MINERAL RESOURCES OF A PORTION OF THE DULUTH COMPLEX AND ADJACENT ROCKS IN ST. LOUIS AND LAKE COUNTIES, NORTHEASTERN MINNESOTA

Minnesota Department of Natural Resources
Division of Minerals
Minerals Exploration Section

Report 93

Hibbing, Minnesota

1977

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Prepared for the Regional Cu-Ni Study
under the cooperative agreement with the
Minnesota Environmental Quality Board
and partially funded by the Legislative Commission
on Minnesota Resources

Hibbing, Minnesota
1977

372056P

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ABSTRACT

The Minerals Division of the Minnesota Department of Natural Resources completed a resource study of an area near the basal contact of the Duluth Complex in St. Louis and Lake Counties of northern Minnesota. A total of 324 of the 500 available drill holes were used in the resource study. The resource estimate was accomplished using a standard perpendicular bisector method of polygon construction. The total area of the polygons was 42.2 square miles. Three tonnage estimates were made in this study. The first estimate is of material with a minimum thickness of 50 feet and $\geq$.5% copper, secondly, material with a minimum thickness of 50 feet and $\geq$10% TiO_2, and finally a 100 foot minimum thickness of near-surface material $\geq$.25% copper. The estimate of material $\geq$0.5% copper is over 4.4 billion tons. Near-surface mineralization $\geq$0.25% copper is over one billion tons, and over 220 million tons of $\geq$10% TiO_2 is estimated. Thirty-six percent of the total holes intersected at least 50 feet of $\geq$0.5% copper and their polygons represented 31% of the total area measured. The average grade of the 4.4 billion tons is estimated at 0.66% copper with a copper to nickel ratio of 3.3:1.

LIST OF FIGURES AND TABLES

MINERAL RESOURCES OF A PORTION OF THE DULUTH COMPLEX AND ADJACENT ROCKS IN ST. LOUIS AND LAKE COUNTIES, NORTHEASTERN MINNESOTA

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Introduction

The Regional Copper-Nickel Study is a comprehensive study of the possible effects on a large area that may be impacted by the mining of copper-nickel sulfides in the Duluth Complex. The Minnesota Department of Natural Resources (MDNR) has been involved in the Regional Copper-Nickel Study from its very beginning, being one of the major regulatory agencies in the state and also administrator of major state mineral ownership in the study area. At the beginning of the study, the Minerals Division of the MDNR was given the responsibility for bedrock geology studies and mineral resource assessment. The Minnesota Geological Survey (MGS) was contracted to study the bedrock geology, and the Minerals Division was to provide mineral resource studies.

Prior to this study, there was a reasonable knowledge of the bedrock geology, but there was no single map that covered the whole study area, although the geology of the entire Duluth Complex was described in Sims and Morey (1972). The Duluth Complex was generally thought of as a series of sheet-like intrusions into and beneath the Keweenawan volcanics. The two major rock series, the anorthositic and troctolitic-gabbroic series, are each composed of multiple intrusions with the older anorthositic series rocks generally being separated from the footwall by the troctolitic series. It is in the troctolitic series rocks that most of the known mineralization occurs, generally at or near the basal contact.

Resource estimates have been made by mining companies in areas they control, but these have not been available to the public. The estimate by Bonnichsen (1974) was the most complete and comprehensive resource estimate available prior to this one. Bonnichsen had data for 24 irregularly spaced drill cores in the Ely-Hoyt Lakes area. He used a one mile wide strip along the basal contact as the area for his estimate. The cutoff grades used in the calculations were 0.5% combined Cu+Ni and 0.25% Cu+Ni. No minimum thicknesses were used, but mineralization was not considered significant unless it exceeded 25 feet-percent and averaged above the cutoff grades for the entire zone. Bonnichsen made two calculations of the resources, one using unlimited influence along strike for the 24 holes (Calculation A), and another limiting the area of influence of any hole to one square mile (Calculation B). The results of his estimates are presented in Table 1. Figure 1 shows the Ely-Hoyt Lakes area of Bonnichsen and its relationship to the Copper-Nickel Study area.

The Regional Copper-Nickel Study has produced two major products pertaining to the geology of the study area through the efforts of the MGS and the MDNR - Minerals Division. The MGS has produced a new geologic map of the entire area (Morey and Cooper, 1977) by compiling all prior data and reinterpreting some of it in light of new data. Maps showing the outcrop and drill hole data base and the lineaments from aerial photo interpretation were also produced. Reports explaining these maps, along with other recent investigations by MGS personnel, have been put together as the final report for contract 07307, AID337600 and presented to the MDNR. The bedrock geology report (Weiblen and Cooper, 1977) effectively summarizes the geology and presents some new ideas on the structure and origin of the Duluth Complex in the study area.

TABLE 1: Bonnichsen's calculations; Estimated tonnage, value, and grade of copper-nickel deposits in the Ely-Hoyt Lakes region for calculations A and B (after Bonnichsen, 1974)

	Calculation A (33.2 mi^2)		Calculation B (15.3 mi^2)	
Cutoff grade	0.25%	0.50%	0.25%	0.50%
Tons* of mineralized material	14.30×10^9	5.85×10^9	5.54×10^9	2.24×10^9
Tons of metal (Cu+Ni)	78.60×10^6	49.18×10^6	29.81×10^6	18.42×10^6
Tons of copper**	58.95×10^6	36.89×10^6	22.36×10^6	13.82×10^6
Tons of nickel**	19.65×10^6	12.29×10^6	7.45×10^6	4.60×10^6
Gross value of metal***	\$117.9 Billion	\$73.8 Billion	\$44.7 Billion	\$27.6 Billion
Average grade (Cu+Ni)	0.55%	0.84%	0.54%	0.82%

* Short tons (2000 lbs.)
** Assuming Cu:Ni ratio of 3:1
*** Assuming a copper price of 50¢/lb. and a nickel price of \$1.50/lb.

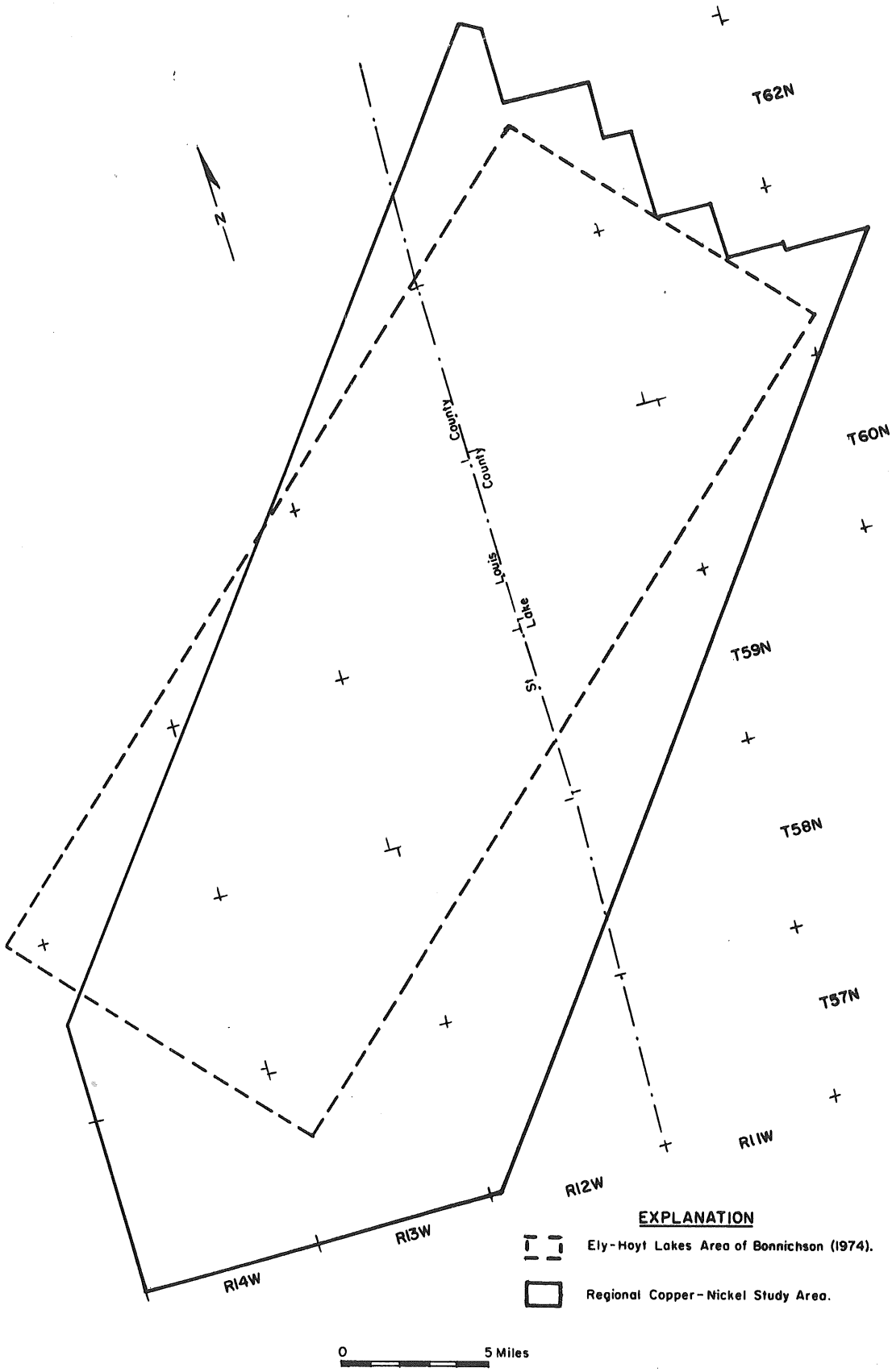


FIGURE I: Study Area Location Map

The second major product of the geologic study is this report on the mineral resources and mineral potential of the Regional Copper-Nickel Study area by the Minerals Division of the MDNR. The report is based on data from about 500 drill holes which were collected by the Minerals Division for this specific purpose. Cooperation by many mining companies, the USGS, the USFS, the USBM, mineral owners, and the MGS was necessary to compile this information. When the study was begun, log and assay data for 66 drill holes in the study area were available, and 103 cores were available for inspection by the public. During the study, the number of cores available for inspection doubled, and log and assay data available was tripled--plus a great deal of limited information on other drill cores was collected. Significant amounts of information on the location of the basal contact, outcrop locations, extent and thickness of the Biwabik Iron Formation, and the overburden thicknesses were also collected during this study.

Data Acquisition Procedures

The acquisition of geologic data for the Regional Copper-Nickel Study formally began with a letter, dated April 29, 1976, from Elwood F. Rafn, Director of the Division of Minerals, to the thirteen mining companies listed below:

American Shield Corporation
Bear Creek Mining Company
Cleveland Cliffs Iron Company
Duval Corporation
Erie Mining Company
Exxon Company, U.S.A.
Hanna Mining Company
The International Nickel Co., Inc.
The New Jersey Zinc Company
Newmont Exploration, Ltd.
Phelps Dodge Corporation
Reserve Mining Company
U. S. Steel Corporation

This letter was very general in terms of the data requested and was only the first formal step in the opening of negotiations for the release of data. Preliminary communication with or data acquisition from the U. S. Bureau of Mines, the U. S. Geological Survey, the Minnesota Geological Survey, and Amax Exploration, Inc. had begun several months prior to Mr. Rafn's letter.

The companies contacted responded to Mr. Rafn's letter at various times over the next few months, generally with questions pertaining to the types of data needed and specific uses. Negotiations proceeded slowly and it became apparent that complete data would not be available in all cases, forcing us to define some minimum "data level" which would be acceptable to the companies and still allow us to complete our assigned tasks. Consideration of the possibilities for the occurrence of different types of mineralization within the study area and the availability of pertinent exploration data led to the formation of the mineralization criteria upon which these estimates are based. Three resource estimates, based on drill core data, have been made for the entire study area. These estimates are described in detail in subsequent sections of this report.

The companies mentioned above were also asked to furnish certain other geologic information along with the assay data. They were asked to furnish outcrop locations and the location of the surface intersection of the basal contact in their areas of interest. In addition to the assay data on drill cores, they were asked to furnish for each core the overburden thickness, depth to the basal contact, rock-type below the Duluth Complex, angle and bearing of the hole, and the depth at which iron formation was intersected. The iron mining companies were also asked to provide information on the thickness of the Biwabik Iron Formation.

The Basal Zone and Mineralization

The major portion of all known mineralization in the Duluth Complex occurs in the "basal zone" which is the lowermost several hundred feet of the Complex rocks. The basal zone has been mapped on the surface as several different rock units, generally characterized by their heterogeneity of rock types and textures. These rocks and textures are described in Weiblen and Cooper (1977) and need not be reiterated here. It will suffice to say that, in general, the basal zone is heterogeneous, inclusion-rich, and contains zones of sulfide mineralization. Disseminated sulfides are the most common type of mineralization, but massive and semi-massive zones are also present. The outcrop width, and presumeably the true thickness of the basal zone, varies significantly within the Copper-Nickel Study area.

The base of the Duluth Complex generally defines the lower limit of copper-nickel mineralization and, therefore, is of interest in this study. The basal contact is not always easily identified because the nature of the contact varies from very sharp to a gradual transition over hundreds of feet, and is often just a zone of interfingering rock types also over hundreds of feet. Nevertheless, Minerals Division geologists and company geologists arrived at numbers for the depth to the footwall for all appropriate drill holes. The resultant structure contour map of the base of the Duluth Complex is shown in Figure 2. The 3,000 foot contour is the deepest shown because of a lack of information beyond that depth. In places along the zone, because of a lack of information, some or even all of the contours are extrapolations from distant data points. There are areas along the contact zone where additional contours could be drawn, but only for short distances along strike. The spacing of the contours indicates a variable average dip with great local variations. Rough

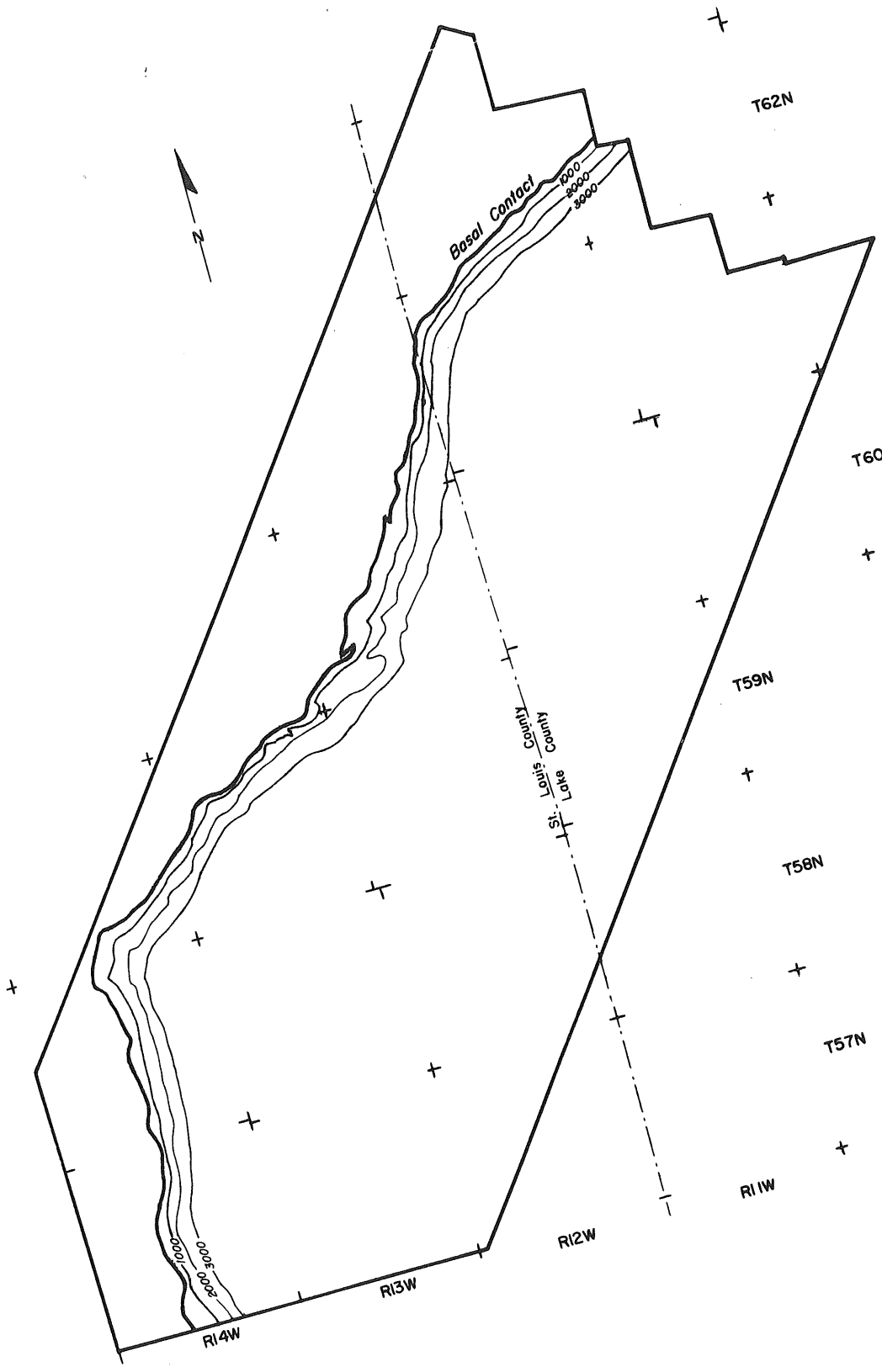


FIGURE 2: Structure Contour Map

calculations, using the basal contact and the 3,000 foot contour as shown in Figure 2, show the average dip to vary from about 20° to about 35°. A reasonable average value would be about 25°, which places the 3,000 foot contour about 1.2 miles from the contact.

Twelve generalized cross-sections have been constructed using the available drill core data. The sections are irregularly spaced along the contact zone, approximately normal to the contact. These sections were chosen because of the alignment or near-alignment of drill holes and not for any other specific purpose. Figure 3 shows the locations of these sections. The letters correspond to the identifying letters on each cross-section. The mineralization indicated by this resource estimate and the faults shown on the geologic map by Weiblen and Cooper (1977) are also shown on Figure 3 to allow the reader to get a better perspective on the mineralization and the basal zone. The detailed geology has been omitted on the cross-section in Figures 4 through 15 because of the scale and because of the terminology differences between companies, or because the data was not available. The mineralized zones shown on the cross-sections are those used in the resource estimate, and it should be emphasized that mineralization not meeting the grade and thickness criteria described previously may exist in any of these holes. These twelve cross-sections are meant to illustrate the general relationships between the Duluth Complex and the rocks it intruded and show the spatial relationships between the copper-nickel mineralization and the host rocks.

Cross-sections A and B (Figures 4 and 5) are in the INCO Spruce or North Lease area, and the good intersections of $\geq$0.5% copper near the contact are the reasons INCO has considered an open pit mine in this area. Note that the mineralization is not always exactly at the base of the

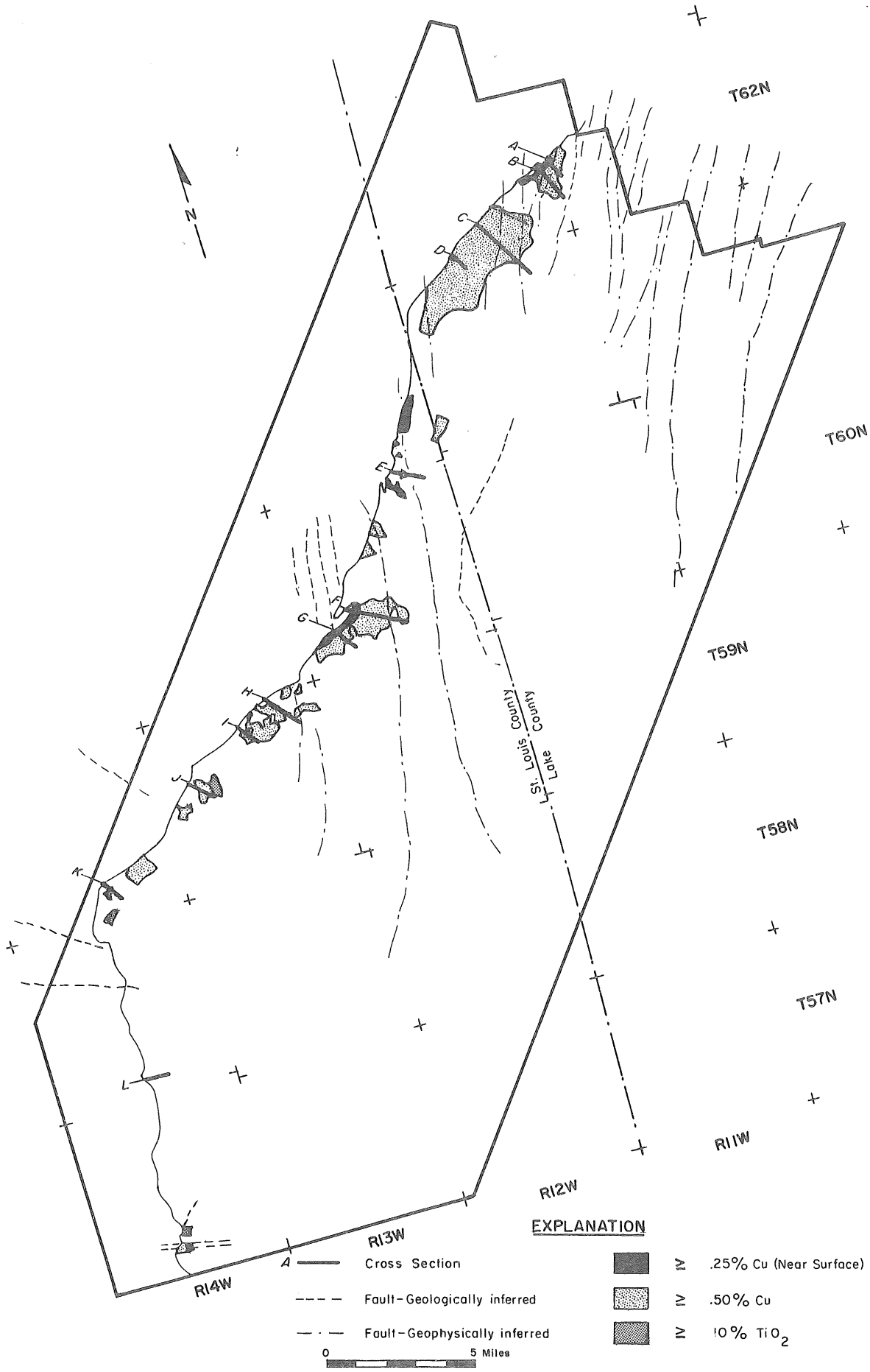


FIGURE 3: Cross Section Location Map

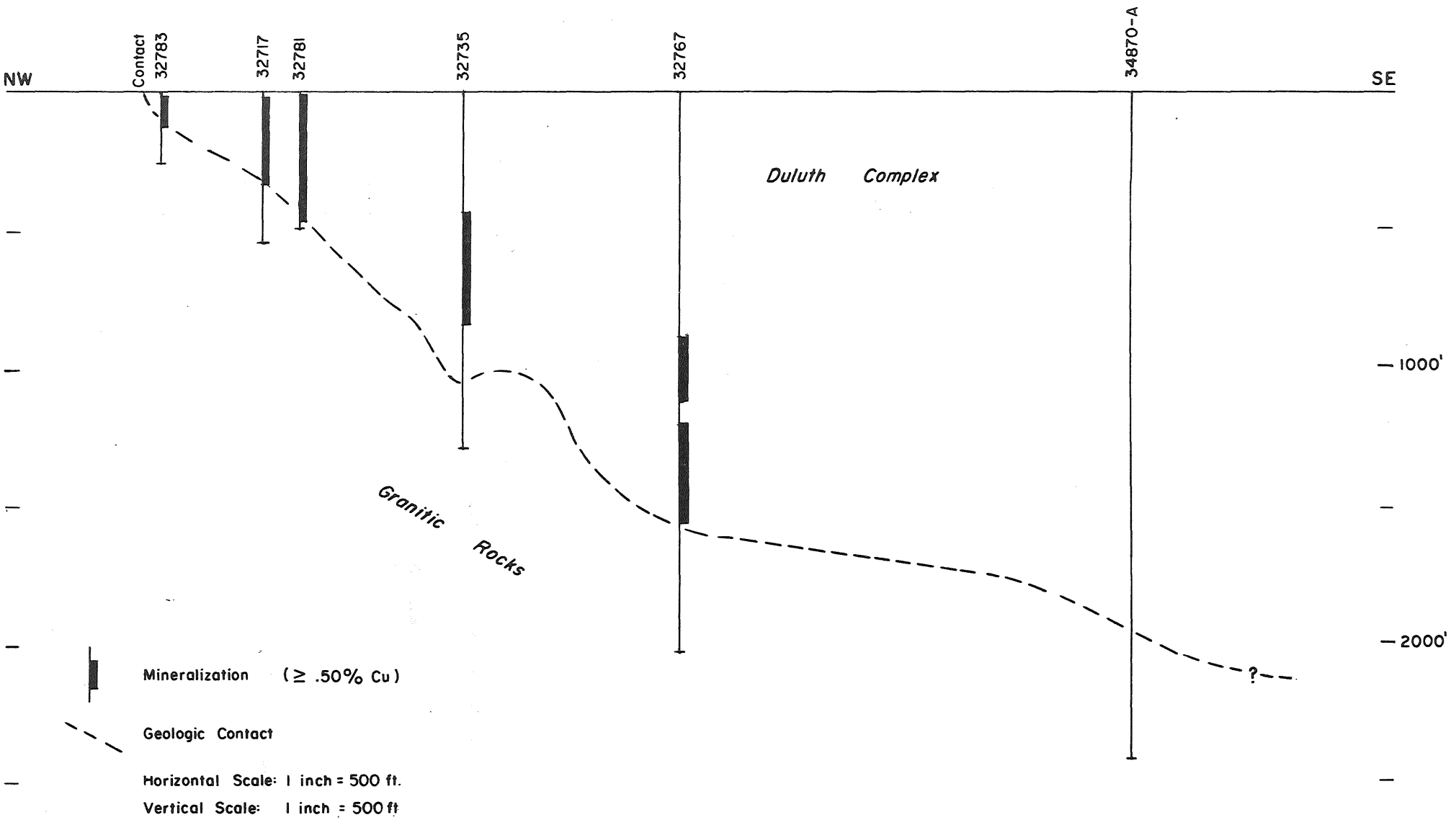


FIGURE 4: Cross Section A

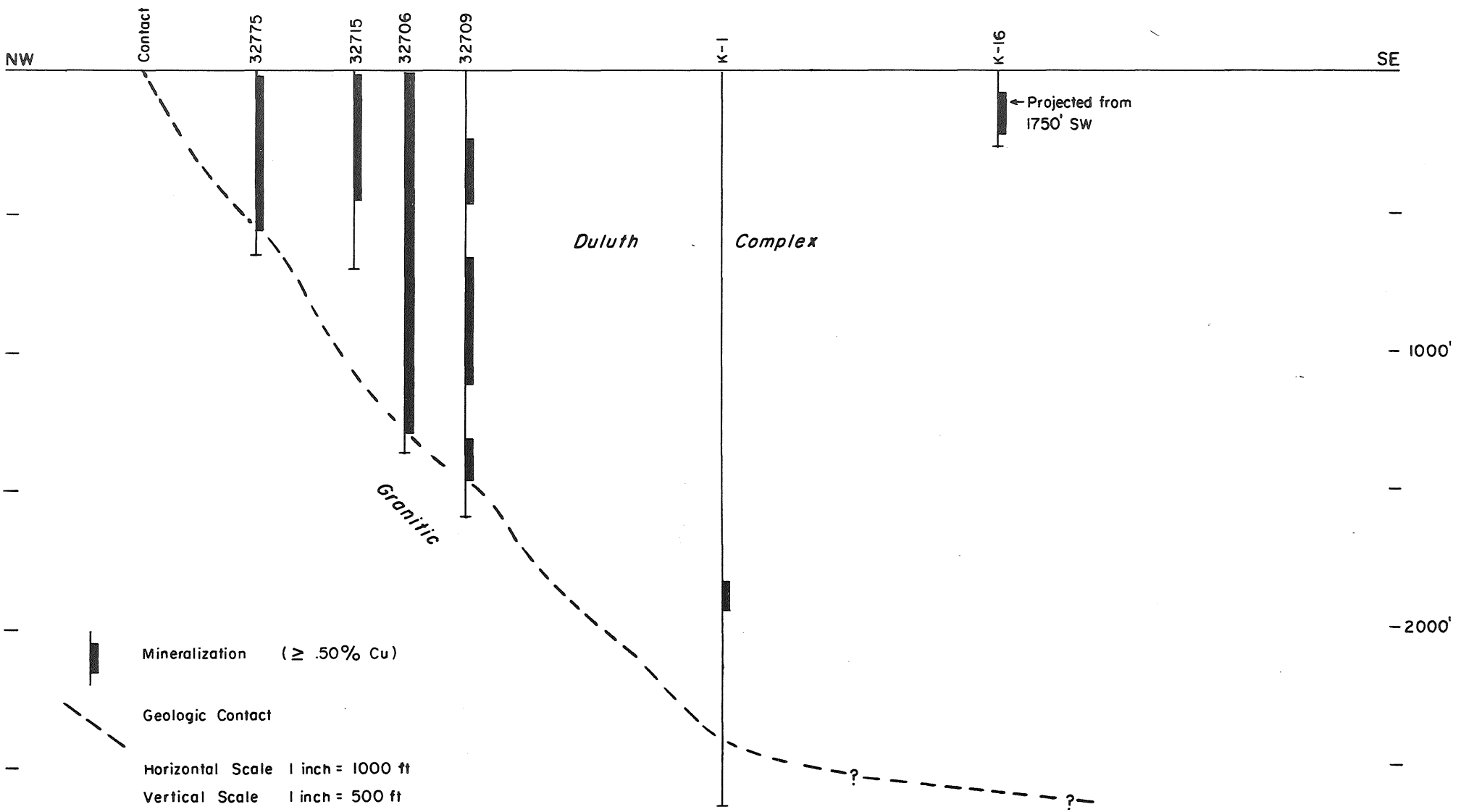


FIGURE 5: Cross Section B

Duluth Complex and is quite thick in this area (over 1,100 feet in places). The mineralization is also not always continuous, posing some correlation problems. Section B illustrates that all of the mineralization is not in the basal zone. The Hanna hole K-16 intersected over 200 feet of mineralization 6,000 feet away from the contact and over 2,000 feet above the base of the Complex.

Cross-sections C and D (Figures 6 and 7) are through the INCO-Hanna-Duval block of mineralization. Note that the mineralized zone in hole #3 on section C transects the Duluth Complex - granite contact. This is not an uncommon feature in the 324 holes used for this resource estimate. Section D again illustrates the irregularity of the $\geq$0.5% copper mineralization with regard to thickness and distance above the basal contact.

Cross-section E (Figure 8) is in the Dunka Pit area drilled by Newmont and Bear Creek mining companies. It illustrates the sporadic nature of the mineralization in this area and also the termination of the Virginia and Biwabik Formation's down-dip.

Cross-sections F and G (Figures 9 and 10) are in the Amax area. They illustrate both near-surface mineralization close to the contact and deeper mineralized zones from 1,000 to 9,000 feet away from the contact. Holes M-25 and BA-2 on section F have $\geq$0.5% copper zones that transect the contact into Virginia Formation and Giants Range Granite, respectively. Note the apparent irregular erosion of both the Virginia and Biwabik Formations shown on section G forming trough or basin structures. This feature is also noticeable on the structure contour map shown in Figure 2.

Cross-sections H and I (Figures 11 and 12) are in the U. S. Steel Dunka Road area. Section H shows the dip to be about 45° near the contact and flattening to about 20° at depth. The discontinuous nature of the

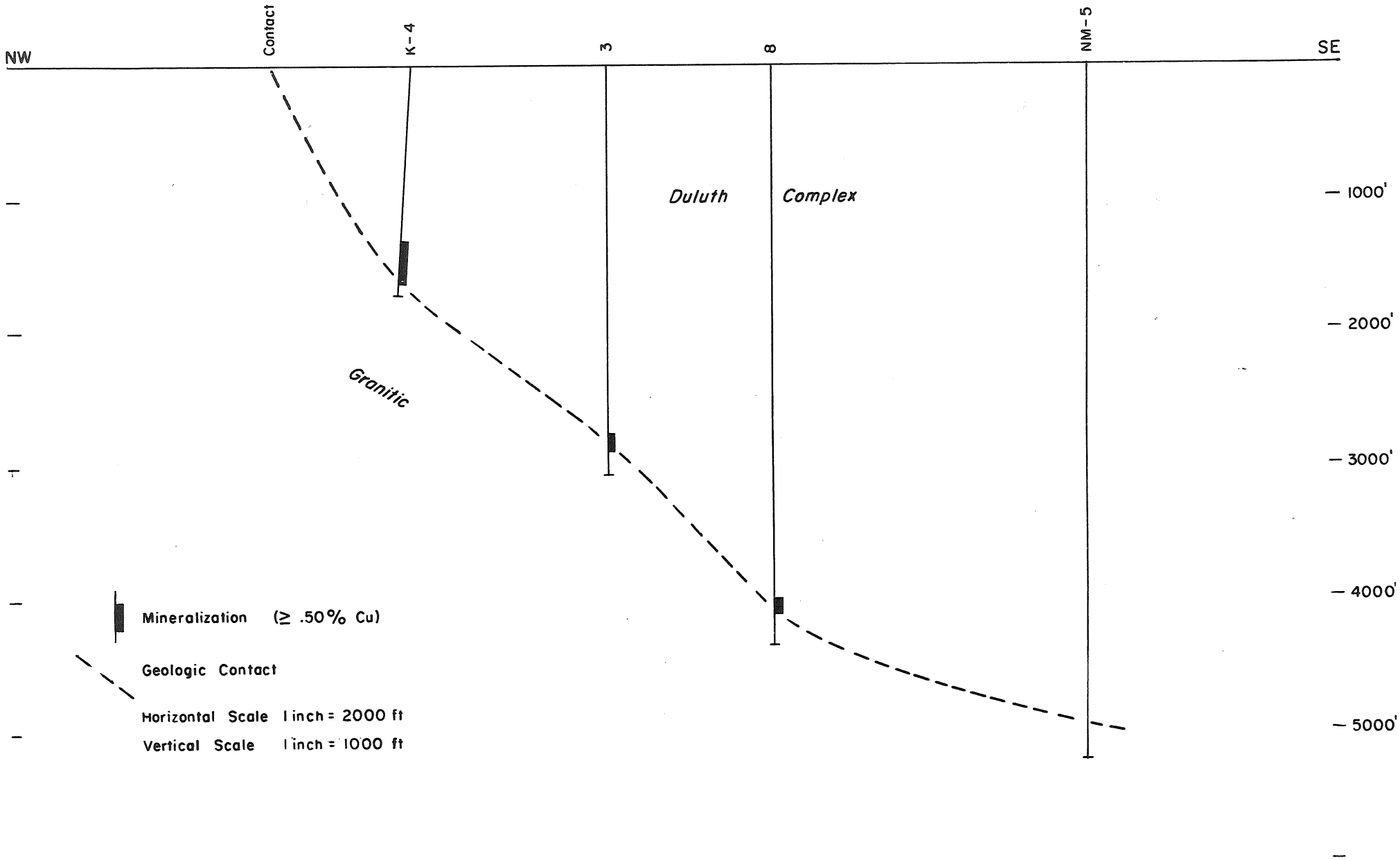


FIGURE 6: Cross Section C

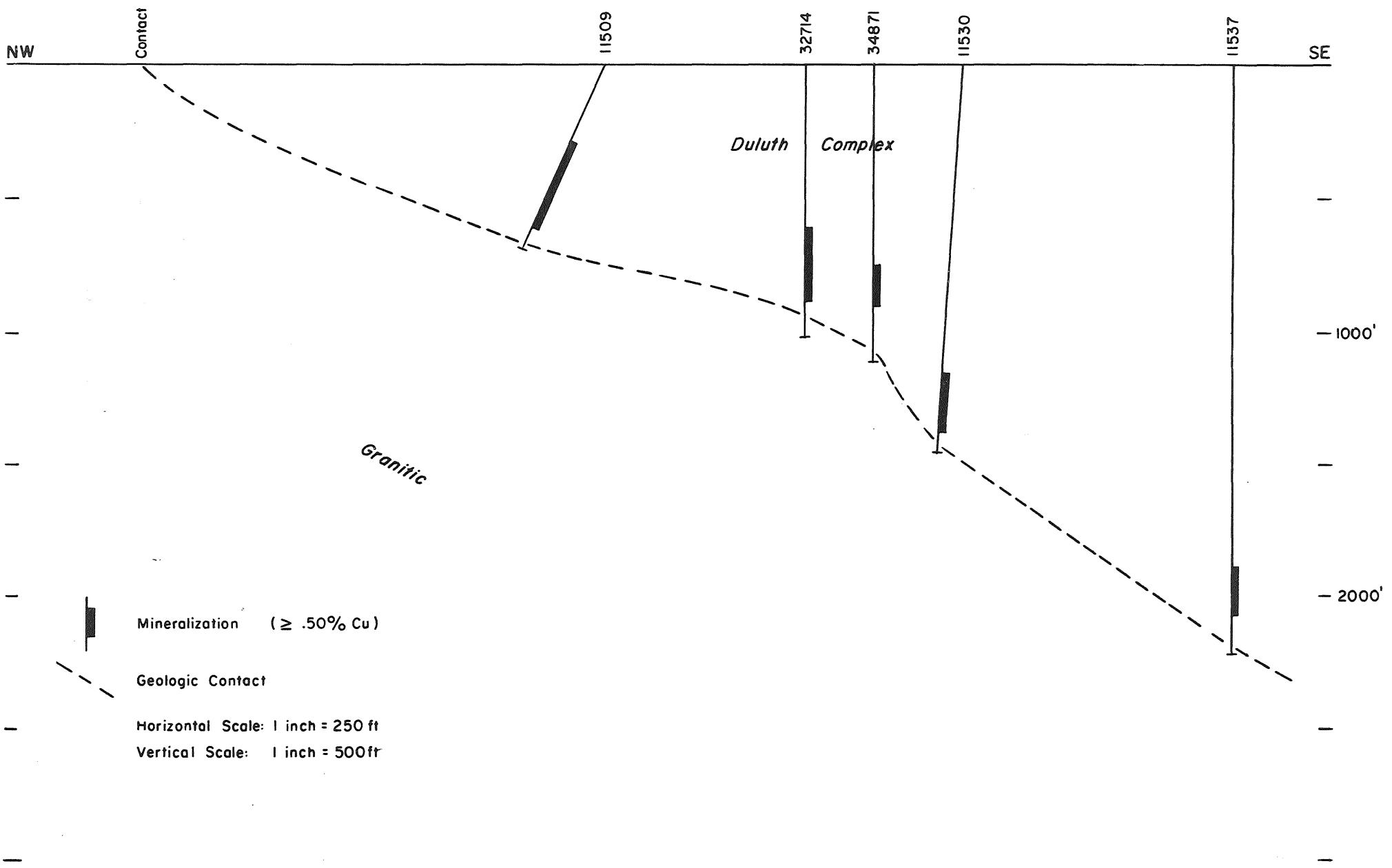


FIGURE 7: Cross Section D

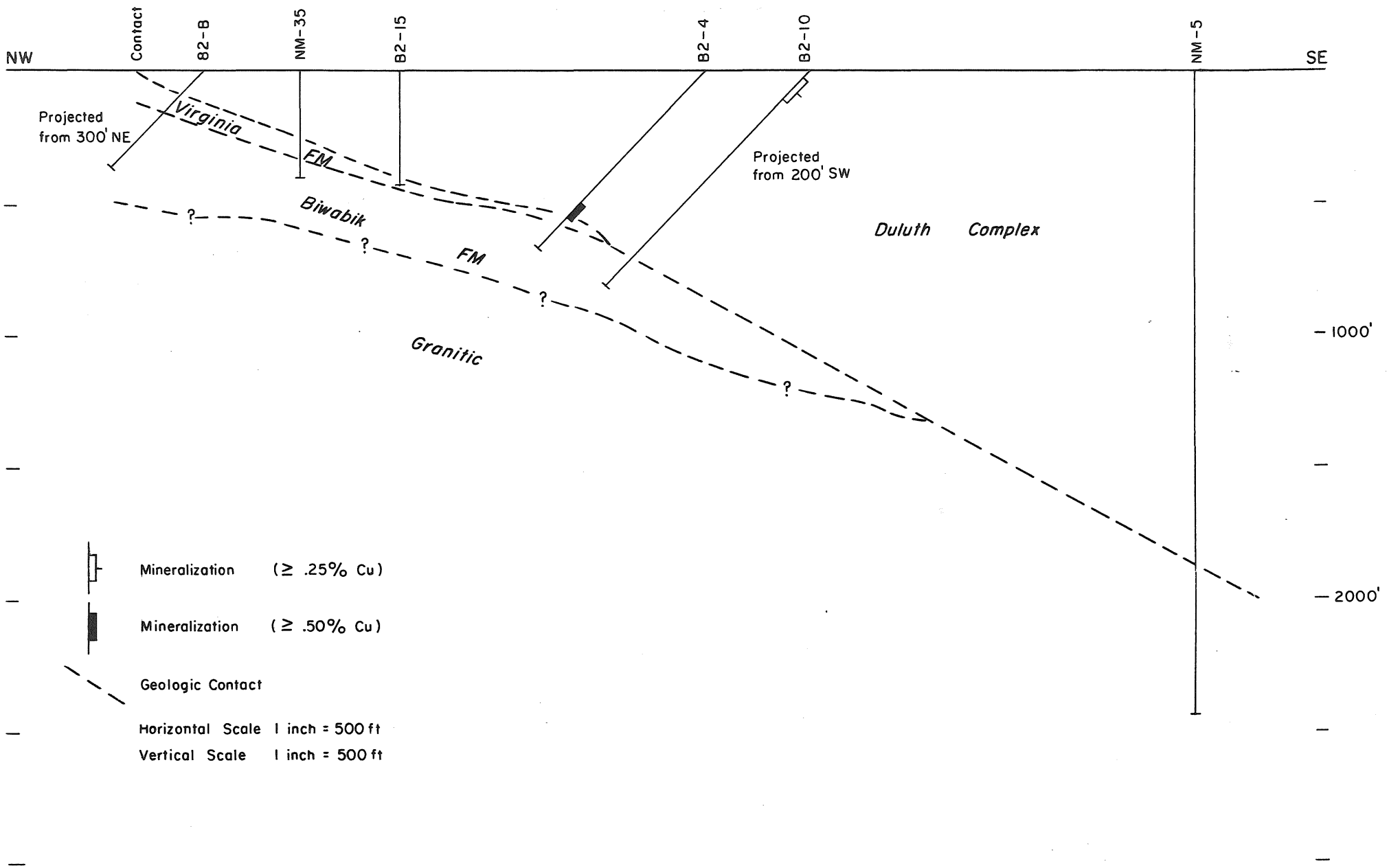


FIGURE 8: Cross Section E

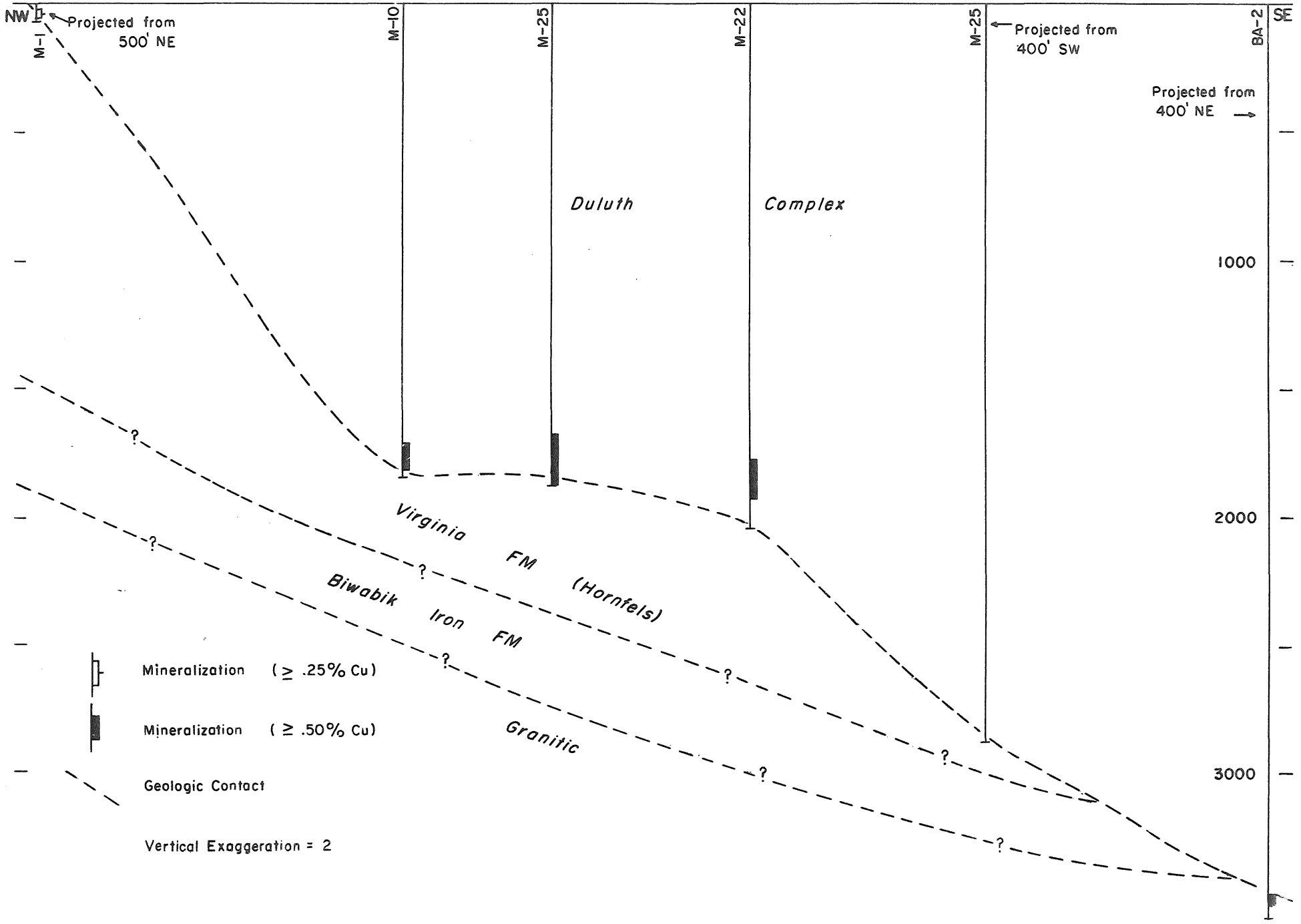


FIGURE 9: Cross Section F

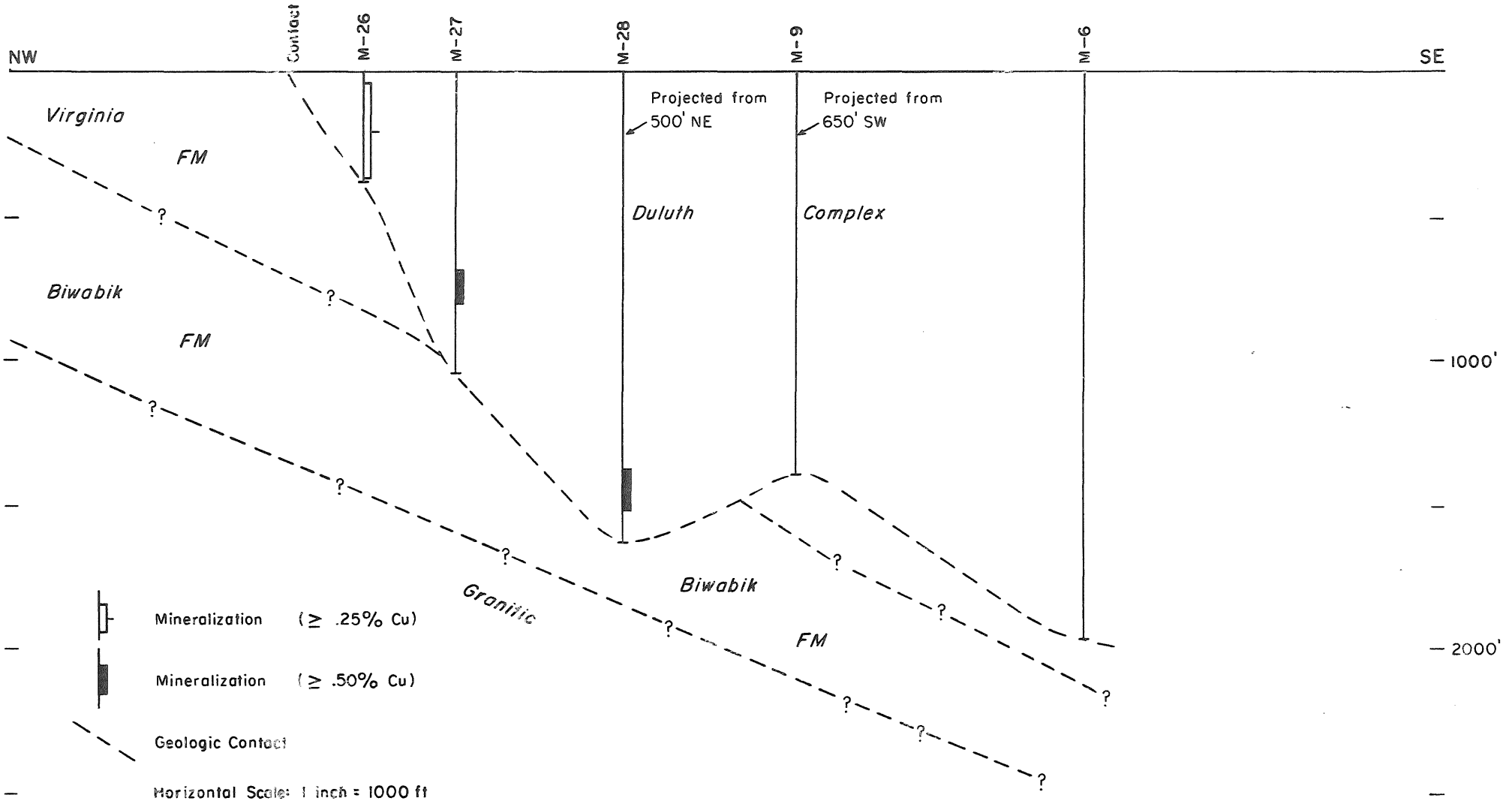


FIGURE 10: Cross Section G

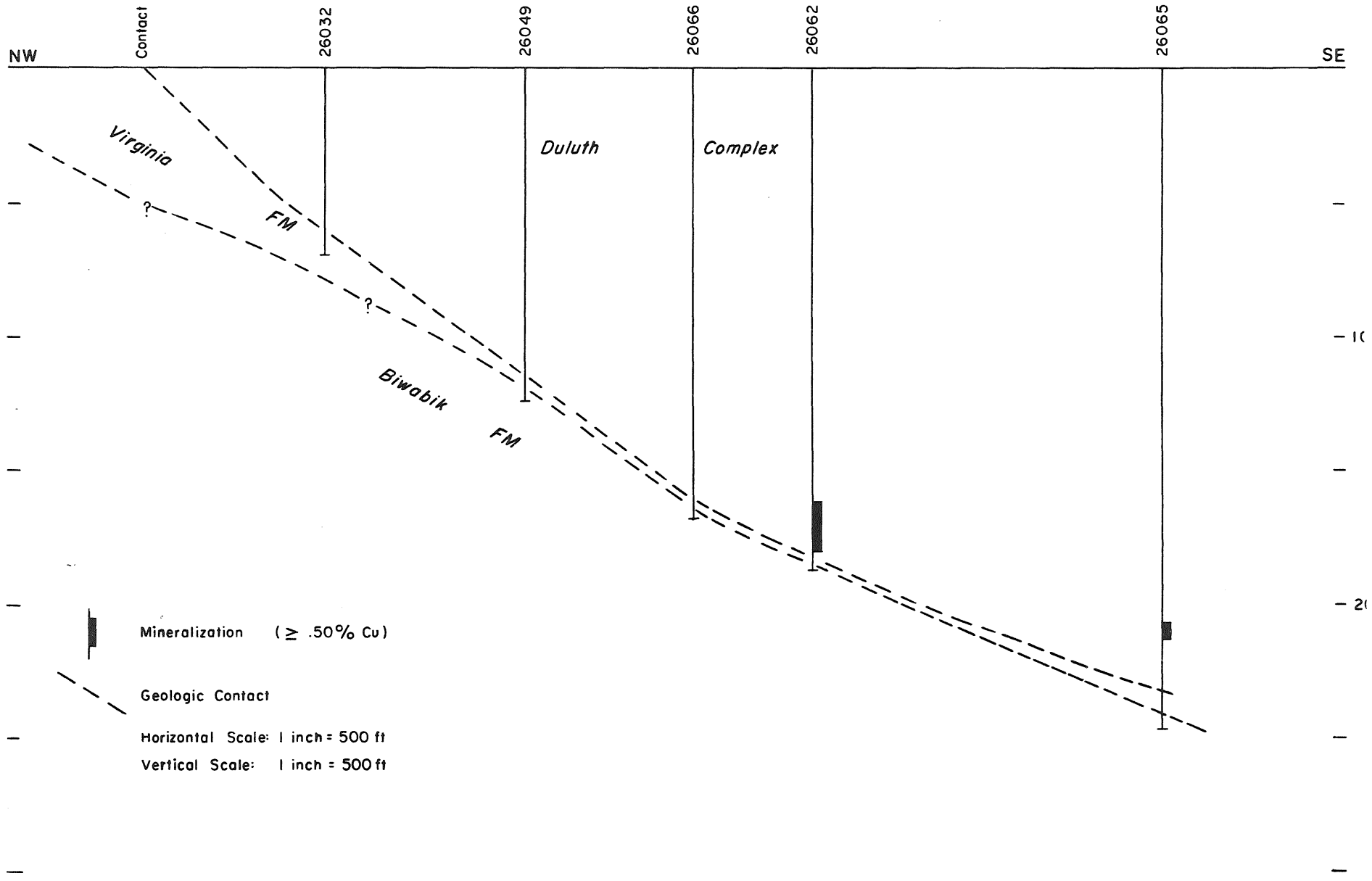


FIGURE 11: Cross Section H

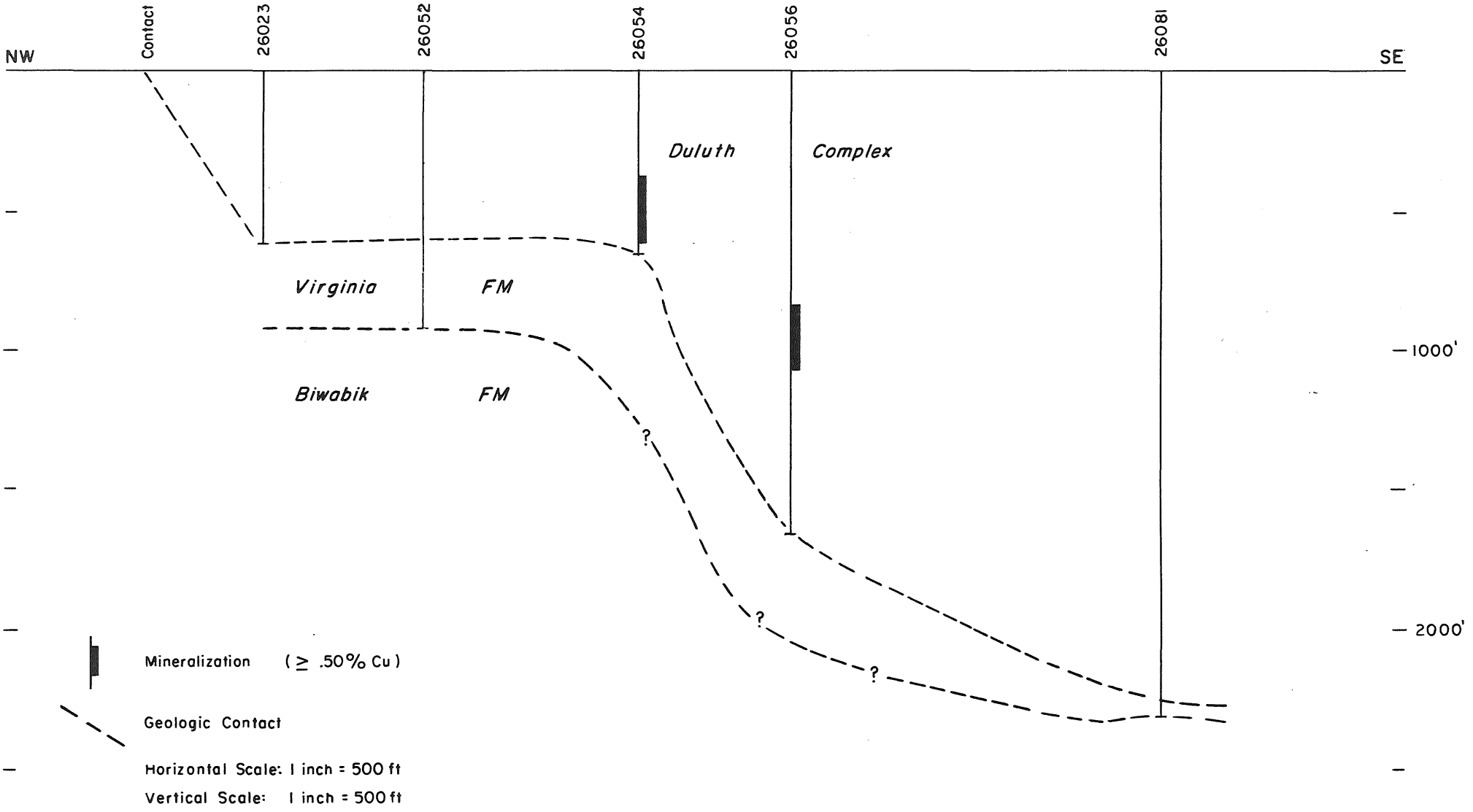


FIGURE 12: Cross Section 1

mineralization is also illustrated along with a thinning but persistent Virginia Formation. Section I shows some of the same features and pronounced changes in dip which could be caused by folding, faulting or erosion of the Virginia Formation.

Cross-section J (Figure 13) is in the area of the old Bear Creek Mining A4 grid, which is now being examined by Exxon. The section does show the near-surface mineralization and the irregular basal mineralization, but the most interesting feature shown is the abrupt change in dip near hole A4-3. Holes A4-4 and A4-5 have been projected onto this section and indicate significant changes in the depth to the footwall along strike as well as the sudden increase in depth to the base of the Duluth Complex down-dip. These abrupt changes in the footwall contact depth could again be caused by faulting, folding, erosion, or a combination of any of these processes.

Cross-section K (Figure 14) is in the Wyman Creek area explored by U. S. Steel. This section shows the sporadic mineralization and the thinning of the Virginia. The indicated dip along the basal contact is about 25° near the surface and flattens to about 15° with depth. Note also that the Biwabik Iron Formation is about 400 feet thick in hole 17700.

Cross-section L (Figure 15) is in an area drilled by INCO, near the St. Louis River. No mineralization meeting the minimum criteria was intersected, but the section shows the relatively even dip of about 35°.

The copper-nickel mineralization associated with the Duluth Complex is of two basic types, massive and disseminated. The disseminated sulfides are the main concern because massive sulfides are known only as thin units. The thin massive zones are known to contain over 10% copper, in some instances and are of definite interest. The main mineralization occurs as

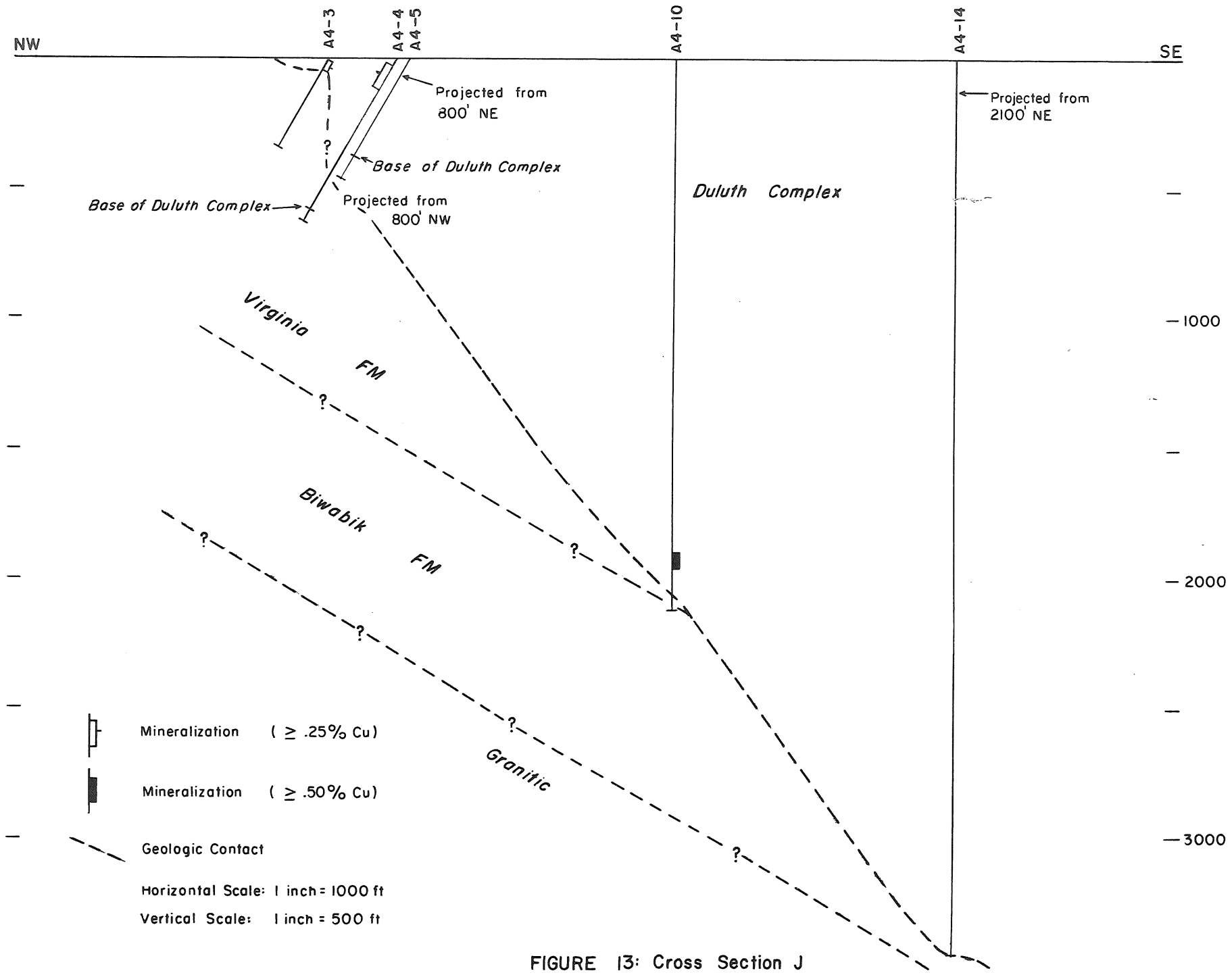


FIGURE 13: Cross Section J

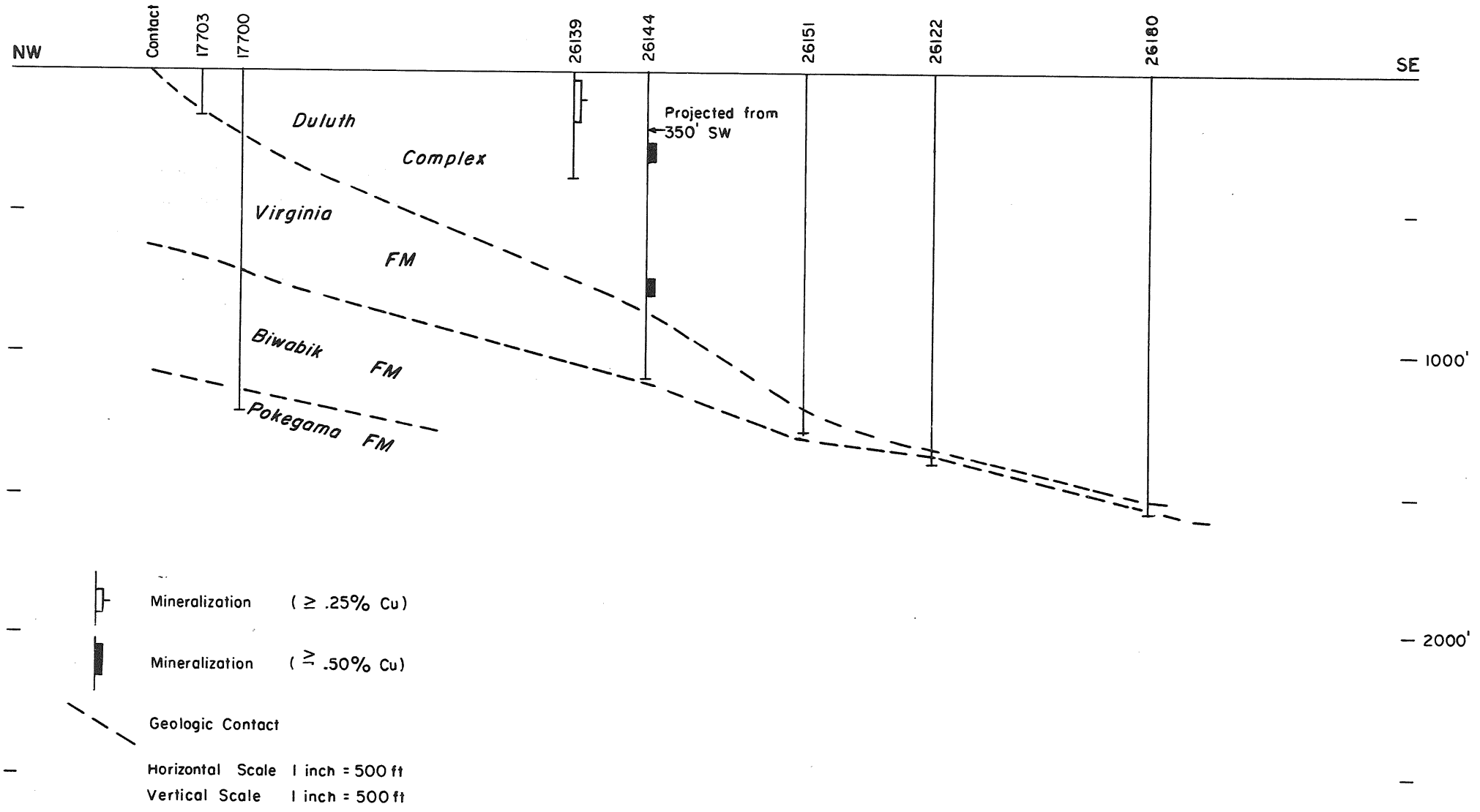


FIGURE 14: Cross Section K

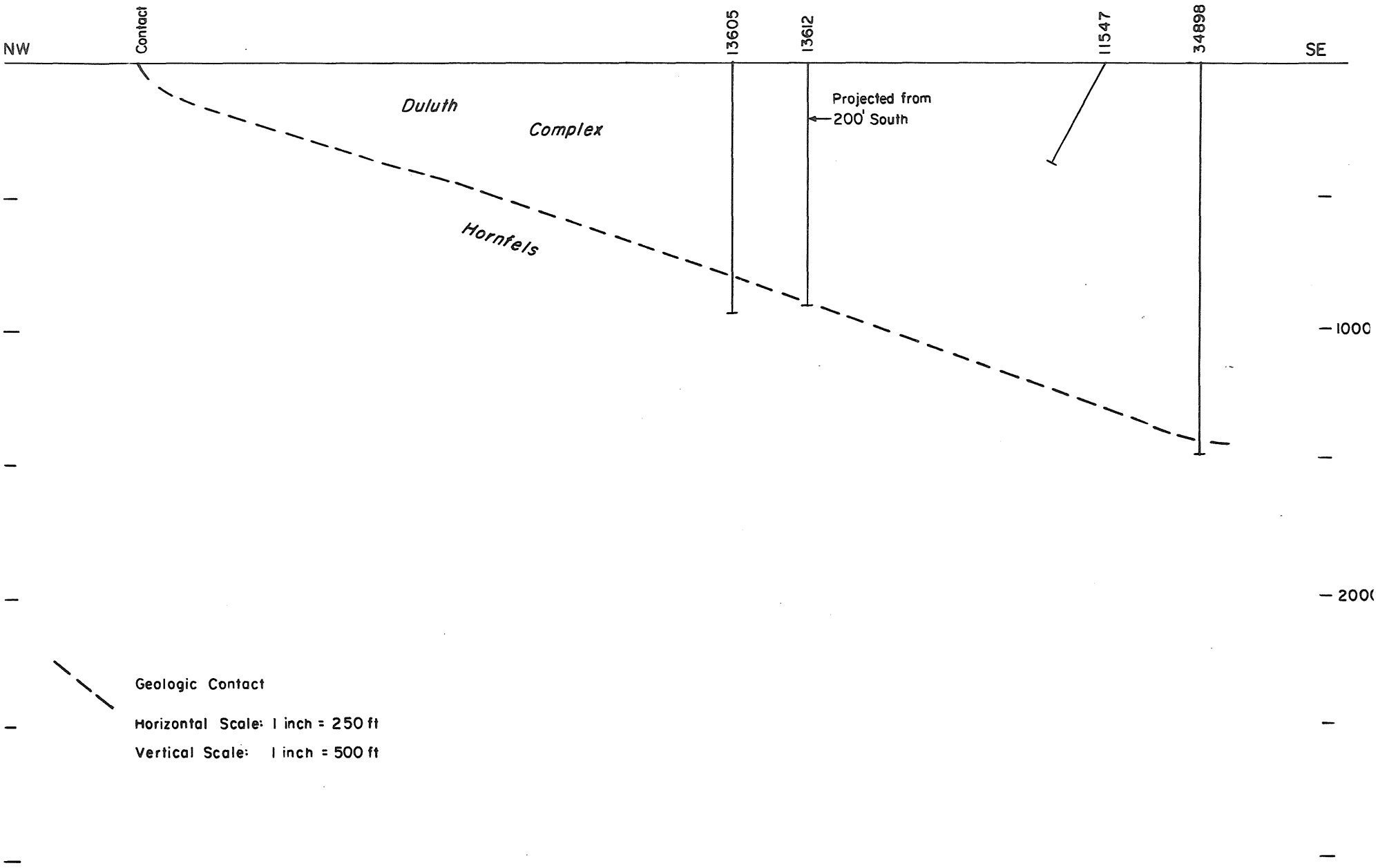


FIGURE 15: Cross Section L

disseminated grains, generally interstitial to the plagioclase laths. The sulfide minerals that occur are quite widely known. The major minerals are pyrrhotite, chalcopyrite, cubanite, and pentlandite. Minor to trace amounts of violarite, mackinawite, pyrite, sphalerite, and bornite are common. Boucher (1975) reports that bravoite, talnakhite, phase X, covellite, digenite, chalcocite, tenorite, cuprite, native copper, and galena have all been identified as occurring in the Duluth Complex. The reader is referred to Boucher (1975), Weiblen and Morey (1976), and Bonnichsen (1972) for more complete information on mineralogy and textures of the sulfides. The overall average grade of the disseminated mineralization, as determined during this study, is about 0.66% copper and 0.20% nickel. This mineralization that is associated with the Duluth Complex is not always in the basal zone nor is it always in the Duluth Complex rocks. Cross-section B illustrates the fact that there is mineralization higher up in the Complex, and that is not the only instance. Several other cross-sections show mineralization below the Duluth Complex and there are many such occurrences. Significant mineralization is known to occur at least 400 feet below the base in at least one instance in the Dunka Pit area.

The titanium mineralization is not well enough defined to say much about, except that it occurs mostly in ultramafic rocks or in the layered troctolitic rocks. It is not generally confined to the basal zone. The major oxide minerals are magnetite, ilmenite and other spinels.

Polygon Method of Resource Estimation

Data acquired for this study included data from about 500 drill cores, mostly within two miles of the outcropping or sub-outcropping basal contact. The types of data available for these holes varied significantly,

and some of the holes did not meet designated minimum data level requirements and could not be used in the resource estimate. In order to qualify for use, it must be known whether or not the hole contains mineralization that meets the specifications which consist of the following three types: Type 1 is a minimum vertical thickness of 50 feet of $\geq$0.5% copper; Type 2 is a minimum vertical thickness of 100 feet of $\geq$0.25% copper in the top 100 feet of the core or core less than 100 feet in length if the base was reached by drilling less than 100 feet and the core was mineralized throughout; Type 3 is a minimum vertical thickness of 50 feet of $\geq$10% TiO_2. Holes that do not indicate any of these types of mineralization qualify for use in the estimate if they were drilled all the way to the footwall. Three hundred twenty-four holes were used in the resource estimate because they met the criteria outlined above, and the locations of these drill holes are shown on Figure 16.

Several assumptions were required in order to make this resource estimate within the allotted time and with the data available. The most important assumption is that of continuity of mineralization between drill holes. The mineralization was assumed horizontal for the purposes of this estimate. All thicknesses for angle holes were corrected to vertical thickness, thus eliminating the possibility of inflating the tonnage. This was done by multiplying the core thickness of the mineralized zones by the sine of the angle at which the hole was drilled.

The mineralized intervals used were determined by mining company geologists and by Minerals Division geologists using the grades of the mineralization types listed above as cutoff grades. Mineralization significantly below the cutoff grades were not included unless they were thin and bounded by zones above the cutoff grade. The average grades for any zone were greater than or equal to the cutoff grades.

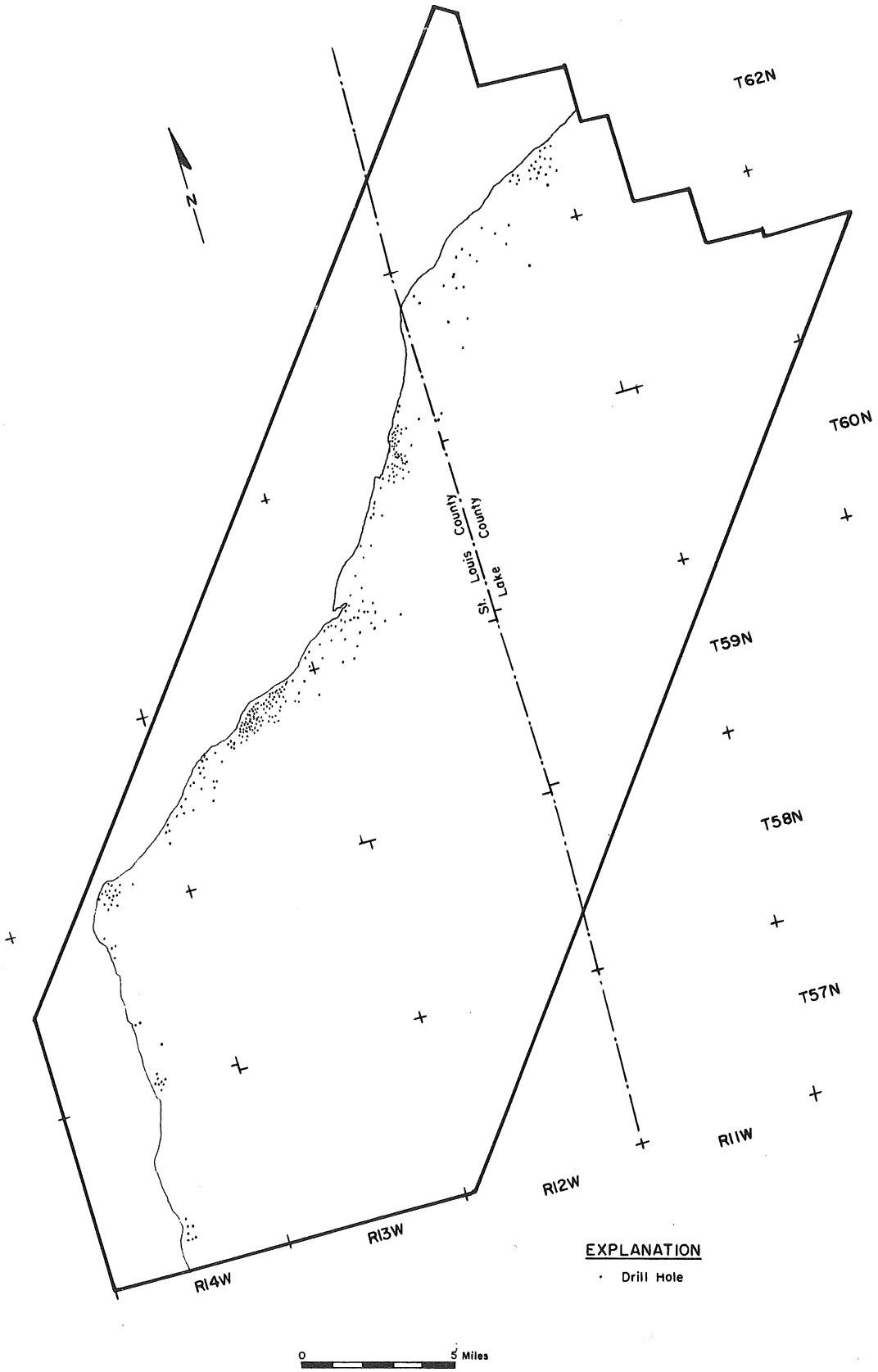


FIGURE 16: Drill Hole Location Map

The surface intersection of the basal contact of the Duluth Complex was determined by using the best data currently available. A difference of opinion as to the location of the contact exists between the Minerals Division and the MGS, so the estimate was made using both versions. The basal contact limits the polygons on the up-dip side, but a system had to be devised for limiting the polygon area down-dip. A standard method, described in Parks (1949), of using perpendicular bisectors for polygon construction was used for this estimate. In order to complete the perimeter polygons, a method was devised whereby incomplete polygons on the down-dip side were completed by scribing arcs, of a radius equal to half the distance to the nearest hole, around such holes and connecting tangents between arcs. The perpendicular bisectors were then drawn to the tangent lines. Figure 17 shows a typical polygon area with the contact, scribed arcs, and tangents to illustrate the method used. Several interpretations are still possible, resulting in variably-sized perimeter polygons. Two methods were used in this estimate; one was totally subjective, drawing tangents only between those arcs which resulted in polygons of reasonable and conservative sizes; the second method used the rule that where the perpendicular bisectors on a down-dip hole converged at an angle less than 45^{o}, an arc was scribed and tangents drawn each way to the next such arc. There was no consistent difference between the polygons produced by the two methods, and, therefore, the second (45^{o} rule) was used for the principal estimates.

The area measured, and therefore the tonnages calculated, vary with the methods and contact locations used. The estimates given in this section was one of several variations. The other estimates vary only in the sizes of the outermost polygons. When first done, tangent lines were

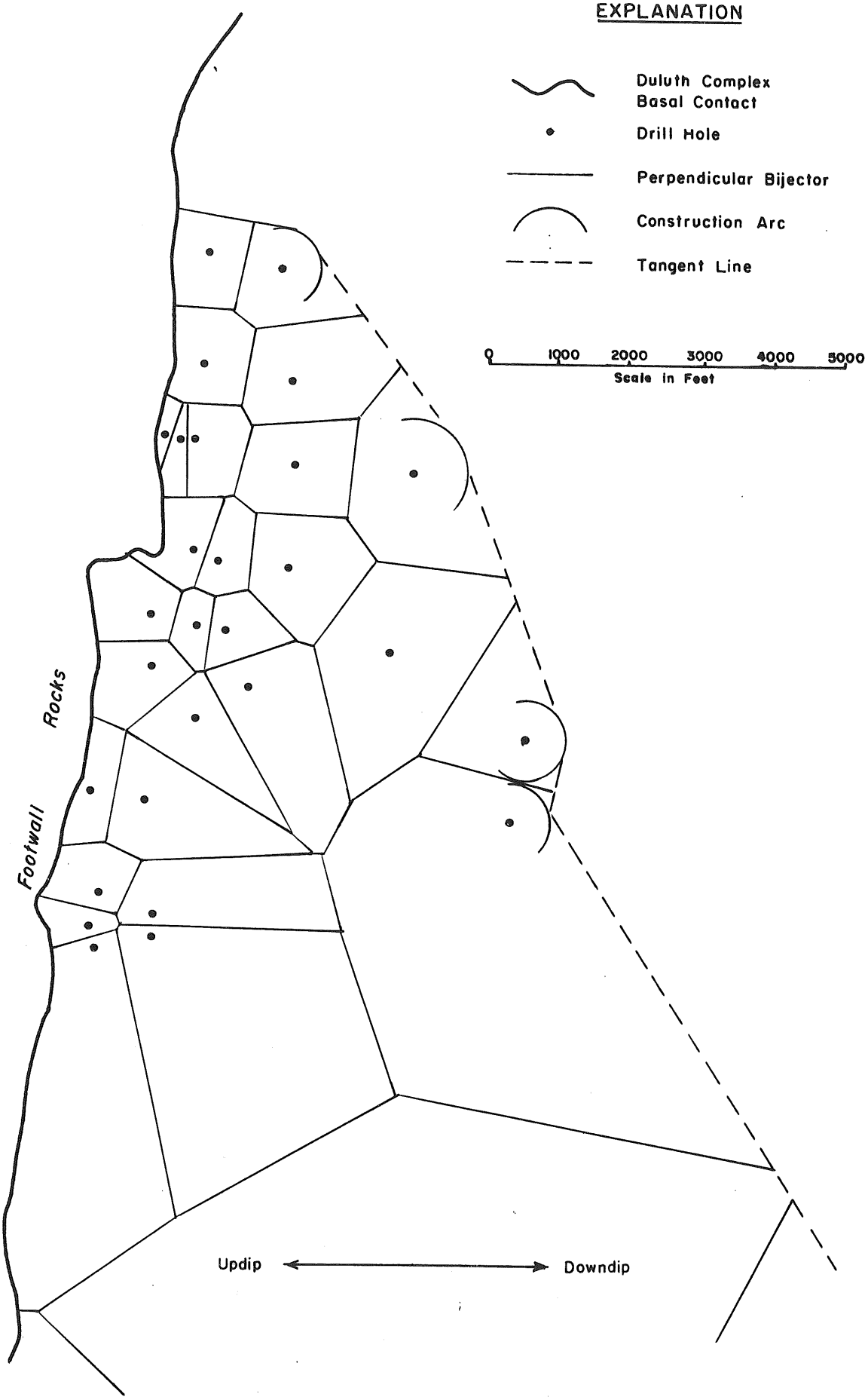


FIGURE 17: Typical Polygon Area

drawn between arcs only where it seemed the reasonable thing to do. The uniform application of the 45° rule resulted in a net gain of 148 million tons, losing tons in some areas and gaining in others. The other major variation tried, using the basal contact location preferred by the MGS, resulted in a net gain of 144 million tons of $\geq$0.5% copper mineralization and a net loss of 5 million tons of $\geq$0.25% copper material.

The polygons were constructed on two base maps, one on a 1:24000 scale map used for all areas except the Dunka Pit area, and a 1:4800 scale map in the Dunka Pit area. The polygons were drawn and measured on the same maps, and areas were determined by averaging several measurements by planimeter. The areas of the polygons were multiplied by the vertical thicknesses of the mineralized zones and divided by the tonnage factor of 11 ft^3/ton to arrive at the tonnages for each mineralization type.

The resultant polygons vary widely in sizes, depending on the amount of data available in any given area. The largest polygon measured was 1.7 square miles and the average polygon was 0.13 square miles. The largest polygon with mineralization $\geq$0.5% copper was 1.4 square miles with the average being 0.11 square miles. The average barren polygon was 0.14 square miles. The total area measured for this study was 42.2 square miles, or about 7.6% of the approximately 560 square miles in the study area, and about 9.8% of the 430 square miles of Duluth Complex in the study area.

The mineral resources in the study area, as shown by this estimate, are quite substantial. The estimates were derived using the contact location preferred by the Minerals Division geologists and the 45° rule for limiting down-dip perimeter polygons. The calculations for resources grading $\geq$0.5% copper total over 4.4 billion tons. One hundred sixteen of the 324 holes contained mineralization which met the $\geq$0.5% copper criterion.

That represents 36% of all holes considered, and those polygons cover 31% of the total area measured. The indicated near-surface mineralization grading $\geq$0.25% copper is over one billion tons. The resource total for material $\geq$10% TiO_2 is over 200 million tons.

Figure 18 is a map showing location of the major concentrations of the three types of mineralization shown by this study. Four major concentrations of the $\geq$0.5% copper mineralization can be seen on the map. These are, from north to south, the INCO Spruce Pit area (700 million tons); the INCO-Duval-Hanna block (2.3 billion tons); the Amax area (800 million tons); and the U. S. Steel Dunka area (300 million tons). Scattered small areas of this type of mineralization occur elsewhere along the contact.

There are two major areas of near-surface mineralization indicated on the map, the INCO Spruce Pit area and in the Amax area. The Spruce area data indicates over 360 million tons of material grading $\geq$0.25% copper, and the Amax area estimate is over 310 million tons of similar grade. These two mineralized zones are indicated by contiguous polygons on the map. Significant tonnages (300 million tons) are indicated in the Dunka Pit area as several isolated polygons. A few small scattered indications do occur elsewhere along the contact, but the above three areas account for over 90% of near-surface ($\geq$.25% Cu) resource.

The titanium resources indicated total over 220 million tons $\geq$10% TiO_2 located in three small areas. The largest of the three areas is the southernmost, the Water Hen area, with an estimated tonnage over 100 million tons. This type of mineralization may be a significant resource in the study area, but it appears that little exploration for this specific type of resource has been done.

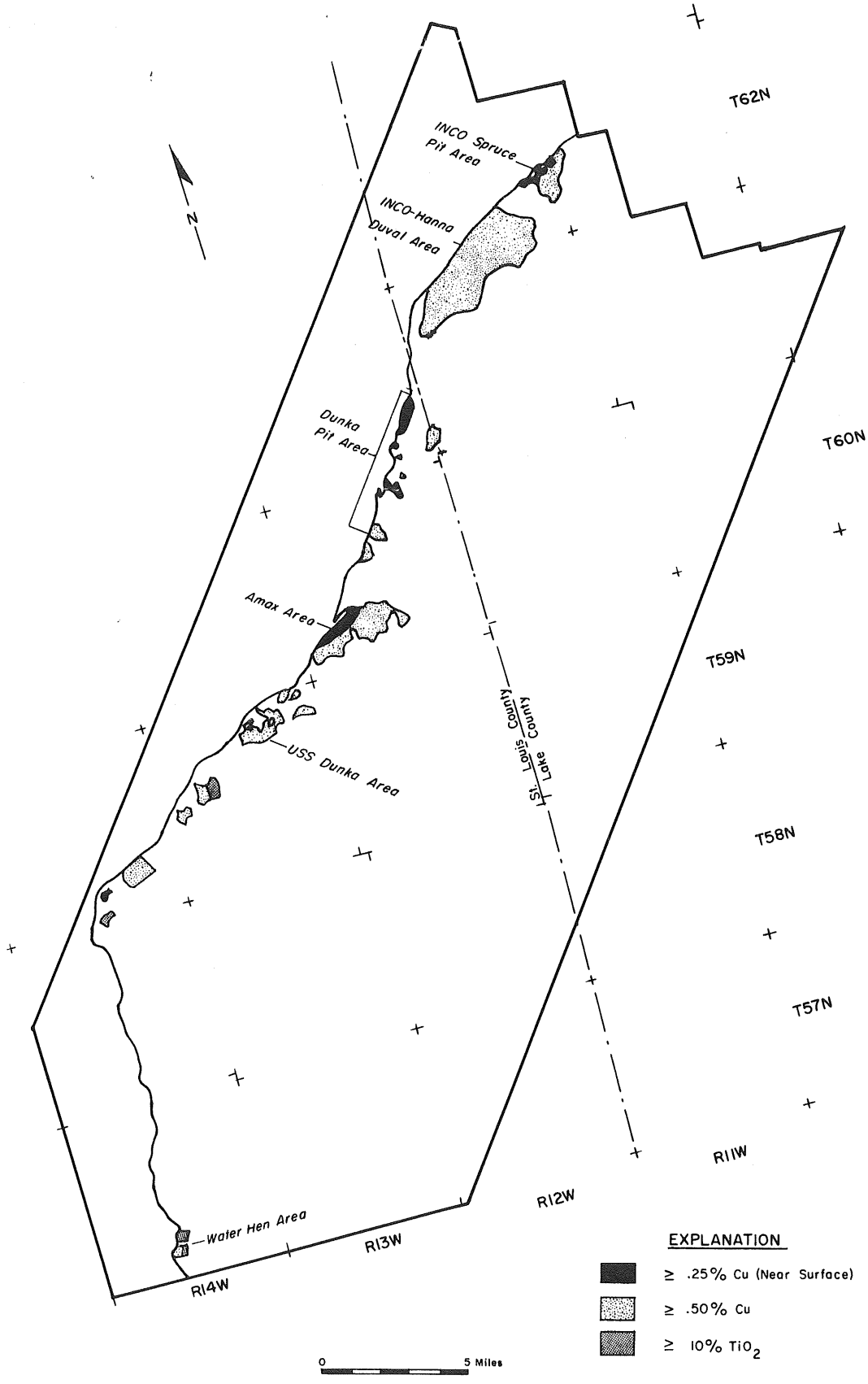


FIGURE 18: Mineralization Location Map

Assay Data Resource Study

The purposes of this study were to develop average grade figures and to see what the effect of lowering the cutoff grade was on the tonnage estimate. This was done using only those holes for which complete assay data was available. This amounted to 122 holes or 38% of the total number of holes used in the main estimate. New polygons were not constructed--the same area of influence was used in this calculation as was used for each hole in the main estimate. The polygons for these holes represent 62% of the area measured in the main estimate. The average area for these 122 polygons is 0.22 square miles, which is significantly larger than the average for the whole study because of a lack of complete assay data for the most heavily drilled areas. The largest polygon of those in this study is 1.7 square miles, the largest polygon with $\geq$0.5% copper mineralization is 1.4 square miles, and the average size of the mineralized ($\geq$0.5%) polygons is 0.29 square miles. Although the polygons are larger than in the complete study, the average thickness of the $\geq$0.5% copper zones in these holes is 126 feet and is 134 feet in the complete estimate.

The mineralization criteria, methods of calculation, and polygon areas are exactly the same as were used in the main resource estimate, but we were able to get a few extra statistics out of this data. For this study, a calculation similar to the $\geq$0.5% copper estimate was made using $\geq$0.25% copper to see what the relationship between tonnage and grade was for these holes. We were also able to determine the actual grades for the estimated tonnages. No titanium estimate was attempted for this study.

The $\geq$0.25% copper in the near-surface mineralization estimate is over 380 million tons or 34% that of the larger study. The average grade calculated for this mineralization is 0.34% copper.

The ≥0.5% copper estimate for these holes was over 2.6 billion tons. Twenty-nine of the 122 holes (24%) were mineralized, and their polygons covered 32% of the area. The tonnage estimated is 59% of the total estimated in the whole copper-nickel study area. The average grade of the 2.6 billion tons is 0.66% copper.

Lowering the grade in the ≥0.5% copper estimate to ≥0.25% copper has the effect of increasing the tonnage by a factor of 2.5 to over 6.6 billion tons. The overall grade of this material is about 0.45% copper. When using the reduced grade, 77 of the 122 holes (63%) are mineralized, and the polygons equal 64% of the total area.

Other Methods of Grade and Tonnage Estimation

To check on the distribution of copper assay values reported in our data, a frequency curve was plotted using 5,293 individual assays. The assay interval had to be ≥5 feet in core length to be used. Shorter intervals were weighted and averaged with adjacent intervals to make at least a five foot total length. The assay values were grouped in intervals of 0.1% (0-.099, .1-.199, etc.) and plotted in percent of the total assays. The resultant curve is shown in Figure 19. The assays from 0-1.4% copper account for 99.9% of the total number of assays that were available to the MDNR for this estimate.

Several calculations were completed, based on this data and the ≥0.5% copper estimate, to determine tonnages and average grades using various cutoff grades. The necessary assumptions are that the curve, which is based on individual assays, is statistically valid, and that it is appropriate to use the tonnage estimate which is based upon 50 foot minimum thicknesses in conjunction with a curve of this type. The curve can be drawn in two ways; a smooth curve can be drawn through all the points

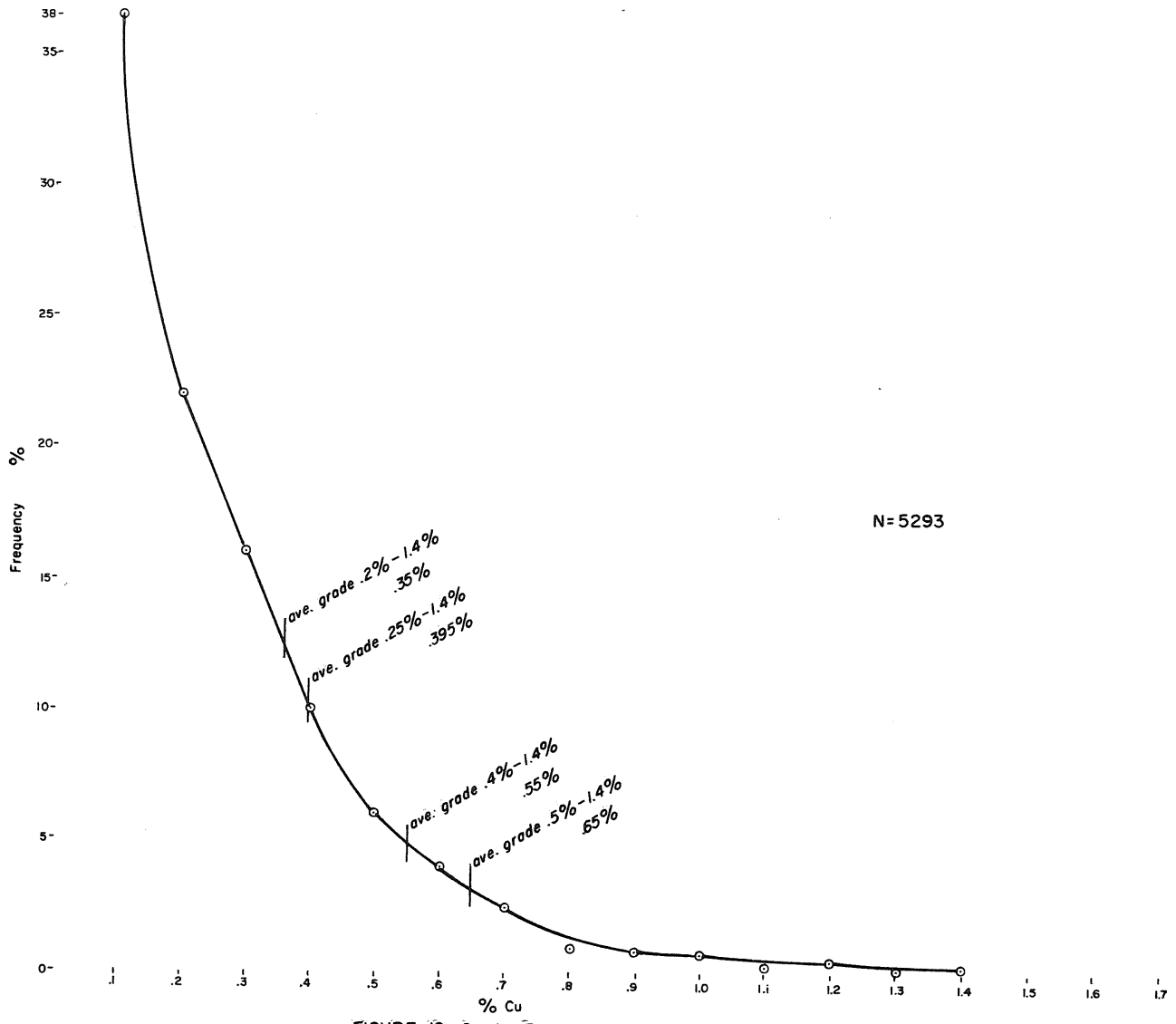


FIGURE 19: Grade-Frequency Curve

except those three below the line (Figure 19), or straight lines can join all of the data points. For the purposes of these estimates, the smooth curve was used because of the smaller increase factor when the cutoff grade is lowered. When the area under the curve from 0.5% copper to 1.4% copper is assumed to represent the 4.4 billion tons of $\geq$0.5% copper in the polygon estimate, several things can be done. The average grade can be calculated by finding the grade that divides the area in half, and this comes out to be about 0.65% copper. Lowering the cutoff grade to 0.25% copper increases the tonnage to over 14 billion tons with an average indicated grade of 0.39% copper. This is an increase factor of about 3.2. When the straight line plot is used, the increase factor is about 3.3.

If the frequency percentages for each of the intervals on the graph (Figure 19) are determined to the nearest tenth of a percent, they are as shown in Table 2. The intervals from 0.5% - 1.4% total 9.4% of all assays used. If that is equated to 4.4 billion tons, that means that 0.1% frequency is equal to about 47 million tons. Based on this assumption, over 15 billion tons are indicated between 0.25% copper and 1.4% copper. The increase factor by lowering the cutoff grade from 0.5% to 0.25% is 3.4 by this method. The average grade, calculated by taking the frequency percent of each interval times the middle grade of each interval (.25%, .35%, etc.) and dividing by the total percent of all intervals under consideration, is 0.44% copper with the 0.25% copper cutoff grade. The average grade using the 0.5% copper cutoff is 0.70% copper, by the same method.

These methods allow a reasonable comparison with Bonnichsen's estimate (1974) of copper-nickel resources, with respect to both grade and tonnages. Using Bonnichsen's 3:1 Cu:Ni ratio and his combined copper-nickel grades of 0.5% and 0.25%, the cutoff grades for percent copper can

TABLE 2: Assay Frequency - Tonnage Calculations

Copper Assay Range	Frequency in Percent	Projected Tonnage
0 - .099	37.9	17,813,000,000
.1- .199	21.9	10,293,000,000
.2- .299	15.5	7,285,000,000
.3- .399	9.5	4,465,000,000
.4- .499	5.7	2,679,000,000
.5- .599	3.7	1,739,000,000
.6- .699	2.4	1,128,000,000
.7- .799	0.9	423,000,000
.8- .899	0.9	423,000,000
.9- .999	0.7	329,000,000
1.0-1.099	0.3	141,000,000
1.1-1.199	0.3	141,000,000
1.2-1.299	0.1	47,000,000
1.3-1.399	0.1	47,000,000
	99.9	

Assumption: .5% Cu - 1.4% Cu = 9.4% frequency $\cong$ 4.4 billion tons

Therefore: 0.1% frequency $\cong$ 47 million tons

.4% - 1.4% $\cong$ 7.0 billion tons

.3% - 1.4% $\cong$ 11.5 billion tons

.25% - 1.4% $\cong$ 15.1 billion tons

.2% - 1.4% $\cong$ 18.8 billion tons

The increase factor from a .5% cutoff to a .25% cutoff is 3.4.

be lowered to 0.4% copper and 0.20% copper to give reasonable comparisons. Results from the frequency graph (Figure 19) show over 7 billion tons with a 0.4% copper cutoff and an average grade of about 0.55% copper. Using the 0.20% copper cutoff, the total is over 17.5 billion tons with an average grade of about 0.35% copper.

By using the percentages shown in Table 2 and the same cutoff grades, 7.2 billion tons averaging 0.60% copper and 18.8 billion tons averaging 0.41% copper are indicated by this method. The increase factors for these two calculations are 2.5 and 2.6, respectively, as compared to the 2.5 increase factor found by Bonnichsen. The average grades given by Bonnichsen for his calculation A are 0.84% and 0.55% combined copper-nickel (see Table 1). This would be equivalent to 0.63% copper and 0.41% copper, respectively. The statistics presented here show that, in terms of average grades, these estimates and Bonnichsen's agree very well, but that Bonnichsen's estimates of the tonnages were indeed conservative. With 13.5 times as much data, the resource has increased by over one billion tons, and we consider these estimates to be conservative. It is felt that if his estimates were not conservative, the tonnages would decrease as the data increased.

Iron Resources

The iron resource of the Copper-Nickel Study area has not been estimated as the other known mineralization was. Data was not as readily available for this resource, particularly in regard to grade and the thicknesses of the members. Information was collected on the total thickness of the Biwabik Formation. Figure 20 shows some of the hole locations and the general location of the major rock units in the area. Table 3 lists the pertinent data for each of the holes. The core

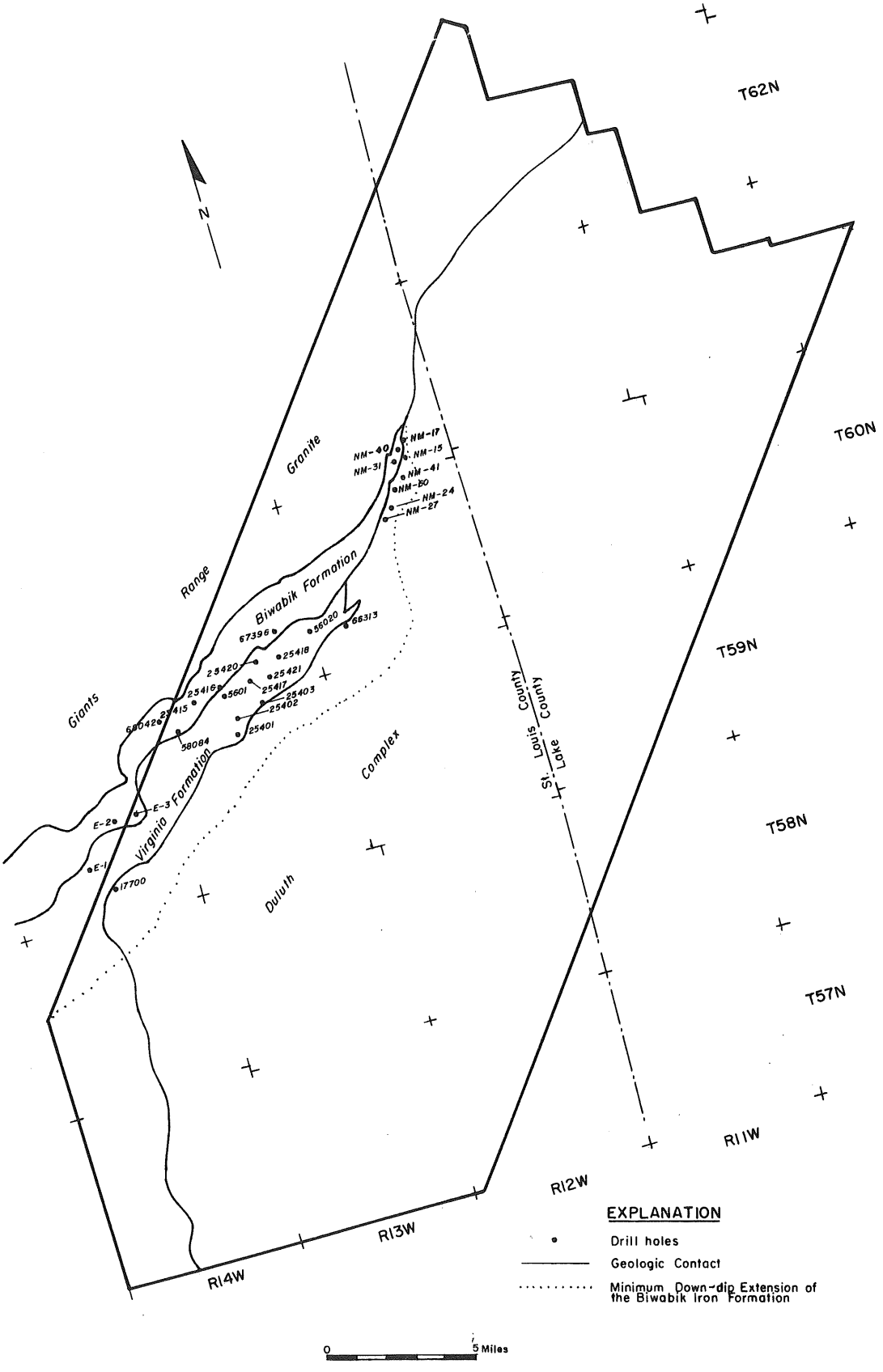


FIGURE 20: Biwabik Iron Formation Drill Data

TABLE 3: Biwabik Formation drilling data

Company	Hole #	Footage	Total Thickness in Feet	
Newmont	NM-17	528 - 735	207	
	NM-40	101 - 365	264	
	NM-15	482 - 690	208	
	*NM-31	170 - +321	+151	209 Ave.
	*NM-41	219 - +400	+181	
	NM-60	350 - 530	180	
	NM-24	382 - 625	243	
	NM-27	449 - 605	156	
Reserve	66313	1,002 - ?		
	5602	74 - 476	402	
	67396	6 - 358	352	
U. S. S.	25418	72 - 476	404	
	25420	67 - 484	417	
	25421	190 - 465	275	
	25403	386 - 776	390	
	25417	45 - 435	390	
	25416	7 - 413	406	
Reserve	5601	40 - 449	409	375 Ave.
U. S. S.	25402	417 - 849	432	
Reserve	70044	22 - 306	284	
U. S. S.	25415	14 - 438	424	
	25401	877 -1,275	398	
Reserve	68042	3 - 256	253	
	58084	21 - 412	391	
Erie	E-3	7 - 495.5	488.5	
	E-2	24 - 525	501	
	E-1	242 - 771	529	489 Ave.
U. S. S.	17700	708 -1,148	440	

* These holes were not drilled completely through the Biwabik Formation.

thicknesses listed in the table are from vertical holes and have not been corrected to true thicknesses. The data is broken into three groups, as shown on the map in Figure 20, and the average thickness for each group is listed. Note that the average thickness increases from 209 feet to 375 feet to 489 feet moving southwestward. There are three operating taconite mines in this area, and it appears that there is room for more such operations, depending on the tenor of the ore.

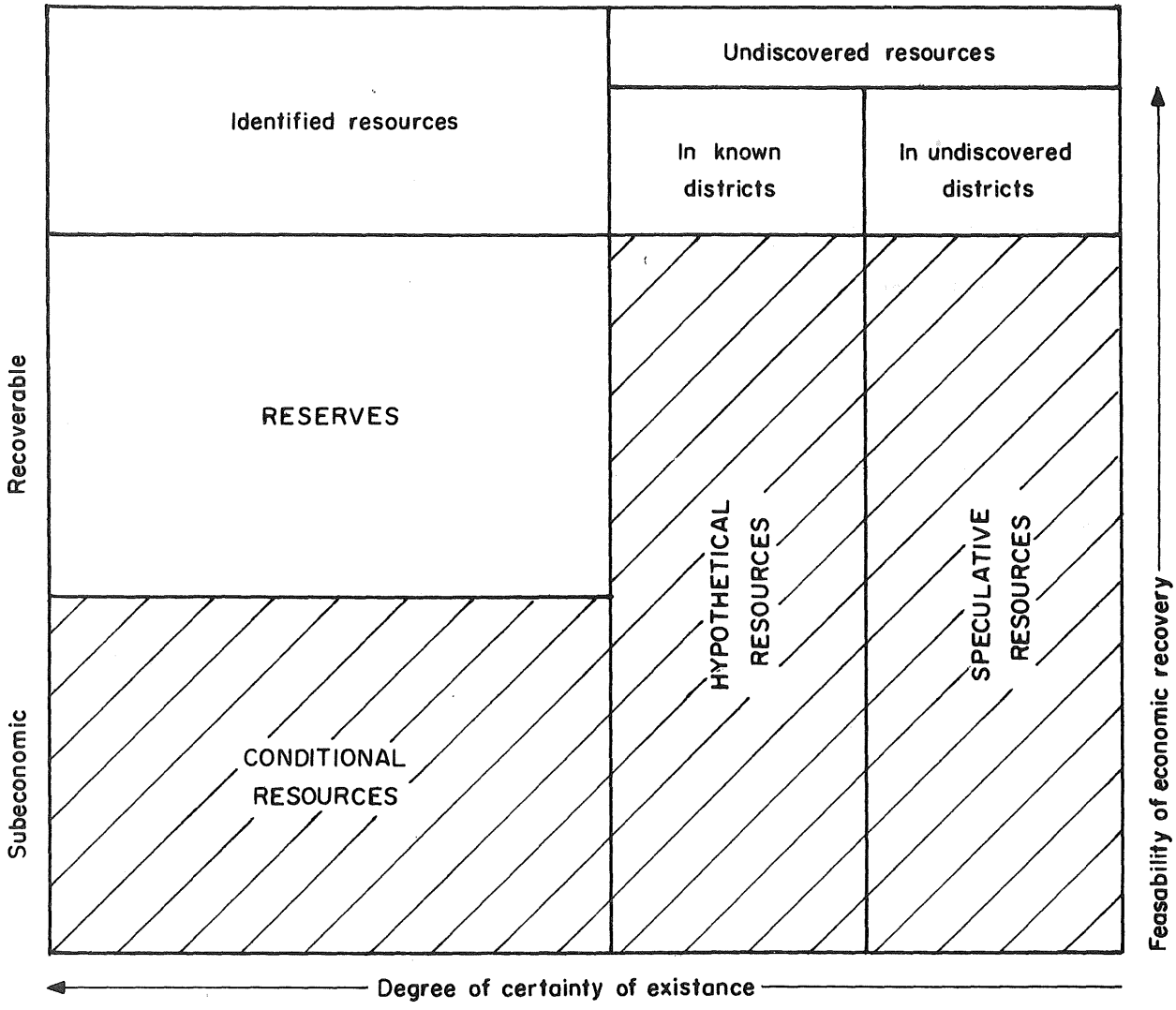
Figure 20 also shows the minimum extent of the Biwabik Formation beneath the Duluth Complex. This line was determined from drill hole data available for this study. It is known with some degree of certainty that the Biwabik is cut off by the Duluth Complex in Townships 60 and 61 North, Range 12 West, but from there to the southwest there is no evidence for similar truncation. The line in the map, therefore, shows the extent of the formation that has been confirmed by drilling.

Copper-Nickel - Resource or Reserve?

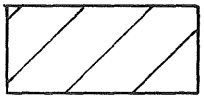
The problem of classifying the material examined during this study into categories which adequately and concisely define the mineralization has been given considerable thought. The classification system used is that of Brobst and Pratt (1973) and is shown in Figure 21. The terminology is defined below, quoted from Brobst and Pratt (1973).

RESERVES: "Known identified deposits of mineral-bearing rock from which the mineral or minerals can be extracted profitably with existing technology and under present economic conditions."

RESOURCES: "Include not only reserves but also other mineral deposits that may eventually become available -- either known deposits that are not economically or technologically recoverable at present, or unknown deposits, rich or lean, that may be inferred to exist but have not yet been discovered."



EXPLANATION



Potential resources = Conditional + Hypothetical + Speculative

FIGURE 21: Classification of Mineral Resources
(After Brobst and Pratt 1973)

CONDITIONAL RESOURCES: "Resources that may eventually become reserves when conditions of economics or technology are met."

HYPOTHETICAL RESOURCES: "Undiscovered resources that we may still reasonably expect to find in known districts."

SPECULATIVE RESOURCES: "Undiscovered resources that may exist elsewhere.

IDENTIFIED RESOURCES: "Specific bodies of mineral-bearing rock whose existence and location are known. They may or may not be evaluated as to extent or grade."

The resources estimated in this study would appear to belong in the conditional resources category. The mineralized areas are all identified in at least one drill core and the blocks with the major tonnages are defined by a minimum of fifteen drill cores each. Several bulk samples for metallurgical testing have been taken from the Duluth Complex. Two exploration shafts have been sunk, one 1,100 feet and one 1,700 feet, and one proposal for an open pit mine has been made and subsequently withdrawn. All of this activity, and the 1,000 to 1,500 drill holes, has yet to result in a producing mine. Therefore, the estimate of 4.4 billion tons of material containing $\geq$0.5% copper must be classified as a subeconomic, identified resource (or conditional resource). The 220 million tons of $\geq$10% TiO_2 material is likewise classified. No estimate of hypothetical resources was attempted during this study, but a great deal of potentially mineralized area remains to be explored.

Comparisons between the resources estimated in this study and estimates of tonnages by mining companies are possible in two areas, the INCO Spruce Pit area and the Amax area. The Spruce Pit area was the site of INCO's proposed open pit. They estimated that they would mine about 273 million tons of ore averaging 0.46% copper and 0.17% nickel from their

pit during the 20 year life of the pit. They did, however, indicate in their 1975 report that mining could continue over a much greater span of time with continuing development and exploration. The INCO Spruce area, as the whole block of mineralized ground is called in this report, is estimated to contain about 700 million tons of $\geq$0.5% copper resource, but this includes properties other than INCO's. The estimated resource in the Amax area is about 800 million tons of $\geq$0.5% copper. Amax presented underground potential estimates of 330-375 million tons of about 0.8% copper and 0.2% nickel at a public Copper-Nickel Study Group meeting on August 11, 1977, in Minneapolis. Amax has also defined 3-6 million tons of 3.0% copper and 0.6% nickel in a semi-massive sulfide zone.

Both of these comparisons are about the same, a little less than half of the resource estimated in each area in this study has been estimated by the companies as reserves in their respective area. The cutoff grades can alter these results considerably, and the cutoff grade used by INCO is not known but would have had to have been less than 0.5% copper. The cutoff grade used by Amax was 0.6% copper. Therefore, if both the INCO and Amax figures were normalized to 0.5% copper cutoffs, the INCO tonnage would be less and the Amax tonnage would be larger. Thus, no consistent relationship appears to exist between this resource estimate and actual reserve estimates by the mining companies, although all of the companies involved have stated that the estimates developed here are reasonable for their respective areas, given the parameters considered and the methods used.

Duluth Complex - Possible Resources

The Duluth Complex is known to contain significant quantities of copper-nickel and titanium mineralization, as shown by the estimates

developed during this study. Associated with the copper-nickel mineralization are quantities of gold, silver, cobalt, and platinum-group metals that are possibly recoverable. Data available from INCO's bulk sample tests on the Spruce deposit indicate recoverable grades of 0.0262 oz/ton silver, 0.00075 oz/ton gold, 0.00107 oz/ton platinum, and 0.00304 oz/ton palladium. Cobalt in the concentrate was 0.14% but was not mentioned as a recoverable metal in the INCO report (1975). There is about a 50% recovery of cobalt in smelting the concentrate and a charge of about $2.50 per pound, so it should be profitable to recover it, with the current price of over $5.00 a pound.

Mineralization types other than the copper-nickel mentioned above are known to occur, or may possibly occur, in the Duluth Complex in economically interesting quantities. The possible resources include nickel-copper, platinum-group metals, vanadium, chromium, aluminum, graphite, and asbestos.

The nickel-copper potential is very real, with indications of mineralization in which the nickel content is higher than the copper showing up in the data received for this study. Rock-types favorable for the occurrence of nickel-rich sulfide deposits (pyroxenites, peridotites, dunites) are known to occur in the Duluth Complex. Some of these occurrences are shown on the map by Weiblen and Cooper (1977), and others have been found by drilling.

Platinum-group metals could occur in sufficient quantities to mine them as the primary metal in the Duluth Complex. They are known to occur in extractable quantities in the copper-nickel sulfide zones and could be concentrated in a single horizon as they are in the Bushveld and Stillwater Complexes. Zones rich in platinoids would be difficult to recognize

because very low concentrations would be economic and because they are not routinely analyzed for. Currently available analytical methods used in platinoid analysis are difficult and expensive to perform and are often of questionable accuracy and precision.

Titanium, vanadium and chromium are metals that occur in oxide zones with iron oxides. Little exploration has been done for any of these metals in the Complex, but oxide zones are common and small quantities of vanadium and chromium have been detected in the Duluth Complex. These metals could occur in economic quantities singly or in combinations, and possibly with copper-nickel mineralization. Copper-nickel and titanium mineralization occur together in the Water Hen ultramafic rocks, in the southern part of the study area.

Aluminum has been considered as a possible product of Duluth Complex rocks, primarily from the anorthosites, for many years. The Al_2O_3 content of anorthosite is generally in the 28-30% range, much lower than the 70-85% found in the common bauxite minerals. Anorthosites are also much more expensive to mine and process. The mining of anorthosites for aluminum is, therefore, currently uneconomic, but large reserves of the metal are known and available from these sources. The tailings from copper-nickel ore processing has recently been considered by the Copper-Nickel Study Group as a source for aluminum. Although the Al_2O_3 content would be lower than anorthosites, the expense of mining and crushing would already be paid by the base metal sales. The technical assessment team of the Copper-Nickel Study Group is currently looking into this possibility. This possibility has also been investigated by the Minerals Resource Research Center at the University of Minnesota.

Massive graphite has been intersected in drill cores from the Duluth Complex and associated rocks. Amax has encountered massive graphite in their drilling, and graphite is abundant in the Water Hen Creek area of T.57N., R.14W. The grades of these occurrences and the quantities involved are not known at this time, but graphite should be considered as a possible resource of this area.

Asbestos is another type of mineralization that may be found associated with the Duluth Complex. No occurrences of economic interest are known at this time, but commercial asbestos minerals do exist in the Complex. Most economic asbestos occurs in ultramafic rocks, of the same types known in the Complex, and, therefore, commerical asbestos is a possible resource.

Copper-Nickel Ratios

The Cu/Ni ratio most frequently mentioned when discussing the Duluth Complex is 3:1. This is the ratio assumed by Bonnichsen (1974) for his resource estimate. Being in the position of having a lot of assay data available, we decided to determine the actual ratios and plot the distribution of the Cu/Ni ratios. It is assumed that all assays used represent the total metal content of the rock. A total of 4,912 individual ratios were calculated and plotted for this study. The copper and nickel values for intervals less than five feet were weighted and averaged with the adjacent values. The ratios were plotted in 0.5 intervals (0-.5, .51-1.0, etc.) and the histogram is shown in Figure 22. It is interesting that the peak occurs from 1.5 to 3.0, much lower than anticipated. This graph is based on individual assays and not strictly on material that could or would be mined, and this may be an important influence. Figure 23 shows the curve produced when the .5 intervals are doubled. By doubling the interval, the highest frequency falls in the 2-3 Cu/Ni ratio range.

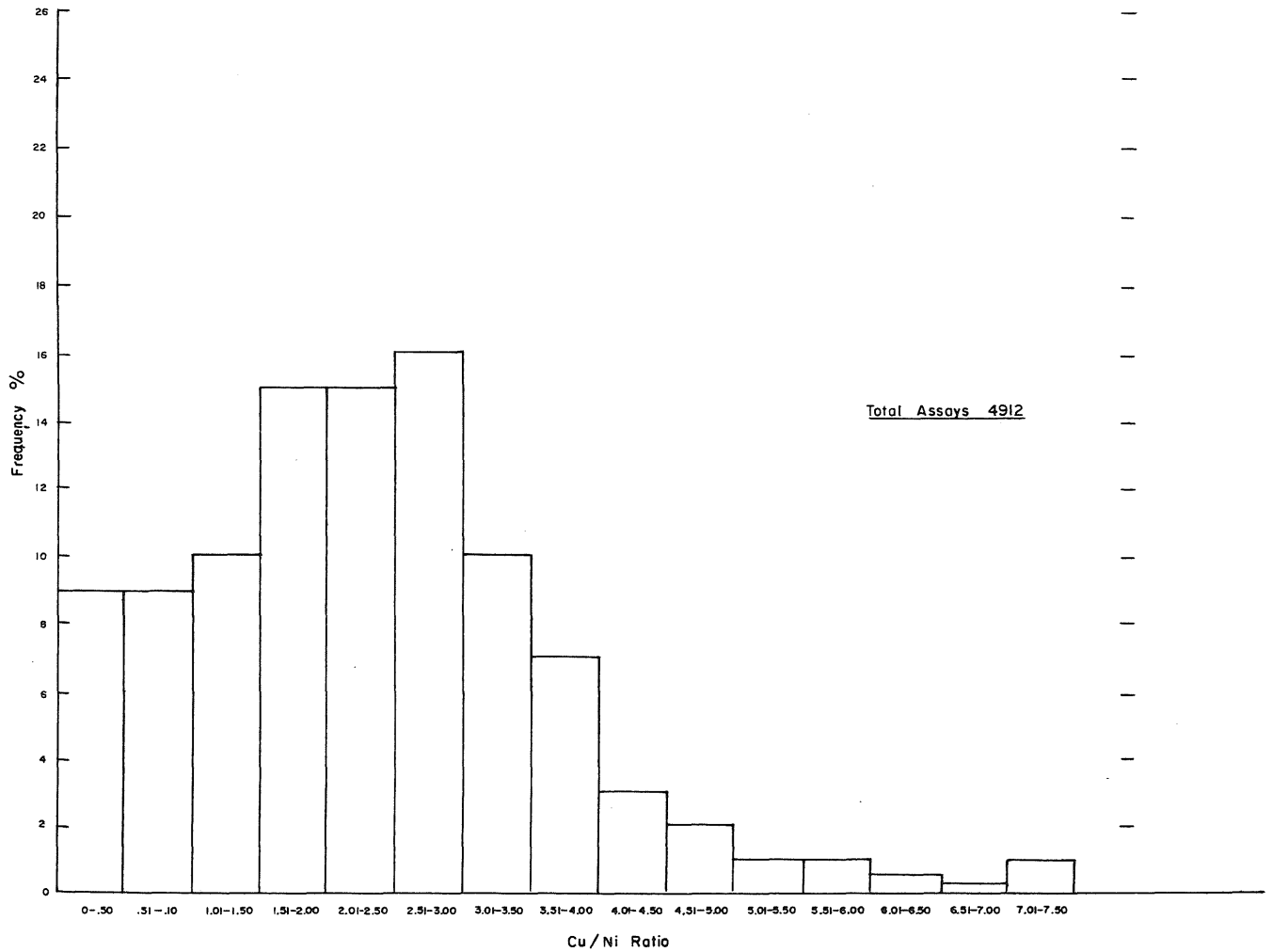


FIGURE 22: Cu-Ni Ratio Histogram

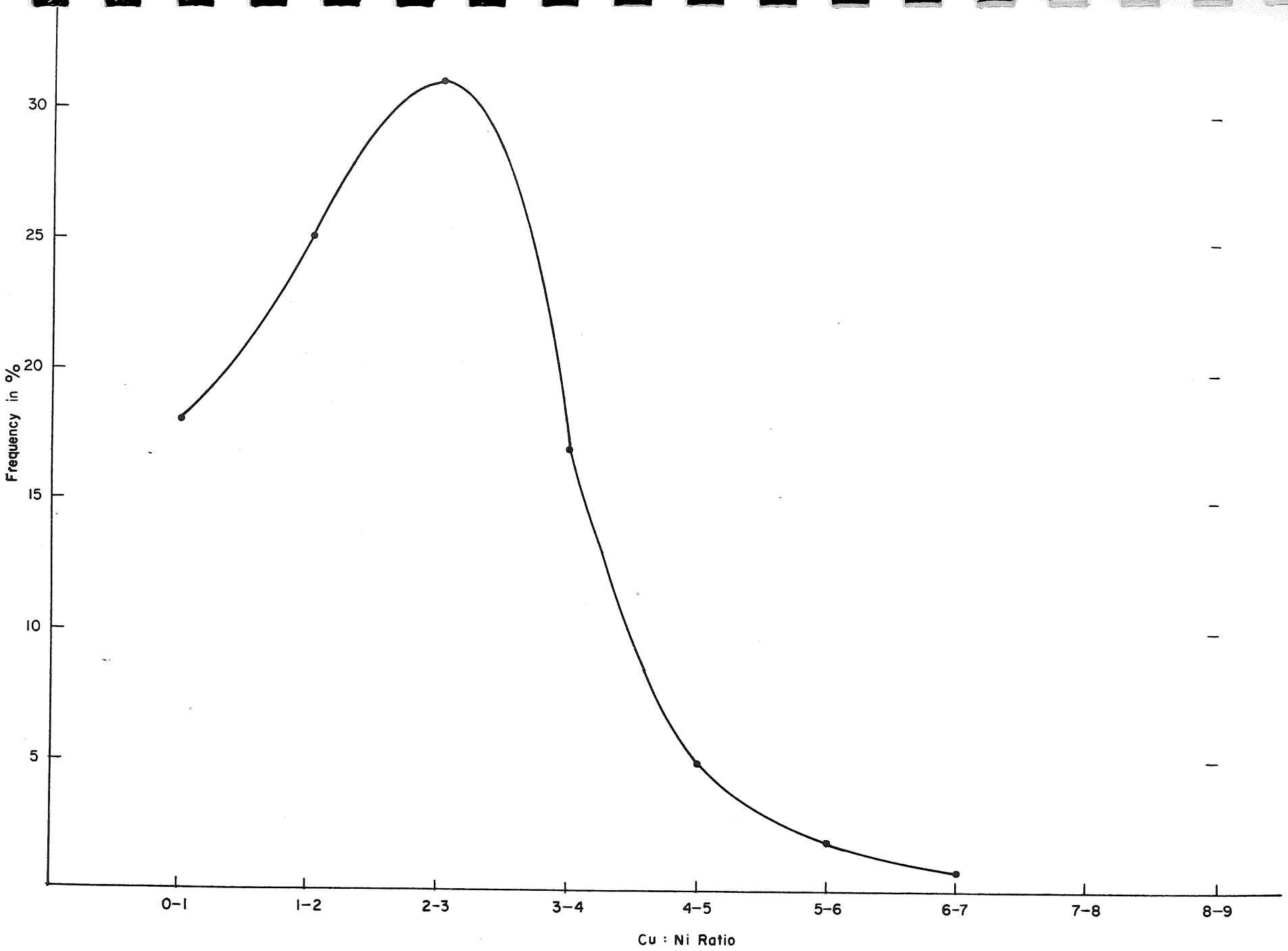


FIGURE 23: Cu – Ni Ratio Frequency Curve

The weighted average for the mineralized zones ($\geq$0.5% Cu) of 26 drill cores is 3.33. The ratios for individual holes vary from 1.26 to 6.33. The near-surface mineralization ($\geq$0.25% Cu) has an average Cu:Ni ratio of 3.59 based on data from eight drill cores. The individual ratios vary from 2.67 to 4.33 in these holes. The ratios from these 34 holes were plotted against depth of the mineralized zones, distance from the contact, percent copper, and percent nickel. These plots are shown in Figures 24 through 27, respectively.

The Cu/Ni ratio does vary from area to area within the Duluth Complex. The Spruce Area of INCO was calculated by them to have a ratio of 2.71 for the 273 million tons within their proposed pit. This ratio was used for the 700 million tons estimated in that block of mineralization. The 2.2 billion tons of $\geq$0.5% copper estimated for the INCO-Hanna-Duval area has a ratio of 3.24. This was calculated using all of the 17 mineralized holes that define the mineralization. The ratio used for the 800 million tons estimated in the Amax area is 4.00. This is based on the ratio determined by Amax for their 330 to 375 million tons of underground potential. The U. S. Steel Dunka area is estimated to have about 300 million tons of resource $\geq$0.5% copper. The ratio determined by U. S. Steel for that resource is 3.20. Using the previously determined ratio of 3.33 for the remaining 400 million tons of the total estimated resource and weighing according to tonnage, the average Cu/Ni ratio for the 4.4 billion tons is 3.30. This result, based on fairly good figures, is very close to the 3.33 arrived at in the calculations above. This indicates that the method used was fairly reliable even though it was based on 26 scattered drill holes.

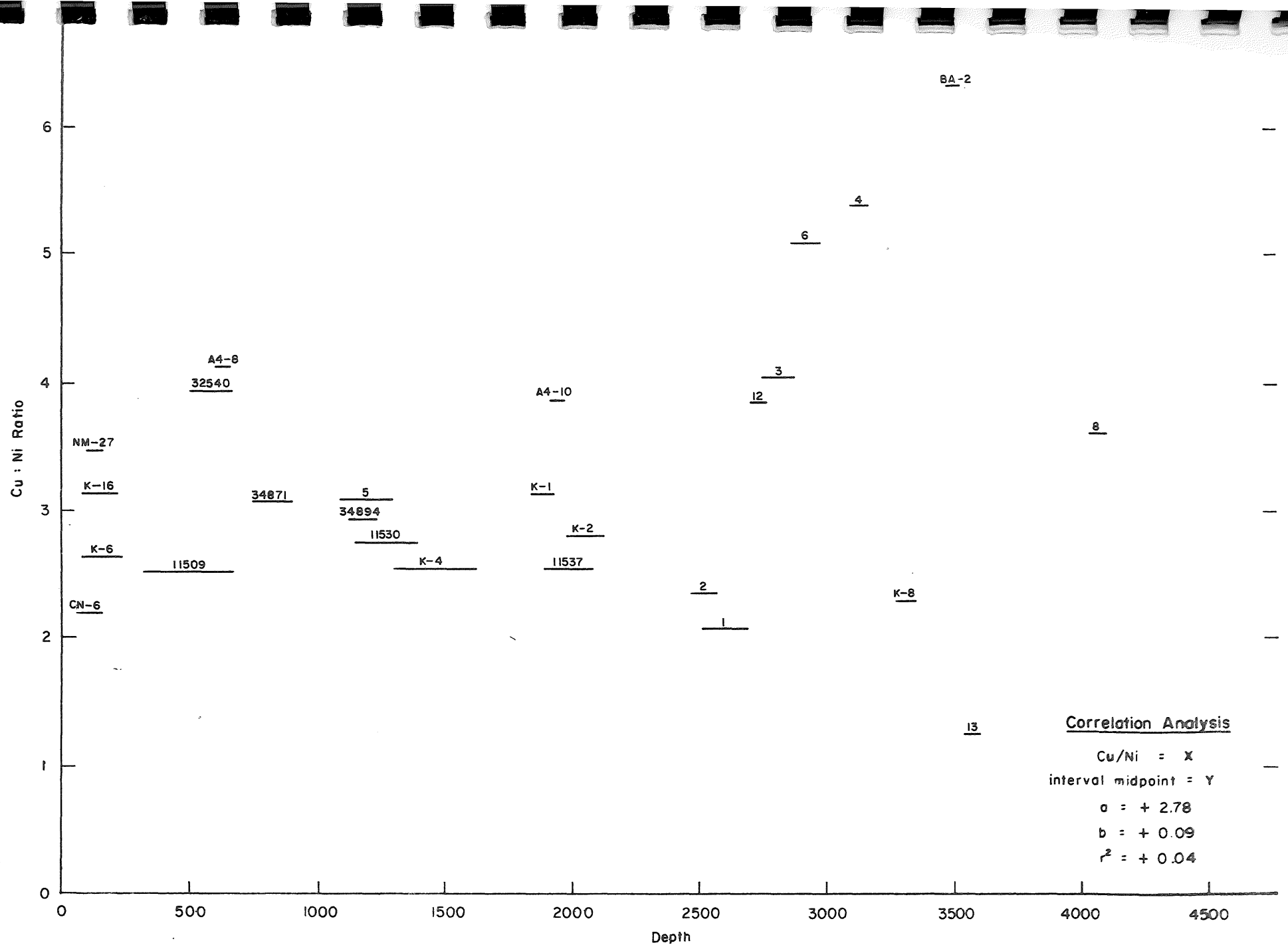


FIGURE 24: Depth vs. Cu-Ni Ratio

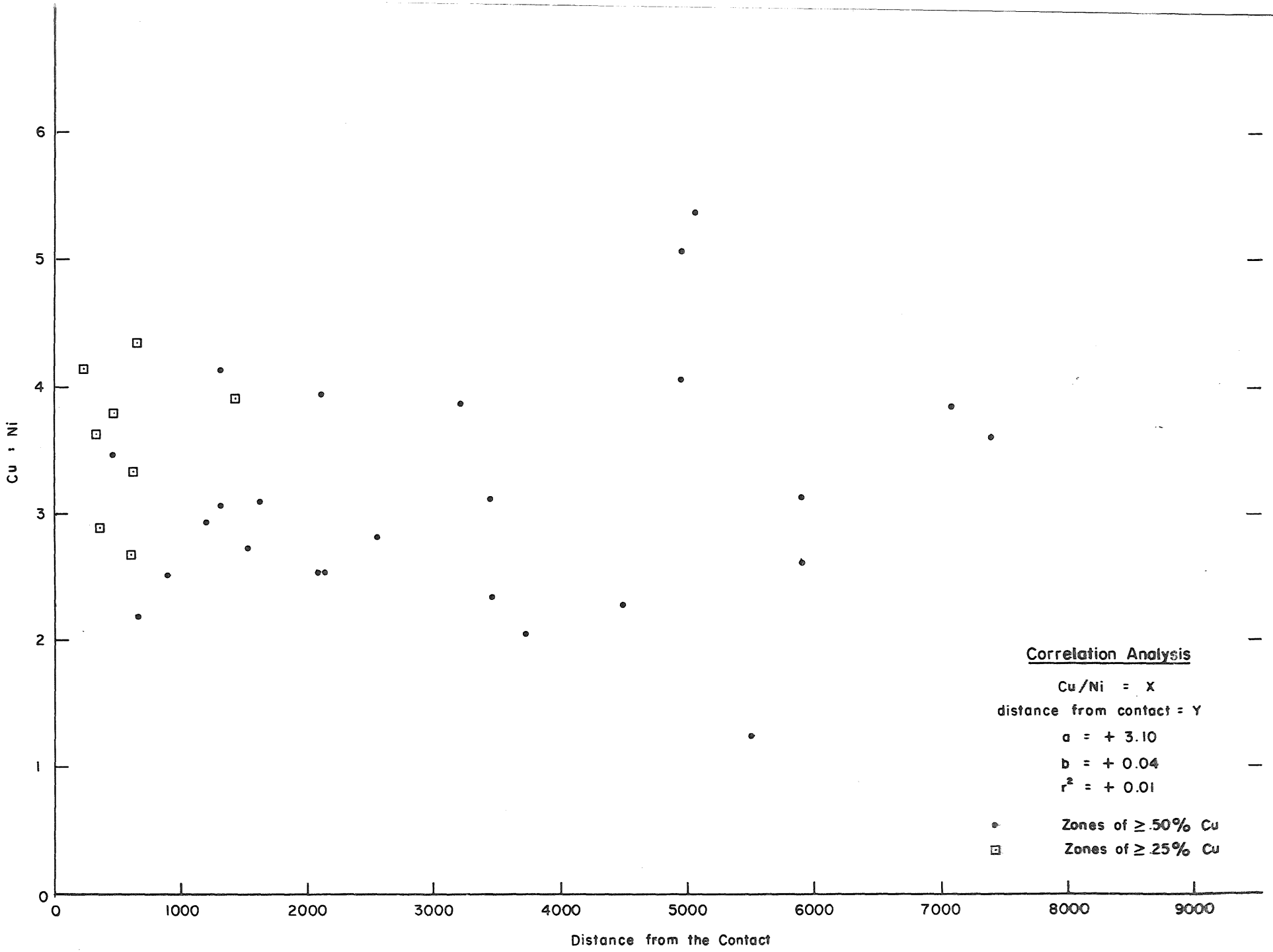


FIGURE 25: Cu-Ni Ratio vs. Distance from Contact

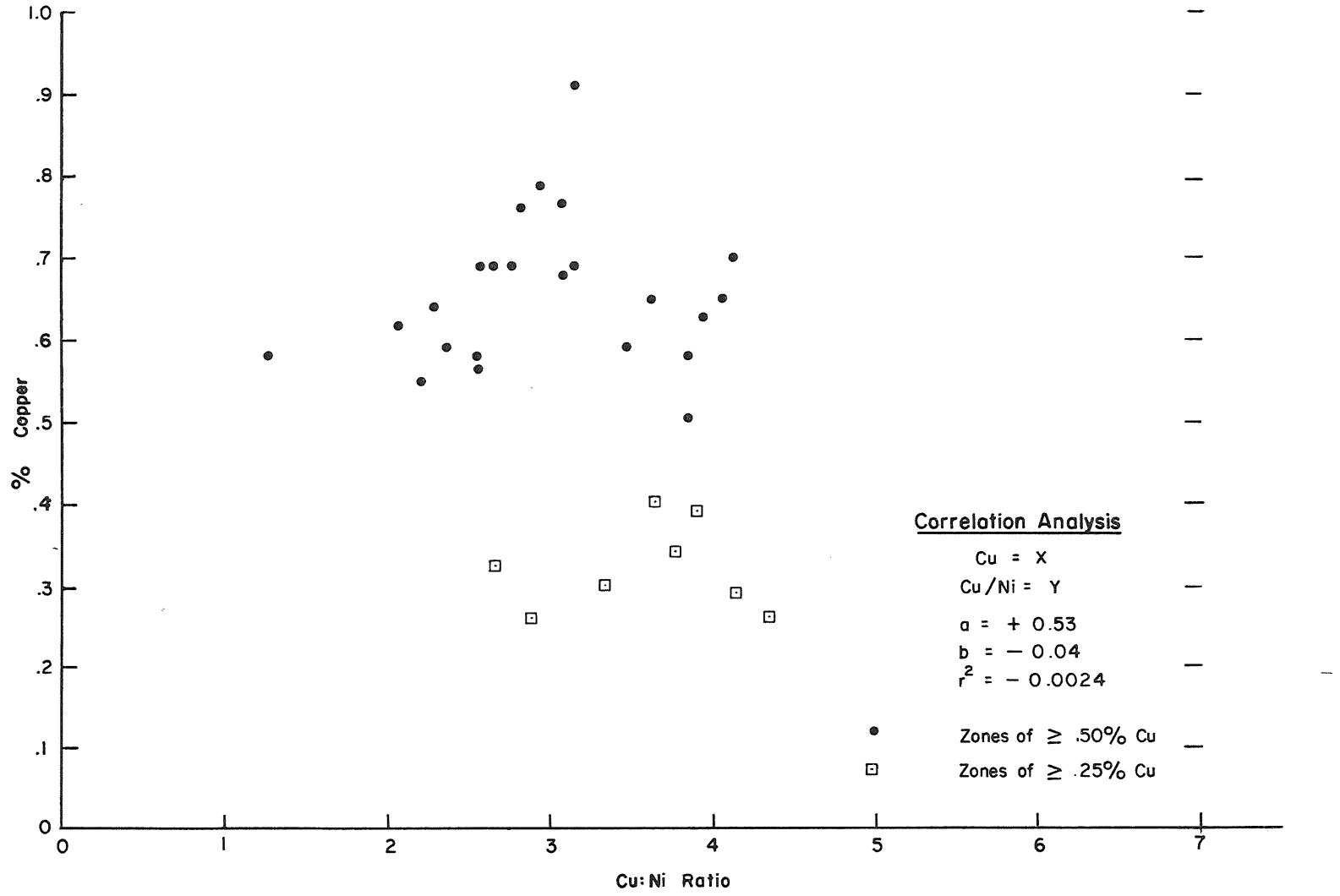


FIGURE 26: % Cu vs. Cu-Ni Ratio

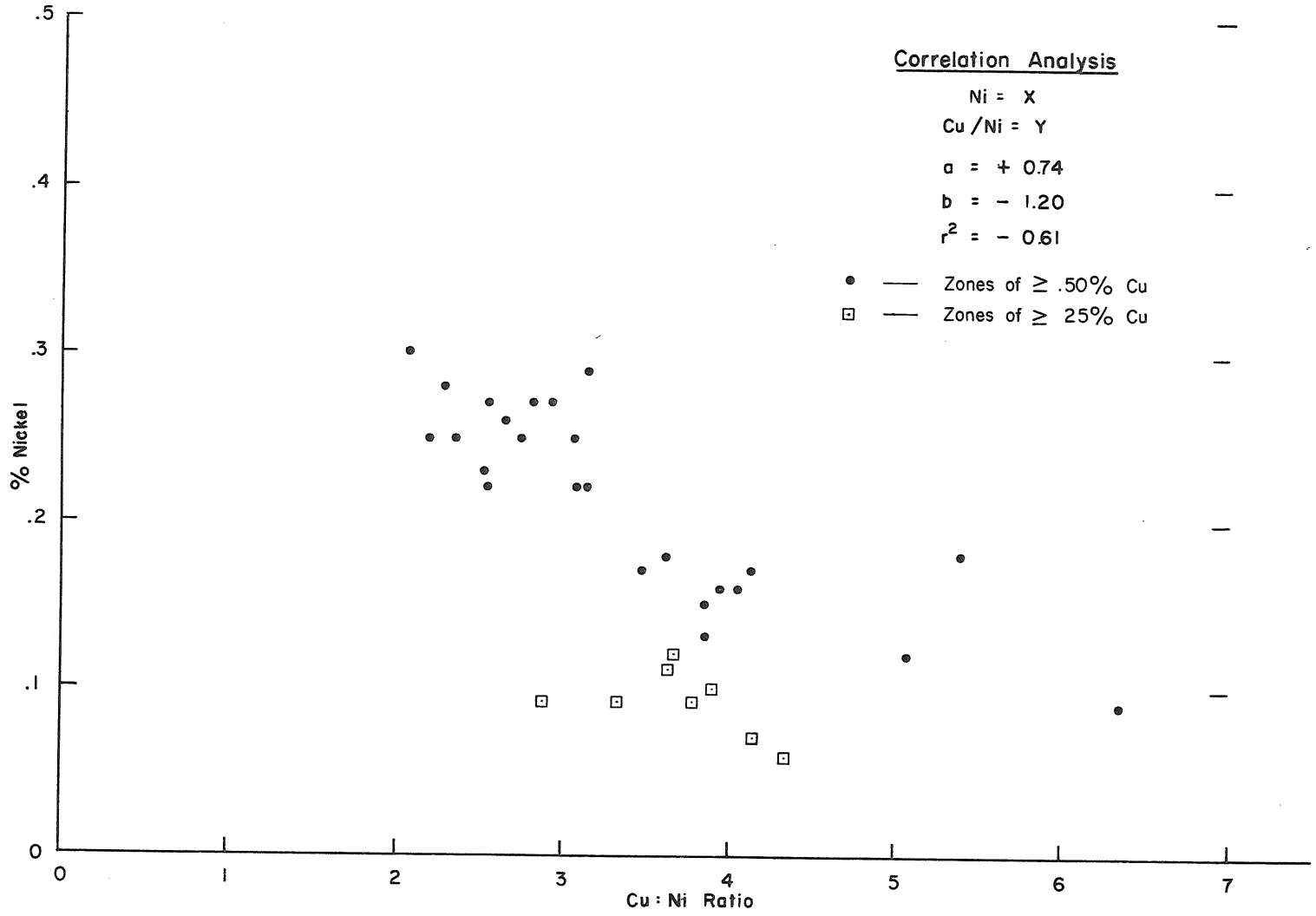


FIGURE 27: % Ni vs. Cu–Ni Ratio

The semimassive sulfides that Amax has defined have a higher Cu/Ni ratio than most of the rest of the resource. At 3% copper and 0.6% nickel, the ratio is 5.0 for this small amount (3-6 million tons) of material.

Figures 24 and 25 show no prominent relationships between the Cu:Ni ratio and depth or distance from the contact, although it appears that the more extreme values are more likely at greater depths and further from the contact. The ratio plotted against percent copper (Figure 26) shows no trends but a strong, almost linear negative relationship appears to exist between nickel content and the Cu:Ni ratio, as shown in Figure 27. An examination of the individual core data showed no consistent variation of Cu:Ni within the mineralized zones, although in one core the ratio decreased steadily downward while in another it increased downward. Based on the data at hand, no apparent areal variation in Cu:Ni ratios occurs.

Sulfur Data

The amount of sulfur in the mineralized portions of the holes on which data was received were tabulated to see what the average sulfur content was. Unfortunately there is not a great deal of data available as Bear Creek Mining and Exxon seem to be the only companies that analyze for sulfur on a regular basis, based on the data obtained for this study. Therefore, data was available on only 41 cores, eight of which contained mineralized zones meeting the $\geq$0.5% copper criteria. The weighted average for the $\geq$0.5% copper zones was 2.64 sulfur. The highest and lowest values per hole were 6.72% sulfur and 0.72% sulfur, respectively.

The other analyzed portions of the 41 holes that did not meet the mineralization criteria had a weighted average of 1.25% sulfur. The highest hole average was 3.44% sulfur and the lowest was 0.08% sulfur. Several of the holes not having significant mineralization may have

lowered the average for this group, but the small number of samples available would appear to make these averages suspect anyway.

Mineralization Restrictions?

The report on the bedrock geology of the study area by Weiblen and Cooper (1977) contains sections with which the MDNR is not in total agreement. These are the sections on "Interpretative Geology" and "Recommendations", specifically. These sections contain speculations or ideas that infer relationships between the basal contact (at the bedrock surface) and mineralization in the basal zone, which are not substantiated by the data collected, or developed, during this resource study.

The location of the intersection of the basal contact of the Duluth Complex with the present bedrock surface is a product of the original location of emplacement and subsequent events. Therefore, it is possible that there is no direct or causal relationship between the present erosional surface and sulfide mineralization. There is, however, a distinct economic relationship between the location of the basal contact on the erosional surface and the search for exploitable mineralization in the basal zone. Using an average assumed dip of 25°-30°, one can see that the limits of geophysical penetration are exceeded very quickly, and drilling is the only practical means of testing the zone. Drilling is very expensive, as is developing a deep ore body, so efforts are concentrated along the strip where the basal zone surfaces.

Weiblen and Cooper (1977) state that the economically interesting sulfides are restricted to a zone about 0.5 km wide along the basal contact. They completed a petrographic examination of samples from a 10 km traverse along State Highway 1, which is roughly normal to the contact. Modal abundances of orthopyroxene, opaque minerals, and biotite show exponential

decreases in moving to the southeast, away from the contact. Weiblen and Cooper speculate that perhaps an exponential function would also describe the lateral and down-dip extensions of mineralization. They also suggest that the inferred faults on the new geologic map may be genetically related to the mineralization and, therefore, may be guides for exploration and of possible use in ore estimation.

These concepts were examined in light of the information made available for this resource study. Figure 28 shows the mineralized areas as determined during this resource estimate. The inferred faults of Weiblen and Cooper have been drawn on the map to show the spatial relationships between them and the mineralized zones. The map shows a somewhat ambiguous relationship between the two. There may be a genetic relationship, but from the data available, it is not readily apparent or consistent. The mineralization is shown to occur almost two miles away from the contact and would appear to contradict the 0.5 km wide mineralized zone mentioned in Weiblen and Cooper (1977). The Amax exploration shaft is nearly a mile from the basal contact, and there is one mineralized hole in the Amax area that is nearly two miles from the basal contact. The idea that sulfides decreased exponentially away from the contact would appear to be true, according to Weiblen and Cooper's data, when moving along the surface. This direction of movement, relative to the basal zone of mineralization, is also vertical, away from the expected mineralization. Thus, one might expect the devrease in products of a diffusion reaction such as is hypothesized by Weiblen and Cooper.

Two things were done in attempting to test the hypothesis that a down-dip limit to mineralization exists. The first thing that was done was to determine the total feet-percent copper in all of the holes where

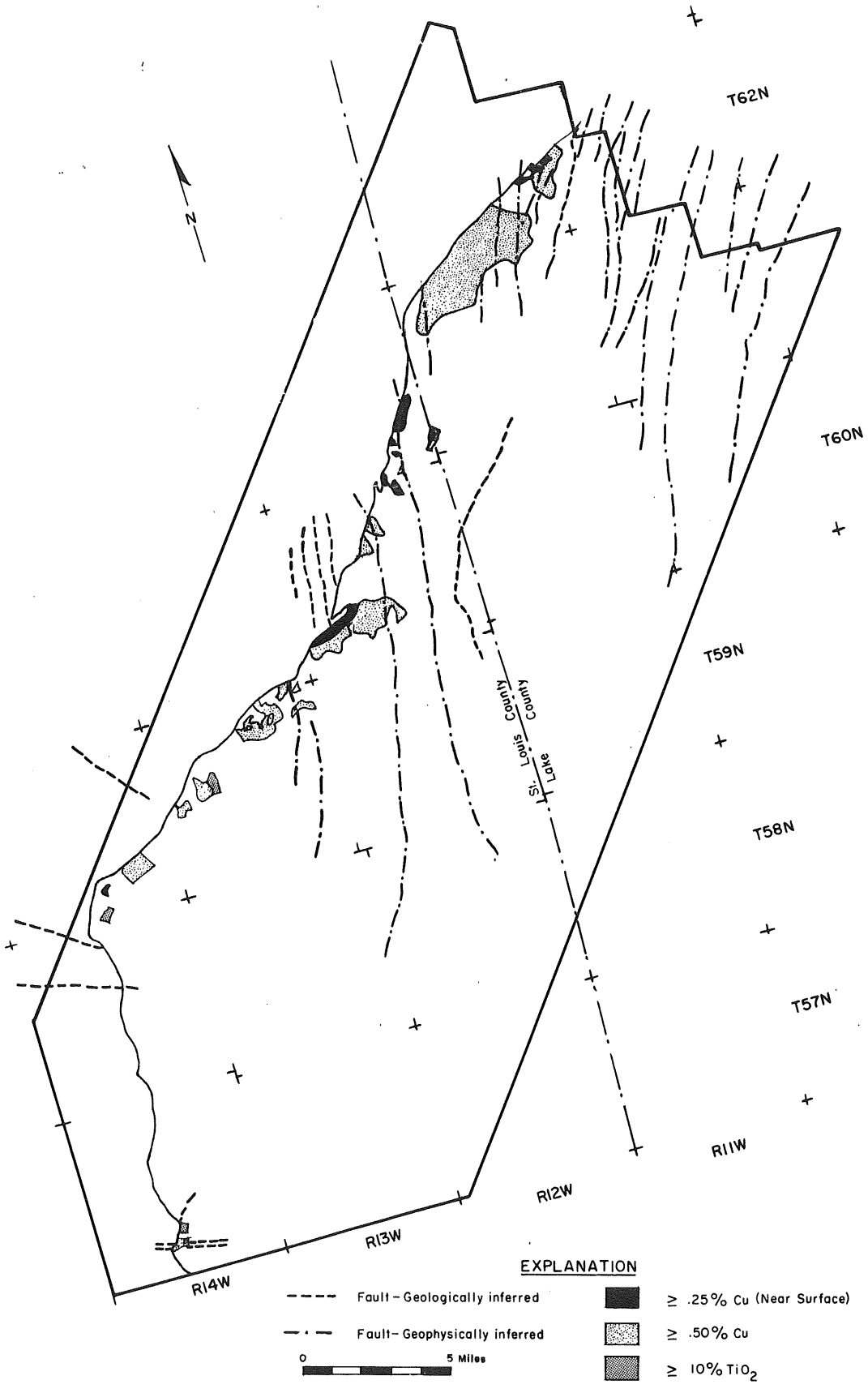


FIGURE 28: Map Showing Inferred Faults

the necessary data was available. The histogram in Figure 29 shows the distribution for the 116 determinations. The curve above represents a doubling of the interval (0-50, 50-100, etc.) and shows the distribution to be approximately lognormal. Figure 30 shows the histogram of the log values in a near normal distribution. Doubling of the log intervals makes the distribution appear more normal with a slight skew towards the low end, as shown in Figure 31. The lognormal distribution shown here is followed by many sets of geological data, especially trace elements according to Koch and Link (1970).

The feet-percent copper values for the drill holes used were then plotted versus distance from the contact, as measured from the nearest point. Figure 32 shows all of the points in this plot, and three lines derived from them. The distribution of data points per 1000 foot interval of distance from the contact shows that there is an exponential decrease in the number of drill holes, moving away from the contact. The average feet-percent copper values per 1000 feet of distance from the contact and the log average of feet-percent copper per 1000 feet of distance from the contact are also shown on this figure. These points form lines that have average slopes of essentially zero, indicating that the average total feet-percent copper in these 116 drill holes does not decrease away from the contact. Correlation analysis between feet-percent copper and distance from the contact indicates a slight but significant positive correlation between the two variables. The coefficient of determination (r^2) equals +0.11 for this data. The curve fit to the data was $y = a+b \log x$. The regression coefficients (a and b) are given in the figure. The values obtained by fitting the data to the exponential curve $y = ae^{bx}$ are also shown on Figure 32. The coefficient of determination by this method is +0.11, exactly the same as in the log curve fit.

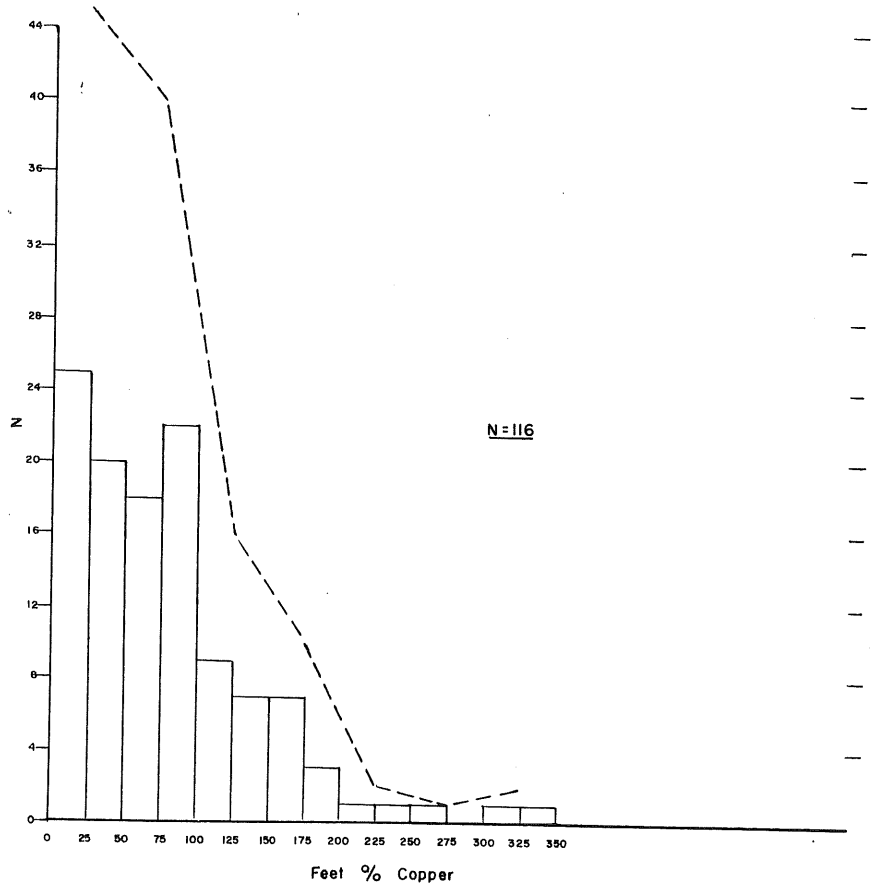


FIGURE 29: Histogram of Total Feet % Copper

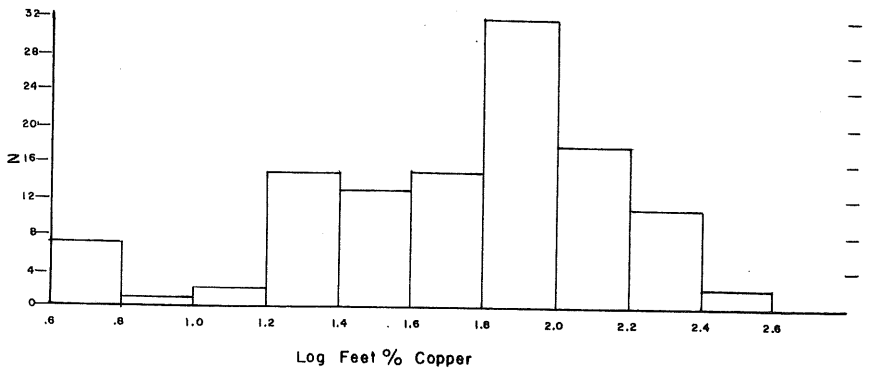


FIGURE 30: Histogram of Log Feet % Copper

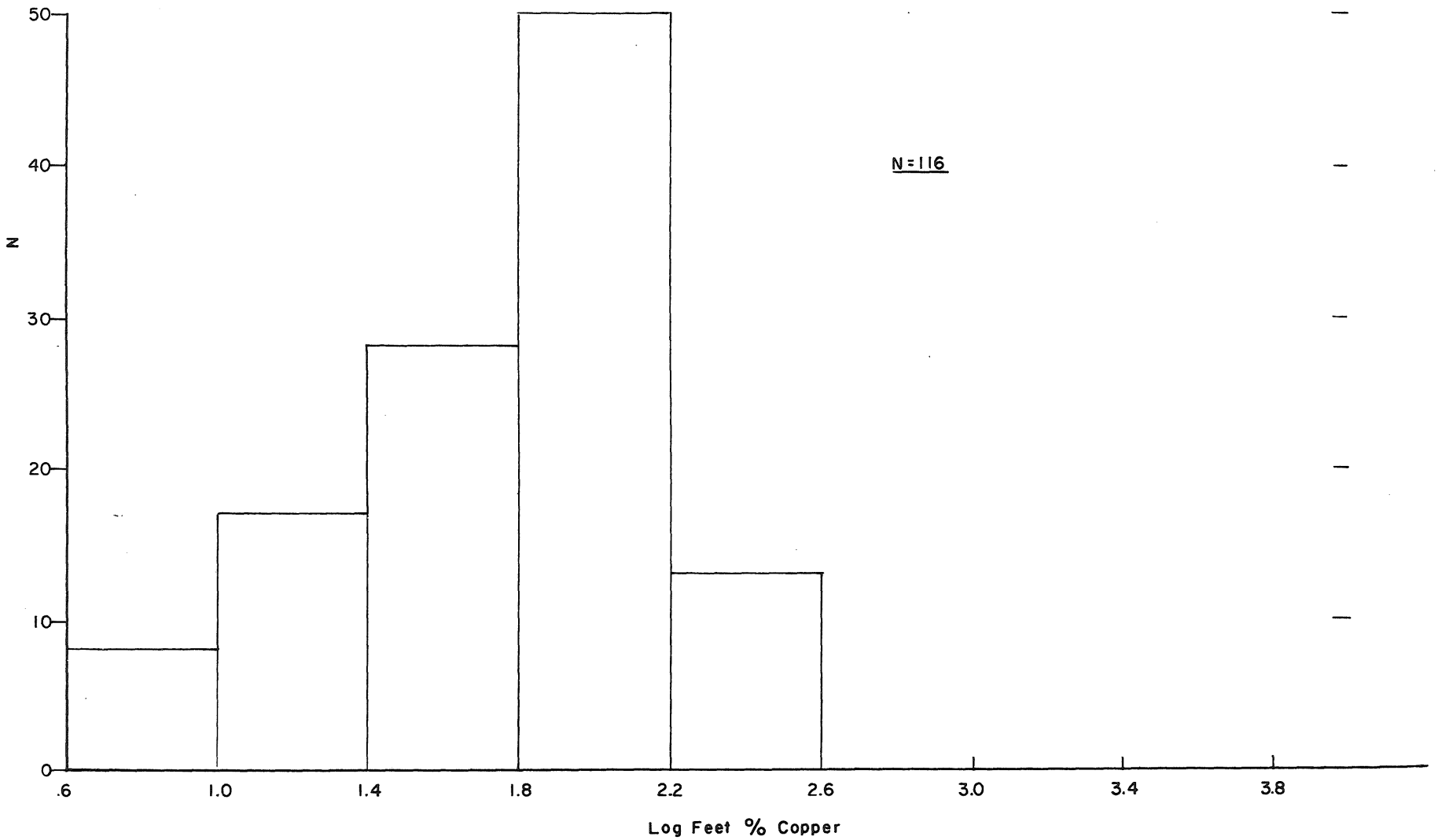


FIGURE 31: Histogram of Log Feet % Copper

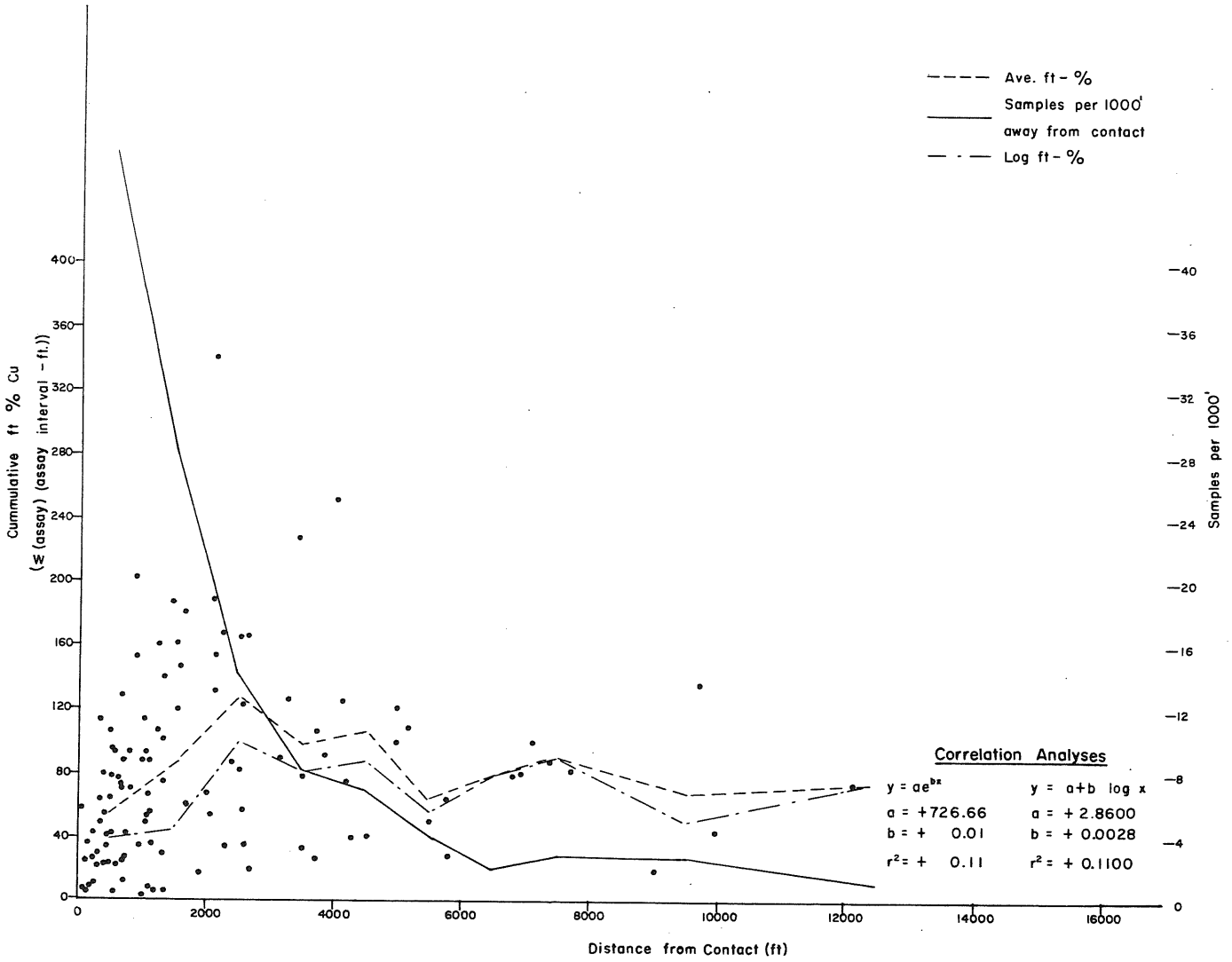


FIGURE 32: Feet % vs Distance from Contact

The second major test of the down-dip limit hypothesis was to compare the thicknesses of the $\geq$0.5% copper zones to the distances away from the contact. These data points are shown in Figure 33, along with the graph of the numbers of data points per 1000 feet of distance from the contact, and the average values and log-average values for each 1000 foot interval. The data points per 1000 foot interval show an exponential decrease away from the contact, similar to the feet-percent graph of Figure 32. The average and log-average lines show slight negative slopes of about -0.1, indicating a slight decrease in thickness of the $\geq$0.5% copper zones away from the contact. The correlation analysis fitting the data to both the log curve $y = a+b \log x$ and the exponential curve $y = ae^{bx}$ produced identical coefficients of determination. The r^2 values were -0.01, indicating no significant correlation between the thickness and distance from the contact. The relative frequency of the thicknesses of the $\geq$0.5% copper zones is lognormal as is shown in Figure 34.

The data presented here show that there is little correlation between mineralization in the basal zone and distance from the surface intersection of the basal contact. Mineralization is shown to exist nearly two miles from the basal contact in quantities and grades that are economically interesting. The amount of data available decreases exponentially with increasing distance from the contact, mainly because of high drilling and development costs at the greater depths likely to be required.

Exploration

Exploration is continuing in the Duluth Complex with at least three major companies still drilling. Exxon and Duval are still drilling as of this writing and Amax is drilling and working on their exploration shaft

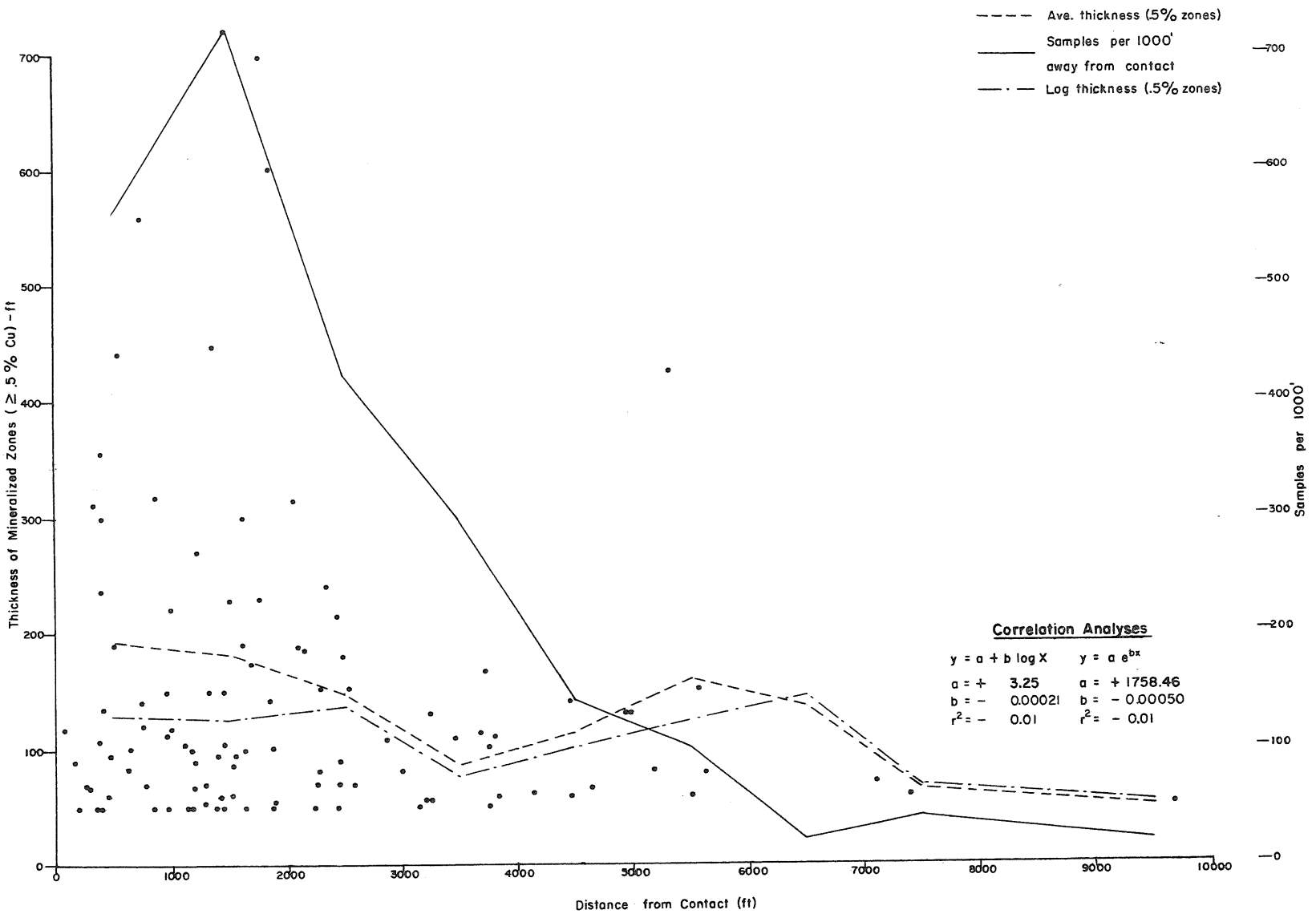


FIGURE 33: ≥ 0.50% Cu Thickness vs. Distance from Contact

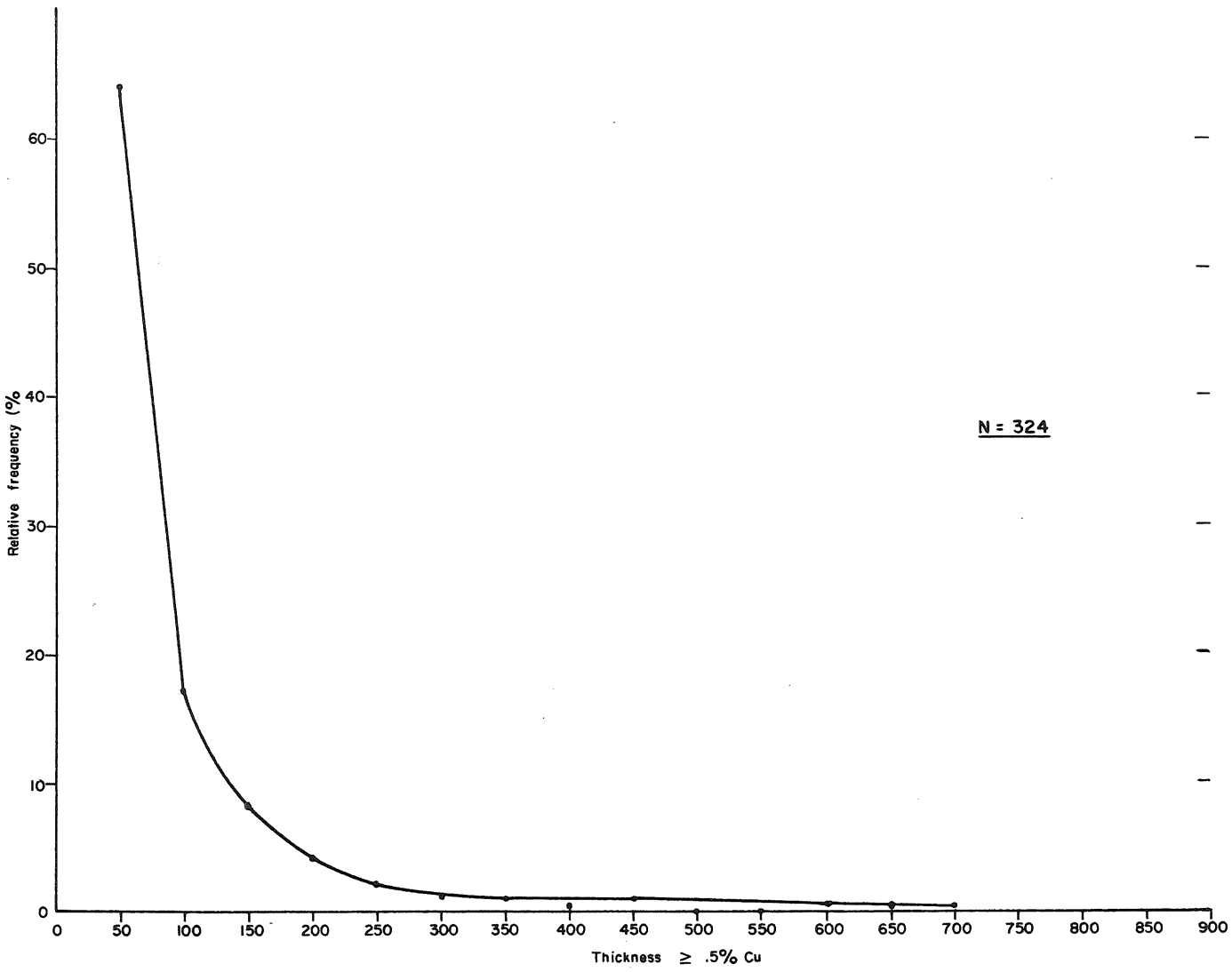


FIGURE 34: Relative Frequency Curve for Thickness ≥ 0.5% Cu

and drifts. Companies still maintaining property control include INCO, Hanna, American Shield, and United States Steel. Exploration in the Complex is difficult and expensive because of the general depth of the mineralized zones. Drilling is virtually the only exploration tool used where mineralization is expected to occur deeper than 1000 feet. Methods such as Induced Polarization and various electromagnetic methods have been used in searching for shallower mineralized zones. Magnetics and gravity may also be used throughout the Complex, but interpretation becomes extremely difficult and tenuous where the deep mineralization is concerned.

Facts that have come to light as a result of this study of the known resources in the Duluth Complex, may be of help in future exploration. First and foremost is the fact that near-surface mineralization has been shown to occur at a considerable distance from the contact. This means that near-surface anomalies further out in the Complex should not be ignored and that the more usual geophysical methods may be of some use. Geochemical methods have been shown to work well for locating near-surface mineralization along the contact in the Duluth Complex (Alminas, 1975), and, therefore, should not be overlooked as an exploration tool away from the contact.

A second feature of the mineralization associated with the Duluth Complex that is of significance to explorationists is the fact that mineralization commonly occurs below the Complex, regardless of the footwall rock-type. The cross sections presented earlier (Figure 4 - 15) illustrate mineralization that transects the footwall contact, and other holes have mineralization wholly below the footwall contact. The most extreme example known is in the Dunka Pit area in hole NM-13. Minerali-

zation occurs in the Virginia Formation hornfels near the top of the hole, in the Biwabik Formation, 140 feet down, and in the Giants Range Granite over 400 feet deep at the bottom of the hole. The deepest mineralization in NM-13 has 40 feet of 0.68% copper and averages 0.56% copper over 50 feet, but did not satisfy the cutoff grade criterion and was not used in the resource estimate. This and other examples indicate that significant mineralization may occur below the Duluth Complex, mineralization that may be missed through premature termination of drilling. The interfingering of rock-types in the basal contact zone and the unpredictable occurrence of the mineralization below the Complex should encourage or justify drilling below the footwall contact in at least some holes.

Explorationists working in the Duluth Complex in search of copper-nickel mineralization will certainly recognize significant mineralization of the visible or obvious types. The possible occurrence of economic platinoids, which may not be obvious or even visible, should also be given consideration during exploration. The two factors mentioned above would also appear worthy of considerable thought when planning exploration programs.

Resource Potential

The potential for valuable or economic mineral deposits within a given area is difficult to determine even when the bedrock geology is known and some exploration data are available. The two main categories of mineralization which have potential in the Study area are iron in the Biwabik Formation and the Duluth Complex types discussed in the section entitled "Possible Resources".

The Biwabik Formation, where it is relatively shallow and mineable with open pit methods, has great potential--the highest in the Study area.

This is shown in Figure 35 as the area of the bedrock exposure from Weiblen and Cooper's 1977 geologic map. The presence of economic iron deposits in the Biwabik Formation is illustrated by the three mines in the map area: Erie's main mine area, the Dunka mine, and Reserve's Peter Mitchell mine. The Biwabik Formation is a sedimentary unit with distinct mappable members which are generally continuous along the strike of the formation. It is not known what the thicknesses of the members are between the operating mines, but it is assumed that economic thicknesses of the presently mined members do exist and that they are of ore grade. This assumption means that the whole outcrop area is exploitable for taconite, using current processes, except for any oxidized zones that may occur, but with presently available technology even these zones can be exploited. The known down-dip extension of the Biwabik Formation is shown on Figure 35 as possible underground taconite potential. The Formation is known to exist at least this far down-dip, but nothing is known about its thickness or grade. Thickness data from a few drill holes was presented in Figure 20 and Table 3 in the Iron Resources section. This area should be considered as potential, but probably only in long-term planning.

The mineral potential in the Duluth Complex is also very good, but has been divided into two sections. The approximately three mile wide band along the contact has been designated as the area of highest potential. This is because all of the identified resource exists within two miles of the contact. There are no known economic deposits in this zone, but some are being evaluated at this time. The resources in this area represent both potential open pit and underground mines. Based on the evidence compiled during this study, the potential for mineralization of the type and grades identified in this estimate occurring in the Duluth Complex

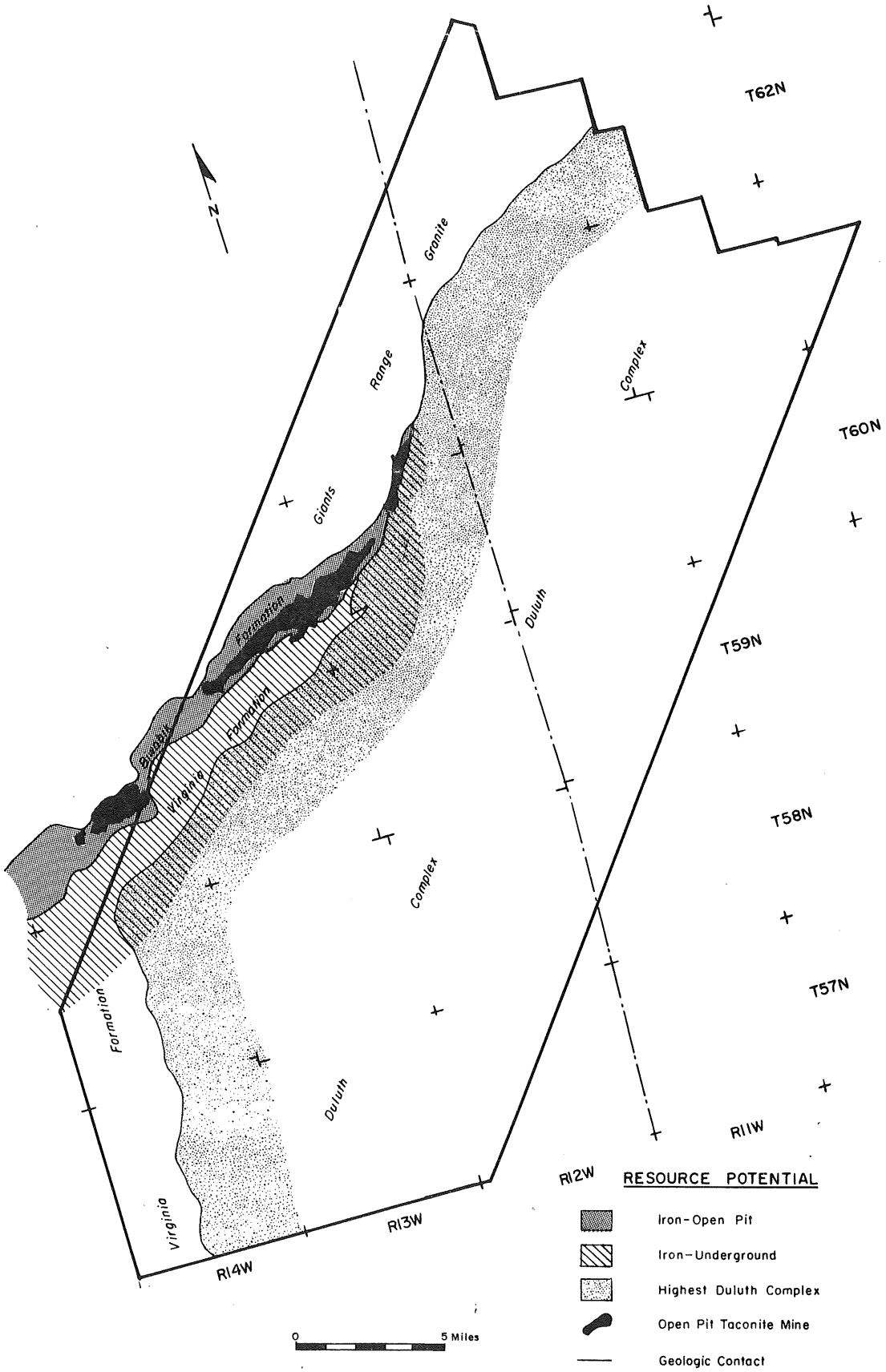


FIGURE 35: Resource Potential Map

more than three miles away from the contact is good. Evidence for significant mineralization occurring outside of the basal zone has been presented in another section, and there is no indication of a down-dip limit on mineralization in the basal zone. The fact that very little is known about the subsurface geology, outside of a two mile strip along the contact, cannot be overemphasized. There are also vast areas in which the bedrock is completely covered and the bedrock geology is not known. Because of these factors, even areas that are covered by anorthositic series rocks have the same good potential for copper and nickel mineralization existing below them. The depths to the possible mineralized areas are completely unknown because no one knows what happens to the basal zone outside of that two mile wide strip. Does the average dip of about 25° continue? Does the dip decrease, increase, or even reverse? Are there mineralized zones (of any type) near the surface in the vast covered areas of the Duluth Complex? These are questions for which there are no answers at this time. It appears there are no reasons for concluding that the area outside the three mile wide band shown in Figure 35 is of low potential, when so little is known about the area and when positive indicators such as those mentioned above exist.

The areas shown in Figure 35 that are not discussed above are generally of low potential, based on presently available data. They are not without potential, however. Barren sulfide zones are known in the Virginia Formation and sedimentary economic sulfides are possible. The Virginia Formation is also a possibility for uranium mineralization. The Giants Range Granite is known to contain showings of fluorite and may be of interest for uranium. The resource potential for these areas is generally much lower than the other areas discussed.

Summary and Conclusions

A survey of the resources in a 560 square mile area in northern Minnesota, as part of the Regional Copper-Nickel Study, conducted by the Minerals Division of the MDNR has shown that significant amounts of mineral resources exist in that part of the Duluth Complex which has been explored. Tonnage estimates of copper-nickel and titanium resources were made using drill hole data from 324 holes and a standard polygon method to calculate the area of influence of each hole. The estimate of material $\geq$0.5% copper, in units $\geq$50 feet thick, is 4.4 billion short tons. Material $\geq$0.25% copper which persists from the top of the core to the base of the Complex, or for at least 100 feet, is estimated at over one billion short tons. The tonnage estimate for material $\geq$10% TiO_2 and $\geq$50 feet thick is 220 million short tons.

The average grade of the material $\geq$0.5% copper is estimated to be 0.66% copper. This figure is based on actual calculation of the average grade for 29 of the 116 mineralized holes. These were the only holes for which complete data were available. An average grade of 0.65% copper was also calculated using a grade-frequency graph that was developed from single assays on sections of core $\geq$5 feet in length. The average nickel content is estimated to be 0.20%. This was determined by dividing 0.66 by 3.3, because the calculated average copper-nickel ratio in the $\geq$0.5% copper zones is 3.3:1.

Information released by Amax indicates that significantly higher grade mineralization exists in their area. They have estimated 330-375 million tons averaging about 0.8% copper and 0.2% nickel as their underground potential. They also have identified 3-6 million tons of semi-massive sulfides averaging about 3% copper and 0.6% nickel.

It is important to realize and stress that certain assumptions are necessary for the completion of a resource study of the type reported here. Because of limits on available time and information, the following assumptions were made. Continuity of the mineralized zones between holes and throughout the calculated area of influence for each hole, or the absence of these zones, is the major assumption. The cross-sections presented earlier illustrate that the chance of error because of this assumption is significant and must be considered in evaluating the results of this study. The attitude of the mineralized zones was assumed to be horizontal for the purpose of the calculations and the thicknesses of angle hole mineralized zones were reduced to vertical thicknesses. This was done because of the variable geologic data available and to insure that the tonnage estimates would be conservative. Assumptions other than these were made but should not severely affect the basic estimates, and they have been explained in the text.

Data presented in this report shows that basal zone mineralization is not the only mineralization that occurs in the Duluth Complex. The mineralized zones that are known to occur above the basal zone may (and should) encourage exploration further out in the Complex, possibly resulting in other similar discoveries.

Correlation analyses of the available data shows that there are no correlations between the thickness of mineralization, or total feet-percent copper, or copper-nickel ratio and distance from the contact. Therefore, no limit can be set for the possible occurrence of mineralization down-dip.

The potential for the existence of significant copper-nickel mineralization appears to be good in all areas of the Duluth Complex and excellent in the area close to the contact. Even though mineralization is

not known in the anorthosites, there would appear to be a good chance for mineralization below the anorthosites. The depths are, of course, completely unknown at present and will likely remain so until new holes are drilled. The potential for titanium mineralization is also good throughout the Complex, as this material is known to exist well away from the contact. The potential for other types of mineralization is harder to define except to say that they are possibilities. The fact that so much of the geology of the Duluth Complex is unknown, because of the glacial overburden, complicates any attempt at assessing the mineral potential.

The value of the metals estimated to be in the Duluth Complex has been computed at approximately current prices. The value of the copper is about $40,656,000,000 for 4.4 billion tons at 0.66% copper ($\geq$.50% copper cutoff), 70 cents per pound, and 100% recovery. INCO reported an 88% recovery of copper from their Spruce Pit area bulk sample testing, and using that figure, that value comes to $35,777,000,000. The nickel value is $42,240,000,000 for 4.4 billion tons at 0.2% nickel, $2.40 per pound, and 100% recovery. Using INCO's recovery figure of 65%, the value is $27,456,000,000. These figures are quite impressive, but one must remember that they are purely hypothetical because all of the resource can never be mined, and there is no value if left in the ground.

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