Distribution of Ore Elements in Rocks for Evaluating Ore Potential: Frequency Distribution of Copper in the Coppermine River Group and Yellowknife Group Volcanic Rocks, N.W.T., Canada

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ABSTRACT

Several investigators have shown that the frequency distribution by size of genetically related economic ore deposits within a given area or rock unit obeys probability laws, with many of these distributions approximating lognormal distribution functions. The lower bounds of these distributions appear to be always 'artificially' limited by economic considerations such as size and grade. The sampled deposits are therefore probably only the extreme right tail of a more general probability distribution for the ore minerals in the given unit, with the lower, much more frequent, components of the distribution being represented by segregations of ore material ranging in size from 'showings' to single grains.

Unfortunately, the function best describing an empirical distribution cannot be relied upon to remain constant across the entire range of size classes. It is therefore not possible to predict, by conventional probabilistic methods, the frequency and size of ore deposits from data on the more frequent size classes of the given unit. It does, however, behoove the geochemist to make the best use of the latter data, which may readily be obtained by chemical analysis of samples from surface exposures, to estimate the ore potential of a rock unit or area. Such data are likely to become among the more useful inputs to mathematical methods of decision making in mineral exploration.

The distribution of copper within two groups of volcanic rock, one containing ore deposits, the other apparently barren, have been compared. Both groups are of dominantly basaltic composition, are of Precambrian age and outcrop over wide areas of the Northwest Territories. The Coppermine River Group contains abundant showings of copper and at least one economic deposit of this metal. The copper ore is believed to have been derived primarily by segregation of copper sulphides from the parent Coppermine River magma. The second group is the Yellowknife Group which, within the area sampled, contains no known copper deposits. HNO_3-soluble copper has been measured on 715 samples of the Coppermine River Group and 195 samples of the Yellowknife Group. The Coppermine River data show the type of distribution which is believed to be the likely accompaniment of ore deposits — a right-skewed distribution which is continuous into the range of thousands of ppm copper. The Yellowknife data are not right-skewed, and no sample exceeds 273 ppm copper.

INTRODUCTION

SEVERAL INVESTIGATORS have shown that, for a given type of mineral deposit within a particular region or geological population, orebodies are distributed by size in a probabilistic fashion, which often approximates a lognormal distribution. Allais (1956) has demonstrated this for metallic mineral deposits, and Arps and Roberts (1958), Kaufman (1963) and others have given many examples of the lognormal distribution of oil-field populations. From the economic geologist's point of view, the important implication of this discovery is that once the frequency distribution of a population of mineral deposits has been determined, further exploration may be carried out for these deposits with a known probability of success and that drilling and other exploratory risk expenditures may be optimized in terms of the probable rewards.

It is apparent that the upper and lower bounds of these frequency distributions must have radically different causes. The upper boundary is of 'geological' origin — that is, there are fewer large deposits than moderate-sized deposits. The lower boundary of the distribution is determined by economic considerations — the smaller the deposit, the less profitable it becomes to work, although the limiting size for any group of deposits is not constant but depends on a large number of geological and economic considerations.

If we consider only the size of mineral deposits, it seems probable that most populations of orebodies are but the artificially truncated upper portion of a more general distribution of ore minerals in a matrix of host rock, provided that the different size classes of this general distribution were formed by essentially the same geological processes. The size classes will range from economic ore deposits down through sub-economic showings or prospects to grains and microscopic particles of ore minerals. For convenience of description, the size range of this population is arbitrarily subdivided into ore deposits, showings and microdeposits (*Figure 1*). For the sulphide deposits described here, a microdeposit is defined as a mass of sulphide that can be contained within the volume of an average-sized rock specimen (0.25 litre).

If, within a given geological region or lithological unit, the ore minerals have a lognormal distribution, or another distribution of known type, that is continuous from ore deposits to microdeposits, a study of the frequent, more easily sampled size classes may be of predictive value in assessing the ore potential of that region or unit. However, rather than measure the physical size of microdeposits, it may often be more practical to measure the distribution of the abundance of ore elements in rock samples from the region or unit. That these two measures are related is

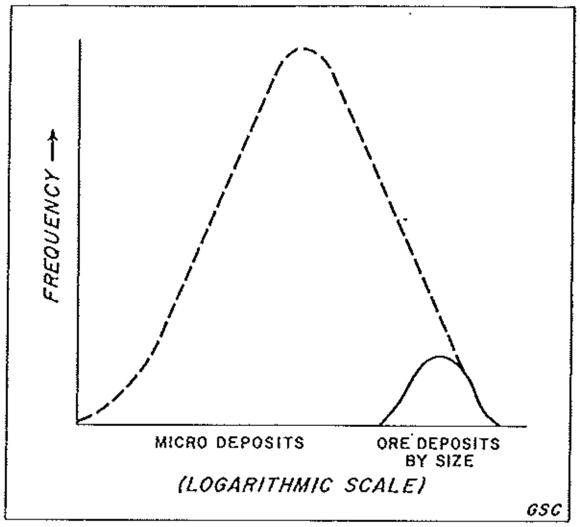

FIGURE 1 — A frequency distribution of orebodies by size may often be the upper, truncated portion of a more extensive population of ore mineral accretions.

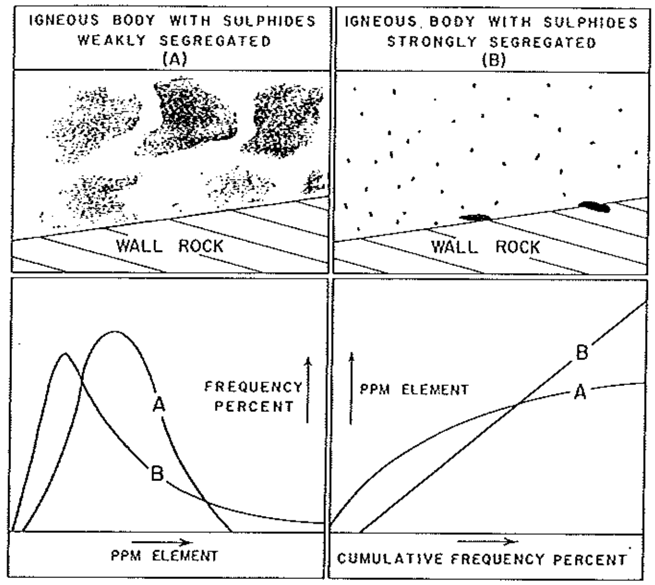

FIGURE 2 — Contrasting frequency distributions for ore elements in rock samples coming from igneous bodies where the ore mineral is alternatively weakly or strongly segregated. Frequency per cent diagram with arithmetic scale for element concentration; cumulative frequency per cent diagram with a logarithmic scale.

readily apparent, but the precise relationship between the chemical composition of rock samples and the size distribution of mineral accumulations within the same unit is likely to be extremely complex.

Considering those sulphide deposits that form by the segregation of the sulphide component within a magma, we may observe two types of distribution (*Figure 2*). In type 'A', the sulphides have not segregated to any marked extent, but remain fairly evenly dispersed through the rock mass. If rock specimens of constant volume are collected non-subjectively from this unit and are analysed for an ore metal, the frequency distribution of the ore metals in this sample may approximate a normal distribution when plotted on an arithmetic scale (*Figure 2*, lower left, curve A). For type 'B' distribution, the same quantity of sulphide in a similar magma has been strongly segregated, the segregations varying in size from mineable orebodies to microdeposits. If rock specimens are taken from this unit, analysed for the same ore metal and the sample concentrations plotted on an arithmetic scale, a distribution that is highly right-skewed relative to the previous type will be observed. If this distribution approximates the lognormal, a straight line will result when the cumulative frequency is plotted against the logarithm of the metal content (*Figure 2*, lower right, curve B). In contrast, the cumulative frequency distribution of type 'A' will be strongly curved. The two contrasting features of the two distributions which can best be observed from the cumulative frequency curves are: (1) over a large portion of the lower and middle parts of the distribution curve 'A', samples are at higher element levels than their equivalents in the type 'B' distribution; (2) type 'A' distribution is truncated at low element contents, whereas type 'B' is continuous up to high metal contents.

To determine whether these theoretical considerations hold true in nature, it was decided to investigate the frequency distribution of an ore element in a rock unit that contained ore deposits of the segregation type and to compare this with the distribution of the same element in a similar rock where such deposits were unknown. The two units chosen are both basic volcanic rocks — the Proterozoic Coppermine River Group that lies near the northern margin of mainland Canada and the Archean Yellowknife Group lying several hundred miles to the south. Both units had been representatively sampled in a reasonably non-subjective manner. The Coppermine River Group contains abundant showings of copper and at least one copper deposit of economic size; the Yellowknife Group has no known showings or deposits of copper within the area sampled. Nature's perversity is demonstrated by the apparent fact (Baragar, 1969) that the Coppermine ore occurrences are not simple segregation-type deposits, but perhaps result from a two-stage process: first the segregation of sulphides, followed by remobilization and concentration of these sulphides. Further, copper occurs within the Coppermine volcanic rocks in two forms — as metallic copper and as the sulphide. A feature that helped to make the study more meaningful was that previous investigations had shown no significant difference in the copper content of the two groups of volcanic rock: — "The distributions of copper analyses in Yellowknife and Coppermine River rocks are very similar yet there is a close association of copper prospects with the latter but not the former. It would appear that an extraordinarily higher copper content in itself is not a significant factor in the localization of copper deposits." (Baragar, 1969, p. 13).

COPPERMINE RIVER GROUP

General Geology

The Coppermine River Group (*Figure 3*) comprises a lower division of predominantly basaltic flows and an upper division of interlayered red sandstone and basalt flows. The best estimate of the age of the group is 1,200 million years and, apart from faulting, the rocks are essentially undeformed. The flows dip northward at 5 to 10 degrees and are unconformably overlain by an even more gently dipping succession of shales, quartzites and limestones, thought to be approximately 600 million years old. The group is very considerably faulted. Some faults transect the entire sequence, conspicuously segmenting it (*Figure 3*), but these faults do not appear to intersect the sediments overlying the unconformity.

The lower division of the group contains a monotonous succession of plateau basalt flows that total about 10,000 feet. Individual flows most commonly vary between 25 to 75 feet in thickness and some have recorded strike lengths of more than 10 miles. Each flow grades upward from a

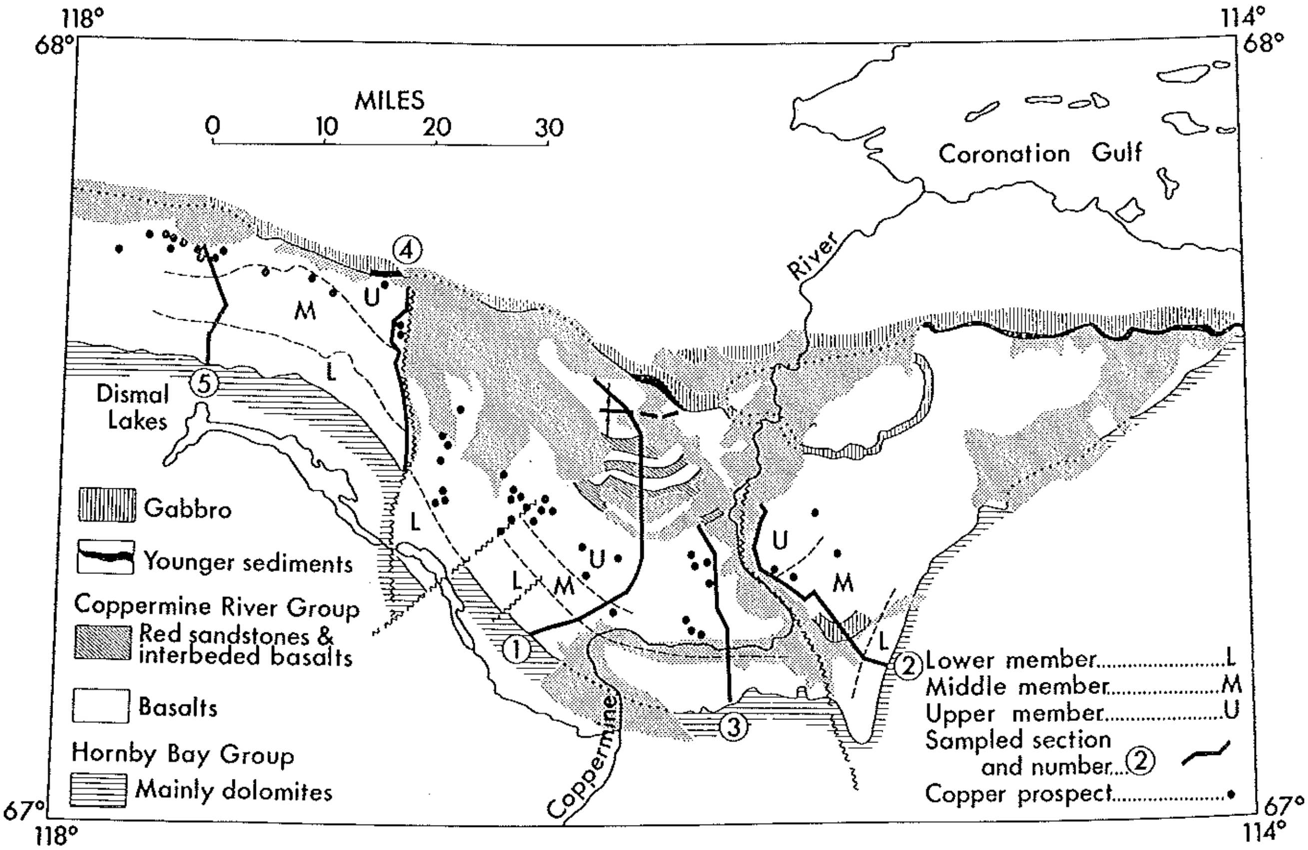

FIGURE 3 — The Coppermine River Group: map showing lithological subdivisions, copper prospects and sampled stratigraphic sections.

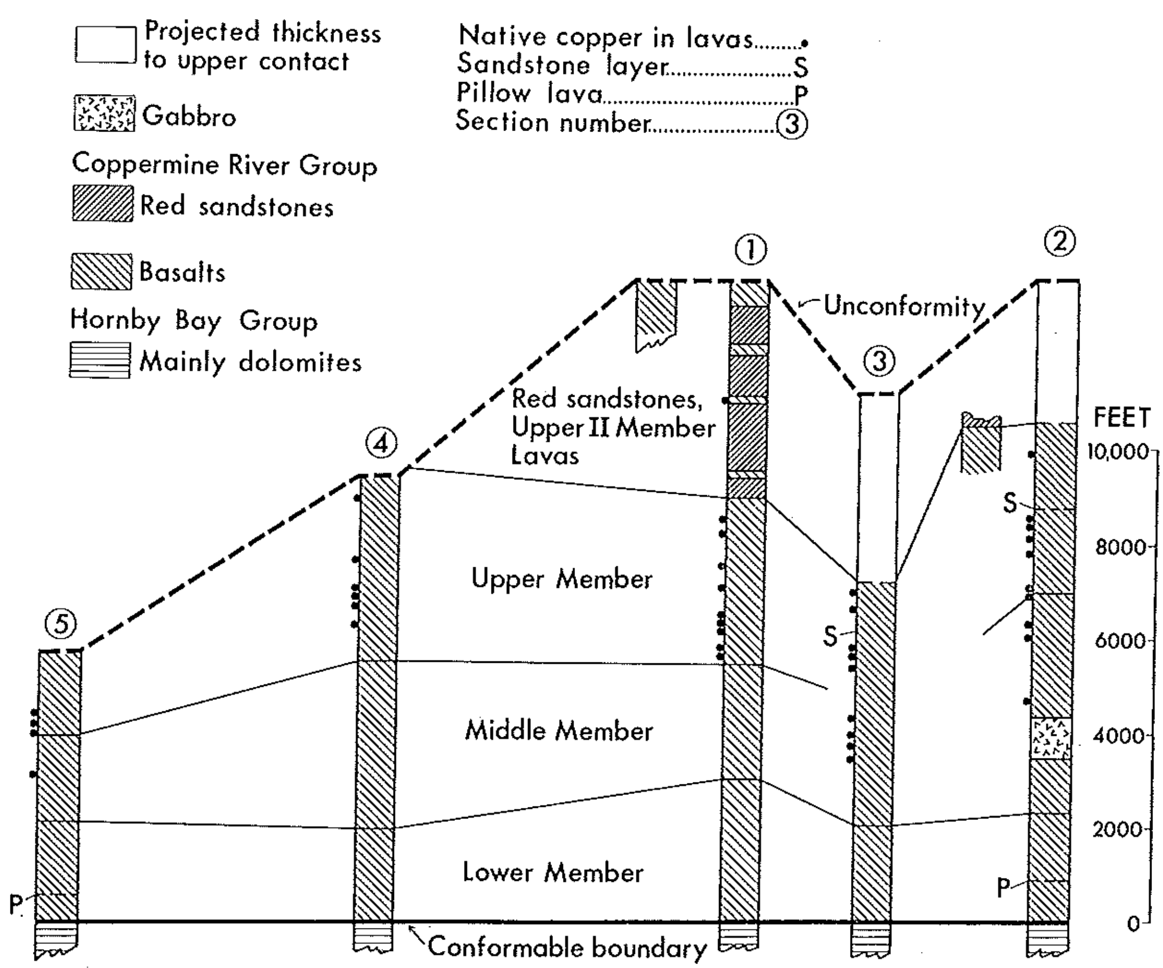

FIGURE 4 — The Coppermine River Group: stratigraphic sections.

massive, dark, basaltic base to a frothy, red, commonly brecciated top. The flow tops may be as much as half the thickness of the flow, but are generally much less. The succession has been subdivided on the basis of field characteristics into lower, middle and upper members, of which the lower member is the best established. The distinction between the middle and upper members is not everywhere evident.

The upper division of the group is a minimum of 4,000 feet thick, and less than half consists of basaltic flows. Stratigraphic sections of the Coppermine River Group at five positions along its strike length are shown in *Figure 4*.

Economic Geology

Copper is the only metal of economic significance that has been recognized to date in the Coppermine River Group. It occurs in two forms; as the native metal within the flows and as sulphide — principally chalcocite — in veins and fractures that cut the flows and, less commonly, within the flow tops. Numerous copper showings or prospects have been found within the volcanic succession, nearly all of them as fracture-filling or vein types. Many of these are shown in *Figure 3*. Kindle (1969) and Kindle and Kirkham (1970) have enumerated the various types of deposit within the area. Only the "47-Zone" of Coppermine River Ltd. is known to be of immediate economic interest. It occurs in a fracture zone closely associated with the Teshierpi fault, one of the major faults transecting the Coppermine River Group, and is reported *(Northern Miner*, 1968) to have an indicated reserve, to a depth of 600 feet, of 3.6 million tons grading 3.44 per cent Cu. In a few places, native copper within the flows is sufficiently rich to be of minor economic interest. One flow sampled by the writers averages nearly 0.1 per cent Cu.

YELLOWKNIFE GROUP

General Geology

The Yellowknife Group of Archean age has an extensive distribution through the Slave Province of the Canadian Shield. It comprises an older formation of volcanic rocks ranging from basalts to dacites and a younger succession of greywackes. The distribution of the volcanic part of the group is shown on the inset maps of *Figure 5*.

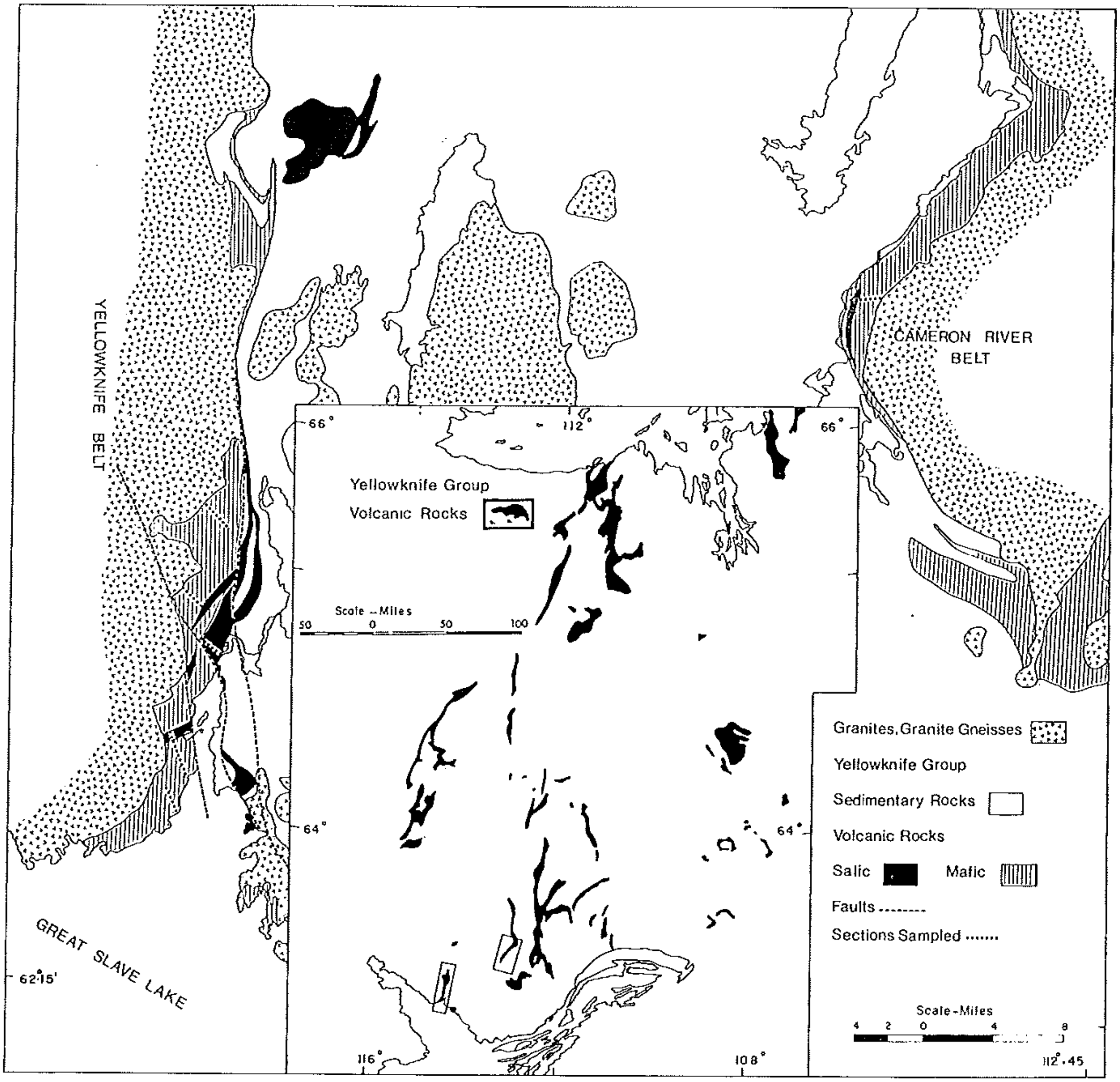

FIGURE 5 — The Yellowknife Group: distribution of sampled stratigraphic sections.

The volcanic rocks are typical of the Archean 'greenstone' belts of the Canadian Shield. They occur as thick sequences of mainly submarine lavas that are predominantly basaltic in composition, but with a salic component that forms about 10 per cent of the assemblage. Two of the better studied remnants of scattered Yellowknife Group volcanic rocks are the Yellowknife and Cameron River belts shown in *Figure 5*. Both were previously sampled in detail (Baragar, 1966) and all samples were re-analysed for copper in the present study.

The Yellowknife belt consists of a homoclinal succession of volcanic rocks that dip steeply eastward. These rocks have been extensively dissected by younger faults, but on the basis of previous geological work (Henderson and Brown, 1966) it is possible to reconstruct a continuous section through the flows that is more than 40,000 feet thick. Two volcanic cycles, each composed of mafic lavas topped by dacite flows, succeed one another. Within each cycle, the composition of the mafic rocks become progressively more salic upward.

The Cameron River belt is a steeply dipping, west-facing succession of mafic volcanic rocks with one intercalated salic layer in the upper part. It is about 9,000 feet thick.

At least half of the flows composing the Yellowknife and Cameron River belts are pillowed, and these are fairly evenly distributed through the sequence. Most, if not all, of the lavas were therefore erupted under water.

Economic Geology

Gold is the principal metal of economic importance associated with the Yellowknife Group and the only metal that has been commercially extracted from it. No significant copper prospects are known from either the Yellowknife or Cameron River belts and they are rare in the Yellowknife Group rocks as a whole. In the southern part of Mackenzie District, the Yellowknife Group rocks have been moderately well explored and the only known copper showings of significance are at Turnback and Benjamin lakes, where they may be of doubtful relationship to volcanic rocks. In the northern part of the Mackenzie District, where the Yellowknife Group is less well known, the relative abundance of copper mineralization cannot be estimated. The High Lake deposit of Kennco near Coronation Gulf is a major copper prospect in the Yellowknife Group.

SAMPLING AND ANALYSIS

A total of 195 samples from the Yellowknife and Cameron River belts and 713 samples from the Coppermine River Group were analysed for copper during the present study. Each sample is a hand specimen weighing roughly ½ pound. The Coppermine River samples were taken partly from six section lines that traverse the group from its base to the topmost flow exposed and partly from locations scattered throughout the remainder of the group. Five of the sections are shown in *Figure 3*. The sixth section is not shown, but lies between sections 1 and 4.

The Yellowknife Group samples were taken along section lines shown in *Figure 5* that traverse the Yellowknife and Cameron River belts and in addition from other scattered locations in these belts. Although sampling of the Coppermine River and Yellowknife groups was not carried out with a strictly non-subjective sampling design, all stratigraphic levels and rock types within each group are well represented in the collections analysed.

Each ½-pound sample was first entirely reduced to ¼-inch chips or less by a 'Chipmunk' crusher. This material was then further reduced to minus 20 mesh in a Braun pulverizer equipped with ceramic plates. Ten grams of this powder were carefully sampled and ground to approximately 150 mesh or finer in an alumina ceramic mill agitated by a paint shaker. The resulting powder was used for analysis.

As the Coppermine River flows contain native copper, it was thought that there might be difficulty in properly grinding and sampling this material. Therefore, a relatively large sample was used for acid attack and each sample reporting values greater than 200 ppm Cu was analysed in duplicate. However, no problems of sample homogeneity were apparent with these procedures and the standard deviation of the repeated analysis of one sample containing 203 ppm Cu was 4.3 ppm.

The analytical procedure consisted of placing 1 gram of sample in a test tube and adding 10 mls of 4N HNO_3. This was heated on a water bath at 90°C for 1½ hours; 40 mls of metal-free water were then added and, after mixing, the solution was allowed to stand overnight. Next day, copper was analysed by an atomic absorption method, using the 3,247-Å line of copper. The solution was excited by an air-acetylene mixture burning in a single-slot burner. The Perkin-Elmer 303 spectrometer had a slit width of 7 Å and a source current of 15 m.a.

TABLE I — Statistical Data for Copper in the Coppermine River and Yellowknife Groups

Lithological unit	Number of Samples	Arithmetic Mean	Standard Deviation	Geometric Mean	Percentiles													
					2.5	5.	10.	20.	30.	40.	50.	60.	70.	80.	90.	95.	97.5	99.
Lower Member	147	72.8	106.	41.2	6.	6.	10.	16.	22.	27.	41.	60.	74.	109.	155.	219.	280.	434.
Middle Member	182	575.	4443.	35.3	1.	1.	4.	8.	13.	18.	32.	51.	76.	190.	400.	592.	782.	2595.
Upper Member	326	251.	1293.	59.4	4.	5.	8.	15.	23.	34.	53.	87.	143.	236.	428.	626.	1110.	2316.
Flows Intercalated with Red Beds	49	158.	241.	73.8	9.	13.	14.	20.	27.	41.	57.	122.	177.	288.	352.	422.	506.	1540.
Gabbro Sill	9	144.	119.	103.							101.							
Total Coppermine River Group	713	289.	2411.	49.3	4.	5.	7.	14.	21.	30.	46.	69.	107.	192.	342.	532.	828.	2090.
Yellowknife Group	195	75.3	61.1	47.7	1.	3.	7.	21.	37.	50.	68.	86.	100.	115.	134.	163.	175.	273.

DISCUSSION OF RESULTS

The various statistical data for copper in the Coppermine River and Yellowknife Groups are tabulated in Table I. In *Figure 6*, the cumulative frequency distribution curves for this element, plotted on a logarithmic scale, are compared for the two series. These curves bear a close resemblance in shape and in relative disposition to distribution curves derived by the theoretical consideration of a metal that has alternatively remained dispersed through a magma or has segregated (*Figure 2*). The distribution of copper in the Coppermine River Group closely approximates a lognormal distribution, as is apparent from the linearity of its curve (*Figure 6*). In contrast, the similar curve for the Yellowknife Group samples is highly curved, more closely approximating an arithmetic normal distribution. Note that up to the 70th percentile, the Yellowknife cumulative frequency distribution lies at higher copper levels than that for the Coppermine River Group, after which it falls off rapidly relative to the latter samples. These features of the distribution curves are reflected in the statistical data for the two groups given in Table I. Although their geometric mean values are closely similar, the arithmetic mean of the Coppermine River Group is higher and the standard deviation very much higher than the equivalent parameters of the Yellowknife Group.

The Coppermine River Group itself provides data to test our earlier predictions. It will be recalled that the copper showings and ore deposit are confined to the middle and upper members of the group. There is no important mineralization in the lower member. In *Figure 7*, the cumulative frequency distribution curves for copper in the lower member of the Coppermine River Group are compared with those for samples from the middle plus upper members. Again, although the contrast is not as striking as that between the Coppermine River and Yellowknife Groups, the same relationship of form and relative disposition of the curves to the presence or absence of mineralization is apparent. The barren unit is again richer in copper over the lower reaches of the distribution curve — here up to the 46th percentile — but above this point the barren unit falls off relative to the ore-bearing middle and upper members.

It is perhaps not too difficult to visualize the Coppermine River Group distribution function, particularly that of the middle and upper members, being continuous (with appropriate change of the measurement criterion) up into the size range of showings and ore deposits. On the other hand, the frequency distribution for the Yellowknife Group tails out at relatively low copper levels.

Our earlier concept of the continuity of a given size frequency distribution from microdeposits, through showings, to ore deposits was based on the assumption that the different size fractions were formed by exactly the same combination of geological processes. For the Coppermine River Group, it is unlikely that this can be precisely true. It would seem likely that there was an initial segregation of copper sulphides in the magma. It is this primary segregation that is probably being principally reflected in the frequency distribution curves. At least two subsequent events affected these primary sulphides. The first was reduction of the copper sulphide to native copper through much of the volume of the flows. The second was mobilization of copper sulphides — perhaps those in the porous flow tops (Baragar, 1969) — and local migration to ad-

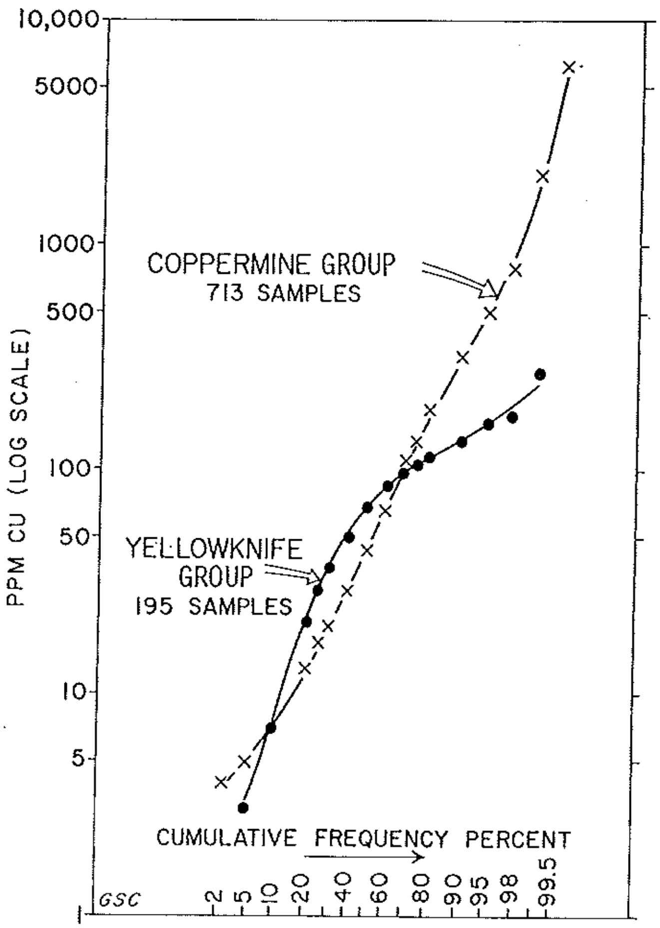

FIGURE 6 — Cumulative frequency distributions for copper in the Coppermine River and Yellowknife groups.

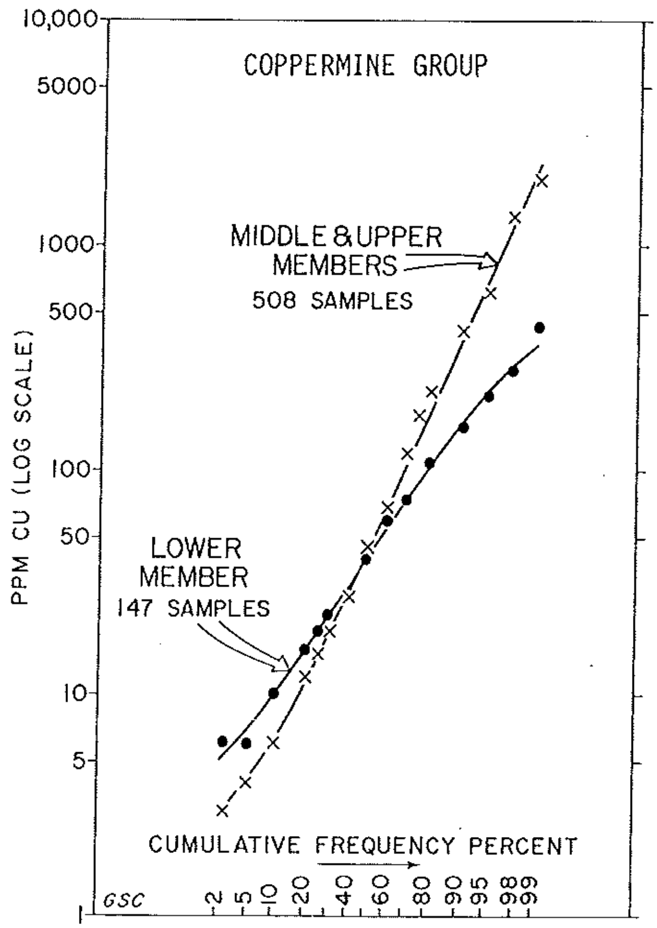

FIGURE 7 — Cumulative frequency distributions for copper in the lower and middle plus upper members of the Coppermine River Group.

jacent fracture zones where the copper was redeposited as sulphides. However, the degree of initial segregation remained a dominating influence on the total process of ore deposition and thus the frequency distribution curves for copper in the Coppermine River Group are an excellent predictor of ore potential.

The Yellowknife Group has a radically different type of frequency distribution for copper than the Coppermine River Group, which is in accord with the apparent absence of similar types of ore deposits in this rock sequence. The dominant type of copper deposit of the Archean 'greenstone' belts is the type commonly referred to as 'massive sulphides'. It is not known if these bodies result from primary segregation of a sulphide component of the magma. It is the writers' plan to sample in detail the different rock units within a mineralized greenstone belt to discover whether the same features of the frequency distribution of ore elements that distinguish the Coppermine River Group from the Yellowknife Group similarly distinguish mineralized Archean belts or rock units from unmineralized sequences.

If we speculate on the fundamental chemical causes for the differences in the distribution curves of copper for the two groups, the most likely control is the original sulphur content of the basic magma. With an abundance of sulphur, the solubility product for copper sulphides will be exceeded early in the crystallization history of the magma and an immiscible sulphide liquid can separate prior to the main period of crystallization of the silicate components. The immiscible sulphide droplets will, therefore, have an opportunity to coalesce, rather than be trapped between silicate crystals. Because of its highly chalcophile character relative to iron, copper will be enriched in these early sulphide liquids. The sulphides which separate later will, therefore, be depleted in copper. These later sulphides are likely to be trapped between silicate crystals and thus become widely dispersed throughout the magma. It is therefore suggested that a high initial sulphur content leads to enrichment of copper in those samples which contain primary segregation components and depletion of copper throughout much of the remainder of the rock — a distribution pattern which we observe for the Coppermine River Group. For a magma with a lower content of sulphur, the solubility products for metal sulphides will not be exceeded early in the crystallization history of the magma. Separation of copper sulphide crystals or liquid will take place later when the individual sulphide grains or droplets are more likely to be trapped between silicate grains and hence be widely dispersed through the basic rock.

There are very obvious difficulties in predicting the presence or absence of ore deposits from the distribution of the more frequent size components of what is presumed to be the same mineralization population. However, the fact remains that, for the examples studied, there is a good correlation between the theoretical and actual distributions for segregation-type ore-bearing and barren rock sequences. Clarification of the problem can only come from further empirical studies of this nature. These studies should aim at discovering whether the microdeposits of sulphide or other ore minerals belong to the same population as the associated showings and ore deposits, and if so to what extent is the distribution function constant over a range of size classes. For the study of segregation-type ore deposits recounted here, the samples were taken from a population consisting of the entire exposed area of the rock units. For other types of ore deposit it may be profitable to restrict the population. Thus, for studies involving hydrothermal ore deposits, vein material might be judged to comprise the population to be sampled.

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