

THE DISTRIBUTION OF Ti, V, Cr, Co and Ni IN THE
MAGNETITES OF THE MOUNT HOPE MINE AND THE
NEW JERSEY HIGHLANDS

By

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Editorial Note

This thesis was originally submitted to the Department of Geology and Geophysics bearing the title "The Distribution of the Trace Ferrides in the Magnetities of the Mount Hope Mine and the New Jersey Highlands".

The advisability of using the word "ferrides", following the terminology of Landergrin (1948), who proposed this term to describe some of the elements of the iron transition groups, has been questioned. The suffix "ide" has a long-established usage in the basic sciences differing from the usage proposed by Landergren. Therefore, the title of the thesis was changed, substituting the symbols "Ti, V, Cr, Co and Ni" for the words "trace ferrides". In reference to this thesis, in publication, and in continuation of this field of research, the term "iron transitional group", appropriately modified, will be substituted for the term "trace ferride".

ABSTRACT

THE DISTRIBUTION OF THE TRACE FERRIDES IN THE MAGNETITES OF THE MOUNT HOPE MINE AND THE NEW JERSEY HIGHLANDS

ALLAN HARRIS JAMES

Submitted to the Department of Geology and Geophysics, Massachusetts Institute of Technology, on August 12, 1954, in partial fulfillment of the requirements for the degree of Sc. D.

The iron deposits of the New Jersey Highlands, from which 1% of the nation's iron ore is won, are predominantly high-grade magnetites found in plunging blade-shaped ore shoots enclosed conformably in pre-Cambrian gneisses. At Mt. Hope mine five ore shoots have been mined for six to ten thousand feet of pitch length.

Gangues of apatite, quartz, feldspars and ferromagnesian minerals are distributed erratically throughout the ores. The magnetite is pure except for minor elements, notably Ti, V, Cr, Co and Ni, here called the TRACE FERRIDES. The trace ferrides are related to iron in atomic configuration, and readily substitute in the spinel structure, the type crystal structure of the magnetite group.

The objective of this investigation was to determine the abundance of the trace ferrides in the New Jersey magnetite ores and from their distribution to develop theories regarding ore genesis.

Geochemical cohesion of the trace ferrides is evidenced in the magnetites by their uniform distribution when compared to the gangue-forming elements; however the trace ferrides do not show a marked covariance. V is slightly enriched in these ores while the other trace ferrides are found in concentrations equal to or slightly less than the average of the earth's crust.

The wall rocks of the Mount Hope Mine, an oligoclase-quartz-biotite gneiss and an alaskite, are distinctive as to trace ferride distribution, and an absence of genetic association with ore is suggested.

The similarity of trace ferride distribution in two ore shoots in different rock hosts is statistically demonstrated, thus suggesting consanguinity of the shoots and an epigenetic origin of the ores. A similarity of trace ferride concentrations in the ore bodies and in sub-hedral magnetite crystals lining the walls of calcite filled veinlets suggests by assoc-

iation that the ores are hydrothermal or pneumatolytic. Metal zoning was not found in the Mount Hope Mine.

Geographically separated ore deposits contain extremes of trace ferride concentration, however, histograms show a smooth variation of abundances approximating a normal distribution of the log of concentration.

In the Dover district, conformance of the ratio V/Cr to a rude zonal pattern radiating from a strong deformational center is pointed out, and the concentration of Cr and impoverishment of V during ore-fluid migration away from this epicenter of ore genesis is suggested.

The New Jersey magnetites are compared to other iron ores and are found to be similar to the pre-Cambrian magnetites of the Adirondacks and Northern Sweden.

It is pointed out that further investigations of a statistical nature are possible and are needed before the hypotheses presented can be strongly supported or clearly rejected.

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ALLAN HARRIS JAMES

BIOGRAPHY

Born in Hollywood, California, in 1911, he attended Stanford University, graduating in mining engineering in 1932. One year of graduate work was completed at the Mackay School of Mines, University of Nevada, in 1934.

From 1934 until the closing of the gold mines in World War II, he worked as a miner, engineer, geologist, and supervisor for gold mining interests in California and Latin America. In 1943 he was appointed underground geologist for the New Mexico mines of the U. S. Smelting, Refining and Mining Co. From 1947 to 1949 he was employed as an exploration geologist by the St. Joseph Lead Co. In 1949 he joined the staff of the Mount Hope mine, Dover, New Jersey, owned by the Warren Foundry and Pipe Corp. and has continued in this employment.

In 1945 he entered the Massachusetts Institute of Technology to study economic geology under professors Warren J. Meade, W. H. Newhouse and P. M. Hurley. In 1950, under the direction of professors P. M. Hurley, W. H. Fairbairn, L. H. Ahrens and W. H. Dennen, he commenced this investigation of the magnetite ores of New Jersey.



Mount Hope Mine

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CHAPTER I

GEOCHEMISTRY OF THE FERRIDES

A - GEOCHEMISTRY OF MAGNETITE

THE FERRIDES

"Ferride" is defined by Landergren (1948) as a collective term for the following elements:

Titanium
Vanadium
Chromium
Manganese
Iron
Cobalt
Nickel

THE PERIODIC CLASSIFICATION OF THE ELEMENTS

	1	2	3	4	5	6	7	8	0	
1	1 H								2 He	
2	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F		10 Ne	
3	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl		18 Ar	
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni
	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br		36 Kr	
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd
	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I		54 Xe	
6	55 Cs	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm		
	63 Eu	64 Gd		65 Tb	66 Dy	67 Ho	68 Er	69 Tm		
	70 Yb	71 Lu		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt
	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85		86 Rn	
7	87	88 Ra	89 Ac	90 Th	91 Pa	92 U				

Fig. I-1

The abundance of the ferrides in the crust of the earth has been calculated by Goldschmidt (1937) as follows:

	<u>Crust, ppm</u>	<u>Igneous Rocks, ppm</u>
Ti	6,300	4,400
V	100	150
Cr	200	200
Mn	930	1,000
Fe	51,000	50,000
Co	40	23
Ni	100	80

The same writer and others have frequently pointed out that this group of elements is found distributed in nature in a significant manner in relation to iron, the principal member of the group.

Calculations of Clark (1889) indicate that iron is the second most abundant metallic element of the lithosphere. In igneous rocks aluminum is the most abundant with a concentration of Al_2O_3 given as 15.34%.

Rankama and Sahama (1950) state that "from a geochemical point of view iron is the most important metal. Along with sulphur and oxygen, iron is the foundation of all considerations dealing with the geochemical character of other elements".

In abundance, titanium holds an intermediate position in the earth's crust, between the major elements and the truly scarce metals. In this study Ti is treated as a trace element.

Manganese holds a position in crustal abundance midway between titanium and the remaining ferrides. For spectrographic reasons manganese was not investigated in the present study.

Vanadium, chromium, cobalt and nickel are scarce both in

the earth's crust and in the materials analyzed in this investigation.

TRACE FERRIDES

Throughout this study Ti, V, Cr, Co and Ni will be called the trace ferrides to distinguish them from iron and, as a matter of convenience, from manganese, which, as noted above, is not considered.

GEOCHEMICAL PROPERTIES OF THE TRACE FERRIDES

The properties of the ferrides significant in geochemical investigations--ionic radii, common valence states, ionization potential, and field function (see Ahrens, 1954) are presented in the table I-1 assembled from Ahrens (1954) and Evans (1937).

In the present investigation an understanding of the behavior of the trace ferrides during the formation of primary rocks and in the presence of certain minerals is important. These are the ore minerals magnetite, titaniferous magnetite, and ilmenite; the gangue and host rock minerals apatite, sphene, quartz, amphibole, biotite and the feldspars.

The uniform field of study and base of reference in this investigation is the high grade magnetite of the many vein-like ore bodies in the New Jersey highlands. Ores high in ilmenite and hematite (and spinel minerals other than magnetite) are rarely observed in the ore masses except possibly on the borders of the district, and therefore are considered in this investigation only because of theoretical and geochemical associations.

TABLE I - 1

RADII OF FERRIDES AND RELATED IONS

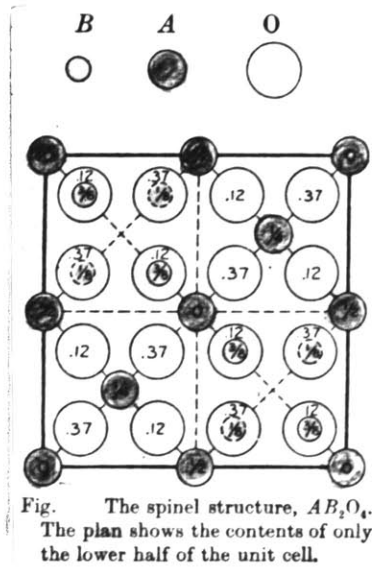
	<u>Fe</u>		<u>Ti</u>			<u>V</u>				<u>Cr</u>		<u>Co</u>		<u>Ni</u>	<u>Ca</u>	<u>Mg</u>	<u>P</u>	
Valence	2	3	2	3	4	2	3	4	5	3	6	2	3	2	2	2	3	5
Ionic Radius(Å)	.74	.63	.75	.76	.68	.88	.74	.63	.59	.63	.52	.72	.63	.69	.99	.66	.44	.35
Ionization Potential Volts	16	30	13	27	43	14	26	48	64	32		17	34	18	12		30	65
Percentage Difference taken with respect to small radius																		
Fe 2+						19						3		7	34	12		
Fe 3+				19			16			2			2					45
Substitution at differing valence																		
Fe 2+		16		3	8		0	17	25				17					
Fe 3+					6			2	8		23	12					3	

MAGNETITE - THE SPINEL STRUCTURE

The spinel structure, the framework of the magnetite family, will be used to illustrate the mode of substitution of trace ferrides in magnetite.

A diagram generalizing the several variations of the spinel structure is as follows (Evans 1946):

Fig. I-2



This corresponds to the composition AB_2O_4 , the formula of the simple spinels. There are 32 oxygen ions in the unit cell. Each A ion is tetrahedrally coordinated with four and each B ion octahedrally coordinated with six oxygen ions. Usually A is divalent and B a trivalent metal, but other cation combinations which yield a neutral electrical balance are admissible. (Evans)

According to Wells (1950 p. 381) magnetite is an inverse spinel with formula $Fe^{3+}(Fe^{2+}Fe^{3+})O_4$. This form $BABO_4$ was originally suggested by Barth and Posnjak (1931). In the

inverse spinel, half the A ions, (Fe^{3+} in magnetite), occupy positions of tetrahedral coordinations, and half, together with all the $\overset{\text{B}}{\text{X}}$ ions (Fe^{2+}) occupy the octahedral positions.

Based principally on a comparison of ionic radii, the following seem to be the most probable sites of substitution of the trace ferrides in the magnetite structure.

Inverse Spinel	A	B	A	O_4
Magnetite	Fe^{3+}	Fe^{2+}	Fe^{3+}	O_4
Proxy				
Cr	Cr^{3+}		Cr^{3+}	
Diff. radii	2%		2%	
Co	Co^{3+}	Co^{2+}	Co^{3+}	
Diff. radii	2%	3%	2%	
Ni		Ni^{2+}		
Diff. radii		7%		
Ti	Ti^{4+}		Ti^{4+}	
Diff. radii	6%		6%	
V	V^{4+}		V^{4+}	
Diff. radii	2%		2%	

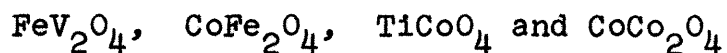
In the case of Ti^{4+} substituting for Fe^{3+} , electrical balance would be satisfied by a higher than normal ratio of Fe^{2+} to Fe^{3+} in the remaining structure. Similarly V^{4+} substituting for Fe^{3+} would be balanced elsewhere in the structure. According to Rankama and Sahama (1949 p. 596) trivalent V is not common in igneous rocks because of its strong reducing character in the presence of ferric iron.

Dana, et al (1944) group the spinel mineral into three series, the end members of which are as follows:

	<u>Spinel Series</u>	<u>Magnetite Series</u>	<u>Chromite Series</u>
X	X Al ₂ O ₄	XFe ₂ O ₄	XCr ₂ O ₄
Mg	Spinel	Magnesioferrite	Magnesiochromite
Fe	Hercynite	Magnetite	Chromite
Zn	Gahnite	Franklinite	Artificial
Mn	Galarite	Jacobsite	"
Ni	Artificial	Trevorite	"

where X represents Mg, Fe, Zn, Mn and Ni.

In addition to the ferride-containing spinels tabulated above, Evans lists the following artificial spinels in which ferrides are the A and B end member constituents:



According to Dana the pure end compounds shown above are rarely found in nature. "In nature there is more or less complete miscibility within each series, whereas there is comparatively little miscibility between the series."

MAGNETITE, TITANIFEROUS

MAGNETITE, TITANIUM SPINEL and ILMENITE

A great deal has been written about the substitution limits of titanium in magnetite. In 1918 Warren wrote "it seems probable that there exists a limited solid solution of the ilmenite and magnetite molecules with a eutectic".

Osborn, (1928) stated "evidence seems to indicate that at the temperature of formation of the ore minerals, there is a considerable solubility of ilmenite in magnetite and the same is true of spinel. On cooling the ilmenite separates from the magnetite parallel to the face of the octahedron and the spinel parallel to the cube".

Anderson (1930) believed that the exsolution patterns could be interpreted to indicate temperature of formation, and Greig (1932) detailed and limited this theory. Newhouse (1936) described the exsolution of ilmenite from magnetite and hematite in the opaque minerals of most igneous rocks. Dana (1944) summarized prevalent current opinion "oriented inclusions of ilmenite in magnetite are generally attributed to exsolution of the former from a higher temperature homogeneous magnetite containing considerable Ti". However, Dana continues to summarize the opinion of others "the presence of ilmenite inclusions is not definite proof of exsolution or of a high Ti iron spinel".

Ramdohr (1953) has recently summarized his work of describing ulvospinel, (identified by x-ray by Morgan) Fe_2TiO_4 .

According to this investigator both pleonaste ($(\text{MgFe})\text{Al}_2\text{O}_4$) and ulvospinel (Fe_2TiO_4) are commonly exsolved from the magnetite of high titaniferous iron ore deposits. It appears that pleonaste belongs in Dana's aluminum spinel series and therefore should not be readily miscible in magnetite, while ulvospinel would appear to belong to the inverse spinel equipoint structure group, having as a more appropriate formula, FeTiFeO_4 , like magnetite, but only slightly soluble in magnetite at ordinary temperatures. According to Dana, the presence of ilmenite as an exsolution product indicates that Ti is not held to any considerable extent in solid solution at normal temperatures.

This series of papers emphasizes the lack of stability of moderate amounts of Ti at low temperature within the magnetite structure, and the existence not only of ilmenite as a discrete titanium-iron mineral, but the existence of the titanium iron spinel, ulvospinel, as a stable product of the exsolution of Ti from the magnetite structure. It is indicated, however, that at the high temperatures of formation of magnetite small amounts of Ti, such as are found in the magnetites under investigation, may be readily accepted in the magnetite structure in preference to forming discrete titanium or titanium-iron minerals or giving strong preference to substituting in other minerals such as the iron-magnesian silicates.

As noted above, V^{4+} probably substitutes in the magnetite structure similarly to Ti^{4+} . Ramdohr (1953) notes the

probability that vanadium is present in the structure of ulvospinel.

Rankama states that V^{5+} replaces P^{5+} in apatitic iron ores, but such a substitution was found not to occur in the material of this study. Vanadium is also said to substitute for Ti^{4+} in sphene (Rankama 1948).

Discrete vanadium minerals are not found in igneous rocks (exception, ardennite, Rankama, 1948).

The following analyses have been selected from Dana as typical of magnetites with and without notable substitutions of other ferrides:

Magnetite, Mineville, N.Y. (A typical pure magnetite)

FeO	30.78%
Al ₂ O ₃	.21
Fe ₂ O ₃	68.27
SiO ₂	.27

Magnetite--titanian, Norway

MgO	5.15
FeO	26.69
Al ₂ O ₃	5.64
Fe ₂ O ₃	54.64
TiO ₂	7.57
SiO ₂	.14

Nickeliferous magnetite, Tirol

FeO	26.93
MnO	3.80
Fe ₂ O ₃	69.32
NiO	1.76

Chromian magnetite, Cr substituted for Fe^{3+} in generally small amounts (no analysis given)

Vanadian magnetite (coulsonite). Amounts of V_2O_5
as high as 4.84% reported (from India) (no analysis
given.

B. FERRIDE CONCENTRATIONS AS CRITERIA FOR THE
DETERMINATION OF ORIGIN OF ROCKS AND ORES

GOLDSCHMIDT'S RULES

The rules of Goldschmidt indicate that the relative abundance of certain elements should be characteristic for each of the stages of geochemical evolution, and to a lesser extent for each of the steps within these stages. Information regarding ferride abundance in rock suites and iron deposits of known or postulated stage in the geochemical cycle of evolution would be of value in studying the origin of the New Jersey magnetites and the distribution of the trace ferrides therein.

In the case of magmatic rock series, firm information concerning trace ferride abundances in many such suites has been published. Goldschmidt (1937) offers the analysis of a typical suite of igneous rocks showing a progressive decrease in the ferride content from early to late magmatic rocks.

	P.P.M.		
	<u>Cr₂O₃</u>	<u>NiO₂</u>	<u>CoO</u>
Early			
Pentlandite	5,000.	4,000.	300.
Gabbro	500.	200.	100.
Diorite	100.	50.	40.
Granite	3.	3.	10.
Nepheline Syenite	1.	3.	10.

Late

Wager (1945) has presented his analyses of a differentiation series from Eastern Upland and compared it with a similar

suite from the Skaergard published earlier by Lundergardh (1949). The abundance of the ferrides in the end members of both series are re-tabulated here. For simplicity in presentation three intermediate rock types with analyses conforming to the general trend of ferride content shown, have been omitted from each suite.

	<u>Skaergard</u>		<u>Upland</u>	
	<u>Early Magmatic Gabbro- Peridotite</u>	<u>Late Magmatic Acid Grano-Phyre</u>	<u>Early Magmatic Pyroxene Hornblende</u>	<u>Late Magmatic Upland Granite</u>
V	100. ppm	10.	330.	40.
Cr	1,150.	3.	150.	4.
Co	80.	3.	40.	11.
Ni	600.	5.	120.	11.

It is clear in the suites of igneous rocks tabulated above that V, Cr, Co and Ni are concentrated in the early magmatic rocks and impoverished in the late rocks.

Landergren has published many determinations of abundance of the ferrides in iron ores, and has classified these ores as to origin. In the case of many of the sedimentary ores, and some of the replacement ores, his classification can hardly be doubted. In identifying magmatic ores and some of the sedimentary ores, the origin of the deposits in question is a problem, and one related to the fundamental questions raised in this investigation.

Such questionable suites should not be used directly in the development of criteria of genetic history. The range of material analyzed by Landergren is indicated in Chapter V,

Figures V-1 to V-5.

TITANIUM

High titanium content is characteristic of many magmatic oxide ores (Rankama 1948 667). The higher amounts shown here are in the neighborhood of 10% Ti, but oxide deposits much higher in titanium are of course well known. The lower limit of Ti concentration in magmatic oxide ores could not be placed because of the question as to origin in ores of low Ti content. The lowest abundance tabulated, 0.01% Ti, a sample of hematite from Bilbao, indicates the Ti content in what is considered to be a pyrometasomatic deposit.

In the exogene ores tabulated, the Ti range is from 7% in a laterite to 0.2% in a sample of a French Minette ore, and 0.06% in presumably reconstituted ore from Vermillion Range.

It is seen that the Ti content of exogene and endogene iron ores covers roughly the same range and is therefore only in extreme cases a diagnostic as to origin and history. However, Ti abundance in relation to iron is usually an important and often distinctive characteristic of the ore from any given deposit. The significance of this ratio in the area under examination will be further developed at an appropriate time.

VANADIUM

Vanadium resembles its neighbors, phosphorus and titanium, in its manner of occurrence. The highest content in igneous rocks is found in those formed during the initial steps of the main stage of crystallization (Rankama, 48) 595). Vanadium is

strongly enriched in the titaniferous iron ores (see Figure IV-2). Sanford Lake, New York is a good example. The apatite-bearing ores are likewise seen to be relatively rich in vanadium. (New Jersey, Kiruna Sweden).

Again, low concentrations of V are found in known pyrometasomatic deposits.

Vanadium is often found highly concentrated in sediments, especially those of biological origin (Rankama et al, 1950). However, it is found in relatively low concentrations in many iron ores of clearly sedimentary origin, and in sedimentary ores concentrated by secondary enrichment (Lake Superior ores).

In general, vanadium in the iron ores of the world is covariant with titanium, but like titanium its concentration is significant but not diagnostic.

CHROMIUM, COBALT AND NICKEL

Chromium, cobalt and nickel are noticeably concentrated in the high titanium ores, above the average for the earth's crust and above the average for iron ores, but like the other trace ferrides, their behavior is not consistent in the purer magnetites. The generally low level of concentration of these elements introduces questions as to the absolute accuracy of any series of analyses under consideration. This question is critical for these elements when comparing one area with another. Comparisons made within suites of similar ores appear to be valid.

CHAPTER II

THE MAGNETITE ORE DEPOSITS OF THE NEW JERSEY HIGHLANDS

A - GEOLOGY OF THE DOVER AREA

AND THE NEW JERSEY HIGHLANDS

The New Jersey magnetite deposits are found in a pre-Cambrian gneissic complex which forms a geological and physiographic province known as the New Jersey Highlands.

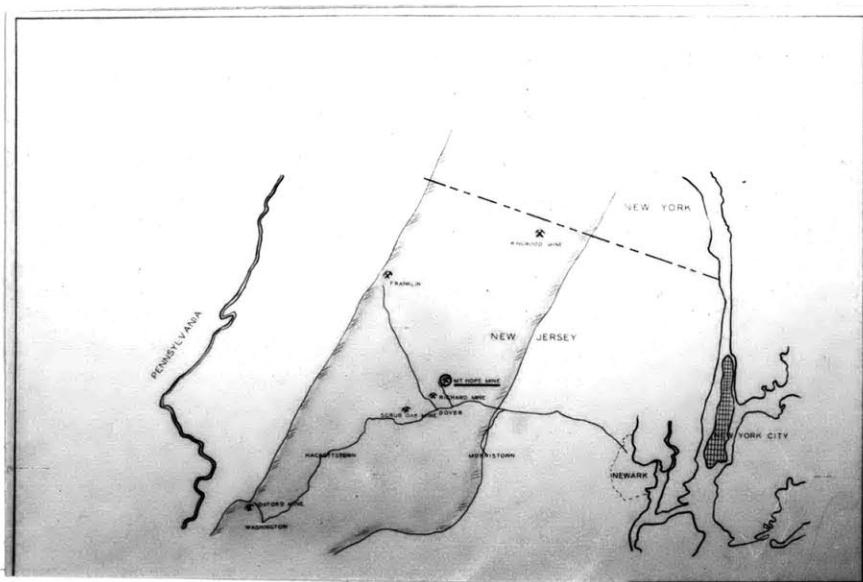


Fig. II-1, Index Map - New Jersey Highlands (Shaded)

This province displays many similarities to the Grenville and associated formations of Northern New York, Ontario, and Quebec, and the rocks may be of the same age.

The geology of the Highlands has been described by Bayley, (U.S.G.S. 1914) who believed the gneisses to be of igneous origin, and the Mt. Hope-Dover area by Sims (U.S.G.S. 1953), who believed the rocks to be interlayered metasediments and in-

trusives. Rocks classified as metasediments by Sims are plagioclase-quartz-gneisses, pyroxene gneisses, and amphibolites, with frequent layers rich in biotite and occasional areas of migmatic rocks of questionable but surely complex history.

Sims describes granitic gneisses--quartz diorite, albite-oligoclase granite, hornblende granite, and alaskite as intrusive into the metasedimentary rocks, but as in other similar areas of ancient crystalline rocks few generally accepted criteria for determining genesis are apparent, and those found are conflicting. All the rocks are gneissic--layered and foliated.

Crystalline limestone (the Franklin limestone) is found in large masses along the eastern portion of the Highlands, and in very minor amounts at one place in the Dover area. About 15% of the area of the Highlands has been mapped in detail by Sims and Hotz. Other maps in similar detail are not available, but Bayley's maps (Bayley et al, 1914) (Kummel, et al, 1933), present generalized descriptions of the remaining area. (Fig. IV-1).

All the rocks are foliated to some degree. In the metasediments layering and foliation are both thought to be largely relics of stratification augmented by interbed shearing and reaction banding. The intrusive rocks are also foliated and banded.

Throughout the Highlands the predominant attitude of the layering and foliation is monoclinal, striking northeast and

dipping steeply to the east. The gneisses of the central and southern portion of the Dover area conform to this attitude, although, north of an east-west line through Splitrock Pond the regional structure swings to a northerly strike. The intersection of these two monoclinial trends is in an area of strong folding, represented by the nose of the Telemark anticline, the Splitrock Pond syncline, and the Cobb anticline. A mass of quartz diorite, a rock type common to the northerly striking area, has moved plastically into the trough of the Splitrock syncline in phacolithic form. This tight fold or phacolith of quartz diorite, which for convenience will be called here the "Splitrock Pond Node" is thought by the writer to be a focal point in the orogenic disturbance which localized iron ore in the Dover area. The Splitrock node will be used as a center of reference in a part of the chapter describing zonal theories.

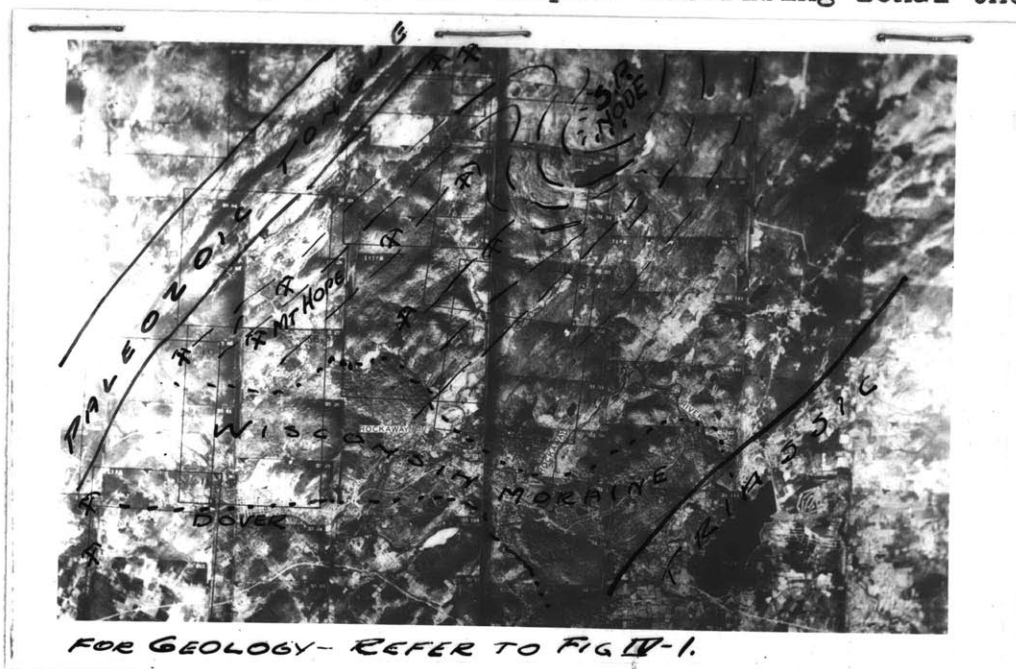


Figure II-2 Aerial Mosaic, Dover Area, Showing Splitrock Pond node.

All folds in the Splitrock Pond area plunge to the northeast at an angle of about 25° to the horizontal.

A lineation prominent throughout the district plunges NE at about 15° . This lineation is expressed as oriented elongated minerals such as quartz and hornblende, linear aggregations of biotite and other ferromagnesian minerals, appearance of drag on many joint and fracture surfaces, and by the intersection of fracture surfaces and foliation. This lineation is approximately parallel to the axes of folding.

The numerous faults in the area may be grouped into two general classes--coaxial and cross cutting. The coaxial faults are the most common and prominent. The plane of the fracture may have any strike and may have any dip in the range between 90° and the angle of plunge of lineation, but all planes of coaxial fracture contain as an element the linear axes. These fractures may be thought of as a family of planes rotating about the plunging axis of lineation. Dip faulting, or faulting in the plane of foliation, is a special case of coaxial faulting. In the general case, the fracture will lie in another plane and the intersection of the fracture with the lithologic layering will parallel and become a part of the ubiquitous linear element. Sims failed to recognize the general relationship of the coaxial faults, and described these as two groups of faults, longitudinal and oblique, with no apparent relationship one to another.

Excellent exposure and detailed mapping in the mines has

clearly shown this family of faults to be a continuously related and complete group. Sims believed these faults to be post-ore (personal communication) as they offset the ore bodies in the mines as much as 40 to 80 feet. The coaxial fractures are important relative to the ore shoots and at least partially control the form of the ore in the plunging blades. For this reason, and because unfractured ore veins are found in the faults cross-cutting the regional layers, the faults must be at least in part of pre-ore age, or at least previous to the last reconstitution of the magnetite bodies.

Two planes of certain joint systems follow the coaxial pattern, whereas other joint systems are independent of the coaxial rule and cross-cut the plunging element.

The cross-cutting faults do not contain the plunging element but cut across it at any angle. This set of fractures includes some of the joints, and on a larger scale certain faults described as later than the ore and possibly post-Cambrian together with structures receiving diabase dikes of Triassic (?) age. Some cross-cutting faults have been observed to contain veined magnetite mineralization, indicating either greater age than commonly supposed or a later generation of magnetite mineralization. Unfortunately, none of these were sampled in the present investigation as no examples have been found at Mount Hope.

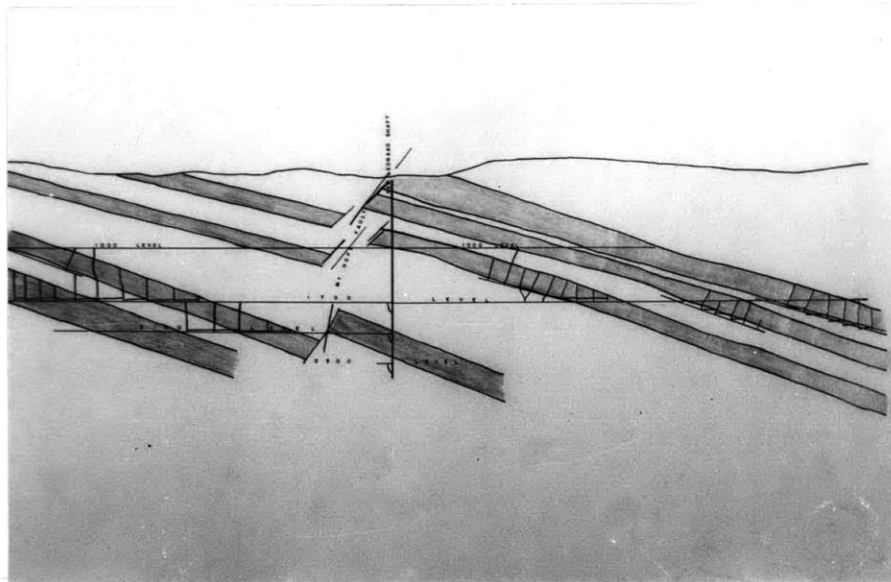


Fig. II-3 Long Section, Mount Hope Mine. 1" = 2,500'

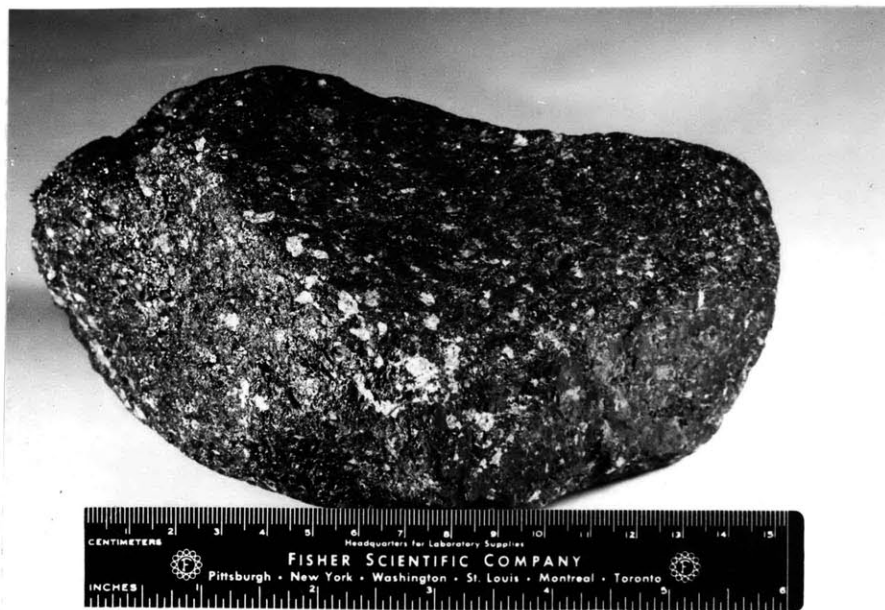
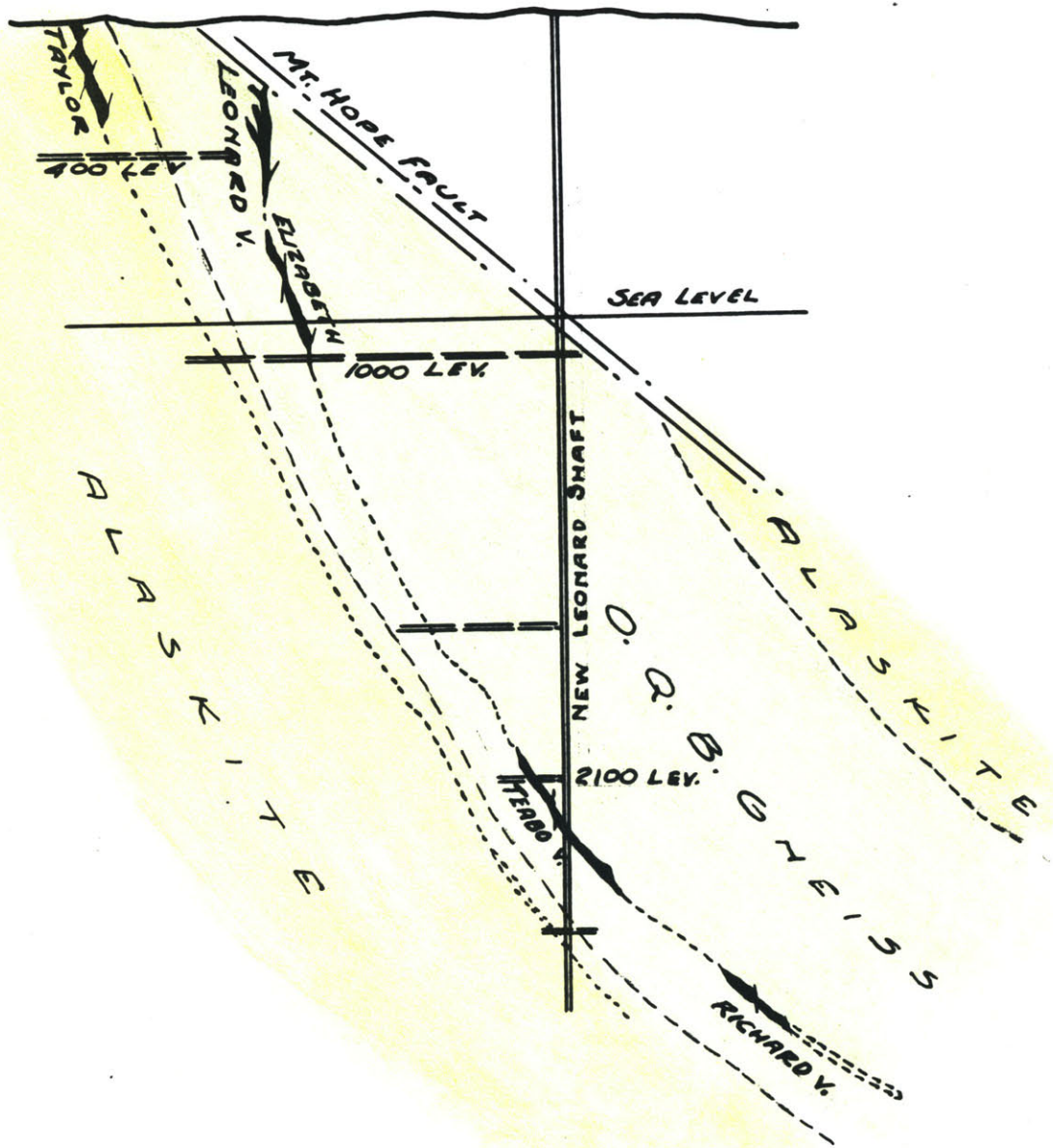


Fig. II-4 High-grade Magnetite. Spots are apatite.



O. Q. B. Gneiss

Alaskite

MOUNT HOPE MINE

CROSS SECTION THROUGH NEW SHAFT

~~ENGINEERING CORP.~~ MOUNT HOPE MINE

DATE July, 1954.

SCALE 1" = 500'

BY

PLATE II
A FIG. II-5.

THE HOST ROCKS

The ore bodies of the Mount Hope-Dover area are found in three classes of host gneisses, the oligoclase-quartz-biotite gneiss, alaskite, and albite-oligoclase granite. The oligoclase-quartz-biotite gneiss and alaskite, enclosing ore bodies mined at Mount Hope mine, Richard mine and Scrub Oak mine are described and studied in some detail in the section describing trace ferrides in wall rocks. The albite-oligoclase-granite, host to the ores at Hibernia, Fairview, and Anomaly is described by Sims (1953). At Ringwood mine, near the New York State line, Holtz (1952) describes the enclosing rock as "dark pyroxene amphibolite, amphibolite, and quartz oligoclase gneisses". Details of the host rocks of the remaining mines have not been published. The generalized rock unit terms of Bayley, the Byram and the Losee gneiss, are therefore used. In general the Byram gneiss is characterized by microcline and microperthite often with considerable quartz. A small per cent of ferromagnesian minerals are present. The Losee gneiss, a rock group high in soda and low in magnesia and potassium, is characterized by orthoclase or oligoclase. Usually it is oligoclase and quartz. Ferromagnesian minerals are present. Sims felt that the terms Losee and Byram used by Bayley were too general to be of value in describing the rocks of the New Jersey Highlands.

ORE GENESIS - HISTORY

The origin of the magnetite ore deposits of the New Jersey Highlands has been variously described.

Rogers in 1840 was the first to study the geology of the ore deposits. He considered the ores to have been emplaced as iron oxide melts injected into the sedimentary gneisses and not contemporaneous with the gneisses. Later Kitchell (1857) described the ore deposits as metamorphosed iron beds within a sedimentary series. This hypothesis was accepted until Bayley, after extensive studies for the U.S.G.S. and New Jersey State Geological Survey put forward a complex theory of magmatic injection and later enrichment by iron-bearing solutions or vapors from a common parent magma. Bayley's work supplied the only comprehensive background of theory and fact until 1953, when the U.S.G.S. published Bulletin 982-G, the fruit of three seasons of intensive field work in the area, by Paul Sims under the direction of A. F. Buddington. Sims' theory of ore genesis may be described as approximating the current generally accepted concept of ore development in metasomatic hypothermal fissure veins. The iron, he believes, traveled from a magmatic source as either pneumatolytic or hydrothermal fluid, replaced microbrecciated wall rocks found in highly fractured zones commonly paralleling the lithologic layering of the gneisses, and in even greater detail paralleling the linear element.

Although the divergent theories of Rogers, Kitchell, Bayley, and Sims have tended to consolidate geological opinion dur-

ing the epoch dominated by each author, many excellent geologists in situations less propitious for intensive localized study and publication have held theories contrary to the theory dominating the period of their thought. Spencer, in 1904, revived the igneous theory of Rogers, Shand in 1947 put forward strong arguments in favor of the emplacement of liquid melts, and Bateman in 1952 convincingly described the origin of similar ores by crystal floating and later injection of the heavy liquid iron oxide residue.

Commercial students of the area, notably Barrett, of Jones and Laughlin Steel Company, who examined and reported on the Mount Hope mine in 1945, (private report), and other economic geologists with extensive backgrounds in the exogenetic iron ores of the Lake Superior region are convinced of the sedimentary origin of the New Jersey ores, so extensively conforming to specific sedimentary horizons, and are able to put forward many cogent arguments and excellent criteria in support of their claims. The works of Guier and Landergren, students of the Swedish ores of similar appearance and composition, suggest other theories of ore genesis for the Swedish ores, and these theories might readily be extended to the New Jersey area.

During the search for information and criteria, especially of a statistical nature, which might be used to clarify the conflicting evidence and opinions regarding genesis of the ores, the idea of a study of the distribution of minor elements was initiated. This study was planned along lines similar to the

work of Landergren in Sweden, but with less emphasis on the chemical relationships and more on the ore environment, with concentration on a specific ore deposit rather than on specimen analysis on a country and worldwide scale.

B - CHEMICAL ANALYSES AVAILABLE

Bayley (Vol. VII, Geological Survey of New Jersey, 1910) describes about 400 iron prospects and mines in New Jersey, giving information as to location, history, extent of prospect or mine opening, width of vein and analysis of ore. For most of the prospects content of iron and phosphorus is recorded, for many Ti, Mg, Ca, and S are given. Many of the old excavations, abandoned after the depressed iron markets of 1883, 1894, and 1907, are now inaccessible because of caving and encroachments of civilization, and the records of Bayley are the only analyses available or likely to be obtained. Later published information often merely summarizes analyses presented originally in Bayley.

The four mining companies now operating in the district have kept systematic records of Fe, P, Ti, Ca, Mg, and SiO₂ in their products. A typical analysis of ore shipped from Mount Hope (composite, part of 1951) is as follows: (Union Assay Office, Salt Lake City):

	Fe	SiO ₂	S	CaO	MgO	Al ₂ O ₃	P	TiO ₂
Lump Ore	61.7	8.1	.16	1.1	.55	1.33	.61	.59
Magnetic Concentrate	67.3	4.3	.14	.27	.40	.78	.12	.88

A semi-quantitative spectrographic analysis for minor elements in Mount Hope ore and concentrate, in which the percentage abundances were estimated from line intensities, is as

follows (Ahrens, analyst):

	Lump Ore %	Concentrate %	
Cr	.002	.002	(Sic)
Co	.005	.005	
Ni	.002	.002	
V	.01	.01	
Cu	.001	.001	
Ag	.0001	.0001	

Sims (1953) reports that hematite, locally called martite, intimately intergrown with magnetite, constitutes about 15% of the ore at the Scrub Oak mine. In certain stoping areas nearly 50% of the iron oxide is "martite". Persistent verbal reports indicate that the hematite-magnetite ratio has decreased with depth at the Scrub Oak mine. Hematite is reported abundantly present in the Ringwood ore deposit and analyses are given by Hotz (1952). At Mount Hope hematite is not found in metallurgical quantities and if present is in concentrations averaging less than one per cent.

C - SAMPLING AND SAMPLE PREPARATION

The iron ores of the New Jersey Highlands are found in a variety of structural settings, enclosed within several wall rock types, each high-grade magnetite mass with its own typical accompanying suite of low-grade ores and gangue minerals. The one persistent feature is massive magnetite found as continuous veins, lenses, and blades. The low-grade masses accompanying the high-grade ore are often of similar shape, forming one or both of the vein walls, or centrally located in the vein. While the high-grade is often distinctly layered, the low-grade materials are complexly banded or even schistose, carrying large percentages of biotite. High-grade masses are of subordinate importance in some bodies. At Scrub Oak mine the magnetite is disseminated throughout one layer of a thick albite-oligoclase-granite horizon and at Anomaly magnetite is disseminated through a more complex zone in similar material and associated amphibolite. At two properties sampled, Scrub Oak and Ringwood, hematite forms a minor but important fraction of the iron oxide.

An attempt to sample and compare analyses representing the host of low-grade ores, ore contact zones and stringers, together with their complex and variagated gangues would lead to a very extended study. In this investigation stringers, veinlets, and contacts were sampled and studied to a limited extent, but the bulk of the samples, chosen to represent portions of

ore shoots and whole mines, were carefully selected hand specimens of high-grade magnetite ore from central portions of massive high-grade veins. Selection was made to give as small a percentage, and therefore as little variety as possible, to gangue materials.

In the sixteen New Jersey mines and prospects sampled, specimens were selected from massive vein exposures, underground when possible, and in those prospects not presently accessible below the surface, from accessible portions of surface cuts. In all cases other than at Mount Hope, samples were chosen to represent the whole mine although often the selection was limited.

At Mount Hope, each sample was chosen to represent a specific location, elevation or geological situation. In the extended shoots, with ratios of exposed length to height of 20 or more to one, sample sections were chosen to represent three or more elevations spaced over the shoot length of several thousand feet. Excellent suites were obtainable from elevations of present operations in Teabo and Taylor veins, but at higher elevations, where operations have been abandoned due to exhaustion of the ores, access could be gained only to certain points in the vein, and sampling had to be limited to these areas. Except for the 400 level in the Taylor vein, no near surface vein in place remains accessible. The surface areas of Teabo were sampled by carefully picking high-grade material from waste dumps of old shafts, known from old maps to have

served limited areas near the surface. At Taylor, samples chosen to represent the surface were taken from selected pieces of high-grade found in shallow cuts across the caved outcrop. These loose surficial materials cannot be considered completely dependable samples of the veins at surface elevations, and analyses and results from them have been qualified and used only with reservations when comparisons are made with other samples of nearly identical composition taken lower in the same shoots. On the other hand, the range in trace ferride concentration in materials taken from different mines is large, and in comparing one mine with another, surface samples from imperfect surface exposures seem valid for the purpose intended.

For extensive sampling and comparison, the Teabo shoot was chosen as typical of the ores enclosed in the oligoclase-quartz-biotite gneiss, and the Taylor as the only shoot at Mount Hope enclosed in alaskite. The bulk of the sampling and all geological interpretations were confined to these two shoots. Several samples were taken at different elevations in the Leonard and Elizabeth shoots and are included in the lists of analyses. No samples were taken in the Richard shoot as exposure on the property of the Warren Foundry and Pipe Corporation was limited to one small section on the 1700 level.

SPECIAL MATERIALS SAMPLED--VEINLETS AND WEBS

Samples were taken of the thin web of ore connecting Teabo and Elizabeth shoots (see plate II-5) on 1000 level (T17), and on 1700 level (T33). These samples, important in the interpretations of ore genesis, are described at an appropriate place. A small cross-cutting veinlet found in the foot wall of Elizabeth shoot was sampled (E126) with results consistent with the other veinlet and web samples. A most interesting and significant geological sample is that of magnetite selected from a small calcite-filled veinlet, (T97C). Each wall of the once open fracture was found coated with a rather uniform 1/8" layer of sub-hedral magnetite crystals (photo--Fig. III-17). The form of this occurrence is such that the magnetite could only have been deposited in the open fissure from a solution or vapor. Such materials are rarely found in the Mount Hope mine and the calcite-filled veinlet was unique in the perfection of its display of magnetite incrustations. The two veinlets analyzed, essentially thin but massive high-grade bodies, were cleaned by magnetic concentration before analysis. In the silicious webs, the magnetite is very finely distributed throughout the fine-grained material, and these samples were analyzed as whole ores.

SILICATE MINERALS SAMPLED

Several minerals, rocks, and aggregates selected from ore gangues or included within the ore were selected for analysis. This material is described in the section on results of analysis

of gangue minerals.

WALL ROCK SAMPLES

In two areas where diamond drill cores were available cross sections were taken consisting of ore samples centrally located in the vein, ore near the rock contacts, rock near the ore contacts and, again, rock 20 to 50 feet distant from the vein. Several inches of core were removed for each sample. Specimens of rock core near the portion sampled were removed for thin sectioning.

CRUSHING AND PULVERIZING

The specimens analyzed were selected pieces of magnetite or rock weighing one to five pounds. These were broken in two, one half saved for examination and the remainder crushed in a laboratory jaw crusher, reduced to about 100 grams by splitting through a Jones riffle, ground to about 40 mesh in a standard Braun laboratory disc pulverizer, and stored in paper envelopes.

MAGNETIC SEPARATION

In those specimens chosen for magnetic separation, ten grams of the pulverized material was weighed out, fed to a Davis Tube magnetic separator, (Photo Fig. II-6) and treated therein for 4 minutes. Tails and magnetic concentrate were collected separately, dried and bagged. The weight of concentrate was recorded.

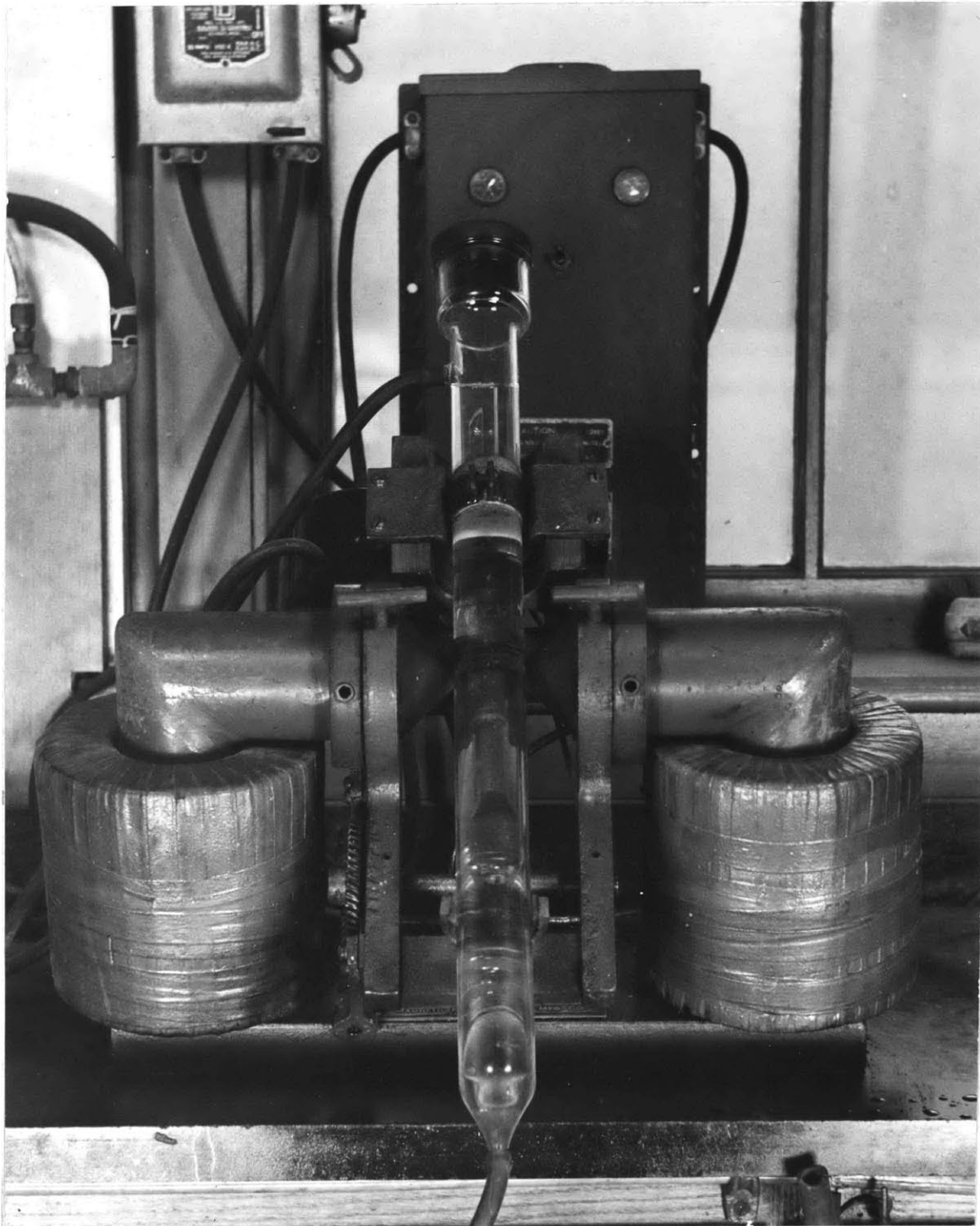


Fig. II-6 DAVIS TUBE MAGNETIC CONCENTRATOR
Glass tube is moved with reciprocating and turning motion while
water flows past pulverized charge between poles.

D - ANALYTICAL PROCEDURE

IRON OXIDE ORES, IRON AS VARIABLE INTERNAL STANDARD

Magnetite samples, both whole ores and magnetic concentrates were prepared for spectrographic analysis by weighing the following ingredients and grinding together for five minutes in an agate mortar.

1 part ore sample

2 parts clean, clear quartz crystal

3 parts graphite (National SP-1)

This mixture was packed into a $7/64$ " x $1/4$ " cavity bored in a $3/16$ " special carbon spectrographic electrode (National Carbon Company). The sample electrode was excited as the anode in a D.C. arc. The electrodes were pre-arc'd at 3 amps for 15 seconds, the current then raised to 7 amps and the charge arc'd to completion, about 3 minutes, 45 seconds.

Plates were Eastman type 103-0, developed for $4\frac{1}{2}$ minutes at 18° C. A 21' Wadsworth stigmatic mounted grating spectrograph with a dispersion of about 2.5 A/mm was used with an 8 step revolving sector in front of the slit.

Two plates were exposed for each arcing, one recording analysis and Fe standard lines for Ti, V, Co and Ni, while the other was placed to record analysis and standard line for Cr.

The lines used were as follows:

Element	<u>Analysis line</u>
	Variable internal standard line.

Ti:	$\frac{\text{Ti } 3199.92}{\text{Fe } 3205.4}$
V:	$\frac{\text{V } 3185.41}{\text{Fe } 3205.4}$
Cr:	$\frac{\text{Cr } 4254.3}{\text{Fe } 4258.}$
Co:	$\frac{\text{Co } 3453.5}{\text{Fe } 3415.54}$
Ni:	$\frac{\text{Ni } 3414.}{\text{Fe } 3415.54}$

The microphotometer used was an Adam Hilger, Ltd. H451 with FR300 Galvoscale projector. A plate calibration was made by selecting the average curve from repeated sector plottings for each of the analysis elements (Ahrens 1950). Net intensity, the line intensity less the background measured near the line, was used in all calculations.

Artificial standards prepared by Ahrens and Holyk at the Cabbot Spectrographic Laboratory, M.I.T. were used. These were made by adding weighed amounts of TiO_2 , V_2O_5 , Co_2O_3 , and NiO to Fe_2O_3 . Seven standards of graduated concentration were available, each containing a known ratio of all analysis elements to the variable internal standard, iron. Each standard was sintered for half an hour at 750°C . Standards were prepared for charging in a manner similar to ores, one part standard, two parts silica, and 3 parts graphite.

The C. P. Fe_2O_3 used in preparations of standards was

known to contain small amounts of the trace ferrides. In order to correct for this, each working curve was adjusted by making trial additions of amounts assumed to represent original impurities in the standard. Thus the working curve was plotted:

$$\frac{\text{Int. analysis line}}{\text{Int. Fe line}} \quad \text{vs} \quad \frac{\% \text{ added element} + \% \text{ assumed impurities}}{\% \text{ Fe}}$$

This trial was repeated with varying assumed quantities until a working curve that was very close to a straight line, at 45° was obtained (Nachtreib 1950).

Impurities determined in the base standard were as follows:

Ti	0.05%	of Fe content
V	0.01%	" " "
Cr	0.003%	" " "
Co	0.003%	" " "
Ni	0.0025%	" " "

About half of the magnetite samples were wet-assayed by standard commercial methods for iron. The remainder of the magnetite samples, comprising simple high-grade magnetite specimens and clean magnetic concentrates, were estimated as to Fe content by comparing with theoretically pure magnetite at 72.4% Fe.

Abundance of a trace ferride in a sample was determined by multiplying %A/%Fe, determined from working curve, by the Fe tenor of the sample.

SILICATE MINERALS EXTERNAL

STANDARDS G-1 AND W-1

Silicate minerals were crushed and pulverized as in the iron oxide ore procedure. One part of the pulverized material was mixed with 2 parts of graphite, ground in the agate mortar and charged in a carbon similar to that used for iron oxide ores. This mixture was arced at 7 amps to completion. Standard granite G-1, standard diabase W-1, (Fairbairn, et al, 1952) and a mixture of equal parts of the two, were used as external standards. At least one standard was arced on each silicate plate. The plate density-intensity curve made for oxide ores was used for silicates, but a working curve was made for each silicate plate, assuming that log intensity vs. log per cent of element would be a straight line with unit slope.

REPRODUCIBILITY

A typical sample of Mount Hope high-grade ore which will be called standard high-grade magnetite ore, and will be identified as BL, was prepared by regrinding the composite lump ore sample representing mine production for a part of 1951. Commercial wet analysis indicated an iron content of 61.2%. This sample was prepared with silica and graphite according to the iron oxide ore procedure. Nine charges of this material were arced, each on a different set of plates. These runs were dispersed throughout the 150 samples arced during this investigation. The per cent standard deviation of the ratio of line intensities I_a/I_{Fe} for each element across the nine plates was

as follows:

Ti	6.2%
V	7.1
Cr	13.3
Co	13.2
Ni	8.9

Deviations of this magnitude are considered satisfactory for this study. The comparatively high deviation for chromium, 13.3%, appeared to be largely due to high background, a characteristic of the wave length used. Other investigators at the Cabot Spectrographic Laboratory, M.I.T., have experienced similar background troubles when working with Cr4254. An improved method of calculating background, for example by the use of Seidel curves, might lead to better reproducibility. The deviation of 13.2% for cobalt is a reasonable working range at the low element of concentrations prevalent throughout the suite of ores. Factors affecting the absolute accuracy of the Ti analysis when ore and standards are of different mineral composition have been pointed out by Kvalheim (1947).

The accuracy of the silicate analysis may be assumed to be in the neighborhood of 20%. (Wm. Dennen, personal communication). Insufficient silicate runs were made to calculate a standard deviation for the silicate procedure when used with these ores.

PREVENTION OF CONTAMINATION

Throughout sample preparation great care was used to prevent contamination. All crushing and grinding equipment was cleaned thoroughly after each run by blowing out with compressed

air. Samples were arranged in sequence so that material rich in trace ferrides did not precede samples poor in trace ferrides. After running rich samples, an extra precaution was taken by blowing out, running a Jones splitter reject fraction of the sample to follow, discarding the product, blowing out again, and then following with the analysis fraction from the splitter. A blank sample of clear quartz was run, giving .004% Ti, by extrapolation on the silicate working curves and a trace of Fe, No, Cr, Co, or Ni lines were found.

CHAPTER III

THE DISTRIBUTION OF THE TRACE FERRIDES IN THE ORES AND ROCKS OF THE MOUNT HOPE MINE

A - THE TRACE FERRIDES IN SILICATE MINERALS AND APATITE

Table III-1 is a tabulation of the percentage abundances of the ferrides in selected crystals of apatite, biotite, and amphibole, and in amphibolite rock. Spectrographic analyses were made by the silicate procedure with standard diabase and standard granite (W-1 and G-1) as external standards.

APATITE

Two samples, Y85S and Y139S, composed of clean apatite crystals selected from crushed high apatite ore were analyzed. Both apatite samples were blanks in Ti, Cr, Co, and Ni. One, Y139S showed a blank in V while Y85S was calculated at 20 P.P.M., hardly more than a trace.

As V^{5+} may substitute for P^{5+} (Rankama and Sahama), or VO_4 for PO_4 in $Ca_5F(PO_4)_3$, the absence of V in the ubiquitous apatite of the Mount Hope ores suggests the probable absence of V^{5+} in the environment of ore formation. V is probably present in these magnetites as V^{4+} , ($r = .63$) replacing Fe^{3+} ($r = .64$), and in appropriate valence balances with Fe^{2+} in the inverse spinel structure. This replacement was mentioned in the section describing magnetite and the spinel structure.

In spite of radius differences, Rankama and Sahama (1949 p 596) explain the concentration of Vanadium in apatite-rich

TABLE III - 1

ABUNDANCE OF TRACE FERRIDES

IN SELECTED MINERALS - PPM

	<u>Ti</u>	<u>V</u>	<u>Cr</u>	<u>Co</u>	<u>Ni</u>
Y35-T Nonmagnetic Fraction of Magnetite Rich in Apatite	1,200	20	0	0	10
Y85-S Selected Apatite Crystals	0	20	0	0	0
139-S Selected Apatite Crystals from 84	0	0	0	0	0
79-T Nonmagnetic Fraction, Micaceous High-grade ore	800	Tr.	2	2	40
77 Biotite select coarse crystals from ore	3,700	20	5	5	62
78 Selected Amphibole Crystal from ore	3,000	60	2	2	30
131 Amphibolite "Horse" Teabo Vein	16,500	170	150	14	23
Standard High Grade Ore - BL	3,300	390	9	13	39

ores of Northern Sweden, as observed by Landergren, as a replacement of P^{5+} in apatite by V^{5+} . Quoting from Rankama and Sahama (page 596), "In apatite V^{5+} may replace P^{5+} (radius 0.35kX). This explains the concentration of vanadium in the apatite-rich iron ores observed by Landergren (1948). Only in these ores and in the titaniferous iron ores does the concentration of vanadium correspond to that found in marine iron-bearing sediments". However, Landergren's interpretation of his own work differs from that put forward by Rankama and Sahama. Quoting Landergren (1948 p 82) "The results (of the analysis of 14 high-apatite ores) are interesting. They show that the quantity of Mn, Co and Ni entering the magnetic fraction and the non-magnetic fraction respectively is dependent on the composition of the gangue, viz. the content of P and the ratio P_2O_5/SiO_2Vanadium is an exception to the rule mentioned. There is no correlation between the two quantities in question, the correlation....practically zero. This lack of correlation is astonishing. It is probably due to the conditions during the mineral-forming process. Therefore, if for some reason the reduction-oxidation potential varied so that the ionic charge of vanadium changed from say $3+$ to $5+$, vanadium could only enter the magnetite structure in the former case, V^{3+} , not in the latter, V^{5+} . If this variation in the ionic charge of vanadium was independent of the quantity of P or the ratio P_2O_5/SiO_2 , the lack of correlation in question can be easily understood". Thus, while there is mutual recognition

of the high V content of the high-phosphorus ore in question, Landergren finds that P and V are not covariant within the high-phosphorus suite of ores and holds that the association is exogenetic in origin, and therefore independent of the formation of the apatite of the ore suite found presently in these ore-bodies. The analytical results at Mount Hope tend to confirm the opinions set forward by Landergren in that the V content of these ores is not controlled by substitution in the apatite.

In general, the lithology of the ores of Northern Sweden and Northern New Jersey is very similar, as are the abundances of the trace ferrides, and similar guest-host relationships might be expected in the two ores.

In the present investigation no attempt was made to determine the presence of P in the magnetite structure. The extreme difference in ionic radius (P^{5+} , $r = .35$; Fe^{3+} , $r = 64$) makes it very improbable that P, other than in small amounts trapped during rapid infall of iron, be found in the magnetite; therefore, it is assumed that all significant P occurs as apatite. By visual observation of the many vein exposures in the mine it is well known that the distribution of apatite is erratic within the ore. Two samples taken a few feet apart are often judged by eye to vary in P content by a factor of ten or more.

Apatite is one of the most common accessory minerals in igneous rocks, accounting for 95% of the phosphorus contained therein according to Rankama and Sahama (1948 p 156). Further,

P is said to follow Ti very closely during magmatic differentiation, with a tendency to concentrate during the early steps of the main stage of crystallization. Thus, P and Ti illustrate a pair of elements which follow each other closely in spite of great differences in their chemical behavior. In view of this association it is interesting to note in the magnetites under investigation, the close association of P and Ti, in spite of nearly complete exclusion of Ti from apatite and probable exclusion of P from the magnetite structure.

Records of mine production indicate that average tenor of elemental P in high-grade ore is about 0.65%, or about double the abundance of Ti.

BIOTITE

One sample of coarse biotite (E33S) selected from the ore zone and one sample, the non-magnetic fraction of an ore specimen (T129T), in which the biotite was the only megascopically identifiable gangue mineral, were analyzed.

In regard to titanium, the results of analysis were as follows (the analysis of standard high-grade ore is included for comparison):

	Ti ppm
Biotite--selected coarse crystal from ore	3,700
Biotite--magnetic tail from ore rich in biotite (fine-grained)	800
Standard Hi-grade (BL) magnetite ore	3,300

The reason for the difference in the Ti content of the two mica samples is not immediately apparent. The materials are not identical and the means of preparation were distinct. It is possible that small amounts of unidentified minerals (other than biotite) were present in the magnetic tails.

According to Rankama and Sahama (p 560, 1949) small amounts of titanium are regularly incorporated in the structures of the femic minerals, the pyroxenes, amphiboles, and biotite quantitatively acting as the most important of the hosts. They state that biotite may contain up to 1.5% of TiO_2 , wodanite, 12% TiO_2 . Perhaps the coarse biotite (E77T) took up Ti in amounts commensurate with the known capacity of the mineral as a host, while the biotite finely divided and scattered throughout the magnetite ore could not compete with the magnetite structure in acquisition of Ti., and was left with only one-fourth of the concentration level attained by the magnetite.

The determination of a vanadium content of trace and 20 ppm in the two biotites analyzed indicates virtual absence of this element. The standard ore, BL, carried 400 ppm vanadium, igneous rocks average 150ppm vanadium according to Goldschmidt and .315 according to Lundergardh. (Rankama and Sahama p 594 1948). Rankama and Sahama quote (p. 597) the following for vanadium contents in two biotites and add a comparison with vanadium content in plagioclase:

	V ppm
Biotite from granite	1,000.
Biotite from monzonite	670.
Plagioclase	7.

It is apparent from these comparisons that the biotite gangues of the Mount Hope ores are not deficient in vanadium because of any inability on the part of the biotite structure to take up vanadium, but rather because in this close association the vanadium has elected the magnetite host which was apparently better able to compete for this element at the time and place of mineral development.

Throughout the comparisons made in this investigation it has been apparent that vanadium, more than any other trace ferride, substitutes in magnetite in preference to other potential competing structures. It is possible that this preference is in part due to the absence of V^{5+} as was shown to be the case with apatite, which commonly substitutes for Al^{3+} . It seems more logical to reason, however, that V^{4+} is strongly attracted to the Fe^{3+} position, from which it differs only 2% in radius, and it is possible that this attraction is enhanced by an excess of Fe^{2+} in the ore which could be readily balanced by V^{4+} or Ti^{4+} , as a 4-2 combination in the inverse spinel type of structure. (See Wells, 1950).

Chromium is found to be deficient in the two biotites analyzed. Its percentage abundance is tabulated here together with the Cr abundance in standard high-grade magnetite, BL, and further compared to the Cr content of biotite as quoted by Rankama and Sahama (1949 p 622).

	Cr ppm
T 79 T Nonmagnetic fraction of ore rich in biotite	2
E 77 S Selected biotite crystal from ore	5
BL Standard high-grade magnetite ore	9

Biotite from Granite (Rankama et al)	1,100
--------------------------------------	-------

According to Rankama and Sahama, Cr^{3+} substituted in the silicates constitutes the bulk of this element in the lithosphere. Cr^{3+} , with a radius of 0.64 compares to Al^{3+} , $r = 0.57$ and Fe^{3+} , $r = 0.67$. Cr, in spite of valence differences, replaces Fe^{2+} and Mg^{2+} in many minerals, but is not found in the feldspars or other minerals in which Al may replace silicon in the silicate tetrahedron.

A comparison of cobalt and nickel in the biotite samples is of interest. Co is deficient in the biotite as compared to standard high grade ore BL, while Ni is equal or slightly enriched:

	Co ppm	Ni ppm
T 79 T Nonmagnetic fraction of biotite-rich ore	2	40
E 77 S Select biotite from ore	5	62
BL Standard high-grade ore	13	39

Biotite from granite (Rankama and Sahama)	2,000
--	-------

This relationship is in accord with the radius ratios involved. The radius difference between Co^{3+} and Fe^{3+} is 2%, Co^{2+} and Fe^{2+} is 3%, that between Ni and Fe^{2+} is 7%. Thus, Co, with the most appropriate radii and more valence possibilities, is enriched in the magnetite, while the concentration of Ni is the same in magnetite and biotite.

According to Rankama and Sahama, Ni is impoverished in amphibole and biotite relative to olivine and hypersthene. The Ni readily replaces Mg in the latter minerals. Ni is consistently enriched in early crystallized magmas and ferromagnesian minerals.

AMPHIBOLE

Two samples of amphibolite were analyzed, the first a selected crystal of amphibole (E78S), a gangue from within the ore mass, the second a specimen of amphibolite rock, T131, taken from an amphibolite lense or "horse" about five feet thick and flanked on both sides by high grade ore.

The selected amphibole crystal contains Ti in approximately the same tenor as the standard high-grade magnetite; however, a very high Ti concentration is found in the amphibolite rock.

Results of spectrographic analysis are as follows:

	Ti ppm
E78S Selected amphibole crystal from ore	3,000
T131 Amphibolite "horse" in Teabo Vein	16,500
BL Standard Magnetite	3,300

Hornblende high in Ti (Rankama and Sahama) calculated from TiO_2	9,000
--	-------

In general, the behavior of Ti in amphibole is similar to its behavior in biotite already described. Titanium, (Ti^{4+}) is known to replace Si^{4+} in the silicon-oxygen tetrahedron, although the difference in radii is large ($Ti\ r = .68$, $Si\ r = .39$). This difference in radii must limit the amount of substitution possible. According to Rankama and Sahama, this substitution is common in small amounts in amphibole and micas but Ti^{3+} is also present in these minerals substituting for Al^{3+} , Fe^{3+} and also Mg^{2+} . Recent studies indicate that Ti-Si substitution might be less important than formerly believed. J. B. Thompson (personal communication) states that all titanium found in the silicates is in the form Ti^{4+} .

Amphibole differs from biotite in that no Ti amphibole is known.

In the competition for Ti within the ore mass, the clean amphibole crystal and the magnetite accepted this element in equal concentrations. In the Mount Hope ores, amphibole and pyroxene are important gangue minerals, less abundant than apatite in the high-grade ore but increasing in abundance in many low-grade ores. It will be seen in the section describing the results of analysis of high-grade ores and their concentrates that the volume of trace ferrides found in the gangue is not sufficient to greatly alter the distribution pattern of these elements in the ore bodies from that which would be obtained from an analysis of selected magnetite alone as the volume of gangue is not great in the high-grade ores and the

differences of ferride concentrations in ore and gangue is consistently small. For this reason the trace ferride content of ferro-magnesian gangue minerals does not affect geological interpretations as to ore genesis based on geographical distribution of these elements. The higher concentration of Ti in the amphibolite rock adjacent to ore will be further discussed.

The site of replacement of Ti in the amphibolite specimen is not known. This material was pulverized and separated magnetically producing 3.4% by weight of highly magnetic fraction. However, the tailing of this separation, which had the appearance of pure amphibole, when tested with a strong magnet, was found to be slightly magnetic. A standard wet analysis for soluble iron in T131 indicated 9.4% Fe. Silicates are not broken down in ordinary wet analysis, and the iron reported must in this case be an oxide. Therefore, small amounts of iron ore are distributed throughout the amphibole crystals in such a fine state that separation by ordinary mechanical means is impossible.

Ni appears to be equally concentrated in amphibolite, amphibole, and the standard high grade ore. Landergren states that "Nickel and cobalt will probably enter any structure of ferromagnesian minerals formed at a certain moment during the crystallization, and other factors than ionic size may cause the changes observed in the Co-Ni ratio with progressive crystallization".

V, Cr, and Co avoid the clean amphibole crystal but are

found in average amounts in the amphibolite with the exception of Cr, which is found to be highly concentrated:

	V	P.P.M. Cr	Co
E78S selected amphibole crystal from ore	60	2	2
T131 amphibolite "horse", Teabo	170	150	14
BL standard magnetite ore	390	9	13

It has been seen that V often faithfully follows Fe^{3+} . It is probable that in the amphibolite vanadium is largely carried in the small magnetic fraction. Its impoverishment in the selected amphibole crystal is marked.

The ready substitution of Cr in the magnetite structure has already been discussed. Rankama and Sahama (1949 p 621) note that chromium present only as traces in the structure of silicates represents the bulk of that element in the upper lithosphere. The location of the Cr concentration in the amphibolite remains undetermined. The presence of such a high concentration of Cr in a rock found in intimate contact with the magnetite ore is of considerable interest.

Concentration of Ti and Cr in amphibolite adjacent to high grade ore is further discussed in the section describing ferride variations within the ore shoots.

In general the tendency of the trace ferrides toward concentration in the clean amphibole is the same as toward the biotite. The sites of high concentration of the trace ferrides in the amphibolite rock were not determined.

B - THE TRACE FERRIDES IN WALL ROCKS

OLIGOCLASE-QUARTZ-BIOTITE GNEISS AND ALASKITE

The five veins mined at Mount Hope are found in two distinct mapable rock units. The first unit, the oligoclase-quartz-biotite gneiss, encloses the Richard, Teabo, Elizabeth and Leonard veins; the second unit, the alaskite, encloses the Taylor vein. These units were named by Paul Sims (U.S.G.S. 1953) on the basis of the petrographic type predominating in the unit. Originally Sims (oral communication) named the first unit the plagioclase-quartz-biotite gneiss, and this name, abbreviated as PQB, is much used by local geologists. However, in publication he changed the name to Oligoclase-quartz-biotite gneiss, and this published name is used throughout this paper. When convenient, it is abbreviated OQB.

Sims describes these rocks as follows:

"METASEDIMENTARY ROCKS.....

OLIGOCLASE-QUARTZ-BIOTITE GNEISS.....The gneiss is a greenish-gray, medium-grained equigranular rock that is composed essentially of 50% to 75% oligoclase (An₁₁-An₁₈), 18% to 36% quartz, and as much as 12% biotite. A small percent of hornblende occurs in some layers, and magnetite is a common accessory mineral. The biotite tends to concentrate into layers and has a marked alignment that gives a prominent lineation to the rock.....

"IGNEOUS ROCKS.....

ALASKITE.....The alaskite is composed essentially of microperthite and quartz. Mafic minerals, principally hornblende, augite, and biotite, constitute less than 5% of the rock."

A tabulation of certain important major elements found in typical samples of the two rock types is condensed from Sims (1953) as follows:

	SiO ₂	Al ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O
OQB Mt. Hope	68.	16.	2.	1.5	6.5	1.8
Alaskite (Hibernia)	77.	13.	Tr	0.8	3.4	4.0

It is seen that the rock types differ substantially both in mode and in analysis. Partially on the basis of differences in petrology and analysis and partially because of structural relationships, Sims considered the two rocks to be of different genetic types, the OQB a sediment, the alaskite an intrusive. Relevant structural interpretations by Sims have not been completely supported by detailed geological studies made during the mining operation (Unpublished maps, staff of Warren Foundry and Pipe Corporation.)

DISTRIBUTION IN THE WALL ROCKS

A visual examination as well as ferride analysis of rock exposures and diamond drill cores together with thin sections indicates that these rocks, the walls of the Mount Hope ore shoots, are uniform neither in petrographic composition nor in

ferride content. Within the group of four OQB samples analyzed, Ti, V, and Ni each vary in abundance in an unrelated manner by factors varying from 3 to 5. (Table III-2.) Cr and Co each vary by factors roughly of ten. These variations take place within a cross sectional distance of less than 100 feet. If a continuous sampling were made of these thin-banded gneisses it is apparent that the maximum deviation would be greater and fluctuations would be more frequent than shown by the few analyses available. This rapid variation of the ferride content in the wall rocks is in sharp contrast to the uniform distribution of ferrides in the high-grade ore, which will be shown to be 25% to 60%, calculated as standard deviations over thousands of feet of ore shoot strike and pitch. (n.b. this comparison is of wall rock in cross section and the ore in strike and pitch. Such a comparison is valuable, but differences in structural relation must be borne in mind.)

The four alaskite samples analyzed are more uniform in ferride content than are the OQB gneisses. As the alaskite carries a smaller percentage of mafic minerals, a lower trace ferride content together with more uniform distribution is to be expected.

Using titanium, determined by external standard, as a variable internal standard, the total iron in the wall rock samples may be roughly calculated by extrapolation on the working curves. This approximate procedure indicates an average of 4.4% of elemental iron in the four alaskite samples, 9.7% in

TABLE III - 2

ABUNDANCE OF FERRIDES

WALL ROCKS - MT. HOPE MINE

	<u>Ti</u>	<u>V</u>	<u>PPM</u> <u>Cr</u>	<u>Co</u>	<u>Ni</u>	<u>Approx.</u> <u>Fe %</u>
<u>O.Q.B. Gneiss-Teabo</u>						
106-OQB-DD Hole T87 F.W. 42 Ft.	6,000	150	62	10	42	8.3
105-Same 10 Ft.	1,600	30	160	2	14	4.5
107-OQB-DD Hole T88 H.W. 24 Ft.	5,400	90	7	8	22	15.0
108-Same 50 Ft.	2,600	60	8	19	32	16.0
<u>Average OQB Gneiss</u>	3,900	80	23	10	28	10.9
<u>Alaskite - Taylor</u>						
110-Alaskite-DD Hole T150 F.W. 30 Ft.	2,200	Tr.	4	5	14	5.5
109-Same 19 Ft.	3,400	30	6	4	18	7.2
111-Alaskite-DD Hole T151 H.W. 0 Ft.	2,300	30	18	6	26	3.0
112-Same 31 Ft.	3,600	30	35	20	46	3.1
<u>Average Alaskite</u>	3,000	20	16	9	26	4.7
Standard High-grade Magnetite Ore BL	3,200	390	9	13	39	61.2

the four OQB samples.

Averages of the several samples of each of the wall rock groups indicates that Ti, Cr, Co and Ni abundances are slightly lower in the alaskite than in the OQB. V is consistently lower by a factor of approximately four.

	P.P.M.					
	Ti	V	Cr	Co	Ni	Fe%
Mean, 4 samples OQB	3,900	80	23	10	28	9.7%
" 4 samples alaskite	3,000	20	16	9	20	4.4%
Percent difference of lower concentration	30%	300%	43%	10%	8%	120.%
Standard magnetite-BL	3,200	390	9.	22.	39	61.2%

It is noted that Ti in the alaskite is about 30% less than in the OQB, while iron is estimated at about half, both as opaques in the modes and from extrapolation on the working curves. In the modes, sphene is estimated as about twice as abundant in the alaskite. This suggests that the increase in Ti relative to iron, in the alaskite, occurs in part as an increase in the sphene content in the alaskite.

It may be argued that similarities in average content of certain trace ferrides, notably Ti and Ni, in walls and ore suggest a genetic relationship between walls and ore. In plates III-1 and III-2 are shown cross sections of veins and wall rocks at points where diamond drill cores and vein were sampled. Be-

TEABO VEIN CROSS SECTION ORE AND O:Q-B. GNEISS WALLS

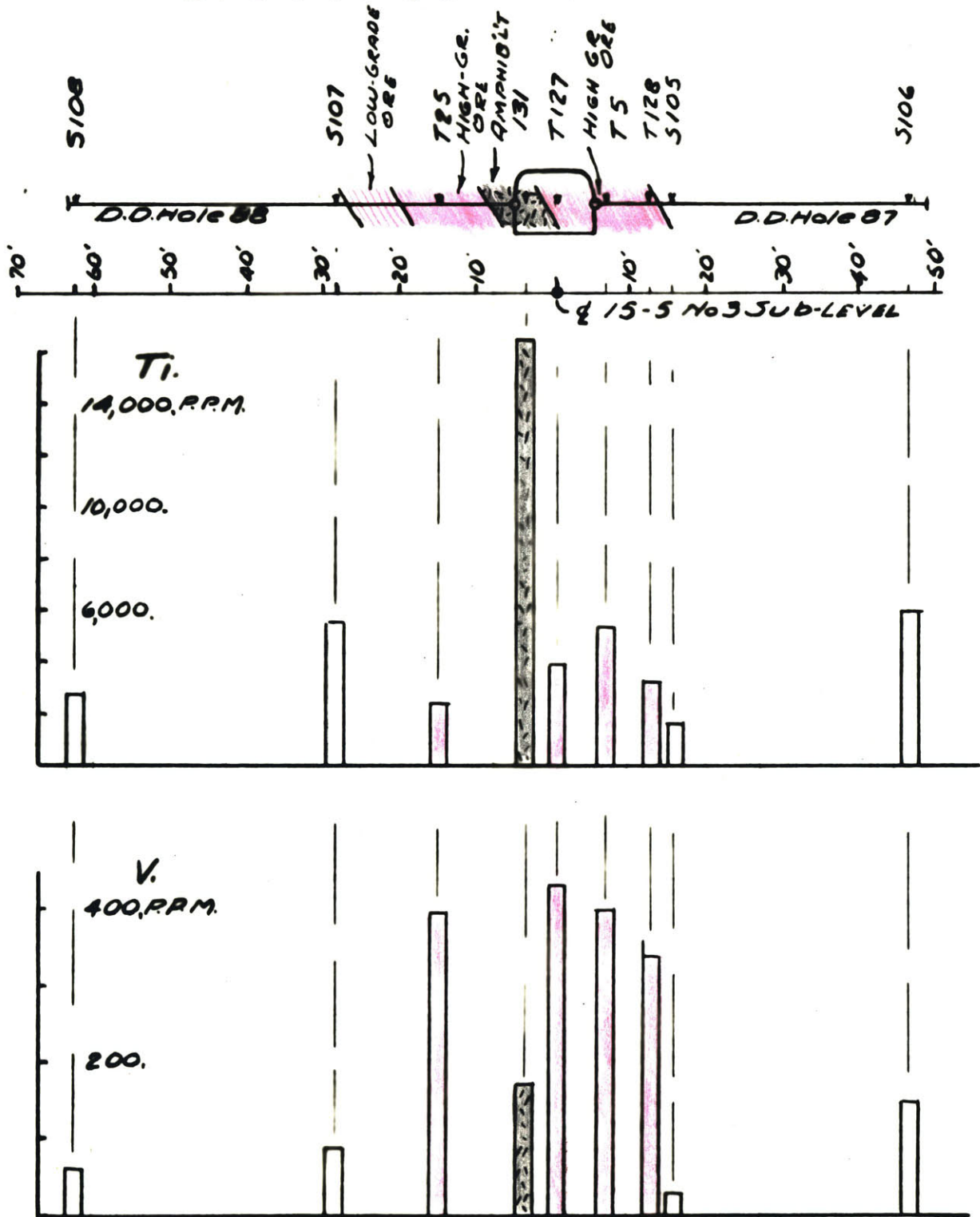


FIG. III-1-a

TEABO VEIN

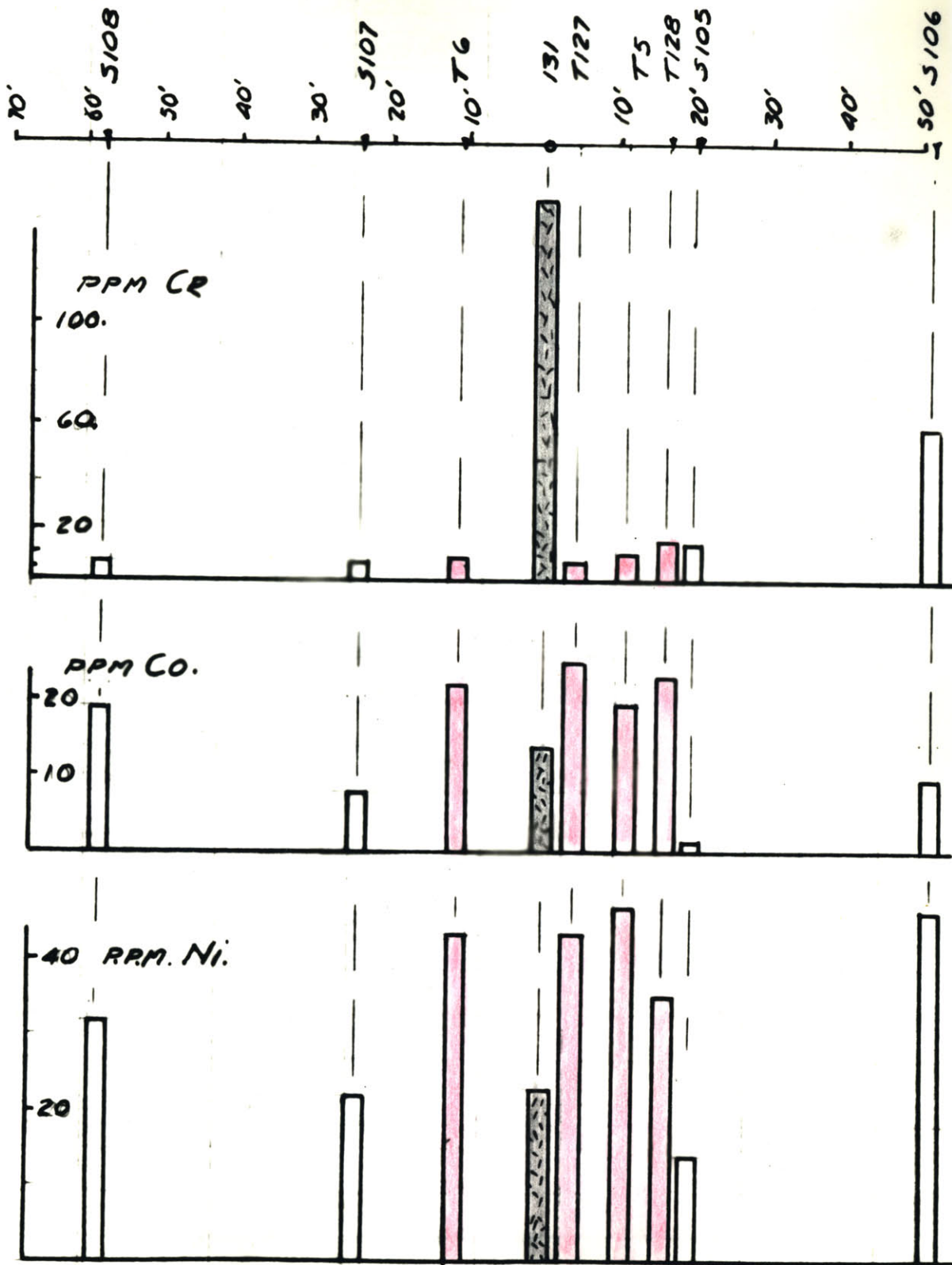


FIG III-1-b.

TAYLOR VEIN CROSS SECTION ORE AND ALASKITE WALLS

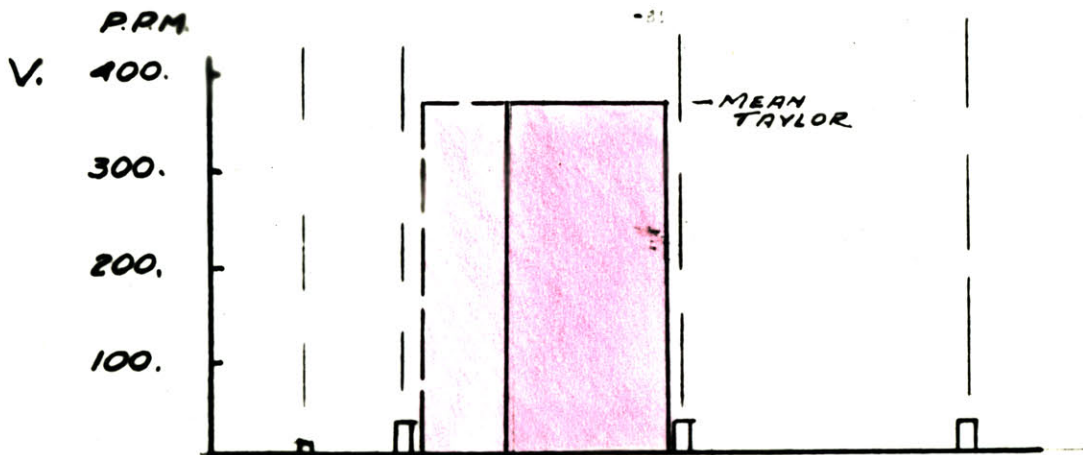
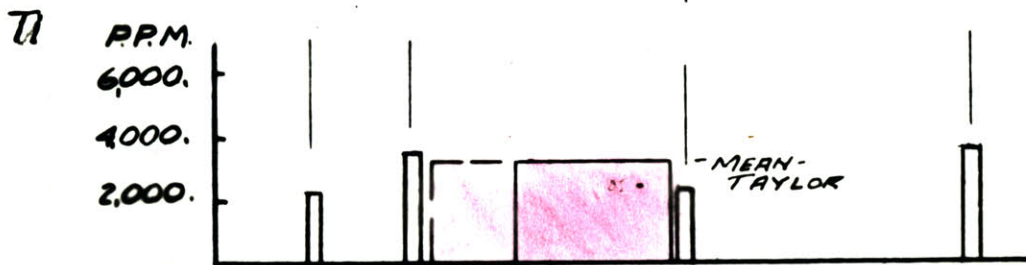
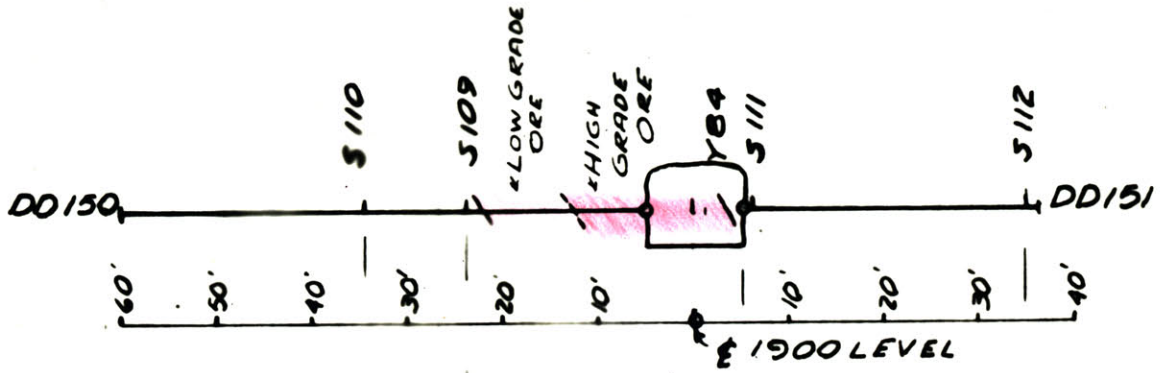


FIG. III-2-a

TAYLOR VEIN

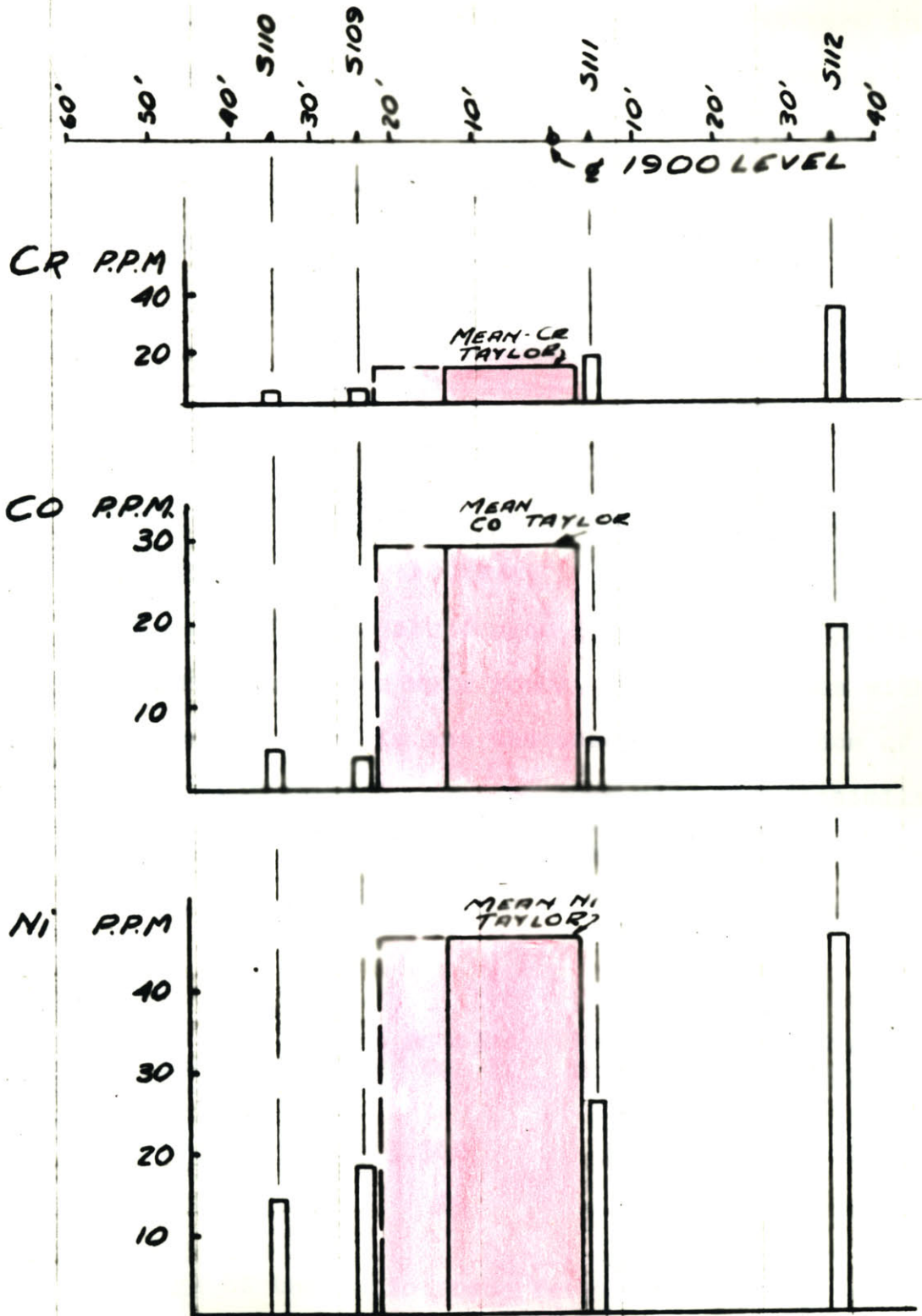


FIG. III-2-b.

low the cross sections are plotted the results of analyses of vein and core samples. In these plots the ordinate is trace ferride abundance in per cent, the abscissa is distance in feet from the center of vein. Examination of these plots indicates that there is no similarity in distribution between ferride abundances in ore and wall rock. The ore here (in the Teabo section) is uniform in its analysis, as it is throughout the mine, while the rock samples vary between one and another by factors ranging up to ten. For this reason the similarity in the Ti and Ni averages of ore and wall rock appears to be fortuitous. It is possible that each group, rock and ore, correlates closely with the average abundances of Ti and Ni in the earth's igneous rocks (Ti 4400 PPM; Ni, 80 PPM).

Further, if ferride abundances in the ore were related by genesis to ferrides in the wall rocks, some covariance with Fe might be expected. This is not the case. A comparison of the similarity of Ti content in ore and rock with the dissimilarity of the Fe/Ti ratio is as follows for Teabo vein and its host rock, the OQB, and also for Taylor vein and its host rock, the alaskite:

	19 Samples Teabo ore	4 Samples OQB	16 Samples Taylor ore	4 Samples alaskite
Average PPM Ti	3,600	3,900	3,200	3,000
Ratio Fe/Ti	178	25	200	15

Plottings of the ratio trace ferride/Fe for all wall rock

TEABO VEIN CROSS SECTION
 ORE AND OQB GNEISS WALLS
 RATIO - FERRIDE TO IRON

FIG. III-3.

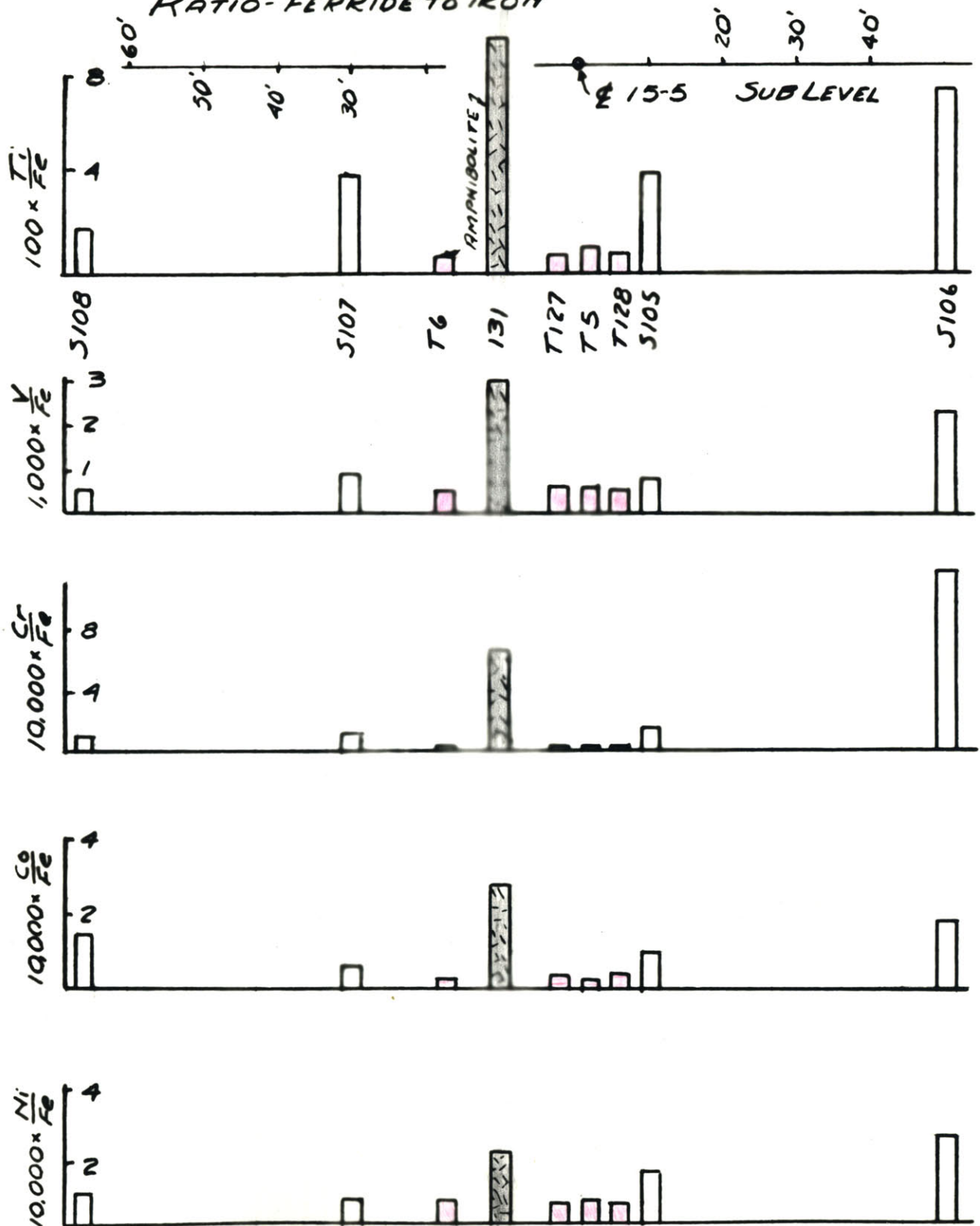
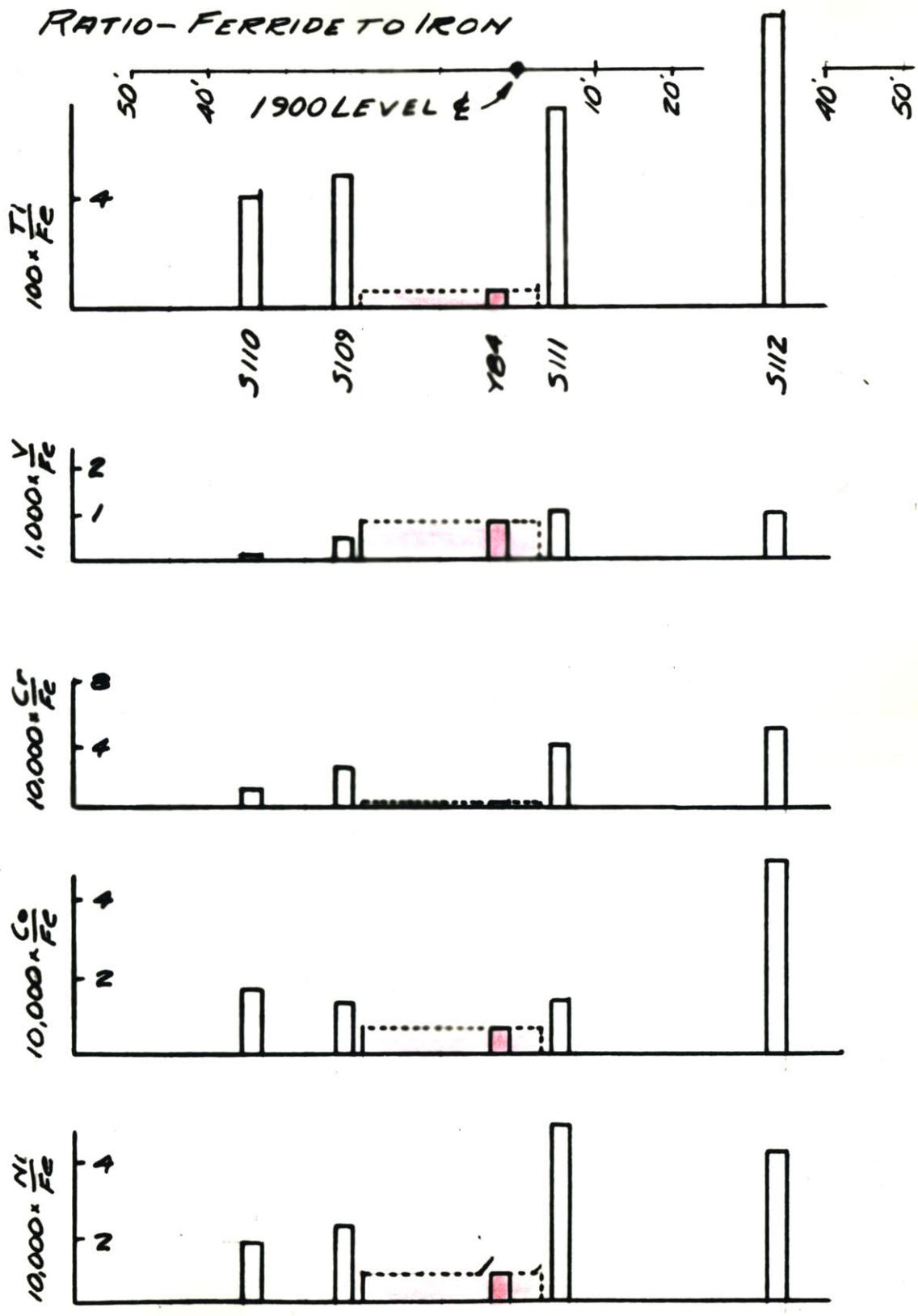


FIG. III-4.

TAYLOR VEIN CROSS SECTION
 ORE AND ALASKITE WALLS
 RATIO - FERRIDE TO IRON



samples, to scale on the vein cross sections, plates III-3 and III-4, further demonstrate the lack of similarity or relationship between ferrides in ore and walls.

SIMILARITIES IN OQB AND ALASKITE

Obvious dissimilarities in the two rock types have been described; however, some similarities in trace ferride content do exist. More fruitful in correlation than the comparison of ore and wall rocks is the comparison of the two wall rock types. The average content of each trace ferride for each of the two rocks differs, as has been noted, by factors ranging up to 2. However, the dispersion of the analyses within each group is great, and individual analyses of each trace ferride for each rock type fall within the field of the other rock type. The dispersion of analyses of the two rock types is similar. The rocks "behave similarly" as to trace ferride content.

The average content of Ti and Ni compare closely, and the dispersion of individual analyses for these elements is comparatively small for both rocks, ranging up to 3 for Ni and 4 for Ti.

Thus these rock units, distinctive in mode and in major constituents as determined from the study of single samples of each type, show some similarities in trace element content when several samples are compared, the similarity being most marked when ranges of abundances are considered. This suggests a genetic relationship between the two. This evidence, together with field evidence (Unpublished work, Warren Foundry and Pipe

Corporation) suggests that these rock units are related as to genesis, probably having been distinctive horizons in the same sedimentary series. This conclusion is at variance with that of Sims.

C - ABUNDANCE OF FERRIDES IN HIGH GRADE ORES,
THEIR MAGNETIC CONCENTRATES, AND TAILS

Early in this investigation it was not known whether comparisons of the various veins and ore deposits should be made upon the analyses of whole selected high grade ores or upon magnetically cleaned fractions. It was felt that the geochemical behavior of pure magnetite should be studied. However, it seemed that magnetic concentration might exclude elemental concentrations of close genetic association which had been rejected from the magnetite during lowering temperature by exsolution, e.g. ilmenite, or during what might be contemporaneous crystallization or metasomatism; e.g. apatite and the ferromagnesian minerals.

Throughout most of the investigation analyses were made of both clear high-grade ore and of the magnetic concentrates of these ores. In Table III-3 are presented: first, a comparison of the results of analysis of eight high grade magnetite-apatite-quartz ores (Teabo vein) and their concentrates; second, a similar tabulation for five samples of high-grade magnetite-apatite-skarn ores (Taylor vein) and their concentrates.

It is seen that in both types of ore and for all elements, except Ti in the skarn ore, the ferrides are slightly concentrated in the magnetic fraction. For titanium in the skarn ore, the average tenor of the concentrate and tails is approximately equal, due in part to the presence of sphene in the skarn tail and in part to the general level of Ti commonly found in the

TABLE III - 3

ORES AND THEIR CONCENTRATES

MT. HOPE MINE

	<u>Ti</u>	<u>V</u>	<u>Cr</u>	<u>Co</u>	<u>Ni</u>
<u>Quartz Apatite Ore</u>					
(Teabo)					
1. Whole high grade ore average of 8 Samples	3,400	360	11	25	40
2. Magnetic Concentrates of line 1.	3,800	410	14	26	45
Tailing - 4 Samples of Line 1 (other tails not analyzed)	1,000	24	2	10	22
<u>Skarn-Apatite Ore</u>					
(Taylor)					
3. Whole Ore Average 5 Samples	3,400	320	13	28	47
4. Magnetic Concentrate of Line 3 Average	3,300	400	16	36	48

skarn minerals.

In 20% of the samples in which tailing as well as concentrate was analyzed, the comparison of tailing with whole ore and concentrate was anomalous. In these cases both concentrates and tails were reported higher in tennor of ferrides than was the whole ore. This anomaly probably resulted from the low relative precision of the external standard technique used in the analysis of tails together with a possible systematic error in the magnetite analysis caused by approximations made in correcting for impurities in the material used as a blank in standardization. Because of the anomalies found in products of magnetic separation, calculations of metalurgical balance between whole ore, magnetic fraction and nonmagnetic fraction are not included.

As the magnitude of the differences in ferride abundances in whole ore and magnetic concentrates is small, it is apparent that either whole ore or concentrates might be used in many geological comparisons without significant differences in quantitative results; however, for the calculated comparisons of vein cross-sections, ore bodies, and mines presented in this study, the per cent abundances determined from clean, whole, high-grade ores have been used. An exception was made in the ores of five of the district mines. For these mines magnetic concentrate and tail intensities were combined by calculation to derive abundances representative of the whole ore.

D - COVARIANCE OF FERRIDES

COVARIANCE IN ORE

The possibility that the trace ferrides might display a marked geochemical cohesion in their distribution within the magnetite mass by demonstrable covariance of elemental concentrations was tested by plotting several series of elemental combinations.

Elemental combinations plotted were:

Ti-V
Ti-Cr
Cr-V
Co-Ni

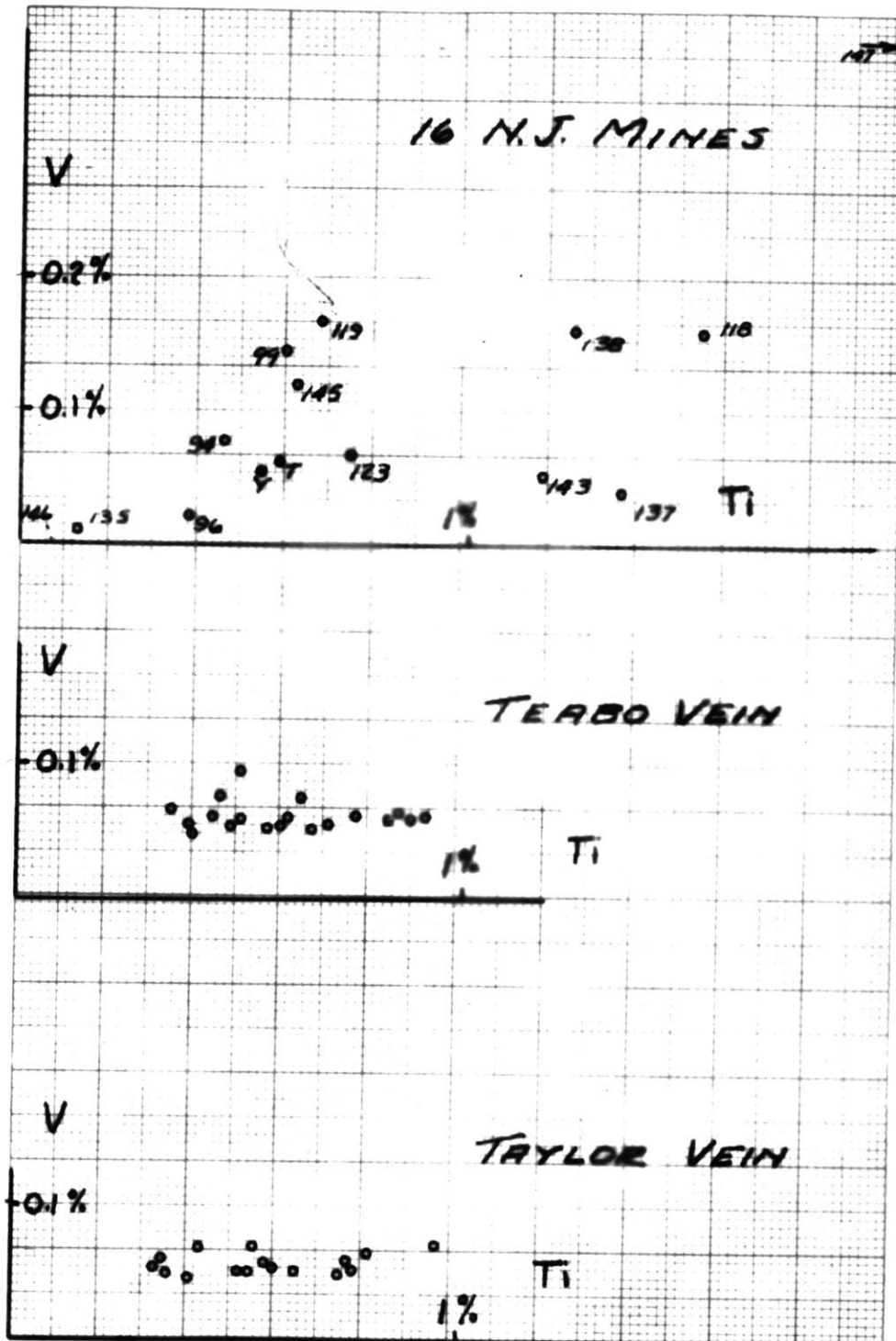
These were plotted for the following series:

1. 16 New Jersey mines
2. Teabo ore shoot 19 samples
3. Taylor ore shot 16 samples

Correlation of elemental concentrations is very slight or notably absent in most of the plottings. On Figures III-5 to III-8 covariance is suggested in the ore shoots, for example, in the relationship between Co and Ni. An examination of the plots, however, is preferable to an attempted verbal description of such weak possible correlations.

In the district plots the most consistent covariation is noted in analyses from Oxford and Van Syckle's mines (see Fig. IV-2.). Oxford is consistently low in trace ferrides, possibly due to proximity to the Franklin limestone belt, while the Van Syckle's is an extreme representative of the group of

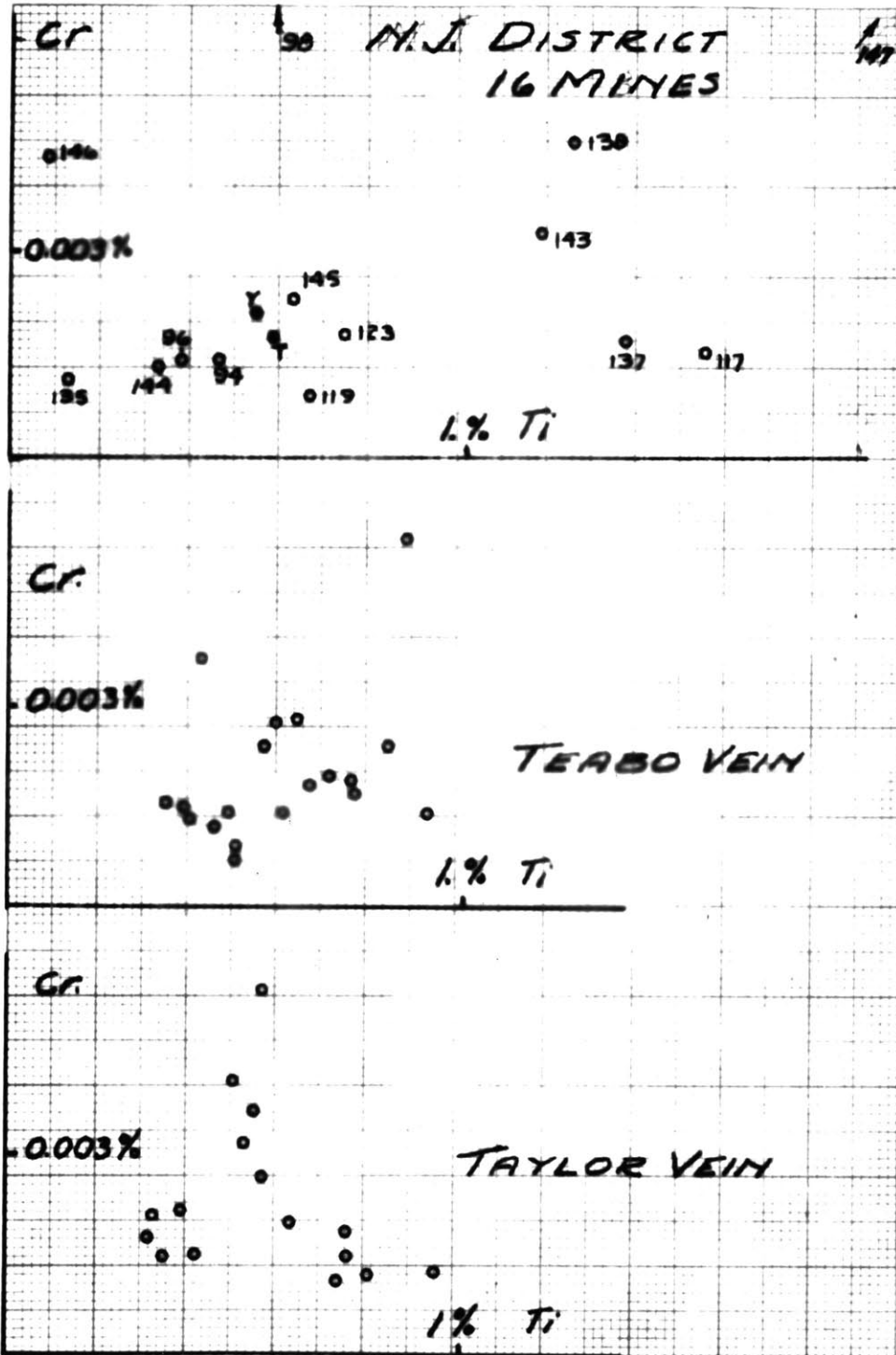
V vs, Ti in NEW JERSEY MAGNATITES



V and Ti expressed as % Fe in sample.

Figure III - 5

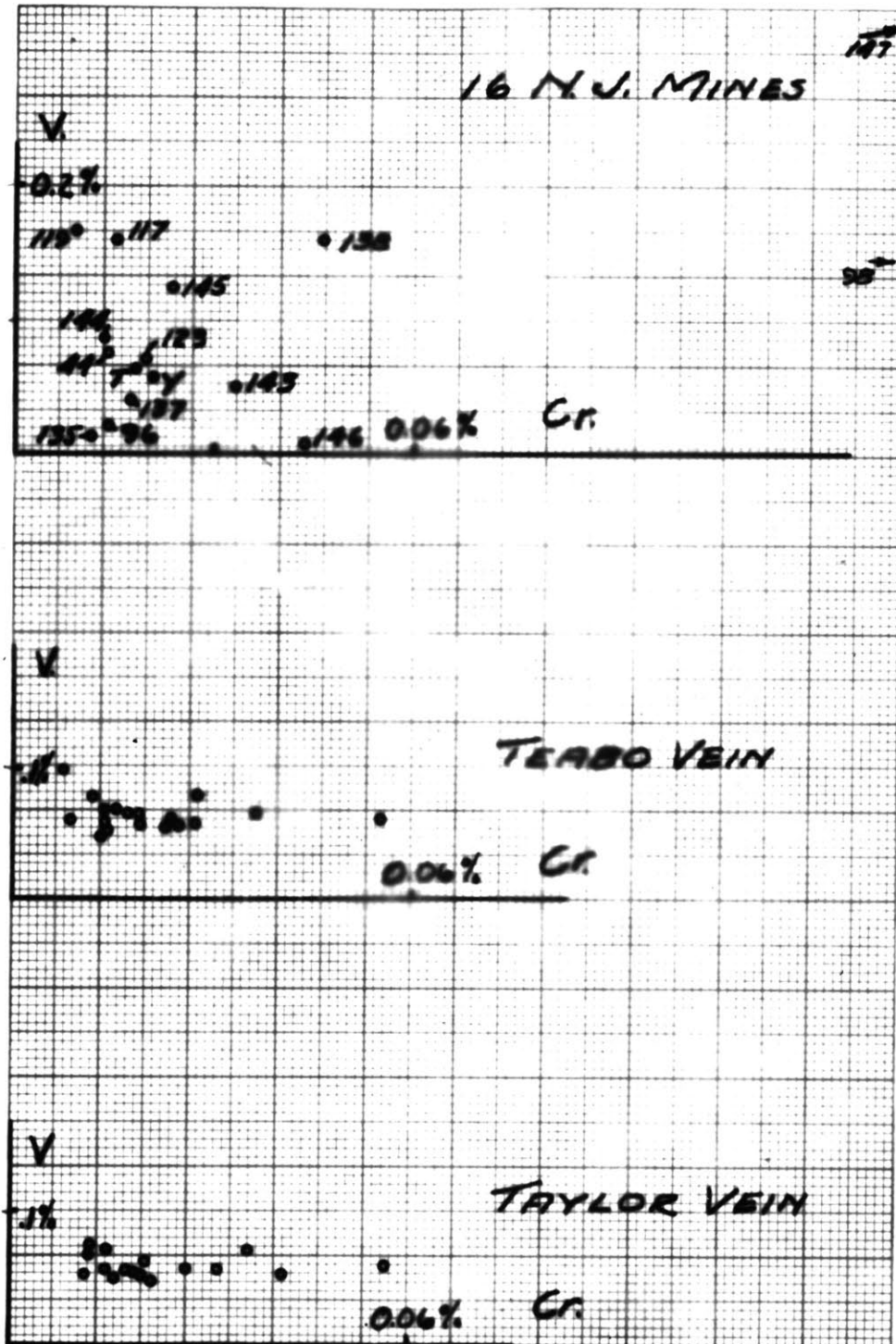
Cr vs. Ti in NEW JERSEY MAGNATITES



Cr and Ti expressed as % of Fe in sample.

Figure III - 6

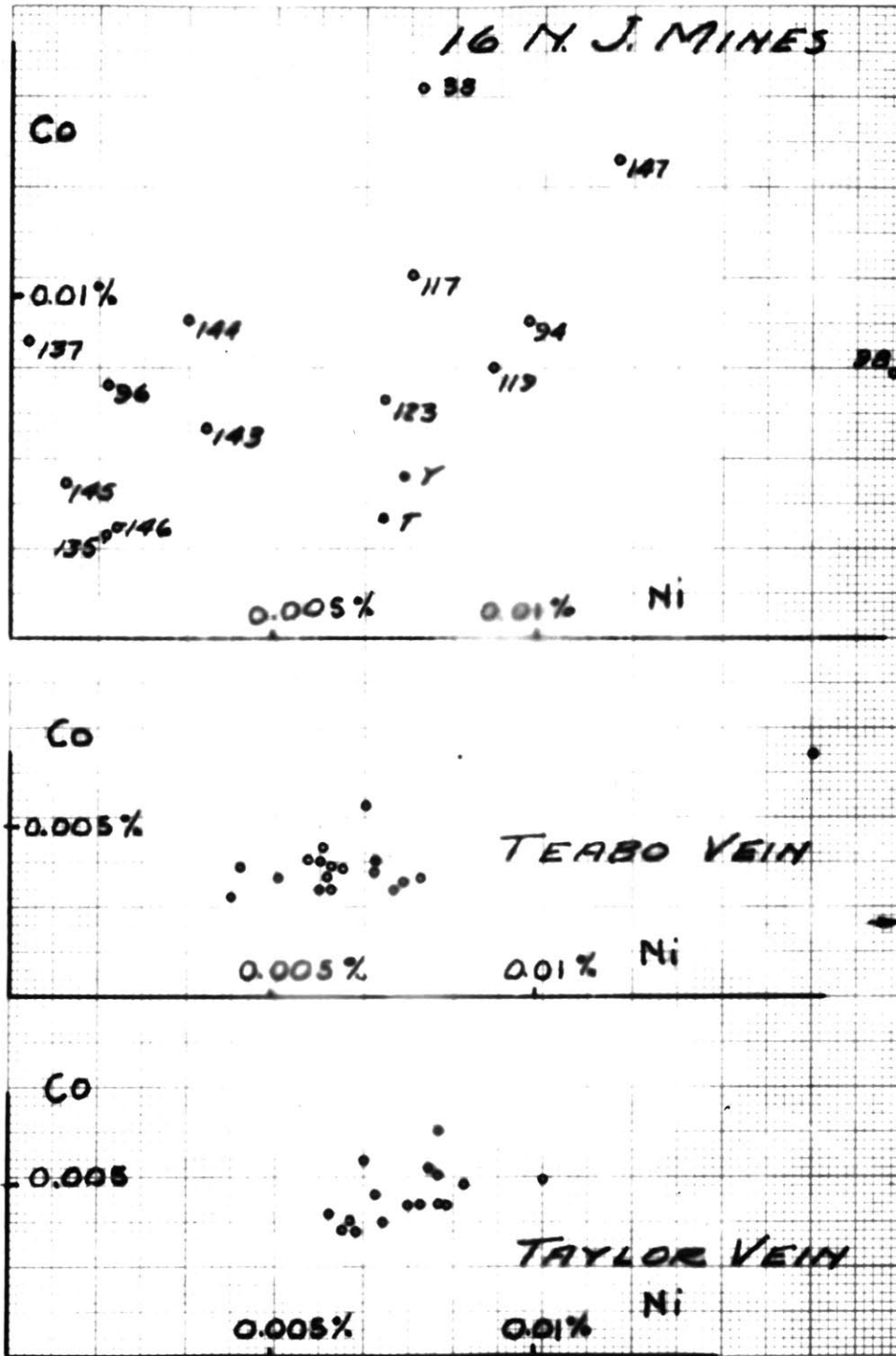
V vs. Cr in NEW JERSEY MAGNATITES



V and Cr expressed as % Fe in sample.

Figure III - 7

Co vs. Ni in NEW JERSEY MAGNETITES



Co and Ni expressed as % of Fe in sample.

Figure III - 8

mines high in titanium. Other members of the high Ti group that were sampled and analyzed, the Baptist Church, and Scofield mines, do not display consistent covariance in the trace ferrides.

In the relationships of Ti and V it is noted that Ti is never more than 3 x V. In the district no lower limit to V is noted.

A suggestion of linear relationship is seen between Cr and Ti in eleven of the sixteen mines. The two ore bodies out of line in the high chromium field, Anomaly (98), and Scrub Oak (146), are both disseminated magnetites. The mines in the low chromium field, Hibernia (119), Scofield (137) and Fairview (117), are all mines in the neighborhood of the Split Rock Pond node. Relationships of concentrations of Cr to disseminated magnetites as well as to certain structural centers will be discussed further in the section on district distribution.

In general, within the Mount Hope mine, geochemical cohesion in the ferrides is manifest only in the uniformity of distribution of trace ferrides. Marked covariance is lacking. Throughout the district a much greater range of variation of abundances is found, and a tendency towards covariation is noted in some ores, especially those of generally high or low trace ferride concentration.

COVARIANCE IN WALL ROCKS

On Fig. III-9 and III-10, O.Q.B. gneiss and alaskite are plotted in the following combinations:

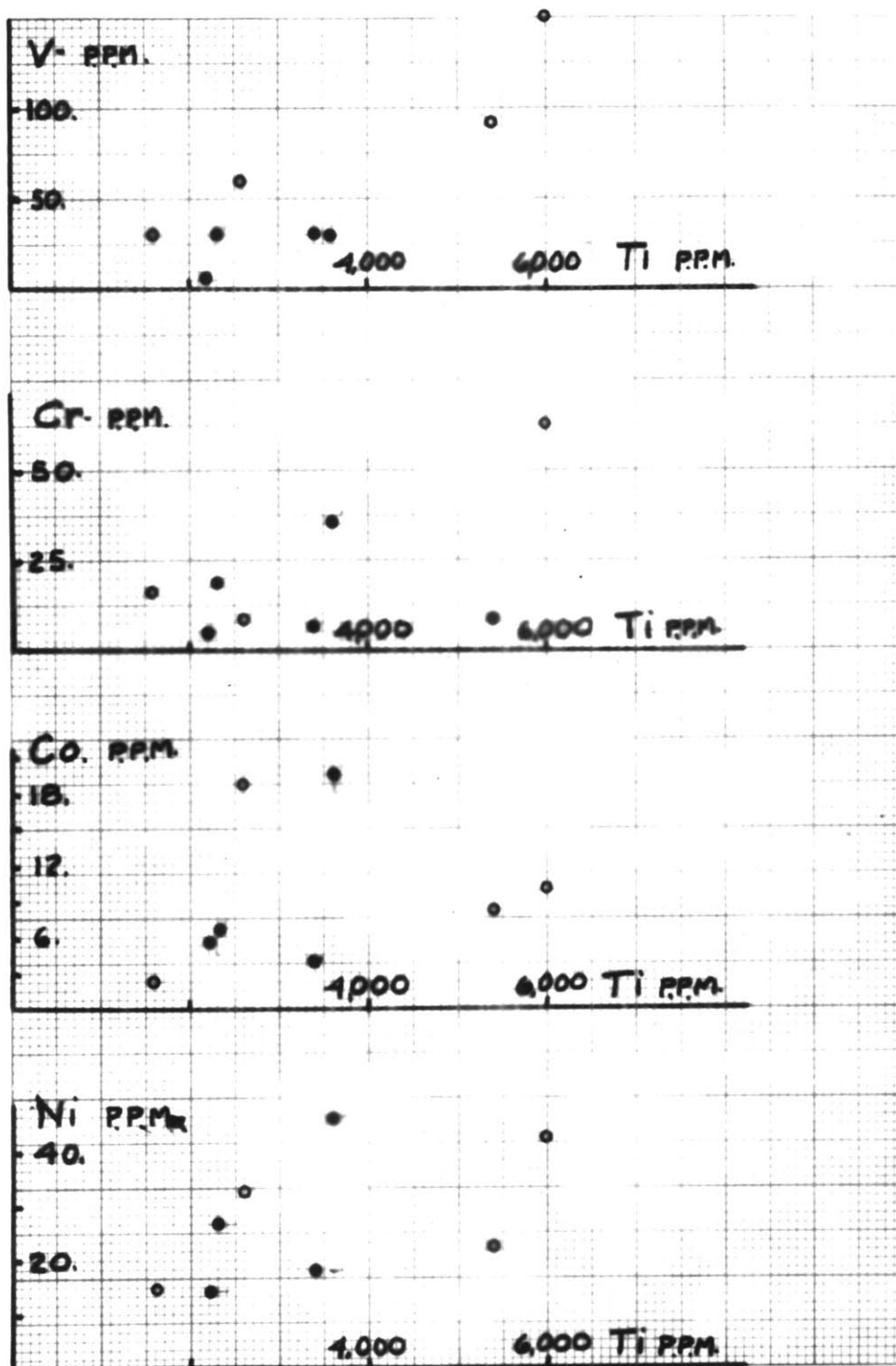
V, Cr, Co, and Ni vs Ti.

Ti, V, Cr, Co, and Ni, vs Fe.

Within the wall rocks no appreciable covariance is noted between the trace ferrides and iron. A tendency toward a linear relationship between Ti and V is noted in the O.Q.B., but more samples would be needed to establish a pattern. If these rocks were uncontaminated magmatic differentiates, a uniformity or close covariance of trace ferrides would be expected. However banded gneisses must be of either a sedimentary origin or of a complex igneous origin, and elemental concentrations are not the result of simple processes.

In order to continue the study of the distribution of the ferrides within the rocks, pulverized samples have been separated magnetically and will be analyzed in the near future.

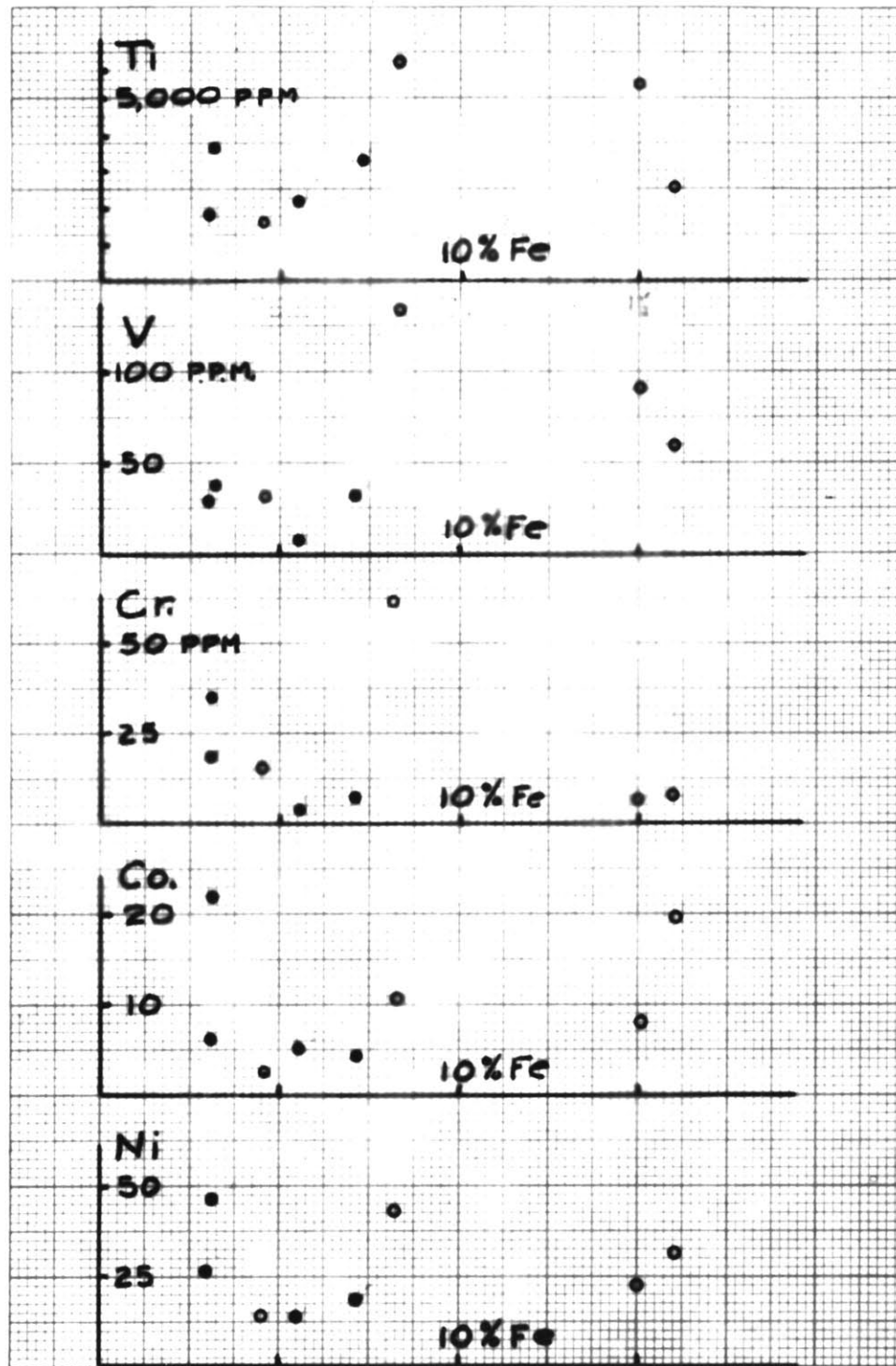
TRACE FERRIDES vs. Ti in O.Q.B. GNEISS AND ALASKITE



- O-Q-B GNEISS
- ALASKITE

Figure III - 9

TRACE FERRIDES vs. Fe in O.Q.B. GNEISS AND ALASKITE



- O-Q-B GNEISS
- ALASKITE

Figure III - 10

E - DEVIATION OF FERRIDE CONCENTRATIONS IN A LIMITED AREA

In order to determine the variations in concentrations of the trace ferrides within a limited volume of magnetite vein at the Mount Hope mine, ten samples of high grade ore were taken at random within a limited area measuring about 120 feet in dip and 50 feet in strike-length in the 15-5 stope of the Teabo vein. Since standard deviations of the analytical results of the samples exceeded 15%, lognormal distribution was assumed (Ahrens 1953). Histograms of log deviations showed reasonable conformance to a normal distribution, Fig. III-11, strengthening the assumption of lognormal distribution.

The lognormal deviation of the 10 samples taken from one area is presented in the following tabulation, Line 2, together with the log-deviations of 9 replicate analyses of one sample, Line 1, replicate sampling divided by replicate analyses, Line 3:

	<u>Percent lognormal deviation</u>					
	Ti	V	Cr	Co	Ni	Av.
1. One sample-(BL) 9 Determinations	6	7	13	13	9	10
2. 10 samples from one area (15-5 Stope)	41	21	34	21	20	27
3. Ratio, line 2 divided by line 1.	7	3.	2.6	1.6	2.2	2.7

This comparison indicates that for V, Co, and Ni a single sample may be accepted as representative of a given area of

DISTRIBUTION CURVES

TRACE FERRIDES, TEN SAMPLES IN ONE AREA

TEABO VEIN

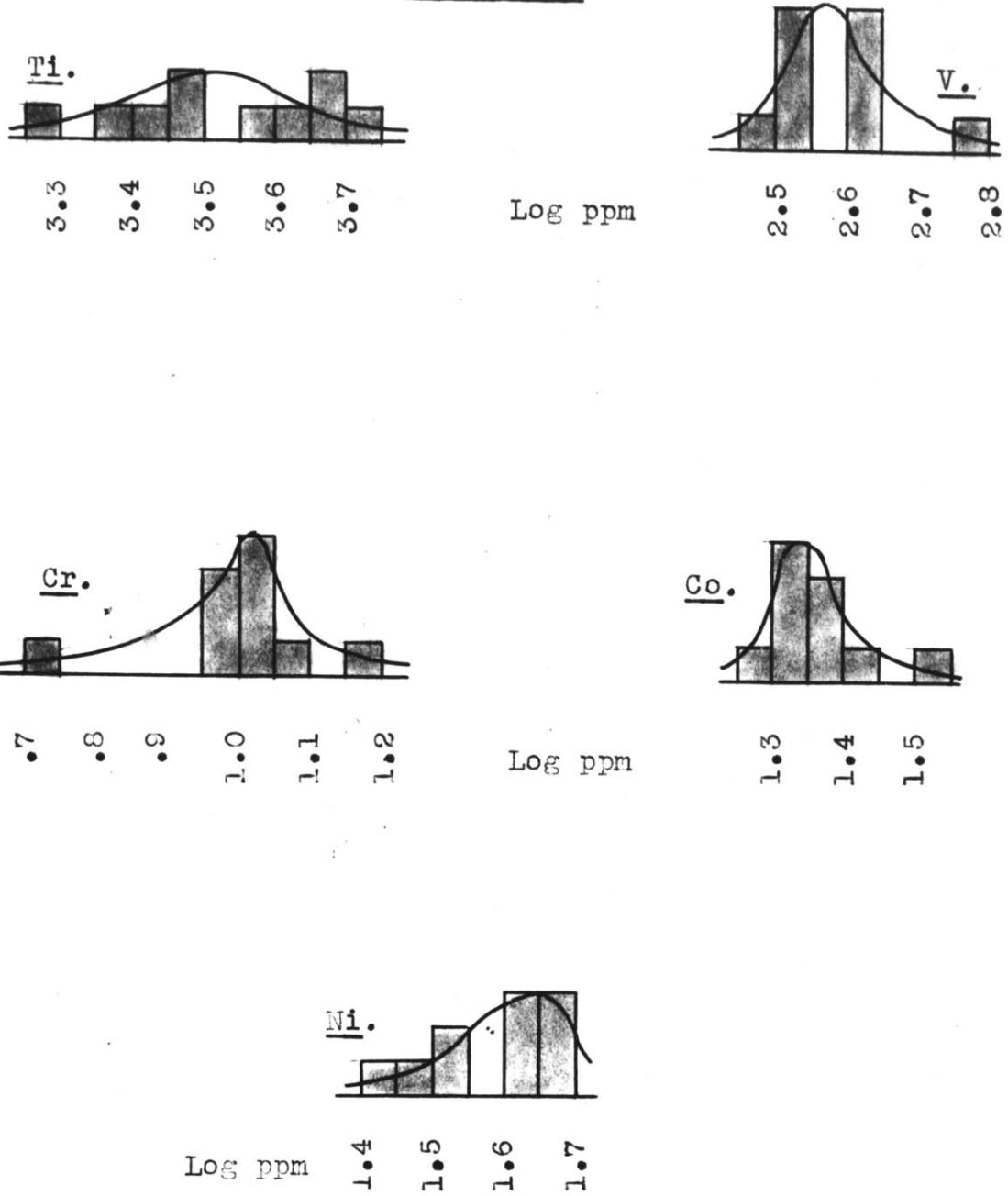


Figure III-11.

vein with a standard deviation of plus or minus 20%. For Cr the deviation is 34% and for Ti the standard deviation of the individual sample is about 40%. By averaging, we may generalize--the individual error is representative of the area sampled with a standard deviation in the magnitude of 30%, or roughly 3x the deviation of the individual analysis in this investigation.

This relationship of deviations indicates that the analytical technique employed is adequate for the volume of vein represented by each sample. If a more extended sampling method were used, e.g., the integration of many samples into a composite for each analysis, a more precise analytical technique might be of value.

The distribution characteristics of trace ferrides within a limited volume of magnetite vein is considered to be a function of the geochemical properties of these elements as well as of their genetic history. These characteristics would be different in other groups, for example Mg, Al, Si and P. Although numerically the standard deviation is affected by the size and pattern of the unit samples, in the relationships presented above it is seen to be fundamentally a function of geological distribution and therefore a characteristic of the vein. It is not a result of the techniques employed in determining this distribution.

F - TRENDS WITHIN THE MINE

RELATIONSHIP OF FERRIDE

CONCENTRATION TO DEPTH

The trace ferride analyses of samples taken at many locations in two ore shoots at Mount Hope indicate no clear systematic trend of tenor with elevation or position within the shoots under the conditions of sampling and analysis used in this investigation. However, slight possible trends may be observed, and the suggestion is noted of an increase in concentration of all trace ferrides at the surface.

Fig. III - 12 to III - 16 graphically display the concentration of trace ferrides in the samples taken at several elevations in the Teabo ore shoot and also in the Taylor.

Sample distribution was largely governed by the accessibility of vein in place. The Teabo ore body above 1400 level is mined out and is inaccessible except for a few locations on the 1000 level. Ore from near the surface may be obtained only by culling old mine dumps around abandoned shafts. There is always an element of doubt when using dump samples. The nature of the old mine openings as known from maps limits the area from which this material must have been mined, but the possibility exists that a piece of high grade ore taken from a dump may have been a part of a veinlet of ore or from a web or stringer zone, and not from a portion of the main ore body. It will be shown that magnetite veinlets and webs tend to contain

CONCENTRATION OF Tl vs. DEPTH

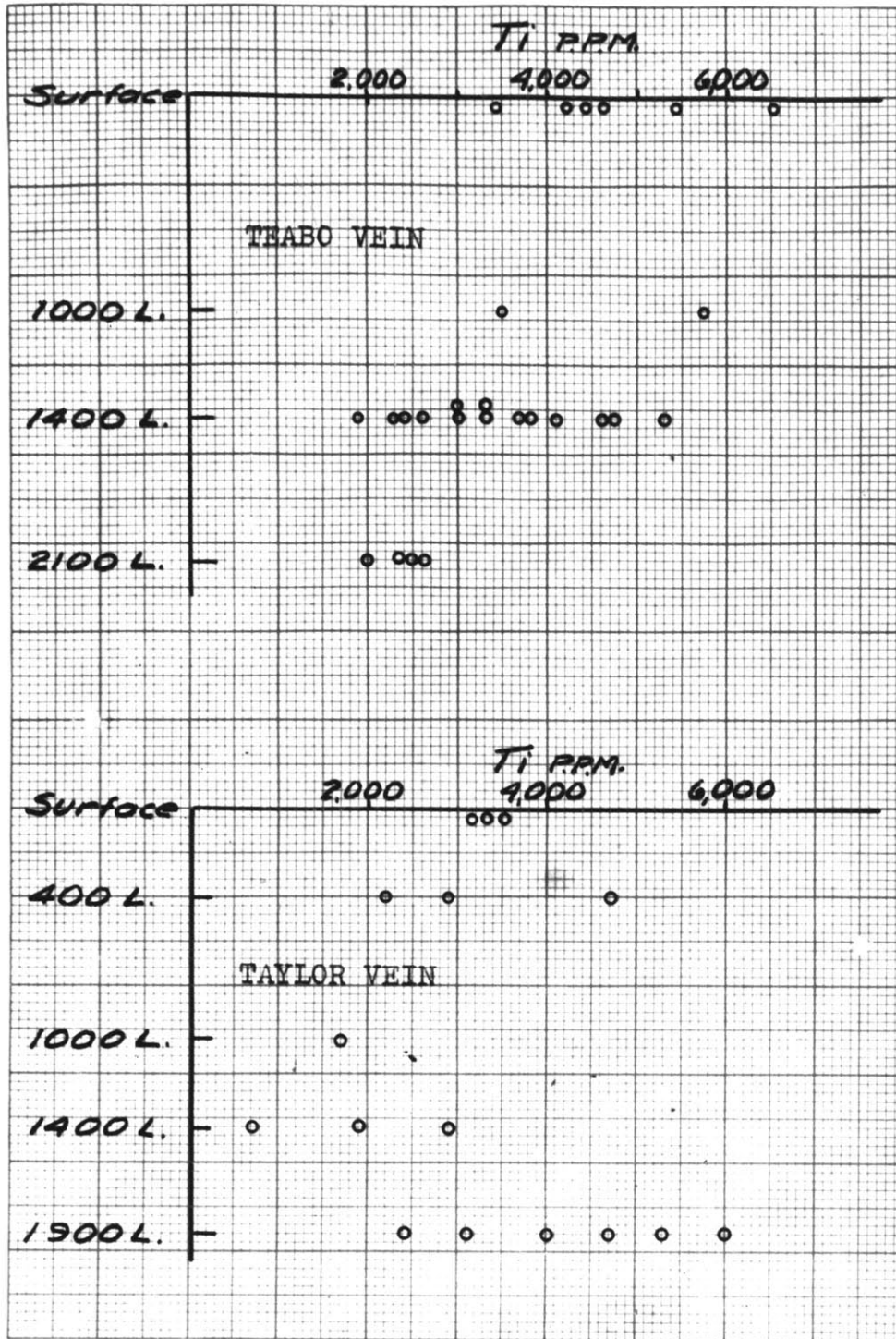


Figure III-12.

CONCENTRATION OF V vs. DEPTH

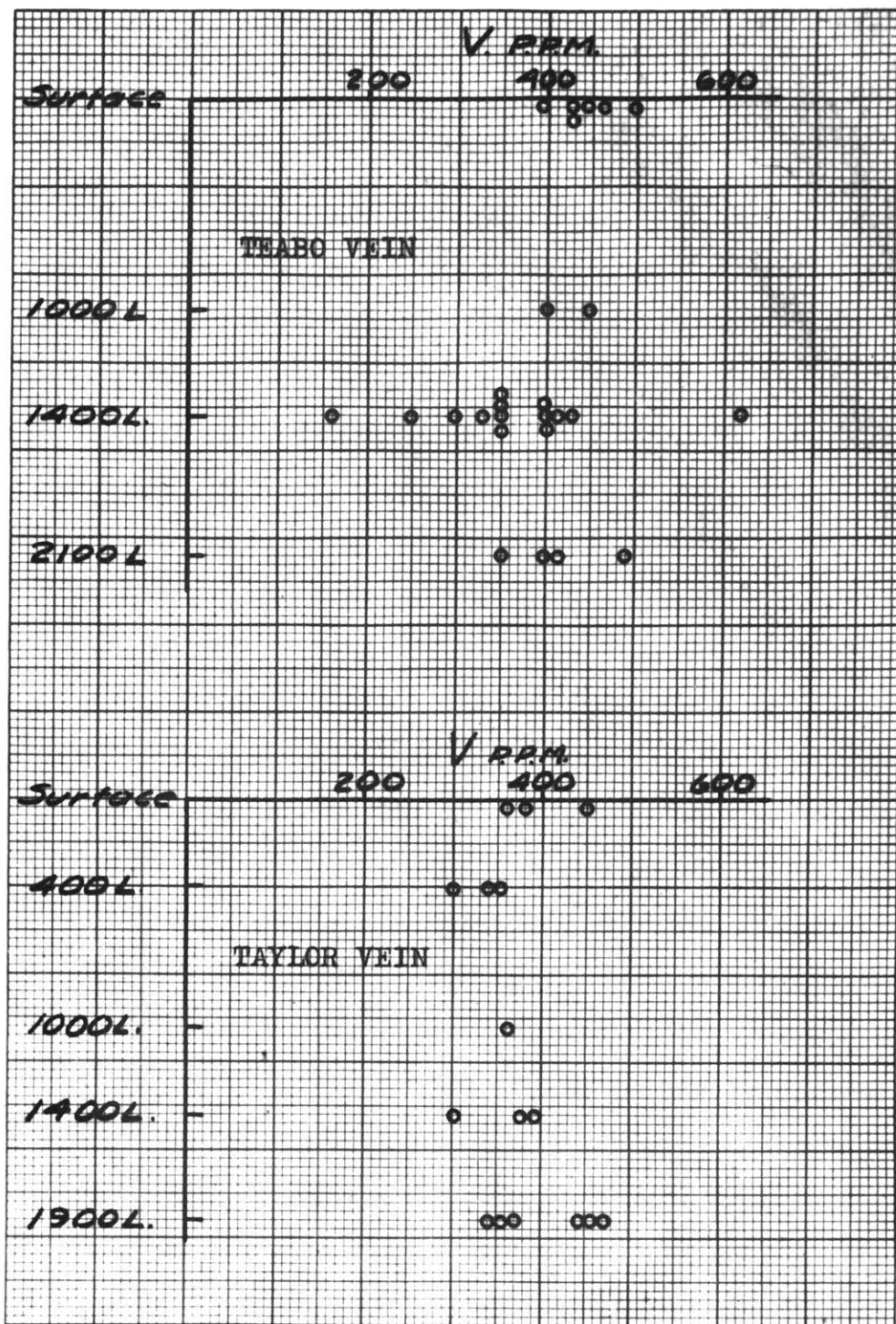


Figure III-13

CONCENTRATION OF Cr vs. DEPTH

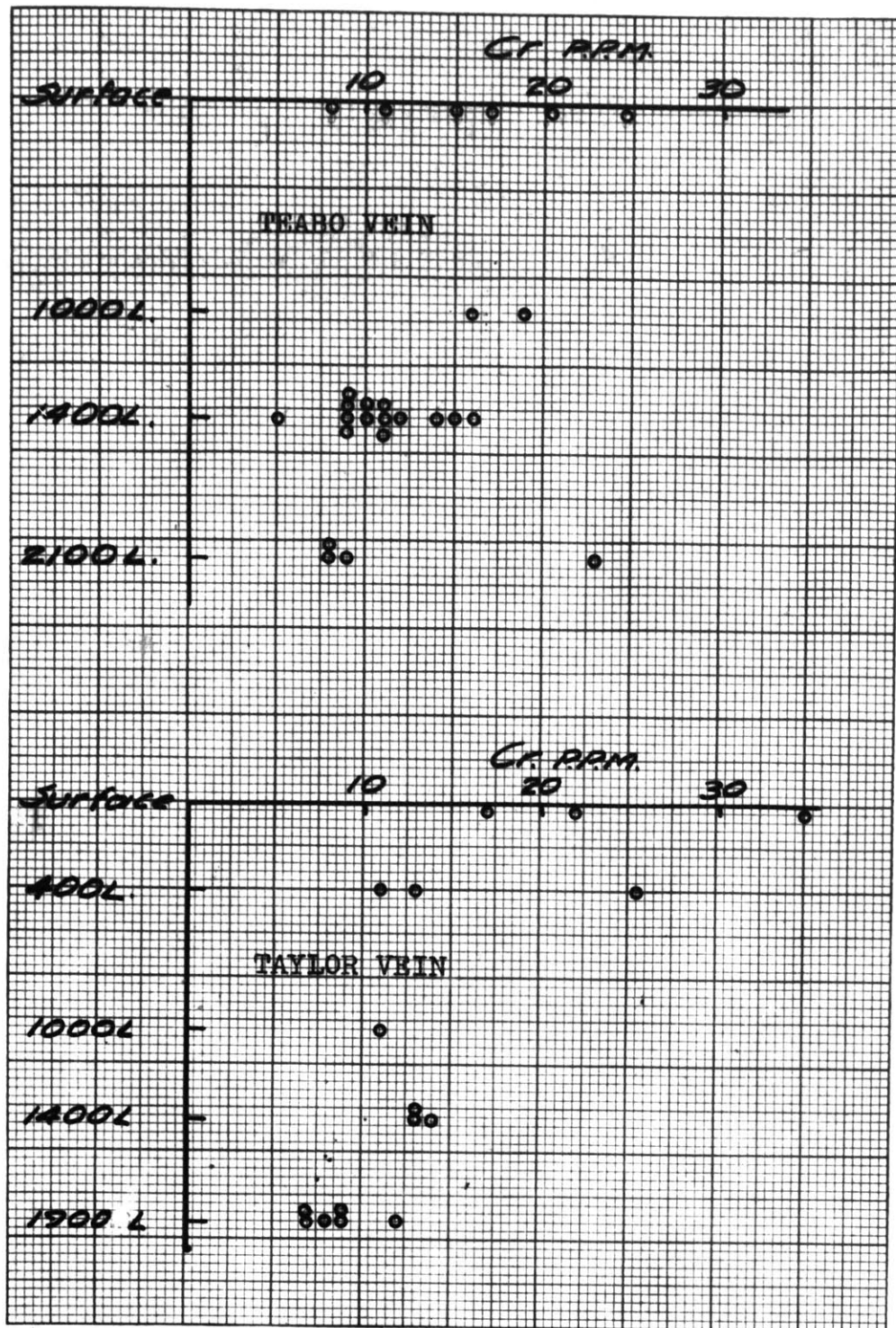


Figure III-14

CONCENTRATION OF Co vs. DEPTH

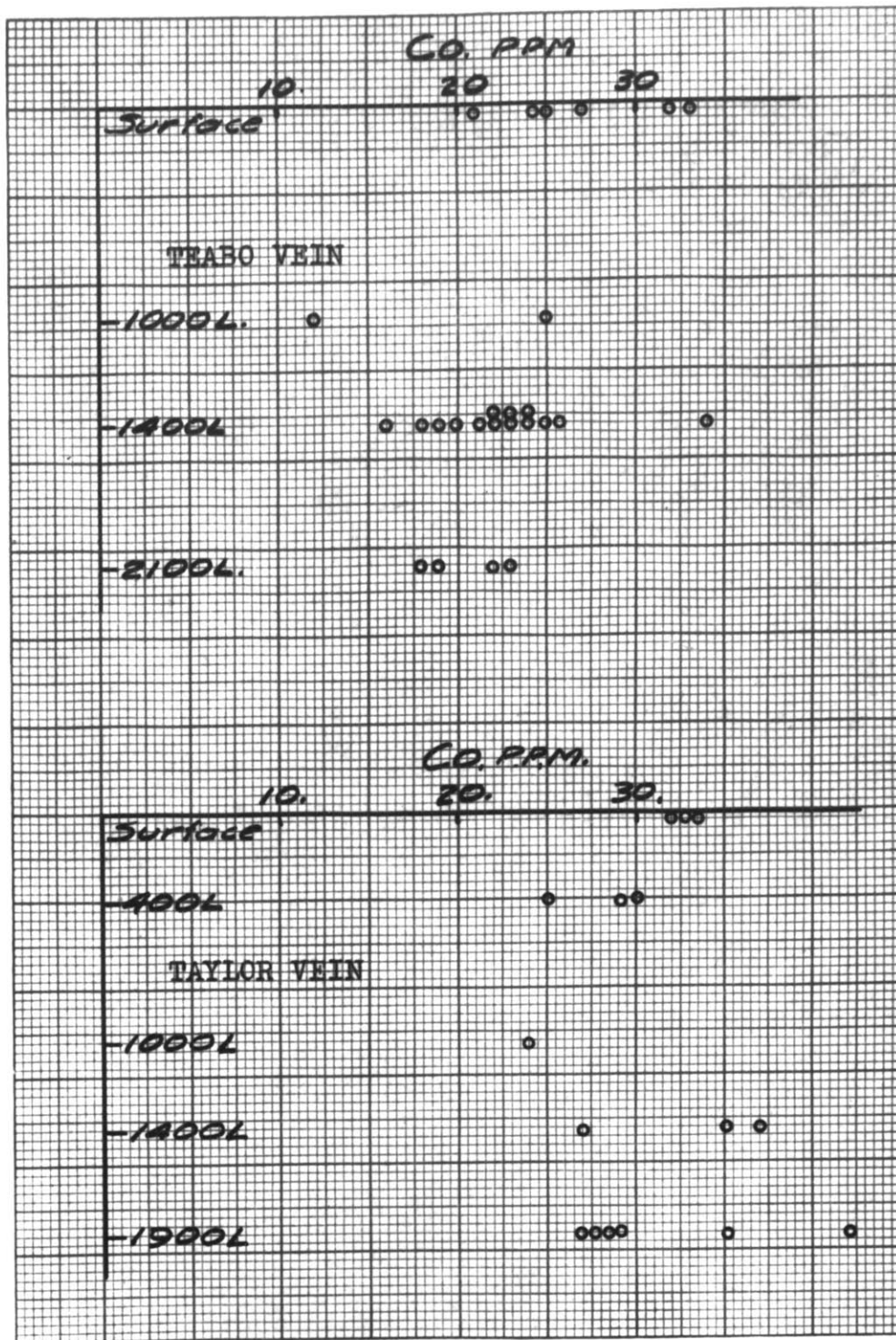


Figure III-15.

CONCENTRATION OF Ni vs DEPTH

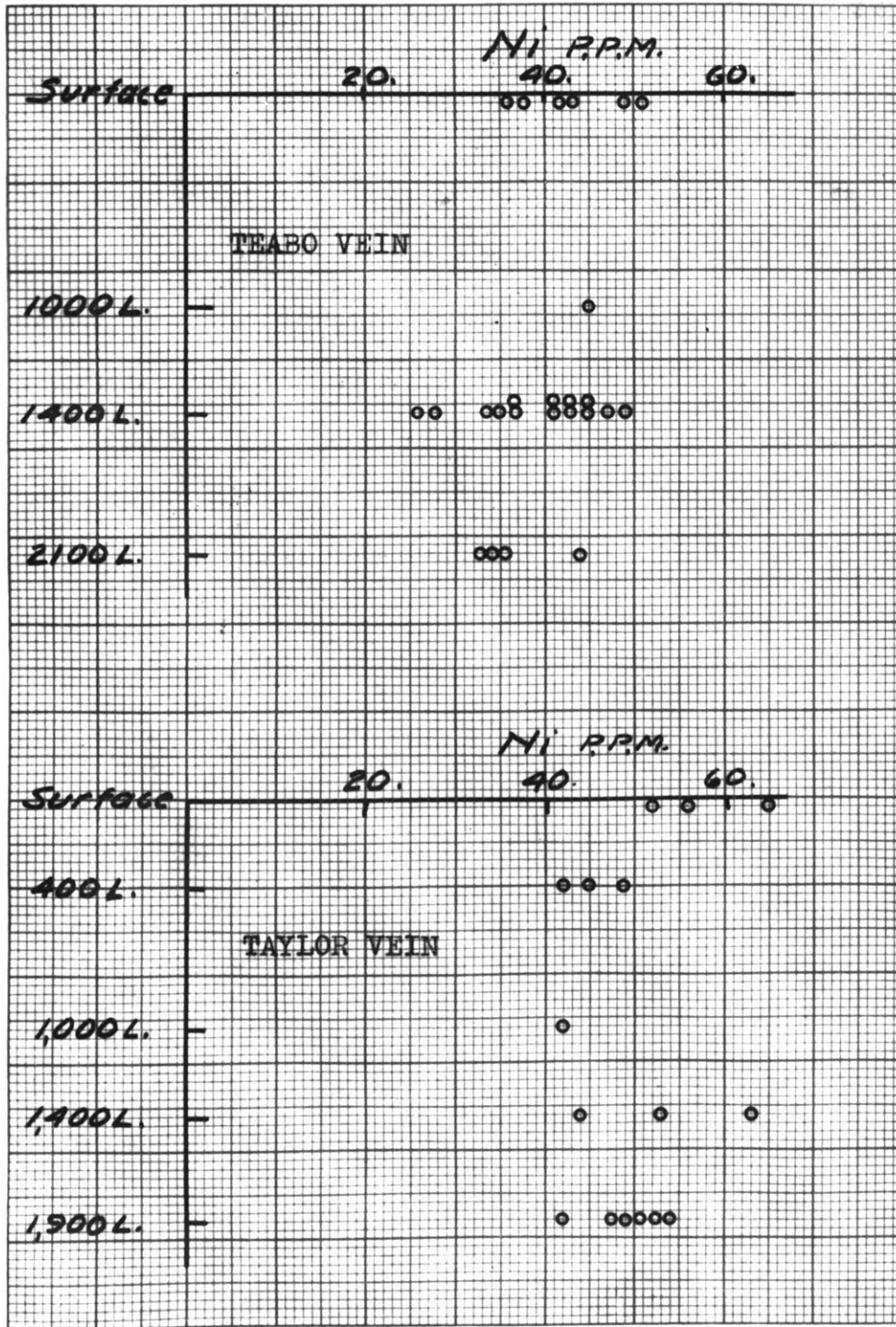


Figure III-16.

elevated amounts of certain trace ferrides, notably Cr; therefore, this surface material may be looked upon to suggest trends but should not be considered as strong evidence in support of vertical zoning.

The exposure of Teabo vein at 1400 elevation, Teabo 15-5 stope, was excellent, and the samples plentiful and well chosen to represent the vein cross-section at that position. The exposure on 2100 level is excellent, but inspection of the distribution of the analytical results indicates that insufficient samples were taken to distinguish statistically this elevation from 1400. Judging from the plots, the difference of means between 1400 elevation and 2100 for the trace ferrides, is in the range of 10% to 50%. Assuming that the standard deviation of log of samplings (λ), is 27% as found in 10 samples from the same area, that 14 samples represent 1400 level and 4 samples the 2100 level, the standard errors, $r = \frac{\lambda}{\sqrt{n}}$ (Sinnott and Dunn 1932) of the means is as follows:

$$r_1, \text{ for 1400} = \frac{27}{\sqrt{14}} = 7.2\%$$

$$r_2, \text{ for 2100} = \frac{27}{\sqrt{4}} = 13.5\%$$

The standard error of the difference of two means is

$$r_d = \sqrt{r_1^2 + r_2^2} = \sqrt{7.2^2 + 13.5^2} = 15\%$$

Thus, there is about one chance in 3 that the two such groups of samples would differ by 15% or more if taken from the same rock mass. A standard error of difference of 15% is too great

to permit statistical significance to be attached to possible differences in means ranging from 10 to 50%.

In the Taylor vein exposures were excellent in the area of present mine operations about 1900 level. Above this elevation, at 1400 elevation and 1000 level, accessible exposures are limited. Fortunately, moderately good exposures are accessible at 400 level, the only ore in place near the surface in the mine that can be reached for sampling. Surface samples from old pits were more satisfactory than the dump samples of Teabo, but material in place at the surface was not available.

Examination of the plots immediately suggests that different areas have distinctive analyses. Individual results are not completely random, but are related to location. Further, trends with change in elevation appear, and with limitations inherent in the small number of samples averaged, may be significant. Excluding the surface samples from consideration, half of the concentration trends are toward increase with depth, half show a decrease with depth. If surface samplings are included seven of the trends indicate an increase in trace ferride concentration at the surface:

		Ti	V	Cr	Co	Ni
Increase at surface	Teabo	I	I	I	I	I
	Taylor	-	-	I	-	I
Decrease at surface	Teabo	-	-	-	-	-
	Taylor	D	-	-	-	-

An increase of trace ferride content in higher elevations is most clearly marked in the case of chromium.

CORRELATION OF TRENDS WITH FACTORS

OTHER THAN ELEVATION

A persistent characteristic found in the plottings of Teabo vein is the high concentration of trace ferrides in the area of 1400 elevation when compared to 2100 level. Mine production sampling has indicated that total iron per unit of area and tenor in Fe of high-grade ore are approximately the same in the two areas. A distinctive difference in environment is found, however, in the presence of extensive "horses" of amphibolite included within the vein in the 1400 area. Amphibolite from this area (sample T131) has been shown to carry high concentrations of certain trace ferrides, notably Ti and Cr when compared to high grade-ore, and possible correlation between these concentrations and concentrations in the adjacent ore should be investigated. In the following tabulation the 1400 level is compared to the 2100 level (part 1.) and amphibolite is compared to high grade-ore (part 2.).

Location of high concentration is marked by X

1.		Ti	V	Cr	Co	Ni
	1400	X		X	X	X
	2100		X			
2.	Amphibolite	X		X		
	Standard BL		X		X	X

Thus, correlation of concentrations in the ore at 1400 level with concentrations in the associated amphibolite is found for three elements, and is not found for two. This sug-

gests no general correlation between concentrations in ore and concentrations in neighboring "horse" rock. A decisive test of such a possible correlation is beyond the scope of the present investigation.

Many other causes of the trends shown may be considered, but means to test the possibilities are not available. Hypothetical causes consistent with each of the commonly debated theories of ore genesis, (melts, replacements, and sediments) might be as follows: 1. For melts; incomplete mixing, local wall rock contamination, local differences in differentiation products; 2. In a metasomatic ore; differences in original concentration in host rock, changes in channelways during ore deposition, or changes in concentration of mobile phase due to reaction; 3. In ores of syngenetic origin such trends might be due to variations in source and distribution of sediments.

TABLE III - 4

DIFFERENCES IN THE MEANS OF TRACE FERRIDE CONTENT

BETWEEN TWO ORE SHOOTS

TEABO AND TAYLOR

Line	<u>Ti</u>	<u>V</u>	<u>Cr</u>	<u>Co</u>	<u>Ni</u>	<u>Average</u>
1. Teabo Ore Shoot - T Teabo, 19 Samples Mean, P.P.M.	3,100	350	10	22	40	
2. Log Normal Deviation of Mean - % = λ_t	36	17	59	28	34	35%
3. Standard Error of Log of Mean, % = $r_t = \frac{\lambda_t}{\sqrt{n}}$	8	4	13	6	8	8%
4. Taylor Ore Shoot - Y Taylor, 16 Samples, Mean, P.P.M.	3,200	370	13	30	50	
5. Log Normal Deviation of Mean, % = λ_y	41	12	60	18	15	29%
6. Standard Error of Log of Mean, % = $r_y = \frac{\lambda_y}{\sqrt{n}}$	10	3	15	5	4	7%
7. % Difference - Teabo Mean, Taylor Mean	3	5	30	36	25	20%
8. Standard Error of Difference $r_d =$ $\sqrt{r_t^2 + r_y^2}$	13	5	20	8	9	11

here:

	Ti	V	Cr	Co	Ni	Av.
% difference in concentration, Teabo and Taylor ore shoots	3	5	30	36	25	20
Standard error of difference	13	5	20	7.5	19	12

The difference in the means of two groups of samples is significant statistically when this difference, expressed in per cent, is several times the standard error of the difference calculated from the normal deviation of each group and the number of samples in each group (Sinnot and Dunn 1932).

In two of the five ferrides compared the difference in means is less or equal to the standard error of difference. In two, the difference in means is less than 50% greater than the standard error of difference. Only in cobalt is the difference in means several times the standard error of difference. Thus the samplings and analyses demonstrate no strong and consistent statistical difference in trace ferride content between the two ore shoots. This is indeed significant considering the magnitude of the major and trace element differences existing throughout the host rocks.

H - CONTACTS, VEINLETS AND WEBS

Several distinctive geological samples, important additions to the body of evidence diagnostic as to ore genesis, were analyzed. These were magnetites near ore contacts with wall rock, magnetite from small veinlets in the walls of ore bodies, and the material, approximately 50% magnetite, from the "ore web" connecting two ore shoots, localized in the same lithologic horizon.

CONTACTS

The analytical results of the near-contact material, magnetite, selected from points about three inches from footwall and hanging wall contacts of the Teabo vein with the O.Q.B. gneiss rock walls, is shown on the Teabo vein cross sections, Fig. III-1. No consistent relationship or trend of relationship between these contact samples, the more centrally taken ore samples, and the wall rock samples is discerned. In this suite the contacts are very similar to central portions of the vein in ferride content, and similarly, it is thought that ferride content of the contact samples is unrelated to tenor of trace ferrides in the wall rocks. However, it is possible that a series of closely spaced samples taken across the contact might show systematic changes in trace ferride content similar to the smooth and continuous variations found by Dennen (1951) across igneous contacts. It is suggested that any further research on the trace ferrides of the Jersey Highlands include several suites of samples closely spaced across well-chosen

geological contacts. Only by this type of investigation can the effects of contamination by wall rock on average and local ferride content be reasonably appraised. The results of veinlet analysis, e.g. high chromium content, suggest the likelihood that systematic smooth changes might be found if a small enough sample interval were chosen.

VEINLETS

A massive magnetite veinlet $3/4$ inches thick crosscutting O.Q.B. gneiss was found and sampled (E126) about 10 feet in the foot wall of Elizabeth vein. A second veinlet, a carbonate-filled fracture varying from $1/4$ inch to one inch wide, the walls of which were lined with a $1/8$ inch thick layer of sub-hedral magnetite crystals was found in a rock slab of O.Q.B. and amphibolite on the old Teabo No. 2 dump. (Photo, Fig. III-17). The magnetite encrusting the walls of this veinlet, cleaned magnetically (T 97 c) was also analyzed. The similarity of trace ferride concentration in both of the veinlets and in the ore of the main vein is remarkable. Only in chromium, which is enriched in the veinlets, is a substantial difference found (see also Figures V-1 to V-5).

From the mode of occurrence of the carbonate-filled veinlet, it is clear that the layers of magnetite crystals covering its walls were deposited from solution or from the vapor phase. The similarities in trace ferrides strongly suggest that the massive magnetite ore bodies were formed at the same time and within a similar environment.

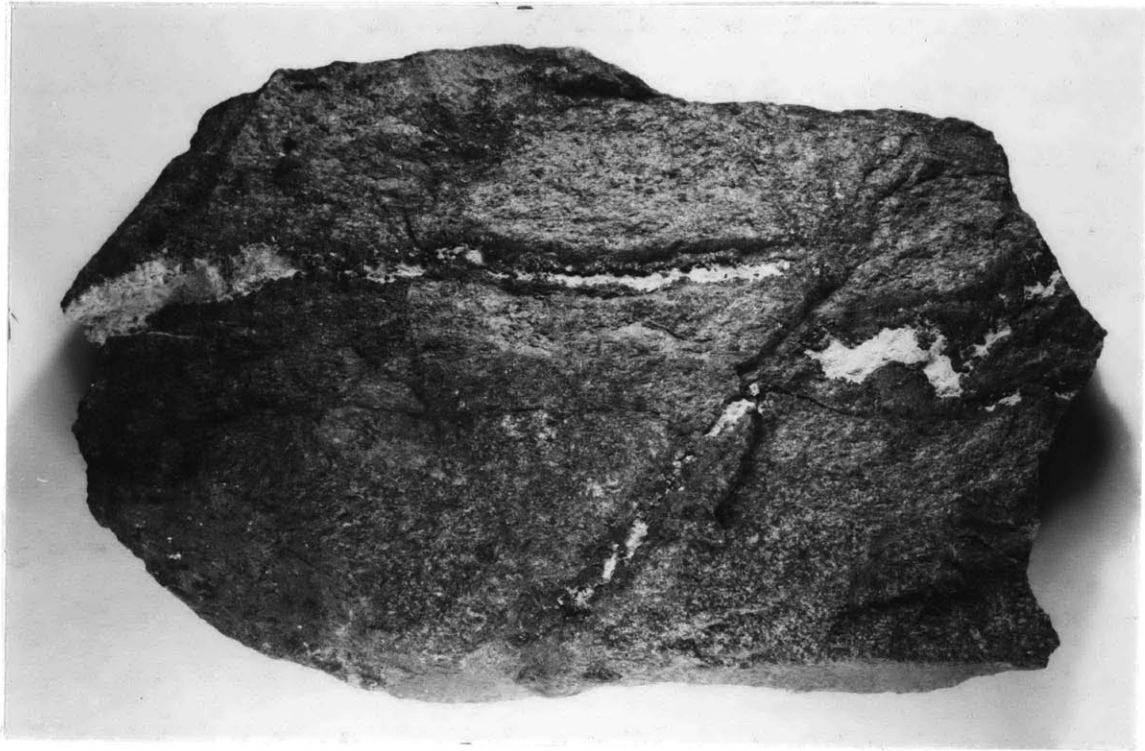


Fig. III-17 Carbonate filled veinlet. Subhedral magnetite crusts (black)

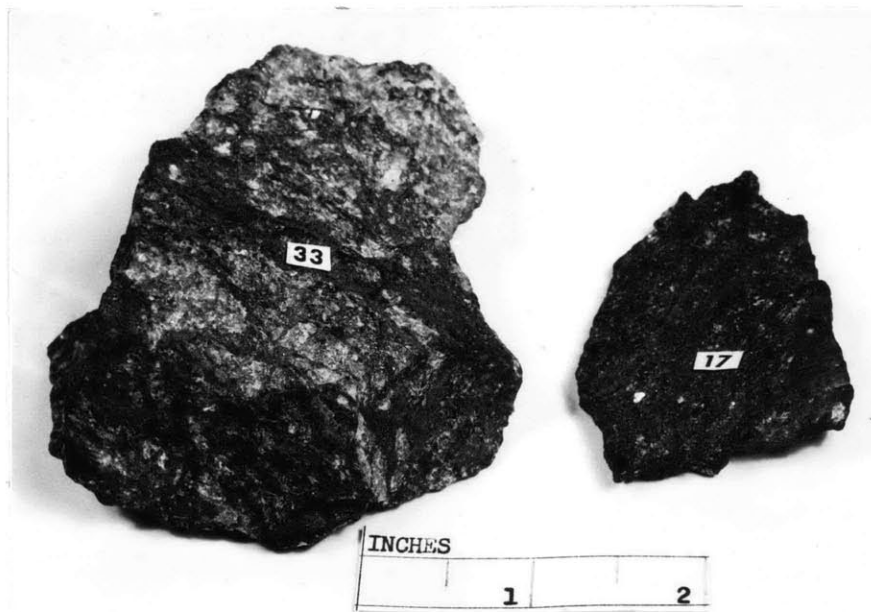


Fig. III-18 Specimens of low grade web.

TABLE III - 5

WEB CONNECTING ORE SHOOTS, VEINLET,

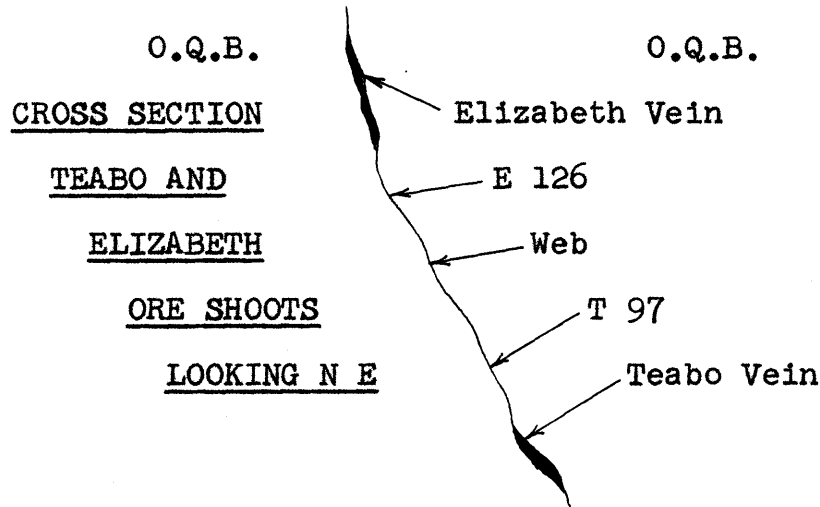
CARBONATE - FILLED VEINLET

	PPM				Ni	Soluble Fe %
	<u>Ti</u>	<u>V</u>	<u>Cr</u>	<u>Co</u>		
17-Web, connecting Teabo and Elizabeth ore shoots, including dark gangue, much amphibole, pyroxene plagioclase - 1000 Level	4,100	160	29	23	26	43.
33-Web like 17, but light gangue, brecciated OQB gneiss, included 1700 Level	4,100	180	26	12	28	30.
T-97C Veinlet with Magnetite crystal crusts, carbonate filling, Magnetic Concentrate	4,800	500	74	18	30	
E-126C, 3/4" Magnetite Veinlet in footwall. Magnetic Concentrate	3,500	470	100	27	46	
Standard High-grade BL	3,300	390	9	13	39	
OQB- Average of 4 Samples	3,900	80	23	10	28	

The high chromium content in the veinlets, enriched 8 to 11 times relative to ore, is believed to have been derived from ore solutions enriched in Cr by intimate contact with the rock walls of the small fissures.

WEBS

The web samples were taken about 150 feet below the bottom of the blade of the Elizabeth Vein (E126) and 150 feet above the top of the Teabo Vein (T 97) (photograph, Fig. III-18).



The "web" material analyzed is 30% to 43% soluble iron (i.e. about half magnetite). The remainder appears to be principally quartz and minor amounts of ferromagnesian minerals. It is a low grade ore and is quite similar to some of the ores within the ore blades. The abundances of trace ferrides in the web were found to be similar to those in ore and to those found in the veinlets with the exception of V, which is half as abundant in the web, and Cr, which, while enriched in the web is less concentrated than in the veinlets. As in the veinlets it is believed that high Cr in the web was deposited from ore

VEINLETS, WEBS and O.Q.B. GNEISS

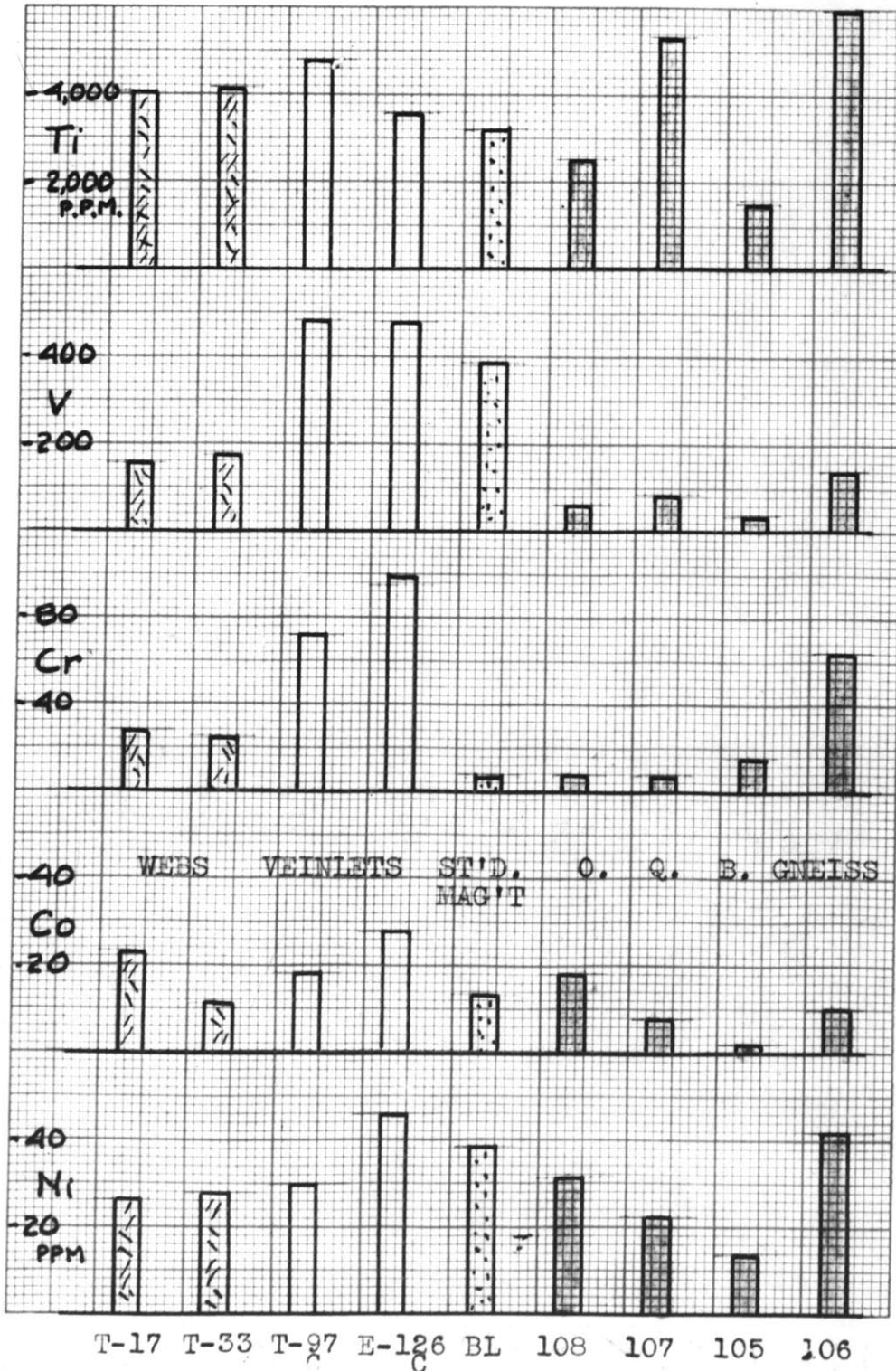


Figure III-19.

solutions enriched in Cr during extended migration of the ore-transporting medium in intimate contact with the wall rock. It is suggested here that V, which has showed a strong preference for magnetite when studied in ores, minerals and gangues, was depleted in the ore-forming fluids during its extended percolation through the fine-grained magnetite breccia probably existing in the web.

The similarities in trace ferride content of veinlets, web, and high grade ore is very convincing evidence of consanguinity of the three materials. Such a conviction may be shaken when one considers the further similarity to the averages of all of the trace ferrides in four OQB gneiss host rock samples. It will be recalled, however, that the wall rock averages were made up of individual samples which differed by factors ranging up to 10, while the abundances within the web and also within the veinlets appear to be more consistent. (Fig. III-19). Therefore, the correlation of trace ferride content in massive ore and in veinlets and webs is thought to be strong and valid.

CHAPTER IV
DISTRIBUTION OF THE TRACE FERRIDES
IN SEVENTEEN NEW JERSEY ORE SHOOTS

A - BAYLEY'S HIGH TITANIUM BELT

Bayley in 1910 observed that several of the mines including and lying north of the Van Syckle's were high in Ti, and that if analyses were available for all New Jersey mines and prospects, a belt of magnetite deposits high in Ti might be found to exist. It may be assumed that early mine operators commonly recognized the presence of Ti in concentrations greater than 1.5%, as furnace men who bought the ores objected to this element for metallurgical reasons. At concentrations lower than this the element was probably not reported. In the descriptions of several hundred mines left by Bayley analyses for Ti were included in about 50. Ten indicated a Ti content of 1.5% or more. These mines are listed in the appendix and plotted on the map of the Highlands, (Fig. IV-1). It is seen that they are aligned approximately in one bifurcating band.

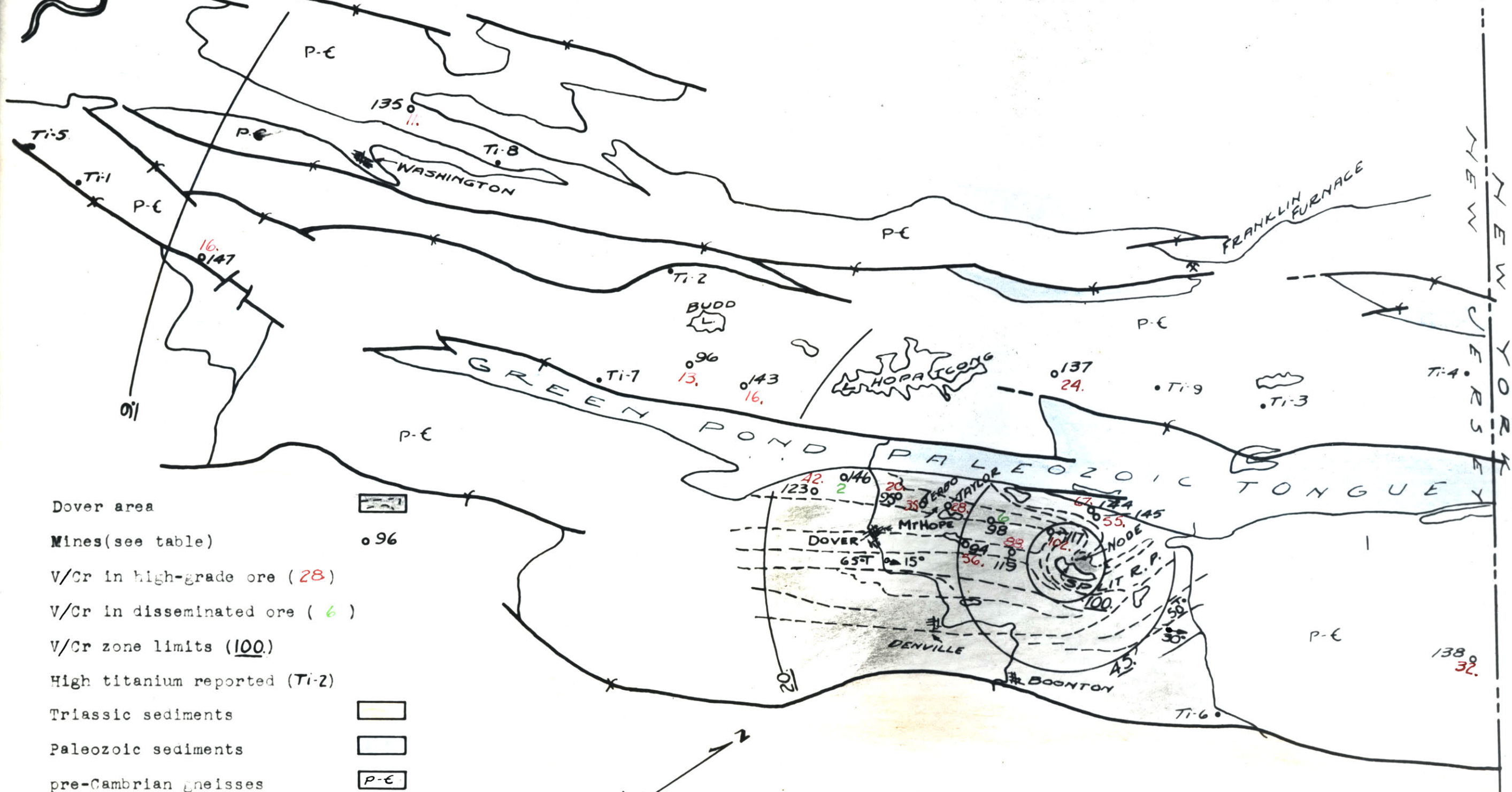
Not enough is known of the details of Highland geology to permit a reasonable explanation of the possible concentration of titanium in the zone mentioned by Bayley. Only one mine in the belt, the Van Syckle's, was sampled in this investigation. These deposits, west of Dover, together with the Jackson's prospect, to the east, could be described as high-titanium zones flanking the Dover area. However, it is equally possible

that these concentrations are related to rock types high in Ti, to original sedimentary horizons, or, as many of the deposits are located close to major Paleozoic displacements, to fault channels outside the Dover area. Much more information should be made available before a geological explanation of this possible high-titanium belt or zone is attempted.

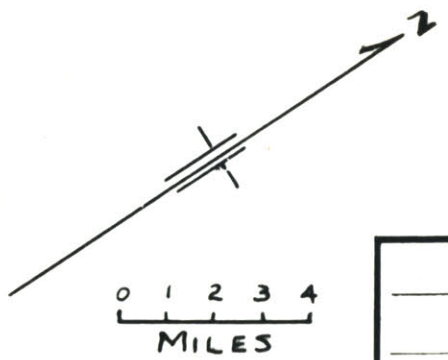
Bayley's statement concerning a possible belt high in titanium is the only reference found describing a pattern of minor elements in the magnetites of New Jersey.

PENNSYLVANIA
DELAWARE R.

Geology:
General--H.3.Kummel, et al, 1933.
Dover area (shaded)--Sims, 1953.



- Dover area
- Mines (see table)
- V/Cr in high-grade ore (28)
- V/Cr in disseminated ore (6)
- V/Cr zone limits (100)
- High titanium reported (Ti-2)
- Triassic sediments
- Paleozoic sediments
- pre-Cambrian gneisses
- Faults
- Lithologic structure
- Plunge of linear elements
- Dip and strike of layers



GEOLOGY--THE NEW JERSEY HIGHLANDS		MT. HOPE MINE	
		DATE	FIG. IV-1. PLATE III-
		SCALE 1"=4 miles	
		BY	

B - VARIATIONS WITHIN THE HIGHLANDS
THE DISTRIBUTION OF THE TRACE FERRIDES

The present investigation was initiated in order to study the distribution of trace ferrides and the possibility of metal-ratio zoning in the Mount Hope mine. However, in order to relate these ores to others in the same geological province, samples from 15 neighboring mines and prospects were taken (Fig. IV - 2 and appendix). In the light of the results at Mount Hope, analyses from the other mines have proved interesting and are presented here as a preliminary investigation or reconnaissance of the distribution of trace ferrides in magnetites of the Highlands.

It has been shown that in general the results of the spectrographic analysis for trace ferrides were accurate with a standard deviation of about 10%, the exact figure differing for the several elements. The individual sample was found to represent, with a lognormal deviation of about 27%, the cross section of an ore shoot and to represent an entire ore shoot with a deviation of 36%. Thus the distribution of trace ferrides throughout the entire shoot is nearly as uniform as within one cross section. The examination and comparison of neighboring ore shoots, the Teabo and Taylor, indicated that although they occurred in different host rocks, the ferride content of one could not be clearly distinguished from the other.

In the comparison of deposits of slightly greater geographical separation, some similarities are noted. For example,

MAGNETITE FROM 17 NEW JERSEY MINES
LOG OF CONCENTRATION--TRACE FERRIDES

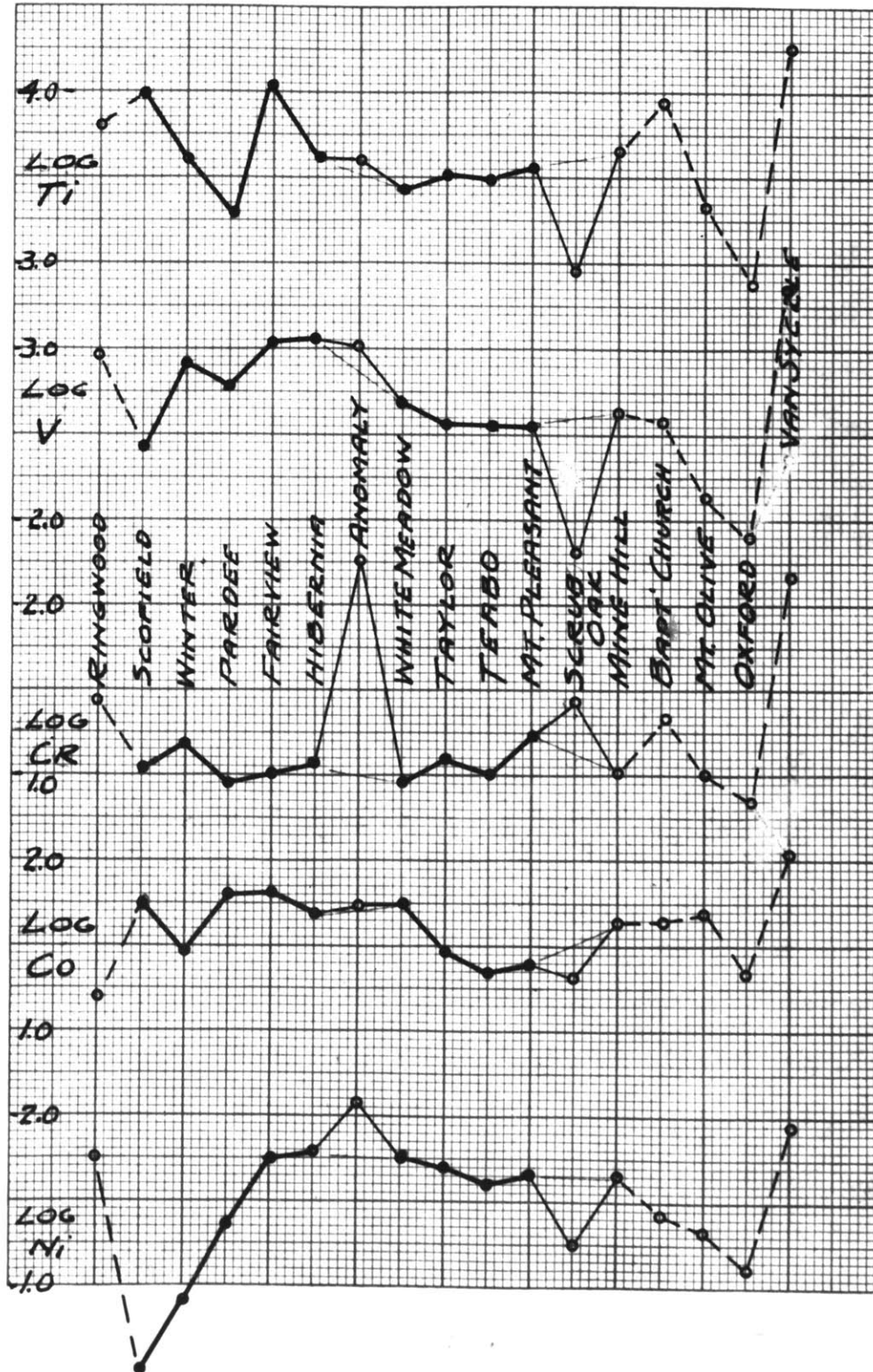


Figure IV-2

the Fairview and Hibernia mines, adjacent geographically, are similar in trace ferride content. The White Meadow vein and Mt. Hope, close neighbors, are related as to trace element concentration. As Fairview and Hibernia are found at the same lithologic horizon; similarities might therefore be expected for several reasons. However, White Meadow and Mount Hope are found in separate horizons, and an explanation other than horizon and host rock similarities must be sought. Deposits further separated often appear to have greater differences in trace ferride content. When the comparison of sample groups is extended to all of the 16 mines sampled in New Jersey, we find that some of the deposits are quite distinctive in analysis and that the lognormal deviation of the entire group has risen to about 150%. However, histograms show a fairly smooth distribution of abundances of trace ferrides (Fig. IV - 3) and suggest that all deposits are related. The more enriched and impoverished deposits e.g. Van Syckle's and Oxford mines, appear to be normal variants within the group.

Table IV-1 represents for convenient comparison the deviations of replicate analyses, the deviations of repeated analyses of one ore shoot, and the deviations of the samples from 16 mines in the New Jersey Highlands. It may be noted that in general the analysis deviation times 4 equals the shoot deviation, the shoot deviation times 4 equals the district deviation.

On Fig. IV-2 the log of each trace ferride abundance has

DISTRIBUTION CURVES

TRACE FERRIDES IN 17 N. J. MINES, ORE SHOOTS, AND

PROSPECTS

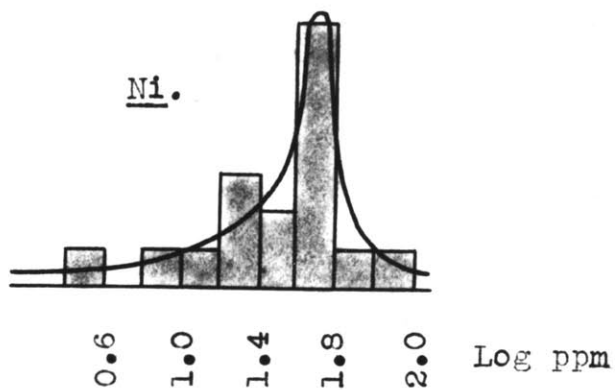
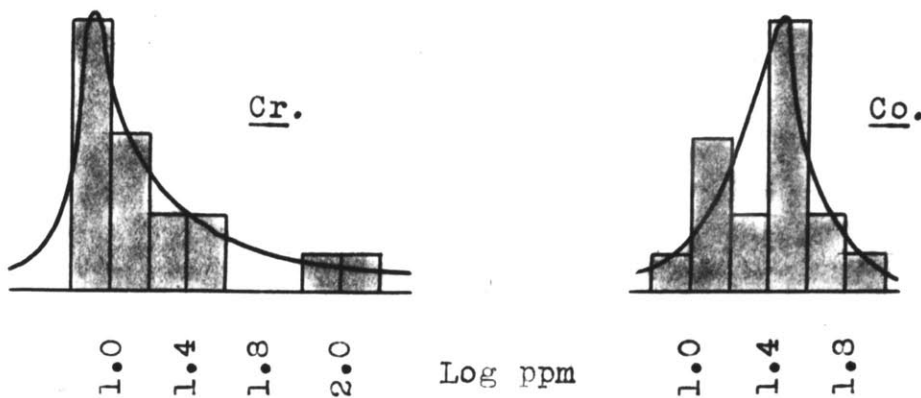
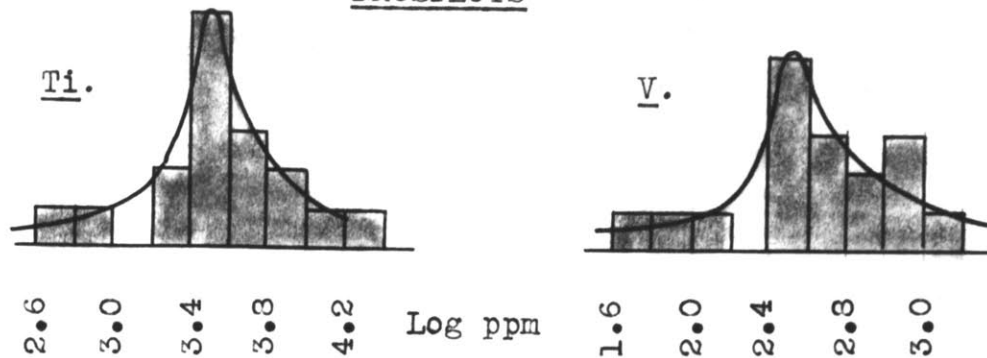


Figure IV-3.

TABLE IV - 1

LOGNORMAL DEVIATION
ONE SAMPLE, ONE ORE SHOOT, THE MINING DISTRICT

	<u>Percent Lognormal Deviation of</u> <u>Trace Ferride Concentration</u>					
	<u>Ti</u>	<u>V</u>	<u>Cr</u>	<u>Co</u>	<u>Ni</u>	<u>Average</u>
One Sample - BL 9 determinations	6	7	13	13	9	10
One Ore Shoot (Teabo) 19 Samples	36	17	59	28	34	35
17 New Jersey Mines	144	182	176	66	182	150

been plotted for each of the 17 New Jersey Mines. Here the ore bodies are arranged in geographical order from northeast to southwest. This arrangement is also related to the distance from each deposit to the Split-Rock Pond node. The Fairview is the closest to the node. The mines to the left of the Fairview are progressively further from the node in the northern sector, those to the right progressively further in the southern sector. The disseminated ores, Anomaly and Scrub Oak, are plotted lightly, as they are not high grade magnetites and may be expected to depart from the magnetite pattern. Mines in the northwest half of the Highlands, separated from the Dover area by the Green Pont Paleozoic tongue, are plotted with dotted lines, as the geological relationships between areas are not known, distances are great, and information fragmentary. The Ringwood mine is plotted similarly for similar reasons.

THE POSSIBILITY OF STRUCTURAL CONTROL

A study of these plots immediately suggests possible concentration trends related to geographical position.

If these ores are of hydrothermal or pneumatolitic origin it is possible that here as in many epigenetic ore districts mineralization activity was controlled by a structural disturbance which deformed, broke, and brecciated the earth's crust, permitting passage of the ore-forming medium from great depths to the surface. Often the structural disturbance is related genetically to the source of the ore fluids, as in the case of ores associated with intrusives. In such cases metal ratio

zones, crosscutting stratigraphic or lithologic elements, are commonly related to these centers of structural and magmatic activity.

THE V-CR RATIO--POSSIBLE ZONING

In this investigation, we have seen that magnetite from veinlets distant from centers of mineralization shows enrichment in Cr, presumably leached from the veinlet walls during extended travel of the ore-transporting medium. The web ores, assuming metasomatic origin of the magnetites, appear to have been similarly enriched in Cr. Likewise the ores of the ore shoots appear to have been enriched at higher elevations, at greater distance from the assumed source of mineralization.

The behavior of V has been found to be the opposite of the behavior of Cr. V is closely coherent with iron. It is more enriched than other trace elements in the magnetic concentrates and relatively depleted in non-magnetic fractions. It is impoverished in webs where ore fluids are assumed to have percolated through much fine grained magnetite which depleted them of vanadium before they reached the sample site. It also showed a slight tendency to concentrate at depth, closer to the assumed source of mineralization.

As Cr concentration in magnetite appears to be a direct function of distance from the structural center, while V concentration appears to be an inverse function, the ratio of the two, V/Cr, should show a maximum of gradient with minimum of irregularities due to secondary causes if plotted geographically

in relation to the postulated structural center of mineralization.

On the map of the Highlands, Fig. IV-1, has been plotted the location of the 17 New Jersey mines studied together with their V/Cr ratios. In the area of known geological detail (Sims, 1953), generalized structure lines have been plotted. These lines approximate the strike of the lithologic layers in this area. The dip of layers and the plunge of the linear element are also shown.

An examination of the structural pattern and of the distribution of the V/Cr values indicates that the Split Rock Pond node, at the intersection of the NE and northerly striking areas and in the trough of the Split Rock Pond syncline, may be tested as a center of structural deformation and foci of epigenetic mineralization. On Fig. IV-1, using the node as a center, circular zones have been outlined in such a manner that the V/Cr ratios for each mine within the Dover area fall within limits designated for the zone embracing that mine. It is noted that regular zones increasing geometrically in radius and regular ratio limits, decreasing geometrically in magnitude may be constructed. (The radii of the zone limits are 1.33×3^n miles; the zone limits are 100×0.45^n in V/Cr, where $n = 0, 1, 2,$ and $3.$)

All of the high grade New Jersey mines analyzed fit into this pattern if we stretch the limits elliptically a bit along the structural trend to cover Ringwood. (If zones really exist,

it is probable that they are elongated to structural lines.) However, a state-wide zonal assumption based on such incomplete information with many prospects not sampled and wide expanses of complex geology unstudied, does not seem justified at this time even as a preliminary working hypothesis. It seems probable that a detailed study of an area as large and complex as the Highlands would reveal not one but several structural foci of mineralization. Zonal patterns conforming closely to that of V/Cr could be constructed for the Ni/Cr ratio and for the Ni/Ti ratio. However, the behavior of Ti and Ni have been less distinctive in the materials studied and theoretical justification for the zones so established is less evident.

A METASOMATIC GENESIS SUGGESTED

Although information is inadequate to support a strong argument for metasomatism, these rough zonal arrangements cross-cut all structural elements and suggest an epigenetic hydrothermal or pneumatolytic control of the trace ferride concentration. If, in a comprehensive study of this area, such a systematic distribution of trace ferrides were substantiated, strong evidence of epigenetic origin of these ores would be made available.

CHAPTER V
COMPARISONS WITH OTHER IRON ORE DISTRICTS
A - GEOCHEMICAL COMPARISONS
INFORMATION AVAILABLE

A graphic survey of trace ferride concentrations in the iron ores of several well-known iron mining districts and a comparison of these with the magnetites of New Jersey is presented in Figs. V-1 to V-5. The plottings of New Jersey ores are from the determinations made during this investigation; the remaining ten districts, three from the United States and seven from Europe, are plotted from analyses published by Landergren (1948). Reference to Landergren's table and sample numbers for the material plotted is in the appendix. Landergren's analyses were made by spectrographic methods, some with internal standards and some by comparison with known standards, except samples high in Ti, which were analyzed chemically. Landergren's work "On the Geochemistry of Swedish Iron Ores and Associated Rocks --a Study on Iron-Ore Formation" is a monumental study describing the geochemical relationships of trace ferrides and other elements as found in the Swedish iron ore districts.

In the graphic comparisons each available analysis has been plotted as a point and the total range of analyses blocked in with solid lines. Representative analyses from each of the 16 New Jersey ore-shoots studied likewise have been plotted. In addition, the geometric mean, the log-deviation, (λ), and

twice the log deviation, 2λ , of the Teabo vein at the Mount Hope mine have been plotted in order to display the range of variation to be expected in one ore shoot. A similar plotting has been made of the mean, λ and 2λ for the replicate analysis of the standard high-grade magnetite sample, BL. In normal distribution, 95% of all samples will fall between $\pm 2\lambda$ and -2λ . To aid in illustrating the discussions of ore genesis which arise in chapter III, H, the abundances of four samples of veinlets and web from Mount Hope mine are also plotted.

A desirable method of presenting the trace ferride analyses of numerous samples from several mining districts would be by means of distribution curves; however, histograms plotted for these suites indicated that the number of analyses available was insufficient to permit the plotting of meaningful curves. Further, the material analyzed by Landergren was from museums, from collections sent by other governments, etc., and information regarding the manner of selecting the individual samples comprising the suites was not available. It is probable that some suites were chosen to represent each of several distinct commercial products, others possibly were chosen to represent the most typical geological examples, still others to represent the extremes of geological interest. Therefore, it seemed best to plot each analytical result, thus showing the abundance range, but avoiding distributional interpretations based on inadequate information.

In the following paragraphs will be found a brief des-

COLOR KEY TABLES V-1 TO V-5

YELLOW--sedimentary ores including secondarily enriched
sediments.

BROWN---lateritic ores.

GREEN---ores of metasomatic derivation.

BLUE----Kiruna type ores, Sweden.

PURPLE--high titanium ores.

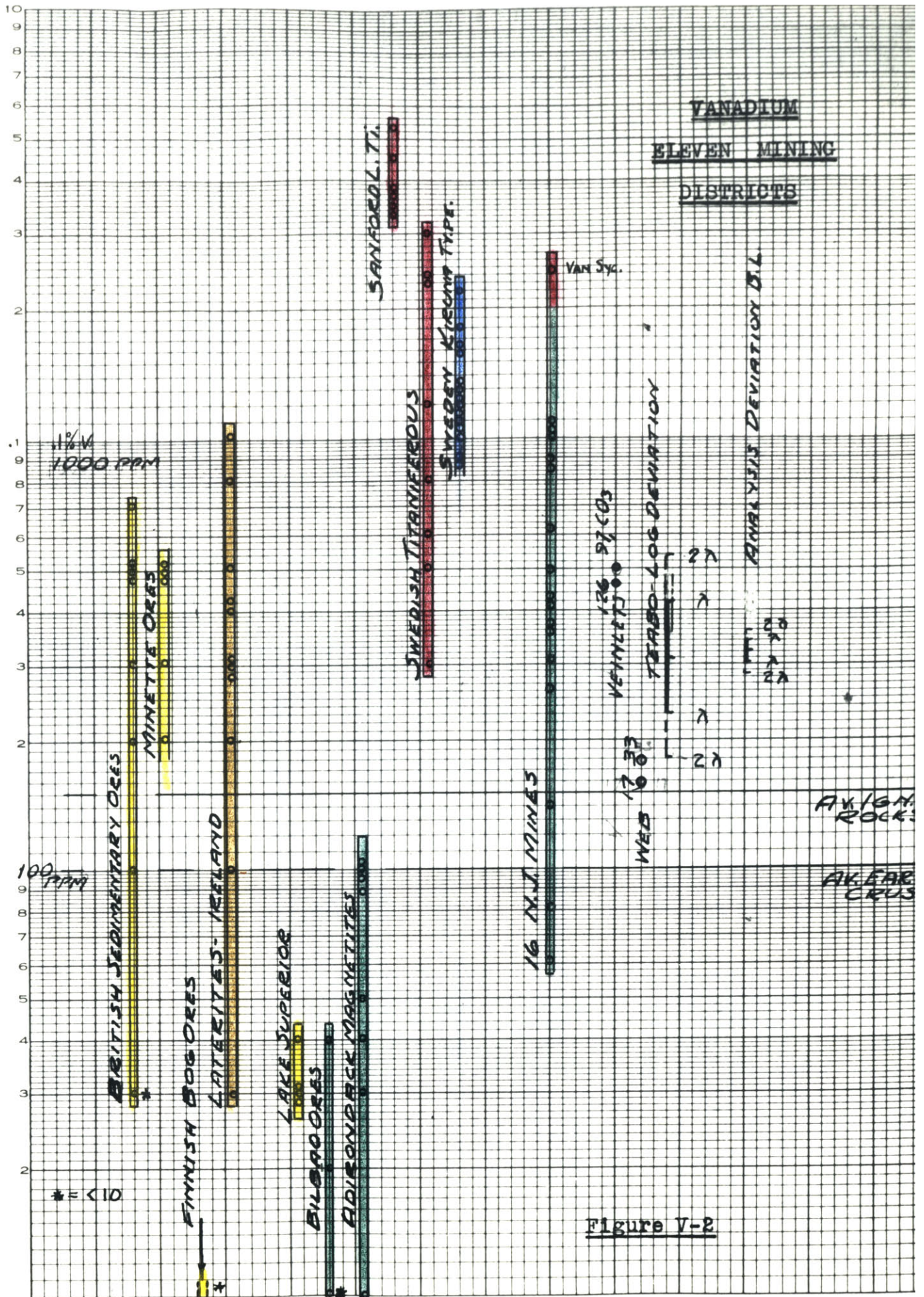


Figure V-2

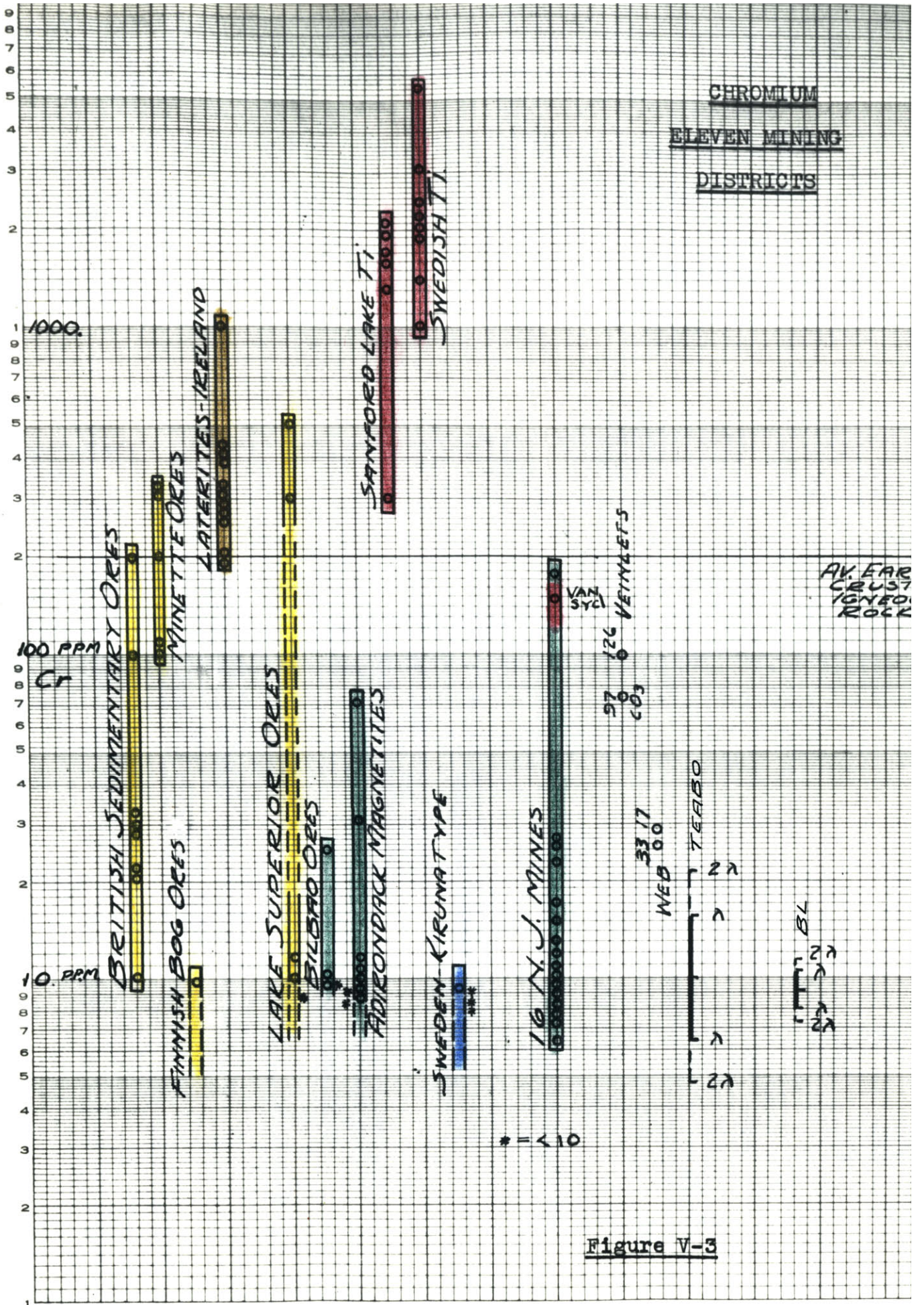


Figure V-3

cription of the geology of each of the mining regions plotted, together with remarks regarding comparative trace ferride contents and ranges.

BRITISH SEDIMENTS

Of the total of eight samples plotted, four are ironstones from Northamptonshire composed of chamositic oolites and sideritic mudstone, three are Frodinham ironstones, all limonitic oolites, while one is the richest of several ferruginous bands in Banbury marlstone.

Geochemically these ores are without great distinction. An examination of the plottings reveals that the abundance range of each trace ferride is generally more or less centrally located in the field of ranges of the eleven ores plotted. Compared to the average trace ferride content of the earth's crust, these ores are normal or slightly concentrated in V, normal in Ni content, concentrated as to Co, the most distinctive element in the suite, and deficient in Ti and Cr. The difference between mean trace ferride content in these ores and the New Jersey magnetites is not great and the ranges of the two ore types overlap for all elements.

MINETTE ORES

The sedimentary minette ores of Luxembourg are oolitic limonites (Lindgren 1933) occurring in shales, sandstones and marls. A low tenor of iron ranging from 31% to 40% and a high phosphorus content, 1.6 to 1.7%, are characteristic. Lindgren cites Cayeux's opinion that the iron replaces calcite oolites,

but adds that this process may be debated. These ores are again typical of those generally considered sedimentary and products of biogenic or exogenic chemical precipitation.

The range of abundances plotted for each of the trace ferrides in the minettes overlaps the range of the same element in the British sediments as well as the New Jersey magnetites, and, like the British sediments, the minettes are without remarkable distinction when compared to other iron ores.

FINNISH BOG ORES

The Finnish bog ores, represented by a 14-sample suite, are of great interest as typical lacustrine sedimentary iron deposits. Their composition is remarkable in that both V and Cr are absent. These elements were reported as less than 10 ppm. The range of Ti in these specimens, more than two magnitudes, is the greatest of any element in any of the suites presented. It is probable that the fourteen specimens making up this suite each come from a separate deposit and therefore the composition of each is a function of the chemical character of the erosion and drainage basin tributary to the site of ore formation.

LATERITES - IRELAND

These ores are rich in Ti, the abundance being closely related to but enriched above the composition of the parent rock, a characteristic common to many laterites. In the formation of laterites Ti forms stable compounds in the katamorphic products and is typically enriched. In describing this suite, Lander-gren notes that concentration of V in individual samples is re-

lated to the composition of the parent rock, being higher in the weathering products derived from basalt, lower when derived from granite. The content of Cr, on the other hand, is independent of the origin of the weathered product.

LAKE SUPERIOR IRON ORES

The Lake Superior iron ores from the Marquette and Vermilion ranges are generally slightly impoverished in the trace ferrides. Ni is the exception in this suite in that it is found in concentrations similar to the averages for the several ores plotted, while Cr abundances are dispersed. These ores are generally conceded to be sedimentary, but as their present constitution, due to secondary supergene enrichment, is the result of transportation of large amounts of material, the trace ferride contents of the ores cannot be considered typical primary concentrations in ores of sedimentary origin. These ores have little in common with the British sediments which display greater abundances in Ti, V, and Co, and even less similarity to the minettes with a common range only in nickel. The Lake Superior ores are strikingly similar to the iron ores of Bilbao, described in the next paragraph.

ORES OF BILBAO, SPAIN

The secondarily enriched metasomatic hematite ores from Bilbao are distinctly impoverished in Ti, V, and Ni. The Cr and Co abundances are within the ranges of several of the sedimentary and bog ores and the high temperature metasomatic ores of the Adirondacks. The protore of this deposit is thought to

be siderite and ankerite averaging perhaps 35% Fe which replaced metasomatically a thick bed of limestone. This material apparently was enriched by weathering and ground water action in a manner similar to the secondary enrichment of the Lake Superior ores. Some ore bodies mined were surficial mantles one hundred feet thick, 3,000 feet wide, and two miles long containing hematite-limonite ores of bessemer grade averaging 50 to 57% Fe (Lindgren 1933). That ores from two districts with different primary histories but both reworked by secondary enrichment processes should display similar concentrations in trace ferrides is of considerable interest.

ADIRONDACK MAGNETITES

The eight samples of these hypothermal metasomatic ores from Essex and Warren counties in the Adirondacks are of high-grade magnetite, containing 48 to 68% Fe, and are characteristic of the commercial ores of that area. These ores are commonly high in apatite content, the product shipped averaging about 0.8% P. Other gangue minerals are mainly feldspars, quartz, pyroxene and hornblende.

Since the ores as well as the geological environment of the Adirondacks are similar to these of the New Jersey Highlands, they will be described in some detail. The Adirondack "highland igneous complex" (Buddington, 1948) comprises 1,000 square miles of gneissic granite and quartz-bearing pyroxene syenite complexly interlayered with smaller amounts of many gneissic rocks. This mass surrounds a core of some 300 square

miles of anorthosites with a complex structure (Balk 1930). Within the gneisses many magnetite deposits occur as massive sheets or veins, plunging cigar-shaped structures connected by non-economic magnetite seams, like the "webs" of Mount Hope, New Jersey, and low grade layers in feldspathic gneisses. The ore shoots conform closely to the dip, strike and plunge of the enclosing gneisses. Within the anorthosite core in the vicinity of Sanford Lake are found the high titanium deposits.

The best recent description of magnetite ore in the Adirondacks is by W.A. Postel, (U.S.G.S. Prof. paper 237, 1952, The geology of the Clinton County magnetite district, New York). Postel describes the ores at Lyon Mountain as invading the Lyon Mountain granite gneiss complex, the magnetite replacing microperthite granite, plagioclase granite, and microantiperthite granite, in which pyroxene and biotite are rare. A second host is a pyroxene-contaminated phase of the foregoing, which forms a "skarn" ore similar to the "skarn" ores of New Jersey. The ores are principally localized on the limbs and in the troughs of synclines several hundreds of feet in amplitude.

Postel found many ores replacing rocks with a cataclastic texture, or associated with hanging or footwall rocks having a cataclastic texture. Micro-shearing, rarely seen in hand specimens, is found in diamond drill cores and in thin sections. In rocks which show mylonitic textures resulting from shear, the magnetite is clearly later than the shear texture. Similar cataclastic and mylonitic textures are found in the New Jersey

ores and are described by Sims (1953). Martite is present in small amounts in the ores. Ilmenite is not seen in hand specimens in Warren County, but the ores range from 0 to 1% TiO_2 , with a high of 2.5% at Palmer Hill where ilmenite is found in polished sections.

Postel gives an excellent historical review of theories of ore genesis for these deposits, which have varied from magmatic injection to pneumatolytic metasomatism. The latter, which has predominated in geological opinions throughout the years, is detailed and supported by Postel.

In abundances of trace ferrides the Adirondack magnetites and the ores of the New Jersey Highlands are nearly identical. An exception is the content of V, which in the Dover ores averages four times the concentration found in the Adirondack magnetites, although the ranges in the two ores overlap. Compared to the average for the earth's crust, the Adirondack ores are impoverished in Ti, V, Cr and Ni. Only in Co is the concentration normal. This contrasts sharply with the uniformly high trace ferride concentrations in the titanium ores from the neighboring anorthosites at Sanford Lake. Possibly this contrast in ores of the same geological province resulted from the concentration of trace ferrides in the early magmatic segregates, which are thought to have contributed the titaniferous ores (Balsley 1943), with resulting impoverishment in trace ferrides in the late magmatic liquid or vapor phases from which the magnetite ores are thought to have been deposited. Pos-

sibly the contrast is the result of the operation of a temperature gradient existing during contemporaneous mineralization, or perhaps zoning by solution enrichment during extended migration, as postulated here for Cr in the Dover area, is the explanation. Whatever the reason may be, the result is repeated in the contrast between the high-titanium-belt ores of the New Jersey Highlands as represented by the Van Syckle's mine, and the Dover area ores. Here the high Ti ores appear to be normal variations of the Highland suite.

SWEDEN, KIRUNA TYPE MAGNETITES

The magnetites of debatable origin from the Kiruna area, like those of the Adirondacks, are strikingly similar to the high grade ores of the Dover Area in geological environment, lithology, mineralogy, and in trace ferride content. Analyses selected from Landergren have been limited to specimens from Kirunavara, the neighboring deposit at Luossavara, and from Gallivare, 100 km to the southeast. These analyses were all made on high grade magnetites ranging from 54.7% to 69.5% Fe. These, the greatest magnetite deposits known, are located in Lapland, the northernmost part of Sweden, close to the Finnish border. Geologically they are a part of the pre-Cambrian Fennoscandian shield. The host rocks at Kiruna are a series of syenitic and quartz porphyries with interlayered amphibolite, greenstones and other complex rocks. The origin of the series is debated. Geijer (1931) is of the opinion that the majority of the rocks are flows and cites well-preserved flow textures

to substantiate his opinions. Others have held the rocks to be intrusive (Geijer, cites Stutzer). Agreement is general among Swedish geologists that the ores were intruded as ore magmas accompanied by volatile mineralizers (Geijer, 1931, Landergren, 1948, Hogbom 1951, Bateman 1951). Geijer, Hogbom and Bateman believe the ores to have been developed during magmatic differentiation while Landergren believes the ores, emplaced as melts, are paligenetic sediments. All emphasize the contemporaneous action of pneumatolytic agents and the presence of metasomatic faces.

Important direct shipping grades of ore at Kiruna are said to average 60 to 67% Fe with special commercial concentrate grades as high as 71.7% (pure magnetite theoretically is 72.4%.) The slight amount of gangue in the whole ores is principally apatite with some diopside, augite, and hornblende. Quoting Lindgren (1933 p. 792) "the ore is said to average 68% iron. The phosphorus is as a rule above 2%....The apatite seems to have crystallized first...sulphur is not above 0.05%, manganese not above 0.70%; a similar amount of magnesia is recorded, about 1.5% silica, 0.75% alumina, about 3% lime, and 0.3 per cent TiO_2 . In places a fluidal structure of the magnetite and branching veinlets of apatite, suggesting an eutectic, are observed in the ore."

The contacts of the magnetite masses with the wall rocks are sharp although veinlets and apophyses of magnetite penetrate the porphyries, and brecciated areas of wall rocks are

cemented with magnetite. The deposits at Gallivare are similar but show signs of strong regional post-ore metamorphism and deformation. Here the ore has been deformed into lenses superimposed on large folds.

It is of interest to note that the criteria repeatedly described in support of the dike-like theory of injection of these masses, -sharp wall contacts, wall rock breccias, with an ore matrix and veinlets and apophyses of ore penetrating the wall rocks,- could also be used to describe many of the vein-type base metal ore deposits of the western United States generally conceded by U.S. geologists to be replacement deposits.

When compared to the averages for the earth's crust and igneous rocks, the ores of Kiruna are deficient in Ti and Cr; slightly enriched in Co and Ni, and considerably enriched in V. The Kiruna ores are very similar in trace ferride concentrations to the ores of the Dover area and the Adirondack magnetites. The Adirondack magnetite ores differ substantially only in vanadium content in which they are lower, averaging about one-fifteenth of the concentration of the New Jersey ores and about one-thirtieth of the concentration of ores of North Sweden. In other trace ferrides, the ranges of elemental abundances from each district overlap.

The dispersion of the analyses of the Kiruna ores is one-half to one-third that of the New Jersey dispersion and is generally less than that of the other iron ores presented. This may be due to the highly concentrated and uniform nature

of the mineralization or to complete mixing and uniform diffusion of trace ferrides and other elements throughout the ore magma; however, the fact that these samples are selected from commercially graded ores with a limited variety of characteristics may account for the uniformity of analysis. If the Dover area analyses were restricted to the whole ore presently shipped, that is lump ores from Mount Hope veins and the Mount Pleasant vein, the range of abundances of trace ferrides would indeed be limited.

The high V content in the Kiruna ores may correlate with the similar high V content of the Swedish titaniferous ores generally considered to be of magmatic association. (However, a contrary inference may be noted. Landergren refrains from discussion of the origin of the high-titanium ores because of insufficient information while, without comment, he presents analyses of laterites from Ireland of very similar trace ferride content.) Landergren generally considers high V to be a criterion typical of the exogenetic cycle, as well as the early phase of magmatic differentiation.

The similarities in trace ferride content in New Jersey, New York and North Swedish ores is all the more interesting in the light of the divergence of geological thought in regard to origin. The writer is inclined to the opinion that ores with differing phase histories are not likely to display similar characteristics as to trace ferride concentration.

THE TITANIFEROUS IRON ORES

Two titaniferous magnetite districts analyzed by Lander-gren have been included in the plottings because of close association with and obvious similarities to the magnetites. The two Ti ores are nearly identical in range, and dispersion of trace ferrides. The ores from Sanford Lake are higher in V concentration but both ores are notably enriched in this element. The similarity in trace ferrides in the high titaniferous suites with the one New Jersey high-Ti deposit, the Van Syckle mine, is also of great interest, and an implication of similarity of geological history and genesis of the Van Syckle's and the other high-titanium ores cannot be escaped. The probability that the Van Syckle's is a normal variation of the New Jersey Highland type of deposit has been discussed.

MAGNETITES OF THE NEW JERSEY HIGHLANDS

In Ti concentration, the range of the New Jersey Highland ores overlaps the ranges of all the other districts except Lake Superior. The median is about double that of the Kiruna and Adirondack magnetites. The trace ferride distribution information available suggests that the differentiation (probably we should say divergence) of the titaniferous and non-titaniferous fractions is less complete in the New Jersey ores, which have been shown to conform closely to a normal distribution pattern. The weight of geological opinion, if expressed in proper terms on this question, would probably be that the titaniferous ores of New York and Sweden are, in both cases, geologically dis-

tinct from the normal magnetites of the same areas and an attempt to integrate them in one continuous distribution pattern would result in a false comparison.

Similarly, the range of vanadium concentration in the New Jersey ores overlaps all the iron ores except Lake Superior and Bilbao, and the titaniferous ores of New York and Sweden.

In chromium, the New Jersey ores overlap all the iron ores, but fall outside the field of the titaniferous ores. However, the analyses of Anomaly and Van Syckle closely approach the lower concentrations reported from Sanford Lake.

In cobalt and nickel, the New Jersey ores overlap all other ranges.

B - SUMMARY--THE TRACE FERRIDES IN THE ORES OF
SEVERAL MINING DISTRICTS

Titanium is concentrated relative to the average abundance in igneous rocks and the earth's crust in the early magmatic ores of Sanford Lake and the Swedish titaniferous deposits as well as in the laterites associated with basic igneous rocks, while the high-temperature metasomatic iron ores of the Adirondacks and New Jersey are of average titanium content. The secondarily enriched ores of both sedimentary and metasomatic derivation, from the Lake Superior region and Bilbao, are distinctly impoverished, while sedimentary ores which have not undergone secondary enrichment are slightly impoverished in Ti. These relationships reflect the insolubility of the element during the secondary processes of the exogene cycle and a rejection of Ti during the biogenic concentration of iron.

Vanadium follows Ti closely in the differentiation of the titaniferous ores. In the high-temperature metasomatic ores the range of V is greater than that found for Ti. The Adirondack magnetites are depleted in this element, perhaps as a result of extensive differentiation. The ores of New Jersey mines are generally slightly enriched in V, but show a large range of concentration thought to be a function of depletion during migration as well as abundance at the genetic source. The secondarily enriched ores are also deficient in V. The

sedimentary ores are slightly enriched in V, reflecting weakly the biophile tendency of the ion.

Chromium follows the already demonstrated tendency of the trace ferrides to concentrate in the high-titanium magmatic ores and to become impoverished in both high and low-temperature metasomatic materials. The abundance range of Cr, over three magnitudes in the suites presented, is greater than that of any other trace ferride. It has been pointed out that at the small concentrations prevalent, contamination from associated rocks during migration may be a factor. The moderate Cr content in the sedimentary ores is in accord with the known lack of biophile characteristics in this element.

Cobalt, in the high-titanium suites, is enriched about ten times, but is of average concentration in the high-temperature and secondary metasomatic ores. Co is decidedly enriched in the sediments, thus conforming to the behavior noted by Rankama and Sahama (1950--"cobalt, rather than Ni, accompanies iron in the sediments").

Nickel is characterized in these ores by a tendency to be average. All groups include samples equal in concentration of Ni to the average for the earth's crust and igneous rocks. The New Jersey ores are the most deficient in this element. It is indeed surprising to find no high concentrations of this markedly siderophile element within the iron ore suites examined. This characteristic might be cited as support for a late magmatic derivation for the endogene magnetite and titani-

ferous ores, a process ably postulated by Bateman (1951).

It should not be overlooked that at these low concentrations significant errors in the absolute values of the trace ferrides may exist although the relative accuracy of the work done by any one analyst is of a high order.

CHAPTER VI

CONCLUSIONS

THE SIGNIFICANCE OF THE DISTRIBUTION OF THE TRACE FERRIDES IN THE MAGNETITE ORES OF THE NEW JERSEY HIGHLANDS

The trace ferrides, Ti, V, Cr, Co and Ni, together with iron, form a geochemically coherent group which is distributed with great uniformity within the spinel-type structure of magnetite ores. Similarities of radii and ionic character permit distribution of these elements to be more uniform than is the case with associated but geochemically distinct elements such as P, Si, Mg, and Al, not of the ferride group. The latter form independent gangue minerals and aggregates erratically distributed within the ore bodies.

Geochemical cohesion is manifested as uniform distribution of the ferrides within the magnetites of the Mount Hope mine and Dover district, but not generally as enrichment or marked covariance. Covariance is noted in some of the ores of extremely high and low concentrations, such as the magnetites from the Oxford and Van Syckle mines, found in dispersed sections of the Highlands, and in other iron-mining districts of diverse geological history.

In general the magnetite ores of the New Jersey Highlands are equal to or deficient in the trace ferrides when compared to the average abundances of these elements in the earth's crust and in igneous rocks. Vanadium is an exception with a median

abundance of nearly four times that found in the earth's crust, while chromium is the most impoverished, with a median order one-twentieth that of the earth's crust and igneous rocks.

The host rocks of the Mount Hope mine, the oligoclase-quartz-biotite gneiss and the alaskite, were found to differ distinctly, one from the other, as to trace ferride concentrations as well as bulk composition and mode.

No correlation was found between the mean trace ferride content of these wall rocks and the trace ferride content of the ores. Further, the magnetite ore bodies were found to be more uniform in content and showed a lower dispersion of trace ferrides than did the wall rocks.

The analysis of ten samples of high-grade magnetite taken from one area 20 x 100 feet in cross-section indicates that trace ferride concentrations vary within a small area by amounts ranging, when calculated as lognormal deviations, from 20% to 41% with an average of 27% for the five elements. Further, this dispersion is rather uniform throughout the Mount Hope ore shoots tested, increasing only slightly as the area tested is expanded.

A comparison of ferride content of two ore shoots within the Mount Hope mine, the Teabo and the Taylor veins, each enclosed within a distinctive wall rock type, indicates that differences of means of trace ferride content of each shoot obtained from the analyses of sixteen to nineteen samples taken from each shoot were not sufficient to differentiate one shoot

from the other.

It is concluded that the ores are metasomatic, replacing a finely brecciated or mylonitic shear zone within which the metasomatic process must have continued for sufficient time to allow equilibrium to become established between the ore-transporting medium and the host material throughout the elongated ore shoots. In the resulting magnetites this equilibrium has obliterated the original differences in trace ferride concentrations found in the different wall rock types from which the mylonites were derived. Indeed the uniformity of trace ferride content in the extended ore shoots and the similarity of trace ferride content in the magnetites of different ore shoots might be used as an argument to support a theory of ore origin as intruded melts, a mode of introduction advocated by many geologists who have studied these ores.

The uniformity and similarity of trace-ferride concentrations within different ore shoots, each with distinctive gangue materials and each enclosed within different host rocks of distinctive composition, is antithetic to the theory of syngenetic origin of these ores, a theory supported by many economic geologists familiar with sedimentary iron ores in other parts of the United States. The amphibolite "horses", or lenses, found in most vein exposures, are charged with the trace ferrides Ti and Cr, in concentrations 5 to 15 times those found in the ores. If these lenses are of sedimentary origin and contributed a part of the variegated gangue miner-

als found in the ores, the magnetites would be more erratic in trace ferride content.

That these ores were introduced by fluids in the form of solutions or vapors is further indicated by a similarity of concentration of trace ferrides in the low-grade web zones connecting separate ore shoots in the Mount Hope mine. These extenuated zones should be relatively inaccessible to melts, and the high gangue content of these low-grade materials would be expected to be reflected in variations in trace ferride concentrations if these ores were once sediments. Further, subhedral crystals of magnetite which encrust the walls of small fractures in the country rocks of the Teabo vein, in a form obviously deposited from solution or vapor phase, were found to be very similar in trace ferride abundances to those found in the massive magnetites of the ore shoots. This suggested that similar phases were involved in the formation of the two types of occurrences--open vein encrustations and massive ores. This reasoning is based on a simple geochemical assumption: GEOGRAPHICALLY RELATED ORES WITH SIMILAR FERRIDE CONCENTRATIONS ARE LIKELY TO HAVE HAD THE SAME GENETIC HISTORY.

A diagnostic characteristic of many epigenetic ore districts is metal ratio or metal concentration zoning, radially and in depth. To test in detail the possibility of the existence of changes in trace ferride concentrations relative to depth, horizontally dispersed sets of samples were taken at

several elevations in two ore shoots at the Mount Hope mine. Differences in concentration, which in certain parts of the shoots changed progressively with elevation, were noted, but these trends were not consistent. Ti concentration increased as the surface was approached in the Teabo shoot, while in the Taylor vein the concentration decreased when traversing from the lowest workings upward to intermediate elevations, then increased again as the surface was approached. Cr, which showed the most pronounced and consistent trend, increased as it approached the surface. The other trace ferrides displayed no consistence in trends with elevation in either shoot. In general, clear zonal trends were not found in the ore shoots within the distances tested, a maximum of two miles of pitch length in the case of the Taylor shoot.

In the ores of the New Jersey Highlands Ti is about ten times as plentiful as vanadium and one hundred or more times as plentiful as the other trace ferrides. This amount of Ti is more than that likely to be derived by contamination from trace content of the vein walls (although they too are relatively high in Ti content). It is thought that the great differences in Ti content found in these ores originated at the genetic source. The small total differences found in limited areas, as in the Dover district, may be due to source differences or to loss to or contamination by wall rock, to temperature gradient, or other causes, possibly developed during migration away from the postulated genetic center at the Split

Rock Pond node.

An increase in content of Cr in the magnetites found in small veinlets, webs and disseminations has suggested that this element has been added to ore solutions by leaching from wall rocks and thus concentrated in the more remote and isolated ores. The average content of Cr in the New Jersey suite is very low, and contamination from wall rocks such as amphibolites, high in Cr, might be expected during extended migration.

In the Dover district, vanadium appears to be concentrated relative to other trace ferrides, close to the structural center of mineralization, and to have been taken up more rapidly than the other elements by the magnetite crystal structure during migration of the ore forming medium. The change of V content due to this is thought to be less than the original state-wide differences in V content related to deep-seated causes. Therefore this depletion of V is best expressed as a change in ratio relative to other ferrides, notably Cr. The plotting on a map (Fig. IV-1) of V/Cr for the high-grade mines of the Dover district reveals a rude zonal distribution of the ratio magnitude with a high in the neighborhood of the Split Rock Pond node. The low-grade disseminated deposits, Anomaly and Scrub Oak, do not conform to the zonal pattern.

Within the Dover district, a similarity of trace ferride content in the high-grade ores of the several mines is noted, although the low-grade deposits, Anomaly and Scrub Oak,

show some distinctive variations. As the area considered is expanded, variations in abundance become more pronounced. Calculated as lognormal deviations, the dispersion increases to an average magnitude, for the five elements, of 150%. Thus it is seen that while the lognormal deviation within one shoot is about four times the analysis deviation, the deviation of all mines within the Highlands is about sixteen times the analysis deviation, or four times the magnitude of the shoot deviation.

Geologically all of the magnetite deposits of the New Jersey Highlands appear to be clearly related one to another. Further, the variations of concentrations of trace ferrides in the Highlands appear to conform to a smooth distribution pattern. The extreme examples, the enriched ores of the Van Syckle mine group and the impoverished ores of the Oxford mine appear to be normal variants of the New Jersey suite. It is interesting to note that these extreme examples are similar in trace ferride content to ores of widely divergent origin from other districts.

Smooth gradients might be related to any one or several continuously varying processes--magmatic differentiation, contamination, reaction of solutions with the environment during travel, and temperature and pressure gradients.

In the New Jersey Highlands suite, selected from one geological and genetic province, the distribution of abundances in a smooth curve is an addition to existing evidence of con-

sanguinity of the group. If, by contrast, a part of the group should show a strong secondary node in the distribution curve, indicating distribution to be bimodal, a distinctive phase, source, timing, or change in environment is suggested. A second geochemical assumption is proposed: IF WITHIN ONE IRON PROVINCE THE TRACE FERRIDE CONTENT OF A SUITE OF ORES IS FOUND TO CONFORM TO A SMOOTH DISTRIBUTION CURVE OF SINGLE MODE, THE SEVERAL DEPOSITS ARE PROBABLY OF A SIMILAR PHASE HISTORY AND FROM ONE OR SIMILAR GENETIC SOURCES.

That the two assumptions suggested are special cases may be shown by testing the converse of each. The converse of the first may be disproved by the second assumption, and the second will apply only if various geological discontinuities do not disrupt the uniform gradients expected in most genetic processes.

Abundances determined by Landergren for ores from several well-known mining regions indicate trace ferride enrichment in the early magmatic ores, represented by the titaniferous deposits of New York and Sweden, and impoverishment of trace ferrides in the ores of secondary enrichment, here represented by samples from Bilbao and Lake Superior areas. The sedimentary collections were not distinctive as to trace ferride content. The ores of the Highlands, and especially of the Dover district, are comparable to the magnetite ores of the Adirondacks and the Kiruna-type ores of Sweden.

It is interesting to note that examples of the extremes of concentration in the New Jersey ores, the Van Syckle and the Oxford, display similarities in trace ferride content to titaniferous ores and magnetite ores, respectively, of the Adirondacks.

The study of the geographical and geological relationships of the minor element concentrations within the ores of one district appears to be more fruitful, in the light of current lack of knowledge of geochemical detail, than the comparison of average concentrations and dispersions in occurrences widely dispersed geographically and genetically.

The present study, covering as it does the whole range of iron ores, from distribution within the mineral to comparisons on a world-wide scale, can only be considered a reconnaissance of the several fields, and conclusions can be considered hardly more than geochemical suggestions. Further investigation is necessary and it is suggested that in the New Jersey Highlands this should proceed along the following lines:

1. A study of the trace ferride relationships in the minerals and several types of ores common to the magnetite province and to the relationships at contacts between minerals, between rocks, and between host rocks and ores.

2. A study of the trace ferride content of the rocks of the New Jersey Highlands, and the mineral associations therein, with special emphasis on the opaque minerals.

3. With information in hand from (1) and (2) above, a detailed study and sampling of 100 or more magnetite prospects in the New Jersey Highland area, with several samples taken from each deposit. The results of this to be tested as to possible zonal distribution and as to petrographic and structural relationships. In this full use should be made of the petrographic and structural work of other geologists active in the district.

4. A study of the possibility of a relationship between the magnetite ores of the Highlands and the zinc-manganese ores of Franklin. The presence of a small amount of zinc in the iron ores at Andover suggests the possibility of a zonal relationship not recognized at present.

APPENDIX A

TITANIUM ANALYSES FROM
HIGH TITANIUM MAGNETITES IN NEW JERSEY HIGHLANDS
AS REPORTED BY BAYLEY (1910)

<u>Map No.</u>	<u>Mine</u>	<u>Fe %</u>	<u>Ti %</u>
t-1	Bloom	37.5	2.86
t-2	Cramer	62.2	4.25
t-3	Day	50.8	3.05
t-4	De Kay Farm	45.7	2.81
t-5	Hager	56.3	2.49
t-6	Jackson	52.9	2.68
t-7	Naughtright	62.1	4.24
t-8	Shafer	45.2	3.02
t-9	Stockholm	67.1	2.07
t-10	Van Syckle's	50.4	7.08

All magnetite prospects listed by Bayley with analyses showing more than 1.50% Ti are listed. These 10 were taken from a total list of 149 prospects and mines. For the majority of the remaining 139, no Ti analysis were listed. It is presumed that ores high in Ti were recognized and are included above.

APPENDIX B

THE DISTRIBUTION OF Ti, V, Cr, Co, AND Ni IN 17 NEW JERSEY MINES, ORESHOOTS AND PROSPECTS

<u>Map and</u> <u>Sample No.</u>	<u>Name</u>	<u>Ti</u>	<u>V</u>	<u>Cr</u>	<u>Co</u>	<u>Ni</u>
138	Ringwood	6400	850	26	16	60
137	Scofield	9800	260	11	58	3
145	Winter	4000	820	15	30	8
144	Pardee	2000	610	9	65	27
117	Fairview	10300	1020	10	66	56
119	Hibernia	4100	1060	12	50	62
98	Anomaly	3800	1020	178	53	123
94	White Meadow	2600	500	9	59	54
Geom. Mean	Taylor	3200	370	13	30	50
Geom. Mean	Teabo	3100	350	10	22	40
95	Mt. Pleasant	3700	340	17	25	46
146	Scrub Oak	500	60	27	21	18
123	Mine Hill	4500	420	10	44	45
143	Baptist Church	8500	370	23	42	26
96	Mt. Olive	2100	130	10	50	21
135	Oxford Mine	700	80	7	21	13
147	Van Syckle's	19100	2400	150	110	90

Note: Mines are listed geographically from North to South.
Pairs of samples have been averaged with lowest number
retained for identification.

APPENDIX C

IDENTIFICATION OF ANALYSES FROM LANDERGREN

USED IN TABLES V-1 TO V-5

(for table and number refer to Landergren, 1948)

British Sediments. Table 44, samples 1 to 7, and 8b

Minettes. Table 53, samples 5 to 9 incl.

Finnish bog ores. Table 41 samples 1 to 14

Laterites, Ireland. Table 47, samples 1 to 11

Lake Superior ores. Table 53, samples 30 to 33

Bilbao ores. Table 53, samples 1 to 14

Adirondack magnetites. Table 53, samples 22 to 28

Sanford Lake. Table 50, samples 18 to 23

Swedish titaniferous ores. Table 50, samples 1 to 8

Kiruna ores. Table 31, samples 1 to 14, ores only.

APPENDIX D

TRACE FERRIDES IN

NEW JERSEY ORES AND ROCKS

RESULTS OF SPECTROGRAPHIC ANALYSIS

Vein identification precedes number, T = Teabo, Y = Taylor
E = Elizabeth, L = Leonard

Following Number, C = Magnetic Concentrate, T = Magnetic Tail,
S = Mineral selected from sample, X = calculated from
Concentrate and Tail.

* = Analysis by Silicate Procedure.

<u>Number</u>	<u>Place</u>	<u>P. P. M.</u>					<u>Soluble Fe %</u>
		<u>Ti</u>	<u>V</u>	<u>Cr</u>	<u>Co</u>	<u>Ni</u>	
T-1	15-5-5 Sub	2,400	350	9	23	41	68.9
T-1-C		3,000	420	7	24	50	
T-2	15-5-5 Sub	1,900	420	9	18	26	62.3
T-2-C		2,200	480	8	19	27	
T-3	15-5-4-Sub	4,700	350	15	25	35	58.7
T-3-C		4,500	350	9	26	40	67.8
T-3-T*		1,100	23	5	8	17	
T-4	15-5-4 Sub	3,000	350	9	22	49	67.7
T-4-C		3,400	400	8	24	51	
T-4-T*		150	38	0	8	20	
T-5	15-5-3 Sub	5,300	400	11	20	47	63.7
T-5-C		5,900	420	160	24	53	70.8
T-6	15-5-3 Sub	2,600	400	10	22	43	69.2
T-6-C		3,300	470	6	20	30	
T-6-T*		200	18	1	16	18	
T-7	15-5-2 Sub	4,100	350	12	34	42	61.1
T-8	15-5-1 Sub	3,800	300	10	22	34	57.6

Number	Place	P. P. M.					Soluble Fe %
		Ti	V	Cr	Co	Ni	
T-8-C		3,800	400	15	30	42	
T-8-T*		2,600	18	1	10	30	
T-9-X	2100 Level	2,000	350	8	18	34	
T-9-C		1,800	370	8	20	35	
T-9-T*		4,000	50	3	3	23	
T-11-C	2100 Level	2,800	540	7	24	43	
T-17	1000L Web- 4 MWY	4,100	160	29	23	26	43.6
Y-25	27 MWY-4 S	6,000	470	8	29	50	
Y-25-T*		5,200	42	3	17	33	
Y-26	27 MWY-6 S	4,700	350	7	27	48	67.1
Y-26-C		4,500	420	8	26	41	
Y-27	27 MWY Top XC (a)	5,100	430	8	28	41	67.7
Y-27-C		5,500	450	7	29	43	
Y-28	27 MWY-1700L	4,000	340	12	28	51	62.0
L-29	1700L. 63MWY	1,700	290	8	21	37	58.1
L-29-C		2,700	430	10	19	51	72.3
E-30	1700 Level	4,100	320	11	24	40	
E-32	1700 Level	3,500	340	8	29	38	
33	Web 1700 L.	4,100	180	26	12	28	30.2
Y-35	1000 Level	1,700	360	11	24	42	
Y-36	1400 Elev.	1,900	380	13	37	44	
Y-37	1400 Elev.	2,900	380	14	27	53	
Y-38	1400 Elev.	700	300	13	35	63	
Y-44	2000 Elev.	3,100	370	9	35	51	

Number	Place	P. P. M.					Soluble Fe %
		Ti	V	Cr	Co	Ni	
E-45	Surface	3,700	430	14	32	47	
E-46	Surface	2,900	470	9	--	37	
T-48	Surface	4,400	430	20	32	43	
T-48-C		4,100	500	15	21	44	71.7
T-49	Surface	6,500	510	24	33	51	
T-49-C		4,900	550	23	20	45	70.8
T-50	Surface	4,200	450	15	21	42	
T-50-C		3,900	470	12	23	40	
Y-51	Surface	3,300	380	35	32	56	
Y-52	Surface	3,200	450	22	33	52	
Y-53	Surface	3,400	360	17	33	65	
Y-60	2000 Elev. c.	4,500	--	9	32	45	64.4
Y-61	Surface c.	2,700	300	18	26	46	56.9
T-62	2100 Level c.	2,500	400	9	19	34	66.2
T-63	Surface c.	4,600	440	17	25	38	63.5
E-64	1700 Level c.	4,500	420	10	25	76	66.3
E-65	Surface c.	2,700	480	13	33	37	66.3
L-66	1800 Elev. c.	2,300	360	7	16	46	63.4
L-67	Surface c.	3,000	380	9	19	45	60.2
Y-70	400 Level	2,900	340	26	30	45	
Y-71	400 Level	4,700	340	11	29	49	
Y-72	400 Level	2,200	300	13	25	42	
Y-72-C		2,200	380	14	28	52	
T-73	15-5 S c.	3,700	410	6	23	51	65.1

<u>Number</u>	<u>Place</u>	<u>P. P. M.</u>					<u>Soluble Fe %</u>
		<u>Ti</u>	<u>V</u>	<u>Gr</u>	<u>Co</u>	<u>Ni</u>	
E-74	1000 Level c.	4,100	370	10	20	44	64.6
E-77-S*	79 Scram, Select Biotite	3,700	20	5	5	60	
E-78-S*	79 Scram select Amphibole	3,000	64	2	2	30	
T-79-C	15-5 High Mica Ore	3,700	400	15	20	46	
T-79-T*		880	Tr.	2	2	40	
T-80	Surface	5,400	430	11	27	36	
T-82	Surface	3,400	400	8	25	49	
Y-84	26 Stope	2,400	450	9	42	53	
Y-85-C	28 Stope	3,300	470	6	32	59	
Y-85-T*		1,200	23	0	0	10	
Y-85-S*	Selected Apatite cry- stals	0	25	0	0	0	
T-91	15-5A-6 Sub	3,000	620	5	24	28	
T-92	15-5A-3 Sub	4,700	400	11	24	45	
94	White Meadow	2,600	500	9	59	54	
95	Mt. Pleasant	3,700	320	18	24	46	
96-X	Mt. Olive	2,100	130	10	50	21	
96-C		2,300	140	10	52	13	
96-T*		550	0	5	40	100	
T-97-C	Surface Veinlet with Carbonate	4,800	500	74	18	30	
98-C	Anomaly	4,200	1,130	214	56	130	34.3
99-C	Anomaly	3,500	900	143	50	116	
T-100	2100 Level-52	2,600	490	8	22	33	

Number	Place	P. P. M.					Soluble Fe %
		Ti	V	Cr	Co	NI	
T-101	2100 Level-50	2,400	400	23	23	44	
T-103	1000 L D.D. R-31 FW Vn.	3,500	450	16	12	136	58.5
T-103	1000 L D.D. R-31 HW Vn.	5,700	400	9	25	45	64.2
T-105*	D.D. 87 HW 10' O.Q.B.	1,600	30	16	2	14	
T-106*	D.D. 87 HW 42' O.Q.B.	6,000	150	62	10	46	
T-107*	D.D. 88 FW 24' O.Q.B.	5,400	90	7	8	22	
T-108*	D.D. 88 FW 50' O.Q.B.	2,600	60	8	19	32	
Y-109*	D.D. 150 FW 19' Alaskite	3,400	30	6	4	18	
Y-110*	D.D. 150 FW 30' Alaskite	2,200	Tr.	4	5	14	
Y-111*	D.D. 151 HW 0' Alaskite	2,300	30	18	6	26	
Y-112*	D.D. 151 HW 31' Alaskite	3,600	30	35	20	46	
117	Fairview	11,500	1,010	10	55	49	
118	Fairview	9,000	1,030	10	77	63	
119	Hibernia Mine	2,200	740	6	52	59	
122	Hibernia Mine	5,900	1,380	18	48	66	
123	Mine Hill-1 Brotherton	6,200	400	11	42	53	
124	Mine Hill-3 Byram	3,800	450	9	42	39	
125	Mine Hill Baker 1. Top.	3,500	400	11	50	45	

Number	Place	P. P. M.					Soluble Fe %
		Ti	V	Cr	Co	Ni	
E-126-C	Veinlet, F.W.	3,500	470	100	27	46	
T-127	15-5A-3 Sub near Foot of HW Vn.	3,800	430	9	25	43	67.7
T-128	15-5A-3 Sub near H.W.	3,300	340	16	23	35	59.2
T-129	15-5A-6 Sub high biotite ore near F.W.	2,300	160	14	19	41	26.7
T-130	15-5A-6 Sub near H.W.	3,300	250	11	16	36	46.8
T-131*	15-5A-6 Sub Amphibolite	16,500	170	150	14	23	9.1
132	BL Average of 9 Determinations	3,260	394	9	22	39	61.2
133	BH	6,200	720	13	46	54	57.1
135X	Oxford Mine	730	80	7	21	13	
135C		800	85	8	21	13	
135T*		270	10	1	20	17	
136C	Oxford Mine	600	70	10	17	10	
137X	Scofield Mine	9,800	260	11	58	3	
137C		10,200	280	12	61	3	
137T*		5,600	20	1	24	6	
138X	Rangwood	6,400	850	26	16	60	
138C		600	850	52	11	206	
138T*		8,000	850	20	18	22	
139*	Selected Apatite Crystals from ore 10-52	0	0	0	0	0	

<u>Number</u>	<u>Place</u>	<u>P. P. M.</u>					<u>Soluble Fe %</u>
		<u>Ti</u>	<u>V</u>	<u>Cr</u>	<u>Co</u>	<u>Ni</u>	
143	Baptist Church	8,500	370	23	42	26	
144	Pardee	2,000	610	9	65	24	
145X	Winters	4,000	820	15	30	8	
145C		4,100	860	16	31	8	
145T*		1,300	10	1	7	0	
146X	Scrub Oak	500	60	27	21	18	
146C		380	70	31	24	13	
146T*		1,200	0	1	0	42	
147X	Van Sycle Mine	19,100	2,410	150	110	90	
147C		18,500	2,700	170	100	82	
147T*		22,000	1,000	40	150	140	

APPENDIX E

WALL ROCKS - MT. HOPE MINE

PETROGRAPHIC DETERMINATIONS by J. F. LYDEN

All percentages are estimates based upon visual observation

<u>Specimen #1</u>	1000 Level Shaft Station (OQB)
Plagioclase feldspar (oligoclase)	45%
Quartz	50%
Apatite	trace
Magnetite	3%
Sphene	1%
Unidentified interstitial material	$\frac{1}{2}$ %
<u>Specimen #2</u>	1700 Level Shaft Station (OQB)
Plagioclase) feldspars	40%
Orthoclase)	
Quartz	35%
Biotite	2%
Hypersthene	15%
Hornblende	5%
Magnetite	1%
Zircon	trace
Sphene	trace
Apatite	trace
<u>Specimen #3</u>	25 Pocket x-Cut (OQB)
Quartz (showing intense strain shadowing)	70%
Orthoclase) feldspars	25%
Plagioclase)	
Apatite	3%
Magnetite	1%
Hornblende)	
Hypersthene)	1%
<u>Specimen #T 87 FW 0-4 High grade ore</u>	15-5 Stope No. 3 Sub HW DDH (High Grade Ore)
Magnetite	95%
Apatite	3%
Quartz	2%
Zircon	trace

Note: T..... refers to diamond drill holes.

Specimen T 87-8 Low grade ore 15-5 Stope No. 3 Sub HW DDH
(Low Grade Ore)

Hypersthene	35%
Hornblende	35%
Magnetite	10%
Plagioclase feldspar	10%
Microcline feldspar	5%
Quartz	5%
Chlorite	trace
Microcrystalline aggregate in fractures of hypersthene	trace
Biotite	trace

Specimen T 87-27.5 OQB - (106) 15-5 Stope No. 3 Sub HW DDH (OQB)

Quartz	45%
Plagioclase) feldspars	50%
Microcline)	
Magnetite (with hornblende rims)	2%
Sphene	1%
Apatite	1%
Rutile (in quartz)	traces

Specimen T 88-2.3 - (131) 15-5 Stope No. 3 Sub FW DDH Amph

Hornblende	98%
Quartz	1%
Magnetite	1%
Apatite	trace

Hornblende badly shattered
Interstitial clay in cracks in hornblende.

Specimen T 88-14 15-5 Stope No. 3 Sub FW DDH
(High Grade)

Magnetite	90%
Apatite	5%
Quartz	2%
Hornblende	1%
Alunite (?) altering to clay like material)	2%

Specimen T 88-18.5 15-5 Stope No. 3 Sub FW DDH
(Low Grade)

Hornblende	25%
Plagioclase (oligoclase)	25%
Orthoclase	25%
Magnetite	10%
Biotite	2%
Sphene	2%
Augite (altered)	2%
Apatite	2%

Zircon	2%
Microcrystalline aggregates	5%
<u>Specimen T 88-24.5 OBO (107)</u>	15-5 Stope No. 3 Sub FW DDH OQB
Plagioclase)	
Microcline) feldspars	50%
Orthoclase)	
Quartz	40%
Biotite	5%
Magnetite	1%
Apatite	1%
Zircon	1%
Sphene	1%
Augite	1%
<u>Specimen T 91-7 Teabo</u>	15-5 Stope No. 5 Sub FW DDH
Biotite	75%
Plagioclase) feldspars	15%
Orthoclase)	
Quartz	10%
Magnetite	10%
Apatite	minor traces
<u>Specimen T 150-8</u>	1900 Level Taylor FW DDH Amph Zone Skarn
Quartz	30%
Augite)	
Hornblende)	30%
Plagioclase	15%
Biotite	10%
Chlorite	5%
Apatite	2%
Zircon	1%
Sphene	1%
Magnetite	1%
<u>Specimen T 150-16</u>	1900 Level Taylor FW DDH Skarn Zone Amph
Riebeckite	70%
Biotite	10%
Orthoclase	5%
Magnetite	10%
Quartz	3%
Sphene	2%
Sericite in interstices	

<u>Specimen T 150-24 Alaskite (109)</u>	1900 Level Taylor FW DDH - Alaskite
Quartz	45%
Plagioclase)	
Microcline (intergrown with the plagioclase))	50%
Magnetite	1%
Sericite, Chlorite, Apatite	3%
<u>Specimen T 150-29 (110)</u>	1900 Level Taylor FW DDH - Alaskite
Microcline)	
Plagioclase) feldspars	50%
Orthoclase)	
Quartz	45%
Sericite	2%
Magnetite	1%
Apatite	1%
Sphene	1%
<u>Specimen T 150-55</u>	1900 Level Taylor FW DDH
Magnetite	75%
Riebeckite	20%
Apatite	3%
Quartz	2%
<u>Specimen T 151-0 (111)</u>	1900 Level Taylor
Orthoclase)	
Plagioclase) feldspars	45%
Quartz	30%
Apatite	5%
Augite	5%
Sphene	5%
Magnetite	2%
Zircon	2%
Sericite	1%
<u>Specimen T 151-18</u>	1900 Level Taylor HW
Plagioclase (ologoclase)	35%
Hornblende)	25%
Augite)	
Quartz	25%
Apatite	5%
Magnetite	5%
Sphene	2%
Zircon	2%
Sericite	1%

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