MINNESOTA GEOLOGICAL SURVEY

Matt Walton, *Director*

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COPPER AND NICKEL RESOURCES IN THE DULUTH COMPLEX, NORTHEASTERN MINNESOTA

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by
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ABSTRACT

The Ely-Hoyt Lakes region, in northeastern Minnesota, contains very large quantities of disseminated copper and nickel sulfides that are potentially minable. The principal sulfides are pyrrhotite, chalcopyrite, cubanite, and pentlandite, and the average copper-nickel ratio in the sulfide concentrations is approximately 3:1. The sulfides are associated with the northwestern margin of the Duluth Complex, a large mafic igneous pluton of Late Precambrian age, and occur principally within the basal zone of the intrusion.

A conservative estimate of the metal resources in the Ely-Hoyt Lakes region, based on assay data available from 24 drill holes, and a cutoff grade, or lower mining limit, of 0.5 percent combined copper and nickel indicates 13.8 million tons of copper and 4.6 million tons of nickel having a gross value of $27 billion.

Although the copper and nickel deposits in the Ely-Hoyt Lakes region are marginal economically, they constitute one of the United States' principal metal resources.

INTRODUCTION

The Ely-Hoyt Lakes region of northeastern Minnesota -- an area about a mile wide and more than 30 miles long -- contains large resources of economically marginal copper and nickel. The copper and nickel occur as sulfide minerals that are associated with a large mafic igneous body known as the Duluth Complex and are concentrated in the basal zone of this body. The deposits have been investigated intermittently by several mining companies for about 20 years, and it is anticipated that mining will be started within the next few years.

Many problems concerning the geology, potential mining methods, and extractive metallurgy of the deposits, as well as legal and environmental issues, remain to be resolved. A part of the region is highly regarded for its scenic attractiveness and forest and wildlife resources, and has a well developed tourist industry. The northern extremity of the region is adjacent to the Boundary Waters Canoe Area (BWCA), an important wilderness preserve. Consequently, there are conflicting views among public officials, industrial and other private groups, and citizens of the state as to how these several resources can be utilized for maximum benefit.

The intent of this report is to provide information on the approximate size and quality of the copper-nickel deposits in the Ely-Hoyt Lakes area, to aid in planning and decision-making. This area contains the largest known quantities of potentially minable copper and nickel in the Duluth Complex, and probably will be the first area to be considered for mining. Also included in the report are data on important known copper and nickel deposits in the world and on past and projected U. S. production and consumption of these metals.

There are several inherent uncertainties in calculating the copper-nickel resources in the Ely-Hoyt Lakes area because of the relatively sparse data available to me. Therefore, the estimates given here should not be considered to be an accurate and complete inventory. Instead, they should be regarded as a conservative indication of the quantity of metal available for potential mining, and should be used as a starting point for more detailed, future assessments.

THE DULUTH COMPLEX

The Duluth Complex is a large body of mafic and anorthositic plutonic rocks of Late Precambrian age that underlies nearly 2,500 square miles of northeastern Minnesota (fig. 1). The complex, together with the lava flows and thick sills that comprise the North Shore Volcanic Group, is part of the Keweenawan geologic province that occupies the Lake Superior basin and adjacent parts of Wisconsin, Michigan, and Ontario, Canada.

The Duluth Complex is a composite intrusive body that was formed from several separate injections of magma over a period of time. The two most abundant rock groups are: (1) troctolite, augite troctolite, and olivine gabbro, each of which typically contains 60-75 percent plagioclase; and (2) anorthosite, gabbroic anorthosite, and troctolitic anorthosite, which typically have 75-95 percent plagioclase. Accordingly, most parts of the complex can be assigned to one of two principal subdivisions, the Troctolitic series and

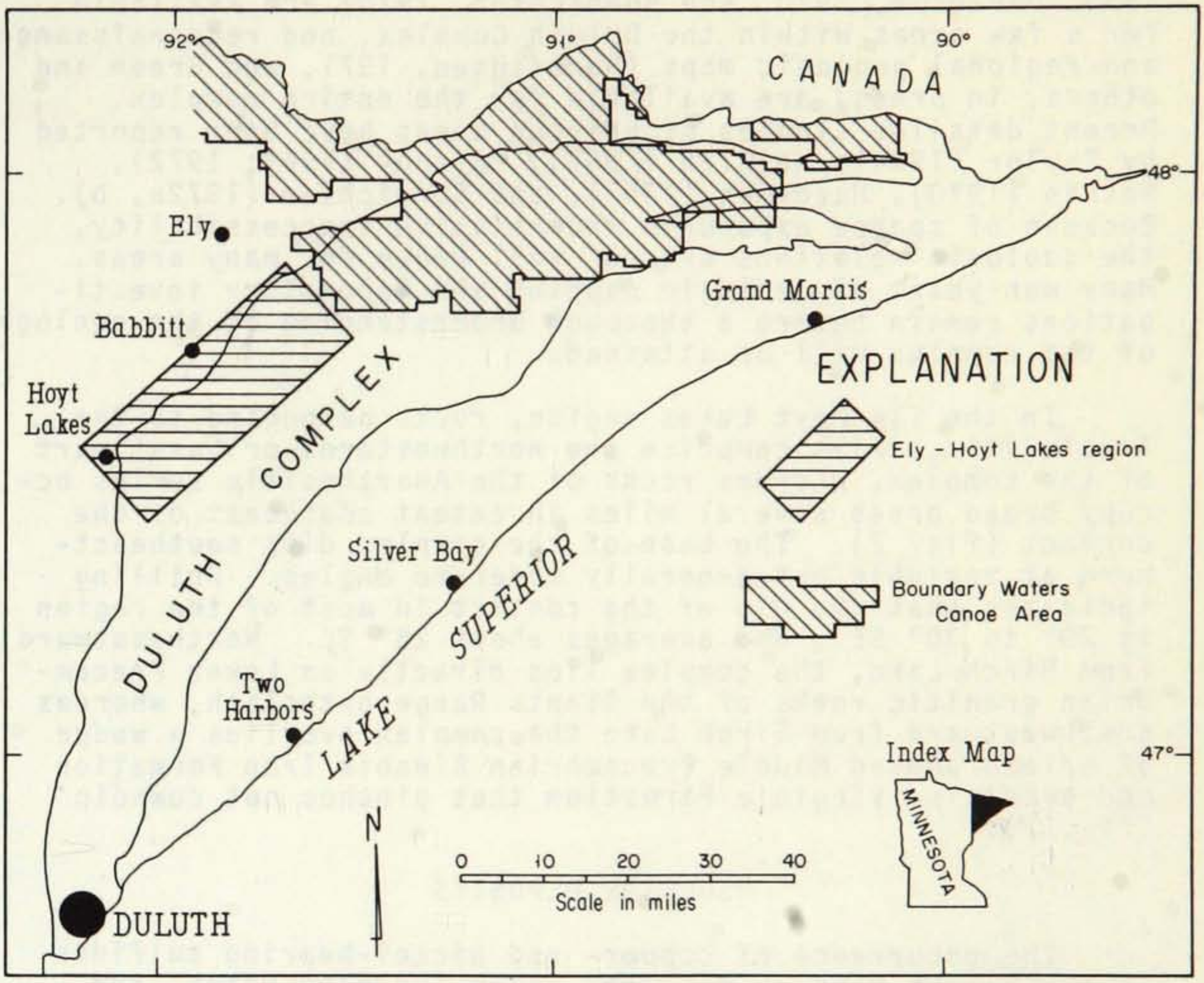


Figure 1. Map of northeastern Minnesota, showing the location of the Ely-Hoyt Lakes region relative to the Duluth Complex and to the Boundary Waters Canoe Area.

the Anorthositic series (Bonnichsen, 1972a). In all parts of the complex, the rocks of the Troctolitic series are younger than those of the Anorthositic series, for they cross-cut and contain inclusions of the latter. Small quantities of other rock types, including gabbro, granite, norite, dunite, picrite, and peridotite, also are present. Most occurrences of these rocks are gradational with, or closely associated with, troctolite, and consequently are considered to be part of the Troctolitic series. In addition, the complex contains numerous thoroughly metamorphosed inclusions of volcanic rocks from the North Shore Volcanic Group as well as of older sedimentary rocks.

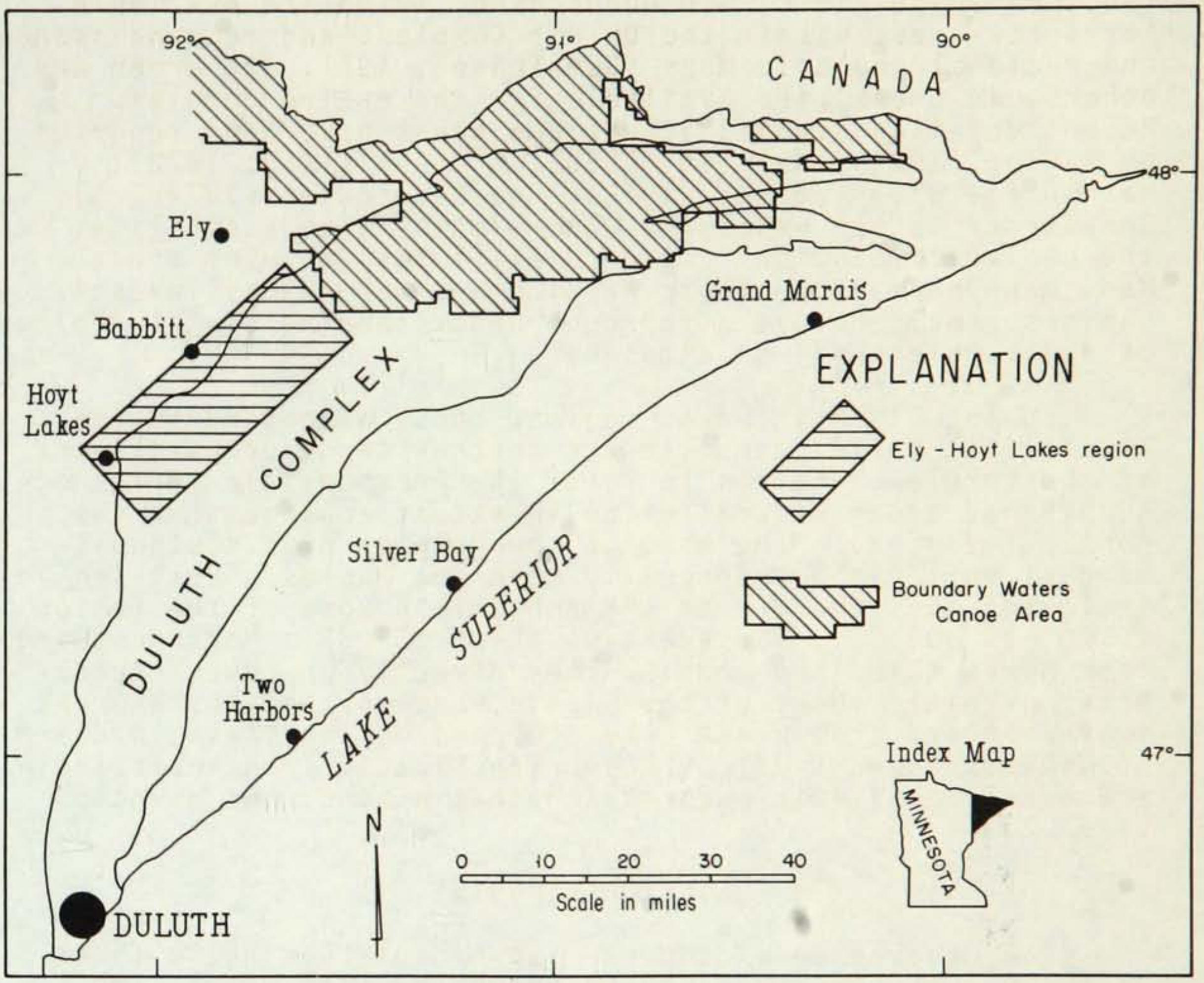
Detailed geologic maps (Taylor, 1964; Green and others, 1966; Davidson, 1970; and Bonnichsen, 1970) are available for a few areas within the Duluth Complex, and reconnaissance and regional geologic maps (Bonnichsen, 1971, and Green and others, in press) are available for the entire complex. Recent detailed studies of various areas have been reported by Taylor (1964), Weiblen (1965), Phinney (1969; 1972), Nathan (1970), Hardyman (1969), and Bonnichsen (1972a, b). Because of sparse exposures and relative inaccessibility, the geologic relations are not well known for many areas. Many man-years of geologic mapping and laboratory investigations remain before a thorough understanding of the geology of the complex will be attained.

In the Ely-Hoyt Lakes region, rocks belonging to the Troctolitic series comprise the northwestern, or basal part of the complex, whereas rocks of the Anorthositic series occupy broad areas several miles in extent southeast of the contact (fig. 2). The base of the complex dips southeastward at variable but generally moderate angles. Drilling indicates that the dip of the contact in most of the region is 20° to 30° SE., and averages about 25° SE. Northeastward from Birch Lake, the complex lies directly on Lower Precambrian granitic rocks of the Giants Range batholith, whereas southwestward from Birch Lake the complex overlies a wedge of metamorphosed Middle Precambrian Biwabik Iron Formation and overlying Virginia Formation that pinches out downdip (fig. 2).

SULFIDE DEPOSITS

The occurrence of copper- and nickel-bearing sulfides in the Duluth Complex has been known for many years, and the search for commercial deposits has been in progress for more than 20 years (Sims, 1968). More than a dozen mining companies and other private groups have conducted extensive geologic and geophysical investigations, and nearly a million feet of core have been drilled. Exploration has revealed the presence of sulfides in many areas outside the BWCA, including the Gunflint area and the southern part of the complex, but the area having the greatest known concentrations is the northwestern margin of the complex between Hoyt Lakes and the BWCA, southeast of Ely (fig. 1). Consequently, this part of the complex appears to have most promise for the development of minable copper-nickel deposits.

A preliminary account of the sulfide mineralization in the Duluth Complex has been published (Bonnichsen, 1972b). Disseminated sulfides occur fairly continuously between Hoyt Lakes and the southern boundary of the BWCA, and are concen-



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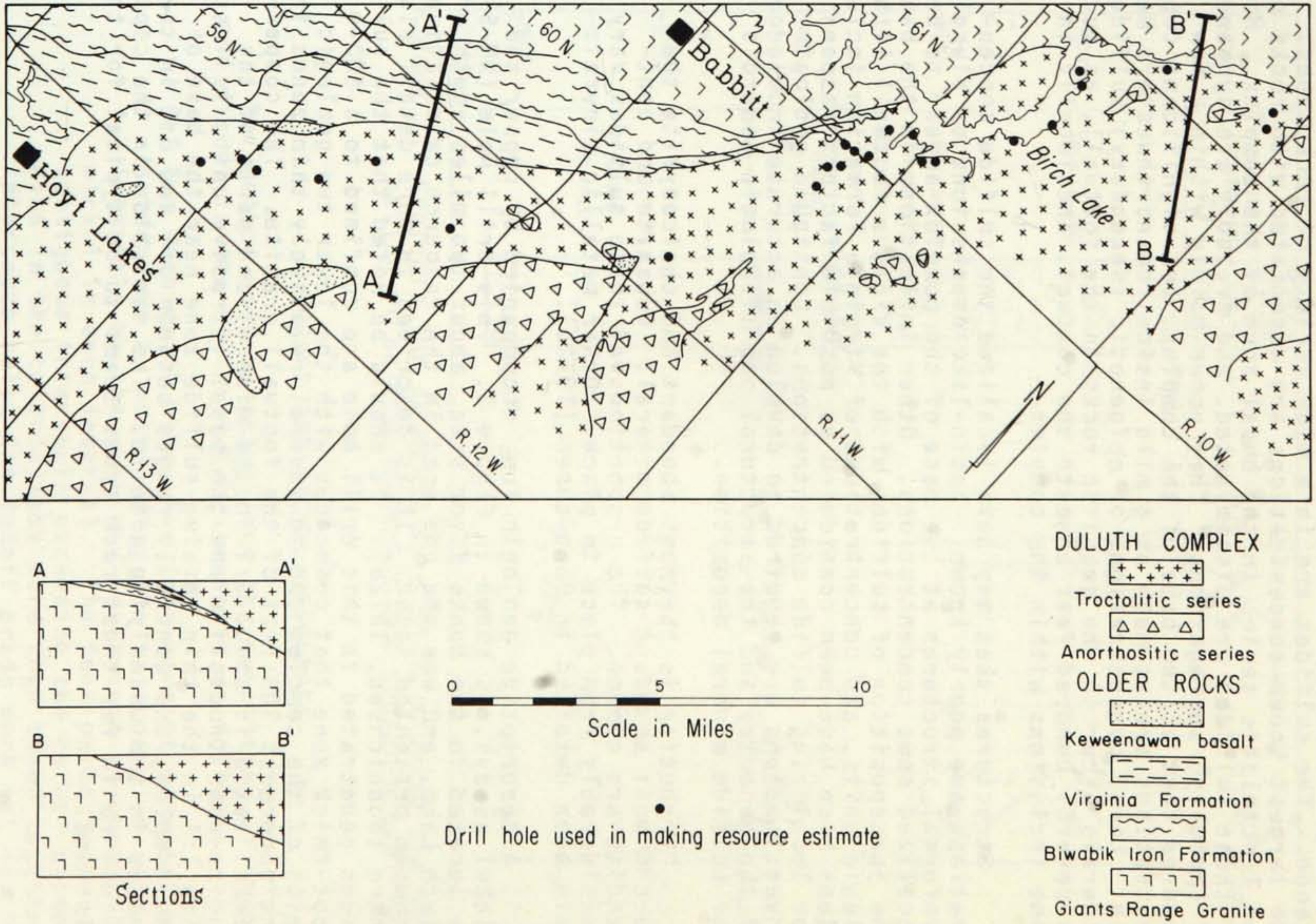

Figure 2. Geologic map and sections, Ely-Hoyt Lakes region, showing locations of the drill holes used for making estimates of the copper-nickel resources.

trated sufficiently in certain areas to have economic significance. The sulfides are in a wide variety of rock types. The largest known concentrations are associated with rocks of the Troctolitic series in the basal zone of the complex. Most of these sulfides are disseminated, and probably are syngenetic (primary) segregations. They occur mainly within a few hundred feet of the base of the complex, but significant concentrations are as much as a mile inside the northwestern margin. Local concentrations of epigenetic (secondary) sulfide minerals occur in the granitic rocks in the footwall, as much as several hundred feet beneath the contact, and locally in some inclusions within the complex.

Structures that may have localized the sulfide concentrations are poorly known. Basin-like depressions or plunging synformal structures at the base of the complex appear to have localized some concentrations. Other inflections in the base, the juxtaposition of sulfides with the various footwall lithologic units, and concentrations of Virginia Formation inclusions also have been considered as possible factors responsible for localizing sulfide concentrations. Continued geologic investigations are required to develop an accurate knowledge of the geometry and the structural and lithologic controls for sulfide mineral deposition.

Pyrrhotite is the most abundant and chalcopyrite the second most abundant sulfide mineral. Cubanite and pentlandite are common. The proportions of these sulfides vary considerably from place to place. Other metallic minerals have been detailed in Bonnichsen (1972b).

A descriptive geologic log, accompanied by copper and nickel assays, is shown in Figure 3. This drill hole (NM-5) is located in the Dunka River area, about two miles south of Birch Lake, and was the one used in the resource calculation example presented later. It is described in more detail elsewhere (Bonnichsen, 1972a). It should be noted that the sulfides penetrated in this drill hole are confined to a 600-foot-thick zone that coincides with the lower two geologic units of the complex and to several relatively thin zones in the uppermost 300 feet of the footwall granite. The copper-nickel ratio is about 3:1 in the mineralized parts of the augite-poor troctolite and the basal intrusive unit, is less than 1:1 in the thin massive sulfide zone near the base of the complex, and generally ranges between 5:1 and 8:1 in the bodies in the underlying granite. The variation in the copper-nickel ratio for these rock types seems to be typical for the district.

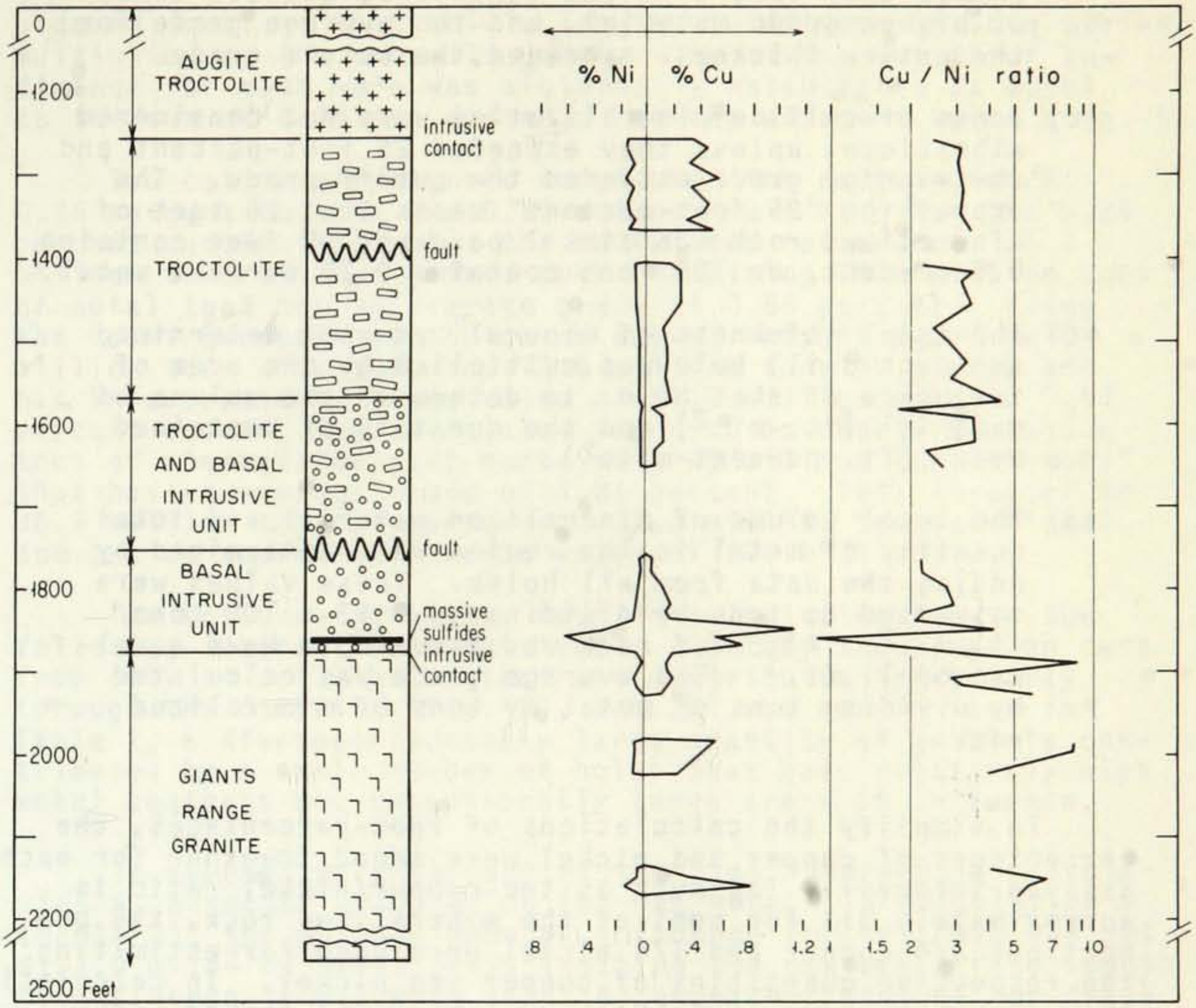

Figure 3. Geologic log of drill core NM-5, showing the distribution of sulfide minerals and copper-nickel ratios.

COPPER AND NICKEL RESOURCES

The method used in estimating the quantities of copper and nickel in the Ely-Hoyt Lakes area is as follows:

(a) For each drill hole, the foot-percent of metal was determined by multiplying the thickness of assayed intervals by the combined percentage of copper and nickel in each interval. The foot-percentages of contiguous intercepts exceeding the cutoff grade used in the calculations were then added together. Intercepts below the cutoff grade were not included unless they were thin and sandwiched between zones of higher grade material, and the average grade for the entire thickness exceeded the cutoff grade.

(b) Zones of sulfide mineralization were not considered significant unless they exceeded 25 foot-percent and the average grade exceeded the cutoff grade. The expression "25 foot-percent" means that 25 feet of mineralized rock contains 1 percent, 50 feet contains 0.5 percent, or 100 feet contains 0.25 percent metal.

(c) The total thickness of mineralized rock determined for each drill hole was multiplied by the area of influence of that hole, to determine the volume of material (ft.-mi.^{2}) and the quantity of contained metal (ft.-percent-mile^2).

(d) The total volume of mineralized material and total quantity of metal in the region were determined by adding the data from all holes. These values were converted to tons by dividing by 2.53 x 10^6 tons/ft.-mi.^{2}. A ton of rock was assumed to have a volume of 11 ft.^{3}. The average grade was calculated by dividing tons of metal by tons of mineralized rock.

To simplify the calculations of foot-percentages, the percentages of copper and nickel were added together for each assayed interval. Inasmuch as the copper/nickel ratio is approximately 3:1 for most of the mineralized rock, the proportions 3/4 copper and 1/4 nickel were used for estimating the respective quantities of copper and nickel. In calculating the values, a price of $.50/lb. was used for copper and a price of $1.50/lb. was used for nickel.

Assays from 24 holes (fig. 2) were used in making the resource estimates. The drill holes range in depth from 219 to 4,835 feet, and all but one are more than 1,500 feet deep. Twenty of the holes penetrated the base of the complex. When a cutoff grade of 0.25 percent copper plus nickel is used, twenty holes contain significant amounts of metal. However, when a cutoff grade of 0.50 percent is used, only 14 holes contain significant quantities. Sample calculations of the foot-percent values for one drill hole (NM-5) are given in Table 1.

In calculation A (table 2) for the district, a one-mile-wide strip of land parallel to the basal contact was considered significant, and the area of influence of each hole was considered equal to that hole's length of influence (along strike) multiplied by the one mile width. The strike length of influence for each hole was arbitrarily established as equal to the sum of half the distance between adjacent holes (fig. 4).

Two cutoff grades were considered for calculation A: 0.25 percent Cu + Ni and 0.50 percent Cu + Ni. For the 0.25 percent cutoff (table 3), the calculated resource is 14.3 billion tons of mineralized rock containing 78.6 million tons of metal that has an average grade of 0.55 percent. Using the Cu:Ni proportions indicated above, this is equal to 59 million tons of copper and 19.6 million tons of nickel and has an approximate gross value of $118 billion. For a 0.50 percent cutoff, the calculated resource is nearly 6 billion tons of mineralized rock containing 49 million tons of metal that has an average grade of 0.84 percent. This is equal to 36.9 million tons of copper and 12.3 million tons of nickel, and has an approximate gross value of $74 billion.

The resource estimates made in calculation A have the following inherent uncertainties: (1) They are based on data from only 24 drill holes that are distributed irregularly through the district (fig. 2), and (2), as can be seen in Table 2, a disproportionately large quantity of metal is contributed by a small number of holes that have relatively high metal contents and exceptionally large areas of influence.

To remove at least part of the bias inherent in calculation A, a second calculation (B) was made. In calculation B (table 2), the maximum area of influence for any hole was set at 1.0 mile^2 by arbitrarily limiting the maximum strike length of influence to 0.5 mile (fig. 4) on either side of any drill hole. This calculation decreases the total area considered significant from the 33.2 mile^2 in calculation A to 15.3 mile^2 for calculation B, and substantially reduces the proportion of the total contributed by any one hole. Limiting the strike length of influence for any one hole to a maximum of 1.0 mile results in the omission of significant parts of the district from consideration, as can be seen in Figure 4.

Cutoff grades of 0.25 percent and 0.50 percent copper plus nickel were considered for calculation B, as for calculation A (tables 2 and 3). For a 0.25 percent cutoff, a resource of 5.5 billion tons of mineralized rock containing nearly 30 million tons of metal with an average grade of 0.54 percent is indicated. This quantity of metal comprises more than 22 million tons of copper and 7.4 million tons of nickel, and has a gross value of nearly $45 billion. For a cutoff grade of 0.50 percent, a resource of 2.2 billion tons of

Table 1. Sample calculation of the quantity of significant mineralized rock in drill hole NM-5.

Depth	Thickness (in ft.)	Percent Cu	Percent Ni	Percent Cu+Ni	Ft.-%	Mineralized rock to consider
1258-1262.5	4.5	.35	.140	.49	2.21	
1262.5-1272.5	10	.47	.150	.62	6.20	
1272.5-1282.5	10	-	-	(.52)	(5.20)	For 0.25% cutoff grade
1282.5-1292	9.5	.32	.105	.425	4.04	1258-1371.5, 113.5 ft. at .543% Cu+Ni for 61.62 ft.-%
1292-1301	9	-	-	(.57)	(5.13)	
1301-1311.5	10.5	.55	.174	.724	7.60	
1311.5-1321	9.5	.32	.100	.42	3.99	
1321-1331	10	-	-	(.52)	(5.20)	For 0.50% cutoff grade
1331-1341	10	.47	.148	.618	6.18	1262.5-1371.5, 109 ft. at .545% Cu+Ni for 59.41 ft.-%
1341-1351	10	.42	.134	.554	5.54	
1351-1361.5	10.5	.29	.089	.379	3.98	
1361.5-1371.5	10	.49	.145	.635	6.35	
1371.5-1407		not assayed				
1407-1412	5	.19	.084	.274	1.37	
1412-1422	10	.26	.075	.335	3.35	1407-1481, 74 ft. at .313% Cu+Ni for 23.17 ft.-%
1422-1432	10	.26	.083	.343	3.43	
1432-1451	19	-	-	(.34)	(6.46)	Not significant (ft.-% too low)
1451-1461	10	.26	.076	.336	3.36	
1461-1481	20	-	-	(.26)	(5.20)	
1481-1813	scattered assays of less than 0.25% Cu+Ni					
1813-1823	10	.19	.063	.253	-	
1823-1833	10	.16	.070	.23	-	For 0.25% cutoff grade
1833-1843	10	.19	.090	.28	2.80	1833-1883, 50 ft. at .842% Cu+Ni for 42.11 ft.-%

1843-1853	10	1.12	.27	1.39	13.90	
1853-1863	10	.52	.59	1.11	11.10	
1863-1873	10	.73	.43	1.16	11.60	For 0.50% cutoff grade
1873-1883	10	.21	.061	.271	2.71	1843-1873, 30 ft. at 1.22% Cu+Ni for 36.60 ft.-%
1883-1892.5	9.5	.16	.018	.178	-	
1892.5-1902	9.5	.18	.042	.222	-	
1902-1911	9	.22	.076	.296	-	
1911-1921	10	.19	.058	.248	-	
1921-1930.5	9.5	.13	.022	.152	-	
1930.5-1979		not assayed				
1979-1988.5	9.5	.55	.065	.615	5.84	
1988.5-1998.5	10	.47	.056	.526	5.26	1979-2027.5, 48.5 ft. at .473% Cu+Ni for 22.92 ft.-%
1998.5-2017	18.5	-	-	(.44)	(8.14)	
2017-2027.5	10.5	.28	.071	.351	3.68	Not significant (Ft.-% too low)
2027.5-2133		not assayed				
2133-2143	10	.11	.027	.137	-	
2143-2153	10	.34	.050	.390	3.90	2143-2173, 30 ft. at .539% Cu+Ni for 16.18 ft. -%
2153-2163	10	.80	.142	.942	9.42	
2163-2173	10	.24	.046	.286	2.86	Not significant (Ft.-% too low)

Summary of significant mineralization

	interval	ft.	Ft.-%	%Cu+Ni
0.25% cutoff grade	1258-1371.5	113.5	61.62	.543
	1833-1883	50	42.11	.842
	Total	163.5	103.73	.634
0.50% cutoff grade	1262.5-1371.5	109	59.41	.545
	1843-1873	30	36.60	1.22
	Total	139	96.01	.691

(The percent Cu+Ni and ft.-% values shown in parentheses were interpolated from adjacent intervals.)

mineralized rock that contains more than 18 million tons of metal with an average grade of 0.82 percent is indicated. This quantity of metal comprises 13.8 million tons of copper and 4.6 million tons of nickel, and has a gross value of approximately $27.6 billion.

Both calculations of the copper and nickel resources are conservative. Four of the 24 holes used in the calculations did not reach the base of the complex, and accordingly may not be deep enough to have penetrated the main mineralized zone. Also, more than half the holes were drilled on lands for which the company leases were later relinquished. These

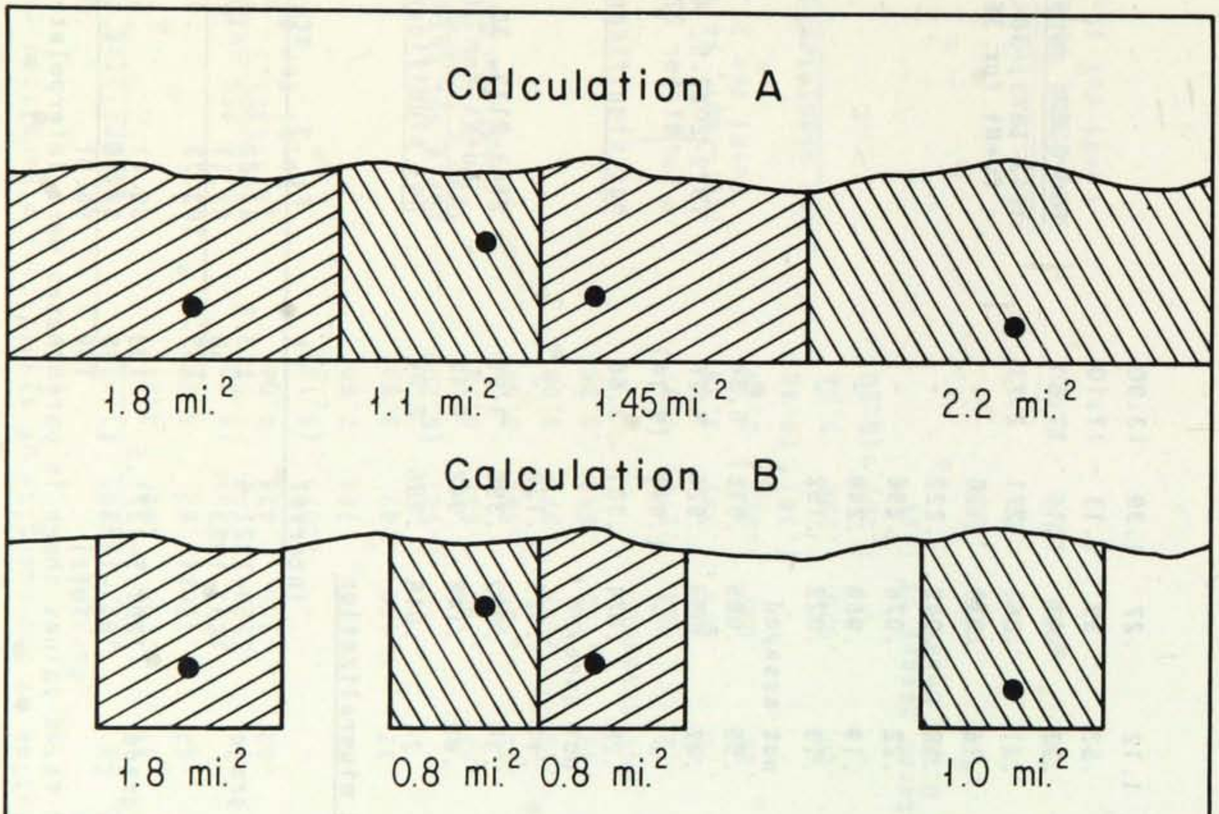

Figure 4. Schematic representation (plan view) of the method used to determine the area of influence for holes used in calculations A and B.

Table 2. Calculation of the total ft.-percent and ft.-percent-mi.^{2} values for cutoff grades of 0.25 percent and 0.50 percent Cu+Ni.

Hole	0.25% cutoff ft	0.25% cutoff ft-%	0.50% cutoff ft	0.50% cutoff ft-%	Calculation A mi^2	A 0.25% cutoff ft mi^2	A 0.25% cutoff ft-%mi^2	A 0.50% cutoff ft mi^2	A 0.50% cutoff ft%mi^2	Calculation B mi^2	B 0.25% cutoff ft mi^2	B 0.25% cutoff ft-%mi^2	B 0.50% cutoff ft mi^2	B 0.50% cutoff ft-%mi^2
1	338	140.9	51	33.9	4.60	1554.8	648.1	234.6	155.9	1.00	338.0	140.9	51.0	33.9
2,3	371.5	245.7	208.5	193.1	4.35	1616.0	1068.8	907.0	840.0	1.00	371.5	245.7	208.5	193.1
4	0	0	0	0	3.65	0	0	0	0	1.00	0	0	0	0
5	77	25.2	0	0	3.50	269.5	88.2	0	0	1.00	77.0	25.2	0	0
6	315.5	258.1	315.5	258.1	2.40	757.2	619.4	757.2	619.4	1.00	315.5	258.1	315.5	258.1
7	0	0	0	0	2.15	0	0	0	0	.70	0	0	0	0
8	70	39.2	50	31.4	1.65	115.5	64.7	82.5	51.8	1.00	70.0	39.2	50.0	31.4
9,10	131.25	112.7	107.25	106.2	1.55	203.4	174.7	166.2	164.6	1.00	131.3	112.7	107.3	106.2
11	0	0	0	0	1.55	0	0	0	0	1.00	0	0	0	0
12	162	53.2	0	0	1.40	226.8	74.5	0	0	1.00	162.0	53.2	0	0
13	300	100.1	0	0	1.20	360.0	120.1	0	0	0.65	195.0	65.1	0	0
14	100	29.4	0	0	1.00	100.0	29.4	0	0	1.00	100.0	29.4	0	0
15	73	39.6	41	26.8	.95	69.4	37.6	39.0	25.5	.70	51.1	27.7	28.7	18.8
16	0	0	0	0	.70	0	0	0	0	.70	0	0	0	0
17	130	62.5	40	31.1	.55	71.5	34.4	22.0	17.1	.55	71.5	34.4	22.0	17.1
18	60	28.2	0	0	.50	30.0	14.1	0	0	.50	30.0	14.1	0	0
19	53	26.7	53	26.7	.35	18.6	9.3	18.6	9.3	.35	18.6	9.3	18.6	9.3
20	163.5	103.7	139	96.0	.30	49.1	31.1	41.7	28.8	.30	49.1	31.1	41.7	28.8
21	280	118.9	50	25.5	.25	70.0	29.7	12.5	6.4	.25	70.0	29.7	12.5	6.4
22	290	134.4	90	74.2	.20	58.0	26.9	18.0	14.8	.20	58.0	26.9	18.0	14.8
23	68.5	53.7	59	51.3	.20	13.7	10.7	11.8	10.3	.20	13.7	10.7	11.8	10.3
24	335.5	124.7	0	0	.20	67.1	24.9	0	0	.20	67.1	24.9	0	0
Total					33.20	5650.6	3106.6	2311.1	1943.9	15.30	2189.4	1178.3	885.6	728.2

(Ft. and ft.-percent values were averaged for holes 2 and 3, and 9 and 10)

Table 3. Estimated tonnage, value, and grade of copper-nickel deposits in the Ely-Hoyt Lakes region for calculations A and B.

	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.

same companies have retained leases on other properties -- for which data are not available -- and it can be presumed that these contain better concentrations of metals than those on which the leases were relinquished. In addition, calculation B is perhaps excessively conservative because it does not consider those parts of the district that are more than half a mile along strike from a drill hole available to me.

COMPARISON WITH WORLD PRODUCTION AND RESOURCES

The copper resource estimated for the Ely-Hoyt Lakes area compares favorably with the total amount of metal known to be present in many of the major copper mining districts of the world (fig. 5). With regard to Figure 5, it should be noted, however, that the quantities of metal indicated for the various producing districts represent past production and unmined reserves, which are known quantities (table 4; fig. 5); whereas the quantity estimated for the Ely-Hoyt Lakes district represents the amount of copper that ultimately may be mined. The actual amount of copper that will be mined in the district will depend on many interrelated economic and social factors, including the tonnage that can be extracted by open-pit versus underground methods. The geometry of the deposits is such that only a small part of the potentially minable copper can be extracted by open-pit mining.

The annual production of primary (newly mined) copper has increased substantially in the United States and throughout the world in recent years, and this trend most likely

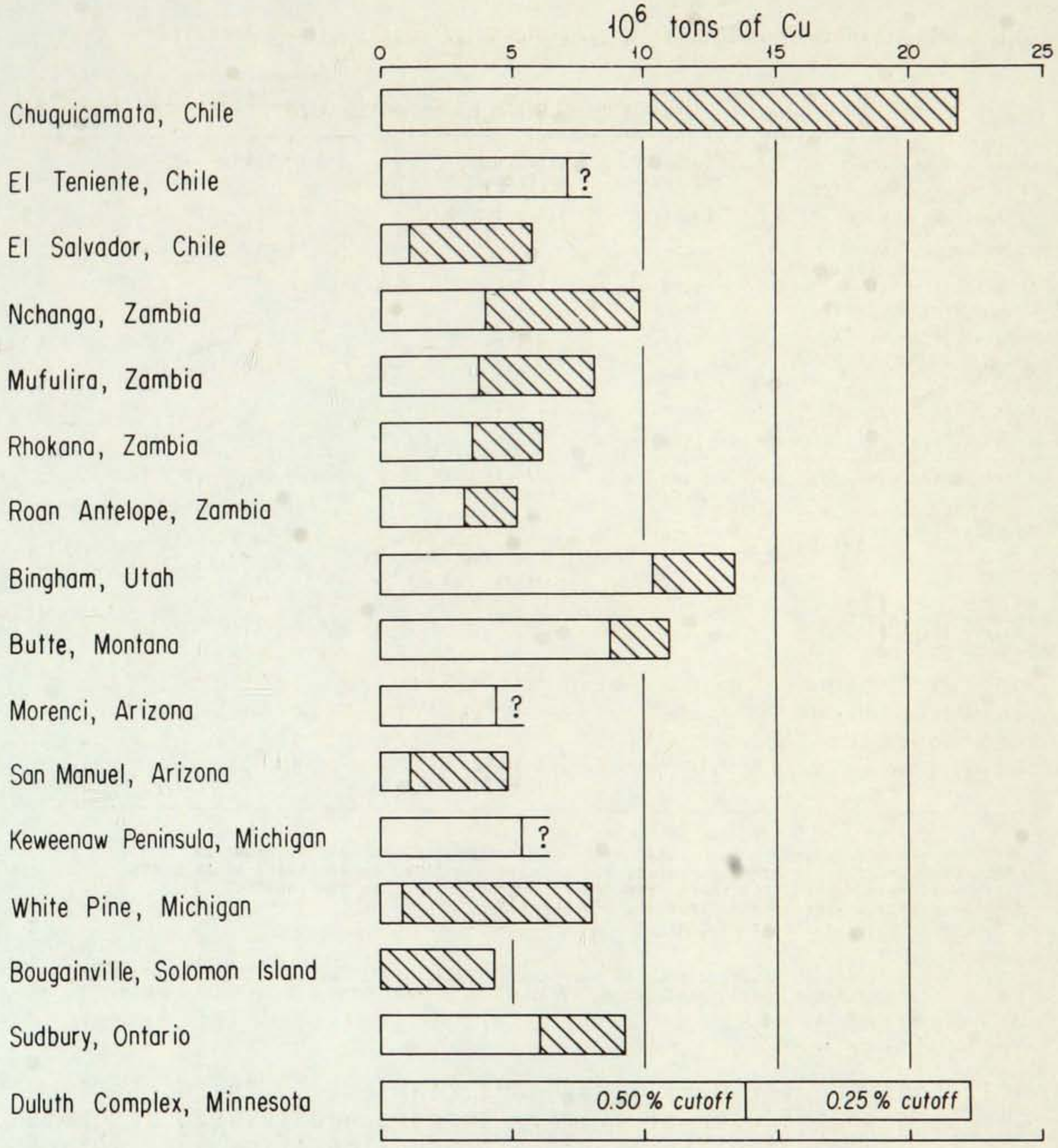

Figure 5. Total recoverable copper in some of the world's principal copper mining districts, compared to the estimated copper resources in the Ely-Hoyt Lakes region. Solid = amount produced; lined = reserves. Estimates given for Duluth Complex are based on lower mining limits of 0.5 and 0.25 percent .

Table 4. Characteristics of some of the world's principal copper deposits.

Mine or District	Type of Deposit*	Main Ore Minerals**	Grade	Mining Method***	Production through 1970****	Est. Reserves ****	Approx. Annual Production ****
Chuquicamata, Chile	P	cp,bn,en, cc,cv,an	oxide 1.63% sulfide 2.0%	0	10.19	>11.65	.30
El Teniente, Chile	P	cp,bn,cc	1.0-2.25%	U	7.06	?	.18
El Salvador, Chile	P	cp,bn,cc	1.5%	U	1.03	4.59	.09
Nchanga, Zambia	B	cc,ma,cu, bn,cp	4.65%	0,U	3.87	5.94	.25
Mufulira, Zambia	B	cp,bn,cc	3.35%	U	3.63	4.42	.16
Rhokana, Zambia	B	cp,bn	3.07%	U	3.46	2.61	.10
Roan Antelope, Zambia	B	cp,bn,cc	3.04%	U	3.19	1.88	.10
Bingham, Utah	P	cp,bn,cc	.75%	0	10.27	>3.17	.28
Butte, Montana	P	cc,en,bn, cv,dg,cp	open pit .75% veins 4.35%	0,U	8.7	2.14	.10
Morenci, Arizona	P	cp,cc,cv	.88%	0	4.4	?	.11
San Manuel, Arizona	P	cp,cc	oxide .70% sulfide .75%	U	1.16	3.64	.09
Keweenaw Peninsula, Michigan	F	Cu	1.48%	U	5.4	?	< .01
White Pine, Michigan	B	cc	1.2%	U	.86	> 7.05	.07
Bougainville, Solomon Islands	P	cp,bn	.48%	0	0	4.32	0
Sudbury, Ontario	M	cp,pn	1.5% Cu 1.5% Ni	0,U	>6.0	> 3.2	.17

*P-porphyry, B-bedded, F-associated with basalt flows, M-magmatic segregation
**cp-chalcopyrite, bn-bornite, cc-chalcocite, cv-covellite, dg-digenite, en-enargite, an-antlerite, cu-cuprite, ma-malachite, Cu-native copper, pn-pentlandite
***0-open pit, U-underground, includes block-caving
****Units of millions of short tons

Sources: American Bur. Metal Statistics Yearbooks; Boldt, 1967; Espie, 1971; Lowell and Guilbert, 1970; McMahon, 1965; Mendelsohn, 1961; Ridge, 1968; Smith, 1967; Titley and Hicks, 1966.

will continue for many more years (table 5). The U. S. is the leading producer of primary copper, and in 1970 accounted for 24.9 percent of the world's production (fig. 6). Between 1845 and 1970, 59 million tons of copper were mined in the U. S.; of this quantity, 31.6 million tons (53.6 percent) were mined in the last 30 years (1941-70) and 13.0 million tons (22 percent) were mined in the last decade (1961-70) (fig. 7). In fact, 2.9 percent of the total tonnage was produced in 1970. An even more pronounced acceleration of copper production has occurred throughout the world in recent years in response to increased industrial demand abroad.

Table 5. Recent world copper production.

	1950		1960		1970	
	10^3 tons	%	10^3 tons	%	10^3 tons	%
U.S.	909	32.9	1080	23.3	1706	24.9
U.S.S.R.	240	8.7	550	11.9	990	14.4
Zambia	328	11.9	635	13.7	765	11.2
Chile	400	14.5	591	12.7	747	10.9
Canada	264	9.6	439	9.5	674	9.8
Rep. Congo	194	7.0	333	7.2	425	6.2
Peru	33	1.2	200	4.3	234	3.4
Philippines	11	0.4	49	1.1	177	2.6
Rep. So. Africa	37	1.3	50	1.1	164	2.4
Australia	17	0.6	123	2.7	152	2.2
Rest of world	327	11.9	590	12.5	820	12.0
Total	2760	100.0	4640	100.0	6854	100.0

(Units: Thousands of short tons of Cu)

(Source: Yearbooks of the American Bureau of Metal Statistics)

If U. S. production of primary copper increases at the same rate as for the years 1961-70, 16.65 million tons will be mined in the 1971-80 decade. This would bring the cumulative production to 75.7 million tons by the end of 1980. If production increases during the period 1971-2000 at the same rate as during the preceding 30 years (1941-70), 68.2 million tons of new copper will be mined, or more than has been mined in all previous time. This would bring the cumulative quantity to 127.2 million tons (fig. 7).

The U. S. Bureau of Mines (Ageton and Greenspoon, 1968) has predicted that the demand for primary refined copper in the U. S. in the year 2000 will be between 4.90 and 7.86 million tons per year, leading to a 1968-2000 cumulative demand of between 96.4 and 128.2 million tons. It further predicted -- if the 1968 ratio of domestic production to copper imports is maintained -- that the cumulative amount of copper mined in the United States during this period will be between 75.4 and 100 million tons. Adding this to the previous U. S. copper production would raise the cumulative production by the year 2000 to between 131.2 and 155.8 million tons (fig. 7), which is slightly more than predicted by simple extrapolation of the 1941-1970 rate of increase.

Table 6. Copper reserves and resources of the United States (after Everett and Bennett, 1967).

(values given in millions of tons of copper)	Reserves		Resources	
	Measured and Indicated	Inferred	Measured and Indicated	Inferred
States east of Mississippi River	8.8	30.5	2.4	45.0
States west of Mississippi River	33.2	13.1	5.1	12.2
Total	42.0	43.6	7.5	57.2

Total copper reserves	- 85.6 million tons
Total copper resources	- 64.7 million tons
Reserves plus resources	150.3 million tons

The U. S. Bureau of Mines (Everett and Bennett, 1967) estimated that the U. S. had copper reserves of 85.6 million tons at the end of 1964 (table 6). Of this amount, 24.5 million tons were measured reserves and the remainder were indicated or inferred reserves. At the end of 1964, potential U. S. copper resources were estimated as 64.6 million tons, mainly in the inferred category (57.2 million tons). As shown in Figure 7, the estimated copper resource in the Ely-Hoyt Lakes district compares favorably with other U. S. copper resources.

In contrast, the U. S. produces very little nickel as compared to copper. Currently, about half the world's production of nickel comes from Canada, although Canada's share has decreased in recent years as new mines have opened in other regions (table 7). Canadian nickel reserves also are much larger than those in the United States (table 8).

In recent years, 70 to 80 percent of the nickel produced in Canada came from the Sudbury district; most of the remainder was obtained from the Thompson district in Manitoba. The Sudbury district contains the world's largest known nickel deposits. More than 6 million tons of nickel have been mined from the district, as well as approximately the same quantity of copper. Extensive reserves remain to be developed. Cornwall (1966) noted that the district contains more than 300 million tons of proven and indicated ore reserves that average 1.5 percent nickel; this quantity of ore contains about 4.8 million tons of nickel, as well as a comparable quantity of copper. Extensive reserves also are known in both the Thompson and Lynn Lake areas of Manitoba and in the Ungava region of northern Quebec.

In the five years from 1966 to 1970, the U. S. consumed an average of more than 160,000 tons of nickel each year, which was imported mainly from Canada. The only significant nickel production in the U. S. has been from a small laterite deposit at Riddle, Oregon. This deposit provides about 10 percent of the primary nickel used in the U.S. each year. The only large nickel resource in the U. S. in addition to the Duluth Complex is the low-grade magmatic sulfide deposit associated with the Stillwater Complex in Montana; both are large bodies of mafic and ultramafic plutonic rocks. Both deposits probably contain comparable nickel and copper resources.

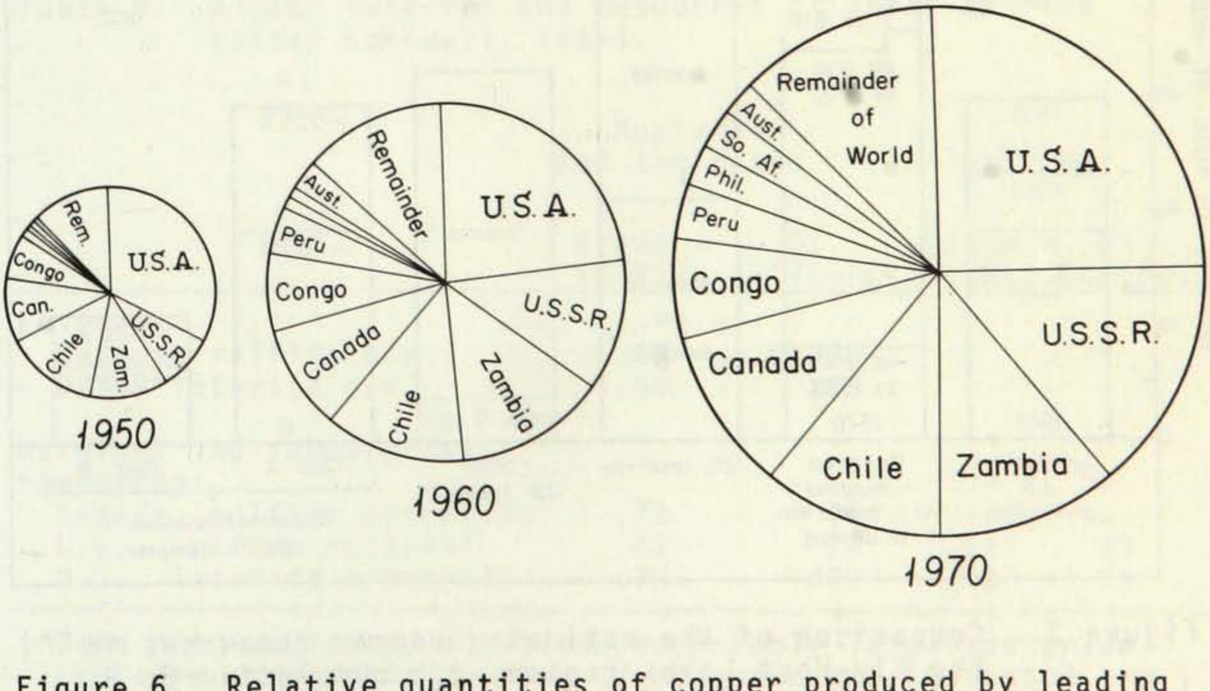

Figure 6. Relative quantities of copper produced by leading countries in 1950, 1960, and 1970.

COPPER AND NICKEL RESOURCES

Although the nickel deposits of the Duluth Complex are substantially lower in grade than those in the Sudbury district, it is interesting to note that the estimated nickel resource in the Ely-Hoyt Lakes district is of the same order of magnitude as the reserves in the Sudbury district.

CONCLUSIONS

1. Large, economically marginal deposits of copper and nickel sulfides are associated with the Duluth Complex in the Ely-Hoyt Lakes region. The principal sulfide minerals are pyrrhotite, chalcopyrite, cubanite, and pentlandite.

2. The principal concentrations of copper and nickel are disseminated deposits in the lower few hundred feet of the Duluth Complex and local massive deposits in granitic footwall rocks. The size, shape, and geometric relations of the sulfide concentrations to lithologic units and structural features of the complex are poorly known.

3. The Ely-Hoyt Lakes region contains the largest known combined copper-nickel resource in the United States. Conserv-

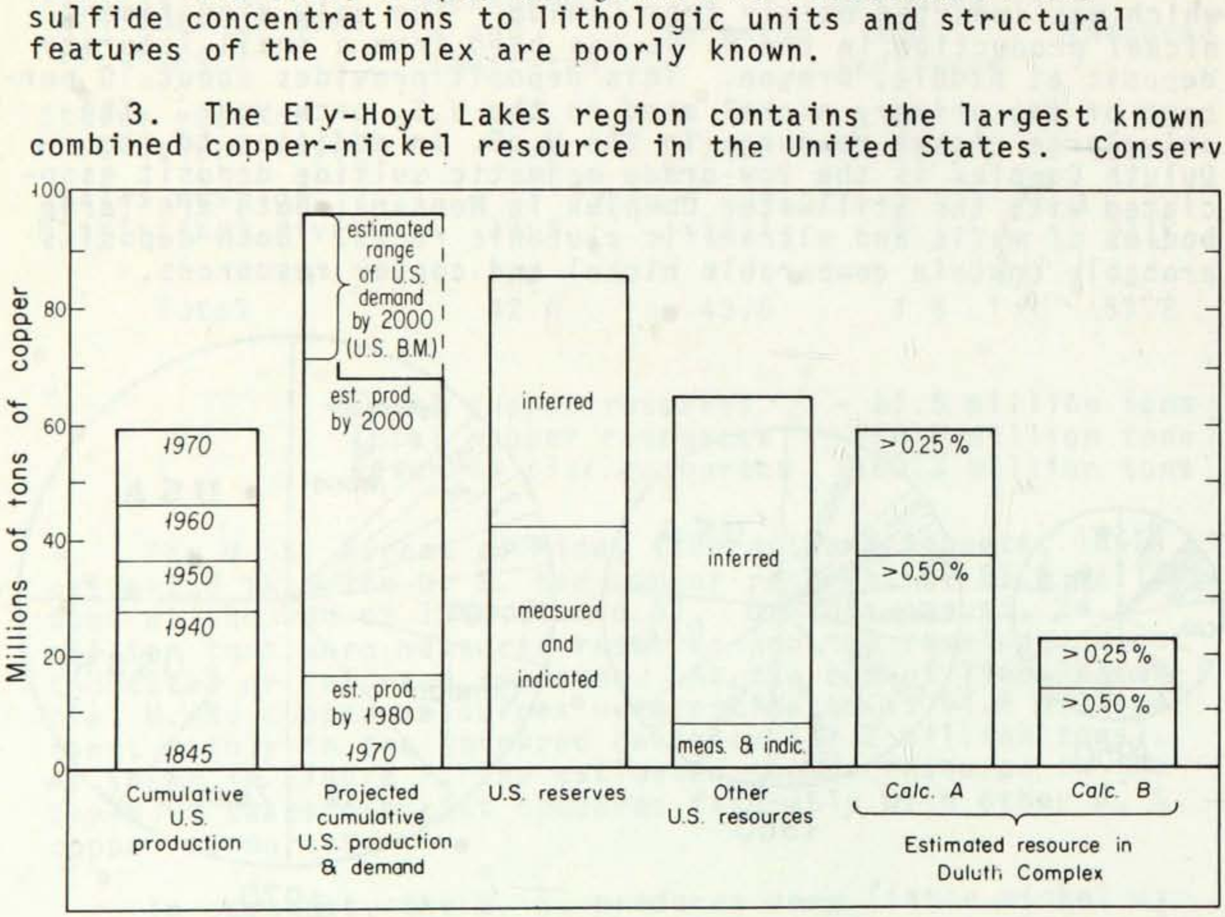

Figure 7. Comparison of the estimated copper resources in the Ely-Hoyt Lakes region with cumulative U. S. production, demand, reserves, and other resources.

Table 7. Recent world nickel production.

	1950		1960		1970	
	10^3 tons	%	10^3 tons	%	10^3 tons	%
Canada	124	76.1	215	60.7	305	49.7
U.S.S.R.	32	19.6	64	18.0	120	19.5
New Caledonia	5	3.1	44.5	12.5	116	18.9
Cuba	-	-	12.5	3.5	40	6.5
U.S.	1	.6	14	3.9	15.5	2.5
Rep. So. Africa	1	.6	3	.8	12	2.0
Finland	-	-	2	.6	5.5	.9
Total	163	100.0	355	100.0	614	100.0

(Units: thousands of short tons of Ni)
(Source: Yearbooks of the American Bureau of Metal Statistics)

Table 8. Nickel reserves and resources of North America (after Cornwall, 1966).

	Measured and Indicated		Inferred	
	Grade (% Ni)	Ni 10^3tons	Grade (% Ni)	Ni 10^3tons
Reserves:				
Canada, sulfide ore	1.46	6,278	*	*
U.S., laterite ore	1.50	243	-	-
Marginal and submarginal resources:				
Canada, sulfide material	.75	16	-	-
U.S., sulfide material	.42	74	.37	93
U.S., laterite material	.78	422	.58	79

(*Data not available, but tonnage probably large and grade probably comparable to that of measured and indicated ore.)

atively, the region contains more than 18 million tons of metal having an average grade of 0.82 percent Cu + Ni. At today's prices, this metal has a value of more than $27 billion.

4. The magnitude of the copper and nickel resources in the Duluth Complex compares favorably with that in some of the larger copper and nickel districts in the world. Accordingly, the region constitutes a major future source of these metals for the United States. More detailed studies of the deposits are needed in order that land-use decisions be made that will best serve the needs of Minnesota and the United States.

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