	17	42
[illegible]	[illegible]	2000	19700	204.0	975	58	65.0	39	39.3	6	55	17	97
[illegible]	[illegible]	3190	38000	495.0	1250	79	102.0	54	58.6	21	53	31	128
[illegible]	[illegible]	2330	21800	149.0	1080	70	83.1	92	61.9	22	50	19	116
[illegible]	[illegible]	2790	18100	139.0	922	67	101.0	61	54.6	18	31	34	66
[illegible]	[illegible]	4520	22700	313.0	1600	105	147.0	31	23.5	16	57	13	68
[illegible]	[illegible]	613	2310	43.8	305	11	27.4	33	43.3	12	17	6	35
[illegible]	[illegible]	1270	9640	90.6	330	12	35.4	14	44.7	<1	13	<1	134
[illegible]	[illegible]	1010	10900	161.0	571	25	55.4	26	46.0	8	36	7	60
[illegible]	[illegible]	933	4530	113.0	434	13	49.1	12	28.4	2	18	3	57
[illegible]	[illegible]	1240	7280	87.6	583	26	52.7	229	185.0	69	54	17	88
[illegible]	[illegible]	837	2360	118.0	260	10	36.8	239	207.0	67	20	12	54
[illegible]	[illegible]	571	2000	60.8	278	18	26.7	70	70.1	12	18	13	33
[illegible]	[illegible]	655	107000	1370.0	267	20	15.3	7	29.1	<1	32	8	55
[illegible]	[illegible]	697	3100	60.1	359	17	31.7	50	41.7	8	20	9	38
[illegible]	[illegible]	1240	10800	81.8	671	34	36.5	155	140.0	41	40	33	131
[illegible]	[illegible]	1190	16300	117.0	525	24	43.4	254	272.0	100	37	17	155

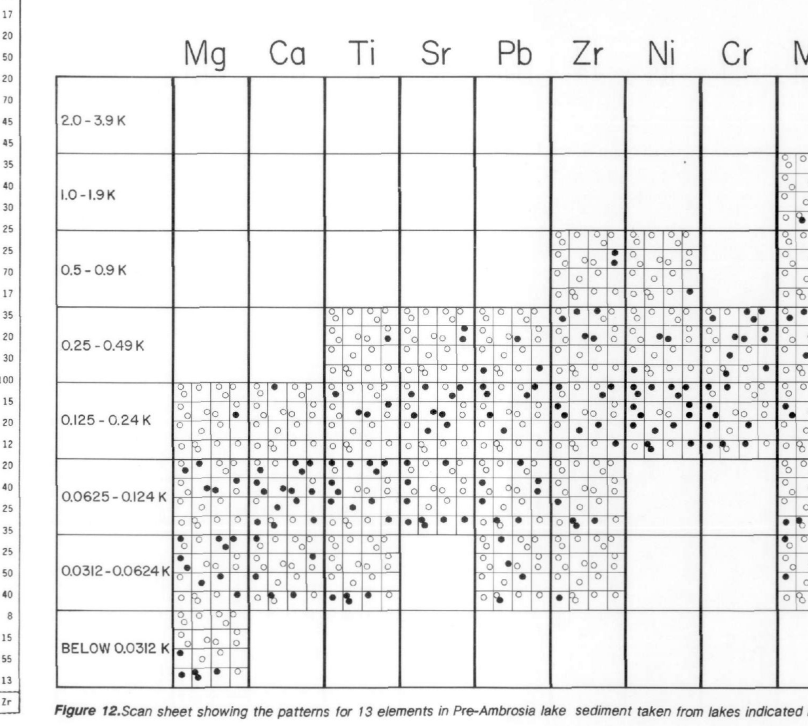

Figure 12. Scan sheet showing the patterns for 13 elements in Pre-Ambrosia lake sediment taken from lakes indicated in Figure 3.

GENERAL SUMMARY AND CONCLUSIONS

The two studies described on this broadsheet together provide information which is essential during the planning of future regional geochemical surveys in the Sudbury area. The study of the 100 km sampling strip focused attention on the different lake types found in the area and demonstrated that a special working curve is required for the establishment of diatom-inferred pH curves for lakes in the Sudbury area. In particular, the Sudbury diatom-inferred pH working curve has a different curve slope from that for the curve developed previously in the Wawa area (*see* Fortescue *et al.* 1984).

Both of the diatom-inferred sediment core curves obtained from the Sudbury area were of particular interest. One curve (for Lake KN4) provides an excellent example of the pH history of the humic pond which was accumulating acidity in both Pre- and Post-*Ambrosia* time at a steady rate. The second curve (for Lake KH4) provides information on the pH history of a lake which was naturally nearly acid prior to 1962 when it commenced to acidify quite rapidly, probably due to acid rain.

The curve for the pH of lakewaters collected from the sampling strip was also of interest because of the relationship between geology and reaction of lake waters. Because the bedrock which underlies the sampling strip is largely metasedimentary which is low in calcium (i.e. quartzites and sandstones etc.) variations in pH of lake water towards the more basic condition found in the sampling strip are thought to be due to local accumulations of calcium carbonate in glacial drift. In the small area which was studied intensively, the effect of such calcium carbonate was considered minimal, resulting in lakewaters with a consistantly low pH.

The study of lake bottom sediments collected from lakes studied in the sampling strip revealed two kinds of geochemical patterns in their data. One kind, typified by niobium and zirconium, shows a relatively uniform content along the length of the sampling strip and may be considered as a control. The other kind of pattern, typified by nickel and copper, is due to fallout of the chemicals derived from the smelter, resulting in a clearly defined geochemical gradient from south to north along the sampling strip (i.e. away from the smelters).

The intensive study area is located near the southern end of the sampling strip closest to the smelters. The analysis of Pre- and Post-*Ambrosia* lake sediment material from the 32 lakes in this area for nickel and copper indicates the uniformity of the effects of fallout of these elements in the 10 by 10 km area studied. It also focuses attention on the need for collection and chemical analysis of both Pre- and Post-*Ambrosia* sediment during future regional geochemical surveys in the area in order to distinguish levels of nickel and copper which are enhanced naturally from those due to smelter activity. A more general interpretation of all elements included in the study of lake sediments from the 10 by 10 km area indicates that the levels for most elements are low using the Clarke Index-I scale. Within the small test area there is some evidence of geochemical gradients which are not considered to be very significant.

CONCLUSIONS

The following general conclusions are drawn from this study:

1. The limnology of lakes in the Sudbury region is complex and varied due in part to the paucity of nutrient elements in the bedrock and in part to the fallout effects of the material derived from Sudbury smelters.
2. In order to prepare diatom-inferred pH data curves from lake sediment cores collected in the Sudbury region it is necessary to use a different calibration curve from that used in the Wawa area.
3. There are at least two types of acid lakes in the Sudbury area: (a) the humic lakes which have been increasing in acidity since Pre-*Ambrosia* time; and (b) lakes affected by acid rain, which have increased sharply in acidity since 1963.
4. The fallout of nickel and copper (and, possibly, other elements) from the atmosphere as a result of the Sudbury smelter activity is detectable in Post-*Ambrosia* lake sediment material collected from lakes situated downwind from the smelters.
5. In any future regional geochemical surveying in the Sudbury area two types of geochemical map should be included. One type would show the amount and distribution of elements in sediments laid down prior to 1890 (i.e. in Pre-*Ambrosia* time) and the other would show the patterns for the same elements in sediment laid down subsequent to the commencement of smelting in the area.
6. The area to the north of Lake Wanapitei, which is underlain by rocks of the Gowganda and Lorrain Formations, includes many acid lakes whose sediment is very low in calcium and other elements in Pre-*Ambrosia* time.

The conclusions which are listed above for the research described here are broadly similar to conclusions drawn by many workers who have studied in detail the limnology and geochemistry of lakes in the Sudbury area. A convenient starting point to this existant information is found in Pinché (1982) who discuss the effects of smelter fallout on lakes in the area and provide a list of references to earlier investigations of the problem. Space does not allow for a discussion of information provided on Sudbury area lakes by others in relation to the data on this broadsheet.

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CREDITS

Compiled by J.A.C. Fortescue, 1985.

Technical editing and layout by J.R. Webb, 1985.

Issued 1985

Information from this publication may be quoted if credit is given. It is recommended that reference to this map be made in the following form:

Fortescue, J.A.C.
1985: Preliminary Studies of Lake Sediment Geochemistry in an Area Northeast of Sudbury, Sudbury and Temiskaming Districts; Ontario Geological Survey, Map 80 756 Geochemical Series. Compiled 1985.