A PROPOSED ORE CONTROL AT THE CORONATION MINE DERIVED FROM EXAMINATION OF THE QUANTITATIVE MINERALOGY

A Thesis
Presented To
The Faculty of the Department of Geology
of
The University of Manitoba

In Partial Fulfillment
of the Requirements for the Degree
of
Master of Science
by
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September, 1964

ABSTRACT

Mineralogical cross-sections of ore bodies on the 300 foot, 600 foot and 900 foot levels of the Coronation Mine have been interpreted in terms of centres of mineralization. The maximum concentration of chalcopyrite occurs closest to these centres, of pyrite and pyrrhotite at some distance from the centres, and of magnetite furthest removed from the centres.

A hydrous halide fluid model is established. Attempts to explain the observed mineralogy by the action of temperature gradients on the fluid model were unsuccessful. Likewise the action of diffusion alone on the fluid model cannot explain the observed mineral distribution. The concept of attenuation is introduced wherein the rate of diffusion of a particle species is related to the product $\sigma \sqrt[2]{M}$, the attenuation coefficient, where σ is the particle radius, and M its molecular weight. Attenuation, acting on the fluid model alone, will not produce the observed mineral distribution, but when considered together with the action of temperature gradients, the observed mineralogy can be well explained by the combined effects of these two processes on the assumed fluid model.

ACKNOWLEDGMENTS

The writer is indebted to the National Advisory Committee for Research in the Geologic Sciences for the financial aid which made this study possible; and to Dr. L. Moxham and Prof. J. Westmore for their invaluable criticism and discussion of the thesis.

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PART 1.

RESULTS

Chapter 1

INTRODUCTION

This study is part of a comprehensive investigation into the general geology, geophysics and origin of the Coronation Mine ore body, located some fourteen miles southwest of Flin Flon, Manitoba. Different organizations are carrying out individual projects under the direction and co-ordination of the Geological Survey of Canada. This thesis proposes a possible ore control based on an examination of the quantitative mineralogy. One hundred and ninety-four specimens from twenty-two diamond drill holes on the 300 ft., 600 ft. and 900 ft. levels were examined using a Swift automatic point counter and reflecting microscope.

It is emphasized that the proposed ore control is not necessarily the control that actually existed. Other controls may explain the observed mineralogy equally well or better, but have not been considered in this thesis.

Chapter 2

GENERAL GEOLOGY

The geology of the mine and the surrounding area has been studied by E. L. Faulkner and the following is a summary of his observations (E. L. Faulkner, 1964, personal communication).

The ore body occurs in a sequence of massive altered dacites, andesites and andesite breccias, with some pillow lavas. The average strike is northwest, the dip 75^0 southwest and the rocks face east. The ore body consists of varying amounts of massive to disseminated pyrite, pyrrhotite and chalcopyrite with minor amounts of magnetite and sphalerite in a series of ore shoots within a concordant shear zone some 900 feet long, 1000 feet deep and up to 200 feet wide. The ore body may be divided into three general sections.

1. The northern section, consisting of massive high grade sulphides, with slight wall rock alteration.
2. The central, low grade section of disseminated and massive sulphides.
3. The southern section, consisting mainly of disseminated sulphides with extensive wall rock alteration.

Each ore shoot plunges to the south at 80°, approximately the same as lineations in the near surface rocks.

The mineralization, wall rock alteration and shearing are closely related.

The wall rock alteration is complex and consists mostly of chlorite, hornblende, garnet and tremolite-actinolite, with some zones containing cordierite and anthophyllite. The alteration is best developed in the southern section, where recrystallization is coarse and skarn like. In the northern section the alteration is patchy and fine grained.

Gangue minerals are very rare and are confined to quartz, quartz-epidote, quartz-carbonate or carbonate infillings of minor fractures formed after the main mineralization.

Intrusive rocks are present, in the form of dikes and irregular masses of porphyritic rocks and diorite masses which pre-date the ore, and a few post ore fine grained mafic dikes. A large syntectonic granodiorite intrusion outcrops within a quarter of a mile of the mine.

Chapter 3

PREPARATION OF SPECIMENS

General

Each specimen was crushed and sieved and the fraction between 28 and 200 mesh was retained. This fraction was mounted in plastic and the specimen was ground, polished and stained before counting.

The specimens consisted of split E-size diamond drill core, in places skeletonized, but usually complete. A small portion of core was retained for later polished section examination, wherever possible. Care was taken to ensure that the retained material approximated the bulk composition of the sample.

Crushing and Sieving

The specimens were first coarsely crushed to the size of a pea using an iron pestle and mortar. The coarse crush was then fed into a rotary pulverizer, and the process continued until the proportions were about: > 28 mesh, 1 part; 28-200 mesh, 6 parts; <200 mesh, 2 parts. The coarse fraction was discarded and the medium and fine fractions were kept and labelled. Although the pulverizer produced much dust, (the loss during crushing being up to 10% in a few cases) it was by far superior to the small stamp mill used initially, in that it was much faster, and produced a higher proportion of medium fraction grains. Chemical analyses of medium and fine fractions show little evidence of differential crushing of minerals, due to varying hardness, or preferred sieving due to cleavage; see Table I below.

TABLE I

CHEMICAL ANALYSES OF
MEDIUM AND FINE GRAINED FRACTIONS
AFTER CRUSHING [1]

Sample		Cu	Fe	Zn
A	medium	20.9	27.6	0.8
	fine	20.2	30.4	0.6
B	medium	2.3	24.0	0.7
	fine	2.3	24.5	0.4
C	medium	6.0	25.6	0.6
	fine	7.2	27.4	0.6

[1] Analyses performed by Manitoba Mines Branch.

A certain amount of metallic iron was introduced into the samples during crushing, but was not troublesome, as the iron particles have a very distinctive curved and feathered appearance, and when stained, react violently and produce a brown halo.

Mounting, Grinding and Polishing

Two different plastics were used for mounting; Ward's Bioplastic, which was used initially, and Quickmount. The latter was found to be more satisfactory than Bioplastic as it is easier to handle, quicker setting and allows greater coverage of the polished surface.

The mounted specimens were first ground on a steel lap using #400 and #600 carborundum powders, until more than one grain thickness had been removed. The specimens were then polished on cloth laps using 6μ and 1μ diamond paste and magnesium oxide powder. The specimens mounted in Bioplastic were susceptible to plucking of the grains, particularly chalcopyrite. This problem was largely eliminated by the use of Quickmount.

Staining

Staining was necessary, for rapid point counting, as immediate visual identification is imperative. Pyrite and magnetite were particularly difficult to distinguish from pyrrhotite and sphalerite in unstained sections.

The stain used was 20% silver nitrate solution (Gaudin, 1935). The colours obtained are slightly different to those described by Gaudin and are as follows:-

Chalcopyrite - sky blue - peacock blue, bright.

Pyrite - tan to buff, bright.

Pyrrhotite - deep blue to pinkish blue, med. - bright.

Sphalerite - white, bright.

Magnetite - unchanged.

Iron (from Pulverizer) - reacts violently, giving brown halo and bright white stain.

Counting

A Swift automatic point counter was used, and approximately 1000 points were counted for each specimen. Of these only 35-45% were on mineral grains, the rest falling on the plastic mounting medium. Attempts to increase the proportion of mineral grains counted by lengthening the setting time of the plastic were unsuccessful, apparently because the grains were in too close contact.

However this proportion is adequate for the great majority of specimens (see Chapter 4).

Chapter 4.

METHOD OF STUDY

General

The present, observed mineralogy of any ore body is the final result of the action and interaction of various physical and chemical processes, which have culminated in the exposure of the ore body. It is to be expected that conditions generally will not have been uniform, either in space or time. Such processes as uplift and erosion are not considered here; rather the intent is to attempt to deduce the nature of the processes which have led to the present mineral assemblages.

None of the phenomena usually attributed to secondary enrichment of the ore are observed at depth in the Coronation Mine; hence, all results and discussion will refer to the primary period of ore formation, or, more correctly, to the last stage of such a period. Whatever the origin of the deposits, the variation in physical and chemical conditions will in general result in mineralogical inhomogeneity. The conditions should not vary in a completely random way, however, but should be governed by physical, chemical and geological principles, and therefore should vary in some accountable manner.

The ore bodies of the Coronation Mine are generally elongate in a direction parallel to the regional shearing. Therefore mineralogical variations in the ore body can be referred to variations in physico-chemical conditions along two axes, one parallel to the elongation, and one perpendicular to it. Further, it would be expected, from geological considerations, that the major variations in conditions will have been perpendicular to the direction of the shearing. Shear zones are eminently suited to the introduction of hydrothermal fluids, or may act as centres for metamorphic differentiation.

It seems, therefore, that the most promising approach is to study the cross sections of the ore bodies, and to attempt to relate the variations in mineralogy to a set of conditions which could have produced it.

The obvious unit to consider is one ore body. The variations in conditions cannot be expected to be smooth and continuous, as they should be ideally. Local inhomogeneities in the original rock mass (structural, textural and compositional) will produce variations in conditions, which will tend to obscure the fundamental mineral variation pattern, which is what is sought. The overall pattern of physico-chemical conditions, and hence the mineralogy, will in general have superimposed upon it secondary effects, which, although they may exhibit great variation are unimportant compared with the basic underlying pattern of mineralogical variation.

Plotting

With these difficulties in mind, it was essential to find a method of presenting the results which, while substantially reducing the effect of the superficial inhomogeneities, would preserve the significant broader variations in mineralogy. Such a method was developed and is explained graphically in Fig. 1.

Essentially the secondary variations are treated as deviations from the mineralogy which would have been produced in a homogeneous rock mass. This method of plotting also tends to reduce sampling errors which arise from the probability that a single sample of E-size diamond drill core is not a representative sample of the rock around it.

Sampling and Counting Errors

To determine the precision of the counting method five samples were analysed for copper and zinc by the Manitoba Mines Branch. These analyses were compared with percentages of the elements obtained by calculation from the point counts of the minerals, assuming that the only

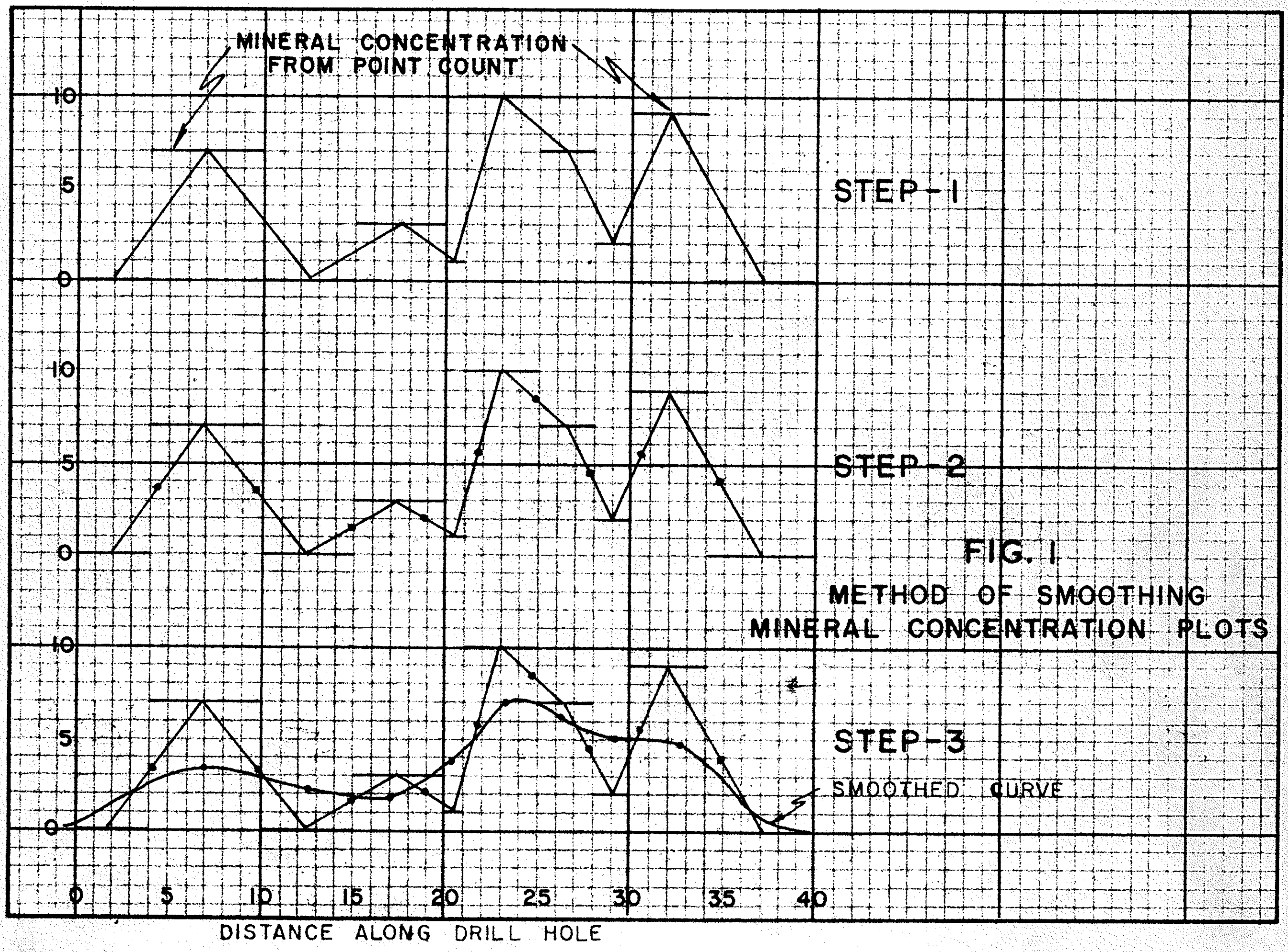


FIG. I
METHOD OF SMOOTHING
MINERAL CONCENTRATION PLOTS

copper bearing mineral is chalcopyrite, and that the zinc occurs only in sphalerite. The densities of the minerals were taken to be chalcopyrite 4.2; pyrite 4.9; pyrrhotite 4.5; magnetite 5.2; sphalerite 4.0; silicates etc. 3.0.

The comparison of results is given below, Table 2.

TABLE 2

COMPARISON OF COPPER AND ZINC DETERMINED
BY CHEMICAL ANALYSIS AND BY CALCULATION
FROM POINT COUNTS

Sample		Cu (Analysis)%	Cu (Point Count)%	Zn (Analysis)%	Zn (Point Count)%
C89	67-70	20.9	23.9	0.8	0
C89	85-90	2.3	1.2	0.7	0.5
C254	110-118.5	6.0	5.1	0.6	0.3
C93	98-102.5	2.7	0.8	0.4	0
C93	72-75	4.7	6.2	0.6	0.2

The results for copper are in reasonable agreement, except for the lower concentrations. Zinc determinations are considerably in error, and the point count values are consistently low. The reason for this is obscure, but it may be that zinc occurs in minerals other than sphalerite. In any event it is not possible to treat zinc quantitatively. Although no chemical check can be made for pyrrhotite and pyrite, it is likely that a counting precision similar to chalcopyrite was obtained.

Unfortunately it is impossible to estimate the errors introduced by the sampling procedure. It is likely that the composition of a sample of diamond drill core will vary considerably from that of the rock mass surrounding the borehole. In this thesis interest centres on the mineralogical variations across the ore bodies, rather than on the composition of individual samples. Therefore by taking sufficient cross sections of the ore bodies, the variances due to sampling should be distinquishable from true rock composition variations. The method used for smoothing the mineral concentration plots will tend to reduce sampling errors, in the same way that it reduces variations due to local rock inhomogeneities.

Chapter 5

MINERALOGY

Qualitative Mineralogy

Ferris (1961) has fully described the qualitative mineralogy of the Coronation Mine; only a short account is given here. The ore minerals present are chalcopyrite, pyrite, pyrrhotite, magnetite and a very little sphalerite. (The term "ore mineral" is used here as defined by Bateman 1959; i.e. "---one that may be used to obtain one or more metals".)

The amount of sphalerite is very small and could not be determined quantitatively from the number of grains counted. Distinction between magnetite, ilmenite and related minerals has not been made. Some specimens were stained with hematite before crushing. Hematite was not observed in the sections, confirming the view that hematite is very minor. The non-opaque minerals have not been differentiated and in this thesis are simply classified as "silicates". A few polished sections were examined, and the observed textures and apparent paragenesis are in agreement with Ferris' more comprehensive study.

The original textures may, however, have been modified by later metamorphism (Froese and Whitmore 1964), and therefore the present textures are unreliable guides to the initial mineralization. Ferris' paragenesis is given in Fig. 2.

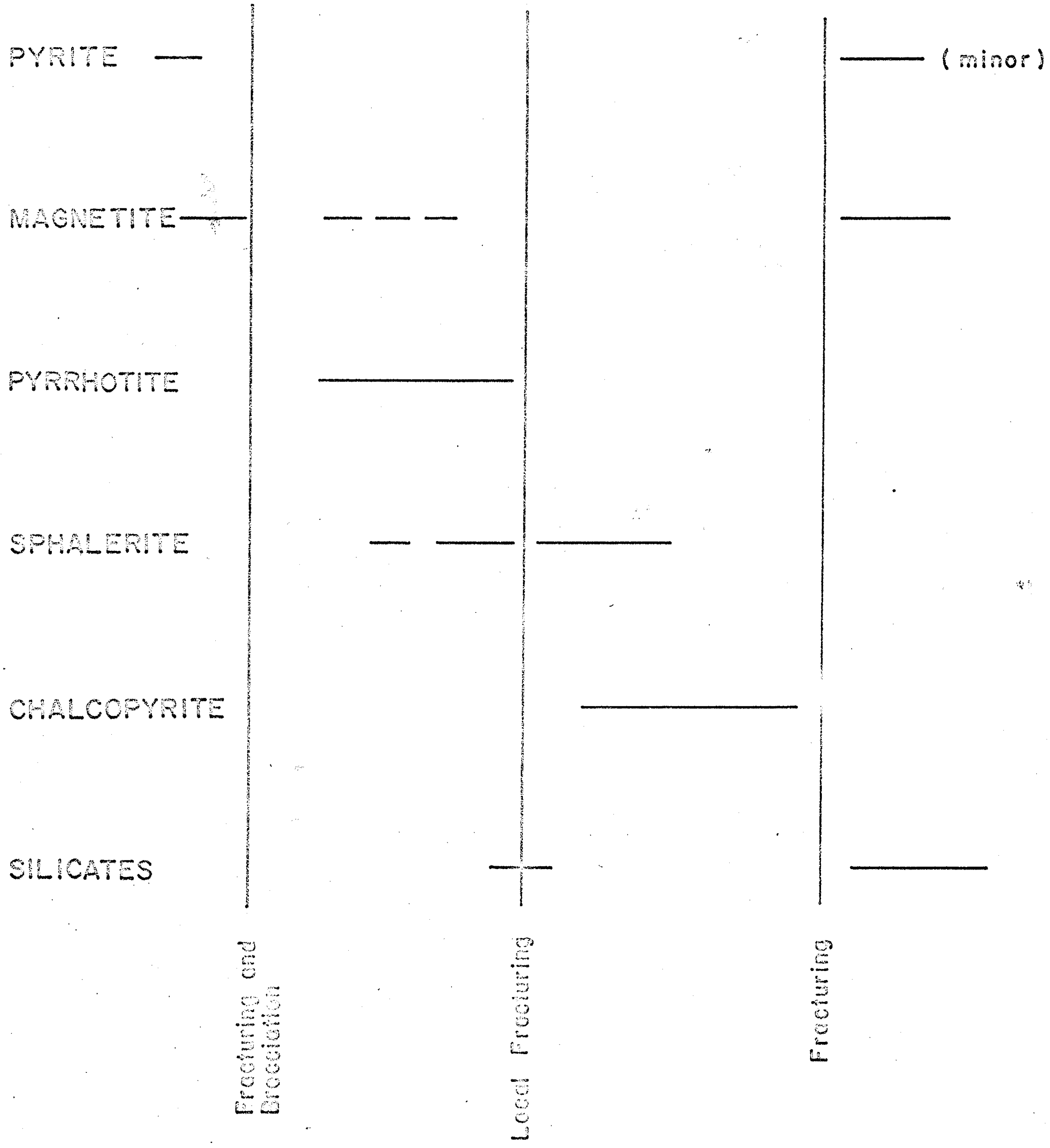


FIG. 2

MINERAL PARAGENESIS

(After Ferris, 1961)

Quantitative Mineralogy

The mineralogical cross sections are shown in Figs. 6 to 16 and the locations of the drill holes in Figs. 17 to 23. The concentration of ore minerals in all boreholes decreases towards the margins of the ore-bodies. Significant patterns of mineral distribution occur. The occurrence of each mineral will now be considered in turn.

The abscissa of each graph represents the location of each sample in the drill hole, and the ordinate represents the concentration of each ore mineral in volume percentage. The observed concentrations are shown as thin horizontal lines, and the curved line represents the smoothed concentration as described on page 11.

Chalcopyrite

In boreholes cutting narrow ore-bodies, the chalcopyrite concentration curve has a single peak near the centre of the ore-body, see boreholes C254 (Fig. 6), C78 (Fig. 7), C231 (Fig. 7). For holes cutting wider ore-bodies, C89 (Fig. 8), C31 (Fig. 9), C93 (Fig. 10), C115-C113 (Fig. 11), C64 (Fig. 12), C34 (Fig. 13), C81 (Fig. 14), the chalcopyrite concentration has a double peak. For many boreholes with double chalcopyrite peaks, the ore-body at that place is or may be inferred to be a composite body, made up of two intersecting ore-bodies. See C81 (Fig. 14), C89 (Fig. 8), C93 (Fig. 10), C34 (Fig. 13), C31 (Fig. 9), C64 (Fig. 12).

Because of this each chalcopyrite peak is interpreted as representing a centre of mineralization.

The regular variation in the concentrations of the other minerals is not as obvious as that of chalcopyrite. However, when referred to the centres of mineralization inferred from the chalcopyrite distribution, the distributions of the other minerals appear to conform to regular patterns.

Pyrite

The concentration of pyrite tends to form a double peak around each mineralization centre. The peaks are not necessarily symmetrical, and the central low concentration in general does not coincide with the chalcopyrite peak. This occurrence of pyrite is very well shown by boreholes C81 (Fig. 14), C93 (Fig. 10), and to a less marked degree by boreholes C254 (Fig. 6), C78 (Fig. 7), C115-C113 (Fig. 11). The pattern is still noticeable in C89 (Fig. 8), C31 (Fig. 9), C231 (Fig. 7), but is completely absent in C64 (Fig. 12), and C53 (Fig. 13).

Pyrrhotite

The concentration of pyrrhotite tends to vary in much the same way as that of pyrite. The typical occurrence is well shown in C81 (Fig.14), C89 (Fig. 8), C31 (Fig. 9), C78 (Fig. 7), and can be clearly seen in C231 (Fig. 7), C115-C113 (Fig. 11), C53 (Fig. 13), C254 (Fig. 6). The effect is completely absent in C64 (Fig. 12), C34 (Fig. 13).

The mineral concentration peaks of pyrite and pyrrhotite occur so close together that it is impossible to determine whether one occurs farther away from the mineralization centres than the other.

Magnetite

The concentration of magnetite fluctuates erratically. The concentration is sufficiently high (up to 10%) to eliminate a pre-mineralization origin for the magnetite distribution. In several boreholes magnetite tends to form double peaks similar to those of pyrite and pyrrhotite, e.g., C254 (Fig. 6), C31 (Fig. 9), C78 (Fig. 7), although the peaks are much less pronounced. In C89 (Fig. 8), the magnetite shows only two peaks instead of the expected four. The origin of the magnetite is doubtless similar to that of the other minerals. The highest magnetite concentration seems to be a little farther away from the mineralization centres than the highest concentrations of pyrite and pyrrhotite, but this may be only apparent.

The concentration peaks of the minerals are, in order of increasing distance from the mineralization centres, as follows:-

Chalcopyrite	Pyrite	Magnetite
	Pyrrhotite	

Increasing distance from mineralization centre →

Chapter 6

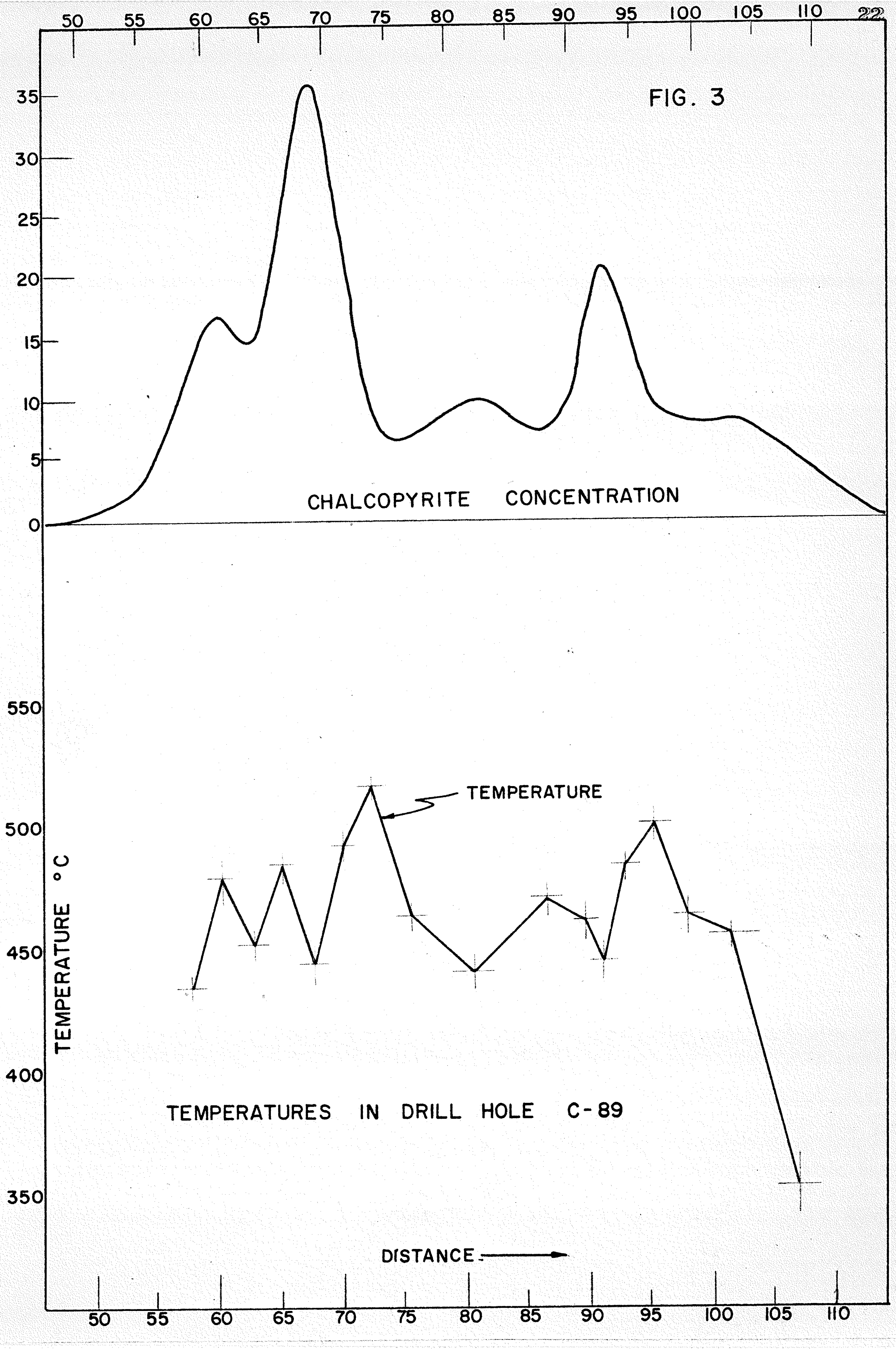
TEMPERATURES IN THE MINE

Ferris (1961) performed a series of temperature determinations throughout the mine using the pyrrhotite-pyrite geothermometer and the sphalerite geothermometer. He concluded that only small temperature gradients could have existed. Because Ferris' samples were widely separated and because of the inference of mineralization centres from the mineral concentration plots, it was considered desirable to determine a temperature profile across one ore body using pyrrhotite from drill core samples. Borehole C89 was selected for this purpose as pyrrhotite and pyrite occurred in all the samples.

Pyrrhotite was separated from the crushed samples using a hand magnet. X-ray powder photographs were taken using filtered iron radiation and an internal quartz standard. The $d_{(102)}$ spacings of the pyrrhotite were determined using the 101 quartz line as a standard. The films were read ten times and the average values of the pyrrhotite $d_{(102)}$ determined. Replicates were run for several samples. The values of $d_{(102)}$ were then converted into temperatures using Arnold's (1962) curves, and are shown graphically in Fig. 3.

Apart from 105'-110' all the determinations lie

FIG. 3


CHALCOPYRITE CONCENTRATION

TEMPERATURES IN DRILL HOLE C-89

between 434°C and 515°C, with an average of 464°C. As the precision of the method is only ± 40°C the variations between these samples may not be significant, although the distribution of temperature values does suggest a possible temperature gradient. The anomalously low value for 105′-110′ may be in error, but four samples from elsewhere in the mine also give low values. It is relevant to note that doubts have recently been expressed as to the validity of the pyrrhotite geothermometer, (H.D.B. Wilson, personal communication).

As the ore bodies have been metamorphosed subsequent to their emplacement (Froese and Whitmore, 1964), it is reasonable to postulate temperature gradients at the time of their formation, with the highest temperatures at the mineralization centres (i.e. the chalcopyrite peaks).

PART 2.

GENESIS OF THE ORE BODIES.

Chapter 1

GENERAL

The shapes of the cross sectional plots (Part 1 Chapter 5) show that the intensity of mineralization generally decreases away from centres where shearing has occurred. Therefore discussion of the genesis may be confined to magmatic and metamorphic processes. The observed mineral distribution and general geology are strongly opposed to formation of the deposits by early magmatic differentiation. However, subsequent injection of a previously segregated sulphide liquid is possible.

It appears that the processes most likely to have produced the ore bodies are hydrothermal activity, injection of a sulphide melt, or metamorphic differentiation. Independent evidence is inconclusive. The close association of the ore with shear zones strongly suggests that these zones have acted as channels supplying heat, or material, or both. The temperature relations support the view that heat has been supplied (Part 1 Chapter 6), and a granodiorite batholith lying about one half - mile east of the mine (E. L. Faulkner, 1964, personal communication) may have been the source of heat and/or fluids. Wall rock alteration of the "skarn" type occurs in the southern ore zones, but is not extensive in the northern deposits (E. L. Faulkner, 1964 op.cit.).

By no means conclusive, this evidence does suggest a hydrothermal origin for the deposits.

The following chapters will be based on the assumption that the ore bodies were formed from fluids flowing along feeder channels and penetrating the country rock. The fluid from which the ore bodies crystallized could have had any composition between an essentially anhydrous sulphide melt and a lower temperature hydrothermal fluid, where water is the dominant constituent. The nearby granodiorite batholith could have exuded hydrothermal fluids, but sulphide melts are more likely to be associated with more basic intrusions, which have not been observed near the Coronation Mine. Wall rock alteration, usually considered to be evidence of hydrothermal activity (Bateman, 1959, p. 103) does occur (E. L. Faulkner, 1964 op.cit.) but is not so great as to eliminate the possibility of a sulphide melt. The temperatures indicated are more typical of hydrothermal conditions than of sulphide liquids, whose temperatures are considered to be higher (c.f. Lindgren's (1933) classification of mineral deposits).

The main controls of mineral deposition in a deposit of this type are 1) the chemical composition of the fluid. 2) the temperature gradients across the ore

The approach used in this thesis has been to create a model representing the composition of the fluid, based on general geochemical principles, and then to determine whether the observed mineralogical

Chapter 2

FLUID MODEL

The following discussion considers only aqueous fluids, although in general, the same principles apply to sulphide melts.

Data on the character of the ore forming fluid has been gathered from a) observations in ore deposits b) sampling of emissions from fumaroles and volcanic vents, and c) from theoretical studies. The acid or alkaline nature of the mineralizing fluid is controversial (Graton, 1940 and Discussion) but direct observations have demonstrated the existence of such molecules as HCl, HF, H_2S, and other volatiles together with metals such as Fe, Sn, Pb, Cu, Zn in the emissions from fumaroles (c.f. Bateman 1959).

Assuming a hydrothermal origin, the properties of

2) The amount of sphalerite in the mine is not large enough to treat on even a semi-quantitative basis; hence it will not be considered here.

3) Small amounts of Cl_2, H_2, O_2, etc. must also be present, as required by the Law of Mass Action. For example, for HCl,

$$\tfrac{1}{2}H_2 + \tfrac{1}{2}Cl_2 \quad = \quad HCl$$

In this case the equilibrium constant K is given by

$$\mathrm{Log}_{10}K \quad = \quad 22.9792 \text{ at } 25^{\circ}C$$

where

$$K = \frac{(HCl)}{(H_2)^{\frac{1}{2}}(Cl_2)^{\frac{1}{2}}}$$, represents the degree of dissociation of HCl.

Thus, the concentrations of H_2 and Cl_2 will be extremely small, but nevertheless finite.

4) It is assumed that by the time the fluid reached the position of the ore bodies, it was already saturated with respect to all the ore minerals.

5) It is assumed that only cavity filling has taken place. The occurrence of the ore bodies in shear zones indicates that openings in the rock, acting as channelways, and therefore presumably filled with fluid, were operative in the formation of the

> ore body, and therefore substantial simple cavity filling may have occurred. Dilation of the rock could have occurred, but evidence is lacking. It is relevant to note that Butler (1932) and Schwartz (1959) consider that during wall rock alteration the later formed minerals depend essentially on the fluid composition. It seems probable, therefore, that relatively small errors will result from considering the process as pure cavity filling.

It is appropriate at this point to consider the physical condition of the "fluid". There is much discussion in the literature as to whether the fluids leaving a nearly crystallized pluton are liquid or gaseous. Gillingham (1948) has shown that steam possesses a measurable solvent power, and that at sufficiently high pressures its solvent capacity for silica equals that of water. It seems that a practical distinction does not exist between liquids and gases under the conditions indicated for the formation of the Coronation Mine deposits. In this thesis the term "fluid" is used without prejudice as to the actual physical condition of the fluid, and it will be assumed that chemical reactions will follow their normal courses, subject to modification by temperature and pressure in either liquid or gas, and that physical processes such as diffusion will not be modified by the state of the fluid. Thus, the fluid model proposed is

> A hydrous halide hydrothermal solution containing copper and iron, existing at temperatures of approximately 500°C, and moderate pressures, moving through channels in shear zones, and depositing ore minerals in the cavities in these shear zones.

Chapter 3

TEMPERATURE AS A CONTROL OF ORE DEPOSITION

Based on the assumptions made in the previous section the formation of minerals from the fluid may be represented by the following set of equations:

For pyrrhotite:

$$FeCl_2 + H_2S \rightleftharpoons FeS + 2HCl + \Delta H_1 \quad \ldots\ldots\ldots 1.$$

For pyrite:

$$FeCl_2 + 2H_2S + Cl_2 \rightleftharpoons FeS_2 + 4HCl + \Delta H_2 \quad \ldots\ldots\ldots 2.$$

For magnetite:

$$3FeCl_2 + 4H_2O + Cl_2 \rightleftharpoons Fe_3O_4 + 8HCl + \Delta H_3 \quad \ldots\ldots\ldots 3.$$

For chalcopyrite:

$$CuCl_2 + FeCl_2 + 2H_2S \rightleftharpoons CuFeS_2 + 4HCl + \Delta H_4 \quad \ldots\ldots 4.$$ [1]

The reactions for magnetite and pyrite could have been written in other ways, bringing in H_2 or O_2 instead of Cl_2. The choice of Cl_2 is not arbitrary, but is made because the

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[1] - Equation 4 should be written

$$CuCl_2 + FeCl_2 + 2H_2S \rightleftharpoons CuS + FeS + 4HCl + \Delta H_5$$

but data is not available for the heat of formation of chalcopyrite. However the heat of reaction of $CuS + FeS \rightarrow CuFeS_2$ is probably negligible compared with ΔH_4 in this equation, and values of K and ΔH for chalcopyrite will be only slightly affected.

concentration of chlorine is likely to be higher than the concentration of either hydrogen or oxygen, because HCl at high temperatures dissociates to a greater extent than does water. Hence Cl_2 will exert the limiting condition on the solubilities of these minerals. To determine the solubilities of the minerals the equilibrium constants, K_1 to K_4 for equations 1 - 4 above are required.

The equilibrium constants for the reactions may be written:-

$$K_1 = \frac{(FeS)\ (HCl)^2}{(FeCl_2)\ (H_2S)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 5.$$

$$K_2 = \frac{(FeS_2)\ (HCl)^4}{(H_2S)^2 (Cl_2)\ (Fe\ Cl_2)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 6.$$

$$K_3 = \frac{(Fe_3O_4)\ (HCl)^8}{(H_2O)^4\ (Cl_2)\ (FeCl_2)^3} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 7.$$

$$K_4 = \frac{(CuFeS_2)\ (HCl)^4}{(CuCl_2)\ (FeCl_2)\ (H_2S)^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 8.$$

Where $(FeCl_2)$ etc. are the concentrations (strictly, the activities) of the components.

From known heats of formation and equilibrium constants for various substances, i.e. H_2S, HCl, FeS etc. etc. taken from the Chemical Rubber Publishing Company Handbook[1] the values of ΔH and K for the above reactions at 25°C. may be computed. These are shown in Table 3, below.

TABLE 3

HEATS OF REACTION (ΔH) AND EQUILIBRIUM CONSTANTS FOR EQUATIONS 5 - 8 AT 25°C.

	ΔH (Kilo Calories)	$\log_{10}K$
Pyrrhotite	7.314	- 5.234
Pyrite	-83.312	-58.605
Magnetite	-12.414	-36.541
Chalcopyrite	-16.112	-53.472

By applying the van't Hoff isochore it is possible to derive the equilibrium constant at any given temperature, providing that ΔH is known, and assuming the latter does not vary significantly with temperature (any variation in ΔH is likely to be small compared with ΔH). Table 4 lists the values of K for the reactions given in equations 5.,6.,7. and 8. for temperatures between 25°C. and 600°C.

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[1] Handbook of Chemistry and Physics, 43rd Edition.

The formula used is:

$$\log_{10} \frac{K_B}{K_A} = \frac{-\Delta H}{2.303R} \times \frac{(T_A - T_B)}{T_A T_B}$$

The effects of pressure have not been allowed for, which may alter the results, but as variations and not absolute values are being considered, this omission will probably not be significant. These variations will probably not be large in any case.

TABLE 4

VALUES OF K_1, K_2, K_3, K_4 FOR TEMPERATURES BETWEEN 25°C. AND 600°C.

Temp. °C	$\log_{10}K_1$	$\log_{10}K_2$	$\log_{10}K_3$	$\log_{10}K_4$
25	-5.234	-58.605	-36.541	-53.472
100	-4.155	-70.887	-38.574	-55.883
200	-3.250	-81.206	-39.908	-57.909
250	-2.927	-84.904	-40.457	-58.630
300	-2.660	-87.940	-40.900	-59.227
350	-2.434	-90.503	-41.291	-59.731
400	-2.243	-92.700	-41.652	-60.160
450	-2.081	-94.530	-41.890	-60.522
500	-1.938	-96.175	-42.134	-60.840
550	-1.813	-97.590	-42.346	-61.119
600	-1.699	-98.865	-42.538	-61.376

These values have been plotted and are shown in Fig. 4 which shows the variation of K with temperature for the various minerals. It is immediately apparent from the figure that large changes of K result from comparatively small changes of temperature, particularly in the case of pyrite. For all minerals except pyrrhotite, K rises with decreasing temperature i.e. more mineralization occurs at lower temperatures.

The problem now becomes one of interpreting the mineralogical distribution in the ore bodies in terms of this temperature solubility data. It has been shown earlier (p.23) that there is evidence for the existence of temperature gradients across the ore bodies, with the highest temperatures having occurred at or near the chalcopyrite peaks. Let us examine the mineral distribution which would result from the action of such a temperature gradient on the fluid model. The temperature will be highest at the channel centre. A certain amount of each mineral will be in equilibrium with the fluid. Further from the channel the temperature decreases. Fig. 4 shows that for chalcopyrite, pyrite and magnetite, K rises with decreasing temperature, i.e., more mineral should deposit as the temperature decreases. Therefore the rock concentrations of these three minerals should rise further away from the channel. For pyrrhotite, the opposite condition occurs, and its concentration should decrease away

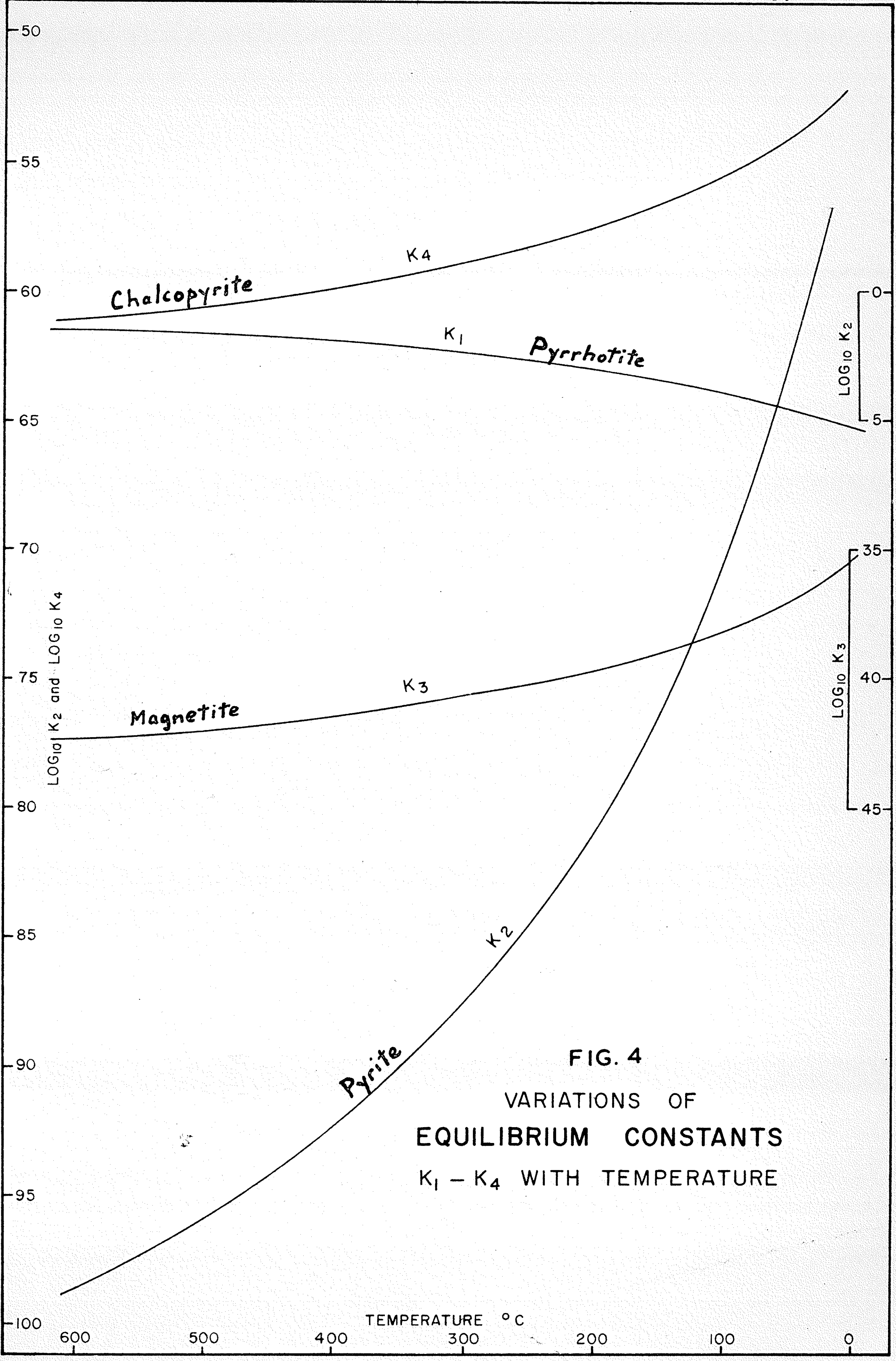

FIG. 4
VARIATIONS OF
EQUILIBRIUM CONSTANTS
$K_1 - K_4$ WITH TEMPERATURE

from the channel. The concentrations of pyrite, magnetite and chalcopyrite would not continue to rise indefinitely, as it is likely that the fluids did not extend beyond the present ore body limits, and in any event, the available material in solution will quickly become exhausted. There should therefore be two optimum points for maximum disposition of pyrite, magnetite and chalcopyrite, removed from the channel centre, and a single maximum concentration for pyrrhotite at the channel centre.

When this expected distribution is compared with the observed mineralogy it is evident that they do not agree. Whereas the concentration curves of pyrite and magnetite do show a double peak away from the channel centre, that of chalcopyrite has only a single, central peak, and the concentration curve of pyrrhotite, instead of having a single, central peak, has a double peak similar to pyrite. It is apparent that the observed mineralogy cannot be explained on the basis of temperature changes alone acting on the model, although temperature may have played an important role.

Chapter 4

MODE OF PENETRATION OF COUNTRY ROCK AS A CONTROL OF ORE DEPOSITION

General

Material may penetrate a rock mass in two essentially different ways, flow and diffusion.

1) Pure flow of fluid involves the transfer of fluid in bulk, the composition of the fluid remaining uniform. The rock mass would be saturated with the fluid, and the dominant direction of flow would be parallel to that in the main channel. This situation would occur where a broad shear zone existed, more permeable at the centre, less permeable away from the centre, but still sufficiently permeable to allow bulk flow of fluid. Fluid in the outer parts of the ore body would continually exchange with fluid on the inside. As the shear zone is more permeable along the main channel, fresh hot fluid would reach the central zone more readily than the more remote parts of the ore body. The wall-rocks will then act as a heat-sink, therefore there will be a temperature gradient outward from the feeder channel, and it is this variation in temperature

to which any mineralogical variations will refer. The effects of temperature variations have been considered in the previous section, and will not be considered further.

2) The other method of transfer of material is diffusion, where ions and molecules migrate through an immobile fluid, or rock mass, under the influence of temperature or compositional gradients.

Although the two processes are fundamentally different, bulk transfer of material grades into transfer by diffusion. Holser (1947) considers that metasomatic processes may be classified on the basis of the size of openings in the rock. He distinguishes four types of openings 1) supercapillary, 2) capillary, 3) grain boundary, 4) intralattice. He considers that flow through supercapillary openings is probably the mechanism by which large quantities of replacing material reach the replacing front. This corresponds to the massive flow described above. Capillary openings will still permit the movement of fluids, although the pattern of flow will be modified by capillary action. Diffusion of ions through the fluid occupying the openings in the rock may also occur. Diffusion experiments by Duffel (1937), showed that the metallic ions of the solute lagged behind the solvent. These ions moved at the same rate that they would in diffusing through an already saturated rock. Duffel points out that the solute must therefore penetrate the rock by diffusion through the liquid that has already occupied the rock pores ahead of the solute. Duffel postulated four causes for the lagging of the solute; a difference in rate of migration of acidic and basic portions of the solution, chemical reaction with the walls, absorption on the walls, and filtration by the rock. Holser dismisses the first and last of these processes as being, for the first unnecessary, and for the last impossible. However, the results obtained by Mackay (1946) and Ovchinnikov (1960) indicate that filtration by the rock may play a considerable part in affecting the rates of migration of ions and other particles.

Ovchinnikov (ibid) conducted experiments on the interaction of basalt with limestone, and determined the relative mobilities of several metal ions. These ions and their relative mobilities are given below.

	K	Na	Fe	Mg	Al	Si
Relative Mobility	85	53	8	7	3	1

Ovchinnikov (ibid) considers that the zonal distribution of various metals is probably governed by the radius of the hydrated ion, and the number and size of the "ultra-pores" in the rocks through which the infiltration of metals takes place. He considers that as the radii of anions, which predominate in ore forming fluids, are appreciably less than the radii of the most common cations, a "forestalling wave" of acid components will develop in front of the mineralizing cations. This "forestalling wave" would be analogous to the effect noted by Duffel, where the solvent penetrates the rock ahead of the solute.

Mackay (1946) likens the action of impermeable rock barriers to the process of osmosis, where a semi-permeable membrane will allow the passage of smaller solvent molecules, but restricts the larger solute molecules. He considers such processes as filtration, osmosis and differential ionic migration to differ only in the size of particle involved and the size of pore or void controlling each process. Mackay, like Ovchinnikov, considers the dominant control of the penetrability of ions to be the size of the hydrated ion, and says that zoning can be qualitatively accounted for on this basis, although he admits that other physico-chemical conditions must also play a large part in the formation of any ore deposit.

The size of opening envisaged by Ovchinnikov and Mackay is more comparable with the "grain boundary" and "intralattice" types of opening of Holser. However, a capillary or sub-capillary opening could produce a similar effect although the degree of ionic separation would be expected to be less perfect, as fluid flow, although restricted, is still possible through this type of opening.

Diffusion as a Mineralization Control

The observed mineral distribution will now be compared with the distribution to be expected if diffusion, as described above, has been the main control of mineralization at the Coronation Mine. Two types of fluid are considered; one essentially sulphidic, the other essentially aqueous. The controlling factor should be the size of the ionic species forming the minerals.

Temperature gradients will also occur in this type of fluid transfer, but in this section the effect of temperature is not considered.

(i) Sulphide Melts.

The mode of occurrence of material in sulphide melts is not well understood. The metals may exist as simple ions in a sulphur rich liquid. Alternatively they may occur as metal-anion complexes. Possible complex ions of this kind might be:-

$(Cu^{2+}S_4)^{6-}$, $(Fe^{2+}S_4)^{6-}$, $(Fe^{3+}O_6)^{9-}$, $(Fe^{2+}O_6)^{10-}$, $(Fe^{2+}S_6)^{10-}$.

These ions are listed in order of estimated increasing size, to be expected from consideration of radius ratios, co-ordinations and electronegativities of the metal ions.

If these ions did exist and their penetrabilities were determined by their size, then the expected order of minerals (from the centre to the margins of the ore-zones) would be:-

Iron sulphides   Magnetite   Chalcopyrite

Increasing distance from channel centre ⟶

In fact chalcopyrite occurs near the channel, and magnetite occurs the greatest distance from the channel (Part 1, Chapter 5). Thus the expected mineral distribution does not correspond with the observed distribution.

If the metals occurred as simple ions in a sulphur rich liquid the distribution should depend on the sizes of the non-hydrated metal ions.

Values of ionic radii taken from Mason (1958) are given below:-

Cu^{1+}	0.96Å
Cu^{2+}	0.72Å
Fe^{2+}	0.74Å
Fe^{3+}	0.64Å

If the ions were solvated,[1] the order of size could well be reversed as the ferric ion would tend to be solvated to a

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[1] - The term "solvated" is used here to mean the addition of solvent molecules to the simple metal ions. The term is analogous to "hydrated" when applied to ions in an aqueous solvent.

greater degree than the copper ions. Ferric iron should travel the greatest and copper the least distance, especially if copper occurs as the monovalent ion. At first sight this agrees very well with the observed mineral distribution, i.e.

Chalcopyrite   Iron sulphides   Magnetite

Distance travelled from channel centre ——————→

On further consideration, however, it appears that theoretically, the concentration of all the minerals should decrease away from the channel. The ferric iron should travel furthest and therefore the slope of magnetite concentration should simply be least steep. The copper ion should travel the least distance, and therefore the slope of the chalcopyrite concentration should be the steepest. However, the maximum concentration of each mineral should be at the channel centre. In fact the concentrations of iron sulphides and magnetite rise to a peak at some distance from the channel centre, and then decrease. This should not occur if the mechanism is as proposed in this latter hypothesis.

It appears in sum that a sulphide melt could not have produced the observed mineral distribution by the action of diffusion alone.

(ii) Hydrothermal Fluids.

If the fluid which deposited the ore minerals was predominantly aqueous, it is possible that some, if not all, of the ions were hydrated. Values for the hydrated ionic radii of various elements are taken from Ovchinnikov (1960), and Szadecky-Kardoss (1958), quoted in Ovchinnikov, and are given in Table 5.

TABLE 5

HYDRATED IONIC RADII ACCORDING
TO
OVCHINNIKOV (1960) AND SZADECKY-KARDOSS (1958).

Hydrated ion	Ionic Radius (Angstroms)	
	Ovchinnikov	Szadecky-Kardoss
S^{2-}	-	2.8
O^{2-}	-	3.1
Zu^{2+}	3.4	3.5
Cu^{2+}	3.35	3.5
Fe^{2+}	3.5	3.5
Fe^{3+}	3.9	4.3

Although differences in size are small, Cu^{2+} is definitely smaller than Fe^{3+}, and S^{2-} smaller than O^{2-}. If the size of the hydrated ion is the factor controlling the penetrability of a given metal as considered by Ovchinnikov and Mackay, then chalcopyrite should occur at least as far away from the channel as magnetite. In fact it does not. Therefore the size of the hydrated ion cannot be the only or even the dominant control of deposition. It remains possible, however, that the minerals have been transported as ions, hydrated or otherwise, if some different process to that considered above has been responsible for the deposition.

Attenuation and its Effect on Ore Deposition

In this section, the concept of diffusion as presented by Mackay (1946) and Ovchinnikov (1960) is reexamined. Although filtration undoubtedly can give rise to fluid inhomogeneity, other factors are probably operative also.

(1) Graham's Law states that the rate of gaseous diffusion through an orifice is a function of the inverse square root of the molecular weight of the gas diffusing; this effect is expressed by a separation of ionic species of different molecular weights during diffusion, without regard to any filtrating mechanism. It is this effect which is utilized in the large scale separation of uranium isotopes by gaseous diffusion.

(2) Mackay and Ovchinnikov (ibid) have considered only the filtrating action of rock masses. Under sufficiently high pressures in rock openings containing fluid the molecules of solvent will be very close together. Such closeness could very well obstruct the passage of solute particles, and give rise to a filtrating effect without the presence of a rock mass containing "ultrapores". During filtration it is likely that the control of penetrability will be the cross sectional area of the particle rather than its radius; that is, the penetrability will depend inversely on the product $\sigma^2\sqrt{M}$ where σ is the molecular radius and M the molecular weight.

An approximate chemical derivation is given in Appendix I which supports the validity of the function $\sigma^2\sqrt{M}$ as a control of penetrability. It appears that the very approximate treatment given in Appendix I does support the somewhat intuitional concept described above.

The expression $\sigma^2\sqrt{M}$ is here termed the "attenuation coefficient", A. It is a measure of the effects due to both filtration and Graham's Law. Thus, the partial pressures or concentrations of the various particle species should decrease exponentially away from the feeder channel according to the equation

$$\log (a_x) = \log (a_o) - C.A.x. \quad ....9.$$

where C is a constant common to all species, (a_o) and (a_x)

are the activities of the particle species concerned at the feeder channel, and at a distance x from the channel, and A $(= \sigma^2\sqrt{M})$ is the attenuation coefficient of the particle with molecular weight M, and radius σ. The equation states that the concentration of a given species decreases exponentially away from the feeder channel at a rate that depends on its attenuation coefficient.

Values for σ, M, and $\sigma^2\sqrt{M}$ for the various particles are given in Table 6. If arbitrary values for (a_o) (the effective concentration at the channel centre) and x (a distance from the channel centre) are assigned, the relative slopes of the graphs of log (a_x) against x of the various species are given by -A $(= - \sigma^2\sqrt{M})$.

By reading off from Table 6 values for the various particles at arbitrary distances from the channel centres, and inserting these values in equations 5 to 8, the relative changes in concentration of the ore minerals with distance can be deduced. (It has been assumed in the calculations up to this point that the equilibrium constant 'K' does not change with distance or temperature).

A convenient method of determining whether the concentration of a given ore mineral increases or decreases away from the channel is to sum algebraically the values of log (a_m), where (a_m) is the activity of a particle species m, e.g., for pyrrhotite:-

TABLE 6

VALUES FOR M, σ, AND A FOR VARIOUS PARTICLES

Particle	M	σ	$A = \sigma\ ^2\sqrt{M}$
H_2	2.02	0.80	0.90
HCl	36.5	1.98	23.65
H_2O	18.01	1.32	7.38
H_2S	34.07	2.08	25.24
Cl_2	71.00	3.96	131.96
Cu^{2+}	63.54	0.72	6.51
Cu^{1+}	63.54	0.96	7.34
Fe^{2+}	55.85	0.74	5.54
Fe^{3+}	55.85	0.64	3.06
Cu^{2+} hydrated	81.55	3.5	110.70[1]
Fe^{2+} "	73.86	3.5	105.20[1](156.7 with 6 mols. H_2O)
Fe^{3+} "	73.86	4.3	158.70[1]
O^{2-}	16.00	1.40	7.89
S^{2-}	32.01	1.84	19.16
O^{2-} hydrated	34.01	3.1	56.00[1]
S^{2-} "	50.08	2.8	55.42[1]
Cl^-	35.50	1.81	19.53

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1 - values for σ from Szadecky-Kardoss. Values for M assuming 1 molecule H_2O.

$$K_1 = \frac{(Po)\ (HCl)^2}{(H_2S)\ (FeCl_2)}$$

$$(Po) = \frac{K_1 (H_2S)\ (FeCl_2)}{(HCl)2}$$

$$\log (Po) = \log K_1 + \log (H_2S) + \log (FeCl_2) - 2 \log (HCl)$$

i.e. $$\log \frac{(Po)_x}{(Po)_o} = K^1 + Cx\left[(\sigma\ {}^2\sqrt{M})H_2S + (\sigma^2\sqrt{M})FeCl_2 - 2(\sigma\ {}^2\sqrt{M})HCl\right] \quad \ldots.10.$$

Where $(Po)_x$, $(Po)_o$ are the rock concentrations of pyrrhotite at distance x from the channel, and at the channel, and

$(\sigma\ {}^2\sqrt{M})H_2S$ ......are the attenuation coefficients of H_2S etc.

If $\Sigma(\sigma\ {}^2\sqrt{M})H_2S$ ......) $= \Sigma A$ is positive, then log (Po) decreases
with increase of x.

If $\Sigma(\sigma\ {}^2\sqrt{M})H_2S$ ......) $= \Sigma A$ is negative, then log (Po) increases
with increase of x.

Where ΣA is the sum of the attenuation coefficients of the chemical species from which the pyrrhotite forms.

It should be noted that the transport of an ion is governed not only by its attenuation coefficient, but also by the requirements of electrical neutrality. For instance in the case of $FeCl_2$, the Fe^{2+} has A = 5.54, whereas Cl^- has A = 19.53. The actual concentration of $FeCl_2$ will be somewhere between these two values, as the Fe^{2+} will tend to drag along Cl^- ions, and the Cl^- ions will tend to hold back the Fe^{2+} ions. In actual fact, the system has to be considered as a whole, all the ions interacting upon each other.

The value of A for $FeCl_2$ will probably lie much closer to the Cl^- value than that of the Fe^{2+}, as it will be easier to "hold back" a small ion than to "drag along" a large one. For the sake of simplicity it is assumed that the values for all the metal ions are in fact those for Cl^-. This does not affect the following discussion.

Values of ΣA for the various minerals are tabulated below, Table 7.

TABLE 7

VALUES OF ΣA FOR THE ORE MINERALS FOR UNHYDRATED METAL IONS

Mineral	ΣA
Pyrrhotite	-2.53
Pyrite	+107.37
Chalcopyrite	-5.06
Magnetite	+ 30.87

These values show that the rock concentrations of pyrrhotite and chalcopyrite should increase with distance from the centres of mineralization and pyrite and magnetite should decrease. This does not correspond with the observed mineralogy. In constructing Table 7, however, it was assumed that the metal ions were not hydrated; A similar table has been constructed assuming the metal ions to have been hydrated, Table 8. The actual number of water molecules attached to each ion does not greatly affect the result (as shown by Fe^{2+} in Table 6); The values of M (molecular weight) used are those for the monohydrates. Parenthetically, the chloride ion will now be retarded by the metal ion.

TABLE 8

VALUES OF ΣA FOR THE ORE MINERALS FOR HYDRATED METAL IONS

Mineral	ΣA
Pyrrhotite	+ 83.14
Pyrite	+193.04
Chalcopyrite	+171.78
Magnetite	+287.88

For the hydrated case, all the minerals should decrease with increasing distance from a centre, which is also inconsistent with the observed mineralogy. It appears, in sum, that the action of diffusion or attenuation alone cannot produce the observed mineralogy.

Chapter 5

ATTENUATION AND TEMPERATURE AS CONTROLS OF ORE DEPOSITION

In this chapter attenuation and changes in equilibrium constant with temperature are considered jointly and a more satisfactory result is obtained.

Unfortunately, at this stage K, the equilibrium constant, cannot be plotted on the same scale as x, distance, or A, the attenuation coefficient, to obtain meaningful results. Aside from all the unknowns in the constant C in the formula

$$\log (a_x) = \log (a_o) - C\sigma \sqrt[2]{\bar{M}}.x \quad ,\text{(Equation 9)},$$

the absolute values of (a_o) and the range of x are also unknown.

Changes in T will also change the attenuation coefficient, but the proportional change for each particle species will be the same. Therefore the change in A occasioned by change in temperature can be compensated for graphically by changing the shape of the curve of K.

A hypothetical case is considered with the reaction concerned being

$A + B = C + D$, where $A + B$ represent two ore forming components and $C + D$ represent an ore-mineral and a co-existing dissolved component.

Therefore

$$K = \frac{(C)\ (D)}{(A)\ (B)}$$

If (C) is the unknown concentration then:

$$\log (C) = \log K + \log (A) + \log (B) - \log (D)$$

$$\therefore \quad \log \frac{(C)}{(C_o)} = k \log K + \sigma_A{}^2\sqrt{M_A} + \sigma_B{}^2\sqrt{M_B} - \sigma_D{}^2\sqrt{M_D} \quad .... \quad 11.$$

Fig. 5 shows the changes in concentration of components A, B and D from the channel outward, due to attenuation. The ordinate represents the concentrations of the various components, the abscissa, x, the distance from the channel. The slope of the lines log (A), log (B) and log (D) correspond with the attenuation coefficients of:-

for A, Fe^{2+} (hydrated); for B, H_2S; for D, 2HCl.

The equilibrium constant K is also shown. The resulting concentration of C is obtained by summing the values of the other variables algebraically according to Equation 11 . This diagram thus shows the change in concentration of C (an ore mineral), resulting from the action of attenuation and temperature gradients on the fluid model.

It is apparent that the concentration of C decreases from the channel to a minimum, and then increases. The initial concentrations of A, B and D, and the value of

K determine where the position of the channel lies on Fig. 5. If the channel lies to the right of the minimum concentration of C, e.g., at A-A, then the mineral will decrease in concentration from the channel outward. If the channel lies to the left of the minimum, e.g., at B-B, then the mineral will increase in concentration from the channel outward. (The rapid rise farther from the channel will not continue indefinitely, for upon deposition, a point will be reached where the amount of metal ion becomes too low to produce mineralization).

Thus we have a mechanism which explains the main features of the ore bodies, i.e., 1) The occurrence of chalcopyrite in single concentration peaks, and the simultaneous occurrence of pyrrhotite and pyrite as double concentration peaks, and 2) The separation of the minerals into copper rich and iron rich assemblages.

Such deviations as occur from this ideal mineralogical distribution are to be expected as a result of later metamorphism and inhomogeneities in the temperature gradient, permeability, etc.

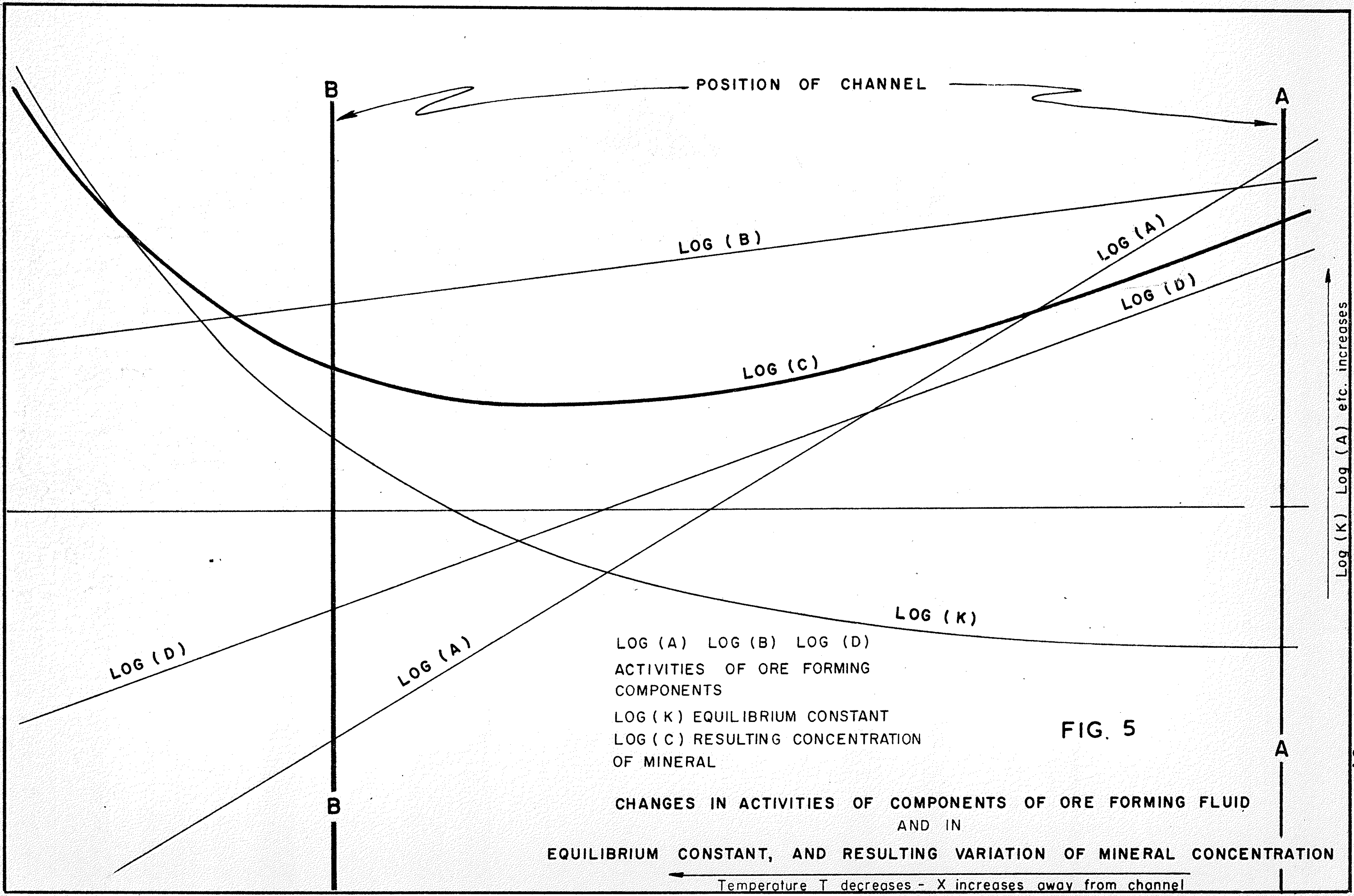

FIG. 5

CHANGES IN ACTIVITIES OF COMPONENTS OF ORE FORMING FLUID AND IN EQUILIBRIUM CONSTANT, AND RESULTING VARIATION OF MINERAL CONCENTRATION

Chapter 6

CONCLUSIONS

Independent evidence suggests that the Coronation Mine ore bodies are ~~magmatic~~ of hydrothermal origin, although recrystallization may have occurred due to later metamorphism. The observed mineral distribution can be well explained by the action of temperature gradients and attenuation on a halide hydrothermal fluid. Although other fluids may also have produced the deposits, thermodynamic data are lacking for such fluids.

Although the evidence is not conclusive, it is considered that these mechanisms warrant consideration as an ore control.

The writer believes that these results justify further investigations into this type of mineralization control. Experimental and theoretical approaches, together with more data on the chemical and physical properties of systems at high temperatures and pressures, could well shed much light on the problems associated with base metal deposits of this type.

APPENDICES

APPENDIX I

DERIVATION OF THE ATTENUATION COEFFICIENT

The derivation that follows is based on equations describing the rigid sphere model of the kinetic theory of gases. For the sake of simplicity a fluid containing only one species of particle is selected. In nature, the various particle species will interfere with each other, but the results should still apply in a qualitative manner. Hirschfelder et. al. (1954, p.14) state that the coefficient of self-diffusion D, is numerically equal to:

$$D = 2.6280 \times 10^{-3} \frac{\sqrt{T^3/M}}{p\sigma^2} \quad \mathrm{cm}^2/\mathrm{sec}$$

where T = absolute temperature, p = pressure in atmospheres, σ = molecular diameter in Angstroms, M = molecular weight. This coefficient is a measure of the flux across some arbitrary interface in the fluid.

Now the flux ψ, i.e. the number of molecules passing through a given area in unit time is defined by:

$$\psi = -D \frac{dn}{dz}$$ where n = number of molecules and

z = distance.

This may be rewritten $\frac{dn}{dz} = \frac{-\psi}{D}$

For steady conditions, for any one molecular or ionic species, and in the case of a linear source channel feeding the rock around it with no deposition, the amount of flux passing a given point will be constant, regardless of its distance from the feeder channel.

$$\therefore \quad \frac{dn}{dz} = \frac{-k}{D}$$

$$\text{Now} \quad D = k' \sqrt{\frac{T^3/M}{p\sigma^2}}$$

At constant volume and temperature, n the number of molecules = k″ p where p is the pressure.

$$\therefore \quad \frac{dp}{dz} = \frac{-K\,p\sigma^2}{\sqrt{T^3/M}}$$

$$\therefore \quad \frac{dp}{p} = \frac{-K\,\sigma^2}{\sqrt{T^3/M}} \quad dz$$

Integrating

$$\int_{Po}^{Px} \frac{dp}{P} = (\ln p)_{p=p_o}^{p=p_x} = \frac{-K\sigma^2}{\sqrt{T^3/M}} \quad (z)_{z=0}^{z=x}$$

$$\ln \frac{p_x}{p_o} = \frac{-K\sigma^2 x}{\sqrt{T^3/M}}$$

$$\therefore \quad p_x = p_o \exp. \frac{-K\sigma^2}{\sqrt{T^3/M}} .x \quad \ldots\ldots\ldots 9.$$

which states that the pressure decreases exponentially from its value at the feeder channel. This formula applies to the case where only one molecular species is present, and takes no account of filtration by the rock, or of the porosity and permeability. No allowance has been made for loss of pressure due to hydraulic flow, or for non steady state conditions.

Apart from these assumptions, those made below are that no loss occurs due to deposition, and that the temperature is constant. (Although the temperature may vary, we are here concerned with the diffusion effect alone, taking no account of temperature changes). However, the time taken for deposition is probably long enough that the amount deposited was negligible compared with the amount transported and in solution at any one place. If these assumptions be granted, then several deductions can be made. The varying factors between the different chemical species present are σ and M. Thus we may write equation 9.

$p_x = p_o e^{-C\sigma^2\sqrt{M}.x}$, where C is a constant common to all particle species.

i.e. $\log p_x = \log p_o - C\sigma^2\sqrt{M}.x.$ ....10.

Substituting activities for pressures.

$$\log (a_x) = \log (a_o) - C\sigma^2\sqrt{M}.x. \quad ....11.$$

This formula gives the activity of a particle species of weight M and particle radius σ at a distance x from a source channel where the activity of the particle is (a_o). The activity decreases exponentially, the rate of decrease at constant temperature depending on the product $\sigma^2\sqrt{M}$. This product is here termed the Attenuation Coefficient, A.

$$A = \sigma^2\sqrt{M}.$$

APPENDIX 2

TABULATION OF RESULTS

The following lists the volumetric percentages of chalcopyrite, pyrite, pyrrhotite, sphalerite and magnetite. All other minerals present are listed as silicates. The concentrations are given in two ways a) volume % of the rock and b) volume % of ore minerals.

The term "grade" as used in this thesis, refers to the total percentage of ore minerals, i.e. the sum of the concentrations of chalcopyrite, pyrite, pyrrhotite, sphalerite and magnetite, and is therefore obtained by subtracting the % of silicates from 100%.

In this thesis all concentrations are expressed as volume percentages unless expressly stated otherwise.

VOLUMETRIC PERCENTAGES OF MINERALS

SAMPLE		LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI- CATES
				% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	%ORE	%ROCK
C231	0-1	3A	1	0.32	50	0.32	50	-	-	-	-	-	-	99
	1-5	3A	0	-	-	-	-	-	-	0.32	100	-	-	100
	5-9	3A	81	58	71	15	18	4.3	5.3	0.40	0.49	4.3	5.3	19
	9-14	3A	82	62	76	11	14	0.37	0.46	-	-	8.0	9.8	18
	14-17	3A	86	44	51	30	35	1.5	1.7	-	-	10	12	14
	17-20	3A	1	0.33	25	0.33	25	-	-	-	-	0.65	50	99
	20-21	3A	24	6.0	25	17	71	-	-	0.29	1.2	0.57	2.4	76
C231	104-107	3B	13	0.62	4.9	7.8	61	4.4	34	-	-	-	-	87
	107-112	3B	17	11	63	4.3	25	-	-	-	-	2.2	13	83
	112-115	3B	9	3.9	42	2.7	29	-	-	-	-	2.7	29	91
C131	71-75	3B	1	-	-	0.66	75	-	-	-	-	0.22	25	99
	75-76	3B	10	2.9	30	5.0	50	-	-	-	-	2.0	20	90
	76-78	3B	7	3.1	47	2.4	37	0.35	5.3	-	-	0.70	11	93

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK
C131 78-80	3B	22	6.7	30	15	67	-	-	0.29	1.3	0.29	1.3	78
80-81	3B	11	3.1	28	4.9	44	0.61	5.6	-	-	2.5	25	89
81-83	3B	8	2.0	26	1.2	16	0.40	5.3	0.40	5.3	3.6	47	92
83-85	3B	41	6.3	15	30	74	0.45	1.1	-	-	4.1	9.8	59
85-87	3B	27	13	49	7.1	26	0.71	2.6	-	-	6.0	22	73
87-90	3B	8	0.66	8.3	0.44	5.6	0.88	11	-	-	5.9	75	92
90-91	3B	5	0.62	13	0.62	13	-	-	-	-	3.7	75	95
C128 56-60	3B	1	-	-	-	-	-	-	-	-	1.3	100	99
60-61	3B	13	1.8	13	6.2	46	0.52	3.8	-	-	4.9	37	87
61-62.5	3B	17	0.67	4.0	5.6	33	0.67	4.0	0.22	1.3	9.6	57	83
62.5-64	3B	27	9.7	37	12	46	-	-	-	-	4.5	17	73
64-65	3B	0	-	-	-	-	-	-	-	-	0.29	100	100
65-70	3B	3	-	-	0.41	13	-	-	0.41	13	2.5	75	97

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK
C64 70-74.5	3C	5	1.3	25	3.3	63	-	-	-	-	0.67	12	95
74.5-75	3C	19	7.2	38	9.7	52	0.36	1.9	-	-	1.4	7.7	81
75-80	3C	38	13	35	22	58	0.35	0.93	0.70	1.9	1.4	3.7	62
80-86	3C	61	35	57	22	36	0.67	1.1	0.67	1.1	3.0	4.9	39
86-93	3C	32	9.2	29	22	69	-	-	-	-	0.92	2.9	68
93-95	3C	10	3.3	33	5.1	52	-	-	-	-	1.4	14	90
95-97	3C	14	2.0	15	7.2	53	4.4	32	-	-	-	-	86
97-100	3C	1	-	-	0.34	50	-	-	-	-	0.34	50	99
100-103	3C	1	-	-	-	-	-	-	-	-	0.70	100	99
103-107	3C	10	6.2	60	3.6	35	-	-	-	-	0.51	5.0	90
107-113	3C	48	12	24	35	74	-	-	-	-	0.80	1.7	52
113-125	3C	2	1.7	71	0.68	29	-	-	-	-	-	-	98
C111 8-11	3C	8	2.3	28	4.3	52	-	-	-	-	1.7	21	92
11-16.5	3C	32	16	49	15	48	-	-	-	-	1.1	3.6	68

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI- CATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK
C115 0-0.5	3C	39	4.1	11	0.41	1.1	32	83	-	-	2.1	5.3	61
0.5-2	3C	6	-	-	0.36	6.3	0.72	13	-	-	4.7	81	94
2-3.5	3C	24	11	47	9.0	37	2.7	11	-	-	1.1	4.5	76
3.5-6.5	3C	87	70	81	3.8	4.4	12	13	-	-	1.2	1.4	13
6.5-9	3C	31	16	51	11	35	4.4	14	-	-	-	-	69
9-15	3C	14	5.1	38	7.7	56	0.29	2.1	-	-	0.57	4.2	86
C113 0-5	3C	30	22	74	3.4	12	2.4	7.9	-	-	1.9	6.5	70
5-10	3C	9	3.2	35	3.7	41	0.50	5.4	-	-	1.7	19	91
10-11	3C	25	5.2	20	15	59	1.5	6.0	-	-	3.7	14	75
11-15	3C	7	0.60	9.1	2.4	36	0.30	4.5	-	-	3.3	50	93
C254 95-100	6B	2	-	-	0.89	36	0.89	36	0.22	9.1	0.44	18	98
100-101	6B	2	-	-	0.27	17	-	-	0.27	17	1.1	67	98
101-105	6B	17	3.0	18	12	74	0.46	2.7	-	-	0.91	5.4	83
105-106	6B	4	0.93	23	1.9	46	0.93	23	-	-	0.31	7.7	96
106-110	6B	25	20	80	4.2	17	-	-	-	-	0.70	2.6	75
110-118.5	6B	27	12	44	11	39	1.0	3.7	0.33	1.2	3.0	11	73
118.5-125	6B	7	0.84	12	4.6	65	1.3	18	-	-	0.42	5.9	93

SAMPLE		LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
				% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROC
C255	56-60	6B	7	2.6	35	3.2	42	-	-	-	-	1.7	23	93
	60-65	6B	5	4.2	85	0.25	5.0	-	-	-	-	0.50	10	95
	65-68	6B	6	2.6	42	3.0	47	0.33	5.3	-	-	0.33	5.3	94
C78	0-5	6C2	0	-	-	0.27	100	-	-	-	-	-	-	100
	5-10	6C2	49	13	27	5.7	11	28	56	-	-	2.5	5.0	51
	10-11.5	6C2	17	7.6	46	1.7	11	4.4	26	-	-	2.9	18	83
	11.5-14.5	6C2	13	1.3	11	0.54	4.3	2.2	17	-	-	8.6	68	87
	14.5-15	6C2	77	1.1	1.4	0.80	1.0	73	95	-	-	2.1	2.8	23
	15-20	6C2	19	2.4	12	5.3	27	5.0	26	-	-	6.6	34	81
	20-22	6C2	20	1.4	7.3	7.0	35	4.6	23	-	-	6.7	34	80
	22-24	6C2	9	0.64	7.0	3.2	35	1.9	21	-	-	3.4	37	91
C81	8-10	6C2	60	1.6	2.6	58	97	-	-	-	-	-	-	40
	10-15	6C2	11	6.2	54	5.2	46	-	-	-	-	-	-	89

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK
C81 21-24	6C2	41	29	70	4.1	10	1.1	2.7	0.27	0.67	6.8	17	59
24-25	6C2	7	2.4	33	0.34	4.8	-	-	-	-	4.5	62	93
25-28	6C2	24	15	65	3.1	13	0.31	1.3	-	-	4.7	20	76
28-30	6C2	43	5.1	12	1.8	4.2	32	74	-	-	4.2	9.8	57
30-34.5	6C2	35	3.8	11	26	75	0.59	1.7	-	-	4.4	13	65
34.5-35	6C2	8	-	-	-	-	-	-	0.32	3.7	8.2	96	92
35-38	6C2	6	-	-	1.2	19	0.29	4.8	-	-	4.7	76	94
38-40	6C2	7	2.1	29	3.8	52	-	-	0.70	9.5	0.70	9.5	93
40-42	6C2	8	1.3	17	0.26	3.4	-	-	-	-	6.0	79	92
42-45	6C2	20	4.8	24	11	53	0.81	3.9	-	-	4.0	20	80
45-50	6C2	2	1.4	58	0.20	8.3	0.20	8.3	-	-	0.58	25	98
50-55	6C1	9	-	-	-	-	2.1	22	-	-	7.2	78	91
55-58	6C1	9	1.4	16	0.29	3.2	1.2	13	-	-	6.0	68	91
58-60	6C1	27	3.7	14	0.33	1.2	17	62	0.33	1.2	6.0	22	73
60-65	6C1	14	2.2	15	5.0	35	0.36	2.5	-	-	6.9	48	86
65-66	6C1	15	1.7	12	3.5	24	3.8	26	-	-	5.6	38	85

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK
C81 66-68	6Cl	18	8.6	49	-	-	3.2	18	1.1	6.1	4.8	27	82
68-70	6Cl	18	11	67	0.84	4.9	-	-	0.28	1.6	4.5	26	82
70-72	6Cl	22	11	50	1.4	6.5	5.8	26	0.36	1.6	3.6	16	78
72-75	6Cl	34	6.2	18	8.0	23	15	45	0.44	1.3	4.0	12	66
75-80	6Cl	7	1.7	24	-	-	1.3	18	-	-	4.3	59	93
80-82	6Cl	10	3.9	41	1.8	19	0.71	7.4	-	-	3.2	33	90
82-85	6Cl	3	2.1	64	0.30	9.1	-	-	-	-	0.90	27	97
85-88	6Cl	0	-	-	-	-	-	-	-	-	-	-	100
88-90	6Cl	1	-	-	-	-	-	-	0.29	33	0.58	67	99
90-95	6Cl	9	1.2	14	0.60	7.0	1.2	14	-	-	5.7	66	91
95-97	6Cl	13	4.4	34	0.44	3.4	4.8	38	-	-	3.1	24	87
97-98.5	6Cl	5	0.41	8.3	-	-	1.6	33	-	-	2.9	58	95
98.5-100	6Cl	2	1.1	50	0.56	25	-	-	-	-	0.56	25	98
100-105	6Cl	0	-	-	-	-	-	-	-	-	-	-	100

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK
C89 45-50	6C	5	-	-	5.3	100	-	-	-	-	-	-	95
50-52.5	6C	2	-	-	0.81	50	-	-	0.41	25	0.41	25	98
52.5-55	6C	33	3.1	9.5	29	87	-	-	-	-	1.3	4.1	67
55-57	6C	7	0.78	11	3.1	43	0.26	3.6	-	-	3.1	43	93
57-60	6C	25	14	57	1.1	4.6	1.1	4.6	1.7	6.8	6.8	27	75
60-62	6C	33	17	53	0.61	1.9	14	44	-	-	2.0	6.4	67
62-65	6C	26	19	71	1.4	5.4	0.94	3.6	-	-	5.1	20	74
65-67	6C	30	2.9	9.8	0.59	2.0	23	76	-	-	3.6	12	70
67-70	6C	71	64	90	0.65	0.93	3.3	4.6	-	-	3.0	4.2	29
70-72	6C	27	17	61	2.6	9.1	1.7	5.8	2.6	9.1	4.3	15	73
72-75	6C	29	7.0	24	1.9	6.5	19	65	-	-	1.2	4.1	71
75-78	6C	12	2.4	20	0.81	6.8	5.4	45	-	-	3.2	27	88
78-85	6C	46	17	37	-	-	27	58	0.29	0.63	1.7	3.8	54
85-90	6C	19	2.8	15	0.31	1.6	13	68	0.62	3.2	2.5	13	81
90-91	6C	15	6.7	44	0.22	1.4	2.2	14	-	-	6.3	41	85
91-93	6C	41	31	75	4.3	10	3.4	8.3	-	-	2.6	6.3	59

SAMPLE		LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
				% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK
C89	93-95	6C	29	13	43	2.8	10	-	-	2.8	10	10	36	71
	95-98	6C	26	11	44	0.59	2.3	8.6	33	-	-	5.3	21	74
	98-100	6C	15	4.3	29	0.50	3.4	4.3	29	-	-	5.8	39	85
	100-105	6C	35	12	35	-	-	20	58	0.30	0.85	2.4	6.8	65
	105-110	6C	5	3.4	67	0.85	17	-	-	-	-	0.85	17	95
	110-120	6C	3	0.28	9.1	1.1	36	-	-	-	-	1.7	55	97
C93	65-70	6C	4	0.89	23	2.1	54	-	-	0.30	7.7	0.30	7.7	96
	70-72	6C	15	3.4	22	11	71	-	-	-	-	1.0	6.8	85
	72-75	6C	31	15	47	16	51	-	-	0.26	0.80	0.26	0.80	69
	75-80	6C	11	-	-	6.8	62	2.5	23	-	-	1.7	15	89
	80-82	6C	6	0.40	6.7	4.5	77	0.79	13	-	-	0.20	3.3	94
	82-86	6C	15	2.2	14	11	70	2.2	14	-	-	0.24	1.6	85
	86-90	6C	21	1.1	5.1	15	69	1.1	5.1	0.22	1.0	4.2	19	79
	90-91	6C	5	0.43	8.0	1.9	36	1.9	36	-	-	1.1	20	95
	91-95	6C	4	0.23	5.9	0.91	24	0.68	18	-	-	2.0	53	96

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK
C93 95-98	6C	5	1.8	39	1.6	33	-	-	-	-	1.3	28	95
98-102.5	6C	14	1.8	13	3.8	28	5.0	36	-	-	3.2	23	86
102.5-105	6C	7	1.6	22	0.68	9.4	0.92	13	0.23	3.1	3.9	53	93
105-106	6C	5	1.3	24	0.22	4.0	0.44	8.0	0.44	8.0	3.1	56	95
106-108	6C	8	3.0	38	0.47	5.9	-	-	-	-	4.4	56	92
108-111	6C	11	1.0	9.3	4.4	39	2.5	22	0.21	1.9	3.1	28	89
111-113	6C	17	3.9	23	1.3	7.8	4.8	29	0.22	1.3	6.6	39	83
113-115	6C	17	6.3	39	4.3	27	3.7	23	-	-	2.1	13	83
115-118	6C	5	-	-	1.7	37	1.5	32	-	-	1.5	32	95
118-120	6C	6	0.66	11	5.0	85	-	-	-	-	0.22	3.7	94
120-122	6C	2	0.22	11	1.4	67	-	-	-	-	0.46	22	98
C34 35-42	9C	0	-	-	0.54	100	-	-	-	-	-	-	100
42-46.5	9C	22	15	69	5.0	23	0.68	3.2	-	-	0.91	4.2	78
46.5-50	9C	2	1.9	83	0.39	17	-	-	-	-	-	-	98
50-55	9C	1	-	-	-	-	-	-	-	-	1.5	100	99

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK
C 34 55-57	9C	3	0.88	33	-	-	0.29	11	-	-	1.5	56	97
57-60	9C	17	12	70	2.1	13	0.90	5.4	-	-	2.1	13	83
60-64.5	9C	3	-	-	0.26	8.3	-	-	-	-	2.8	92	97
64.5-67	9C	41	26	63	1.5	3.8	11	27	0.76	1.9	1.5	3.8	59
67-73.5	9C	21	13	61	3.6	17	1.9	9.3	0.28	1.3	2.2	11	79
73.5-75	9C	14	2.3	16	7.8	56	0.75	5.5	-	-	3.0	22	86
C 31 34-37	9C	19	4.5	23	5.1	26	7.3	38	0.32	1.6	2.2	11	81
37-40	9C	39	14	37	1.3	3.4	18	46	0.27	0.68	5.3	14	61
40-45.5	9C	32	18	57	5.2	16	5.6	18	-	-	3.0	9.3	68
45.5-48	9C	6	1.2	18	0.88	14	2.9	45	0.29	4.5	1.2	18	94
48-50	9C	18	1.7	9.5	0.29	1.6	12	65	-	-	4.3	24	82
50-54	9C	28	2.3	8.3	0.66	2.4	20	73	0.66	2.4	3.9	14	72
54-59	9C	20	12	59	0.49	2.4	5.2	26	-	-	2.7	13	80
59-64	9C	13	8.7	68	-	-	2.1	16	-	-	2.1	16	87

SAMPLE		LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
				% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK
C31	64-69	9C	21	14	64	1.0	4.9	2.5	12	-	-	4.2	20	79
	69-74	9C	41	31	76	4.7	11	2.6	6.4	-	-	2.4	5.9	59
	74-76	9C	16	11	68	-	-	3.4	21	-	-	1.8	11	84
	76-80	9C	2	0.25	11	0.25	11	0.49	22	-	-	1.2	56	98
	80-85	9C	5	0.24	5.3	0.24	5.3	0.24	5.3	-	-	3.9	84	95
C56	15-20	9C2	12	6.6	54	2.1	17	1.6	13	-	-	1.8	15	88
	20-25	9C2	12	4.4	35	2.9	24	3.2	25	-	-	2.0	16	88
	25-30	9C2	6	2.5	41	0.84	14	1.1	18	0.28	4.5	1.4	23	94
	40-45	9C2	20	11	57	0.65	3.3	3.9	20	-	-	3.9	20	80
	45-50	9C2	40	28	69	0.38	0.95	8.4	21	0.38	0.95	3.4	8.5	60
	50-55	9C2	4	0.73	20	2.0	53	0.24	6.7	0.24	6.7	0.49	13	96
C56	70-73	9C1	3	-	-	0.56	20	-	-	0.56	20	1.7	60	97
	73-75	9C1	38	7.9	21	26	70	3.1	8.3	-	-	0.52	1.4	62
	75-80	9C1	15	13	85	1.9	13	0.28	1.9	-	-	-	-	85

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE % ROCK	CHALCOPYRITE % ORE	PYRITE % ROCK	PYRITE % ORE	PYRRHOTITE % ROCK	PYRRHOTITE % ORE	SPHALERITE % ROCK	SPHALERITE % ORE	MAGNETITE % ROCK	MAGNETITE % ORE	SILICATES %ROCK
C56 80-83.5	9C1	26	21	80	0.61	2.4	4.6	18	-	-	-	-	74
83.5-85	9C1	3	1.8	54	1.0	31	0.5	15	-	-	-	-	97
85-90	9C1	1	0.26	25	0.51	50	-	-	-	-	0.26	25	99
C53 0-3	9D	1	-	-	0.32	50	-	-	-	-	0.32	50	99
3-7.5	9D	25	13	54	8.9	36	1.4	5.8	-	-	1.2	4.8	75
7.5-12.5	9D	23	3.8	17	8.8	39	4.2	19	-	-	5.7	25	77
12.5-17.5	9D	22	10	47	6.8	31	2.0	9.1	-	-	2.8	13	78
17.5-22	9D	51	24	48	2.7	5.3	23	44	0.23	0.44	1.4	2.7	49
22-25	9D	4	2.4	57	-	-	-	-	-	-	1.8	43	96
25-30	9D	0	-	-	0.38	100	-	-	-	-	-	-	100
C253 8.5-13	9D	14	9.5	66	2.6	18	2.3	16	-	-	-	-	86
13-18.5	9D	23	6.7	29	15	66	1.2	5.1	-	-	-	-	77
18.5-19.5	9D	29	11	38	17	60	-	-	-	-	0.74	2.6	71

OTHER SAMPLES

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILICATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	%ROCK
C128 0-3.5	3 -	22	16	72	4.7	21	0.28	1.2	0.55	2.5	0.83	3.7	78
C121 5-10	3 -	39	30	75	8.9	23	0.29	0.73	0.29	0.73	0.29	0.73	61
C85 9-15	6 -	8	3.7	44	4.4	52	0.37	4.4	-	-	-	-	92
C85 29-30	6 -	63	40	63	23	37	-	-	-	-	0.36	0.57	37
C85 60-61	6 -	6	0.45	7.7	-	-	-	-	-	-	5.4	92	94
C85 91-94	6 -	15	8.1	53	0.84	5.5	0.28	1.8	0.28	1.8	5.9	38	85
C252 34-35	9 -	15	13	85	1.8	12	-	-	0.51	3.3	-	-	85

AVERAGED VALUES

ORE BODY	3C												
TOTAL ORE BODY		20.75	9.71	46.80	8.92	43.00	0.99	4.77	0.08	0.39	1.05	5.06	79.25
C64		18.75	7.33	39.11	10.36	55.28	0.23	1.23	0.12	0.64	0.71	3.79	81.25
C111		23.69	11.16	47.10	11.22	47.38	0.00	0.00	0.00	0.00	1.31	5.53	76.31
C113-C115		24.39	14.46	59.29	5.31	21.77	2.90	11.89	0.00	0.00	1.72	7.05	75.61

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	%ROCK
ORE BODY	3B												
TOTAL ORE BODY		11.41	3.46	30.32	4.74	41.53	0.48	4.21	0.08	0.70	2.65	23.23	88.59
C231		14.01	6.25	44.60	4.82	34.40	1.20	8.57	0.00	0.00	1.74	12.42	85.99
C131		13.07	3.54	27.10	6.29	48.17	0.35	2.68	0.07	0.54	2.81	21.51	86.93
C128		7.15	1.24	17.34	2.48	34.68	0.11	1.54	0.17	2.38	3.15	44.06	92.85
ORE BODY	6B												
TOTAL ORE BODY		12.75	5.70	44.70	5.19	40.70	0.60	4.71	0.10	0.78	1.16	9.10	87.25
C254		15.38	6.66	43.30	6.49	42.20	0.81	5.27	0.14	0.91	1.28	8.32	84.62
C255		6.13	3.27	53.37	1.92	31.33	0.08	1.31	0.00	0.00	0.86	14.03	93.87
ORE BODY	6C												
* TOTAL ORE BODY		16.30	5.49	33.67	3.87	23.75	3.89	23.85	0.17	1.04	2.88	17.69	83.70

* DDH #C78 not used in calculations.

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILI-CATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	%ROCK
ORE BODY	6C2	20.91	5.35	25.57	6.86	32.80	5.05	24.15	0.04	0.19	3.61	17.26	79.09
(C81 Total length		14.51	4.04	27.85	4.37	23.75	2.39	16.47	0.09	0.62	3.62	24.95	85.49
(C89		22.58	9.80	43.40	2.21	9.79	7.53	33.34	0.31	1.37	2.73	12.09	77.42
(C93		10.97	2.13	19.41	5.27	48.03	1.51	13.76	0.09	0.82	1.97	17.95	89.03
(C81	6C2	20.73	6.23	30.04	9.18	44.29	2.09	10.08	0.07	0.34	3.16	15.24	79.27
(C78	6C2	20.97	4.04	19.28	3.39	16.17	9.49	45.28	0.00	0.00	4.04	19.28	79.03
C81	6C1	10.46	2.61	24.96	1.23	11.76	2.59	24.76	0.11	1.05	3.92	37.96	89.54
ORE BODY	9C												
TOTAL ORE BODY		15.92	8.67	54.49	1.94	12.18	3.22	20.22	0.11	0.69	1.98	12.44	84.08
C34		11.15	6.63	59.46	1.85	16.58	1.18	10.59	0.09	0.81	1.40	12.56	88.85
C31		20.87	10.44	50.02	1.69	8.10	5.68	27.22	0.10	0.48	2.96	14.18	79.13
C56		14.66	8.49	57.90	2.27	15.48	2.33	15.89	0.12	0.82	1.45	9.89	85.34
C56 (15-55)		15.75	8.88	56.38	1.48	9.40	3.07	19.50	0.15	0.95	2.17	13.78	84.25
C56 (73-90)		13.06	7.92	60.60	3.47	26.56	1.22	9.34	0.08	0.61	0.37	2.83	86.94

SAMPLE	LEVEL AND ORE BODY	GRADE	CHALCOPYRITE		PYRITE		PYRRHOTITE		SPHALERITE		MAGNETITE		SILICATES
			% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	% ROCK	% ORE	%ROCK
ORE BODY	9D												
TOTAL ORE BODY		19.45	8.13	41.80	5.95	30.60	3.85	19.80	0.03	0.15	1.49	7.66	80.55
C53		19.22	8.08	41.95	4.44	23.05	4.69	24.16	0.03	0.16	2.02	10.49	80.78
C253		19.96	8.24	41.29	10.11	50.64	1.54	7.72	0.00	0.00	0.07	0.35	80.04

APPENDIX 3

TEMPERATURE DETERMINATIONS BY THE PYRRHOTITE-PYRITE GEOTHERMOMETER

SAMPLE		TEMPERATURE °C
C89	55-57	434 ± 4
	57-60	434 ± 6
	60-62	478 ± 10
	62-65	451 ± 7
	65-67	483 ± 5
	67-70	443 ± 8
	70-72	491 ± 7
	72-75	515 ± 4
	75-78	461 ± 5
	78-85	439 ± 7
	85-90	468 ± 8
	90-91	459 ± 8
	91-93	442 ± 9
	93-95	482 ± 5
	95-98	498 ± 9
	98-100	460 ± 11
	100-105	452 ± 5
	105-110	349 ± 21
C34	64.5-67	425 ± 6
C231	5-9	406 ± 13
C254	105-106	415 ± 10
C93	111-113	409 ± 10

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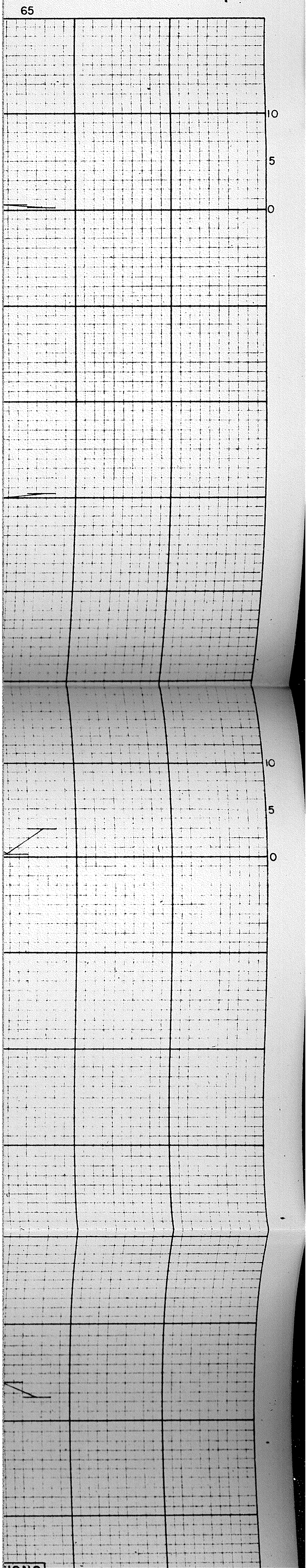

65
10
5
0
10
5
0
IONO

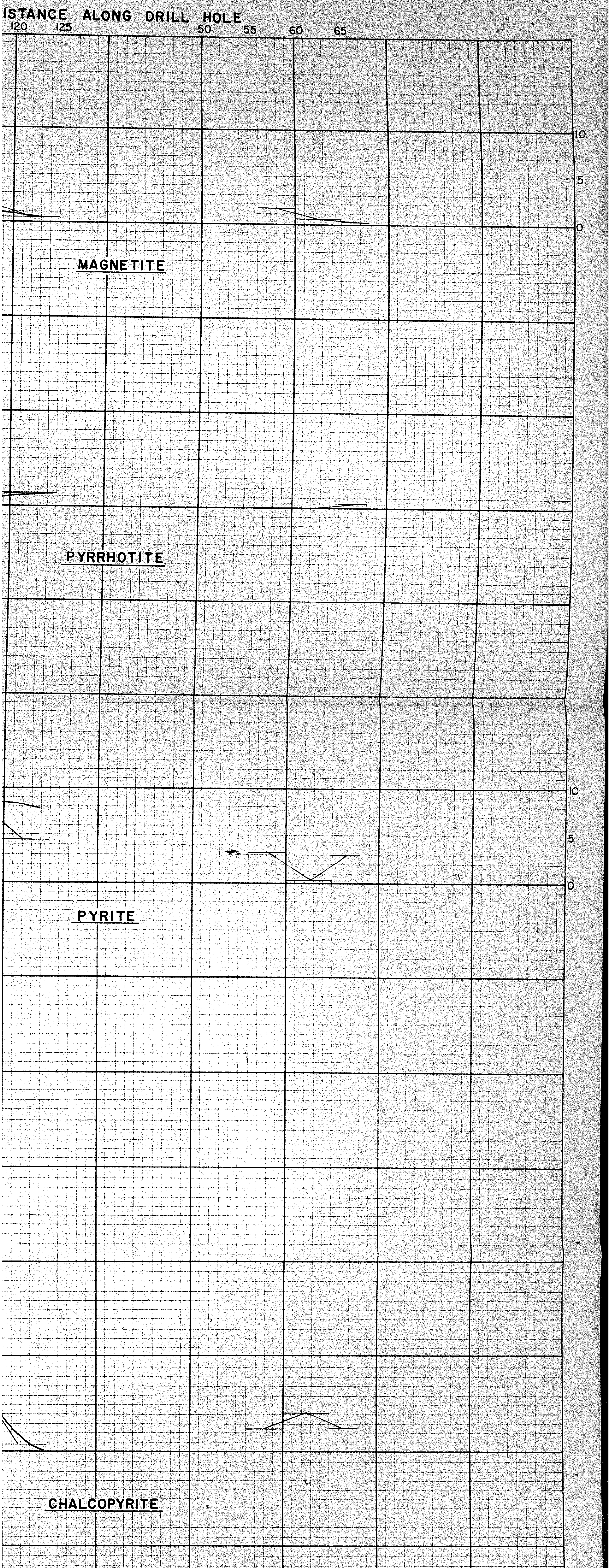
ISTANCE ALONG DRILL HOLE
120
125
50
55
60
65
10
5
0
MAGNETITE
PYRRHOTITE
10
5
0
PYRITE
CHALCOPYRITE

FIG. 6

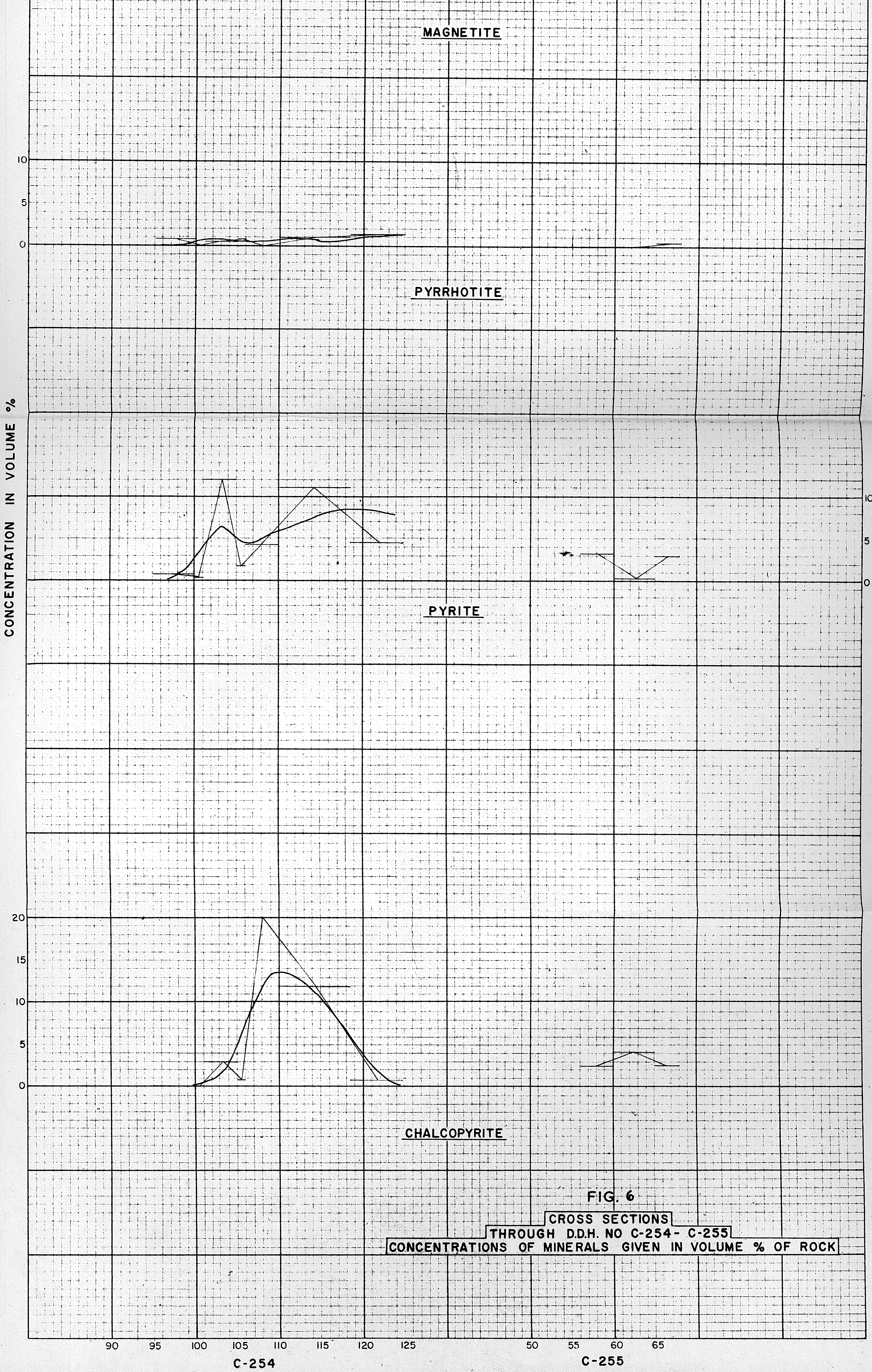


FIG. 6

CROSS SECTIONS
THROUGH D.D.H. NO C-254- C-255
CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK

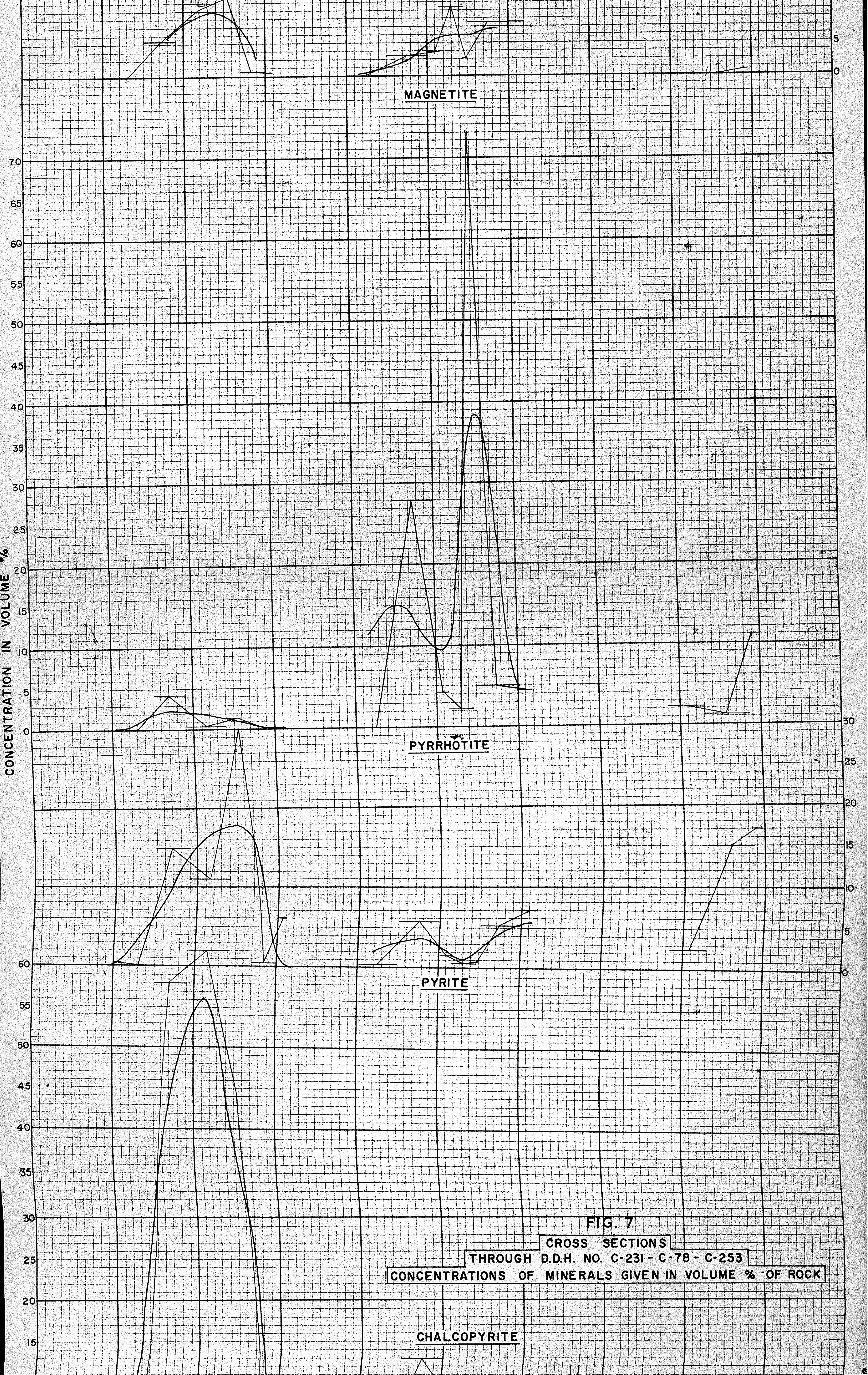
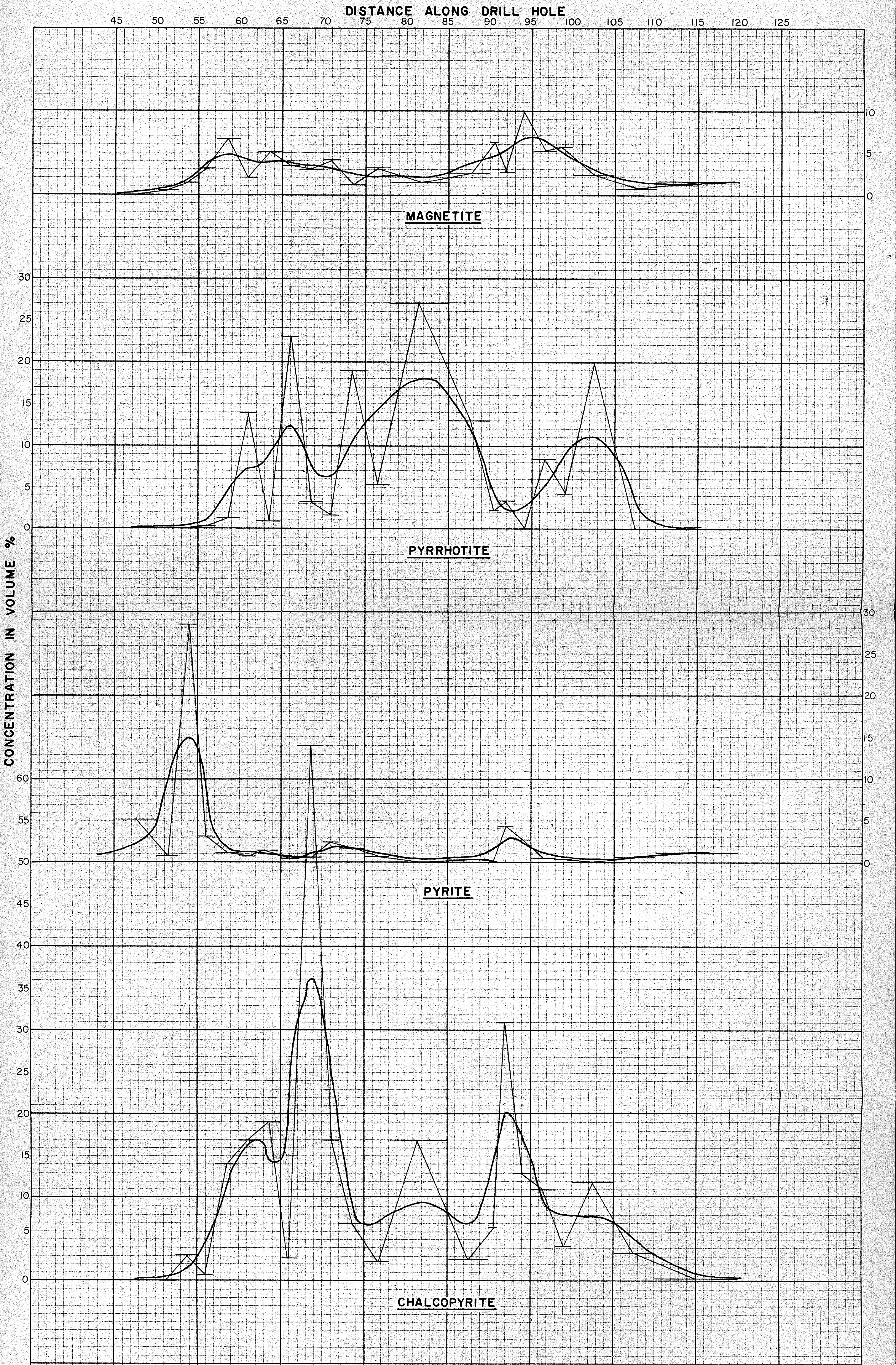


FIG. 7

CROSS SECTIONS

THROUGH D.D.H. NO. C-231 - C-78 - C-253

CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK


DISTANCE ALONG DRILL HOLE
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
10
5
0
MAGNETITE
30
25
20
15
10
5
0
PYRRHOTITE
CONCENTRATION IN VOLUME %
30
25
20
15
10
5
0
60
55
50
PYRITE
45
40
35
30
25
20
15
10
5
0
CHALCOPYRITE

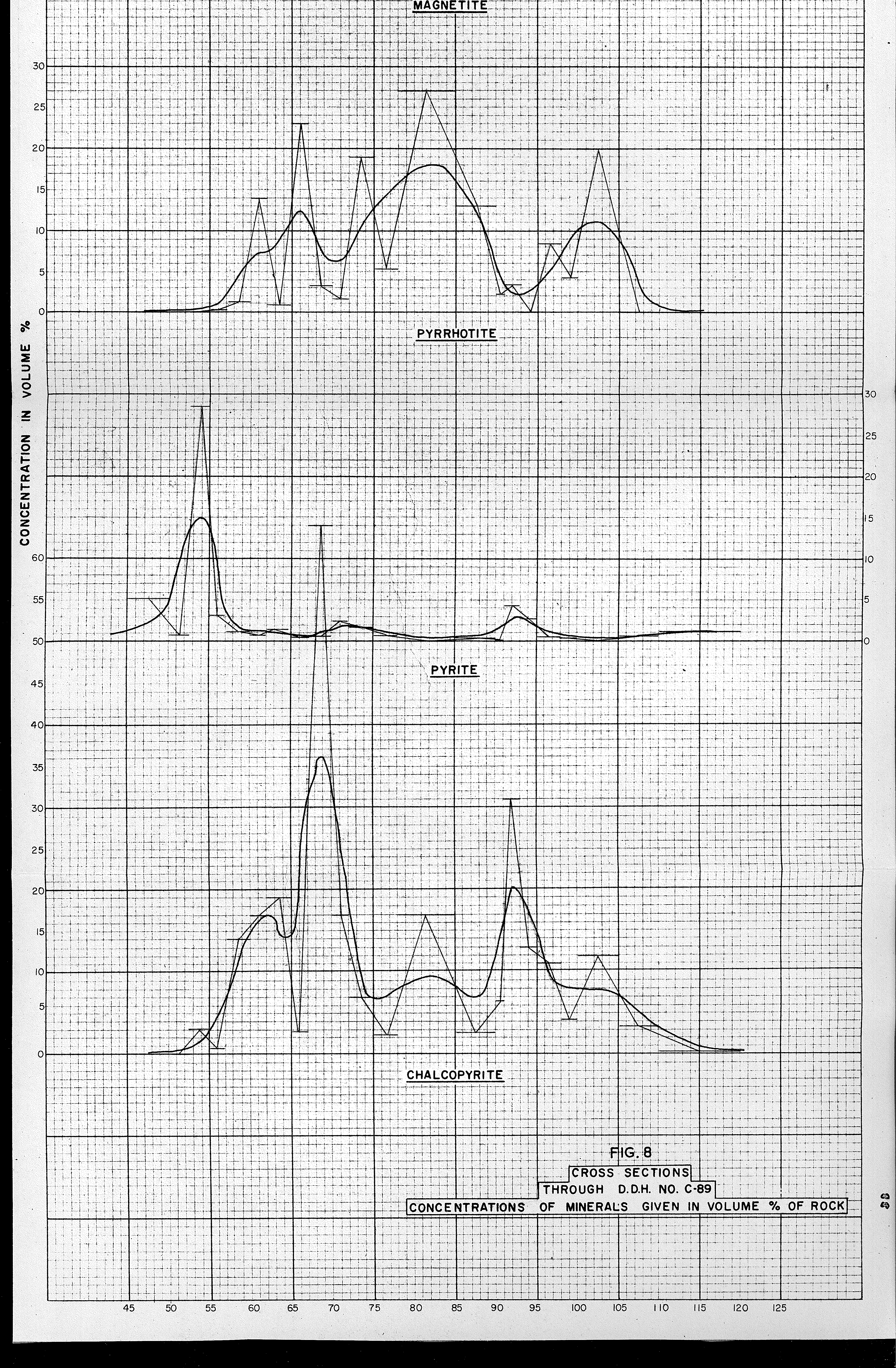
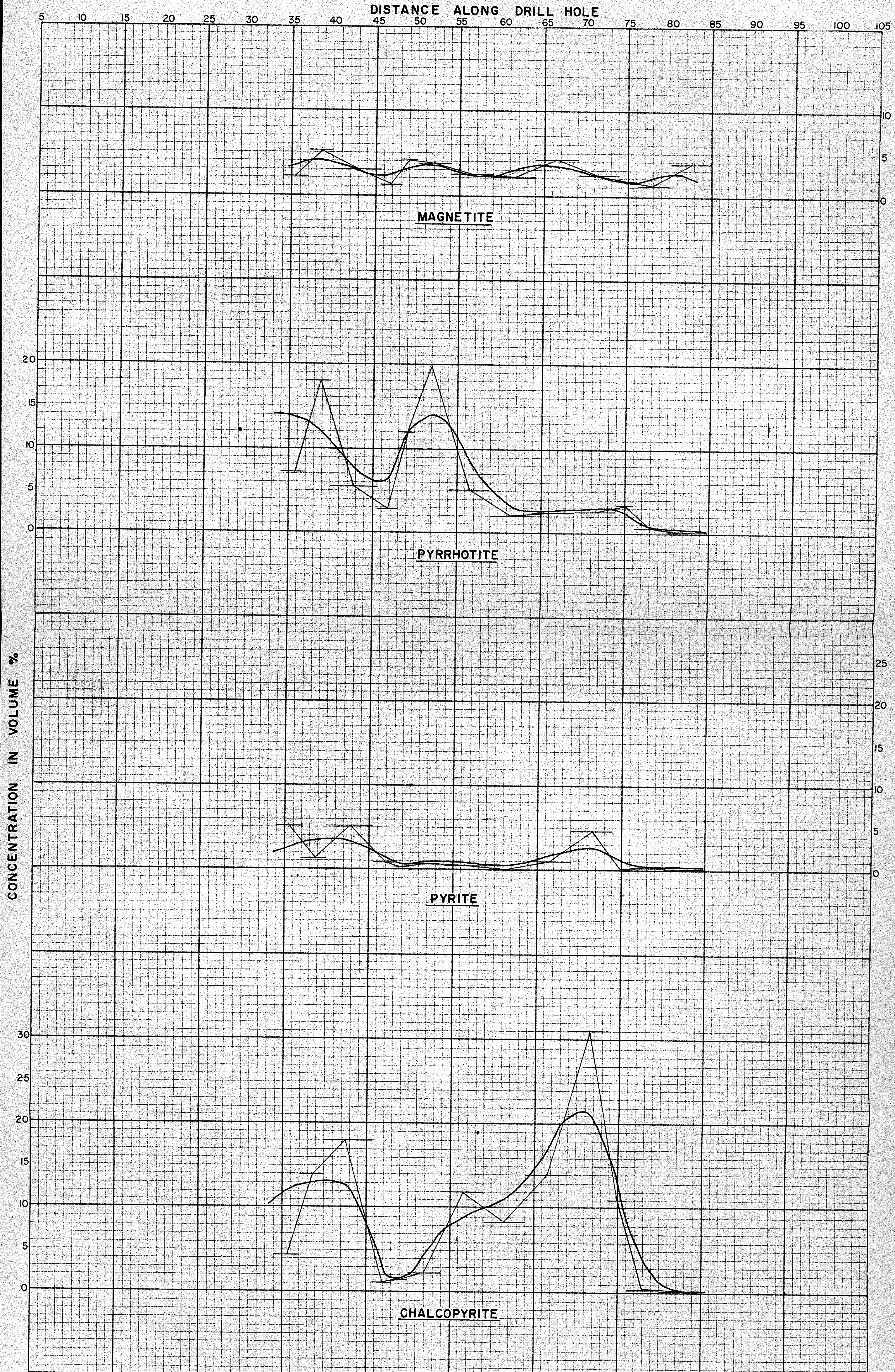


FIG. 8

CROSS SECTIONS
THROUGH D.D.H. NO. C-89
CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK


DISTANCE ALONG DRILL HOLE
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
10
5
0
MAGNETITE
20
15
10
5
0
PYRRHOTITE
CONCENTRATION IN VOLUME %
25
20
15
10
5
0
PYRITE
30
25
20
15
10
5
0
CHALCOPYRITE

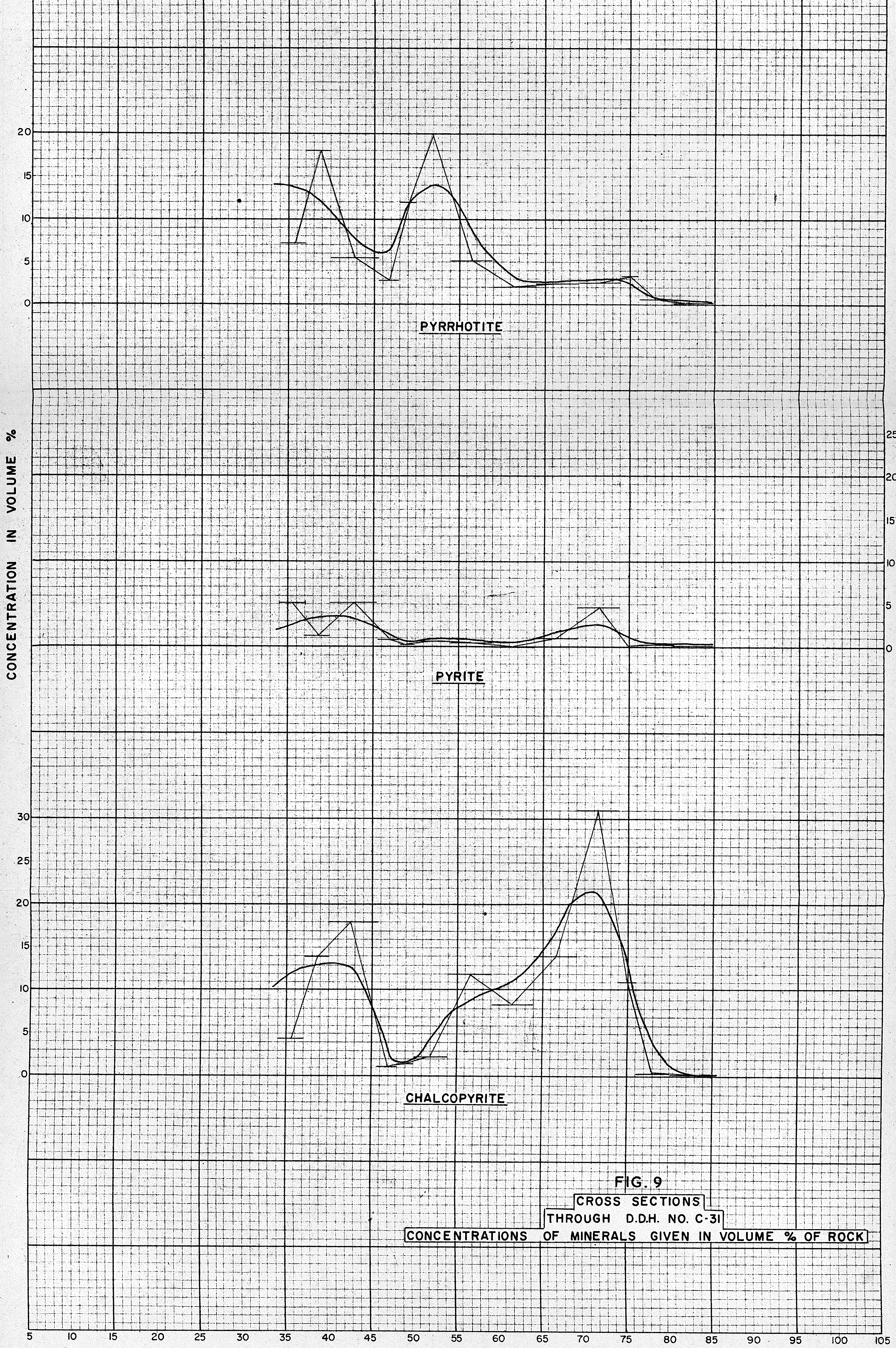
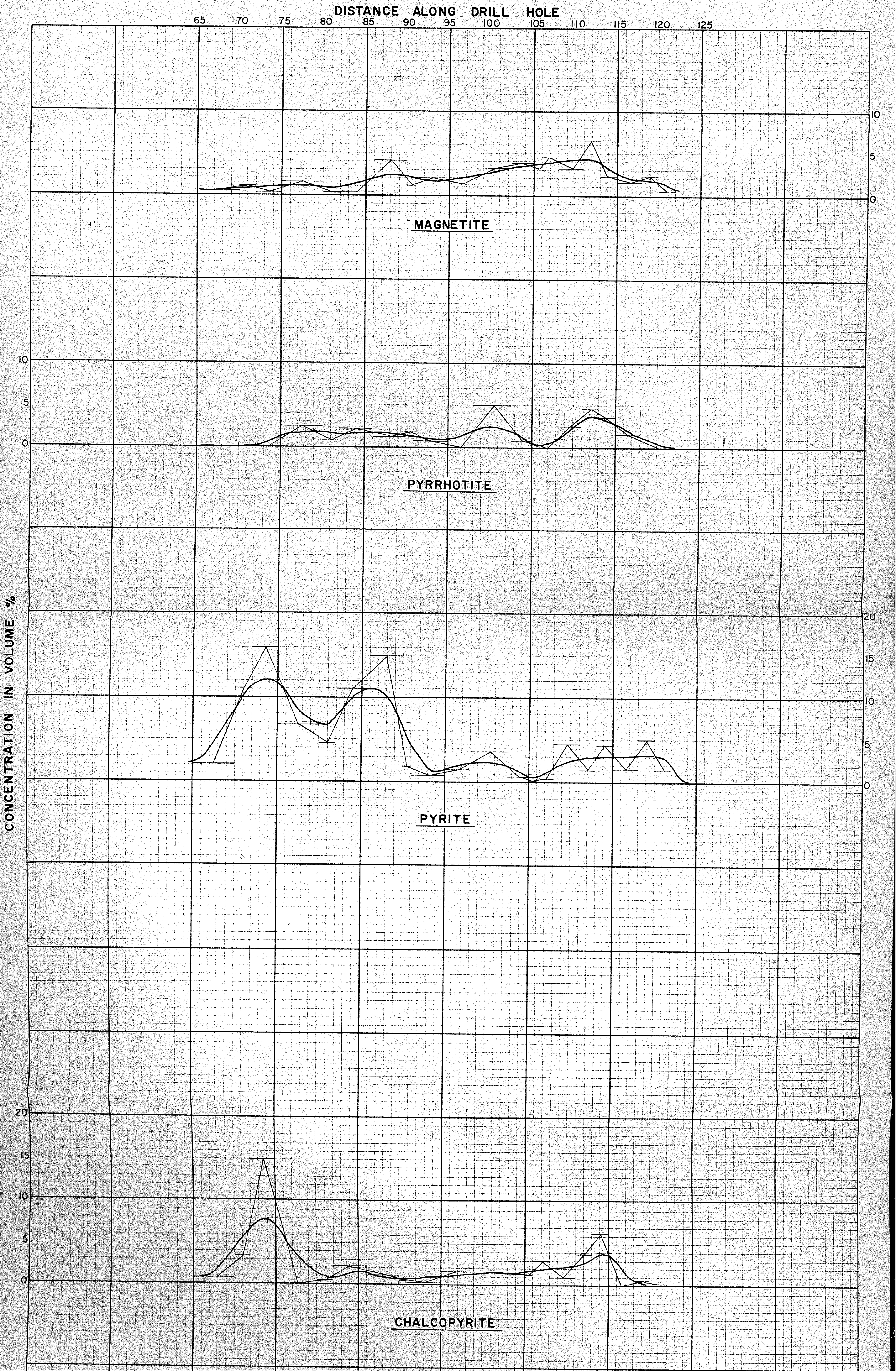


FIG. 9

CROSS SECTIONS

THROUGH D.D.H. NO. C-31

CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK


DISTANCE ALONG DRILL HOLE
65
70
75
80
85
90
95
100
105
110
115
120
125
CONCENTRATION IN VOLUME %
10
5
0
MAGNETITE
10
5
0
PYRRHOTITE
20
15
10
5
0
PYRITE
20
15
10
5
0
CHALCOPYRITE

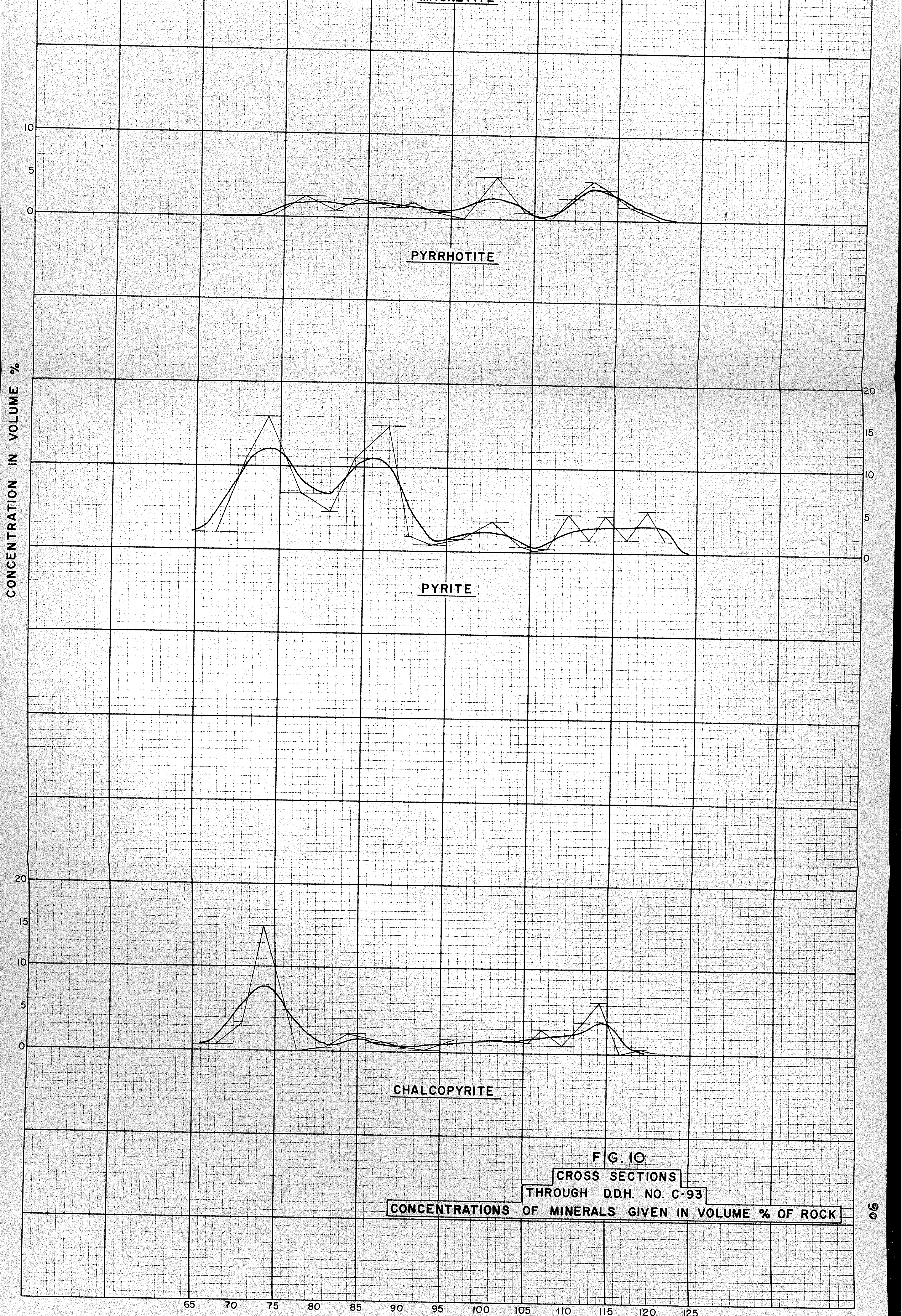
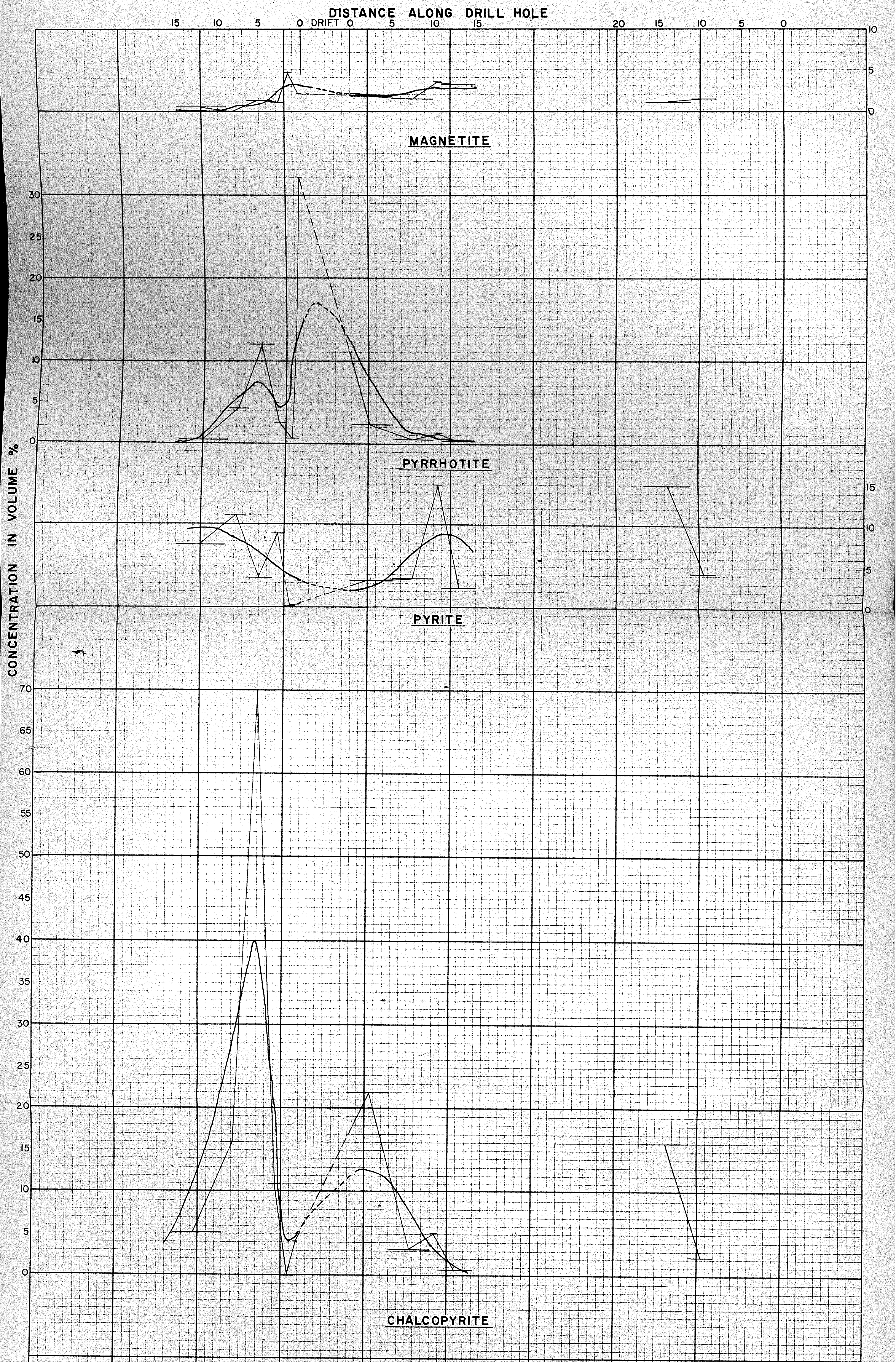


FIG. 10
CROSS SECTIONS
THROUGH D.D.H. NO. C-93
CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK


DISTANCE ALONG DRILL HOLE
15
10
5
0
DRIFT
0
5
10
15
20
15
10
5
0
MAGNETITE
PYRRHOTITE
PYRITE
CHALCOPYRITE
CONCENTRATION IN VOLUME %
10
5
0
30
25
20
15
10
5
0
15
10
5
0
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0

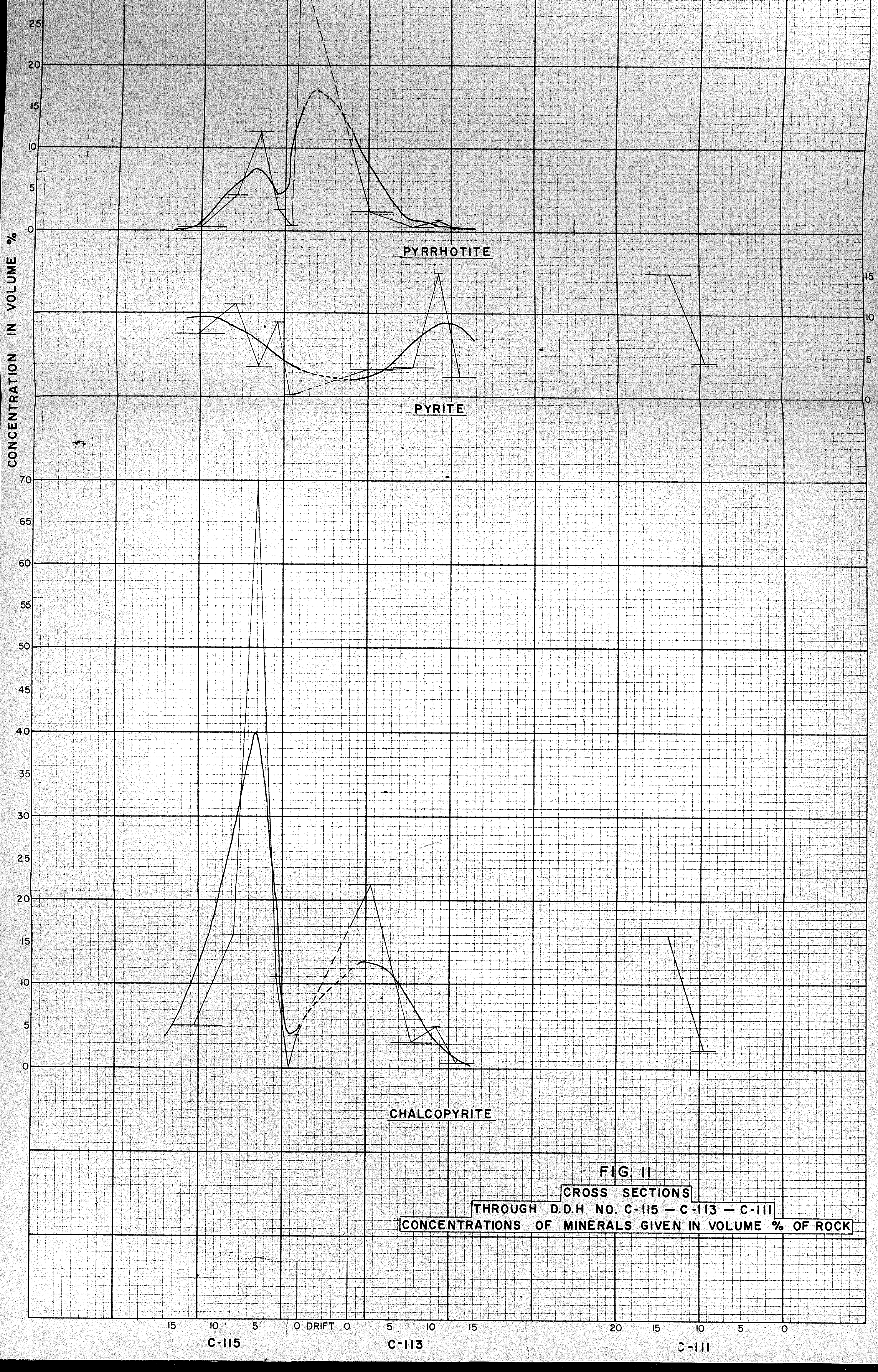
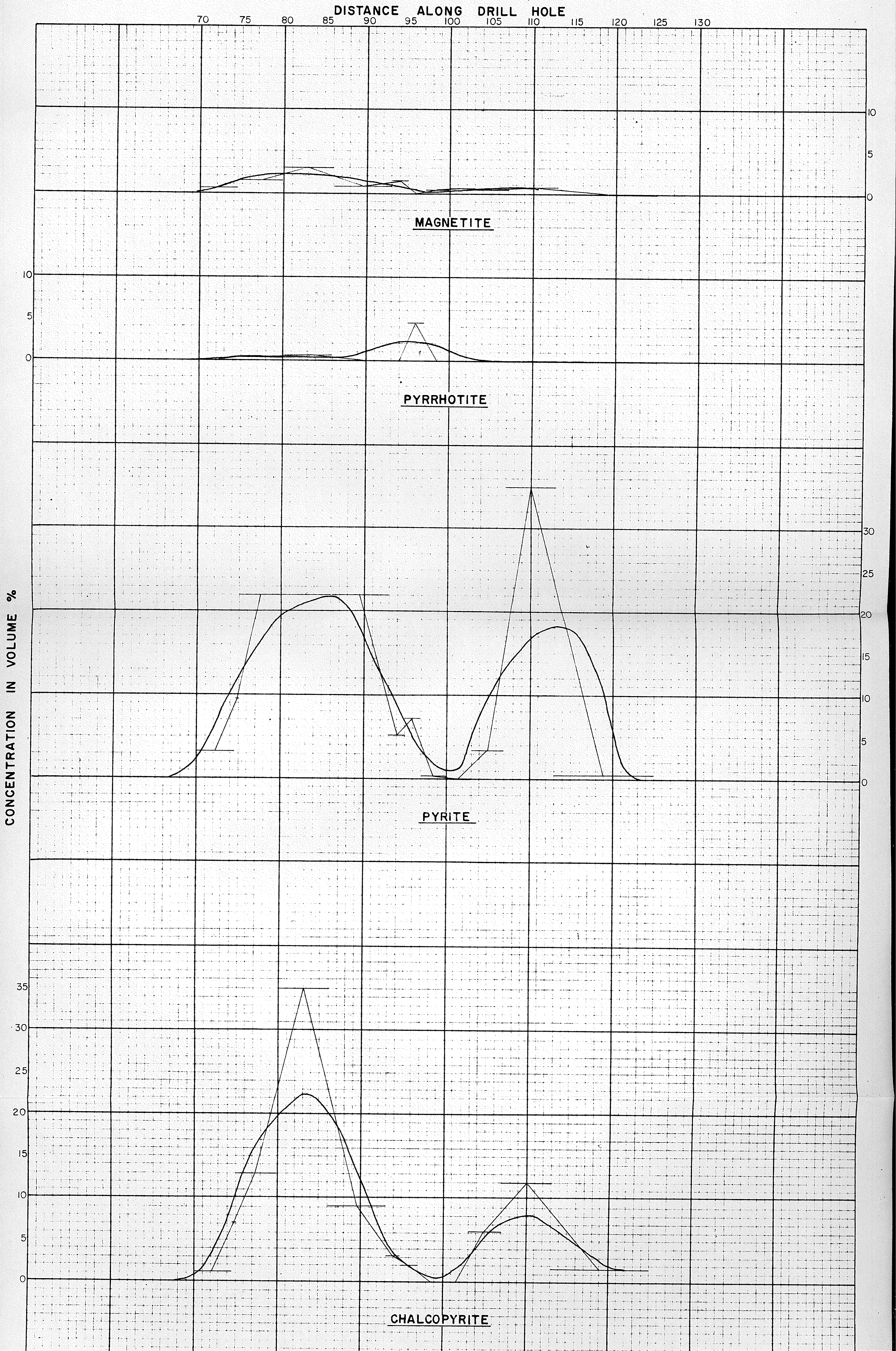


FIG. 11

CROSS SECTIONS

THROUGH D.D.H NO. C-115 — C-113 — C-111

CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK


DISTANCE ALONG DRILL HOLE
70
75
80
85
90
95
100
105
110
115
120
125
130
CONCENTRATION IN VOLUME %
10
5
0
MAGNETITE
10
5
0
PYRRHOTITE
30
25
20
15
10
5
0
PYRITE
35
30
25
20
15
10
5
0
CHALCOPYRITE

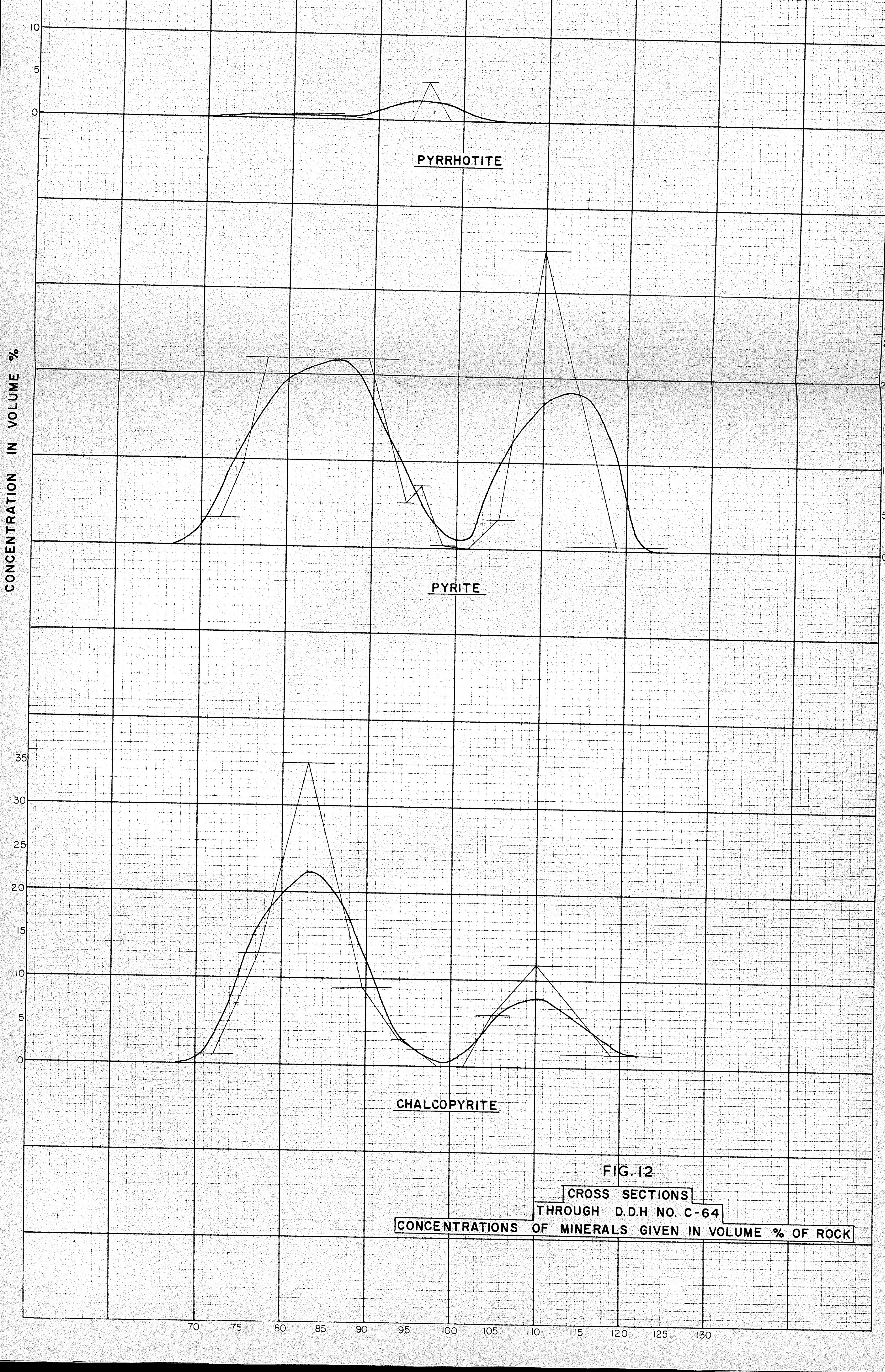
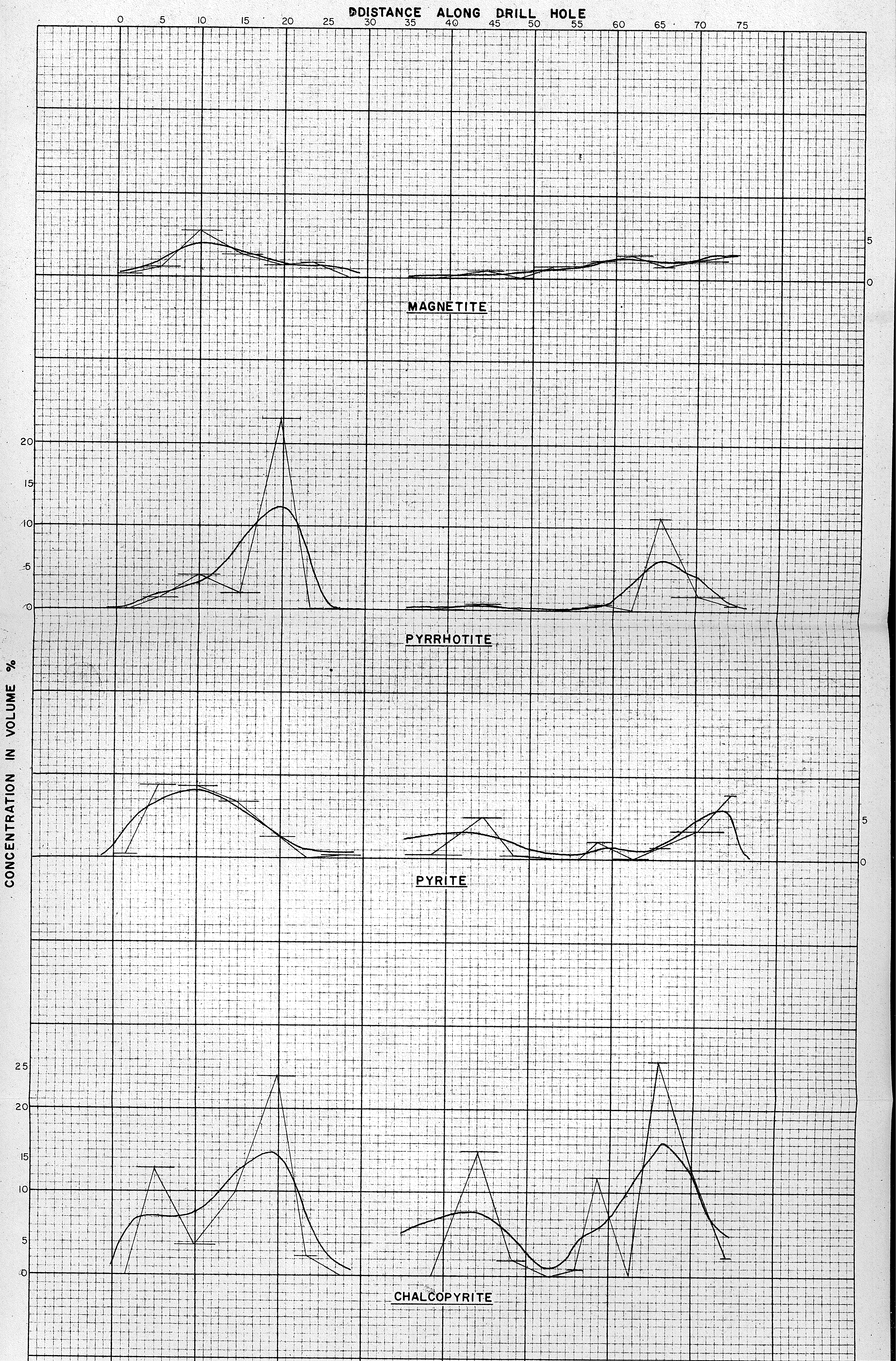


FIG. 12

CROSS SECTIONS

THROUGH D.D.H NO. C-64

CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK


DISTANCE ALONG DRILL HOLE
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
5
0
MAGNETITE
20
15
10
5
0
PYRRHOTITE
CONCENTRATION IN VOLUME %
5
0
PYRITE
25
20
15
10
5
0
CHALCOPYRITE

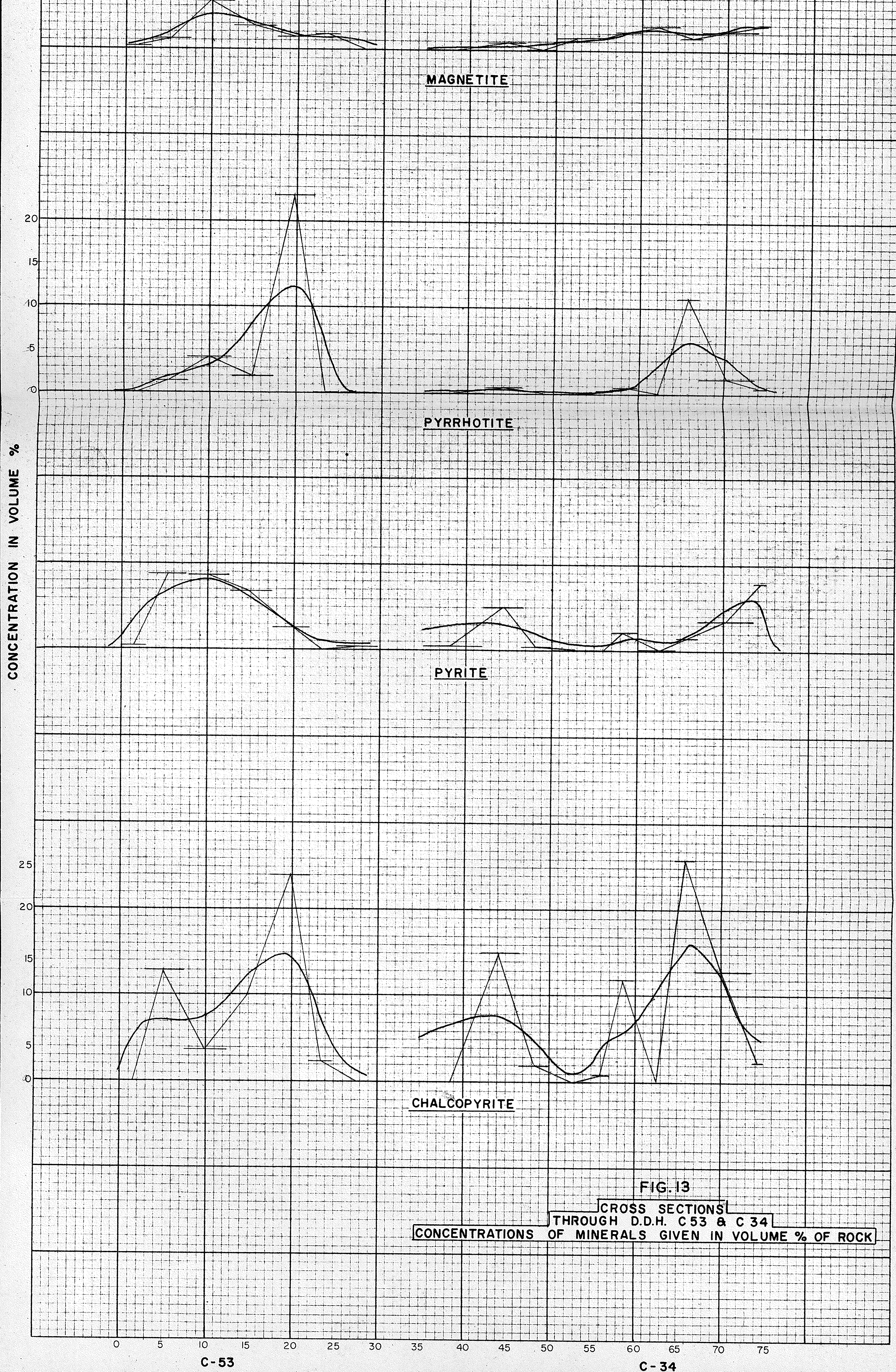


FIG. 13
CROSS SECTIONS
THROUGH D.D.H. C53 & C 34
CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK


DISTANCE ALONG DRILL HOLE
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
CONCENTRATION IN VOLUME %
10
5
0
MAGNETITE
30
25
20
15
10
5
0
PYRRHOTITE
55
50
45
40
35
30
25
20
15
10
5
0
PYRITE
25
20
15
10
5
0
CHALCOPYRITE

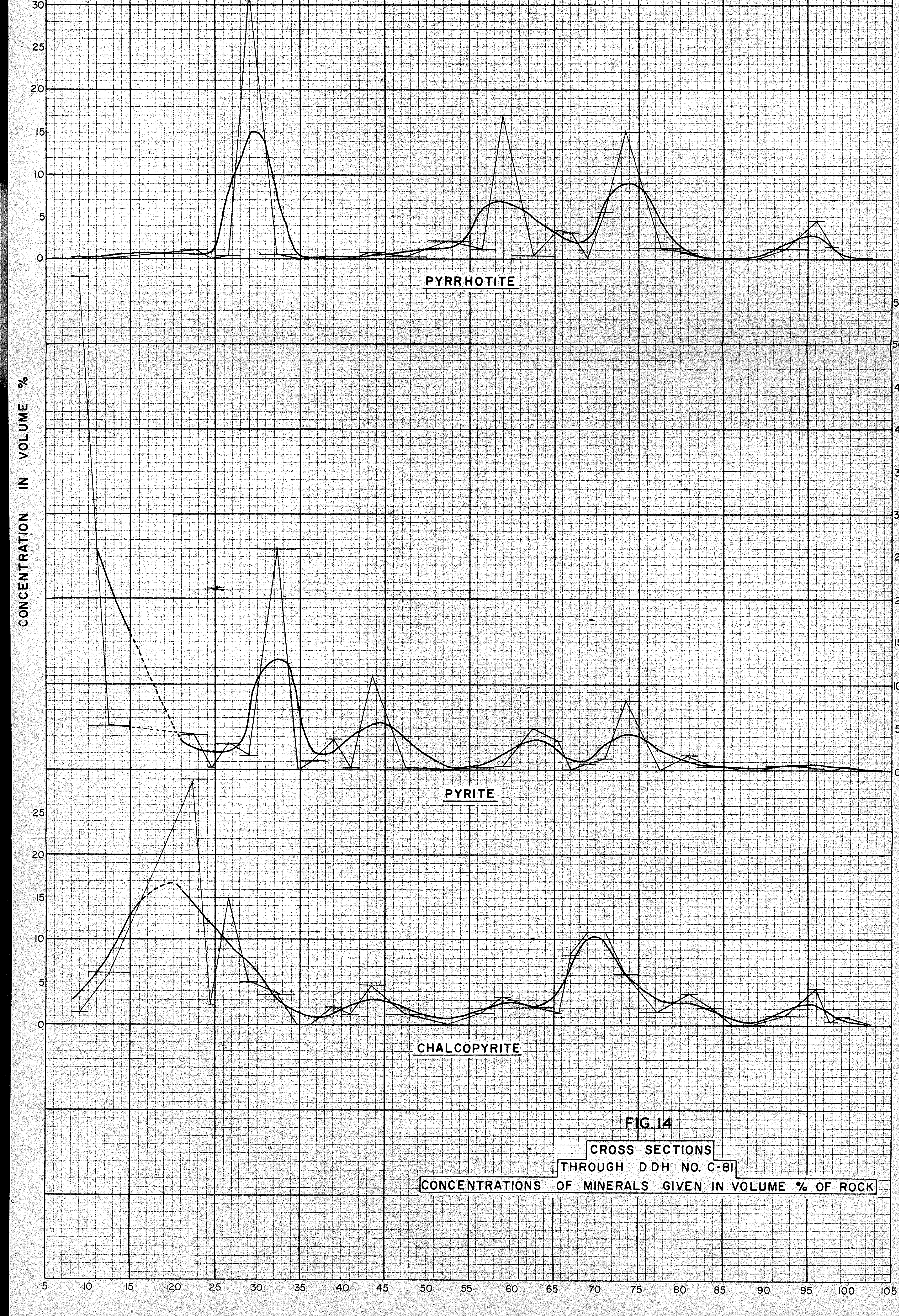


FIG. 14

CROSS SECTIONS
THROUGH DDH NO. C-81
CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK

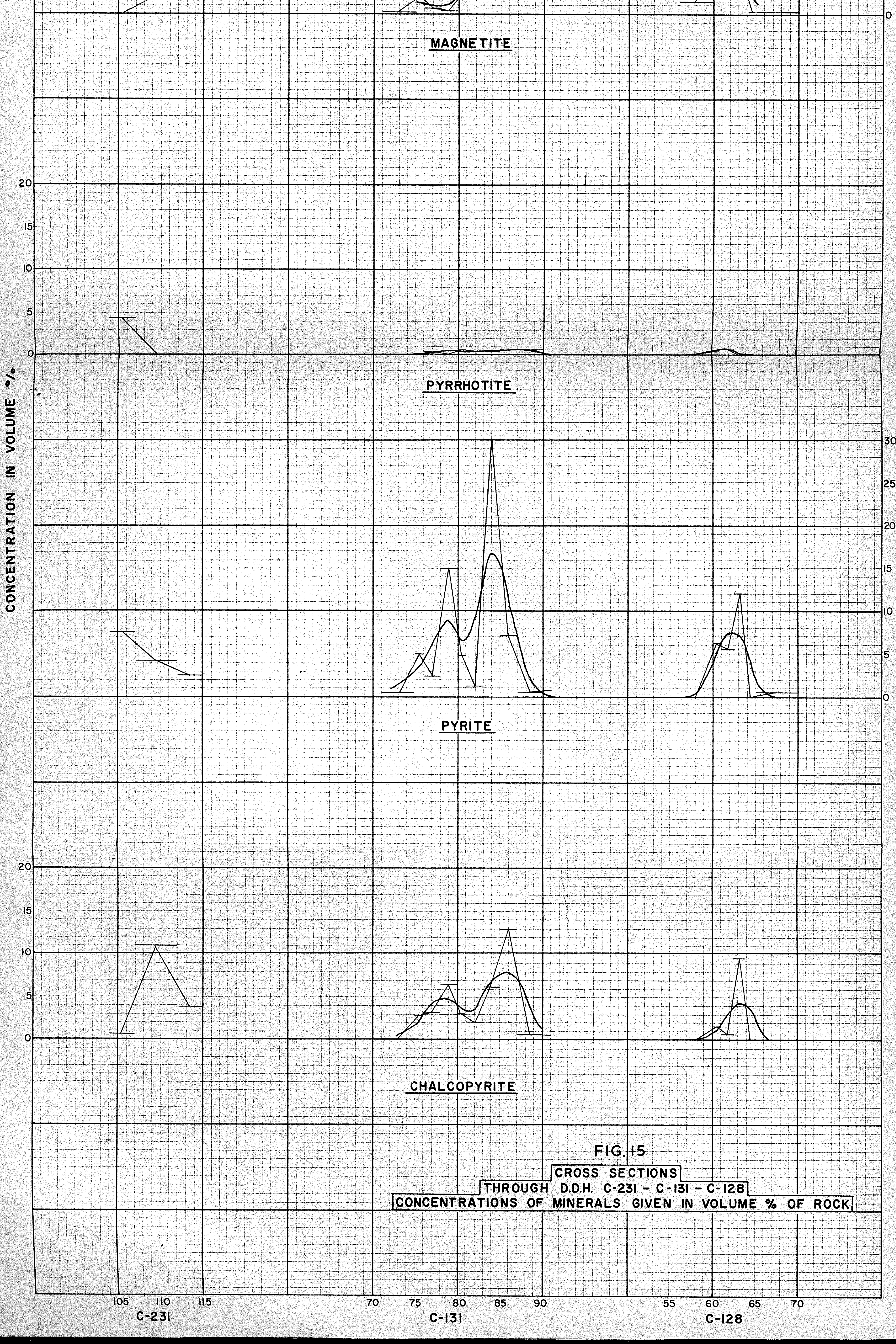
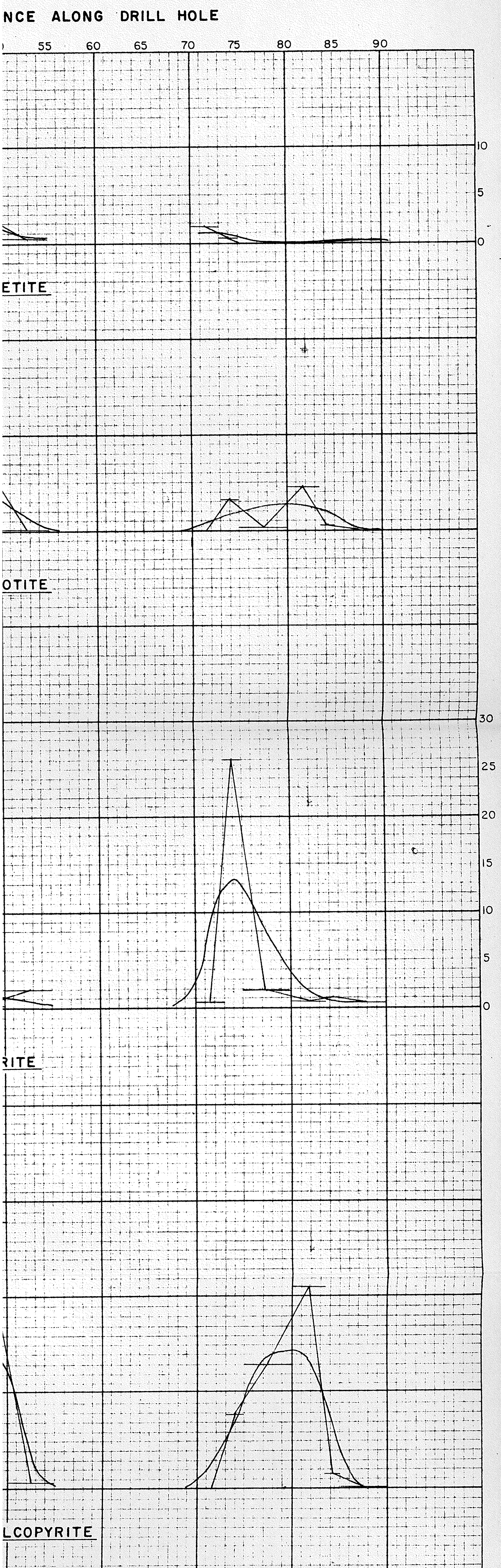


FIG. 15

CROSS SECTIONS
THROUGH D.D.H. C-231 - C-131 - C-128
CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK


NCE ALONG DRILL HOLE
55
60
65
70
75
80
85
90
10
5
0
ETITE
OTITE
30
25
20
15
10
5
0
RITE
LCOPYRITE

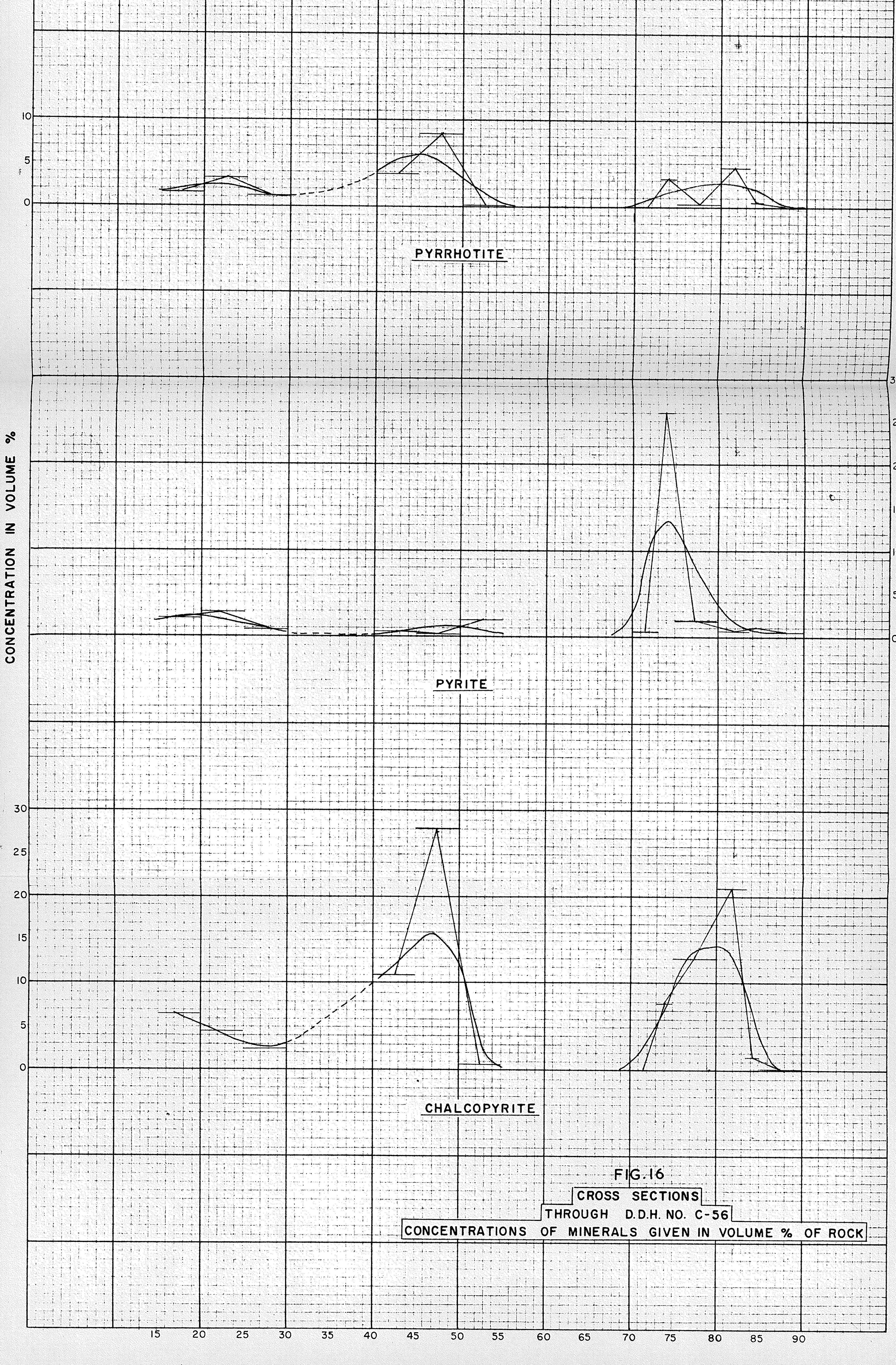
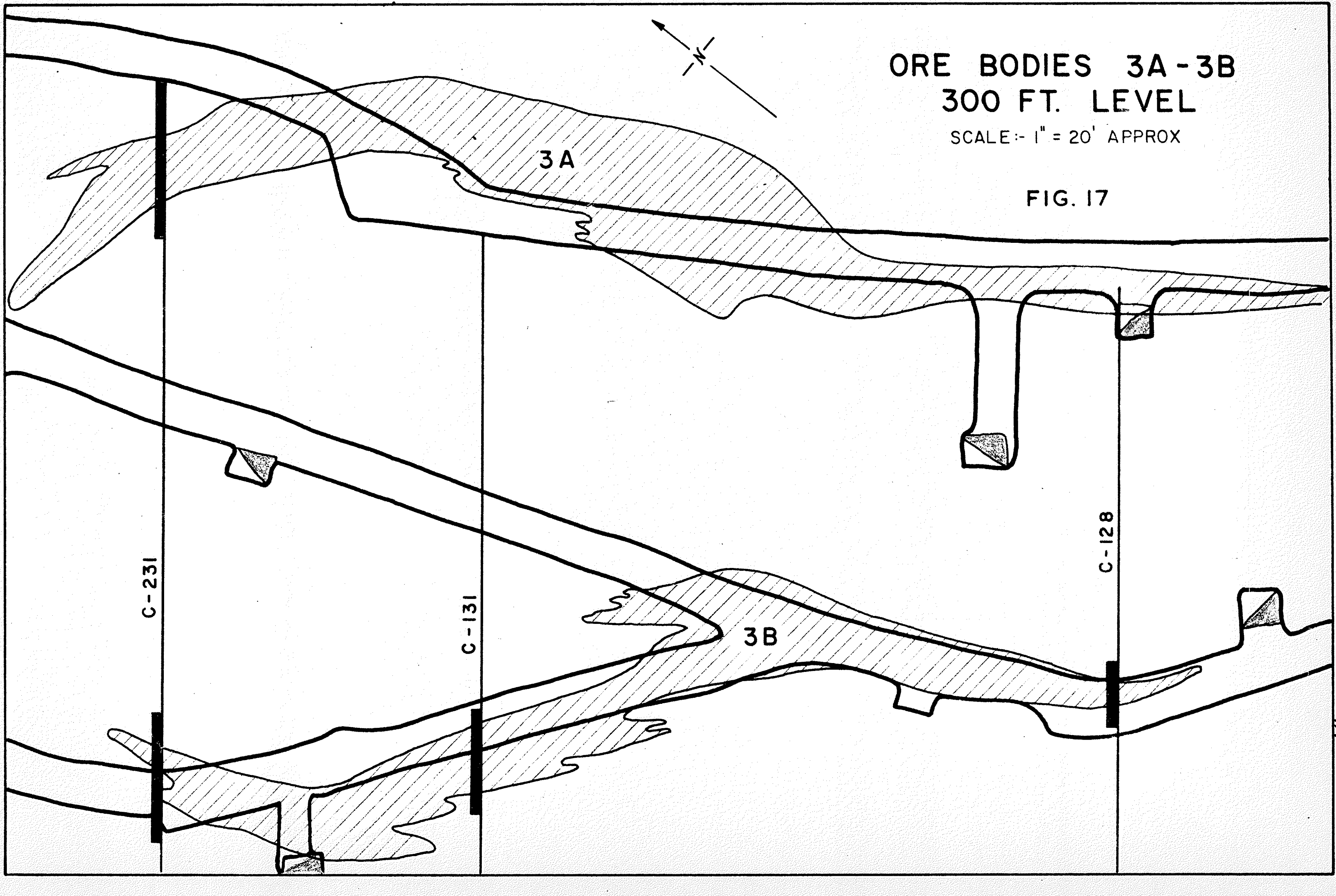
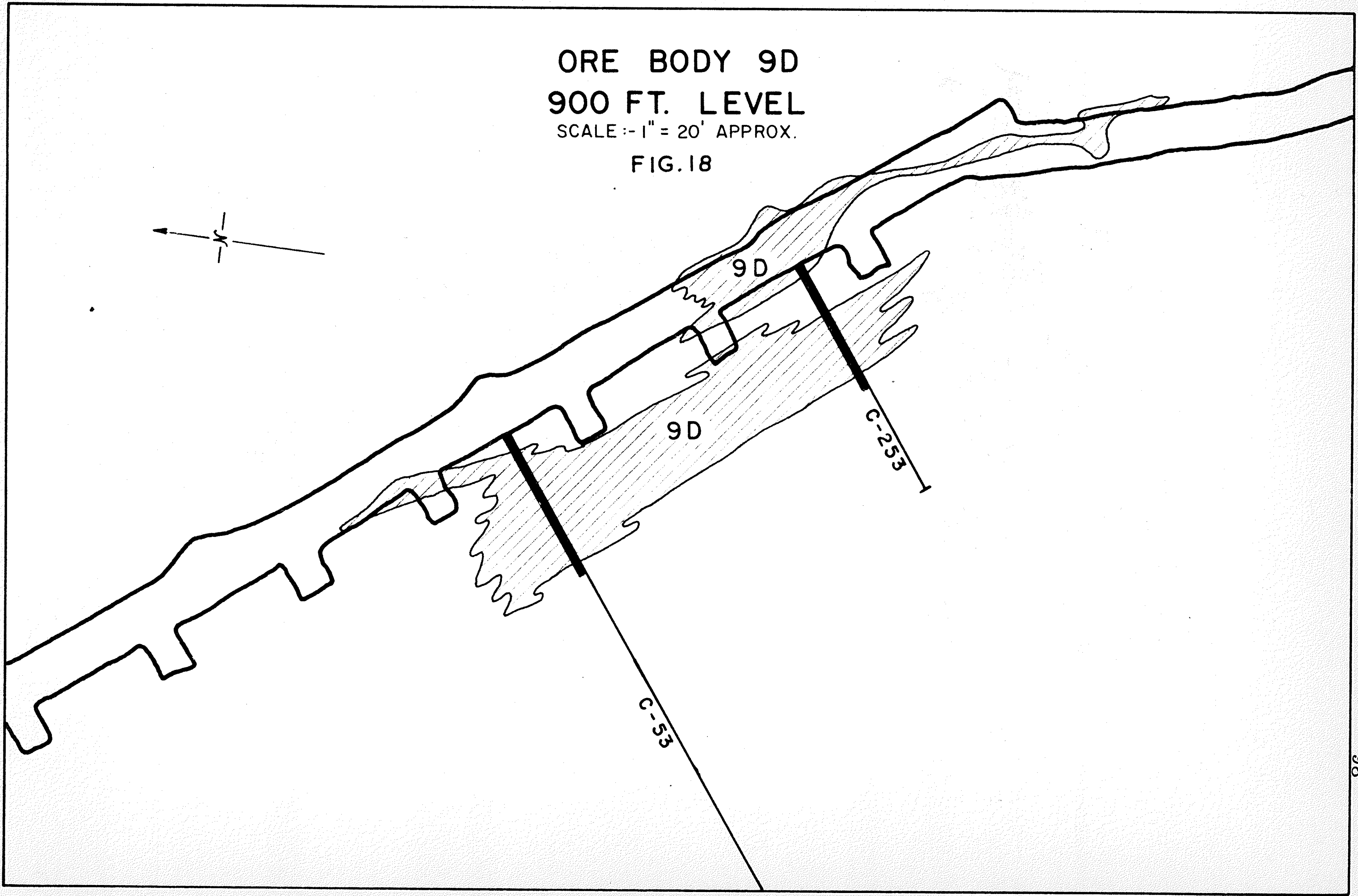


FIG. 16
CROSS SECTIONS
THROUGH D.D.H. NO. C-56
CONCENTRATIONS OF MINERALS GIVEN IN VOLUME % OF ROCK

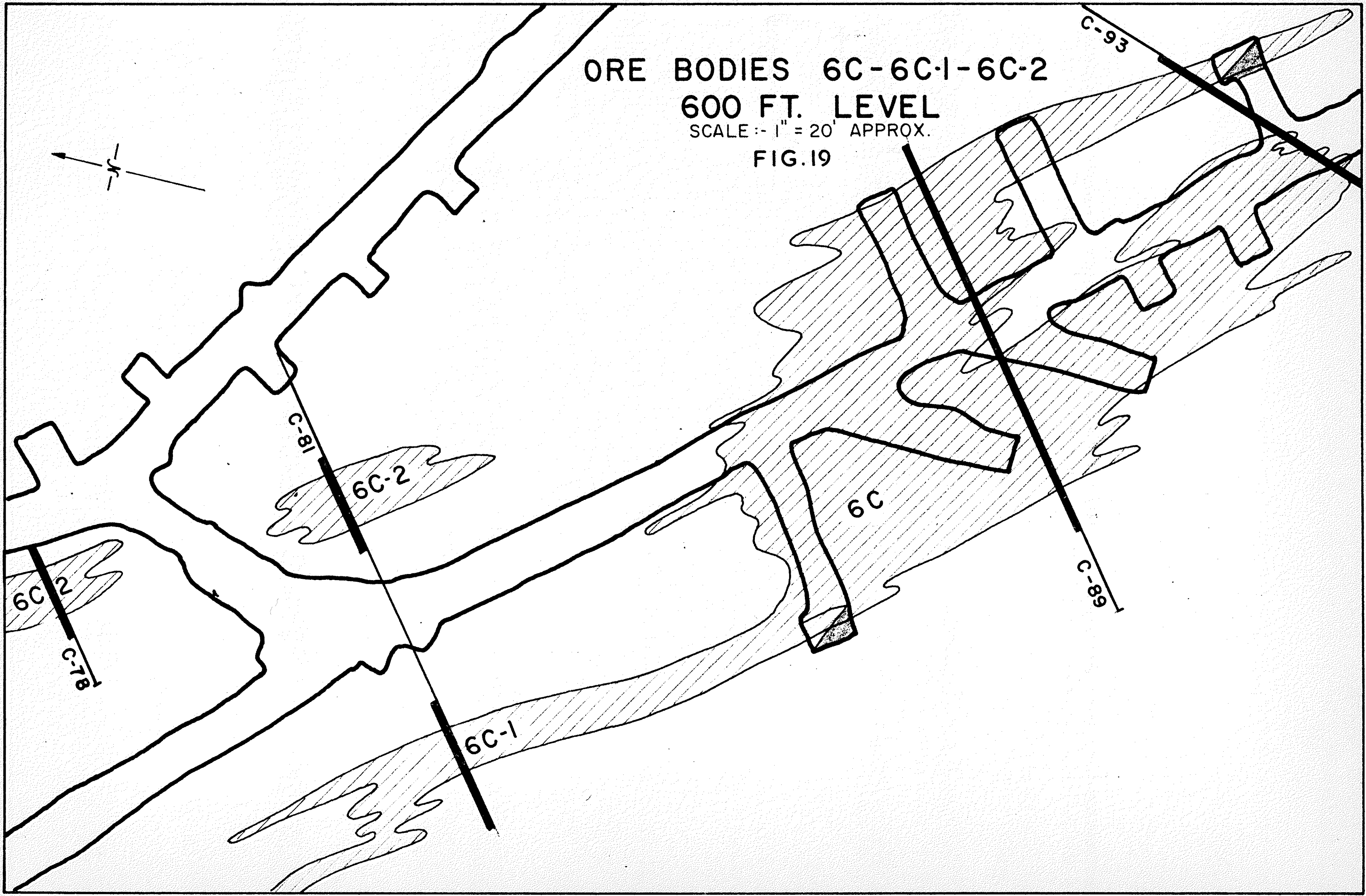


ORE BODIES 3A-3B
300 FT. LEVEL
SCALE:- 1" = 20' APPROX

FIG. 17



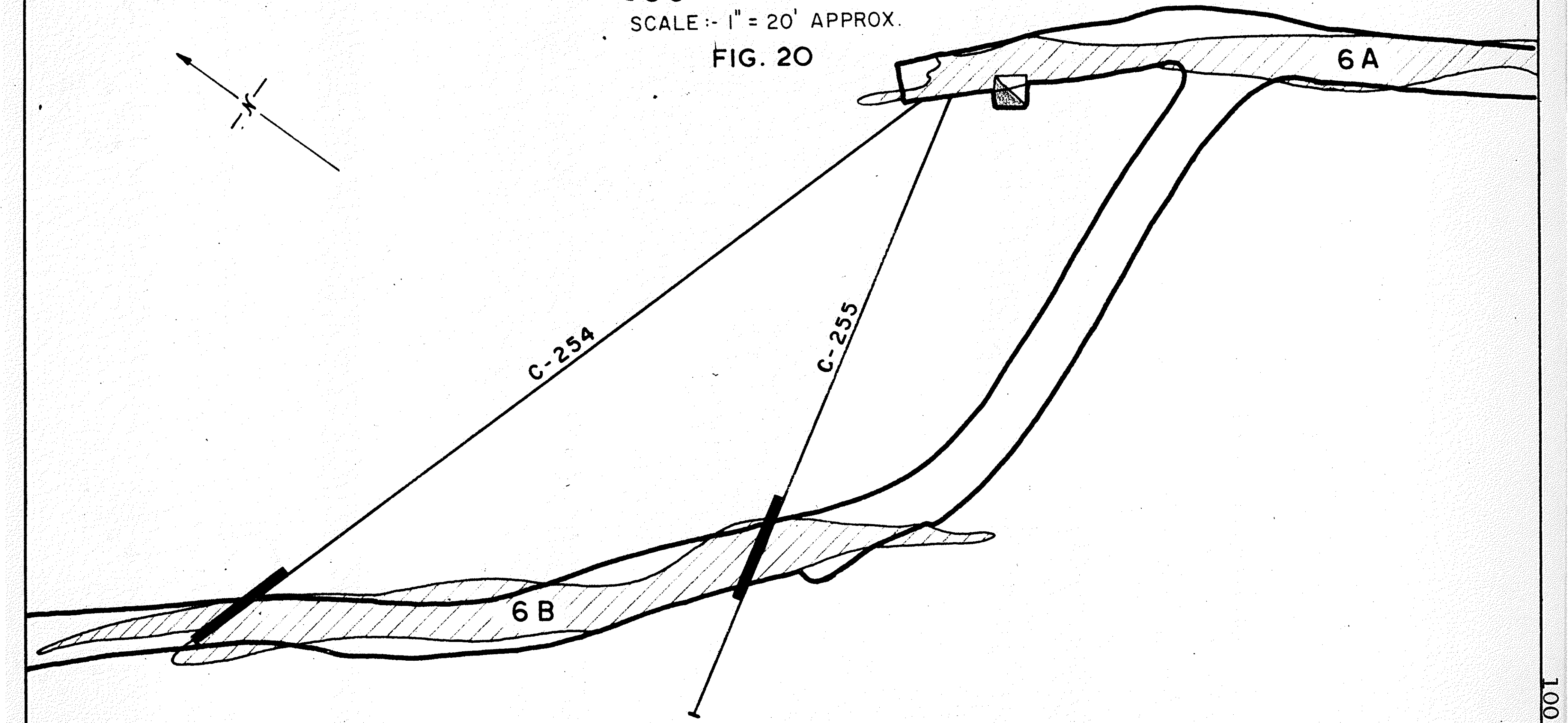
ORE BODY 9D
900 FT. LEVEL
SCALE :- 1" = 20' APPROX.
FIG. 18

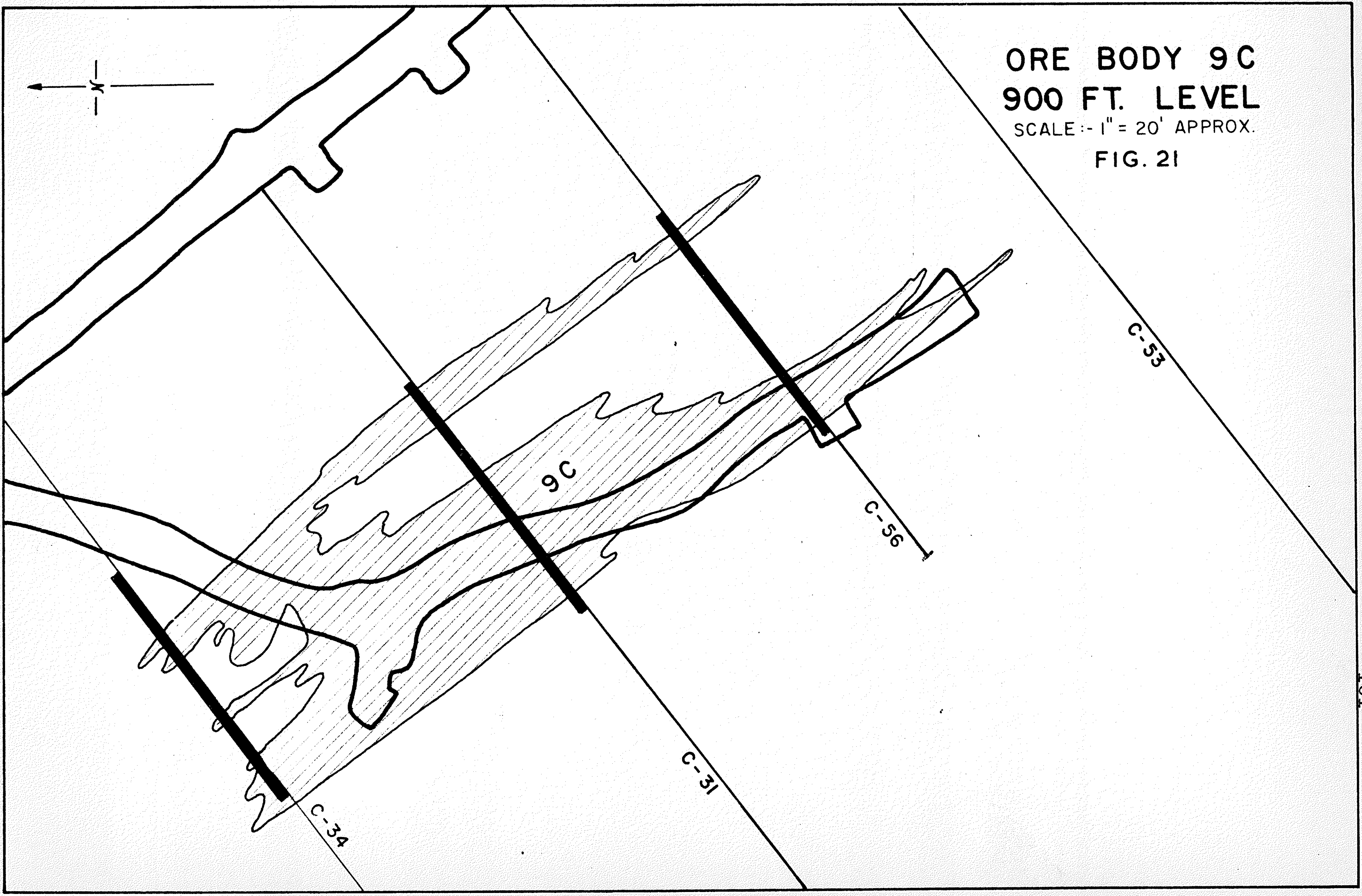


ORE BODIES 6C-6C-1-6C-2
600 FT. LEVEL
SCALE :- 1" = 20' APPROX.
FIG. 19

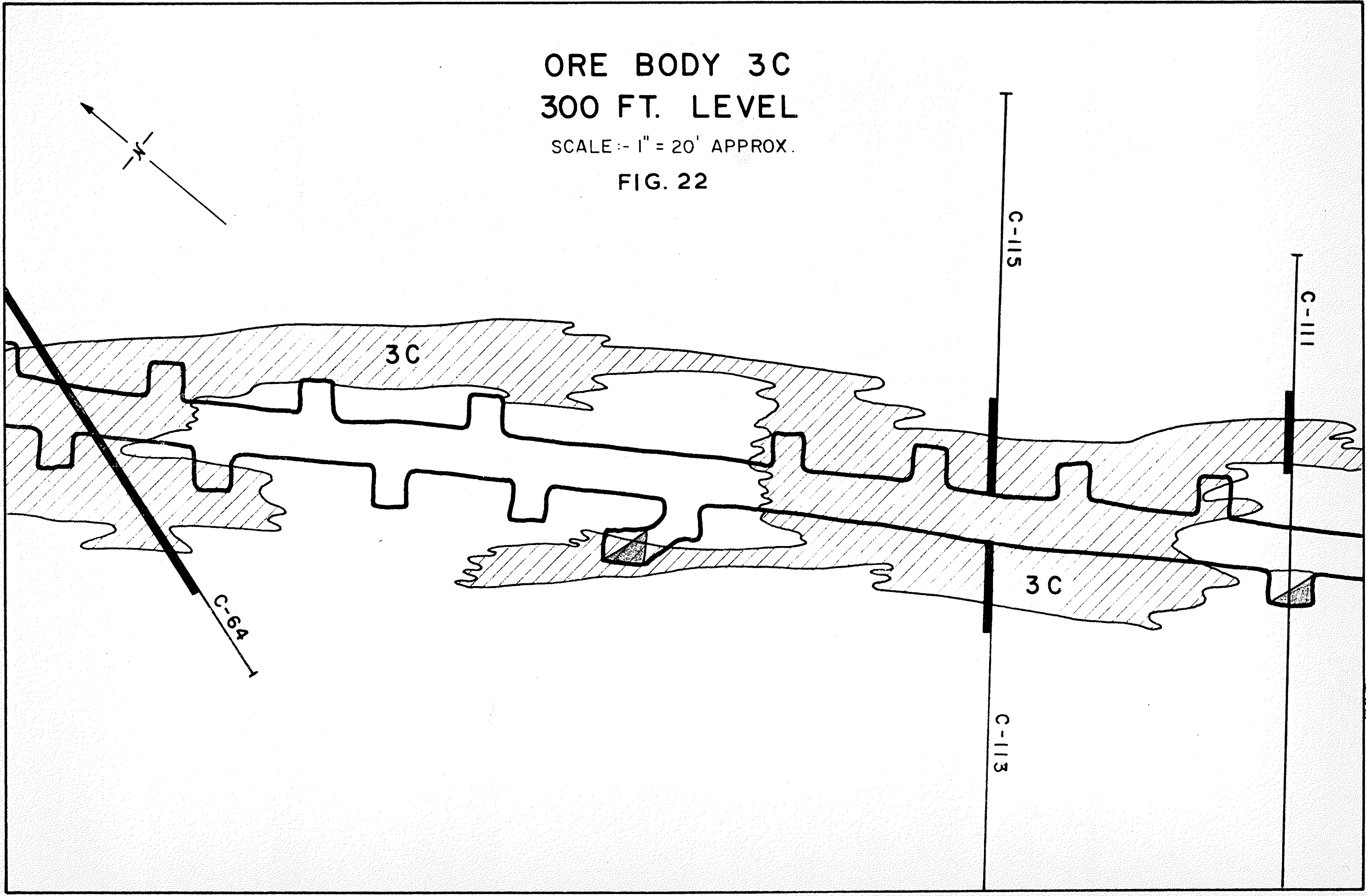
ORE BODIES 6A - 6B
600 FT. LEVEL
SCALE :- 1" = 20' APPROX.

FIG. 20





ORE BODY 9C
900 FT. LEVEL
SCALE :- 1" = 20' APPROX.
FIG. 21



ORE BODY 3C
300 FT. LEVEL
SCALE :- 1" = 20' APPROX.
FIG. 22