SULFIDES IN THE BIRCHDALE - INDUS AREA, KOOCHICHING COUNTY, MINNESOTA

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SULFIDES IN THE BIRCHDALE-INDUS AREA, KOOCHICHING COUNTY, MINNESOTA

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INTRODUCTION

The Birchdale-Indus area has been examined for economic mineral deposits for many years. This area was first examined by prospectors looking at surface outcroppings and then by mineral and mining companies using more sophisticated equipment and techniques. Initial drilling was for iron ore, and four drill holes were drilled into magnetic anomalies. The first exploration by major companies for base metal sulfide deposits began in 1966. Exploration activity has been continuing in the area although no economic deposits have been announced to date. All of the significant sulfide discoveries in the area will be discussed in more detail below.

OCCURRENCES

THE BIRCHDALE AREA

This area is located three miles south of the small town of Birchdale, near the southern edge of a granitic pluton called the Birchdale Granite. The area of interest is located in portions of Sections 15, 16 and 21 in T.159N., R.27W. The area was the first explored by mining companies who were quick to notice the geophysical anomaly which occurs here. The anomaly area has been explored by three mining companies, all of whom drilled the anomaly. A total of nine holes were completed. The most recent drilling was done late in 1974. Other work in the area includes geochemical and geophysical surveys by Meineke, Gilgosch and Vadis (1976), and Meineke, Vadis and Gilgosch (1976), respectively; and an unpublished thesis by Listerud (1974). The last two drill cores became available after the work by Listerud was completed. Figure 1 is a map showing the outcroppings, drill hole locations, and the boundary of the Birchdale Granite.

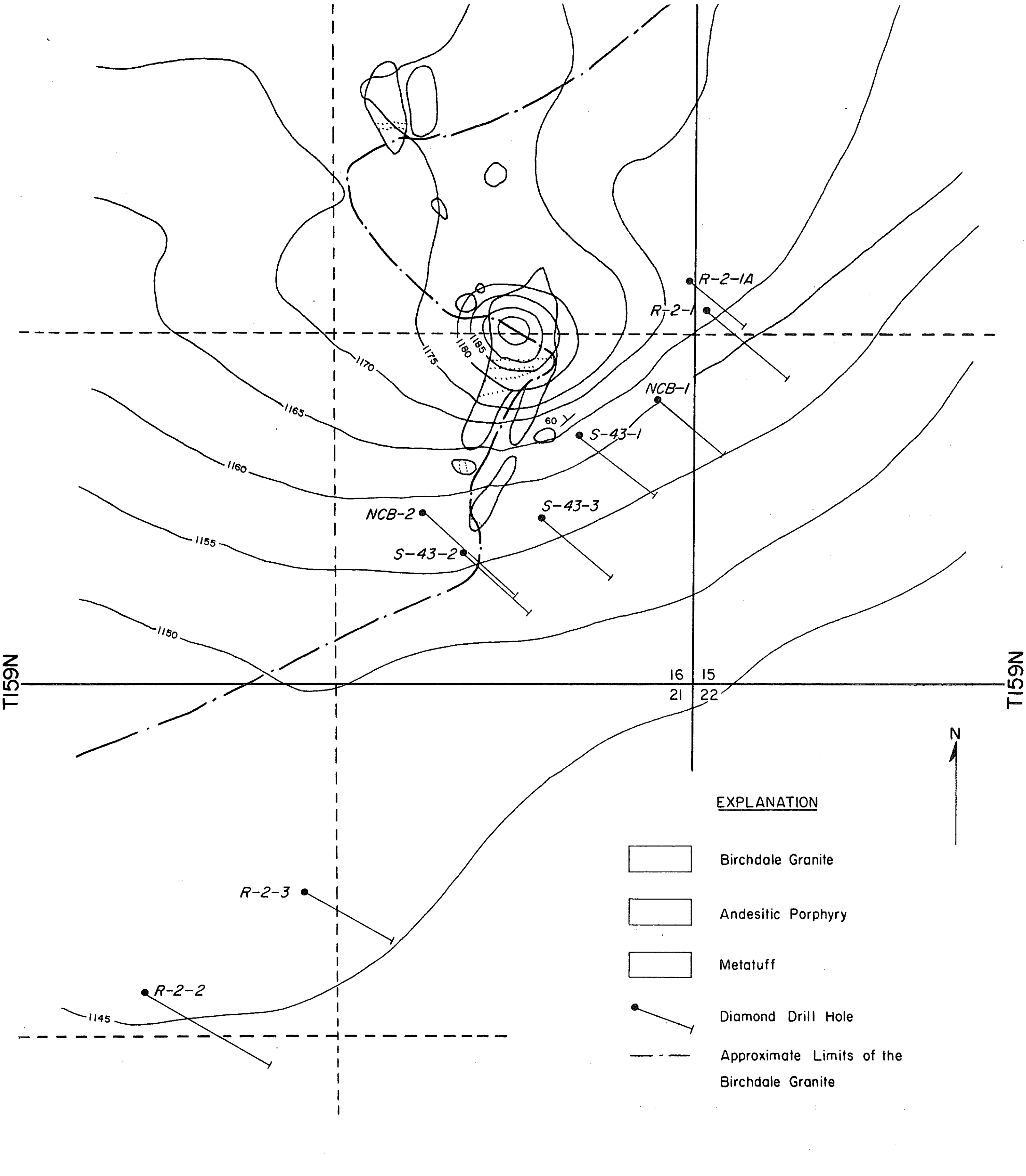

FIGURE 1: Geologic Map of the Birchdale Area

SCALE 1" = 500'

500 250 0 250 500 1000 FEET

CONTOUR INTERVAL 5 FEET

Drill holes R-2-2 and R-2-3 were drilled on the southwest extension of the anomaly and no basis for correlation with the rocks intersected in the other holes has been found. The correlation between the rocks intersected in the other seven cores are shown in Figures 2 and 3. The stratigraphic column is shown in Figure 4.

The sulfides in the Birchdale area occur in both massive and disseminated zones. The main sulfide zones are shown in Figures 2 and 3 by the dashed enclosures. The sulfide minerals, as observed by Listerud (1974), listed in order of their relative abundances are: pyrrhotite, pyrite, chalcopyrite, sphalerite, pentlandite, marcasite and cubanite. Pyrrhotite exists in both its hexagonal and monoclinic forms with both granular and feathery exsolution-type textural relationships. An intermediate phase between pyrrhotite and pyrite was observed in several sections. This phase was also observed by Ramdohr (1969) in other localities where pyrite is replacing pyrrhotite. He has shown it to be essentially an aggregate of very fine-grained pyrite or marcasite. The most common sulfide assemblages are: pyrrhotite-pyrite-chalcopyrite, pyrrhotite-chalcopyrite, pyrrhotite-chalcopyrite-sphalerite, and pyrrhotite-chalcopyrite-pentlandite. Listerud found that these four assemblages accounted for over half of his total observations with the pentlandite-bearing assemblage present mostly in the mafic intrusive rocks. Marcasite was observed only in late veins and fracture fillings. Cubanite was found in trace amounts in only one sample.

The massive sulfides in this area have been investigated by Listerud (1974), and he reports: "Several massive and semimassive sulfide zones were intersected in the drilling of the Birchdale anomaly. In Unit E (interbedded metasediments and metatuffs), the main sulfide-bearing horizon, several of these massive sulfide zones occur. The massive zones vary in thickness from about six inches to about ten feet. The contacts vary from sharp to

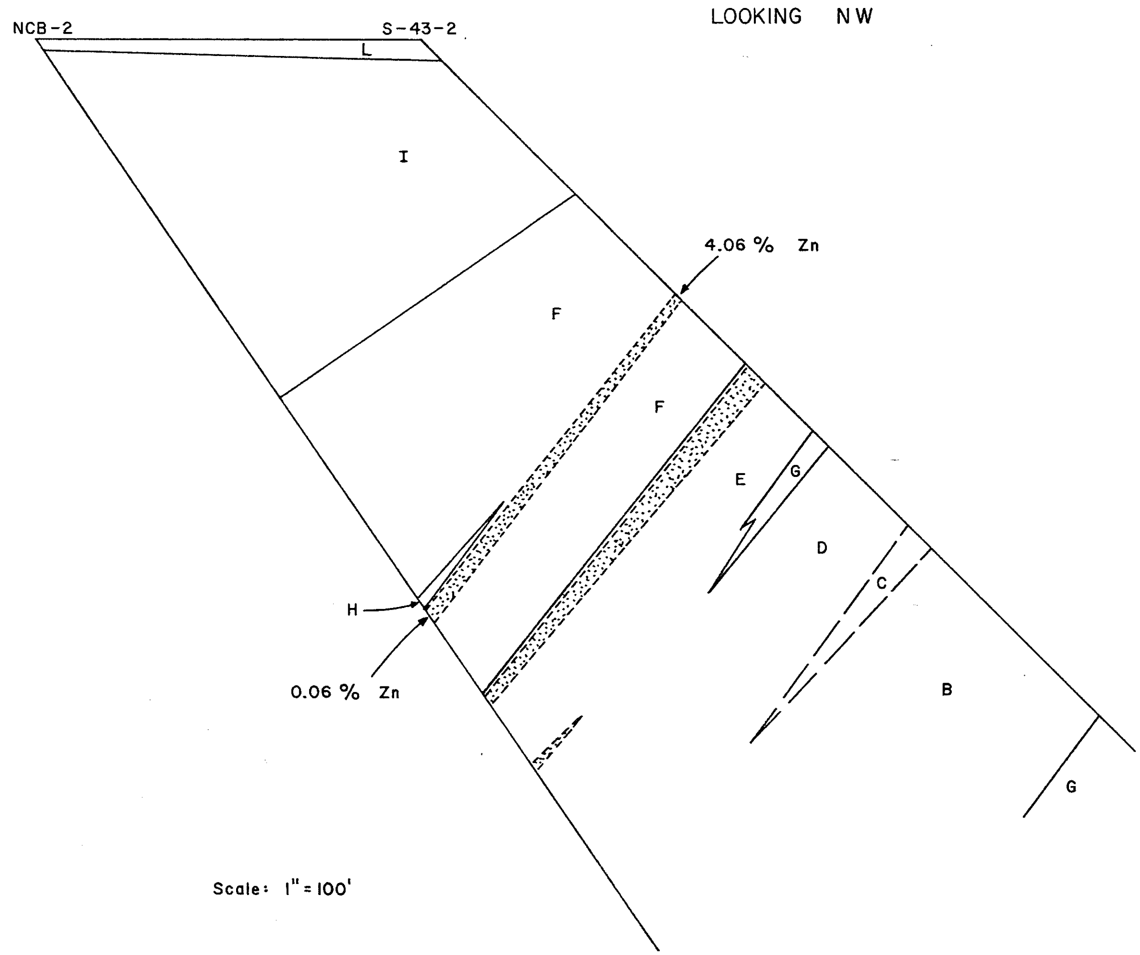

FIGURE 2: Fence Diagram #1

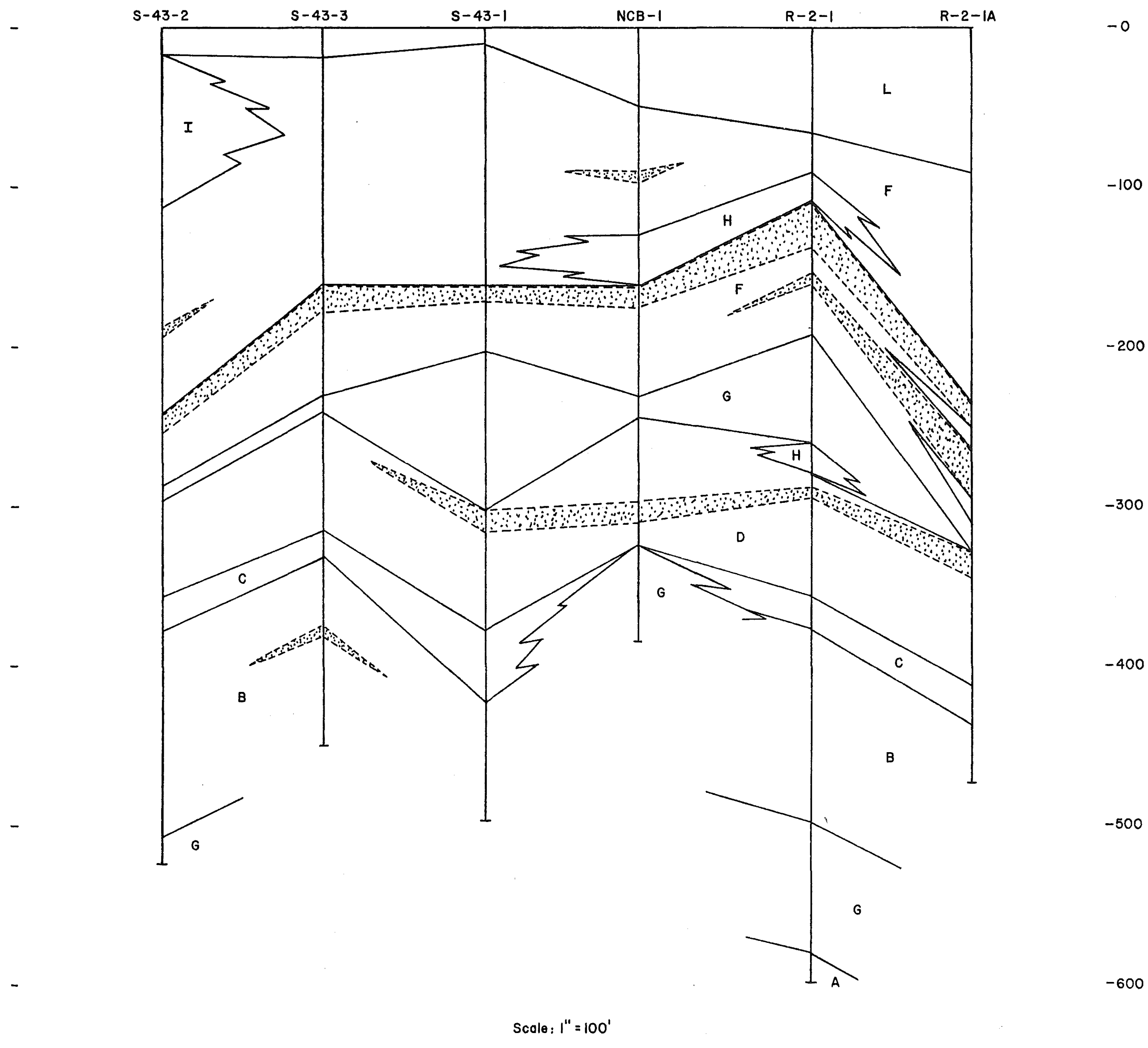

FIGURE 3: Fence Diagram #2

FIGURE 4

BIRCHDALE AREA
STRATIGRAPHIC COLUMN

CENOZOIC	L	GLACIAL TILL AND LAKE SEDIMENTS
	K	GRANITIC PEGMATITE DIKES. This unit is found only in outcrop and includes tourmaline-bearing dikes.
	J	PORPHYRITIC ANDESITE AND TRACHY-ANDESITE DIKES. This unit is found only in outcrop.
	I	BIRCHDALE GRANITE. These rocks are pink, coarse to medium-grained, and massive.
LOWER PRECAMBRIAN	H	ANDESITE AND DIORITE INTRUSIVES. The rocks occur in irregular zones and are fine-grained and porphyritic to coarse-grained and massive.
	G	MAFIC IGNEOUS ROCKS. These rocks may be intrusive or extrusive, fine to medium-grained, massive, and dark green.
	F	FELSIC TO INTERMEDIATE METATUFFS. These rocks are fine to very fine-grained, light colored, massive to thin banded, with andesitic lapilli zones. Occurs in outcrop and drill core.
	E	INTERBEDDED GRAPHITIC METASEDIMENTS AND METATUFFS. This is the main sulfide-bearing unit. The metasediments are fine-grained, gray to black and the metatuffs are coarser grained and green.
	D	TUFFACEOUS METASEDIMENTS. These rocks are fine-grained, gray, green, or brown, well foliated, thick to thin banded and sometimes graphitic.

C AGGLOMERATIC METATUFF. This unit contains lapilli to bomb-sized fragments of andesitic composition in a slightly more felsic fine-grained matrix.

B METASEDIMENTS. These rocks are fine to medium-grained, gray or brownish, biotite-rich and usually thick bedded.

A METASEDIMENTS. These rocks are very fine-grained, gray, thick-bedded, and were intersected only in drill hole R-2-1.

gradational into disseminated or semimassive zones. The amount of massive sulfides in Unit E increases towards the northeast. The massive sulfides are composed almost entirely of pyrrhotite with only traces of chalcopyrite and pyrite. No pentlandite or sphalerite were observed in the massive sulfide zones. The pyrrhotite occurs as polygonized grains with traces of chalcopyrite and pyrite along the grain boundaries. The massive sulfides commonly show a swirly flow structure and often carry fragments of the host rocks." A zone of massive sulfide was also intersected in Unit D of the four northeasternmost cores. It is very similar to those in Unit E. The mineralogy and textures are virtually identical, even down to the stress twins and kink bands in the polygonized pyrrhotite. Two massive pyrite zones were intersected, one four foot zone in NCB-1 and an 18 foot section in R-2-2. The pyrite zone in NCB-1 is vuggy and in a very fine-grained matrix of metatuff. The other pyrite zone contains 10-50% pyrite and is massive at the top and grades downward into disseminated sulfides. The grain size of the pyrite decreases downward and there are indications that the pyrite has replaced pyrrhotite. Elongate, commonly oriented inclusions of pyrrhotite in the pyrite grains indicate that this may have originally been a pyrrhotite body in which pyrite has replaced pyrrhotite.

Disseminated sulfides are quite common in these rocks, and the disseminated zones containing 5-20% sulfides have provided the best assay results. These zones also contain more sulfide phases than the massive zones. Pyrrhotite, pyrite, chalcopyrite, and sphalerite are the most common phases but pentlandite also occurs in some zones. The best zinc mineralization was intersected in S-43-2 between 184.5 and 187 feet. This zone is in Unit F and is shown in Figures 2 and 3. The core is missing, but the Ridge Mining Company log described the section as being an andesitic tuff with 5% pyrrhotite and pyrite with 5-10% sphalerite in possible slump structures.

Mineralization of this type was not noted in any of the other cores, although the sphalerite in the disseminated zones does occur in bands parallel to bedding. Interesting copper-nickel mineralization was observed in core R-2-2. The upper contact zone of a metagabbro (510-531 feet) contained disseminated pyrite, pyrrhotite, chalcopyrite, and pentlandite. Photographs showing the minerals and textures of the sulfides in the Birchdale area can be found in Listerud (1974).

The base metal content of the sulfide zones is generally low. The highest was the sphalerite-bearing zone from 184.5 to 187 feet in S-43-2. The Ridge Mining Company log indicated 4.06% zinc and 0.25 oz/ton silver. The copper-nickel zone in the metagabbro of R-2-2 was shown on the Exxon Company log as having an assay of 0.28% copper and 0.23% nickel over a six foot interval. Traces of gold were also found in this zone. Mining company data indicates that the best results for zones other than those mentioned above were: traces of gold, 0.09 oz/ton silver, 0.19% copper, and 0.21% zinc.

The trace element distribution along strike in the main sulfide horizon of Unit E and vertically in core R-2-1 were investigated by Listerud (1974). Although the number of samples was small (16) and not enough to make it statistically valid, some trends were observed. The samples were analyzed for copper, nickel, cobalt, zinc, and manganese by atomic absorption methods. The results from samples in the massive sulfide zone of Unit E show that copper values are always higher than zinc, although erratic in absolute values, and that nickel and cobalt generally increase to the northeast. Trends in metal ratios also exist in this zone. Cobalt:nickel, copper:zinc, cobalt:manganese, and copper:copper+zinc all increase to the northeast. The results from the low sulfide metasediments and metatuffs of R-2-1 showed no trends in absolute values, but some were shown by metal ratios. Cobalt: nickel, copper:zinc, and copper:copper+zinc increase upwards while nickel: manganese and cobalt:manganese remain constant. The geological implications of the results are uncertain at this time, but studies such as this may prove useful in exploration when an ore body is discovered and trace element trends are characterized for this area.

The origin of the sulfides intersected in this area are thought to be mostly of syngenetic origin by Listerud (1974). Although the sulfides exhibit very few structures or textures attributable to their original state, he feels that the position in and the relationships with the enclosing rocks, the close association with graphite occurrence and abundance, and the banding of the sphalerite parallel to the bedding indicate deposition of sulfides as primary constituents of the rocks. Greater detail is available on petrology, mineralogy and general geology of this area in Listerud's paper of 1974. Information on the exploration that occurred after this paper is available at the Minerals Division, Department of Natural Resources at Hibbing, Minnesota.

THE EMO MAFIC INTRUSIVE

In the Emo area, mapped by Fletcher and Irvine (1955), there occurs a mafic intrusive complex which has been explored for copper-nickel mineralization. This mineralized area is shown in Figure 2, east of Emo. A description is included here because the edge of the intrusive where the mineralization occurs is less than a mile from the northern border of the Birchdale-Indus area. The intrusive is composed of norite, hypersthene gabbro, and diabasic gabbro arranged as a belt around a granitic intrusive. Diabasic gabbro forms the central portion of the complex and is partially rimmed by hypersthene gabbro. The norite only occurs on the southern margin of the complex and contains the sulfide mineralization of interest. The norite is 75% hypersthene with minor labradorite, enstatite, and olivine. Bodies of massive and disseminated copper-nickel sulfides occur in the norite; however, they are currently uneconomic. Fletcher and Irvine (1955) report that they occur without structural control and are composed of pyrrhotite, pyrite, pentlandite and chalcopyrite with very minor violarite and sphalerite. They report one grab sample from a test pit that assayed 2.52% nickel, but state that the more abundant disseminated zones contain about 0.3% each of copper and nickel.

INDUS TEST PIT AREA

This area is located in the SW¼ of the NW¼ of Section 16, T.159N., R.25W. The name is a result of three test pits and a shaft which were found during the mapping of the area. The locations of the test pits, shaft, and drill holes are shown in Figure 5. A diabase dike with an outcrop width up to 150 feet trends northwest across the middle of the area. Outcroppings of felsic-intermediate metavolcanic, pyroclastic, and volcaniclastic rocks are found on the southwest side of the dike. The general strike is N40°E with a dip of 60-70° to the northwest. The sulfides in these rocks occur in massive, semimassive, and disseminated zones. The test pits and shaft are located where the sulfide zones crop out. This work was completed in the late 1950's by two brothers from Minneapolis, but no results are available. The Minnesota Department of Natural Resources has been working in this area since first becoming aware of the outcropping massive sulfides. Their work included soil geochemistry, various geophysical surveys, drilling, and geologic work. The results of the geochemical and geophysical surveys have been discussed by Meineke, Gilgosch and Vadis (1976), and Meineke, Vadis and Gilgosch (1976), respectively. The rocks intersected in core drilling were rich in sericite (up to 25% near the bottom of IH-10). A brief description of the rocks is given below. Core IH-10 is a sulfide-rich felsic metatuff from 20.5 to 47.1 feet which becomes agglomeratic towards the base. It increases in sericite content and decreases in sulfide content downward. Core IH-11 is a weathered breccia from 8.7 to 12.7 feet and a felsic metatuff

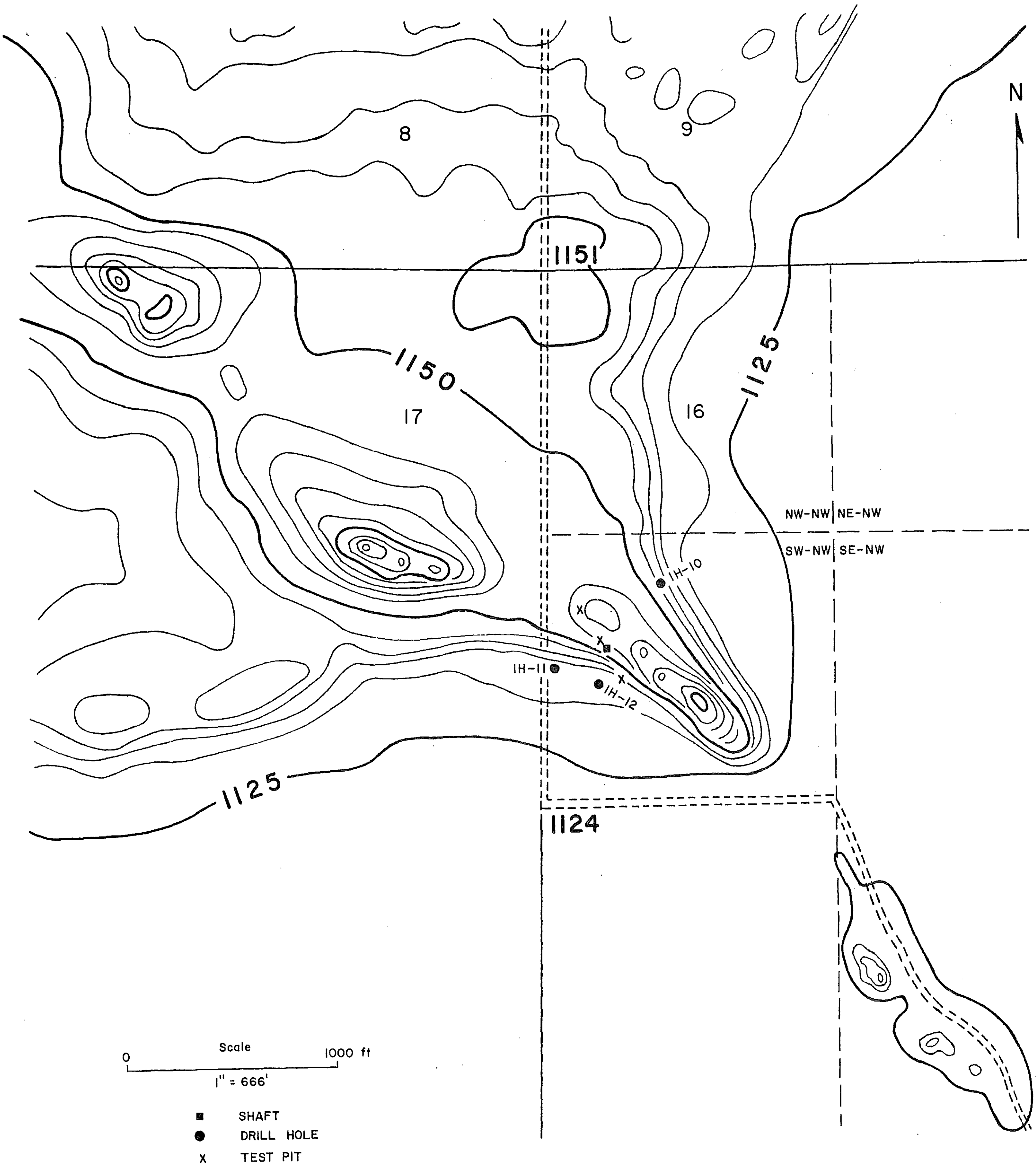

FIGURE 5: Map of the Indus Test Pit Area

from 12.7 to 24.2 feet. Core IH-12 consists of alternating intermediate metavolcanics and felsic metatuffs from 16.8 to 42.8 feet.

The sulfides in this area occur mainly in the felsic metatuffs. Disseminated sulfides also occur in the more mafic rocks and in the dike rock. The known sulfide-bearing zone on the southwest side of the dike is about 400 feet wide. This zone occurs on the other side of the dike also, but no outcrops are known. IH-10 was drilled on a geophysical anomaly and intersected massive sulfides, thereby proving the zone on the northeast side.

The sulfide minerals observed in polished section include pyrrhotite, pyrite, chalcopyrite, marcasite, sphalerite, mackinawite, and intermediate or alteration phases not positively identified. One very tiny bleb of gold was also observed in a section from IH-10. Pyrrhotite and pyrite account for at least 90% of the sulfides in any sample, with alteration products and marcasite ranging up to 10%. Chalcopyrite may comprise up to 1% of the sulfides while the others are present in only trace amounts. Pyrrhotite is present in both hexagonal and monoclinic forms.

The massive sulfide textures observed were of two basic types. The first is comprised of polygonized pyrrhotite as the major mineral. The pyrrhotite exhibits strain features such as stress twinning and kink bands, and hexagonal and monoclinic pyrrhotite in the exsolution-like texture similar to that observed by Listerud (1974) in the Birchdale area sulfides. A few sections were made up of more irregularly shaped grains without the good annealed texture. The other minerals occur as inclusions in pyrrhotite, as blebs or grains between pyrrhotite polygons, or as tiny blebs in gangue. Samples from the largest test pit (the furthest to the SE) exhibit an odd alteration of the pyrrhotite along grain boundaries and fractures in the pyrrhotite. "Feathery" alteration zones occur. The center of the alteration zones is a white, fairly hard, anisotropic mineral with a softer, greenish phase between this and the pyrrhotite. These two phases are harder than pyrrhotite, but possibly softer than pyrite. It is thought that these phases are probably close to pyrite in composition and the start of alteration of pyrrhotite to pyrite. The alteration of pyrrhotite to pyrite, with the "intermediate phase", described in the section on the Birchdale area, is also found in these samples along fractures. Alteration of sulfides to iron oxides is also observed in these samples.

The other massive sulfide type observed is characterized by large pyrite grains which have replaced pyrrhotite. The replacement of pyrrhotite (or growth of pyrite crystals) apparently took place in at least two stages. There are crystals of pyrite which polish well and are inclusion-free which have been overgrown by a slightly softer, inclusion-rich pyrite. These inclusions are pyrrhotite, chalcopyrite, gangue, oxides, and marcasite. Marcasite is observed included in pyrite and with pyrite inclusions. This tends to support the two stage theory, with marcasite forming between the two pyrite stages or during the second stage. The other trace minerals may occur in pyrite, gangue, or in the pyrrhotite matrix between pyrite grains.

The disseminated sulfides in the country rocks are mostly pyrite and pyrrhotite, but have not been examined in polished section. The dike rock contains traces of pyrite and chalcopyrite. The chalcopyrite occurs as "clouds" of very fine-grained blebs in gangue minerals.

A great deal of analytical work has been done on the rocks from this area. The three drill holes have been split and assayed for copper, nickel, zinc, cobalt, silver, and gold in one foot intervals. The highest values obtained for each element are shown below. Values are in parts per million except for gold and silver which are in ounces per ton.

Element	IH-10	IH-11	IH-12
Cu	172	108	89
Zn	416	1104	220
Ag	0.05	0.01	0.01
Au	0.006	0.003	0
Ni	67	91	510
Co	168	82	92

Sampling and analysis of both float and outcropping rocks produced results lower than the values given above.

These sulfides appear to be syngenetic with the enclosing tuffs and volcaniclastics. The 400 foot section of sulfide-bearing rocks is only intermittently exposed, but the major sulfide zones are in the felsic tuffs between more andesitic units. This zone is less than half a mile northwest of outcropping magnetite iron formation and other metasediments, and the sulfides are probably related to the increasing volcanic activity in nearby areas.

SECTIONS 3 & 4, T.158N., R.27W.

This area was explored by the Exxon Company in 1970-71. Two holes, about 500 feet apart, were drilled to intersect a geophysical anomaly. These were the only holes drilled for massive sulfides to the south of the large magnetic high that extends across the map area. Hole R-4-1 intersected 183 feet of massive to semimassive pyrrhotite in a brecciated metagraywacke. Hole R-4-2 cut a 17 foot massive pyrite zone and a 20 foot zone of massive pyrrhotite in volcaniclastic metasediments and a brecciated, felsic metatuff, respectively.

The sulfide minerals observed in polished sections of these zones are: pyrrhotite, pyrite, chalcopyrite, sphalerite, mackinawite, marcasite, cubanite, and pentlandite. Pyrrhotite is by far the most abundant with pyrite firmly in second place. Chalcopyrite, sphalerite, mackinawite, and marcasite are common accessory minerals, although present in only trace amounts. Cubanite and pentlandite were observed in only one section each, and only in trace amounts. The most common assemblage is pyrrhotite-pyrite-chalcopyrite. The assemblage pyrrhotite-pyrite-chalcopyrite-sphalerite is the next most common, with most other assemblages found only in one polished section. The textures observed in the massive pyrite zone in R-4-2 is described as subhedral to euhedral pyrite crystals with inclusion-rich overgrowth which have replaced pyrrhotite and gangue minerals. The overgrowth inclusions are pyrrhotite, gangue, chalcopyrite, and marcasite. Traces of chalcopyrite and pyrrhotite also occur as disseminations in the gangue. The massive pyrrhotite zones have textures similar to those observed in the massive sulfides at Birchdale. The pyrrhotite is poorly to well-polygonized, has both monoclinic and hexagonal in an exsolution-type intergrowth, and has stress twins and kink bands. Accessory minerals generally occur at the grain boundaries. Pyrite often replaces small amounts of pyrrhotite along fractures or grain boundaries.

The base and precious metal contents of these sulfide zones are very low. The high values for company assay and the writer's grab sample results are: 0.024% Cu, 0.031% Zn, 0.050% Co, 0.013% Ni, 0.06 oz/ton Ag, and 0.001 oz/ton Au.

SECTION 20, T.159N., R.27W.

This area was explored by the Texas Gulf Sulfur Company in the winter of 1969. Their work included drill holes R.R.6-1 and R.R.6-2 which were drilled 1,200 feet apart on the same conductor in the SE¼ of Section 20. Hole R.R.6-1 intersected a 20 foot zone of massive to semimassive pyrite-pyrrhotite in metasediments and R.R.6-2 hit about 10 feet of massive and semimassive pyrite in a metasediment and conglomerate sequence.

The sulfides examined from R.R.6-1 contained from 35% to 63% total sulfides, averaging about equal amounts of pyrrhotite and pyrite with minor to trace amounts of chalcopyrite, cubanite, and mackinawite. The intermediate phase between pyrite and pyrrhotite, which was described earlier, is also present in minor amounts. The texture is pyrite grains in polygonized and slightly stretched pyrrhotite, with the accessory minerals as tiny inclusions or blebs along grain boundaries. The pyrite grains have subhedral to euhedral inclusion-free centers with inclusion-rich overgrowths. The pyrite is replacing both gangue and pyrrhotite. The pyrrhotite is intergrown monoclinic and hexagonal types, which also show kink bands and stress twins. Pyrrhotite is also being replaced by limonite along some grain boundaries. Mackinawite and cubanite occur in chalcopyrite, probably as exsolution products. Some chalcopyrite appears to rim both pyrite and pyrrhotite and may be the latest stage of the mineralization.

The only analytical data available is the analysis of one grab sample from the middle of the sulfide zone. The results are: 0.174% Cu, 0.003% Zn, 0.013% Co, 0.029% Ni, 0.081% Mn, 0.03 oz/ton Ag, and no Au.

The pyrite zone in R.R.6-2 was examined in only one polished section. The sample was 97% sulfide, 99% of which was pyrite. Pyrrhotite and chalcopyrite were present as inclusions in the pyrite. Texturally, it looked like that in R.R.6-1 except that the replacement by pyrite was vertually complete.

Analytical results are also from one grab sample near the middle of the zone. Base metal content is again very low with the results being: 0.013% Cu, 0.010% Zn, 0.013% Co, 0.004% Ni, 0.212% Mn, 0.03 oz/ton Ag, and no traces of Au.

SECTION 30, T.159N., R.27W.

Exxon Company drilled two holes into a geophysical conductor in the NW¼ of this section. The holes were R-3-3 and R-3-4 and they intersected massive sulfides in felsic volcaniclastics of 12 and 8 foot thicknesses, respectively. These zones were not examined microscopically but appear similar to other massive pyrrhotites with scattered pyrite alteration and traces of chalcopyrite. The sulfide content is 10-60% and the base metal content is very low. Exxon assay results indicate the highest values are: 0.03% Cu, 0.015% Zn, 0.011% Co, 0.019% Ni, and 0.03 oz/ton Ag. Spectrographic analyses indicate traces of Mo, Sn, V, In, Os and Y.

SECTION 36, T.160N., R.26W.

This area has not been drilled in search of base metal sulfides, at least so far as is known. There is, however, an outcrop of sulfide-rich rock on the bank of the Rainy River below Manitou Rapids. The location of this outcrop is about 2,800 feet west of the section line or about 500 feet west of marker #175 as shown on the Manitou Quadrangle topographic map. Some geophysical work has been done in this area (Meineke, Vadis and Gilgosch, 1976). The area was prospected some time ago, as there are shallow test pits on the slope above outcrop. The pits have been partially filled with organic matter and slumping overburden. The outcrop at the river bank is poorly exposed, being gossany, moss covered and partially covered by slumping surface material. Massive pods and disseminations of sulfides along with sulfides in two fracture or breccia zones were observed in a very fine-grained, intermediate metatuff or metavolcanic. These sulfides were pyrite and pyrrhotite with traces of chalcopyrite. Additional work on the geology of the area has not been done since the discovery of this outcrop, but several outcrops of felsic metatuff and agglomerate are known in the area. Analysis of a gossany sample showed 0.19 oz/ton Ag, 0.003

oz/ton Au, 0.004% Co, 0.018% Cu, 0.008% Ni, and 0.020% Zn.

SECTION 18, T.159N., R.27W.

An extensive outcropping of pillowed greenstones occurs in the west-central portion of this section. Several areas on this outcrop show sulfide and oxide patches up to a foot in diameter, which are generally interstitial to the pillows. The sulfides were not examined in polished section as a fresh sample was not obtained. The sulfides appeared to be mostly pyrite-pyrrhotite but were oxidized quite heavily. Two samples of this oxidized material were assayed for Cu, Co, Zn, and Ni. The highest results are: 0.015% Cu, 0.020% Zn, 0.013% Co, and 0.010% Ni. Fresh unmineralized rock averaged about 0.006% Cu. It should be noted that a strong soil geochemical anomaly was detected by the Minnesota Department of Natural Resources in this area. Results of that and geophysical surveys across this area have been discussed by Meineke, Gilgosch and Vadis (1976), and Meineke, Vadis and Gilgosch (1976), respectively.

SECTION 14, T.159N., R.28W.

An outcrop of thin-bedded intermediate metatuffs was examined on a hill near the center of this section. The rock was rusty from oxidation of the disseminated sulfides and also contained streaks of malachite. No analysis is currently available.

SUMMARY

The massive sulfides known in this map area generally appear to be of two types. One is the massive pyrite bodies which, upon examination, appear to have replaced massive pyrrhotite. The other type is the massive pyrrhotite which exhibits a polygonized or annealed texture. Hexagonal and monoclinic pyrrhotite in a feathery, exsolution-type texture seems nearly ubiquitous in the pyrrhotite bodies. Strain features such as stress twinning and kink bands are equally as common. Thus it appears that these strain features in the Birchdale sulfides, attributed by Listerud (1974) to late adjustments due to the intrusion of the Birchdale Granite, may actually be due to a late regional stress. This late event might also be related to the pyrite replacements, which are also thought to be late because of the associated marcasite (a low temperature mineral). The pyrrhotite to pyrite ratio is now probably about 3:1 in these sulfides but probably was much higher before this widespread alteration. Some late chalcopyrite mineralization may also have been associated with this event.

Disseminated sulfides are very common throughout the area, but only certain horizons have them in significant amounts. As was mentioned earlier, the mineralogy is not the same as in the massive sulfides, and the assays are frequently higher. A simple explanation for this could be that a relatively constant amount of zinc and copper were available and, during times of rapid sulfide formation and deposition, their concentrations were diluted by the tremendous quantities of iron sulfides.

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