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EXPLORATION GEOCHEMISTRY OF QUATERNARY DEPOSITS IN NORTHWESTERN KOOCHICHING COUNTY, MINNESOTA

Minnesota Department of Natural Resources
Division of Minerals
Minerals Exploration Section

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I. INTRODUCTION

Much of northwestern Koochiching and northeastern Lake of the Woods Counties are underlain by felsic to mafic Lower Precambrian metavolcanic rocks (Ojakangas, 1972). Early prospecting was conducted in this region, but intensive exploration for volcanogenic massive sulfide deposits did not commence until 1967 and has continued in varying degrees to the present. The exploration for massive sulfide deposits has not resulted in the discovery of a mineable deposit, although significant amounts of zinc were drilled on the Smart property (Figure 1). Showings of copper and zinc have been encountered in several other localities throughout the region.

The Division of Minerals of the Minnesota Department of Natural Resources has the responsibility for the administration of the approximate ten million acres of state controlled mineral lands. This responsibility includes the administration of state mineral leases. To date, over 40,000 acres of state controlled mineral lands have been leased in the region shown on Figure 1. These leases were issued to four companies. All of these leases are now terminated.

It is also the responsibility of the Division of Minerals to assess the mineral potential of state controlled mineral lands. By 1972, the mining company exploration had diminished considerably in this region, but the Division of Minerals considered the geologic

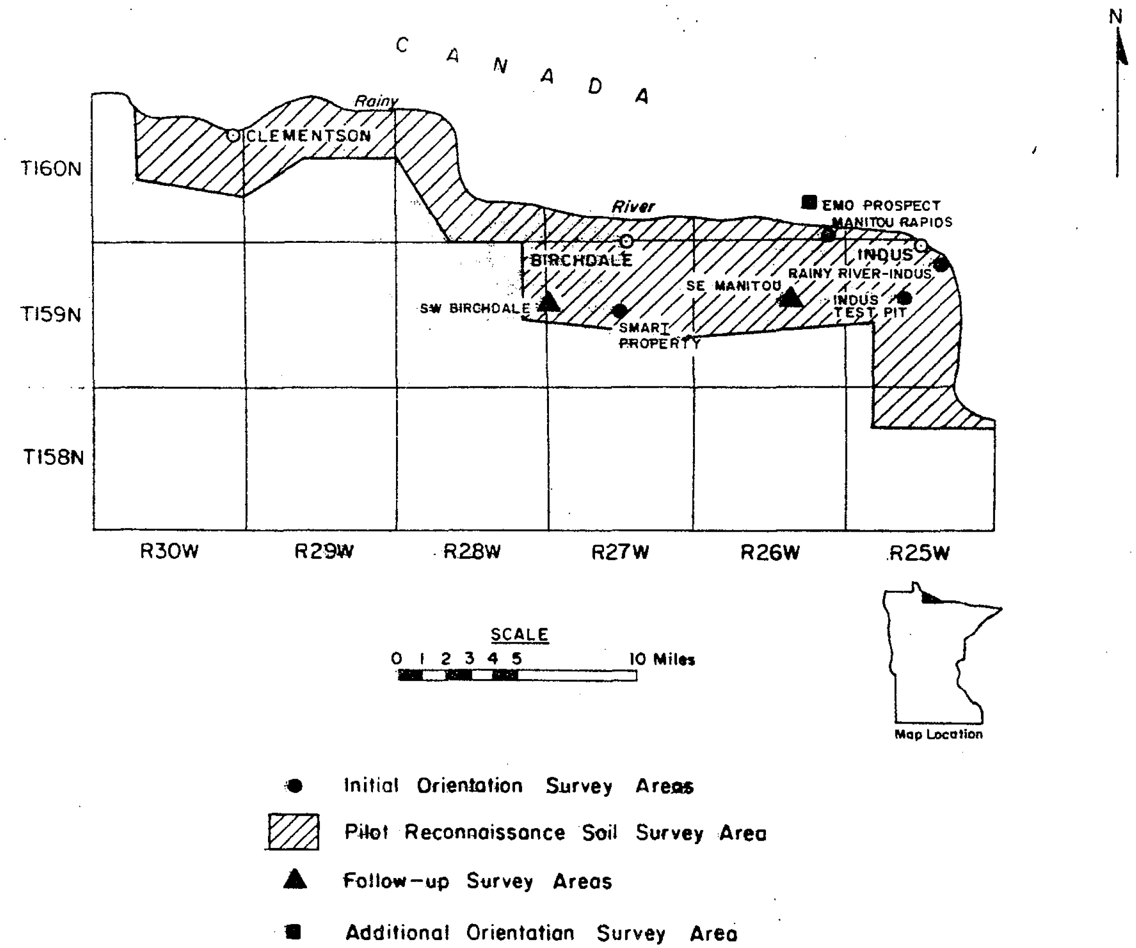

FIGURE 1: Map showing location of geochemical surveys in northwestern Koochiching and northeastern Lake of the Woods Counties, Minnesota

environment favorable for the occurrence of economic sulfide deposits. As a result, it was decided to conduct surveys to evaluate the mineral potential of state controlled mineral lands in this region.

The mining companies had conducted airborne electromagnetic and magnetic surveys. They followed up these surveys with ground geophysics and drilled some of the most promising conductors. Due to the extensive geophysical surveys that had been done, the Division of Minerals decided to attempt to utilize the chemical properties of the Quaternary deposits of the region as a means of generally delineating potential areas, in combination with existing geologic and geophysical data.

Geochemical exploration methods are not applicable in all glacial terrains and are especially questionable in this region where the glacial drift is predominantly a clayey till. Therefore, it was necessary to conduct orientation studies in order to determine if mineralization was reflected in the Quaternary deposits.

During the summer of 1972 the orientation studies were completed with results indicating limited success. However, it was decided to conduct a pilot reconnaissance soil survey during the summer of 1973 (Figure 1). The results of this survey indicated some anomalous areas, two of which were followed up with detailed sampling. In 1974, it was decided to conduct an additional orientation study on another mineralized area near Emo, Ontario. As a result of limited success with geochemical methods in the region, it was decided to discontinue any major effort in the area until a new approach to the problem could be developed. However, several interesting anomalies were located by the geochemical surveys which deserve further consideration.

The results of these geochemical surveys are mainly presented in written form in this report. A considerable number of maps, profiles and charts have been prepared from these surveys which are available for examination at the Division of Minerals, Minnesota Department of Natural Resources, Hibbing, Minnesota.

II. QUATERNARY GEOLOGY

The terrain of the region is generally of low relief with isolated mounds of outcrop. More than 95% of the region is covered by Quaternary deposits which attain a thickness of over 175 feet in the southern portion (Figure 1). The Quaternary deposits generally thicken southward. These deposits unconformably overlie the Precambrian bedrock.

Matsch (1973) conducted a reconnaissance survey of the Quaternary geology in this region. The findings of this survey are summarized in cross-section (Figure 2). The cross-section is taken on an approximate north-south line extending from the Rainy River south. See Figure 1 for the location of the Rainy River.

The remaining observable direct effects of glaciation are the result of two glacial lobes of the late Wisconsin period of glaciation: The first was the Rainy Lobe, which moved from a northeasterly direction and the St. Louis Sublobe, which came from the west and northwest and overrode the Rainy Lobe deposits (Matsch, 1973). This period of glaciation ended about 10,000 years ago.

The only observed deposits of the Rainy Lobe is the glacial outwash shown on Figure 2. This outwash is bouldery and composed of granite, mafic igneous rocks and graywacke (Matsch, 1973). Although further investigations would be necessary to determine the western most advance of the Rainy Lobe, roches moutonées with a Rainy Lobe ice-direction have been observed as far west as SW Birchdale (Figure 1). Therefore, Rainy Lobe till may also exist in this region.

The St. Louis Sublobe extended northward to approximately 18 miles north of the town of Indus (Figure 1) and eastward to 22 miles east of the town of Indus (Matsch). The Indus Formation (Figure 2) is an informal

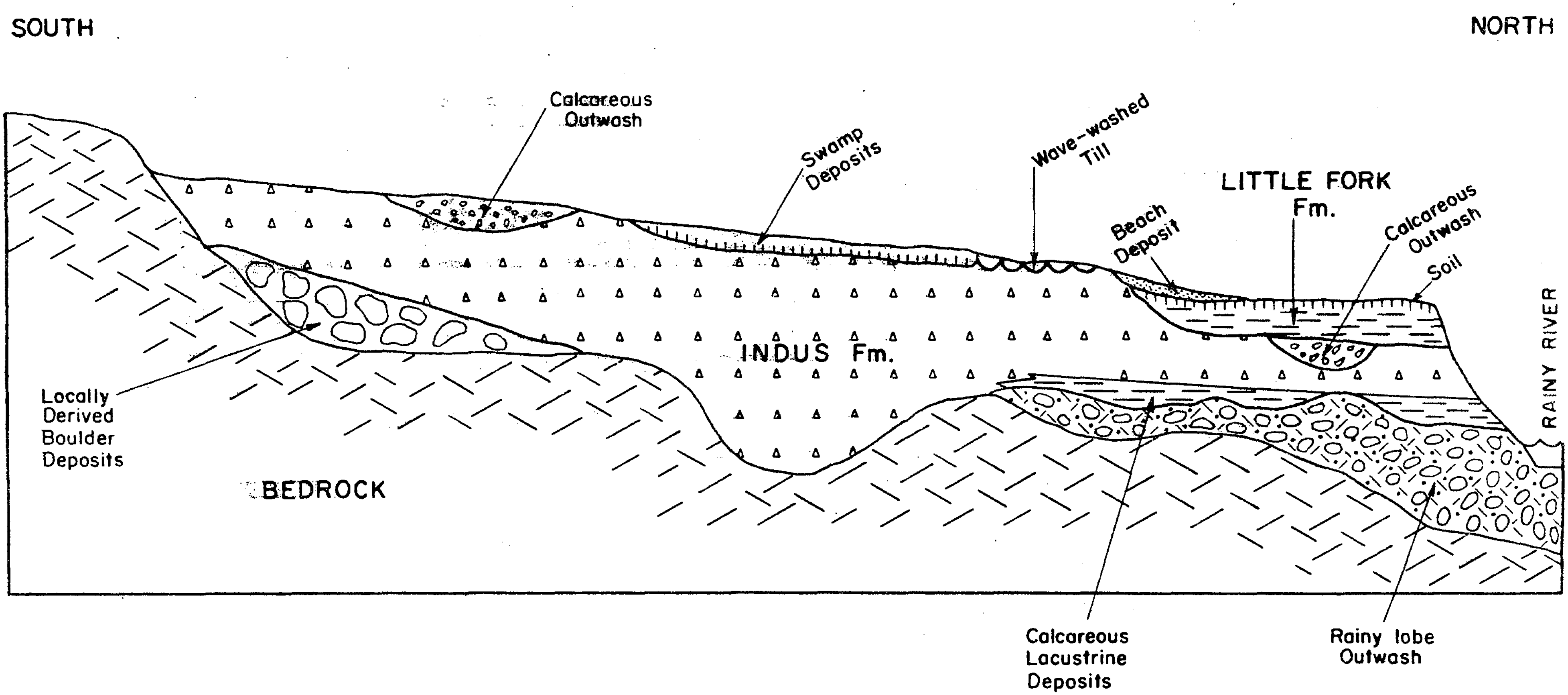

FIGURE 2: Generalized Cross-Section of Northern Koochiching County. (Not to scale) (From Matsch, 1973)

rock-stratigraphic name assigned to the St. Louis Sublobe till by Matsch (1973). This till is composed of silt and clay with mainly carbonate and granite pebbles (Matsch, 1973). The carbonate pebbles originate from Paleozoic rocks to the west and northwest (Matsch, 1973). This till has been oxidized to depths up to ten feet. Locally derived boulder deposits are known, from drilling, to occur near the base of the Indus Formation (Figure 2).

Drilling of the Indus Formation at the Indus Test Pit and at SW Birchdale (Figure 1) indicated an increase in the frequency of angular, locally derived, rock fragments near the bedrock surface. Also, weathered sulfides were found in the unoxidized till overlying a massive sulfide zone at the Indus Test Pit.

At the Emo Prospect (Figure 1) a large gabbroic intrusive has been mapped. An examination of the Indus Formation overlying the gabbro indicated that less than one percent of the pebbles and boulders represented this gabbroic intrusive. Granite and carbonate rocks were the predominant clast type.

In several areas, the Indus Formation has been found to be nearly devoid of clasts.

Two sets of glacial striations are found in the region. The striations resulting from the Rainy Lobe have a bearing of S30° to 60°W and those from the St. Louis Sublobe have a bearing of S70°E to due east. Well developed roches moutonées were observed throughout the region with the same general bearing as indicated for the Rainy Lobe striations. Roches moutonées developed by the St. Louis Sublobe are conspicuously absent. Near the Emo Prospect, an extensive outcrop area has well developed Rainy Lobe striations and roches moutonées, but the only imprint left by the St. Louis Sublobe is striations crosscutting those of the Rainy Lobe.

Matsch (1973) has interpreted the origin of the Indus Formation as the result of mixing of a sandy textured till from the west with silt and clay calcareous lacustrine sediments formed by a proglacial lake formed in front of the advancing glacier. The calcareous lacustrine deposits are illustrated on Figure 2.

In places, the St. Louis Sublobe, as indicated by the Indus Formation, advanced over the lacustrine deposits and Rainy Lobe outwash with little deformation of either.

Based on the above evidence it has been concluded that the Rainy Lobe was an eroding glacier, and, generally, the St. Louis Sublobe was not. As a result, much of the Indus Formation is probably ablation till composed of proglacial lake sediments, detritus of remote origin, and probably includes deposits from the Rainy Lobe. Locally, however, a lodgement (basal) till is present, at least south of the Rainy River, as evidenced by the locally derived angular clasts near the bottom of the Indus Formation in some areas.

Calcareous outwash formed by the St. Louis Sublobe is known to occur at several localities in the region (Figure 2)(Matsch, 1973).

The Little Fork Formation (Figure 2) is an informal rock-stratigraphic name assigned to a variable thickness of thin bedded calcareous silt, clay, and fine sand that is interpreted to be a lacustrine sediment by Matsch (1973). This sediment is generally found at elevations less than 1,125 feet (Matsch, 1973). Matsch (1973) has interpreted this formation to be sediment deposited in Glacial Lake Agassiz.

On Figure 2 a wave-washed till is shown which, according to Matsch (1973), represents the beaches and shoreline of Glacial Lake Agassiz. The maximum elevation of the wave-washed till is at approximately 1,150 feet (Matsch, 1973). The wave-washed till generally follows strand lines which are evident on the topographic maps and have resulted in a concentration of boulders at the surface due to the wave action removing finer sediments. Beach deposits (Figure 2) consisting of a sorted sand were encountered during the geochemical surveys.

Extensive organic-rich swamps are associated with poorly drained, low-relief terrain below elevations of about 1,150 feet (Matsch, 1973). Generally, the sediments in these swamps grade vertically from plant detritus, to peat, to organic-rich silt, to fine silt and clay within ten feet of the surface (Matsch, 1973).

Eng has suggested from his air photo interpretations of the region that stagnant ice of the Rainy Lobe may have been overthrust by the advance of the St. Louis Sublobe. If this occurred, Eng further suggests that much of the topography observed in this region today may be the result of the melting of Rainy Lobe stagnant ice after deposition of the Indus Formation and possibly even the Little Fork Formation.

Much still remains to be learned about the glacial geology of this region; however, the information presented here enables the construction of a model which can be used for geochemical exploration studies.

III. RELATION OF QUATERNARY GEOLOGY TO THE APPLICATION OF GEOCHEMICAL METHODS

Generally, soil geochemical exploration methods are readily applicable in residual soils. Where residual soils have been developed by weathering of the parent bedrock, mineralization of the bedrock is usually also reflected in the residual soil and stream sediments of the area. In continentally glaciated terrain, however, the glacial drift is not always representative of the underlying bedrock. As a result, the first consideration for any geochemical exploration program in continental glacial terrain must be the Quaternary geology.

Till is usually the most representative of local bedrock of all glacially derived materials. An advancing glacier may incorporate in it material from the underlying bedrock which then is mechanically dispersed in a down-ice direction. This mechanical dispersion can enable detection of mineralization in the bedrock, if the mineralization is located at the bedrock surface. Mechanical dispersion can only take place when a glacier is eroding and is usually well reflected in the lodgement (basal) till. Ablation till, on the other hand, is usually of more remote origin in comparison to the lodgement till and, as a result, does not contain the amount of mechanically derived local bedrock found in lodgement till. Furthermore, due to glacial mixing, the amount of locally derived material decreases upward in the till section and down-ice direction. As a result, mineralization may not be detected by geochemical methods which sample the till at the ground surface if the till is very thick.

In addition to mechanical dispersion, hydromorphic dispersion of metal ions may take place if the till is permeable and satisfactory chemical conditions exist.

From the previous section on Quaternary geology, the St. Louis Sublobe generally appears to have been a non-eroding glacier, composed mainly of detritus of remote origin. However, in some localities it appears that the Indus Formation is representative of underlying bedrock to some degree. Also, the Indus Formation is generally impermeable and the carbonate content of the till is high. Therefore, hydromorphic migration of metal ions is greatly restricted.

The calcareous outwash of the St. Louis Sublobe and the Rainy Lobe Outwash (Figure 2), as with any glacial outwash, generally is of remote origin. Hydromorphic migration of metal ions from a bedrock source could occur in the non-calcareous Rainy Lobe Outwash, but would be greatly impeded by the high carbonate content of the St. Louis Sublobe Outwash.

The beach deposits and the Little Fork Formation deposited in a very large lake (Glacial Lake Agassiz) would not be expected to reflect mineralization. These deposits resulted mainly from sorting of the Indus Formation.

The swamp deposits in the region generally owe their trace element content to the Indus Formation, but because of the chemical complexities were generally regarded as an undesirable geochemical sample media at this time. As is later described in this report, the geochemical contrast in the Indus Formation is very small and, therefore, it was concluded that a geochemical threshold would be indistinguishable from the erratic metal values usually observed in peat. However, where mineralization exists very near to the ground surface, limited hydromorphic transport may give a recognizable geochemical contrast in some swamp deposits.

Stream sediments were also considered to be an undesirable geochemical exploration sample media, mainly because they are derived from the Indus Formation and dilution of anomalous with background materials had probably resulted but were tested with some success at the Emo Prospect. Where the stream bed is very close to mineralization, anomalous values may result from hydromorphic dispersion, or even from mechanical derivation of mineralized material.

It was concluded that the Indus Formation was a poor geochemical exploration sample media, but the best for the region. Because of the scarcity of locally derived bedrock material, the lodgement (basal) till may be the only reasonable sample media. However, as described in Section II, the St. Louis Sublobe in some cases overrode pre-existing glacial deposits and, therefore, even the lodgement till would not reflect underlying bedrock.

IV. INITIAL ORIENTATION SURVEYS

Four areas were selected for the initial orientation surveys (Figure 1). The objective of these surveys was: (1) to determine the variation of trace element concentrations vertically in the Indus Formation, especially in the basal till, and (2) to test surface soil sampling methods. The results of these surveys are summarized below.

All soil and till samples, unless otherwise specified in this report, were dried, broken up and screened to -80 mesh. The -80 mesh sample was digested in concentrated HF, HCl and HNO_3, and then diluted for atomic absorption analysis.

A. Smart Property

At the Myron Smart property, a 2½ foot intersection of 4% zinc had been drilled (Listerud, 1976). This is the best known economic type mineralization on the Minnesota side of the Rainy River in this region. The assumption was made that this zinc-rich zone extended to the bedrock surface. Available geologic information was used to project the assumed suboutcrop location of the mineralization. The estimated depth to bedrock is in the range of 20 to 30 feet.

1. Till Sampling

Two types of drilling were used to obtain a vertical profile of the till down-ice direction and over mineralization: (1) Iwan post hole auger operated by hand, and (2) split tube power driven sampler. These results are summarized below.

Seven holes were drilled with the Iwan Auger. These holes ranged in depth from 5 to 15 feet. All seven holes were terminated due to auger refusal on boulders.

Nickel, cobalt and copper were generally constant in the vertical section. Zinc displayed occasional erratic high values, and in three holes tended to increase down the hole. The concentration range and 50% cumulative value for the metals analyzed are given below in Table 1. All metals except zinc had an approximate monomodal lognormal distribution. Zinc was bimodal, which may indicate that the higher concentration mode represents zinc related to the mineralization.

TABLE 1: Statistics for Iwan Auger samples - Smart Property (in ppm)

Metal	Range	50% Cumulative Value
Co	9- 66	43
Cu	12- 47	26
Ni	25-118	64
Zn	36-300	61
Mn	292-740	410

The coefficient of correlation was determined between several of the metals (Table 2). The only significant correlations obtained were Co/Mn and Cu/Zn with a slight correlation for Cu/Mn.

TABLE 2: Coefficients of correlation for Iwan Auger samples - Smart Property

	Co	Cu	Ni	Zn	Mn
Co	1			-0.12	
Cu	-0.04	1		0.57	
Ni	-0.04	-0.24	1		
Mn	0.46	0.20	0	0.12	1

In order to normalize the effect of coprecipitation and scavenging of trace metals by Fe-Mn hydroxides, the trace metal/Mn ratios were determined for the Iwan Auger samples (Table 3).

TABLE 3: Manganese ratios for Iwan Auger samples - Smart Property

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	2- 17	10	10	33
100(Cu/Mn)	3- 12	8	7	30
100(Ni/Mn)	7- 34	20	15	33
100(Zn/Mn)	8- 79	44	18	57

The Co/Mn, Cu/Mn and Ni/Mn were generally constant in the vertical section. Zn/Mn displayed occasional erratic high values similar in contrast to the zinc concentrations for the Iwan Auger samples.

Four holes were drilled with the power driven Split Tube sampler which provided a less disturbed sample. These holes ranged in depth from 16 to 34 feet. All four holes were terminated because they encountered a large granite boulder deposit which apparently lies immediately above the bedrock. As a result, basal till samples could not be obtained.

All metals analyzed, except zinc, were nearly constant down the hole. Zinc tended to be more erratic than other metals, but not to the degree observed in the Iwan Auger holes. In one hole, zinc was consistently higher in the unoxidized till as compared to the oxidized till. This drilling indicated an increase in copper and zinc in two holes drilled toward the western part of the area as compared to those drilled in the eastern part of the area.

The concentration range and 50% cumulative value for the metals analyzed is given below in Table 4. All metals, including zinc, exhibited an approximate monomodal lognormal distribution. For the Split Tube samples, as shown in Table 4, the 50% cumulative concentration of zinc is higher than all other metals except manganese.

TABLE 4: Statistics on Split Tube samples - Smart Property (in ppm)

Metal	Range	50% Cumulative Value
Co	13- 42	29
Cu	10- 30	20
Ni	22- 54	35
Zn	35- 90	57
Mn	304-832	420

The coefficients of correlation for the Split Tube samples are shown in Table 5. Significant to good correlations resulted for all metals calculated.

TABLE 5: Coefficients of correlation for Split Tube samples - Smart Property

	Co	Cu	Ni	Zn	Mn
Co		1		0.48	
Ni	0.39	0.66	1	0.62	
Mn	0.34	0.58	0.73	0.73	1

The metal/Mn ratios for the Split Tube samples are given in Table 6.

TABLE 6: Manganese ratios for Split Tube samples - Smart Property

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	3- 12	8	7	30
100(Cu/Mn)	3- 6	5	5	20
100(Ni/Mn)	5- 11	8	8	17
100(Zn/Mn)	8- 20	14	13	19

As compared to the Iwan Auger samples, the manganese ratios for the Split Tube samples have a narrower range, are not skewed to the right and have lower variation. In vertical section, the Split Tube sample manganese ratios are less erratic than that for the Iwan Auger samples. The Zn/Mn ratio increases in the two holes drilled toward the western part of the area as compared to those drilled in the eastern part of the area.

2. Soil Sampling

Following the drilling, soil sampling was also done. The soil is generally a podzolic type where the ground is reasonably well drained. The Ah (decomposed organic material mixed with mineral soil) and the B-horizons were sampled. Generally, the Ah-horizon occurred at 3 to 8 inches and the B-horizon was sampled at 8 to 15 inches. Twenty sites were sampled.

Results for all metals, except zinc, were quite uniform in both the Ah and B-horizons. One sample site near the east side of the area gave a zinc anomaly in the Ah-horizon which was twice background.

The concentration range and 50% cumulative value for all metals analyzed is given below in Tables 7 and 8. All metals exhibited an approximate monomodal lognormal distribution.

TABLE 7: Statistics for Ah-horizon samples - Smart Property (in ppm)

Metal	Range	50% Cumulative Value
Co	21- 70	43
Cu	14- 61	21
Ni	19- 61	36
Zn	48-176	74
Mn	220-840	Not Determined

TABLE 8: Statistics for B-horizon samples - Smart Property (in ppm)

Metal	Range	50% Cumulative Value
Co	31- 74	52
Cu	10- 35	17
Ni	31- 62	43
Zn	46- 76	57
Mn	156-680	Not Determined

Some coefficients of correlation were determined for the Ah and B-horizon samples which are given in Tables 9 and 10.

TABLE 9: Coefficients of correlation for Ah and B-horizon samples - Smart Property

	Ah-horizon	B-horizon
Cu/Zn	0.59	0.31
Ni/Co	0.89	0.80
(Cu+Zn)/(Ni+Co)	0.31	0

TABLE 10: Coefficients of correlation between the Ah and B-horizons for various metals - Smart Property

	Ah/B
Co	0.71
Cu	0
Ni	0.59
Zn	0

The metal/Mn ratios for the Ah and B-horizons are given in Tables 11 and 12.

TABLE 11: Manganese ratios for Ah-horizon samples - Smart Property

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	4- 23	14	12	47
100(Cu/Mn)	2- 16	9	7	61
100(Ni/Mn)	4- 23	14	10	52
100(Zn/Mn)	9- 39	24	20	43

TABLE 12: Manganese ratios for B-horizon samples - Smart Property

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	6- 32	19	18	37
100(Cu/Mn)	2- 17	10	6	50
100(Ni/Mn)	6- 34	20	16	43
100(Zn/Mn)	10- 35	22	21	35

The manganese ratios for all metals, especially zinc and copper, in the Ah and B-horizons displayed higher values over the eastern portion of the area.

3. Discussion

Results of the orientation survey on the Smart Property indicate that an extensive granite boulder deposit exists on top of the bedrock. This boulder deposit could possibly be pre-St. Louis Sublobe. Furthermore, the boulder deposit prevented the sampling of basal till.

Drilling did indicate lateral trends and an increase in zinc with depth. To a lesser degree, the same was observed for copper. The Iwan Auger samples gave a bimodal lognormal distribution for zinc as opposed to the monomodal distribution for the Split Tube samples. The bimodal distribution may have resulted from contamination, as the Split Tube samples would generally have a much lower risk of contamination.

The coefficients of correlation for the Iwan Auger samples (Table 2) are drastically different than those for the Split Tube samples (Table 5). The only explanation for the gross differences suggested at this time is that the major portion of the Iwan Auger samples are from the oxidized till, whereas the Split Tube samples are from both the oxidized and unoxidized till.

For the Split Tube samples, significant to good correlation exists between manganese and all other metals which suggests the metals, in part, are tied up in manganese hydroxides which were formed prior to, during and after glaciation. Most hydroxides existing in the unoxidized till may have formed in the hypothesized pro-glacial lake. The significant to good correlation of nickel with cobalt, copper and zinc (Table 5) would be expected if a large portion of these metals are tied up in the manganese hydroxides.

The normalization of metal concentrations by the metal/Mn ratios for the Split Tube samples generally smoothed the data, and indicated higher Zn/Mn ratios in the western portion of the area.

The only correlation between metals, other than manganese, for Iwan Auger samples (Table 2) exists between copper and zinc. This relationship is generally exhibited by these two metals both vertically and laterally in the till. Such a relationship in the absence of other correlations suggests a common source for copper and zinc.

The metal/Mn ratios for the Iwan Auger samples had little effect on the data, yielding approximately the same information as the metal concentrations themselves.

The metal concentrations in the Ah and B-horizon samples did not reflect mineralization. One sample site in the Ah-horizon indicated zinc to be approximately twice that of all other Ah-horizon samples. The metal/Mn ratios gave higher values especially for zinc and copper in the eastern portion of the area.

B. Indus Test Pit

At the Indus Test Pit, generally barren semi-massive to massive pyrite and pyrrhotite occur within a volcanic sequence (Listerud, 1976). The Quaternary deposits range in thickness from zero to over 20 feet. This area presented an opportunity to examine reflections of the local bedrock and sulfide in the Indus Formation.

1. Till Sampling

As with the Smart property, two types of drilling were used to obtain a vertical profile of the till: (1) Iwan post hole auger operated by hand, and (2) power driven Split Tube sampler. These results are summarized below.

Five holes were drilled with the Iwan Auger. These holes ranged in depth from 4½ to 9 feet. All five holes were terminated due to auger refusal on boulders. Most, if not all, of the holes were over sulfide.

Copper, cobalt, nickel and zinc varied vertically in the Iwan Auger samples with depth. Often two or more of these metals exhibited a parallel relationship with depth. One hole gave an increase in metal, zinc only, with depth. Two holes down-drainage from the outcrop of sulfide exhibited a drastic decrease vertically in copper, cobalt, nickel and zinc, until the unoxidized till was reached. The metals in these two holes remained relatively constant in unoxidized till.

The concentration ranges for the metals analyzed are given in Table 13. The lead and silver was analyzed for samples from only one hole.

TABLE 13: Ranges of metal concentrations for Iwan Auger samples - Indus Test Pit (in ppm)

Metal	Range
Co	26- 82
Cu	7- 62
Ni	36-100
Zn	34-110
Mn	260-710
Pb	18- 21
Ag	All less than 2

The metal/Mn ratios for the Iwan Auger samples are given in Table 14.

TABLE 14: Manganese ratios for the Iwan Auger samples - Indus Test Pit

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	8-15	12	11	17
100(Cu/Mn)	3-14	8	6	35
100(Ni/Mn)	13-21	17	16	14
100(Zn/Mn)	11-23	17	16	19

The metal/Mn ratios in vertical profile exhibited trends generally similar to the metal concentrations for the Iwan Auger samples.

Three holes were drilled with the Split Tube sampler. These holes reached bedrock at a depth of 9 to 20 feet. Basal till samples were collected. Two of these holes were over semi-massive to massive pyrite and pyrrhotite.

The concentration ranges for the metals analyzed in the Split Tube samples are given in Table 15.

TABLE 15: Ranges of metal concentrations for Split Tube samples - Indus Test Pit (in ppm)

Metal	Range
Co	9- 45
Cu	11- 45
Ni	15- 69
Zn	36-109
Mn	272-728

Two of the Split Tube holes decreased in zinc between 2 to 4 feet below the surface, at which point the zinc remained constant with depth, except where it increased in the basal till. One of these holes (IH-10) is shown in Figure 3. This distribution of zinc does not appear to be related to the ground water, but may be related to surface drainage.

The Split Tube drill hole (IH-10), shown in Figure 3, was located immediately over 40 to 80% pyrite and pyrrhotite which contained traces of copper and zinc. Near the bedrock-Indus Formation contact in basal till, the zinc concentration increased 100%. A heavy mineral separation of the samples (specific gravity greater than 2.50) resulted in a zinc contrast in the basal till six times that of the samples in the upper portion of the hole, as shown in Figure 3. Copper, nickel and cobalt in the heavy minerals gave a 100% increase in the basal till.

The metal/Mn ratio statistics for the Split Tube samples are given in Table 16. The Zn/Mn ratio suppressed the zinc anomaly in the basal till of IH-10; however, the Zn/Mn in the heavy mineral fraction of the basal till was 300% greater than the upper portions of the drill hole. In the other Split Tube holes, the metal/Mn ratios in vertical profile exhibited trends generally similar to the metal concentrations.

TABLE 16: Manganese ratios for Split Tube samples - Indus Test Pit

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	2- 8	5	4	34
100(Cu/Mn)	2-10	6	6	34
100(Ni/Mn)	9-24	16	14	28
100(Zn/Mn)	5-12	8	9	22

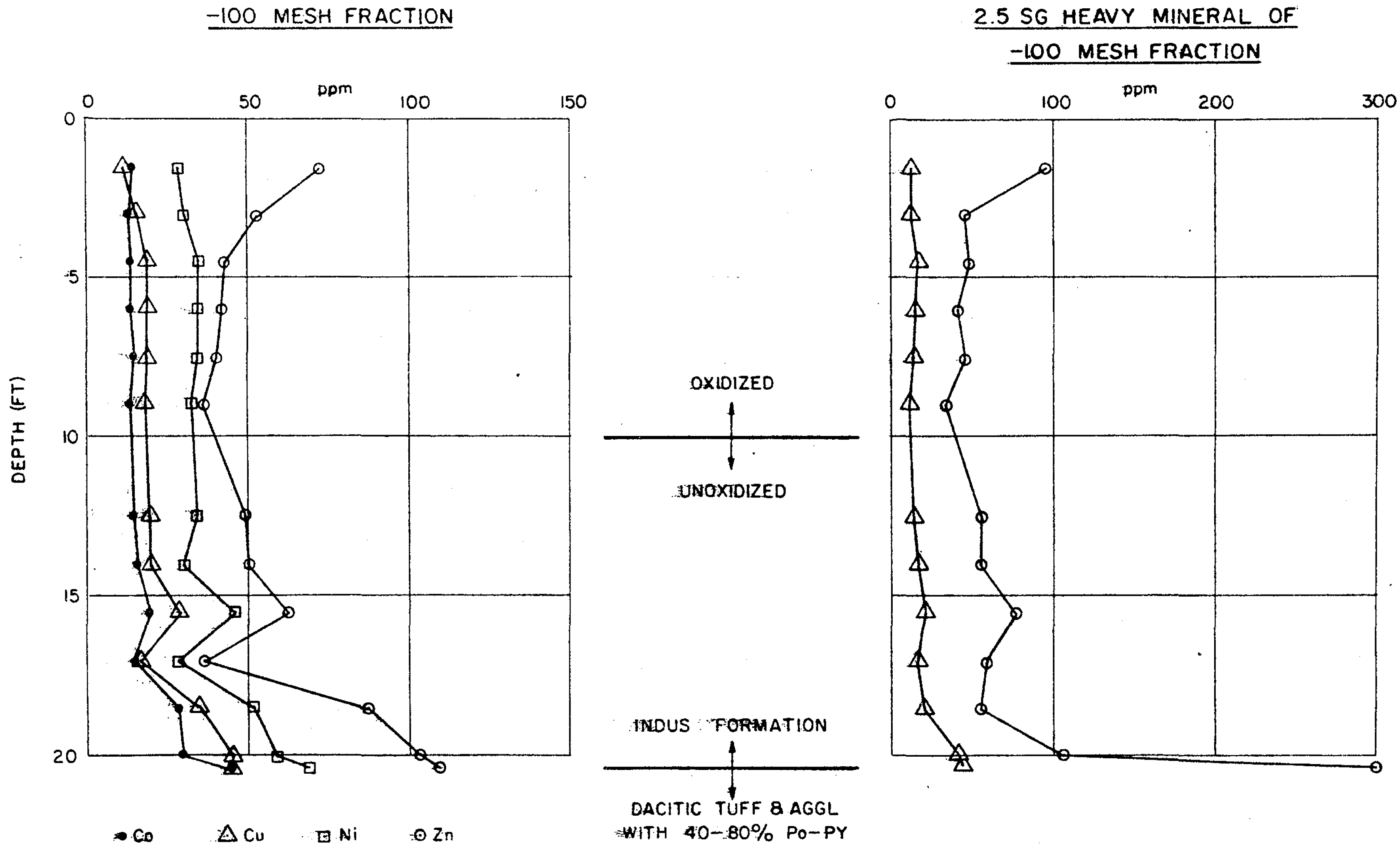

FIGURE 3: Trace metal profiles of drill hole IH-10
from Indus Test Pit

2. Soil Sampling

Following the drilling, soil sampling was also done at the Indus Test Pit. The soil is a podzol in freely drained areas, a podzolic in areas where the drainage is impeded, and gleyed where drainage is poor to waterlogged.

The Ah, B and C horizons were sampled. Twenty-nine Ah-horizon samples were collected. The iron hydroxide rich, blocky lower portion of the B-horizon was sampled at 47 sites. The C-horizon (oxidized Indus Formation) was sampled in the depth range of 15 to 43 inches at 48 sites. The ranges of thickness of the soil horizons encountered are given in Table 17.

TABLE 17: Ranges of thickness for soil horizons - Indus Test Pit (in inches)

Horizon	Thickness Range
F-H	1-6
Ah	½-3 (absent in podzols)
Ae	2-10
B	4½-16

The concentrations of metals in the Ah-horizon is very erratic along the sampling lines, especially for zinc. The range, mid-range and arithmetic mean for the elements analyzed is given in Table 18. An anomaly for cobalt, copper, nickel and zinc, generally twice background or less, occurs over the main sulfide zone. However, in the northern area sampled, where another less defined smaller sulfide zone exists, zinc attains values 2 to 4 times those in the southern area.

TABLE 18: Statistics on Ah-horizon samples - Indus Test Pit (in ppm)

Metal	Range	Mid-Range	Arithmetic Mean
Co	19- 94	57	61
Cu	8- 87	48	35
Ni	22- 96	59	53
Zn	62- 320	191	137
Mn	328-2950	1639	1212

Examination of the data in Table 18 indicates that zinc, manganese, and, to a lesser degree, copper are skewed to the higher concentrations. Although statistical analysis was not performed on this data, visual examination of the data indicates a bimodal distribution for these metals. This observation suggests that possibly anomalous concentrations of zinc, manganese and copper occur. However, examination of the data for each sample suggests that the zinc and copper are related to manganese hydroxides which normally contain high concentrations of metals. As a result, the metal/Mn ratios were calculated in order to normalize values (Table 19). As shown in Table 19, the metal/Mn ratios are also skewed to the right which suggests that anomalous metal may be reflected in the Ah-horizon. The Zn/Mn ratios do indicate some poorly defined anomalies.

TABLE 19: Manganese ratios for Ah-horizon samples - Indus Test Pit

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	2-15	8	6	52
100(Cu/Mn)	1-11	6	4	68
100(Ni/Mn)	1-14	8	6	59
100(Zn/Mn)	7-30	18	13	45

The metal values in the B-horizon were much less erratic than the Ah-horizon. Two sample sites over the north side of the main sulfide zone yielded zinc 2 to 3 times the background values. The statistics for the elements analyzed are given in Table 20.

TABLE 20: Statistics on B-horizon samples - Indus Test Pit (in ppm)

Metal	Range	Mid-Range	Arithmetic Mean
Co	33-110	71	68
Cu	13- 36	25	26
Ni	42-103	73	64
Zn	48-252	150	86
Mn	200-705	452	537

The skewness of zinc to the right is mainly the result of the two high values previously mentioned.

The metal/Mn ratios in the B-horizon (Table 21) smoothed the data considerably. Anomalous areas of Zn/Mn are indicated on the north side of the main sulfide zone and in the northern area previously mentioned. The anomalies produced by the manganese ratios are less erratic and better defined than those from the metal concentrations.

TABLE 21: Manganese ratios for B-horizon samples - Indus Test Pit

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	6-27	16	13	35
100(Cu/Mn)	2-10	6	5	27
100(Ni/Mn)	8-24	16	12	27
100(Zn/Mn)	10-30	20	16	28

The metal in the C-horizon behaved similar to the B-horizon, except the concentration in the B-horizon is generally higher for all metals as would be expected. As with the B-horizon, zinc values as high as 2 to 4 times background occur on the north side of the main sulfide zone. The statistics for the elements analyzed are given in Table 22.

TABLE 22: Statistics on C-horizon samples - Indus Test Pit (in ppm)

Metal	Range	Mid-Range	Arithmetic Mean
Co	20- 78	49	50
Cu	15- 39	27	23
Ni	27- 84	56	50
Zn	34-220	127	65
Mn	298-650	474	441

Zinc is again skewed to the right as a result of the higher values on the north side of the main sulfide zone.

The metal/Mn ratios (Table 23) smoothed the data for C-horizon samples. The Zn/Mn ratio indicates an anomaly again on the north side of the main sulfide zone, where the Zn/Mn ratio reaches a contrast as high as 300% over background.

TABLE 23: Manganese ratios for C-horizon samples - Indus Test Pit

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	5-17	11	12	30
100(Cu/Mn)	4-10	7	5	23
100(Ni/Mn)	8-17	12	11	17
100(Zn/Mn)	9-45	27	15	36

Ah, B and C-horizon samples from eleven sites over the main sulfide zone were analyzed for sulfur and iron. Statistics for these elements are given in Tables 24 and 25.

TABLE 24: Statistics on sulfur analysis of soil - Indus Test Pit (in ppm)

Horizon	Range	Median	Arithmetic Mean
Ah	130-780	360	406
B	50-310	110	158
C	90-310	160	195

TABLE 25: Statistics on iron analysis of soil - Indus Test Pit (in percent)

Horizon	Range	Arithmetic Mean
Ah	1.6-2.7	2.1
B	2.0-3.2	2.7
C	1.7-2.4	2.2

Most of the eleven sites sampled are directly over the main sulfide zone. Therefore, additional sampling and analysis would be necessary away from the sulfide zone in order to determine the effect of the sulfide on the distribution of sulfur in the soil. Even in their absence, several observations can be made from the work completed.

Sulfur has high mobility in the form of sulfate in the surface and ground water, except under reducing conditions. Meyer (1973) has found that sulfur concentrates in the A-horizon bonded in the structures of organic compounds, and hydrous iron oxides of the B-horizon.

Table 24 shows sulfur to be concentrated in the Ah-horizon as compared to the B and C-horizons. In addition, sulfur is higher in the C-horizon as compared to the B-horizon. The C-horizon is oxidized till (Indus Formation) with a lower iron content (see Table 25) than the B-horizon, but does contain mechanically derived sulfide which may explain the difference.

The highest sulfur values were obtained for all soil horizons down-drainage from the sulfide zone in a poorly drained, gleyed, podzolic soil. The increase in the gleyed soil suggests that sulfur was precipitated in the more reducing environment.

The sulfur content of the Ah-horizon was very erratic as compared to the B and C-horizons. Although correlation analysis was not performed, visual examination of the data indicates that the sulfur content of the Ah-horizon has poor correlation to that of the B and C-horizons. In contrast, the B and C-horizons exhibit a parallel relationship.

Visual examination of the data also indicates that in the Ah-horizon sulfur has a weak correlation with iron and manganese. However, sulfur in the B and C-horizons appears to correlate well with iron and manganese. Fe/Mn ratios indicate a fairly consistent value of 0.5.

In addition to sulfur occurring in organics and Fe-Mn hydroxides, it may also be precipitating as sulfide in the gleyed soils.

3. Discussion

At the Indus Test Pit, the till could be sampled all the way down to bedrock, which was not possible at the Smart property due to the boulder deposit. As a result, basal till samples could be obtained.

In two of the Iwan Auger and two of the Split Tube holes, the metal values decreased vertically in the oxidized till indicating that the metal distribution had resulted from both surface and ground water transport of the metal ions. In these same holes the metal concentrations remained constant in the unoxidized till above the basal till.

The Split Tube hole (IH-10) which reached bedrock over massive iron sulfide did give a 100% increase for zinc in the basal till. In addition, the heavy mineral separation gave a 600% increase for zinc in the basal till as opposed to the upper portions of the hole. The strong reflection of zinc in the heavy minerals indicates that zinc is mechanically derived and of local origin.

The metal/Mn ratios for both the Iwan Auger and Split Tube samples did not significantly improve the data.

The Ah-horizon did give anomalous values for copper, cobalt, nickel and zinc over the main sulfide zone and over a smaller sulfide zone to the north. The values were very erratic as is common with the Ah-horizon. The metal values correlated well with the manganese values. The B and C-horizons did yield anomalous zinc values on the north side of the main sulfide zone. These anomalies deserve further attention.

The metal/Mn ratios for the Ah, B and C-horizon samples smoothed the data and gave better anomaly definition than the metal concentrations.

Although surface and ground water migration of the metals was evident from the drill hole samples, the generally clayey and silty composition and high carbonate content of the till greatly restricts migration of these metals. The Ah-horizon samples represent a sampling depth of several feet by the roots and the resultant decay of pre-existing plants at the surface. Through eluviation of the A-horizon, the B-horizon also reflects subsurface mineralization. In addition, the formation of the B-horizon also concentrated metal in the uppermost portions of the till. The C-horizon, even though oxidized, does reflect mechanically derived metals due to the limited migration of metals following oxidation. Partially oxidized sulfide clasts were found in the drill hole samples which indicate that the oxidation is greatly retarded due to the low permeability of the till.

The high mobility of sulfur as compared to all the other elements analyzed may be a useful guide to mineralization in this area. The low permeability and high alkalinity of the Indus Formation greatly restricts the migration of cobalt, copper, nickel and zinc, but appears to allow migration of sulfate to some degree. Further work is necessary to evaluate the use of sulfur in this area.

C. Rainy River - Indus

As part of a Precambrian geologic survey of this region by R. W. Ojakangas, diamond drilling was conducted in this area (Figure 1) to determine the nature of bedrock over a major magnetic anomaly (Meineke, Vadis and Gilgosch, 1976).

Split Tube samples were taken in the Indus Formation above mafic sub-outcropping bedrock which contained chromium in the range of 500 to 1,200 ppm. The thickness of the Indus Formation in the drill hole was 28 feet. Although a basal till sample was not obtained, till samples were collected from the surface to a depth of 20 feet. These samples indicated a 300% increase in chromium with depth. The chromium concentrations ranged from 21 to 64 ppm. Because of the low mobility of chromium, it was concluded that the chromium distribution observed was the result of mechanical dispersion by the St. Louis Sublobe.

D. Manitou Rapids

As part of the Precambrian geologic survey of this region by R. W. Ojakangas, diamond drilling was done near Manitou Rapids to determine the nature of the bedrock (Figure 1).

A coarse-grained dacitic tuff was intersected by diamond drilling. Nineteen Split Tube samples were taken of the Indus Formation before reaching bedrock. The thickness of the till was 50 feet.

The ranges of metal concentrations for the nineteen samples are given in Table 26.

TABLE 26: Ranges of metal concentrations for Split Tube samples - Manitou Rapids (in ppm)

Metal	Range
Co	20- 47
Cu	8- 77
Ni	22- 70
Zn	30-112
Mn	218-744

Zinc displayed the greatest variation through the till profile. Above the water table, the water table occurring at 7 feet below the surface, all metal values remained low and slightly erratic. Below the water table from a depth of 7-30 feet, all metals remained nearly constant except zinc doubled, while cobalt, copper and nickel remained about the same concentration as above the water table.

In the depth range of 30-50 feet, normal till was encountered, which contained angular mafic rock fragments with intervals of sand and gravel. In this depth range, all metals were erratic and increased in concentration. Zinc attained values greater than three times those encountered in the oxidized till.

The distinct difference in trace element concentrations between the upper and lower portions of the unoxidized till suggests that the upper portion may be ablation till as opposed to the lower portion which may be lodgement till. The lower portion, based on its clast content, appears to be more locally derived.

Metal/Mn ratios (Table 27) generally smoothed the data, but displayed a vertical profile similar to the metal concentrations.

TABLE 27: Manganese ratios for Split Tube samples - Manitou Rapids

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	4- 11	8	6	28
100(Cu/Mn)	4- 16	10	8	28
100(Ni/Mn)	6- 18	12	10	27
100(Zn/Mn)	8- 35	22	17	34

E. Conclusions

The initial orientation surveys previously described yielded only limited success. The Indus Formation is composed mainly of material of remote origin. However, in some areas, suboutcropping mineralization is reflected in the lower portion of the till, more often only in the basal till.

Surface and ground water migration of metals does occur in this region; however, the clayey and silty composition and high carbonate content greatly restricts migration.

Where the Indus Formation is thin, at least less than 50 feet, the underlying mineralization may be reflected in the Ah, B or C-horizons of the soil. The Ah-horizons yield more widespread anomalies with a higher contrast over background values than the B or C-horizons, but are more difficult to interpret because of their erratic nature.

The Ah-horizon samples represent a sampling depth of several feet by the roots and the resultant decay of pre-existing plants at the surface. Through eluviation of the A-horizon, the B-horizon also reflects subsurface mineralization. The C-horizon, even though oxidized, does reflect mechanically derived metals, because oxidation and migration of the metals is greatly retarded due to the low permeability and high alkalinity of the till.

The metal/Mn ratios for the drill hole samples generally display a distribution similar to the metal concentrations. However, for all soil horizons, the normalization of the metal concentrations by manganese generally reduces the erratic concentrations resulting from varying amounts of Fe-Mn hydroxides and, thereby, smoothes the data. As a result, anomalies are better defined.

Although the low permeability of the Indus Formation does restrict the migration of cobalt, copper, nickel and zinc, it does appear to allow greater migration of sulfate, based on limited testing. As a result, further research should be conducted to evaluate the use of sulfur as a geochemical tool in this area.

Basal till appears to be the most reliable sample media for this region, although it does not occur in all areas. The cost of obtaining basal till samples generally precludes its use as a reconnaissance geochemical method; however, it can be a useful tool for evaluating target areas.

Even though the Ah, B and C-horizons reflect mineralization to a lesser degree than the basal till, soil sampling appeared to be the only reconnaissance geochemical exploration method which deserved further attention. Therefore, a pilot reconnaissance soil survey was conducted as described in the next section.

V. PILOT RECONNAISSANCE SOIL SURVEY

Based on the conclusions outlined in the previous section, it was decided to conduct a pilot reconnaissance soil survey. The purpose of this survey was to determine if significant trace metal variations existed in the soil which could be related to mineralization. If the pilot survey was successful, the method would be applied to the entire region. Due to the uncertainty of the application of this method, it was considered unwise to sample the entire region at the outset.

A 1/2-mile sample spacing was selected. To reduce survey cost and time, sampling was done only along roads accessible by automobile. The area surveyed is shown on Figure 1. Samples were collected 50 to 100 feet away from the road ditch to avoid contamination.

The area selected for the pilot survey has the thinnest Quaternary deposits in the region; generally less than 100 feet. However, it was not expected that suboutcropping mineralization could be detected in the soil where the till is thicker than 50 feet. Therefore, it was anticipated that the soil survey would only reflect mineralization in islands within the pilot study area where the till is less than 50 feet.

As described in Section II, glacial lake sediments and swamp deposits mantle considerable portions of the Indus Formation in the region. Sampling of the swamp deposits (peat) was generally avoided, except for some selected tests that were done which are not discussed in this report. Swamp peat or gyttja deserve further study as a geochemical sample media in this region.

As mentioned in Section II, the maximum elevation of Glacial Lake Agassiz was approximately 1,150 feet in this region. Below this elevation, wave-washed till is common. Below 1,125 feet, scattered to continuous outliers of lacustrine sediments (Little Fork Formation) of variable thickness occur.

Restricting the pilot survey to elevations greater than 1,125 feet would have greatly reduced the size of the survey area. Therefore, sampling was conducted below this elevation in an attempt to at least obtain samples of the Indus Formation beneath the Little Fork Formation. Three conditions were encountered when sampling below this elevation: (1) lacustrine sediments thicker than two feet and the till could not be easily sampled, (2) lacustrine sediments less than two feet thick and a till sample was obtained, and (3) no lacustrine sediments existed at some sample sites.

The Ah, B and/or C-horizons of the soil were sampled at one hundred and eleven sites. Sixty-seven of the sample sites were below the 1,125 foot elevation. At ten of the sample sites, the Indus Formation was sampled beneath the Little Fork Formation generally at a depth less than 42 inches. At twelve sites, outwash was intercalated with till. At twenty-two sites, Little Fork Formation beach deposits or outwash were too thick to enable sampling of the till. The soils encountered in the pilot survey were similar to those described in Section IV for the Indus Test Pit.

Soil samples were collected from the wall of approximate two foot diameter pits excavated with a shovel. The pits readily enabled examination of the soil horizons and reduced sample contamination as compared to using a soil auger.

The sample preparation and analytical methods used are the same as those described in Section IV. Combined sampling and analytical precision, as determined by replicate sampling and analysis, was found to be generally less than ±20%.

A. Results

Ah-horizon samples were collected at 108 sites of the 111 sites sampled. The range, mid-range, arithmetic mean and percent coefficient of variation for these samples is given in Table 27. The percent coefficient of variation is equal to 100 $(S/\bar{X})$.

TABLE 27: Statistics on Ah-horizon samples for Pilot Reconnaissance Soil Survey (in ppm)

Metal	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
Co	16- 79	48	44	31
Cu	4- 540	272	33	187
Ni	14- 107	61	36	35
Zn	27- 160	94	77	132
Mn	20-2300	1160	546	61

Comparison of the mid-range and arithmetic mean (Table 27) indicates that copper is considerably skewed to high concentrations, nickel and manganese have a moderate positive skew, and cobalt and zinc have little to no skew. The percent coefficient of variation indicates that copper and zinc exhibit a large variation in comparison to the other metals.

B-horizon samples were collected at 95 of the 111 sites sampled. The statistics on these samples are given in Table 28.

TABLE 28: Statistics on B-horizon samples for Pilot Reconnaissance Soil Survey (in ppm)

Metal	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
Co	21- 96	59	56	30
Cu	4- 204	104	27	88
Ni	19- 92	56	51	33
Zn	18- 110	64	71	30
Mn	48-1230	639	449	46

Comparison of the mid-range and the arithmetic mean (Table 28) reveals that copper is notably skewed to the high concentrations, manganese has a moderate positive skew, zinc has slight negative skew, and cobalt and nickel have virtually no skew. The percent coefficient of variation indicates that copper has considerably more variation than the other metals.

C-horizon samples were collected at 87 of the 111 sites sampled. The statistics on these samples are given in Table 29.

TABLE 29: Statistics on C-horizon samples for Pilot Reconnaissance Soil Survey (in ppm)

Metal	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
Co	15- 76	46	40	36
Cu	10- 76	43	26	50
Ni	19- 98	59	43	34
Zn	36- 108	72	59	25
Mn	160-1086	623	423	49

Comparison of the mid-range and the arithmetic mean (Table 29) indicates that copper has a definite positive skew; nickel, zinc and manganese a moderate positive skew; and cobalt a slight positive skew. Copper and manganese display a higher degree of variation as compared to the other metals.

Observations from those sample sites which encountered Indus Formation are described below. As previously mentioned, the general area covered by the reconnaissance soil survey is shown on Figure 1. The specific sites and areas referred to below are shown on Figure 4.

The highest concentrations of cobalt occur in the Ah, B and C-horizons one mile south of Indus. High values of cobalt were also found at SW Birchdale and SE Manitou.

At SW Birchdale, the highest copper values for the entire survey were obtained. The Ah-horizon yielded 540 ppm, the B-horizon 204 ppm, and the C-horizon 76 ppm. High copper values occurred in the Ah-horizon 1½ miles west of Indus (82 ppm) and one mile west of Birchdale (60 ppm). The C-horizon also yielded high copper 4½ miles south of Indus (50 ppm) and at SE Manitou (53 ppm).

A high nickel value (90 ppm) was obtained from a site 1½ miles east of Birchdale.

High zinc values occurred in the Ah-horizon 1½ miles west of Indus (160 ppm), one to two miles west of Birchdale (91 to 135 ppm), at SW Birchdale (132 ppm), and one mile northeast of Birchdale. In the B-horizon, high zinc was obtained at Indus Test Pit (107 ppm), SE Manitou (105 ppm), and six miles east of Clementson (99 ppm). Scattered values of zinc greater than 90 ppm occur in the B-horizon 2½ miles east of Birchdale, two miles west-southwest of Birchdale, and 3½ miles south of Birchdale. The C-horizon gave 96 ppm zinc three miles west-southwest of Birchdale.

Metal/Mn ratios were determined for all soil horizons in order to normalize the varying amounts of manganese which greatly

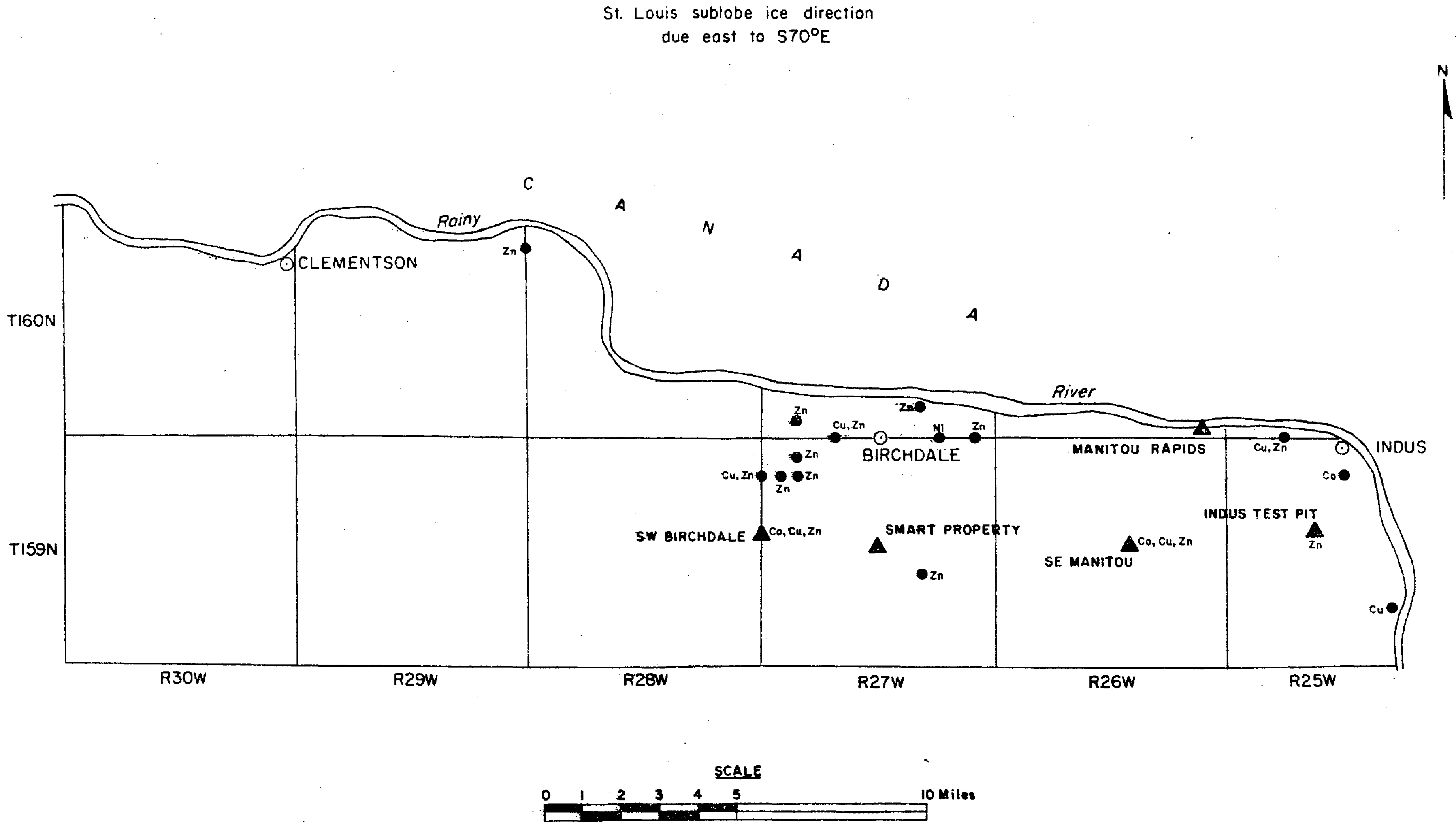

FIGURE 4: High metal values in Ah, B or C-horizon samples -
Pilot Reconnaissance Soil Survey

influence the trace metal concentrations. The statistics on these ratios are presented in Tables 30, 31 and 32.

TABLE 30: Manganese ratios for Ah-horizon Samples - Pilot Reconnaissance Soil Survey

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	1- 76	39	12	86
100(Cu/Mn)	1- 33	18	7	104
100(Ni/Mn)	1- 83	42	10	100
100(Zn/Mn)	2-100	48	18	84

TABLE 31: Manganese ratios for B-horizon samples - Pilot Reconnaissance Soil Survey

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	3- 75	39	15	59
100(Cu/Mn)	1- 49	25	6	92
100(Ni/Mn)	3- 52	28	13	53
100(Zn/Mn)	7- 63	35	18	46

TABLE 32: Manganese ratios for C-horizon samples - Pilot Reconnaissance Soil Survey

Ratio	Range	Mid-Range	Arithmetic Mean	% Coefficient of Variation
100(Co/Mn)	3- 22	12	10	38
100(Cu/Mn)	3- 17	10	6	33
100(Ni/Mn)	6- 21	14	11	26
100(Zn/Mn)	7- 37	22	15	28

Comparing Tables 27, 28 and 29 with Tables 30, 31 and 32 reveals several features. For all soil horizons the percent coefficient of variation for cobalt (Tables 27, 28 and 29) is nearly identical. However, for Co/Mn the variation differs greatly between horizons (Tables 30, 31 and 32). The variation for cobalt (Tables 27, 28 and 29) is less than Co/Mn (Tables 30, 31 and 32). The greater variation for Co/Mn as compared to cobalt suggests that cobalt is more related to other components of the samples than manganese hydroxides.

For copper the Cu/Mn ratio decreased the variation for Ah and C-horizons but not for the B-horizon. This suggests that copper is related to manganese hydroxides.

For the Ah and B-horizons the variation for nickel by using Ni/Mn ratio increased as compared to Tables 27 and 28. As for cobalt, this suggests that nickel does occur to a larger extent in other components of the sample than manganese hydroxides.

In Ah-horizon, Zn/Mn increased the variation, but for the B and C-horizons (Tables 28 and 29 compared to Tables 31 and 32) they are identical.

The metal/Mn ratios, especially for copper and zinc, tended to smooth the data as compared to metal concentrations.

A separate evaluation was made of select Indus Formation B and C-horizon samples where a good quality till existed. That is, only sample sites with abundant pebbles and boulders, without intercalated outwash, were considered. This resulted in the statistical analysis of 41 B-horizon and 34 C-horizon samples. Lognormal analysis was done on the data. Table 21 gives some of the results of this analysis. The percent coefficient of variation in Table 33 is defined for this table to equal 100(S/50% cumulative value).

TABLE 33: Statistics on select B and C-horizon samples - Pilot Reconnaissance Soil Survey (in ppm)

Metal	Horizon	Range	% Cumulative Value 50%	95%	% Coefficient of Variation
Co	B	32- 84	63	81	16
Co	C	23- 65	42	60	33
Cu	B	6-204	24	39	46
Cu	C	14- 76	22	35	36
Ni	B	23- 78	56	71	14
Ni	C	26- 68	44	64	32
Zn	B	36- 99	79	95	18
Zn	C	36- 76	58	74	21

Comparing Tables 28 and 29, which include all samples from the pilot reconnaissance soil survey, with Table 33 indicates: (1) the select samples have a narrower concentration range for all metals except copper which remains the same, (2) the percent coefficient of variation for the select samples is less than those for the entire survey, and (3) the arithmetic means from Tables 28 and 29 are not significantly different from the 50% cumulative values in Table 33.

Examination of the lognormal cumulative percent graphs of the select samples indicates that both the B and C-horizon cobalt, nickel and zinc approximately follow a monomodal lognormal distribution. The distributions for these metals in the B and C-horizon is approximately parallel with the B-horizon having the highest concentrations. Copper, however, exhibits a trimodal distribution in the B-horizon and a bimodal distribution for the C-horizon. The highest modes for both B and C-horizon copper resulted from the

SW Birchdale samples. The distributions for the B and C-horizon copper is approximately parallel with the B-horizon copper having a slightly higher concentration.

B. Discussion and Conclusions

Noticeable variations are apparent from the pilot reconnaissance soil survey; however, the variations are small. The highest values obtained for the various metals analyzed were generally 2 to 3 times the background value for these metals. Metal/Mn ratios tend to smooth the data, especially for copper and zinc, which results in better anomaly definition. This low contrast is a result of the extensive dilution of locally derived material with material of remote origin and homogenization of the resulting till by the St. Louis Sublobe.

To further evaluate the significance of the metal variations obtained in this survey, additional samples were collected around several sample sites to determine if large variations existed adjacent to the sample site. Although the results are not presented here, it was found that the variation in metal concentrations around a sample site was generally less than 20%.

If the anomalous values obtained are related to mineralization, application of soil sampling methods is restricted to those areas where the till is less than 50 feet thick and where the Little Fork Formation and swamp deposits do not inhibit sampling of the till.

Also, because of the low permeability of the Indus Formation, it is anticipated that the anomalous values obtained in this survey, if related to mineralization, are mainly mechanically dispersed down the ice direction from their source. The St. Louis Sublobe ice direction is noted on Figure 4.

Also, because of the low contrast between anomalous and background metal values, extreme care is necessary when sampling and analyzing the soils from this area.

In order to examine the nature of the anomalies obtained in the pilot reconnaissance soil survey and attempt to locate a source for the anomalous metals, two areas were selected for follow-up surveys. The areas selected are SW Birchdale and SE Manitou which both had anomalous copper and zinc from the reconnaissance survey. These surveys are described in the next section.

VI. FOLLOW-UP SURVEYS

A. SE Manitou

At an area called SE Manitou (Figure 4), as indicated in Section V, the pilot reconnaissance soil survey located a site where the C-horizon gave 53 ppm copper and the B-horizon gave 105 ppm zinc. High cobalt values were also obtained.

To determine the extent, nature and possibly the source of this anomaly, soil samples were taken at 12 sites in the vicinity of the original sample site. Five Ah-horizon, eleven B-horizon and eight C-horizon samples were collected within approximately 2,500 feet of the original site. The statistics on the metal concentrations of these samples is given in Tables 34, 35 and 36.

TABLE 34: Statistics on Ah-horizon samples - SE Manitou (in ppm)

Metal	Range	Arithmetic Mean
Co	32- 64	47
Cu	21- 36	28
Ni	34- 42	39
Zn	68- 124	95
Mn	560-1900	1097

TABLE 35: Statistics on B-horizon samples - SE Manitou (in ppm)

Metal	Range	Arithmetic Mean
Co	31- 82	64
Cu	17- 48	29
Ni	34- 78	59
Zn	67- 115	89
Mn	420- 672	528

TABLE 36: Statistics on C-horizon samples - SE Manitou (in ppm)

Metal	Range	Arithmetic Mean
Co	34- 71	49
Cu	16- 43	26
Ni	35- 78	50
Zn	40- 140	74
Mn	368- 540	465

Although further sampling is necessary, the results of the twelve sites sampled did indicate anomalous values using the reconnaissance survey in Section V as a datum. Comparing Tables 27, 28 and 29 in Section V with Tables 34, 35 and 36 reveals that the zinc in all three soil horizons at SE Manitou is anomalous. The cobalt in the C-horizon is also anomalous. In fact, the 115 ppm zinc in the B-horizon and the 140 ppm zinc in the C-horizon is higher than the zinc for any samples of those respective horizons in the pilot reconnaissance soil survey.

Metal/Mn ratio smoothed the data and to some degree suppressed the anomalies.

No major attempt was made to locate the source of the anomalous metal. Further work should be done to delineate this anomaly and attempt to locate its source.

B. SW Birchdale

At SW Birchdale (Figure 4), as indicated in Section V, the pilot reconnaissance soil survey located a site where the Ah-horizon gave 540 ppm copper and 132 ppm zinc, the B-horizon gave 204 ppm copper and the C-horizon gave 76 ppm copper. These copper values were the highest obtained for the entire reconnaissance survey. High cobalt values were also obtained.

To determine the extent, nature and possibly the source of this anomaly, soil samples were taken at 89 sites in the area. Fourteen Ah-horizon, ten B-horizon and 89 C-horizon samples were collected within approximately 3,000 feet of the original site. Mainly C-horizon samples were collected because of the probable mechanical origin of anomalies in this region, and A and B-horizon samples could not be taken in a large portion of the area which had been cultivated. The statistics on the metal concentrations of these samples is given in Tables 37, 38 and 39. The original anomalous sample site from the pilot reconnaissance soil survey is not included in these tables. The Ah and B-horizon samples are from the near vicinity of the original sample site, therefore, accounting for their more anomalous values in comparison to the C-horizon samples. Lead was analyzed in on 76 of the 89 C-horizon samples.

TABLE 37: Statistics on Ah-horizon samples - SW Birchdale (in ppm)

Metal	Range	Arithmetic Mean
Co	26- 54	42
Cu	11- 440	113
Ni	24- 54	35
Zn	38- 188	86
Mn	172-1400	562

TABLE 38: Statistics on B-horizon samples - SW Birchdale (in ppm)

Metal	Range	Arithmetic Mean
Co	38- 74	56
Cu	12- 105	44
Ni	33- 61	43
Zn	60- 168	87
Mn	200-1160	519

TABLE 39: Statistics on C-horizon samples - SW Birchdale (in ppm)

Metal	Range	Arithmetic Mean
Co	20- 62	39
Cu	13- 74	23
Ni	27- 64	38
Pb	12- 41	24
Zn	35- 80	50
Mn	300- 660	440

Comparing Tables 37, 38 and 39 with Tables 27, 28 and 29 of the pilot reconnaissance soil survey (Section V) reveals that in the Ah and B-horizons the mean copper and, to a lesser degree, zinc is higher for SW Birchdale. However, the C-horizon statistics are nearly the same for both surveys. Table 40 includes only ten C-horizon samples from the near vicinity of the original sample site which is approximately the same site from which the Ah and B-horizon samples were taken.

TABLE 40: Statistics on C-horizon samples near original sample site - SW Birchdale (in ppm)

Metal	Range	Arithmetic Mean
Co	29- 62	43
Cu	22- 74	42
Ni	32- 50	40
Zn	47- 115	62

Comparing Tables 29 and 39 with Table 40 indicates a considerably higher mean for only copper in Table 40.

Metal/Mn ratios generally smoothed the data. For Cu/Mn anomalies, up to 3 times background occurred in the same area as the anomalous copper.

The major portion of the anomaly is 200 to 300 feet long by not more than 150 feet wide. It lies on the up-ice side of a major outcrop. Attempts to trace dispersion of metals up the ice direction were unsuccessful. A definite dispersion direction could not be established from the trace elements. Glacial striations in nearby outcrops indicate a near due east ice direction.

The following hypotheses were formed and tested: (1) the anomaly was mechanically derived from nearby mineralization, (2) the anomaly is hydromorphic as a result of copper leached from nearby outcrops and not related to mineralization, and (3) the anomaly resulted from some type of human contamination.

To test these hypotheses, an electromagnetic survey was conducted over the area (Meineke, Vadis and Gilgosch, 1976). Several large conductors were located, with two small shallow conductors in the immediate vicinity of the central portion of the copper anomaly. Two holes were drilled in this area with the

Iwan auger taking till samples approximately every foot until bedrock was reached. These holes reached bedrock at 7 and 12 feet. In both holes, compact basal till with angular clasts were found in the bottom portions. Analysis of the till samples from these holes indicated that copper and zinc were anomalous and consistent with depth. A slight increase was observed in the basal till but not high enough to indicate nearby mineralization. The statistics on the metal values from the 17 samples in these holes is given in Table 41.

TABLE 41: Statistics on Iwan Auger samples - SW Birchdale (in ppm)

Metal	Range	Arithmetic Mean
Co	21- 61	37
Cu	26- 52	35
Ni	33- 57	41
Zn	60- 85	71

The relatively uniform metal values with depth in the till suggested that the anomaly was not the result of hydromorphic migration or contamination. If such had occurred, the metal values should be more erratic, especially in this low permeability till.

It is not uncommon for glacially dispersed material down the ice direction from mineralization to contain anomalous islands of till, especially considerable distances from mineralization. The anomaly encountered in this area, as previously mentioned, is on the up-ice side of a major outcrop which suggests that pressure-melting may have occurred in the sole of the glacier at the bedrock projection thereby depositing the anomalous till. The closest known outcrops are 1½ miles up-ice direction. Ojakangas has reported malachite in these outcrops.

The authors suggest that airborne electromagnetic surveys of this area be examined to determine if conductors do exist in the up-ice-direction from this anomaly. These surveys were not available to the authors.

C. Discussion and Conclusions

In order to determine if the high values obtained in the pilot reconnaissance soil survey are significant, and to determine if soil sampling is applicable as a reconnaissance method in this region, it is necessary to determine the source of the anomalies at SE Manitou and SW Birchdale.

No major attempt was made to locate the source at SE Manitou. However, at SW Birchdale an extensive follow-up survey was conducted which suggested the anomaly is of mechanical derivation, and represents an island of anomalous till a considerable distance down-ice from its source. To test this hypothesis, airborne surveys up-ice from the anomaly should be evaluated; however, these surveys were not at our disposal. Without these surveys, considerable ground geophysics, soil and drill hole till sampling would be necessary over a very large area.

As a result, it was decided to conduct an additional orientation survey over another mineralized area called the Emo Prospect in order to further evaluate the nature of geochemical dispersion before attempting further work at SW Birchdale.

VII. ADDITIONAL ORIENTATION SURVEY

Upon completion of the follow-up surveys outlined in Section VI, it was determined desirable to conduct an additional orientation survey over known mineralization in order to further evaluate the use of geochemical exploration methods in this region. Soil, till and stream sediment surveys were conducted.

At an area called Emo Prospect (Figure 1) pods of 0.5% Cu+Ni occur in a mafic intrusive complex. The mineralization outcrops in some areas and probably suboutcrops. Extensive diamond drilling has been done on this prospect. Over mineralization, the Indus Formation is generally less than 60 feet thick and averages approximately 15 feet.

Examination of the Quaternary geology indicated that the ice direction is the same as previously described in this report. The mafic intrusive complex covers about five square miles. Examination of farmer's rock piles and road cuts of the till over the mafic intrusive complex and down-ice from the complex revealed that clasts of the mafic complex occurred infrequently. The C-horizon soil sampling and two Iwan auger drill holes seldom encountered either gabbroic or angular clasts. The Indus Formation at the Emo Prospect appeared to be less representative of local bedrock compared to the other areas investigated in this region.

A. Soil and Till

To determine if the copper-nickel mineralization was reflected in the soils, 64 sites were sampled. Twelve Ah-horizon, 12 B-horizon and 64 C-horizon samples were collected over the area. The Ah and B-horizon could not be sampled at most sites because much of the land had been cultivated. The statistics on the soil samples are given in Tables 42, 43 and 44.

TABLE 42: Statistics on Ah-horizon samples - Emo Prospect (in ppm)

Metal	Range	Arithmetic Mean
Co	42- 68	55
Cu	7- 64	22
Ni	28- 76	45
Zn	40-148	74
Mn	202-874	662

TABLE 43: Statistics on B-horizon samples - Emo Prospect (in ppm)

Metal	Range	Arithmetic Mean
Co	30- 70	59
Cu	12-202	36
Ni	26-192	65
Zn	50- 79	67
Mn	380-586	462

TABLE 44: Statistics on C-horizon samples - Emo Prospect (in ppm)

Metal	Range	Arithmetic Mean
Co	20- 80	46
Cu	11-246	25
Ni	18-258	46
Zn	28-142	58
Mn	188-1112	459

Most of the Ah and B-horizon samples were over or very near the mineralized area.

Comparing Tables 27, 28 and 29, from the pilot reconnaissance soil survey with the tables above reveals several interesting features. For the Ah-horizon, the Emo Prospect has somewhat higher cobalt, nickel and manganese, but lower copper. The B-horizon at the Emo Prospect has somewhat higher copper and nickel. The C-horizon yielded similar values in both cases. The means in Tables 27, 28 and 29 mainly reflect background values of the region. The lack of significantly higher values indicates the till generally does not reflect the underlying mineralization at the Emo Prospect.

Examination of the metal distribution and trends over the area indicates that in the Ah-horizon cobalt, copper and nickel do not produce an anomaly.

In the B-horizon, cobalt, copper and nickel give a poorly defined anomaly 1½ times the background. At one sample site a few tens of feet from mineralized outcrop, mineralized, glacially derived boulders were found in the pit dug for the soil samples. It was only this sample site which gave highly anomalous samples: 202 ppm for copper as compared to a background of 12-14 ppm, and 192 ppm for nickel as compared to a background of 26-48 ppm.

For the C-horizon, cobalt, copper and nickel gave a poorly defined anomaly 1½ times background. For the single highly anomalous sample site mentioned in the last paragraph, copper was 246 ppm compared to a 11-20 ppm background and nickel was 258 ppm compared to a 20-40 ppm background.

For the highly anomalous sample site, the higher concentrations of copper and nickel in the C-horizon as compared to the B-horizon, especially for nickel which tends to be enriched in the B-horizon, would suggest a mechanical (glacial) origin for these metals.

Several metal ratios were examined for the C-horizon. The ratios of Cu/Co and Ni/Co did not yield any apparent trend. Cu/Ni did give a poorly defined anomaly 1½ times background. The Cu/Ni ratio for the anomalous site mentioned above was 0.95 as compared to the 0.4-0.5 observed for most C-horizon samples. The ratio of Cu/Ni in the bedrock based on diamond drilling is approximately 1.5. The higher ratio in the anomalous site again suggests mechanical (glacial) origin for the metals. The lower ratio (0.95) as compared to the bedrock can probably be attributed to the oxidation of the C-Horizon during which copper, having a relatively higher mobility than nickel, was leached to a greater extend than nickel.

Metal/Mn ratios were also determined. For both Cu/Mn and Ni/Mn the data was considerably smoothed compared to the concentrations of copper and nickel; however, anomaly contrast was not improved.

Generally the gleyed soils, as in other surveys conducted in this region, have higher metal concentrations when compared to freely drained soils. Under reducing conditions, cobalt, copper, nickel and zinc have low mobilities. As a result, the metals do not leach out of these soils and concentrate metals that are introduced.

Analysis was done on two size fractions of four background and one highly anomalous C-horizon samples. These results are presented in Tables 45 and 46.

TABLE 45: Statistics on two size fractions of four C-horizon background samples - Emo Prospect (in ppm)

Metal	Arithmetic Mean -80+120	-120
Co	41	36
Cu	21	25
Ni	43	40
Zn	57	62
Mn	487	458

TABLE 46: Statistics on two size fractions of a highly anomalous C-horizon sample - Emo Prospect (in ppm)

Metal	-80+120	-120
Co	52	64
Cu	214	270
Ni	200	250
Zn	56	70
Mn	370	506

In Table 45 for the background samples, no significant difference is observed between the two size fractions. In contrast, Table 46 indicates that the metals are enriched in the finer fraction. The fact that the C-horizon is oxidized till for the highly anomalous sample in Table 46, and that manganese is also enriched in this sample, suggests the metals are contained in the manganese and probably iron hydroxides. Shilts (1975) reports that Fe-Mn hydroxides are concentrated in the fine fractions of oxidized till.

A limited number of B and C-horizon samples were analyzed using a weak extraction (0.5N HCl). The concentrations for background samples were very low indicating an absence of weakly bonded metal ions. For the highly anomalous sample described previously, the percent of metals extracted by this extraction method were much higher than those in the background samples. This supports the previous suggestion that the metals in the C-horizon highly anomalous sample are bonded in the Fe-Mn hydroxides. Tests in our laboratory have indicated the 0.5N HCl extraction will attack Fe-Mn hydroxides to a larger degree than clay and silicate minerals (Meineke and Klaysmat, 1976).

Two Iwan auger holes were drilled 400 feet down-ice from the largest outcrop of mineralization to determine whether or not the metal values increased with depth, and in the basal till. These holes reached depths of 2½ and 7 feet before reaching boulders or bedrock. The statistics on nine samples obtained from these holes are presented in Table 47.

TABLE 47: Statistics on Iwan Auger samples - Emo Prospect (in ppm)

Metal	Range	Arithmetic Mean
Co	18- 60	36
Cu	16- 30	21
Ni	28- 60	40
Zn	24- 72	49
Mn	324-468	382

The results of the drill samples are negative. In fact, they are lower than the C-horizon samples for the entire survey shown in Table 44, which includes a substantial number of samples of background value.

Nine C-horizon samples, some remote from mineralization and some over and/or down-ice from mineralization, were selected for heavy mineral (greater than 2.95 specific gravity) separation. The -60+230 mesh fraction was selected for the heavy mineral separation. These results are given in Table 48.

TABLE 48: Statistics on the analysis of the -60+230 mesh fraction and the heavy mineral (>2.95 SG) fraction of the -60+230 mesh fraction of C-horizon samples from the Emo Prospect (in ppm)

Metal	-60+230 Range	-60+230 Mean	-60+230 Heavy Minerals Range	-60+230 Heavy Minerals Mean
Co	60- 100	70	-	-
Cr	20- 60	40	360- 490	440
Cu	12- 20	17	20- 30	22
Fe	7,200-8,800	8,100	46,000-50,000	48,000
Mg	-	-	37,000-45,000	41,000
Mn	280- 440	373	2,800- 3,300	3,000
Ni	40- 60	48	30- 60	42

It is evident from Table 48 that the chromium, iron, magnesium and manganese resistate minerals, and secondary iron and manganese hydroxides, predominate in the heavy mineral fraction. If sulfides did occur in the C-horizon samples originally, they have been decomposed in the oxidized till. As a result, copper and nickel do not exhibit an increase parallel to the other metals.

An examination of the distribution and trends of the metals in the -60+230 mesh fraction indicates that cobalt, copper, chromium, titanium and zinc do not exhibit an anomaly over the mineralized area. Nickel did yield a poorly defined anomaly 1½ times background. The ratio of Cu/Ni did indicate a poorly defined anomaly 1½ times background. The metal/Mn ratios significantly smoothed the data. Cu/Mn did not indicate an anomaly; however, Ni/Mn gave 1½ contrast and Co/Mn two times background contrast.

The heavy mineral fraction of the -60+230 mesh fraction did not yield an anomaly for chromium, magnesium and titanium, but did give a 1½ times background anomaly for copper, nickel, zinc, Ni/Mg and Ni/Cr. The heavy minerals did respond to the mineralization but with a low 1½ times background anomaly. Ni/Mn gave a two times background anomaly.

B. Stream Sediments

Clastic sediments were collected from the active sediment of streams at 14 sites in the Emo Prospect area. The -80 mesh fraction of the sediments were analyzed by the method described in Section IV. The ranges of metal values are given in Table 49.

TABLE 49: Metal concentrations in stream sediments - Emo Prospect (in ppm)

Metal	Range
Co	32- 70
Cu	10- 30
Ni	40- 76
Zn	51- 272
Mn	180-1,140

A stream down-ice direction from the mineralization gave a copper anomaly twice background. Metal/Mn ratios smoothed the data considerably. The stream down-ice direction gave a well defined anomaly for Cu/Mn twice background. A weaker Ni/Mn anomaly also occurs in the same area.

C. Conclusions

The Indus Formation at the Emo Prospect appears to be less representative of the local bedrock than any other area investigated in this region.

Considerable copper-nickel occurs in outcrop and probably suboutcrops at the Emo Prospect; however, it is poorly reflected in the overlying soils and till. The copper and nickel values in the soils and till are approximately the same as the background values found for the pilot reconnaissance soil survey (Section V). The anomalies were poorly defined and generally did not exceed a contrast of 1½. Metal/Mn ratios did smooth the data, but contrast remained the same as with the metal concentrations. Basal till samples near mineralization did not yield anomalous values.

Clastic stream sediments gave a well defined anomaly with a contrast twice background, especially by using Cu/Mn ratios, down-ice from the deposit. Based on the fact the Indus Formation is not representative of the local bedrock at the Emo Prospect, it is significant that the copper-nickel mineralization was reflected in the stream sediments. This may indicate that stream sediments could give a larger contrast in areas where the till is more locally derived.

VIII. CONCLUSIONS AND RECOMMENDATIONS

As discussed in Section III of this report, till of all glacial deposits is usually the most representative of the underlying bedrock. However, even till can be of remote origin, as is mainly the case in northwestern Koochiching County. Even a till of remote origin, but one with certain necessary physical and chemical characteristics, may allow hydromorphic migration of trace element ions. However, the Indus Formation possesses both low permeability and high alkalinity and, as a result, hydromorphic migration of trace elements is also greatly inhibited.

In most glacial tills, the amount of locally derived bedrock material decreases vertically upward in the till section. Therefore, basal till is usually the best geochemical sample media. If the till is exceedingly thick, the surface expression of mineralization may not occur or may be so weak that it is not detectable among the normal trace element variations observed at the surface. The thickness of till above which underlying mineralization is not detectable at the surface depends upon the percent of locally derived bedrock contained in the till.

For the surveys discussed in this report, the basal till did reflect underlying bedrock and/or mineralization to a reasonable degree, with some exceptions. At the Smart Property, basal till was not encountered because of the extensive boulder deposit immediately overlying bedrock. At the Emo Prospect, the basal till appeared to be almost completely of remote origin. It is generally concluded that basal till has application as a geochemical sample media for detailed exploration in this region.

Geochemical soil surveys, for the reasons mentioned above and based on the results of surveys discussed in this report, reflect underlying mineralization to a lesser degree than the basal till, and in some cases do not reflect underlying mineralization. This conclusion applies to the total digestion of the -80 mesh, Ah, B and C-horizon soils used in the surveys described in this report. As a result, the geochemical methods applied in these surveys have limited application in this region. However, the soil surveys described in this report did locate significant anomalies at SW Birchdale, Indus Test Pit, SE Manitou and other areas shown on Figure 4 which deserve further consideration.

Based on the results of the surveys described in this report, several recommendations are made for further research into geochemical exploration methods in this region. Because of the nature of glacial deposits and the sluggish streams in this region, it does not seem that stream sediments would reflect mineralization; however, the stream sediment survey at the Emo Prospect does appear to reflect mineralization. Therefore, further research should be conducted on the use of stream sediments in this region.

Sulfur has a high chemical mobility under all but reducing conditions. The high alkalinity of the glacial deposits in this region does inhibit the chemical migration of most trace metals, but not sulfur. Research was conducted on sulfur at the Indus Test Pit, but this study was too limited to evaluate the use of sulfur as a geochemical pathfinder. Further research should be done on the use of sulfur in this region.

The evolution of gaseous mercury from sulfide deposits will find its way to the surface even under low permeability conditions which exist in the Indus Formation. Studies should be done at the Indus Test Pit to determine if the sulfide zones are detectable by use of mercury in the soil.

Much of northwestern Koochiching County is covered by peaty swamp deposits. The use of peat or swamp gyttja as a geochemical sample media deserves consideration.

Geochemical methods are an added tool which should not be overlooked in minerals exploration. Geochemical methods are well developed for residual soils, but are in their infancy in areas of glaciated terrain. As our understanding of the glacial and chemical dispersion of trace metals increases, so will the applicability of geochemical methods in glacial terrain.

The Minnesota Department of Natural Resources has been active in the application of lake sediment, soil, and stream sediment geochemical methods in several areas of northern Minnesota. These surveys have been conducted in areas where the glacial deposits are far more representative of the local bedrock than the Indus Formation described in this report.

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