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**CHARACTERIZATION OF ACCESSORY
MINERALS IN THE
BIRMINGHAM RED
IRON ORES AND
EUFAULA FERRUGINOUS
BAUXITE DEPOSITS
IN ALABAMA**

Bureau of Mines Open File Report 23-82

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FOREWORD

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**COLOR ILLUSTRATIONS REPRODUCED
IN BLACK AND WHITE**

TABLE OF CONTENTS

	<u>Pages</u>
Foreward	2
List of Illustrations	5
List of Tables	7
Summary	9
Introduction	10
Objectives	12
Acknowledgments	13
I. Birmingham Red Iron Ores	14
A. General Character	14
B. Iron Ore Lithologic Variations	14
C. Mode of Occurrence of Phosphorous	18
1. Mineralogy	18
a. Coarse sand-size collophane grains	18
b. Apatite invertebrate bone fragments	24
c. Conodont fragments	24
d. Fine to very fine sand-size collophane	24
e. Collophane fillings of fossil chambers	27
f. Collophane replacements of fossil fragments	27
g. Collophane replacements of calcite grains	30
h. Spots of collophane replacement of sparry calcite	30
i. Rings of collophane in hematite oolites and flaxseed	30
j. Films of collophane on quartz grains	31
k. Films of collophane on feldspar grains	31
l. Veinlets in feldspar grains	34
m. Small grains of collophane in hematite	34
n. Tiny disseminated collophane grains	34
o. Tiny collophane grains clustered in hematite	35
2. Modal Analyses of Collophane and the Abundance of the 15 Collophane Types in the Four Iron Ore Lithologies	37
3. Potential Separability of Collophane from Various Iron Ores	43
4. Suggestions on Beneficiation	58
D. Other Minerals	59

II. Eufaula Ferruginous Bauxites	60
A. General Character	60
B. Varieties of Ferruginous Bauxites	60
C. Mode of Occurrence of Iron	61
1. Mineralogy	61
a. Iron concretions	61
b. Goethite	63
c. Hematite	66
d. Lepidocrosite	67
e. Pyrite	67
f. Marcasite	69
g. Siderite	69
h. Ilmenite	69
2. Suggestions on beneficiation	69
D. Other Minerals	70
III. Further Work Recommended	71
IV. Selected References	72
V. Statement of Patents or Inventions	74
VI. Conclusions	75
VII. Appendices	76
A. Appendix A. Descriptions of selected polished thin sections of Birmingham iron ores.	76
B. Appendix B. Descriptions of polished thin sections of Eufaula ferruginous bauxites.	100
C. Appendix C. The Luminoscope and cathodoluminescence.	118
D. Appendix D. X-ray diffractograms of Eufaula ferruginous bauxites.	120

LIST OF ILLUSTRATIONS

	<u>Pages</u>
Figure 1. Triangular diagrams showing the major constituent variations in the four iron ore lithologies.	16-17
Figure 2. Photomicrograph of sand-size carbonate-fluorapatite grain containing abundant clastic quartz inclusions.	22
Figure 3. Scanning electron microscope - energy dispersive spectroscopic (SEM-EDS) analysis of sand-size carbonate-fluorapatite grain.	22
Figure 4. SEM-EDS analysis of a trilobite fossil fragments.	25
Figure 5. Luminoscope micrograph of an invertebrate bone fragment.	25
Figure 6. Transmitted light micrograph showing a cusp-shaped banded apatite grain interpreted to be a conodont fragment.	26
Figure 7. Luminoscope micrograph showing two collophane faecal pellets.	26
Figure 8. Transmitted light micrograph showing two collophane grains deposited within the chambers of a bryozoa fragment.	29
Figure 9. Luminoscope micrograph showing bryozoa fossil fragments.	29
Figure 10. Luminoscope micrograph showing a collophane ring in a hematite oolite together with many tiny disseminated collophane grains.	33
Figure 11. Luminoscope micrograph showing a clastic potash feldspar grain with marginal replacement by collophane.	33
Figure 12. Luminoscope micrograph showing tiny grains of collophane clustered in portions of hematite areas.	38
Figure 13. SEM micrograph showing abundant collophane.	38
Figure 14. Histograms showing abundance of collophane types in the four types of iron ore.	48
Figure 15. Equidimensional to elongate goethite grains about 30-60 μm across which exhibit varying amounts of bauxite inclusions. 160X.	64
Figure 16. Goethite (light gray) concentrated in rims 5-125 μm thick around pisolites. 160X.	64
Figure 17. Goethite (light gray) lining small vugs. Tiny hematite grains (white) 1-3 μm across occur at the base of the goethite and are disseminated throughout the bauxite. 400X.	65
Figure 18. Tiny, irregularly shaped goethite grains, 1-10 μm across, disseminated in bauxite. 500X.	65

- Figure 19. A hematite grain 37 μm across surrounded by smaller (less than 5 μm) disseminated hematite grains. 400X. 68
- Figure 20. Pyrite concretions, originally 75-150 μm across, altering to goethite. 500X. 68

LIST OF TABLES

		<u>Pages</u>
Table I.	Summary of iron ore samples examined and described.	15
Table II.	Phosphorous-bearing mineral grains in Birmingham iron ores listed in approximate order of abundance.	19
Table III.	Electron microprobe analyses of carbonate-fluorapatite sand-size grains.	23
Table IV.	Electron microprobe analyses of fine to very fine sand-size faecal pellets.	28
Table V.	Electron microprobe analyses of collophane rings within hematite oolites.	32
Table VI.	Electron microprobe analyses of tiny disseminated collophane grains.	36
Table VII.	Electron microprobe analyses of tiny clustered collophane grains.	39
Table VIII.	Percent of each phosphate grain type in selected iron ore lithologies.	41
Table IX.	Percent of each phosphate grain type in bulk iron ore specimens.	42
Table X.	Percent of each phosphate grain type in flaxseed-type iron ores.	44
Table XI.	Percent of each phosphate grain type in sandy-type iron ores.	45
Table XII.	Percent of each phosphate grain type in fossiliferous-type iron ores.	46
Table XIII.	Percent of each phosphate grain type in oolitic-type iron ores.	47
Table XIV.	Calculation of percent of each phosphate grain type in Big Seam iron ore.	50
Table XV.	Calculation of percent of each phosphate grain type in Irondale iron ore.	51
Table XVI.	Calculation of percent of each phosphate grain type in Big Seam plus Irondale iron ore.	52
Table XVII.	Calculation of percent of each phosphate grain type in Big Seam iron ore previously mined.	53
Table XVIII.	Calculation of percent of each phosphate grain type in Big Seam iron ore reserves.	54
Table XIX.	Amounts of collophane removable by beneficiation of Big Seam iron ore as predicted from microscopic examination of ore textures and grain sizes.	55

Table XX.	Calculation of the percent of each phosphate grain type in Big Seam iron ore reserves using averages rather than type specimens to characterize the iron ore lithologies.	57
Table XXI.	Summary of iron minerals in Eufaula bauxites specimens.	62

SUMMARY

The character of phosphorous-bearing minerals in the Birmingham red iron ores and iron-bearing minerals in the Eufaula bauxite deposits in Alabama has been intensively studied by petrographic, ore microscopic, luminescent microscopic, scanning electron microscopic, electron microprobe, and x-ray diffraction techniques. A total of 15 types of phosphorous-bearing mineral grains have been recognized to occur in four lithologic varieties (flaxseed, sandy, fossiliferous, and oolitic) of Birmingham iron ores. Each of the 15 grain types has its own characteristic size, shape, and distribution. The largest grains are carbonate-fluorapatite (collophane) faecal pellets which average about 1/2 to 3/4 mm across and exhibit only minor intergrowth with hematite. These grains can be readily separated from the iron ores by beneficiation. The second-largest grains are also carbonate-fluorapatite faecal pellets; they are about 100 μm across and 180 μm long and exhibit varying degrees of replacement by hematite. Only a portion of these grains, perhaps about 20%, can be expected to be liberated from material ground to pass through a 400 mesh. The remaining 13 types of phosphorous-bearing mineral grains (also mainly carbonate-fluorapatite) are much finer-grained, averaging only 5 to 30 μm across, and little or none of these grains would be liberated from hematite at an economically practical grind.

Size measurements of the various phosphorous-bearing grains, modal analyses of 23 polished sections of the four iron ore varieties, and analysis of intergrowth textures between collophane and hematite permitted an estimate of potential liberation of phosphorous from the iron ores by beneficiation. These data indicate that about 27% of the phosphorous may be removed by beneficiation of iron ores of the lithologic character of those formerly mined in the western portion of the Birmingham district. About 60% of the phosphorous in the iron ore reserves which remain in the central and eastern portions of the district appears to have the potential for liberation by beneficiation. Fine grinding, selective flocculation, and flotation may constitute the best beneficiation technique for future research.

Goethite and hematite are the most important iron minerals in Eufaula ferruginous bauxites, but pyrite, marcasite, and siderite are important iron minerals in some varieties of ferruginous bauxite, and lepidocrocite and ilmenite are present locally in minor quantities. The coarsest iron-bearing grains are concretions about 1/4 to several inches across. Fine-grained goethite and hematite (1-135 μm across) are also abundant in those specimens representative of the largest reserves of ferruginous bauxites in the Eufaula district. Although simple screening will remove the coarsest iron-bearing grains, research on the utilization of high gradient magnetic separation to reduce the amounts of fine iron-bearing grains is recommended.

INTRODUCTION

The research discussed in this report involves two different types of ores: 1) the Birmingham, Alabama iron ores, and 2) the Eufaula, Alabama bauxites. Although the great steel-producing district of Birmingham, Alabama was originally built at that location because of the presence of abundant iron and coal resources, and although a large reserve of 5.2 billion tons of iron ore remains in the district (Simpson, et al., 1978), the utilization of these large domestic reserves has gradually declined. Significant mining of Birmingham iron ores ended by 1962 and no mining has occurred since 1973. The raw material for the blast furnaces of the Birmingham area now consists of iron ores and agglomerated iron oxide products primarily imported from Venezuela. Because this source of supply could become vulnerable to political and other actions of foreign governments, it is in the best interest of the United States to bring about a sufficient improvement in the Birmingham iron ores, by beneficiation, that they could again be utilized.

There are several problems involved in the utilization of the Birmingham red iron ores; these include their low iron grade, fine-grain size, and relatively high phosphorous content. Previous research on the beneficiation of these ores by the U.S. Bureau of Mines (Hertzog, 1935; Feld, 1960; Perry, 1962; Lamont, 1973) and the University of Alabama (Hanna and Rampacek, 1980) had succeeded in producing iron concentrates of sufficiently high grade, but most of those products contained too much phosphorous. Because of those deleterious phosphorous contents and because previous microscopic studies of the ores had located only a single grain (Hertzog, 1973) or minor amounts of the phosphate mineral (Lamont, et al., 1973), the present intensive microscopic study was undertaken to identify the phosphate minerals and to determine their grain sizes, shapes, and distributions.

In contrast to previous work, this investigation has: 1) found a large number of phosphate mineral grains which occur in 15 different grain types characterized by their sizes and shapes, 2) counted about 1000 of these grains in each of 23 polished thin sections of typical ore in order to perform model analyses, 3) calculated from these analyses the abundance of each phosphorous mineral type in each of four iron ore lithologies, and 4) estimated the potential liberation of phosphorous which may be expected for the iron reserves remaining in the Birmingham district. These detailed microscopic observations and measurements should provide an excellent foundation of mineralogical and textural information for additional beneficiation research on the Birmingham red iron ores.

The second portion of this research report involves ferruginous bauxites in the Eufaula, Alabama district. The United States is dependent upon foreign imports for 93% of its bauxite and alumina consumption (Stampfer and Kurtz, 1977). Many of those countries which serve as the major suppliers have recently organized under the International Bauxite Association. The formation of this international cartel, together with a degree of political instability in some of the exporting nations (Australia, Jamaica, Surinam, Guinea, Guyana), indicates that the supply of alumina raw materials to the United States could become vulnerable to political unrest and economic

actions taken by foreign countries. Therefore, it is important to the national welfare to increase the reserves and supply of domestic bauxite. One of the most important domestic bauxite reserves, one which is utilized only to a very limited extent, is that which occurs as ferruginous ($>1\frac{1}{2}\%$ Fe_2O_3) bauxite. A reserve of two to ten million tons of ferruginous bauxite has been estimated to occur in the Eufaula district (Clarke, 1977). If these estimates are correct, and if this resource could be utilized, it could increase domestic reserves by as much as 25%.

The Eufaula ferruginous bauxites were examined by petrographic, ore microscopic, and x-ray techniques to identify the iron-bearing minerals, measure their grain sizes, and to study their texture and distribution. A previous study by Clarke (1977) has found goethite. The present investigation has identified seven iron-bearing minerals to occur in several types of ferruginous bauxite. These mineralogical determinations, together with grain size measurements, should provide a good basis for additional research on beneficiation methods to reduce the iron content of these ferruginous bauxites.

All of the research for this report was conducted at the Rolla campus of the University of Missouri, except for the electron microprobe analyses which were carried out at the Columbia campus of the same university.

OBJECTIVES

This investigation has consisted of two separate studies: 1) Birmingham, Alabama red iron ores, and 2) Eufaula, Alabama ferruginous bauxite deposits.

The principal objective of the study of the Birmingham red iron ores was to identify the minerals which contain the small amounts of phosphorous present in those ores. Another objective was to determine the average grain size, characteristic shape, distribution, and abundance of those phosphorous-bearing mineral grains and their degree of intergrowth with iron minerals. Such information will be very useful in future beneficiation research on Birmingham iron ores. A subsidiary objective was to identify other minerals present in the iron ores, including those which dilute the ore and those which may constitute potential health or environmental hazards.

The principal objective of the study of the Eufaula ferruginous bauxite deposits was to identify the minerals which contain the small to moderate amounts of iron present in those bauxite deposits. A related objective was to determine the grain size, characteristic shape, distribution, relative abundance of those iron minerals and their degree of intergrowth with the bauxite. Such information may aid in attempts to diminish the iron content of ferruginous bauxites by beneficiation. A subsidiary objective was to identify other minerals which dilute the bauxite or which may constitute health or environmental hazards.

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Ralph Coleman, U. S. Bureau of Mines-Rolla, performed a chemical analysis of the bulk iron ore sample. John L. Thompson, UMR Materials Research, ran the SEM-EDS determinations. David R. Rothbard, UMC Geology, ran the electron probe analyses. Patrick J. Kelley, UMR undergraduate student, helped with the preparation of illustrations. Tammy T. Carroll and Linda C. Martin typed the manuscript.

I. BIRMINGHAM RED IRON ORES

A. General Character

The Birmingham, Alabama red iron ores are typical Clinton-type sedimentary iron formations of Silurian age. The iron ore occurs as thin beds or seams, usually 24 feet or less in thickness, in the Red Mountain Formation, which consists primarily of sandstones, shales, and minor limestones. The Big Seam contains the most important reserves in the Birmingham district and it has an average grade of about 36 to 37% Fe. Lower grade iron reserves occur in ferruginous sandstone in the Red Mountain Formation above the Big Seam (Simpson, et al, 1978)¹. The Big Seam iron ore probably was deposited in a lagoon (Sheldon, 1962) or barrier bar (Chowns and McKinney, 1980) sedimentary environment.

The major constituents in the iron ore are: hematite, calcite, and quartz. Almost all of the iron occurs as very fine-grained hematite in a variety of forms. Much of the hematite has formed as partial replacements of calcitic fossil fragments. Hematite also is abundant in the form of concentrically-banded oolites and as elongate or "flaxseed" oolites. Hematite also forms a very fine-grained matrix between fossil fragments and oolites. Minor hematite occurs as coarser crystals serving as oolite nuclei and as relatively coarse-grained specular hematite in disseminated replacements in some oolite nuclei. Calcite occurs primarily as fossil fragments of bryozoa, brachiopods, crinoids, echinoids, trilobites, and ostracods. Calcite occurs in lesser amounts as internally-banded, sparry calcite cement. Quartz occurs as round to subrounded fine to coarse sand grains.

B. Iron Ore Lithologic Variations

Previous investigations have generally separated Birmingham iron ore into two types: fossiliferous and oolitic. Our examinations of 23 polished thin sections (Table I) show that four types of iron ores can be readily distinguished under the microscope and that these have important differences in phosphate mineral grain character. The four types are distinguished by their relative abundances of the major constituents. The four types are:

- 1) flaxseed,
- 2) sandy,
- 3) fossiliferous, and
- 4) oolitic.

Fossiliferous-type iron ores consist primarily of calcitic fossil fragments partly replaced by hematite, and may contain lesser amounts of quartz sand, hematite oolites, and hematite flaxseeds. Sandy-type iron ores contain abundant quartz sand grains together with many calcitic fossil fragments, and usually minor oolites and flaxseeds. Oolitic-type iron ores are dominated by hematitic spherical to ovate "true" oolites, and contain some fossil fragments and minor flaxseeds. They lack coarse-grained quartz sand grains, but

¹The names and dates in parentheses refer to the references given in the section on Selected References given in this report.

Table I

Summary of Iron Ore Samples Examined and Described

<u>Polished Thin Section Number</u>	<u>Sample Number</u>	<u>Sample Site Drill Hole</u>	<u>Ore Type</u>	<u>Degree of Weathering</u>
PTS-1	BS-1	Mine Bulk Sample	Flaxseed	Unweathered
PTS-2	78-(26)63	DDH-3	Flaxseed	Unweathered
PTS-3	78-(26)63	DDH-3	Fossiliferous	Unweathered
PTS-4	2668.5	DDH-3	Flaxseed	Unweathered
PTS-5	78-(26)72.5	DDH-3	Fossiliferous	Unweathered
PTS-6	2677.5	DDH-3	Oolitic	Unweathered
PTS-7	2680	DDH-3	Oolitic	Unweathered
PTS-11	2672	DDH-3	Flaxseed	Unweathered
PTS-12	3249	DDH-1	Flaxseed	Unweathered
PTS-13	3255	DDH-1	Sandy	Unweathered
PTS-14	3260	DDH-1	Sandy	Unweathered
PTS-15	3261	DDH-1	Sandy	Unweathered
PTS-16	3264	DDH-1	Oolitic	Unweathered
PTS-17	3527	DDH-2	Flaxseed	Unweathered
PTS-18	3530	DDH-2	Flaxseed	Unweathered
PTS-19	3532	DDH-2	Flaxseed	Unweathered
PTS-20	3538	DDH-2	Sandy	Unweathered
PTS-21	3541	DDH-2	Flaxseed	Unweathered
PTS-BS-2	BS-2	Mine Bulk Sample	Sandy	Unweathered
PTS-BS-3	BS-3	Mine Bulk Sample	Fossiliferous	Unweathered
PTS-BS-4	BS-4	Mine Bulk Sample	Flaxseed	Unweathered
PTS-BS-5	BS-5	Mine Bulk Sample	Fossiliferous	Unweathered
PTS-BS-6	BS-6	Mine Bulk Sample	Flaxseed	Unweathered

DDH-1 - East Portion of District SE $\frac{1}{4}$ of NW $\frac{1}{4}$ of NE $\frac{1}{4}$, Sect 31, T185, R2W
 DDH-2 - Central Portion of District NW $\frac{1}{4}$ of SW $\frac{1}{4}$ of SW $\frac{1}{4}$, Sect 36, T185, R3W
 DDH-3 - West Portion of District NE $\frac{1}{4}$ of SE $\frac{1}{2}$ of NE $\frac{1}{4}$, Sect 4, T185, R3W
 BIRMINGHAM SOUTH QUADRANGLE, ALA.

Figure 1-A. Triangular diagram showing the major constituent variations in the four iron ore lithologies.

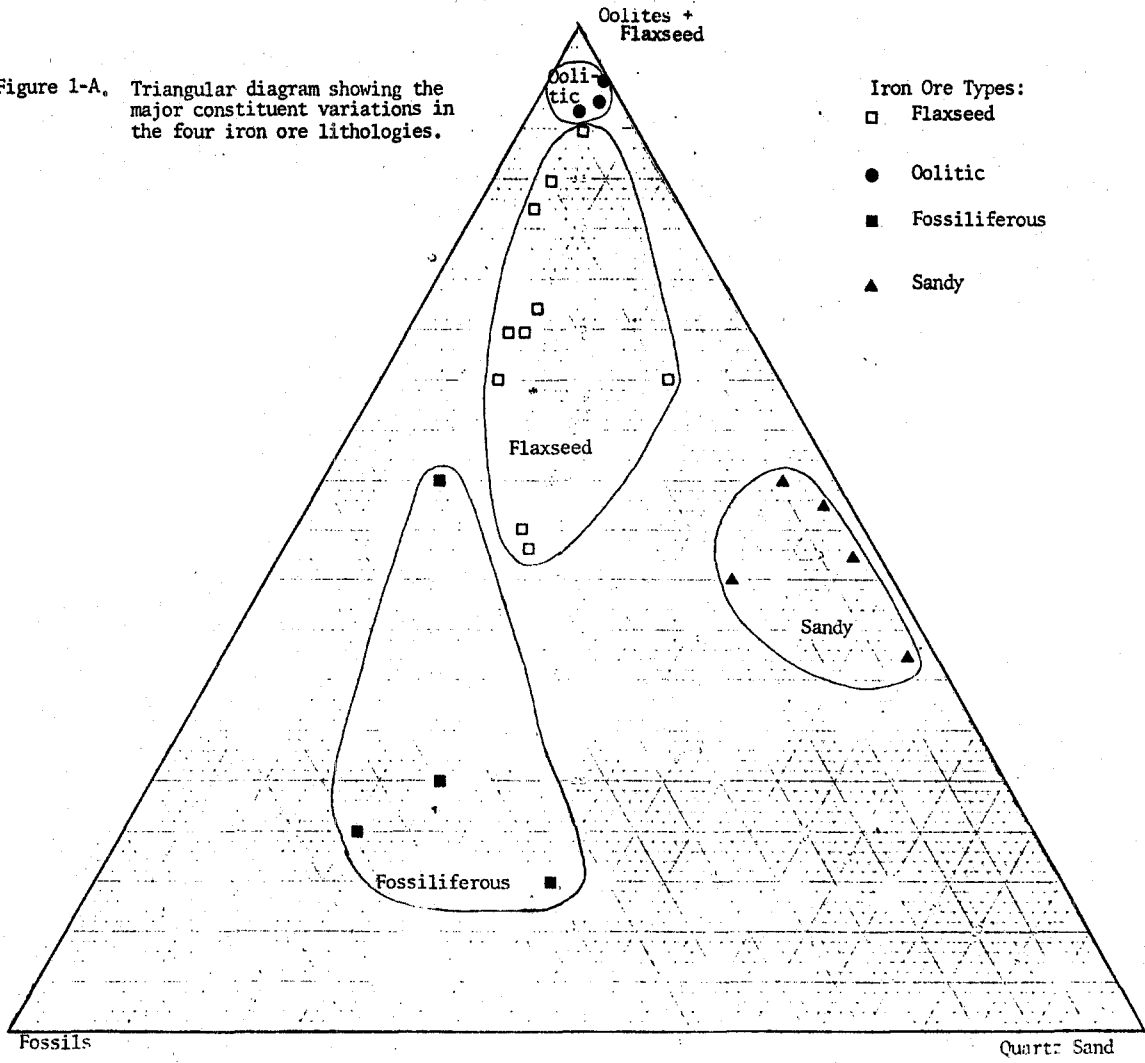
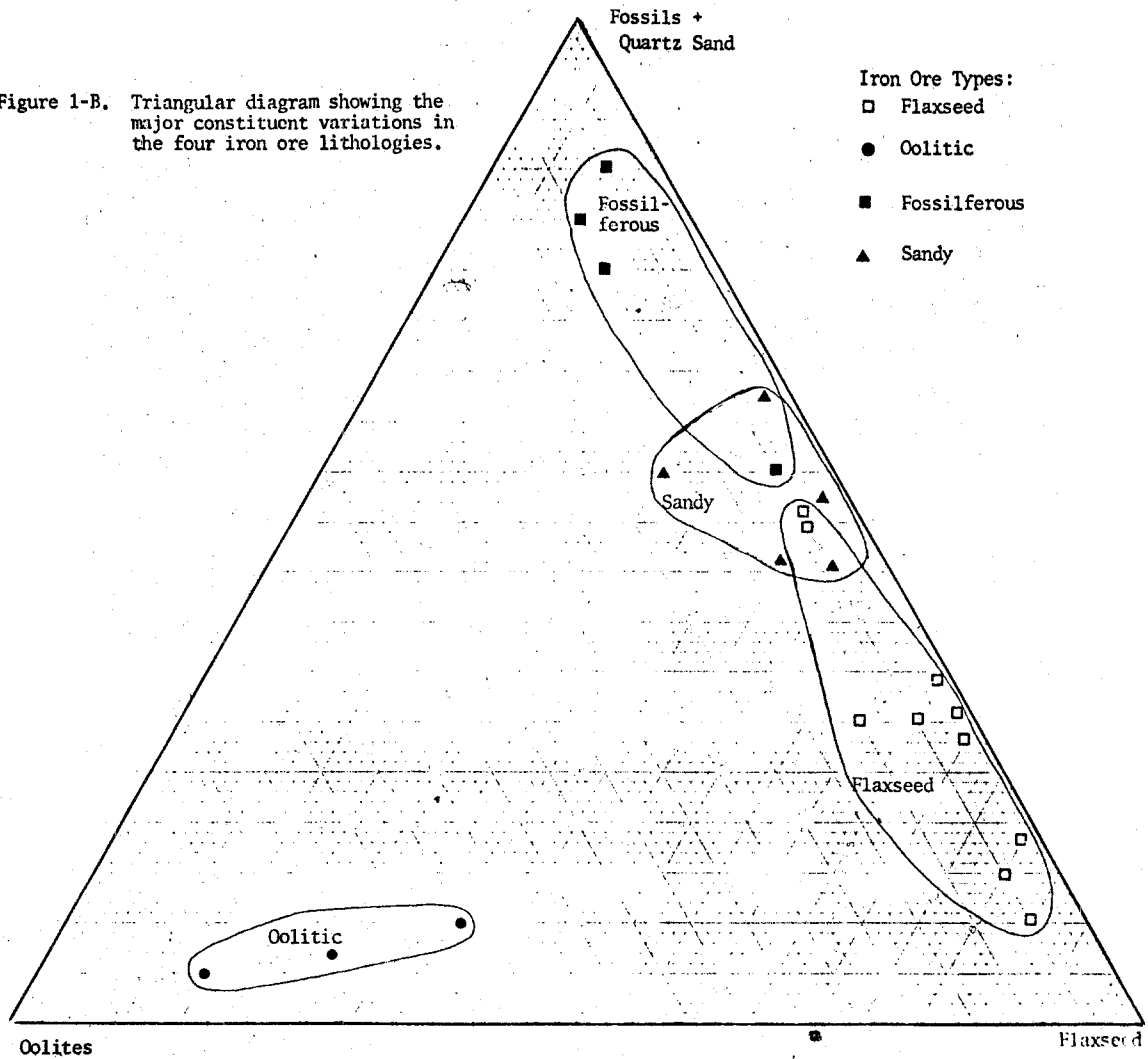


Figure 1-B. Triangular diagram showing the major constituent variations in the four iron ore lithologies.



contain smaller quartz grains of fine sand size. Flaxseed-type ores are more abundant than those with "true" oolites, and they are comprised of abundant hematitic flaxseeds, some clastic fossil fragments and variable amounts of quartz sand grains. The amount of each of the major constituents and their variations in the four iron ore lithologies is shown in Figure 1.

C. Mode of Occurrence of Phosphorous

The mode of occurrence of phosphorous in the Birmingham iron ores has constituted the principal objective of this research grant. Previous investigators who had sought to identify the phosphorous minerals had found only a single grain (Hertzog, 1935) or very minor amounts (Lamont, et al, 1973). The present investigators have: 1) found a large number of phosphorous-bearing mineral grains which occur as 15 different types characterized by their sizes and shapes, 2) counted about 100 of these grains in each of 23 polished thin sections of the ore to perform modal analyses, 3) calculated the abundance of each phosphorous-bearing mineral type in each of the four iron ore lithologies, 4) estimated the potential separability of phosphorous-bearing mineral from the various iron ores, and 5) have prepared some general suggestions on the significance to beneficiation process that have resulted from the observed character of the phosphorous-bearing mineral grains. Each of these topics is successively discussed in the following sections of this report.

1. Mineralogy

A total of 15 different types of phosphorous-bearing mineral grains have been identified in the Birmingham iron ores (Table II). Each of these 15 varieties are distinguished by their own characteristic size, shape, and distribution. Most of these varieties consist of a light brown isotropic material generally referred to as collophane in petrographic studies.

The character of the phosphorous-bearing mineral grains was studied by a combination of eight microscopic and electron beam microanalysis techniques. These include: 1) transmitted light, 2) simultaneous transmitted and inclined reflected light, 3) reflected light, 4) luminescent microscopy, 5) scanning electron microscope (SEM), 6) scanning electron microscope-energy dispersive spectroscopic analysis (SEM-EDS), 7) electron microprobe, and 8) x-ray diffraction. For each of the 15 varieties of phosphorous-bearing mineral grains, their characteristic: 1) size, 2) shape, 3) color and other distinctive properties, 4) abundance, 5) luminescent character, 6) distribution, 7) probable genesis, 8) locking with hematite and gangue minerals, and where appropriate 9) SEM-EDS and 10) x-ray diffraction data are described in the following sections.

a. Coarse sand-size collophane grains-

One of the most important varieties of phosphorous-bearing mineral grains is that which is present in the form of coarse sand-sized grains (Figure 2). Mineralogically the grains are collophane. The collophane grains range in size from about 200 μm to $2\frac{1}{4}$ mm and average about one-half to three-quarters mm in diameter. Their shapes are mostly round to subround to ovate. A few are distinctly elongate.

Table II

Phosphorous-bearing Mineral Grains in Birmingham Iron Ores
Listed in Approximate Order of Abundance

Sand-size collophane
Fine to very fine sand-size collophane
Collophane replacements of calcite grains
Tiny collophane grains clustered in hematite
Collophane fillings of fossil chambers
Collophane replacements of fossil fragments
Tiny collophane grains clustered in hematite
Tiny disseminated collophane grains
Films of collophane on quartz grains
Films of collophane on feldspar grains
Small grains of collophane in hematite
Rings of collophane in hematite oolite and flaxseed
Apatite invertebrate bone fragments
Conodont fragments
Veinlets in feldspar grains

Although most of the collophane grains are readily recognized under the petrographic microscope by their light brown color (and isotropic character), and some are even dark brown, others are almost colorless and appear similar to quartz sand grains under ordinary light. The grains can be distinguished with difficulty under reflected light due to their slightly higher reflectance ($R=5.9$) than that of quartz ($R=4.5$). The collophane grains commonly contain smaller quartz grain inclusions which average about 10 to 100 μm in diameter. The quartz inclusions vary greatly in abundance. Although some collophane sand grains are free from quartz inclusions, most have rather abundant inclusions, and some grains contain more than 50% quartz inclusions.

The sand-size collophane grains are rather abundant and as many as 12 grains are observed in some polished thin sections. Because of their large size these grains contain a large part of the total phosphorous present in much of the iron ore. Calculations based upon modal analyses of the phosphorous-bearing mineral varieties present, indicate that about one-third to one-half of the total phosphorous present is present as this type in bulk iron ores from Birmingham. The amounts of this phosphorous type vary with the iron ore lithology. It is most abundant in sandy and flaxseed iron ores, less abundant in fossiliferous, and absent from oolitic iron ores.

Most of the collophane grains are enclosed in a matrix of hematite, but exhibit little or no replacement by hematite. A few grains show minor replacement spots of hematite along their margins. Rarely, the grains are partially replaced by fine-grained hematite throughout. Such grains are only partially visible or not visible at all with transmitted light under the petrographic microscope because the tiny 1-10 μm hematite grains scattered throughout the 30 μm thick section of collophane render the latter mineral opaque. Only under the luminescope, due to their light violet luminescence, is the extent of such phosphate grains evident.

The sand-size collophane grains are probably faecal pellets (animal droppings) which have experienced some degree of abrasion as a result of rolling in an agitated sea floor environment. The faecal pellet origin is evidenced by the ovate to elongate shapes and smooth exterior margins of some grains. The presence of quartz inclusions and their variable abundance is characteristic of faecal pellets dropped by burrowing animals which are indiscriminant in their food intake from the sea bottom sediment. This is typical of the food habits of worms. The size of these grains is typical of faecal pellets from gastropods (snails). The presence of small amounts of irregularly shaped calcite in some of the collophane grains indicates that they developed in part or wholly by phosphatic replacement of faecal pellets which originally perhaps contained much calcite. That many of the collophane grains may have been moved after hardening and deposited as partly abraded clastic grains is indicated by their common subround character, an average size close to that of the quartz sand grains, and especially by smooth exterior margins which transect quartz grain inclusions.

Because the sand-size phosphorous-bearing grains are mostly free from hematite and are coarse-grained they will be predominantly released as particles free of hematite upon fine grinding and be separable from a hematite concentrate.

Although most grains of this type of phosphate mineral can be readily recognized without the use of the luminescope, that instrument was useful to locate additional grains which were partly replaced by hematite, as indicated earlier. The luminescope also was used to show that two other types of brownish colored grains were not phosphatic. These were 1) iron stained trilobite fossil fragments and 2) coarse sand-size grains which contain quartz sand inclusions. The luminescence of both types of grains show that they are predominantly calcite and contain only very subsidiary amounts of collophane locally replacing the calcite.

The scanning electron microscope with an energy dispersive spectroscopic analyzer (SEM-EDS) was utilized to confirm that these sand-size grains were a phosphorous-containing mineral. Numerous grains were analyzed and found to consist primarily of calcium and phosphorous. Figure 3 is an example of one grain analyzed. The SEM-EDS was also used to show that certain other grains in the iron ores were not phosphatic. Trilobite fossil fragments typically are light to dark brown in color and appear under transmitted light to be somewhat similar to the collophane grains. SEM-EDS analyses showed that they contain calcium and small amounts of iron (accounts for brown stain) and lack phosphorous. Figure 4 is an example of one grain analyzed.

The electron microprobe was utilized to further confirm that the collophane sand-size grains were a phosphorous-bearing mineral, and to determine their CaO , P_2O_5 , and F contents. Five analyses were performed on each of seven grains in two polished thin sections. The resulting analyses, given in Table III, show that the grains contain an average phosphorous content of 15.03% (calculated from 34.43% P_2O_5) and about 3% fluorine (indicating that it is a fluorine-bearing rather than hydroxyl (OH)-bearing collophane. The sums are about 83 to 87% and a portion of the remaining 13 to 17% presumably is present as carbonate but CO_2 was not determined.

Finally, three of these grains were analyzed by x-ray diffraction to determine if they had a submicroscopic crystallinity. All three grains gave an x-ray pattern for francolite or carbonate-fluorapatite. The term collophane is normally used for the isotropic carbonated calcium phosphate mineral observed under the microscope in sedimentary rocks when no x-ray analyses have been performed; for those collophane grains which exhibit an x-ray pattern the terms carbonate-fluorapatite (if F-bearing) or carbonate-hydroxylapatite (if OH-bearing) (McConnell, 1973). Thus, the x-ray and electron microprobe data indicate that the sand-size phosphatic grains should be called carbonate-fluorapatite.

The other varieties of phosphatic grains which are termed collophane in succeeding sections of this report may also have a submicroscopic crystalline structure and would also be referred

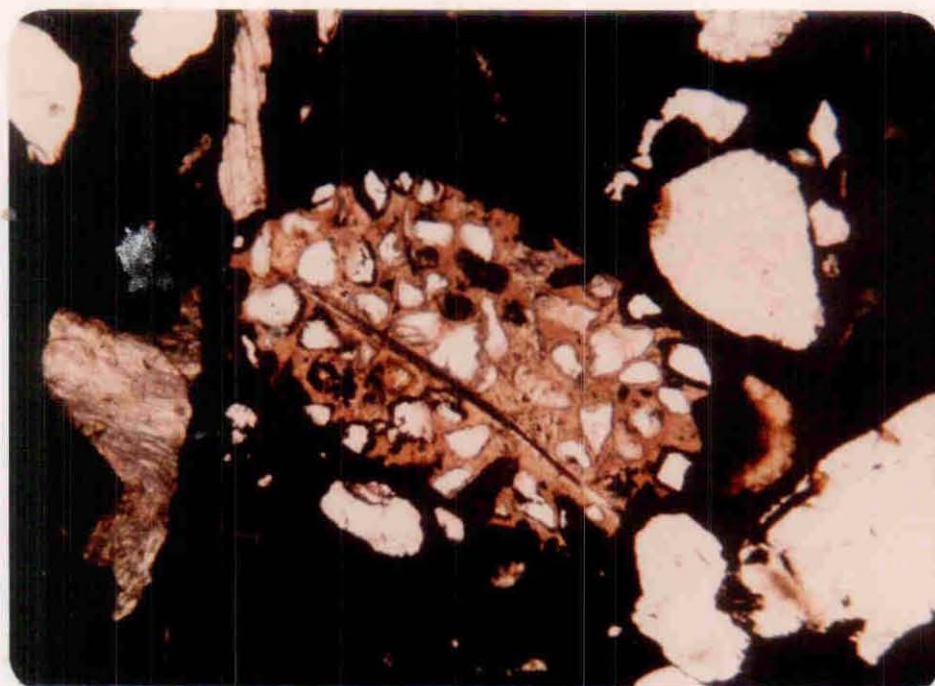


Figure 2. Photomicrograph of sand-size carbonate-fluorapatite grain containing abundant clastic quartz inclusions, an abundant type of phosphate grain in Birmingham iron ores. Grains of this type average 1/2 to 3/4 mm in diameter and should be separable from the iron ore by fine grinding and beneficiation. The grains originated as snail or worm droppings (faecal pellets) and have experienced some transportation and abrasion. Clastic quartz grains (white) and brachiopod fossil fragments (light gray) occur in hematite (black).

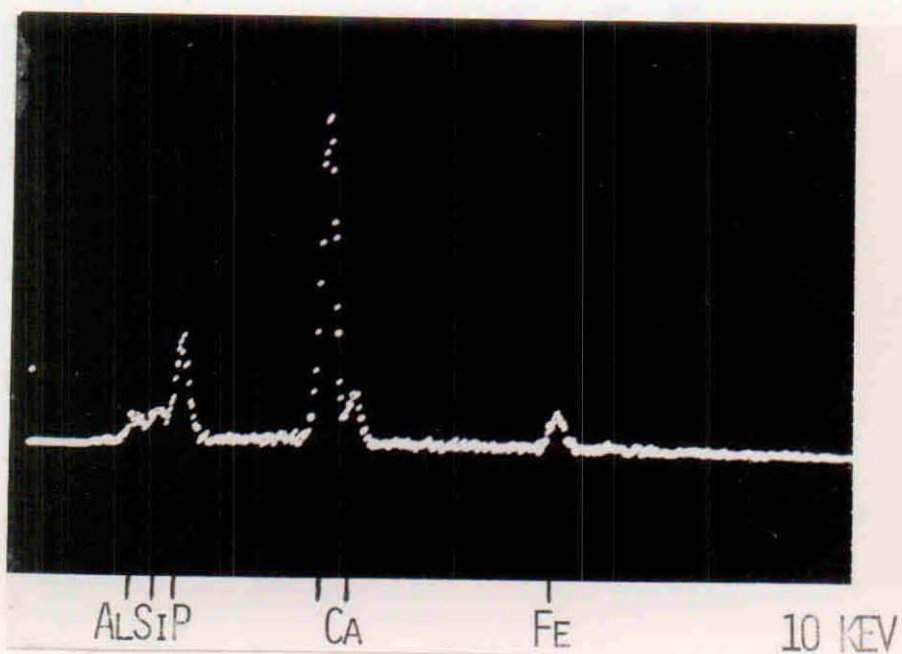


Figure 3. Scanning electron microscope - energy dispersive spectroscopic (SEM-EDS) analysis of sand-size carbonate fluorapatite grain.

Electron Microprobe Analyses of Collophane Sand-Size Grains
(5 analyses of each grain)

		CaO	P ₂ O ₅	F	Sum
PTS-1	Grain 1	49.44	34.49	2.85	86.78
PTS-1	Grain 2	48.55	34.08	2.93	85.56
PTS-1	Grain 8	49.53	34.66	3.06	87.26
PTS-12	Grain 2	46.74	34.90	2.93	84.57
PTS-12	Grain 3	49.97	34.86	3.75	88.58
PTS-12	Grain 6	46.94	33.44	2.93	83.31
PTS-12	Grain 7	45.82	34.56	2.96	83.34
Average		48.14%	34.43%	3.06%	85.63%

34.43% P₂O₅

15.03% P

to as carbonate-fluorapatite (those types analyzed by electron microprobe show about 3% fluorine) but they are too small to conduct this by x-ray diffraction of individual grains in place in the polished thin sections. Also, because of their small size and occurrence with other phosphorous-bearing mineral grains, could not be separated and concentrated for powder diffraction

b. Invertebrate bone fragments

Irregularly shaped fragments, about the same size as the coarse sand grains of the previous section, are characterized by a banded internal texture and well developed anisotropism observable in transmitted light (Figure 5). They are interpreted to be fragments of invertebrate bones because of their shapes and banded character. Their composition as a calcium phosphate was established electron probe analysis. Their fine crystallinity indicates that they are apatite. They luminesce light blue to purple. They are very rare and have been included with the sand-size carbonate-fluorapatite grains for modal analysis purposes.

c. Conodont fragments

Rare cusp-shaped grains about 400 μm long were observed (Figure 6). They consist of anisotropic banded apatite and are believed to be conodont fragments. They luminesce light purple. They also are very rare and have been included with the sand-size carbonate-fluorapatite grains for modal analysis purposes.

d. Fine to very fine sand-size collophane faecal pellets

Another important form of phosphate mineral is that which occurs as elongate grains with lobate shapes typical of faecal pellets (Figure 7). These grains are smaller than the coarse sand-size grains previously described. They range from 30 μm to 350 μm and average about 100 μm across and 180 μm long, and are about the size of the fine to very fine sand. The faecal pellets commonly form the nucleus for hematite oolites and flaxseed, but some occur in areas of calcite relatively free from hematite. They lack the quartz inclusions so common in the sand-size carbonate fluorapatite grains, but exhibit a wide variation in the amount of irregularly shaped calcite inclusions resulting from collophane replacement of former calcite faecal pellets. For the purpose of modal analyses, this type of collophane was sometimes subdivided into two groups: 1) those which consisted mainly of calcite with some collophane replacement ("calcite replacements"), and 2) those which are mainly collophane with little or no calcite left ("faecal pellets").

Faecal pellets of this type are most abundant in oolitic iron ore where they constitute 43% of the total phosphorous-bearing mineral grains present. They are next most abundant in fossiliferous iron ores (32%) and least abundant in flaxseed (14%) and sandy (13%) ores.

The genesis of this type of collophane involves their deposition as dominantly calcitic faecal pellets which were subsequently

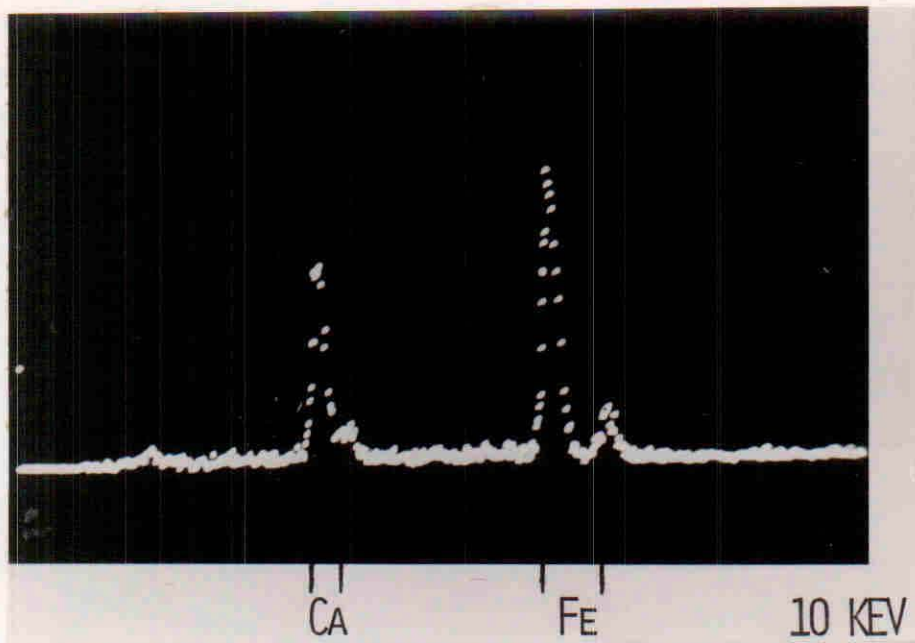
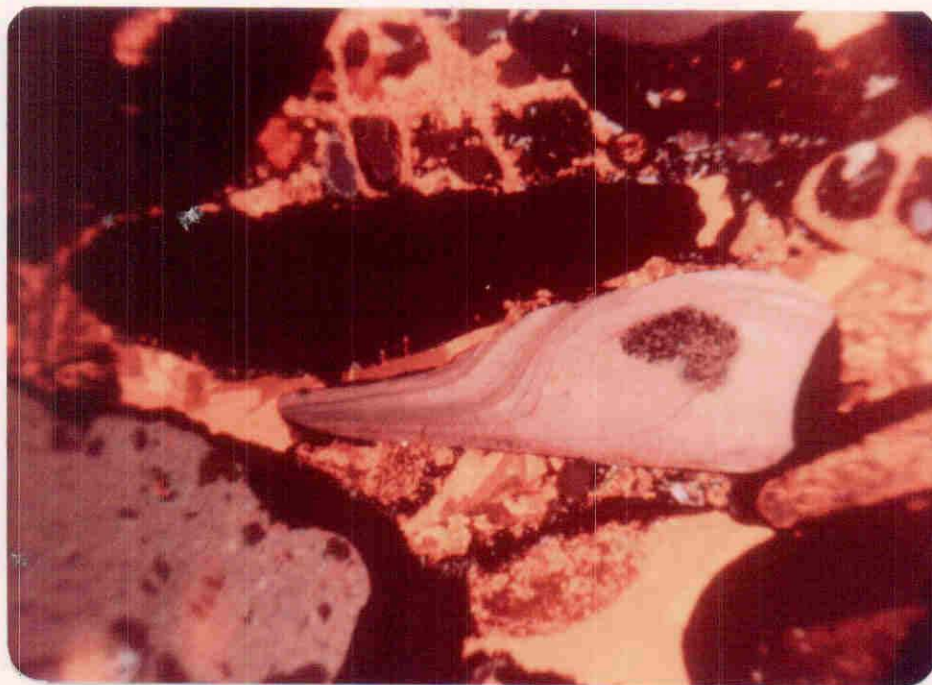


Figure 4. SEM-EDS analysis of a trilobite fossil fragments showing that the brownish color is due to iron staining.



100 μm

Figure 5. Luminoscope micrograph of a rare apatite invertebrate bone fragment (light purple) showing a banded internal texture. A sand-size phosphate intraclast (light purple) is present in the lower left, calcite (orange) and hematite (black) are major constituents.

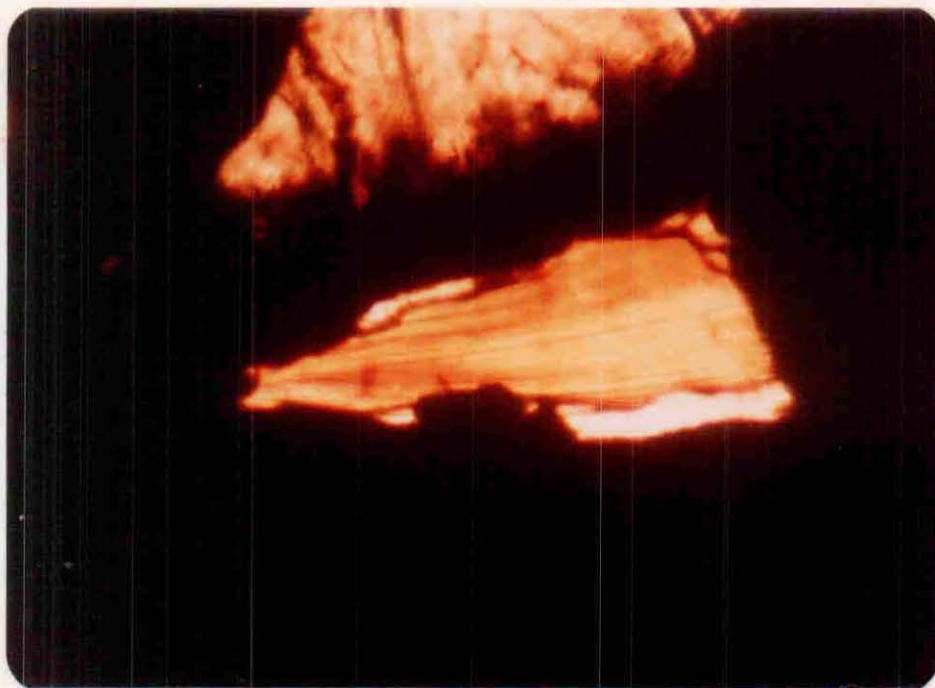
50 μm

Figure 6. Transmitted light micrograph showing a rare cusp-shaped banded apatite grain (brown) interpreted to be a conodont fragment.

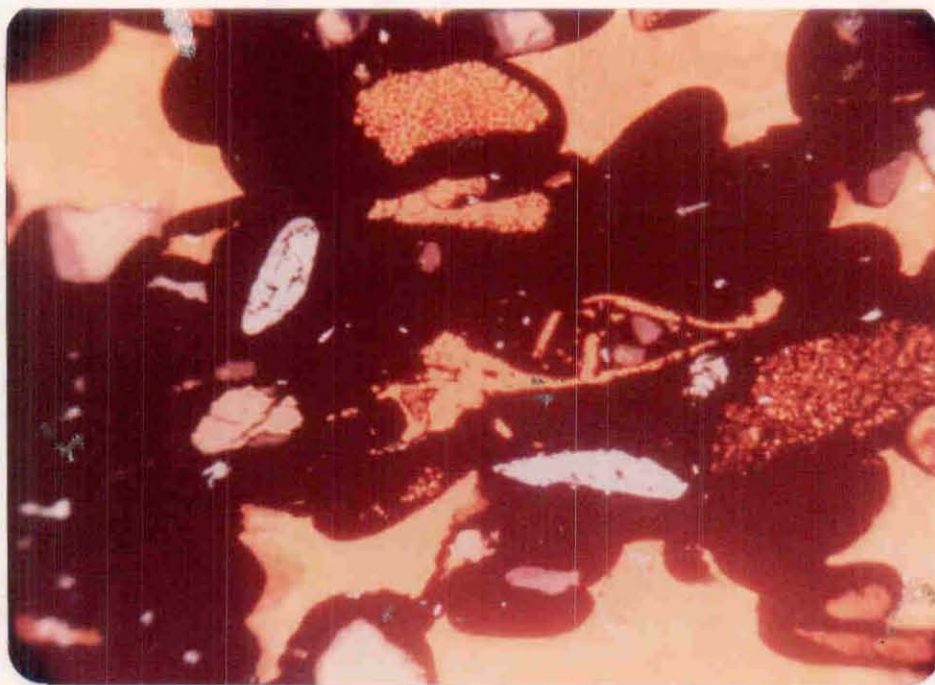
100 μm

Figure 7. Luminoscope micrograph showing two collophane faecal pellets, (light blue) both of which exhibit distinct elongations. These faecal pellets originated as droppings from trilobites or other silurian animals. Faecal pellets are an abundant form of phosphate-bearing mineral in Birmingham iron ores. Hematite oolites (black), have nuclei of fossil fragments (orange; mostly bryozoa and echinoid) and fine clastic quartz (white) and are cemented by sparry calcite (uniform orange). Additional tiny grains of collophane (light blue) are contained mostly in hematite.

partly to completely replaced by collophane. Trilobites were one animal form present that produced faecal pellets of this size.

Only about one-fifth of the total faecal pellets present in the iron ores can be detected by microscopic study with transmitted light. The majority of the pellets require Luminoscope study in order to be recognized due to their light violet luminescent color. This is because the faecal pellets are not only coated by layers of hematite, they also contain very fine-grained (1-10 μm) disseminated red earthy (and locally specular) hematite replacements which render the collophane opaque. These intergrowths with hematite indicate that much of this form of collophane would be expected to form locked particles with hematite even after fine grinding. Perhaps about one-quarter of this collophane type would be liberated from hematite.

SEM-EDS and electron microprobe analyses show that this type is a carbonated fluor-calcium phosphate. Table IV summarizes 40 electron probe analyses on seven grains in two polished thin sections. This type contains 16.29% P and 2.92% F.

e. Collophane fillings of fossil chambers

The deposition of collophane is favored by the reducing environment present within the chamber (zooecia), of fossil fragments, particularly bryozoa (Figure 8). These grains have a relatively wide range of size, from 20 μm to 1000 μm and average about 30 μm . Their shapes are irregular. They are most abundant in fossiliferous iron ore, next most abundant in flaxseed ore, and form only a minor constituent in sandy and oolitic iron ore lithologies.

Because bryozoa fossil fragments are commonly replaced by hematite, the collophane fossil fillings are usually intimately intergrown with hematite. The largest portion of this type of collophane would be expected to form locked particles with hematite even with fine grinding. It would be expected that most of the collophane fossil fillings would not be separable from hematite.

f. Collophane replacements of fossil fragments

In addition to the deposition of collophane within the chambers of fossil fragments, collophane also replaces the chamber (zooecia) walls of fossil fragments, particularly those of bryozoa (Figure 9). The chamber walls are about 10-30 μm thick, but their replacement is extremely variable, ranging from incipient to complete replacement. Echinoid and brachiopod fragments less commonly exhibit small amounts of replacement by collophane. This type of collophane commonly exhibits light blue luminescence. The fossil replacements by collophane are most abundant in fossiliferous iron ores where they constitute about one-quarter of the total collophane present. They constitute only about 6% or less of the total phosphate mineral present in the other three iron ore lithologies.

Fossil fragments showing collophane replacement are almost entirely enclosed in areas of hematite and also commonly are partly replaced by hematite. It would be anticipated that this type of hematite would largely form locked particles with hematite and most of it would not be liberated from the

Table IV

Electron Microprobe Analyses of Collophane Faecal Pellets
(4-8 analyses for each grain)

		CaO	P ₂ O ₅	F	Sum
PTS-12	Grain 8	51.80%	38.46%	3.09%	93.35%
PTS- 6	Grain 1	50.85	36.69	2.79	90.32
PTS- 6	Grain 2	49.82	35.86	2.42	88.11
PTS- 6	Grain 3	53.25	39.43	3.12	95.80
PTS- 6	Grain 4	51.94	37.38	3.37	92.69
PTS- 6	Grain 5	53.53	39.52	3.32	96.37
PTS- 6	Grain 6	50.56	33.90	2.35	86.81
Averages		51.68%	37.32%	2.92%	91.92%

37.32% P₂O₅

16.29% P

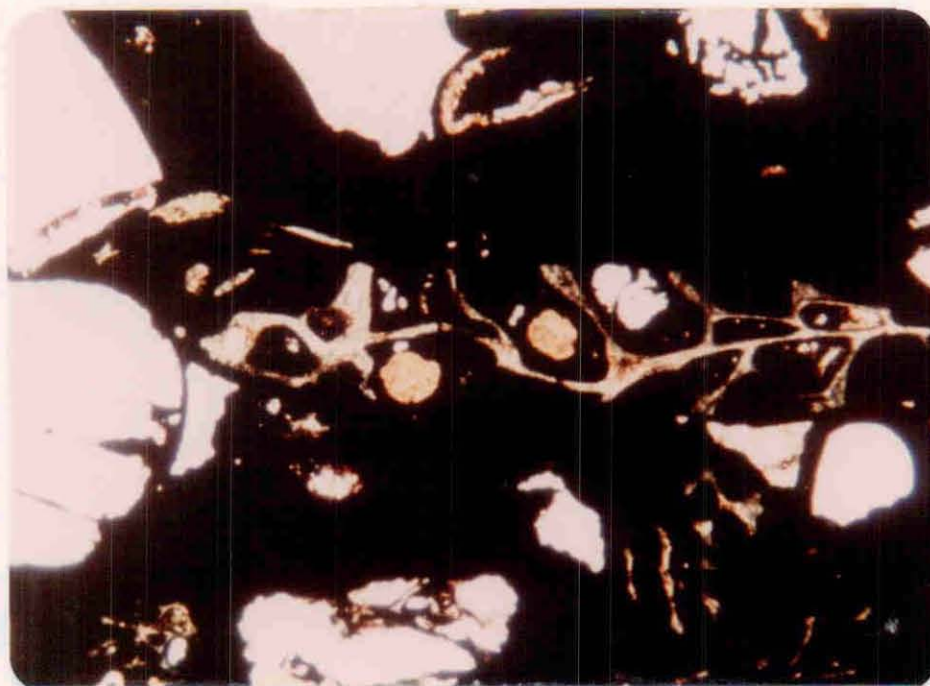
250 μm

Figure 8. Transmitted light micrograph showing two collophane grains (light brown) deposited within the chambers (zoecia) of a bryozoa fragment. The reducing environment within the bryozoa chambers (zoecia) favored the deposition of collophane during sediment diagenesis. Fossil fillings are an important form of phosphate mineral in Birmingham fossiliferous iron ores. Clastic quartz grains (white) are enclosed in hematite (black).

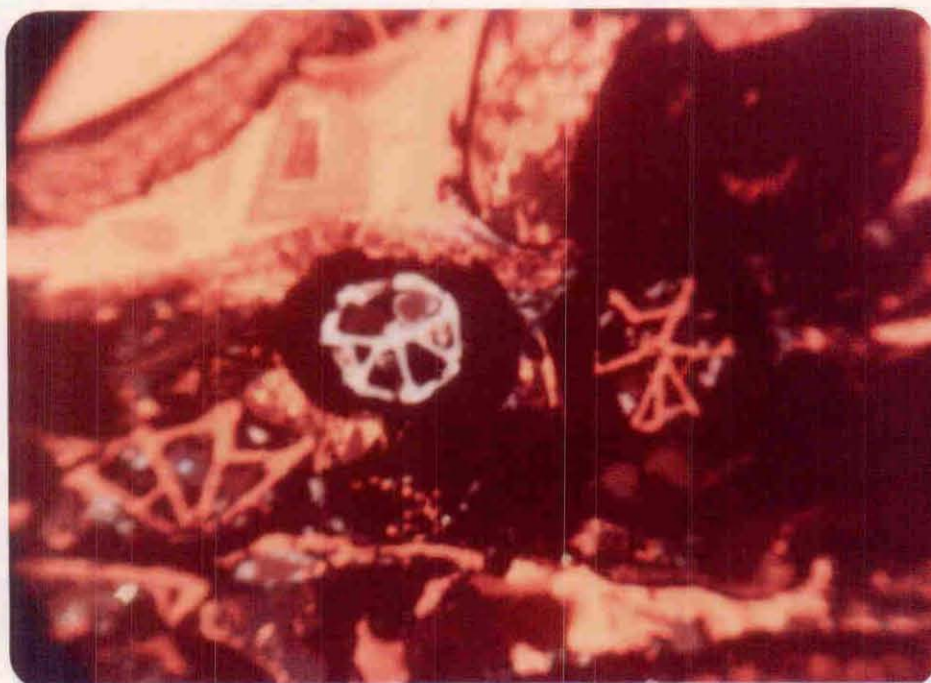
100 μm

Figure 9. Luminoscope micrograph showing two bryozoa fossil fragments, one largely unreplaced by collophane, (yellow orange) and the other almost completely replaced by collophane (blue). Both are encased in hematite (black). Small grains of collophane (light purple) also are contained within bryozoa fragments as partial fillings of calcite fossils (orange). Sparry calcite cement (orange, banded) occurs at upper left.

hematite by beneficiation even after very fine grinding.

g. Collophane replacements of calcite grains

A minor type of collophane is that which occurs as grains which are partial replacements of calcite grains of uncertain origin, but most are probably fossil fragments. These grains differ from the calcite replacements previously described in section d in that they are not enclosed in hematite oolites. They exhibit a wide range of size but perhaps average about 30 μm . Their shapes are irregular. Their luminescent color is light purple. This form constitutes an average of less than 2% of the total collophane grains in all four iron ore lithologies. Because these collophane grains are enclosed almost entirely in calcite, they would be expected to be readily separable from hematite during beneficiation.

h. Spots of collophane replacement of sparry calcite

Another minor type of collophane is that which forms small grains replacing sparry calcite cement. These grains range from about 10 to 30 μm and average 20 μm . Their shapes are irregular. They luminesce light purple. Their greatest abundance is in oolitic iron ores where they average about 4%, and in the other three types of iron ore lithologies this collophane type constitutes about 1% of the total collophane present. These collophane replacements are contained entirely within calcite and would be expected to separate from hematite during beneficiation.

i. Rings of collophane in hematite oolites and flaxseed

Collophane occurs in small amounts within hematite oolites and flaxseeds as rings. (Figure 10). The rings average about 5-10 μm in thickness but may be as thick as 20 μm or more. Collophane rings as thin as $\frac{1}{2}$ - 1 μm are revealed by high magnifications under reflected light (800X) and SEM (3000X). The rings may be spaced throughout the hematite oolite or they may be bunched together to form what appears to be a single ring at lower magnifications. Although some rings form continuous bands of uniform thickness, many are discontinuous and feather out along their circumference. The rarest form is one in which continuous rings are so abundant that they comprise an oolite that is nearly all collophane. Some collophane of this type forms solid cores in hematite oolites that are difficult to distinguish from fine sand size faecal pellet nuclei except that their shapes are more perfectly ovoid. Some rings form around bryozoa fossil nuclei which have been replaced by collophane.

Only a rare collophane ring can be detected with ordinary transmitted light. Most rings are best detected by their light violet luminescence. The thinnest rings can be distinguished best by reflected light or SEM.

The abundance of collophane in the form of rings is not great. Although it is most common in oolitic and flaxseed type iron ore lithologies, it comprises less than 1% on the average of the total collophane present in all of the four ore types.

The collophane rings have originated as chemically precipitated material intercalated with bands of iron minerals and partly were formed as replacements of selected bands in the oolites. The very thin nature of many bands suggests that they were formed as chemically deposited layers on former surfaces of oolites. The discontinuous nature of other rings suggests that they formed by replacement.

The intimate intergrowth of the collophane rings together with their thin character indicates that most of this type of collophane would form locked particles with hematite and be difficult to separate from a hematite concentrate.

Table V gives the average of six electron microprobe analyses of the ring type of collophane. It contains 14.28% phosphorous.

j. Films of collophane on quartz grains

Collophane forms very thin films on clastic grains of quartz and other minerals. The films are rather uniform in thickness and average about 5 μm . Clastic grains contained in hematite areas most commonly exhibit the films. In those areas the films are obscured by hematite and are not visible under ordinary transmitted light. They were best observed under the luminoscope due to their light purple luminescence.

This type of collophane forms a minor constituent in most iron ore specimens. Together with the feldspar coatings described in the following section, they constitute less than 1% of the total collophane in the sandy and flaxseed iron ore lithologies, but they may comprise 10% or more of the total collophane in some fossiliferous and oolitic specimens.

The collophane films have formed as chemical coatings which have been deposited upon the clastic quartz grains, probably during diagenesis of the enclosing sedimentary rock.

Because the collophane coatings on quartz are commonly in areas of hematite, a significant portion of this collophane variety will form locked particles with hematite. Perhaps as much as 75% of this collophane will not be separable from hematite. A smaller portion, perhaps about 25% would be expected to remain attached to quartz and go to the tails.

k. Films of collophane on feldspar grains

Collophane also forms coatings on clastic feldspar grains especially potash feldspar (Figure 11). Although some of the coatings are thin films of uniform thickness, more commonly they exhibit highly irregular inner margins against the feldspar formed by partial replacement of the feldspar.

Table V

Electron Microprobe Analyses of Collophane Oolite Rings

PTS-6 (6 analyses)

CaO	P ₂ O ₅	F	Sum
45.70%	32.71%	2.74%	81.15%

32.71% P₂O₅

14.28% P

100 μm

Figure 10. Luminoscope micrograph showing a collophane ring (light purple) in a hematite oolite together with many tiny disseminated collophane grains (light blue luminescence) mostly contained in hematite (black) but partly in calcite (orange).

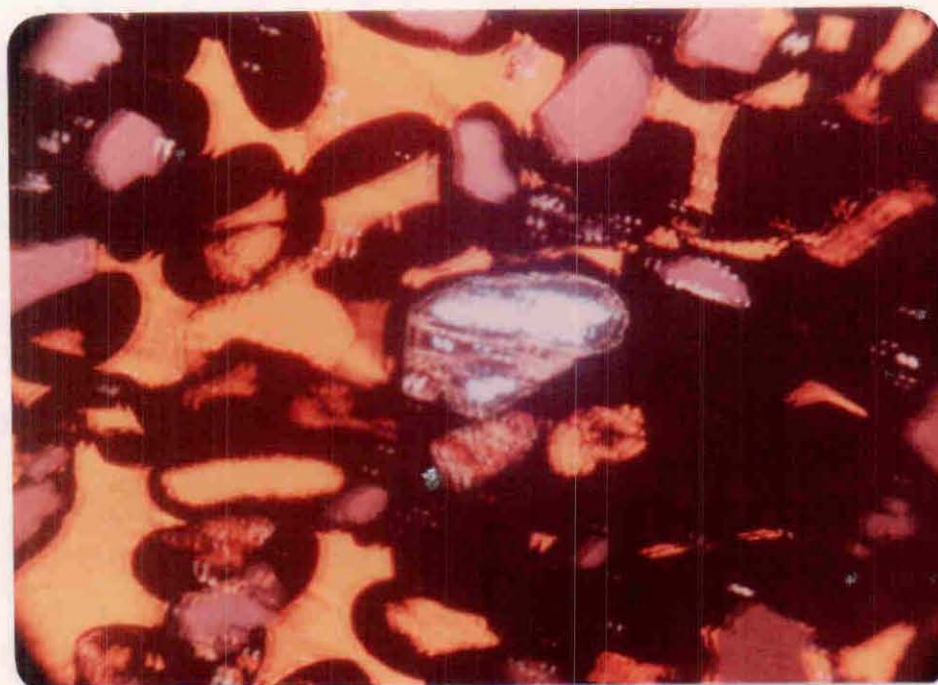
100 μm

Figure 11. Luminoscope micrograph showing a clastic potash feldspar grain (bright blue) with marginal replacement by collophane (light purple). Collophane also largely replaces a calcite nucleus (orange) within a hematite oolite (black) immediately below the feldspar grain. Locally, clastic quartz grains (dull purple) have thin partial collophane coatings such as the one to the immediate right of the feldspar grain. Calcite (orange) occurs both as hematite oolite nuclei and as a cement around the oolites.

All stages of replacement are exhibited, from initial thin rims through complete replacements where the feldspar has gone entirely to collophane or collophane and clay. The collophane coatings average about 5-10 μm in thickness.

Because the mode of occurrence of this type of collophane is much like that of sericite and because the luminescence of sericite is similar to the light purple or blue of this collophane, its identity was checked and confirmed by SEM-EDS.

l. Apatite veinlets in feldspar grains

Rare veinlets of crystalline apatite traverse some clastic feldspar grains. Their crystallinity is indicated by their first order gray color of anisotropism in transmitted light. Their compositions were confirmed by SEM-EDS. Because of their rarity they have been included with the films on feldspar grains for purposes of modal analyses.

m. Small grains of collophane in hematite

Small angular grains of collophane which occur in hematite areas are moderately important to the total phosphorous content of some iron ore lithologies. The grains range in size from about 10 to 40 μm and average about 15 μm . They are characteristically angular in shape and appear to have a genesis that involved sea bottom fragmentation or diagenetic replacement of previously formed fragments. They are most abundant in fossiliferous iron ores and tend to occur near the margins of bryozoa fragments. They are less common in the other three types of iron ore lithologies. All of these small grains are enclosed in hematite areas and would be expected to form mainly binary locked collophane-hematite particles. Most of the grains of this type of collophane would not be expected to separate from hematite.

n. Tiny disseminated collophane grains

Tiny grains of collophane are disseminated throughout most areas of hematite and calcite (Figure 10). Although the grains can be as large as 20 μm , most are about 5 μm and are detectable only at high magnifications. Although these grains can be observed under ordinary transmitted light where they occur in calcite groundmass most occur in areas of hematite where they can be recognized only under the luminoscope. All quantitative evaluation of the abundance of this type of collophane has been done under the luminoscope. These grains luminesce light blue and contrast to the light purple luminescence shown by most of the previously described collophane types. Both colors of luminescence are probably caused by the presence of small amounts of rare earth elements in the collophane; the cause for two different luminescent colors is probably a function of different rare earth element populations or differing amounts of certain rare earths.

The shapes of some of the disseminated grains appear to be platy under medium magnifications (200X), but examinations of the "plates" with the SEM at higher magnification (3000X) show that some of the grains are elongate due to their occurrence as partial rings in the outer portions of hematite oolites and that most of these grains have irregular shapes.

This type of collophane comprises a small but persistent portion of all of the iron lithologies. It averages about 5% of the total collophane in the sandy, fossiliferous, and flaxseed lithologies. In oolitic iron ore the disseminated 5 μm collophane grains average about 10% and may constitute as much as 20% of the total collophane present.

The size, shape, and distribution of the tiny collophane grains suggests that they have formed as chemically precipitated grains, partly replacing calcite.

The results of nine electron microprobe analyses of this type of collophane are given in Table VI. They have an average phosphorous content of 16.07%.

Most of the disseminated 5 μm collophane grains occur within or at the edge of hematite areas and would form binary locked particles with hematite. Most of this type would not be separable from hematite.

o. Tiny collophane grains clustered in hematite

One of the most important types of collophane is that which occurs as tiny grains clustered in certain portions of the hematite areas (Figure 12). The grains average about 5 μm and reach a maximum of 10 μm . None of these grains are visible in ordinary transmitted light and their presence becomes known only under the luminoscope. Their shapes are observed with SEM at 3000X to be irregular. In contrast to the disseminated collophane grains described in the previous section, these grains are clustered together in certain areas, restricted to certain hematite areas, lacking from hematite oolites, and luminesce light purple.

Within a given specimen the abundance of this type of collophane varies greatly. It is absent from all calcite, hematite oolites, and hematite flaxseeds. It occurs in areas of former mud which contain tiny particles of clay, quartz, and rare feldspar, and which are intensively permeated by hematite. Although some of these mud areas may be devoid of collophane or contain only minor collophane, locally such areas may consist of as much as 50% collophane.

In oolitic and flaxseed iron ore types an average of about 25% of the collophane occurs as clustered tiny grains and in some specimens about 65% is present in this form. In sandy and fossiliferous iron ores an average of about 5% and up to 23% of the total collophane occurs as this type.

The genesis of the tiny clustered collophane may involve both clastic and chemically deposited grains. The fact that

Electron Microprobe Analyses of Tiny Disseminated Collophane Grains
PTS - 6 (9 analyses)

	CaO	P ₂ O ₅	F	Sum
Grains in Hematite Oolite	51.78%	37.51%	3.56%	92.85%
Grains near Hematite Oolite	53.23	37.05	3.13	93.41
Grains in Calcite	50.92	35.88	3.15	89.96
Averages	51.98%	36.81%	3.28%	92.07%

36.81% P₂O₅

16.07% P

most of the grains are about the same size as that of recognizable clastic quartz and feldspar grains of very fine silt to clay size suggests that the collophane grains also may be of clastic origin. Locally, the collophane in the mud areas occurs as films coating the clastic quartz and feldspar grains indicating that at least in these instances it has been chemically deposited. Some of this phosphorous may have been initially adsorbed on hematite and subsequently redistributed.

Because of its very fine grain size and intergrowth with hematite, this type of collophane would be expected to form predominantly binary locked hematite-collophane particles. The tiny clustered collophane particles would largely not be separable from hematite.

Because this type of collophane was found to occur in materials that might be expected to contain sericite and because sericite commonly exhibits a light blue luminescence similar to that of collophane, there was concern during the course of this study that some or all of this type might be sericite. SEM-EDS and electron microprobe techniques were utilized to further examine the tiny clustered grains. Scans with SEM-EDS showed that both P (in collophane) and K (in sericite) were present in the mud areas. In electron absorbance images at 3000X with SEM (typical SEM micrographs) four phases were distinguishable. Each of the phases were identified by EDS on many $\frac{1}{2}\mu\text{m}$ spots. The darkest phase is quartz. A second phase, nearly as dark as the quartz and characterized by platy shapes, was identified to be sericite. The sericite plates are not, however, very abundant. The most abundant phase is medium gray and was identified by SEM-EDS to be collophane (Figure 13). The final phase identified is hematite.

The mud areas were also studied by electron microprobe techniques. The collophane grains were readily distinguished by their medium gray character in electron microprobe absorbed current images. Electron microprobe X-ray scans for phosphorous also confirm the abundant distribution of tiny clustered collophane grains in the mud areas. The average of eight electron probe analyses of this type of collophane is given in Table VII.

2. Modal analyses of collophane and the abundance of the 15 collophane types in the four iron ore lithologies.

A total of 23 polished thin sections were subjected to a type of modal analysis in order to better evaluate the quantitative significance of each collophane type in the iron ores. The procedure consisted of first determining the percent of carbonate-fluorapatite sand size grains. For all of the sections, except five of the six bulk sample sections, this was accomplished by automatic image analysis equipment in transmitted light. A stylus was used to trace the outlines of each of the carbonate-fluorapatite grains and trace the rock portion of each of the polished thin sections. The equipment automatically calculated the area represented by each carbonate-fluorapatite grain and computed the total area represented by carbonate-fluorapatite sand size grains in each section. The percent

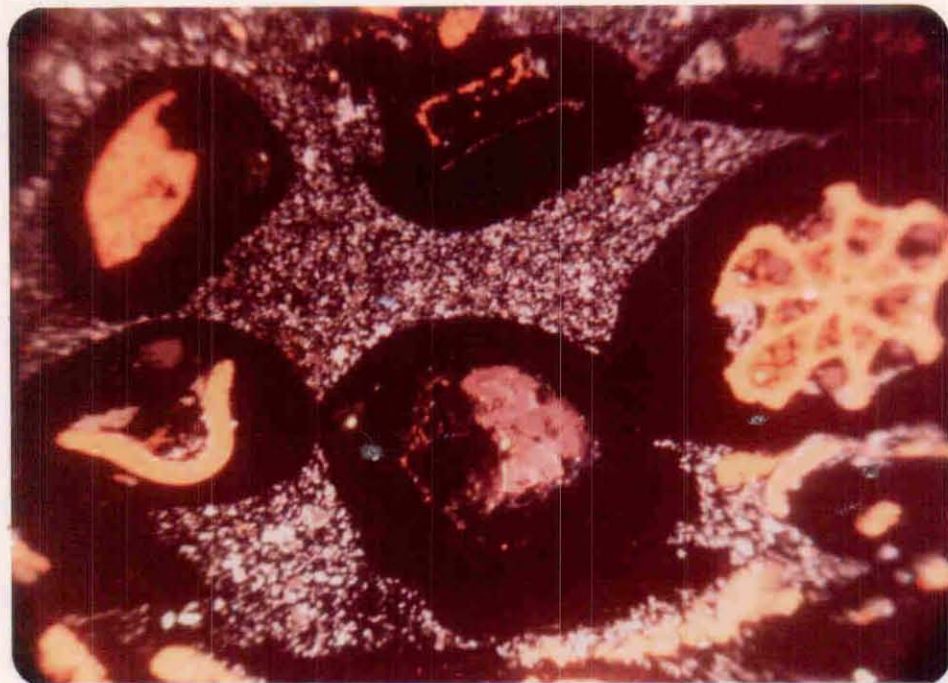
100 μm

Figure 12. Luminoscope micrograph showing very abundant, tiny ($5\ \mu\text{m}$) grains of collophane (light purple) clustered in hematite areas between hematite oolites (black). This is an important form of phosphate occurrence in oolitic and flaxseed types of Birmingham iron ores. A small part of the collophane in those areas occurs as thin ($5\ \mu\text{m}$) coatings on tiny clastic quartz grains (dull purple). Minor collophane occurs as fillings in the bryozoa fragment (orange) on the right and as a partial coating of the large clastic quartz grain (dull purple) which forms the nucleus of the hematite oolite in lower center.

1 μm

Figure 13. SEM micrograph showing abundant collophane (medium gray), dispersed hematite (white), some quartz (dark gray; irregular shape) and minor sericite (dark gray, platy).

Table VII

Electron Microprobe Analyses of Tiny Clustered Collophane Grains

PTS-5 (8 analyses)			
<u>CaO</u>	<u>P₂O₅</u>	<u>F</u>	<u>Sum</u>
45.32%	31.78%	3.19%	80.29%

31.78% P₂O₅

13.87% P

carbonate-fluorapatite of this type was then determined by dividing by the total area of the section. For five of the bulk samples (those other than number 1), the areas represented by the sand size carbonate-fluorapatite grains were calculated from their diameters measured with an ocular micrometer. The abundance of the other 14 types of collophane were determined under the Luminoscope. The number of grains of each type of collophane within an ocular view were counted and this was repeated for a succession of views forming a single traverse across the section. The totals were multiplied by a factor (usually 14) to make them representative of the entire section. The modal percent of each collophane type was calculated by multiplying the number of grains times the average size of that type and then dividing by the total area of the section. These procedures provide semi-quantitative data which are sufficient to indicate which collophane types are most important and to allow an estimate of the amounts of phosphorous which may be expected to separate from the iron by beneficiation.

The results of the modal analyses are presented in six tables. Table VIII lists the results for six polished thin sections from representative iron ore lithologies. Four of the specimens (3538, 78-65, 78-77.5, and 3530) were those selected to be most representative of their lithology (i.e., a type sample). Sample number 1 was selected to represent a bulk ore sample collected from one of the mines in the Birmingham district. Sample number 3249 is a mixed lithology intermediate between sandy and flaxseed.

The importance of Table VIII is that it reveals a wide variation in the abundance of some of the types of collophane from one type of iron ore lithology to another. For example, sand size carbonate-fluorapatite grains account for more than 86% of the total phosphorous-bearing mineral present in the sandy iron ore (PTS 3538), but constitute only about 10% in the fossiliferous ore (PTS 78-65), and are absent from the oolitic iron ore. Similarly, collophane in the form of faecal pellets constituting the nuclei of hematite oolites accounts for about 50% of the total phosphorous-bearing mineral present in the oolitic iron ore (PTS 78-77.5), but it is of much less importance in the flaxseed and fossiliferous iron ores. These data indicate that the relative volumes of each of the four iron ore lithologies must be considered in order to predict the ultimate phosphorous separability that could be expected for the Birmingham ores.

The results from modal analyses of polished thin sections prepared from six separate specimens from a bulk mine sample are presented in Table IX. The five additional specimens (2, 3, 4, 5, and 6) were analyzed to examine the variation of abundance of each of the types of collophane within the bulk sample and to compare the averages from the six samples with the percentages determined for sample number 1. The bulk sample shows variations similar to those found between the four iron ore lithologies. For example sand size carbonate-fluorapatite percentage varies from 5% to 67%, and faecal pellet oolite nuclei vary from 2% to 51%. These variations in collophane types reflect the variations in iron ore lithology in the bulk sample. For most collophane types the average

Table VIII
Percent of Each Phosphate Grain Type in Selected Iron Ore Lithologies

Drill Core No.	3249	3538	78-65	78-77.5	3530
Thin Section No.	12	20	3	6	18
Iron Ore Type	Bulk Sandy-Flaxseed	Sandy	Fossiliferous	Oolitic	Flaxseed
Phosphate Types:					
Sand size	30.73	86.44	10.09	0	34.70
Nuclei in Hm Oolites:					
Calc Replacements	18.07	3.53	28.76	43.23	15.67
Faecal Pellets	8.33			9.57	
Clustered Tiny "Trash"					
Grains in Hm	12.59	0	0	0	30.95
Small Grains in Hm	5.30	1.58	10.49	11.53	10.68
Scattered Tiny Grains in Hm & Gg	8.20	4.21	13.05	18.72	0
Fossil Fillings	9.84	3.27	27.58		6.86
Fossil Replacements	2.74	0.24	5.33	3.82	3.06
Calcite Grain Repl.	0.27			3.51	
Spots of Calc Repl.	1.48	0.21	3.52	2.11	5.29
Films on Qz Grains	1.71	0.51	11.18	2.80	0.45
Films on Fd Grains	0.69			2.97	2.55
Rings in Hm Oolites	0.07			1.76	
TOTAL	100.02	99.99	100.00	100.02	100.01
Equivalent P	0.34	0.21	0.268	0.225	0.37
Chemical Analysis	0.40	~0.27-0.30	0.36	0.27	~0.38-0.42

Hm = hematite
Calc = calcite
Gg = gangue
Repl = replacement
Qz = quartz
Fd = feldspar

abundance for the six bulk specimens is not greatly different than that in specimen number 1.

The four tables, X, XI, XII, and XIII, are the result of further efforts to characterize each of four iron ore lithologies. For this purpose, modal analyses were performed on an additional 12 polished thin sections and those results were averaged together with the previous results for the 11 sections in Tables VIII and IX. The total 23 sections and those results were the four iron ore lithologies to obtain the average percent of each collophane type in each ore lithology. Upon comparing the results presented in Tables X, XI, XII, and XIII, with those in Table VIII, it is apparent that the general importance of each collophane type remains the same although the precise percentage may vary somewhat for certain types from the type example of the lithology to its average. Figure 14 visually depicts the percentages.

Tables VIII through XIII also provide an opportunity to evaluate whether the 15 types of phosphorous minerals adequately account for the total phosphorous known by chemical analyses to be present in the various iron ore samples. To accomplish this purpose, the total percent collophane was calculated for each specimen and multiplied by 15.03% to convert it to the percent phosphorous (P), the amount of phosphorous contributed to the ore specimen in the form of the total 15 collophane types. Because each of the chemical analyses represents about a one foot length of drill core and the modal analyses are from about a one inch sample within the one foot interval, their comparison cannot be expected to be as close as would be the case if the chemical analyses were from the same one inch samples. In spite of this potential problem, the comparisons given at the bottoms of the six tables indicate a very close match for most samples. The close match indicates that all (or essentially all) of the phosphorous-bearing minerals have been found and that they are represented by the 15 types.

3. Potential separability of collophane from various iron ores

In order to utilize the microscopic data presented in the previous section on the abundance of the 15 types of collophane to predict the potential separability of collophane from the various iron ores by beneficiation, the following study and calculations were performed. In addition to the 23 polished thin sections previously studied (Table I), another 36 thin sections were examined in order to classify them according to iron ore lithology. The total 59 sections were then utilized to refine the megascopic ore lithologies previously determined by careful logging of the core from three diamond drill holes. These data were then utilized to determine the total percent of each of the four iron ore lithologies present in the Big and Irondale Seams in each of the three drill holes. For example, of the total footage of Big Seam in the three drill holes, 42.3% was flaxseed ore, 23.7% consisted of sandy ore, 17.5% was fossiliferous ore, and 16.5% consisted of oolitic iron ore lithology. These values are shown at the top of Table XIV. The numbers in each column are derived by multiplying

Table X
Percent of Each Phosphate Grain Type in Flaxseed-type Iron Ores

Polished Thin Sec. No.:	11	12	17	4	19	21	BS-4	18	BS	2	Average Percent	
Drill Core No.:	2672	3249	3527	2668.5	3532	3541	3530	1	78-63			
Phosphate Types:												
Sand size	22.31	27.43	11.32	54.38	23.37	4.70	44.32	5.64	34.70	30.73	48.17	27.91
Nuclei in Hm Oolites:	5.76	16.93	15.30	8.50	1.63	3.28	6.42	0.520	15.67	18.07	0.69	14.18
... Calc. Replacements												
Faecal Pellets	12.63		9.55	4.40	4.48	23.95	3.98	1.37		8.33	5.0	
Tiny Clustered Grains in Hm	7.79	6.02	11.01	9.35	65.66	56.40	35.27	65.05	30.95	12.59	20.23	26.14
Small Grains in Hm		13.86	1.89	1.51	0.51	0.22	3.85	0.85	10.68	5.30	6.58	4.11
Tiny Scattered Grains in Hm & Cg	5.07	4.99	17.70	6.56	0.69	3.11	0.06	0.36	0	8.20	12.96	5.43
Fossil Fillings	23.47	12.78	14.90	8.60	1.85	6.12	2.35	11.02	6.86	9.84	3.44	9.31
Fossil Replacements	20.61	10.74	16.81	5.91	0	0.23	1.76	13.56	3.06	2.74	0	6.86
Spots of Calc Replacement	10.09	3.18	.23	0	1.27	0	0	0.21	5.29	1.75	2.60	1.33
Films on Quartz	0.69	33.13	1.29	0.26	0.14	.10	0	1.342	0.45	1.71	0.27	11.13
Films on Fd	1.13		0	0	0	0	0	.0082	2.35	0.69	0	
Rings	0.44	0.94	0	0.54	0	0	1.96	0	0	0.07		0.36
TOTAL	109.99	100.0	100.0	100.01	99.6	97.89	99.97	99.9	100.01	100.02	9.94	96.76
Equivalent P	0.19	0.40	0.18	0.17	0.30	0.20	0.23	0.45	0.37	0.34	0.14	0.27
Chemical Analysis	.44	0.35	.30	.42%	.35	.30			.38-.42	.40	.33	

Table XI

Percent of Each Phosphate Grain Type in Sandy-type Iron Ores

Polished Thin Sec. No.:	20	BS-2	15	14	13	Average Percent
Drill Core No.:	3538		3261	3260	3255	
Phosphate Types:						
Sand size	86.44	67.03	59.0	73.45	32.84	63.75
Nuclei in Hm Oolites:						
Calc. Replacements	3.53	0.53	4.17	1.47	0.90	12.95
Faecal Pellets		5.53	11.76	7.59	29.86	
Tiny Clustered Grains in Hm	0	16.47	4.79	5.75	4.85	6.37
Small Grains in Hm	1.58	4.07	1.20	0.32	2.60	1.95
Tiny scattered Grains in Hm & Gg	4.21	2.57	2.20	6.03	5.03	4.01
Fossil Fillings	3.27	3.56	2.93	0.53	7.59	3.58
Fossil Replacements	0.24	0	9.74	2.97	15.47	5.68
Spots in Calcite	0.21	0	1.24	0.45	0.87	0.55
Films on Quartz Grains		0.23	2.52	0.45	0	0.86
Films on Fd Grains	0.51		0.45	0.16	0	
Rings in Hm Oolites	0	0	0	0.83	0	0.17
TOTAL	99.99	99.99	100.0	100.0	100.01	99.87
Equivalent P	0.21	0.17	0.12	0.36	0.19	0.21
Chemical Analysis	0.30	0.27-0.30	0.19	0.19	0.27	

Table XII
Percent of Each Phosphate Grain Type in Fossiliferous-type Iron Ores

Polished Thin Section No.:	3	BS-3	BS-5	5	Average Percent
Drill Core No.:	78-65			78-72.5	
Phosphate Types:					
Sand size	10.09	14.96	28.11	18.44	17.9
Nuclei in Hm Oolites:					
Calc. Replacements	} 28.76	8.77	6.70	0.34	} 28.17
Faecal Pellets		15.96	44.49	7.65	
Tiny Clustered Grains in Hm	0	0	0	18.11	4.23
Small Grains in Hm	10.49	6.79	11.07	1.96	7.58
Tiny Scattered Grains in Hm & Gg	13.05	1.99	0	0	3.76
Fossil Fillings	27.58	4.23	0.97	41.95	18.68
Fossil Replacements	5.33	46.00	5.41	.45	14.30
Spots of Calc. Replacements	3.52	0.68	3.24	0.10	1.89
Films on Quartz	} 1.18	0	0	10.05	} 3.06
Films on Fd		0	0	1.01	
Rings	0	0.61	0	0	.15
TOTAL	100.00	99.99	99.99	100.06	99.72
Equivalent P	0.27	0.18	0.05	0.21	0.18
Chemical Analysis	0.36			.44	

Table XIII
Percent of Each Phosphate Grain Type in Oolitic-type Iron Ores

Polished Thin Section No.:	6	16	7	Average Percent
Drill Core No.:	2677.5	3264	2680	
<hr/>				
Phosphate Types:				
Sand size	0	11.61	0	3.87
Nuclei in Hm Oolites:				
Calc. Replacements	43.23	11.00	12.48	} 44.56
Faecal Pellets	9.57	47.27	9.77	
Tiny Clustered Grains in Hm	0	0	66.70	22.23
Small Grains in Hm	11.53	1.40	1.43	4.77
Tiny Scattered Grains in Hm & Gg	18.72	20.06	1.09	13.29
Fossil Fillings		1.33	0	1.72
Fossil Replacements	} 3.82	1.24	6.96	2.73
Spots in Calc.	5.62	6.09	0.67	4.13
Films on Quartz	2.80	0	0.54	} 2.10
Films on Fd	2.97	0	0	
Rings	1.76	0	0	0.59
<hr/>				
TOTAL	100.02	100.00	100.00	99.99
Equivalent P	0.225	0.11	0.182	0.172
Chemical Analysis	0.27	.30	.21	

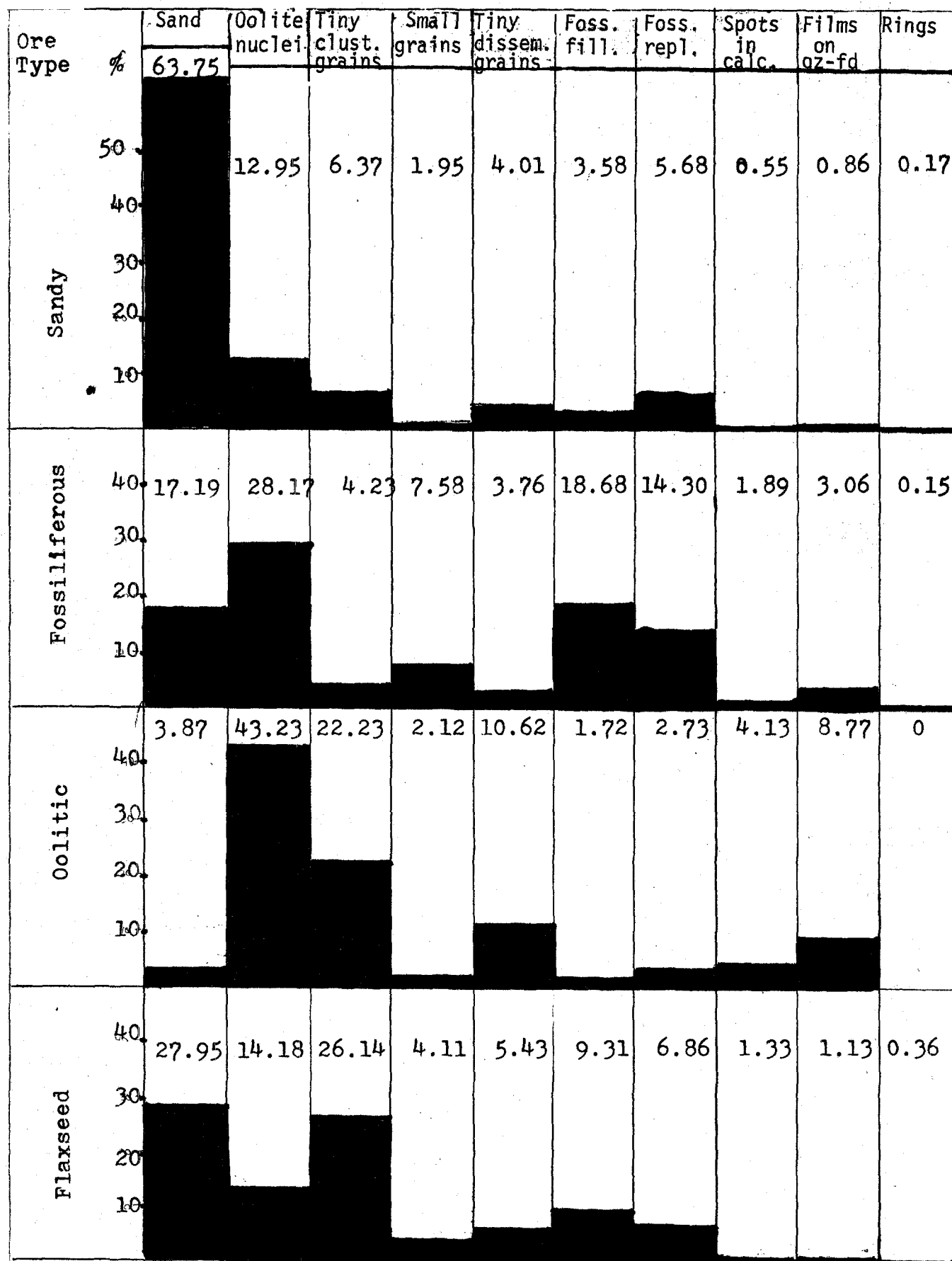


Figure 14 - Histograms showing abundance of collophane types in the four types of iron ore

the percent of a given lithology times the percent of each collophane variety present in the type lithologic specimen as previously given in Table VIII. For example, 42.3% flaxseed ore was multiplied times 34.70% sand size francolite grains in the type flaxseed specimen (PTS 3530) to obtain the value of 14.68% francolite sand in the flaxseed portions of the Big Seam. Similar calculations were carried out for the other three lithologies and the four were then totaled to obtain that percent, 36.94%, of the total phosphorous mineral present in the Big Seam, that occurs as sand size francolite. These calculations were repeated for each collophane variety. Finally, the percents of the various collophane types were placed into one of two columns at the far right of Table XIV, based upon whether they would be expected to: 1) form a predominance of locked collophane-hematite particles and go mainly into an iron concentrate, or 2) form free collophane particles or collophane locked with calcite or quartz and go mainly in a tailing. The totals of these two columns indicate the amounts of collophane that are predicted from these microscopic studies to partition into the two mill products produced from Big Seam ore as represented by the three drill holes. About 45% of the collophane (and thus phosphorous) could be separated by beneficiation; 55% would remain in the form of locked particles in the iron concentrate.

Similar calculations were performed on the iron ores of the Irondale Seam and these results are given in Table XV. Combining the results for the two seams, Big and Irondale, in their relative proportions, the totals are as given in Table XVI. The results of these two tables appear to have little significance at the present time because if mining were to resume the Irondale Seam probably would not be taken along with the more important Big Seam.

The results of Table XIV have been recalculated to take into account the extent to which each of the drill holes represent past and present iron ore reserves in the Birmingham district. The three drill holes were selected at approximately equal intervals in an east-west direction across the iron district. The westernmost hole intersected iron ores typical of those which have been mined in the district in the past and the recalculated results for this hole are shown in Table XVII. The central and easternmost holes are representative of iron ore reserves which remain in the district and the recalculated results for these two holes are shown in Table XVIII. The significant conclusion that results from these calculations is that whereas it would be expected that only about 27% of the total phosphorous mineral (and thus phosphorous) could have been removed by beneficiation of iron ores previously mined in the district, it is predicted from these microscopic studies that about 60% of the phosphorous can be beneficiated from the remaining reserves (Table XIX). This results primarily from the fact that iron ore lithologies further to the east toward the barrier sand bar contain greater amounts of the sand size francolite grains which are the variety of phosphate mineral grains most amenable to beneficiation.

Table XIV.
Calculation of Percent of Each Phosphate Grain Type in Big Seam Iron Ore

Iron Ore Type Percent in Big Seam	Flaxseed 42.3%	Sandy 23.7%	Fossiliferous 17.5%	Oolitic 16.5%	Total	Hm Conc	Gg Tail
Phosphate Types:							
Sand	14.68	20.49	1.77	0	36.94		36.94
Nuclei in Hm Oolites:	2.40	0.84	5.03	8.71	16.98	13.58	3.40
Clustered Tiny Grains	13.09	0	0	0	13.09	13.09	
Small Grains in Hm	4.52	0.37	1.84	1.90	8.63	8.63	
Scattered Tiny Grains	0	1.00	2.28	3.09	6.37	6.37	
Fossil Fillings	2.90	0.78	4.83	0.50	9.01	9.01	
Fossil Replacements	1.29	0.06	0.93	0.13	2.41	2.41	
Calcite Replacements	2.24	0.05	0.62	0.93	3.84		3.84
Films on Qz + Fd Grains	1.18	0.12	0.21	0.95	2.46	1.85	0.61
Rings in Hm oolites	0	0	0	0.29	0.29	0.29	
					<u>100.02</u>	<u>55.23</u>	<u>44.79</u>

Table XV
 Calculation of Percent of Each Phosphate Grain Type
 in Irondale Ore

Iron Ore Type Percent in Irondale Seam	Sandy 25.8%	Fossiliferous 3.2%	Oolitic 61.3%	Flaxseed 9.7%	TOTAL
Phosphate Types:					
Sand size	22.30	.32	0	3.37	26.0
Nuclei in Hm Oolites	0.91	.92	32.37	0.55	34.75
Clustered Tiny Grains in Hm	0	0	0	3.00	3.00
Small Grains in Hm	0.41	.336	7.07	1.04	8.86
Scattered Tiny Grains in Hm & Gg	1.09	.42	11.48	0	12.99
Fossil Fillings	0.84	.88	1.95	0.67	4.34
Fossil Replacements	0.06	.17	0.39	0.30	0.92
Calcite Replacements	0.05	.11	3.45	0.51	4.13
Films on Qz + Fd Grains	0.13	.04	3.53	0.27	3.98
Rings in Hm oolites	0	0	1.08	0	1.08
					100.05

Table XVI

Calculation of Percent of Each Phosphate Grain Type
in Big Seam plus Irondale Iron Ore

Iron Ore Type	Flaxseed	Sandy	Fossiliferous	Oolitic	TOTAL
Percent in Big and Irondale Seams	.35%	.24%	.14%	.27%	
Phosphate Types:					
Sand size	12.15	20.75	1.41	0	34.31
Nuclei in Hm Oolites	1.98	0.85	4.03	14.26	21.12
Clustered Tiny Grains in Hm	10.83	0	0	0	10.83
Small Grains in Hm	3.74	0.38	1.47	3.11	8.70
Scattered Tiny Grains in Hm & Gg	0	1.01	1.83	5.05	7.89
Fossil Fillings	2.40	0.79	3.86	0.80	7.85
Fossil Replacements	1.07	0.06	0.75	0.23	2.11
Calcite Replacements	1.85	0.05	0.49	1.52	3.91
Films on Qz + Fd Grains	0.98	0.12	0.17	1.56	2.83
Rings in Hm oolites	0	0	0	0.48	0.48
					<u>100.03</u>

Table XVII

Calculation of Percent of Each Phosphate Grain Type
in Big Seam Iron Ore Previously Mined

Ore Types	Flaxseed	Sandy	Fossiliferous	Oolite	Total	Hm Conc	Gg Tail
Percent	28	4	34	34			
Phosphate Types							
Sand size	9.27	3.46	3.43	0	16.61		16.10
Nuclei in Hm Oolites	1.60	0.14	9.78	17.95	29.47	23.58	5.89
Tiny Clustered Grains	8.67	0	0	0	8.67	8.67	
Small Grains in Hm	2.99	0.06	3.57	3.92	10.54	10.54	
Scattered Tiny Grains	0	0.17	4.44	6.36	10.97	10.97	
Fossil Fillings	1.92	0.13	9.38	1.04	12.47	12.47	
Fossil Replacements	0.86	0.01	1.81	.26	2.71	2.71	
Calcite Replacements	1.48	0.01	1.20	1.91	4.6		4.6
Films on Qz + Fd Grains	0.78	0.02	0.40	1.96	3.16	2.34	0.79
Rings in Hm Oolites	0	0	0	0.60	.60	.60	
					99.81	71.88	27.38

Table XVIII

Calculation of Percent of Each Phosphate Grain Type in Big Seam Iron Ore Reserves

Ore Types Percent	Flaxseed	Sandy	Fossiliferous	Total	Hm Conc	Gg Tail
	56	42	2			
Phosphate Types						
Sand size	19.43	36.31	0.20	55.94		55.94
Nuclei in Hm Oolites	3.18	1.48	0.58	5.24	4.19	1.05
Tiny Clustered Grains	17.33	0	0	17.33	17.33	
Small Grains in Hm	5.98	0.66	0.21	6.85	6.85	
Scattered Tiny Grains	0	1.77	0.26	2.03	2.03	
Fossil Fillings	3.84	1.37	0.55	5.76	5.76	
Calcite Replacements	2.96	0.09	0.07	3.12		3.12
Films on Qz + Fd Grains	1.57	0.21	0.02	1.80	1.35	0.45
Rings in Hm Oolites	0	0	0	0		
				98.07	37.51	60.56

Table XIX

Amounts of Collophane Removable by Beneficiation of
 Big Seam Iron Ore as Predicted from Microscopic Ex-
 amination of Ore Textures and Grain Sizes (Grind:
 100% - 400 mesh)

	Percent Collophane Expected to go to:	
	<u>Fe Conc</u>	<u>Tail (Qz-Fd)</u>
1. Iron Ores Previously Mined in the District	71.88	27.38
2. Iron Ores Throughout the District (includes 1 & 3)	55.23	44.79
3. Iron Ore Reserves Remaining in the District	37.51	60.56

Finally, the effects of utilizing the average percents for the phosphate mineral types determined in Tables X, XI, XII, and XIII as opposed to using the values determined for the type iron ore specimens (Table VIII) is explored in Table XX. The procedure, for example, consisted of multiplying the percent of flaxseed ore in the Big Seam reserves (56%) by the average percent sand size carbonate-fluorapatite in flaxseed iron ores (27.95%) from Table X to obtain the amount (15.68) of sand size carbonate-fluorapatite grains in flaxseed ores in the Big Seam reserves. Additional similar calculations result in Table XX for average ore lithologies which can be compared to Table XVIII for type samples. The amount of the total phosphorous which would be expected to be separable decreases from 60% to 53% for those iron reserves remaining in the district.

Table XX

Calculation of Percent of Each Phosphate Grain
Type in Big Seam Iron Ore Reserves Using Averages Rather
than Type Specimens to Characterize the Iron Ore Lithologies

Ore Type Percent	Flaxseed	Sandy	Fossil- iferous	Total	Hm Conc.	Gg Tail
	56	42	2			
Phosphate Varieties:						
Sand Size	15.68	26.78	0.36	42.82		42.82
Nuclei in Hm Oolites	7.81	5.44	0.56	13.81	11.05	2.76
Tiny Clustered Grains	15.76	1.42	0.08	17.26	17.26	
Small Grains in Hm	1.78	0.82	0.15	2.75	2.75	
Tiny Scattered Grains	3.06	1.68	0.08	4.82	4.82	
Fossil Fillings	4.96	1.50	0.37	6.83	6.83	
Fossil Replacements	3.62	2.39	0.29	6.30	6.30	
Spots in Calcite	0.64	0.23	0.04	0.91		0.91
Films on Qz + Pd	0.52	0.36	0.06	0.94	0.71	0.24
Rings in Oolites	0.17	0.07	0.003	0.24	0.24	
TOTAL				96.68	49.96	46.73

4. Suggestions on beneficiation

The preceding findings on the size, shape, and distribution of phosphate mineral grains provide a data base upon which a number of observations can be made regarding the potential to reduce the phosphorous content of the Birmingham iron ores by beneficiation. The coarsest grains of phosphate mineral, the sand size carbonate-fluorapatite grains, would be expected to separate cleanly, for the most part, from hematite at a fine grind of say 100% - 400 mesh (or even coarser). A grind to that size would probably liberate only about one-quarter of the collophane faecal pellet grains present as hematite oolite nuclei, although the finer grinds would be expected to enhance the liberation of this collophane type. A small portion, perhaps about one-quarter, of the collophane films on clastic quartz and feldspar grains may remain locked to the quartz and feldspar and go into a tailing product. That type of collophane present as calcite replacements will readily be beneficiated with calcite in the tails. All of the remaining collophane types are so fine-grained and so intimately intergrown with hematite that they will form predominantly locked collophane-hematite grains at any practical grind.

The type of beneficiation process selected would be expected to modify the above results to varying degrees. For example, if the Birmingham iron ores were to be treated by roast reduction and magnetic concentration, a larger proportion of the collophane would be expected to go into the iron concentrate. This would be particularly true for the faecal pellets which serve as nuclei for hematite oolites because they commonly are clouded with tiny hematite grains which upon reduction to magnetite are commonly sufficient to pull a locked particle, consisting mostly of collophane into the magnetic concentrate. A small portion, perhaps 5-10%, of the sand size carbonate-fluorapatite grains also would go to the magnetic concentrate for the same reason. These considerations suggest that roast reduction-magnetic concentration would not be the best beneficiation technique to employ as regards the phosphorous content of the final iron product.

With regard to beneficiation processes utilizing gravity, collophane has a specific gravity of about 3.0 which is considerably less than hematite at 5.0 but significantly higher than calcite and quartz with about 2.7. Previous sink-float studies (e.g., U.S. Bureau of Mines RI 7728) have commonly employed heavy liquids of 2.94, 3.30, and 4.20; the largest proportions of phosphorous have gone into two fractions; 1) sink 2.94, float 3.30, and 2) sink 3.30, float 4.20. The present microscopic studies suggest that a large part of the phosphorous present in fraction (1) occurs as free carbonate-fluorapatite (and collophane) grains which have gone with that fraction due to their specific gravity of about 3.0. In contrast, the phosphorous present in fraction (2) probably occurs primarily in the form of locked collophane-hematite grains. The problem with most gravity techniques of beneficiation (e.g., spirals and Reichert cones) is that they require that the heads be of a relatively coarse grind which would tend to increase the degree of collophane (and carbonate-fluorapatite)-hematite locking.

Consideration of the mineralogy and fine-grained character of the Birmingham iron ores suggests that research into beneficiation techniques along the line of that utilized at the Tilden mine in northern Michigan might be fruitful. At the Tilden mine low grade, fine-grained hematite ores are treated by flocculating the iron oxide particles and selectively floating non-slime silicious particles. The very fine grind (-500 mesh) effectively utilized at Tilden would help liberate additional (but not all) phosphorous from the Birmingham iron ores.

D. Other Minerals

In addition to the phosphate minerals previously described in detail, other minerals which occur in or were sought in the iron ores include: 1) hematite and other iron minerals, 2) minerals which dilute the grade of the iron ore, and 3) minerals which could constitute potential health or environmental hazards.

The principal iron mineral in the Birmingham ores is fine-grained earthy hematite. Hematite also occurs as minor specularite replacements of some oolite nuclei. Rare coarse clastic grains of hematite serve as oolite nuclei. Some hematite oolites exhibit thin bands of an iron-aluminum silicate which alternate with hematite bands. The bands are commonly about one-half to one micrometer in thickness. Although they are not visible in transmitted light, they are readily observed at high magnifications under reflected light and with the SEM. X-ray diffraction analyses and SEM-EDS indicate that many of these bands are chamosite, a chlorite mineral. SEM-EDS also shows the presence of an unidentified potassium-calcium-bearing phase in the thin bands. The central portions of some fossil replacements by iron exhibit yellow to yellowish brown internal reflections similar to that of goethite under combined transmitted and inclined reflected lighting. Rare tiny grains of pyrite occur in some carbonate-fluorapatite or collophane grains where they were protected from the surrounding more oxidizing environment. Although siderite has been reported to occur in the district, none was detected during this microscopic investigation.

The principal diluent mineral is calcite. Calcite occurs primarily as fossil fragments but also to a lesser extent as sparry calcite cement. Although dolomite has been reported to occur in the ores, none was detected during the present study. Although part of the carbonate is more darkly luminescent than the majority of the calcite grains, the color of luminescence is that of calcite rather than dolomite, and testing with Alizarin red dye gives the red stain characteristic of calcite.

Quartz is the next most important diluent mineral; it occurs as clastic sand grains. Feldspar is a minor mineral which occurs in clastic grains. Most is potash feldspar, but some feldspar grains are polysynthetic twinned plagioclase. Fine-grained clay particles may be present in the ore but the iron minerals prevent them from being clearly observed. Minor sericite was identified by SEM-EDS to occur in some of the hematite-rich portions.

No minerals which form a potential health or environmental hazard were identified in the Birmingham iron ores. No arsenic-bearing nor asbestos minerals were detected during the course of this microscopic examination.

II. EUFAULA FERRUGINOUS BAUXITES

A. General Character

The Eufaula bauxite deposits in Alabama are typical of the Coastal Plain deposits located in southeastern Alabama and southwestern Georgia. The deposits occur in The Nanfalia Formation (Eocene) near the base of the Tertiary rock column (Clarke, 1972).

Most of the bauxite ores in the Eufaula district contain less than 1.5% Fe_2O_3 , but some of the more iron-rich ore, ferruginous bauxite, contains from 3 to 15% Fe_2O_3 . The estimated reserve of the ferruginous bauxite ranges from 2 to 10 million tons (Clarke, 1977).

Gibbsite is the major constituent of the ferruginous bauxite. Kaolinite, which is a minor constituent throughout the deposits, is concentrated near their margins. Diaspore and boehmite are rare or absent. Seven iron minerals can be identified in the several varieties of the ore.

B. Ferruginous Bauxite Varieties

The relative importance of each of the several varieties of ferruginous bauxite in the Eufaula district with respect to total reserves is as follows:

About 75% of the district's reserves consists of "irony bauxite" (A. P. Green, Spec. No. 1) and "high-iron bauxite" or "pink ore" (Harbison-Walker, Spec. No. 3). Megascopic iron concretions in the latter variety are called "iron sores" (PTS-APG-G, 15). About 20% consists of "greenish bauxite" (Didier-Taylor, Spec. No. 1), and 5% of "red ore" (A. P. Green, Spec. No. 4). Some individuals use the term "red ore" in a broad sense. A less important variety, pyrite-bearing bauxite, is tan (A. P. Green, Spec. No. 5) and dark gray to black and lignitic (Didier-Taylor, Spec. No. 4). Siderite-bearing bauxite (A. P. Green, Spec. No. 7) is rare. Some marginal kaolin ore is colored by the presence of fine-grained iron minerals and occurs as yellow kaolin ore (A. P. Green, Spec. No. 3) and streaky pink kaolin ore (A. P. Green, Spec. No. 2).

The iron mineralogy of three specimens of medium to high-grade bauxite (Didier-Taylor, Spec. Nos. 2, 3, 5) was compared with that of the ferruginous bauxites.

C. Mode of Occurrence of Iron

The mode of occurrence of iron in the Eufaula bauxites has been the principal objective of this portion of the research grant. Seven iron minerals have been identified and found to occur in eight or more forms. These iron minerals have been identified and studied primarily by reflected light microscopy but X-ray diffraction analyses of all of the specimens and concentrates prepared from the specimens have also been used to confirm optical identifications.

1. Mineralogy

Table XXI lists the iron minerals found in each bauxite specimen and gives shape, size, and abundance for those iron mineral varieties in more detail.

a. Iron concretions

Iron concretions (called iron sores in the district) constitute a large part of the iron present in the iron bauxite and high-iron bauxite varieties of ferruginous bauxite. The concretions vary in size from about one-quarter inch or less up to several inches across. Although the shapes of some are nearly spherical, most are ovate to elongate tubular. Some are quite irregular in shape.

Within a given bauxite deposit, iron concretions of a given general size range tend to occur in certain favored horizons or portions of the deposit. Many of the more tubular concretions are partly connected one with the other.

Most concretions have a white exterior coating consisting mainly of gibbsite, but sections through the concretions typically reveal an outer shell which is light red to light yellow and an inner portion which is dark red to bluish black. The inner portion typically becomes more porous inward until the center of the concretion itself may consist of a large void space.

By reflected light microscopy the lighter colored outer portions of the concretions can be observed to contain abundant, very fine-grained hematite. The grains appear to be irregular in shape and they are only one to two Mm across. Locally the light colored areas are traversed by veinlets, 30-65 μm across, which are composed of both hematite and goethite. The darker red to bluish black portions of the concretions consist of dense hematite. Although most of those areas consist of very fine-grained iron oxide, the hematite is densely clustered together to form areas that are comprised almost entirely of hematite. Hematite crystals as large as one-half centimeter long project into the central cavities of some concretions.

Although lepidocrosite has been detected by X-ray diffraction to occur in an iron concretion from the McLeod deposit in the Eufaula bauxite district (Lukas, 1978), all of the concretions X-rayed during the course of this study lacked lepidocrosite. Boehmite was rarely detected by X-ray

Table XXI Summary of Iron Minerals in Bufaula, Alabama Bauxite Specimens

Specimen No.	Ore Type	Importance ¹	Section No.	Iron Minerals	Shape	Size	Abundance
A.P. Green 1	Irony Bauxite	80%	PTS-APG-1	Hm	Round to 6-sided	20-60 μm , up to 200 μm	Abund.
				Hm	Irreg.	1-2 μm	Abund.
				Hm	Irreg.	1-20 μm	Minor
Harbison-Walker 3	High Iron Bauxite "Pink Ore"	75-80%	PTS-HW-3	Hm	Irreg.	1-13 μm	Abund.
Iron Concretions			PTS-APG-6,15	Goe	Round	15-85 μm	Common
Abundant form of iron				Hm	Round	$\frac{1}{2}$ -1 inch	Abund.
Didier-Taylor 1	Greenish Bauxite	20%	PTS-DT-13	Goe	Coatings	25 μm	Minor
				Goe	Irreg.	1-40 μm	Common
				Hm	Irreg.	up to 200 μm	
				Py	Irreg.	1-50 μm	Some
						1-50 μm	Common
						up to 160 μm	Abund.
A.P. Green 4	Ferruginous Bauxite "Red Ore"	5%	PTS-APG-2	Sid (X-ray only)	Equidimensional	35-130 μm	Common
				Goe	Irreg.	35-130 μm	Abund.
				Goe	Round	65-130 μm	Common
				Goe	Round	5-125 μm	Common
				Goe	Irreg.	1-5 μm	Some
				Goe	Cubes	110 μm	Rare
				Hm	Plates	30-80 μm	Some
				Lep	Irreg.	1-5 μm	Rare
A.P. Green 3	Yellow Kaolin Ore		PTS-APG-8	Goe	Irreg.	1-6 μm	Abund.
Peripheral shell in most bauxite deposits				Hm	Irreg.	1-6 μm	Minor
A.P. Green 2	Pink Streaky Kaolin Ore		PTS-APG-9	Hm	Irreg.	1-7 μm	Abund.
				Hm	Plates	20 μm	Minor
				Goe	Irreg.	1-7 μm	Minor
A.P. Green 5	Pyrite-Bearing Bauxite	5%	PTS-APG-5	Py-Mc	Round	75-150 μm	Common
				Py	Spheres	12 μm	Some
				Goe	Round	75-150 μm	Common
				Goe	Irreg.	1-3 μm	Common
Didier-Taylor 6a	Iron Sulfide Concretions		PTS-APG-14	Py		125 μm ; clustered	very abund.
Didier-Taylor 4	Lignite and Pyrite-Bearing Bauxite	1%	PTS-DT-10	Py	Irreg.	1-10 μm	Some
				Hm	Irreg.	1-9 μm	Minor
				Goe	Irreg.	1-9 μm	Minor
A.P. Green 7	Siderite-Bearing Bauxite	Minor	PTS-APG-7	Hm	Irreg.	1-6 μm	Abund.
				Hm	Platy	10-45 μm	Minor
				Goe	Irreg.	1-8 μm	Some
				Py	Irreg.	1-5 μm	Minor
				Sid (X-ray only)			Abund.
Didier-Taylor 3	High-Grade Bauxite Ore	-	PTS-DT-11	Goe	Irreg.	1-15 μm	Minor
				Hm	Irreg.	1-15 μm	Minor
				Py-Goe	Round	75-160 μm	Some
				Py-Mc	Spheres	25-35 μm	Some
Didier-Taylor 5	High-Grade Bauxite Ore "Pink Ore"	-	PTS-DT-12	Py-Goe	Spheres	7-42 μm	Common
				Py	Round	125 μm	Some
				Goe	Irreg.	1-20 μm	Common
Didier-Taylor 2	Medium-Grade Bauxite Ore	-	PTS-DT-4	Goe	Irreg. grains	2 μm	Common
				Goe	Veinlets	1 μm	Some
				Goe	6-sided	1s25 μm	Rare

1. Percent of reserves of ferruginous bauxite

Hm = hematite
 Goe = goethite
 Py = pyrite
 Sid = siderite
 Lep = lepidocrocite
 Mc = marcasite

diffraction and only in samples taken from the outer edges of concretions.

b. Goethite

Goethite is the principal iron mineral in the red ore, yellow kaolin ore, and medium- and high-grade ores. It forms an important iron phase in the high-iron bauxite, greenish bauxite, pyrite-bearing bauxites, and siderite-bearing bauxite. Goethite occurs as a minor iron mineral in pink streaky kaolin ore.

Under the reflecting light microscope goethite can be observed to exhibit a wide variety of forms, especially in red ore (A.P. Green specimen number 4). Much goethite occurs in grains about 35 to 135 μm across. The grains are equidimensional to elongate in shape (Figure 15). They exhibit a wide range in abundance of bauxite inclusions. Some goethite grains contain only a small amount (about 5%) of small (about 3-6 μm) inclusions of bauxite. Other goethite grains have about the same size and shape but contain many more bauxite inclusions which commonly constitute 30-60% of these grains.

A second type of goethite, which occurs in the same bauxite specimens and appears to be gradational into the first type of goethite grains, is that which occurs as grains or wispy irregularly shaped areas of goethite. Such areas are comprised predominantly of bauxite together with smaller percentages of exceedingly fine-grained goethite. The individual goethite grains in such areas are about 1-5 μm across, but most are partly clustered together.

Although most Eufaula bauxites are not especially pisolitic, the red ore contains moderately abundant pisolites. These pisolites locally control the distribution of goethite within a specimen. Goethite commonly forms rims 5 to 125 μm thick around pisolites and may fill areas between pisolites (Figure 16). Elsewhere goethite is concentrated within the pisolites. Part of that goethite is sponge-like, and part is very fine-grained (1-5 μm) dull goethite which is densely clustered in the central portions of some pisolites.

Goethite occurs in the red ore and in the high-iron bauxite as coatings of the inner surface of small vugs up to 130 μm across. The coatings are 3-20 μm thick and give way to fine-grained hematite as the vug base. The hematite also is disseminated in the underlying bauxite (Figure 17).

Goethite also occurs as very tiny grains (Figure 18), about 1-10 μm across, which are disseminated throughout many of the ferruginous bauxites, including the high-iron bauxite, greenish bauxite, red ore, siderite-bearing bauxite, medium- and high-iron bauxites and both types of ferruginous kaolin ores.

Goethite occurs as partial to complete replacements of iron sulfides in pyrite-bearing bauxites, and these are discussed subsequently under the iron sulfide minerals.

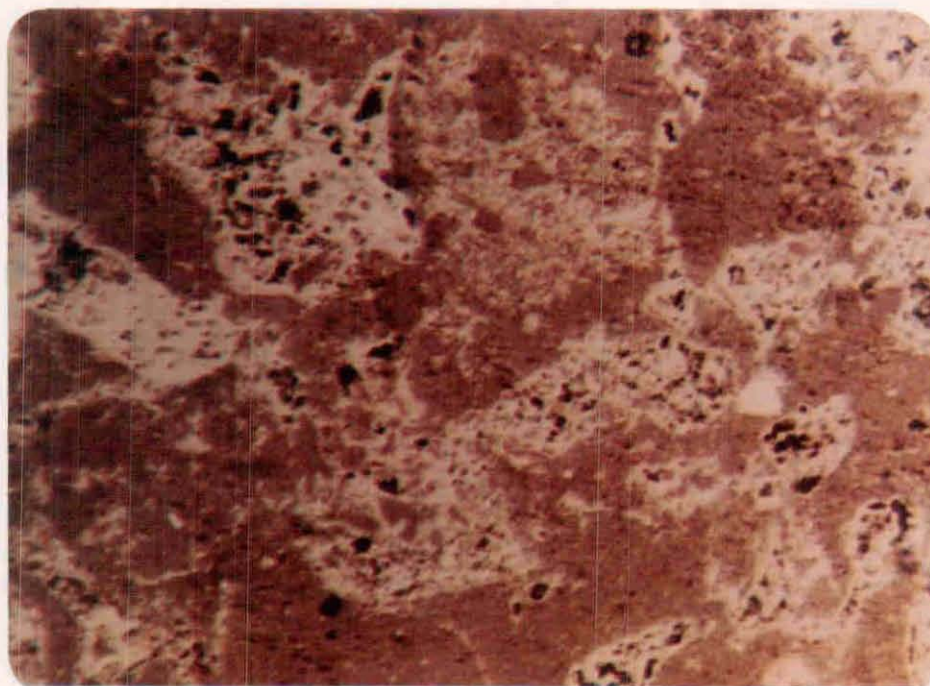


Figure 15. Equidimensional to elongate goethite grains (light gray) about 30-60 μm across which exhibit varying amounts of bauxite inclusions (dark gray). Those in the center have abundant inclusions; those at the left and right margins have few inclusions. Typical of some ferruginous bauxites.

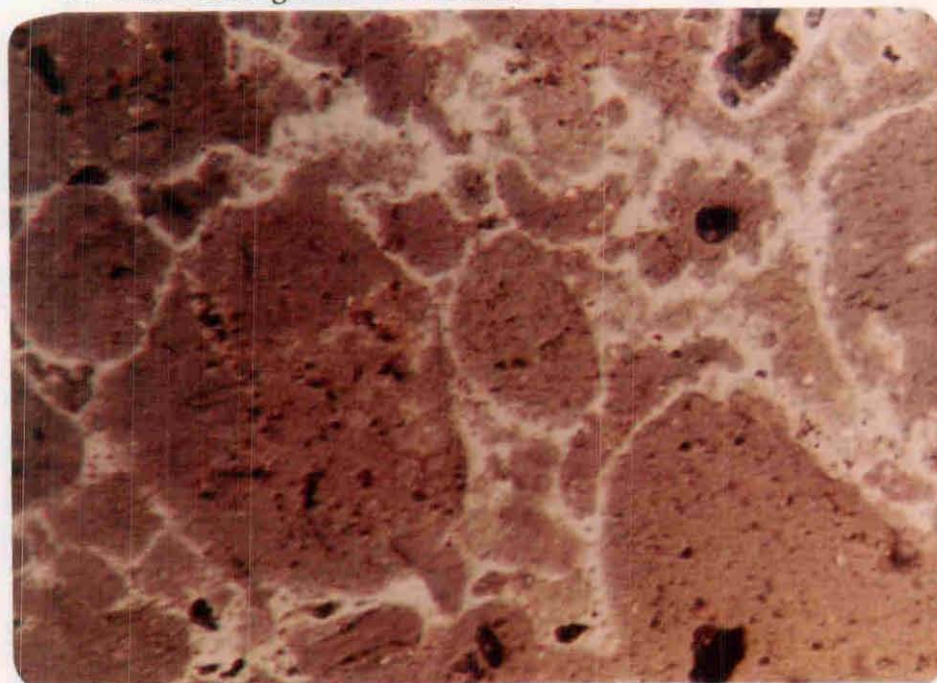
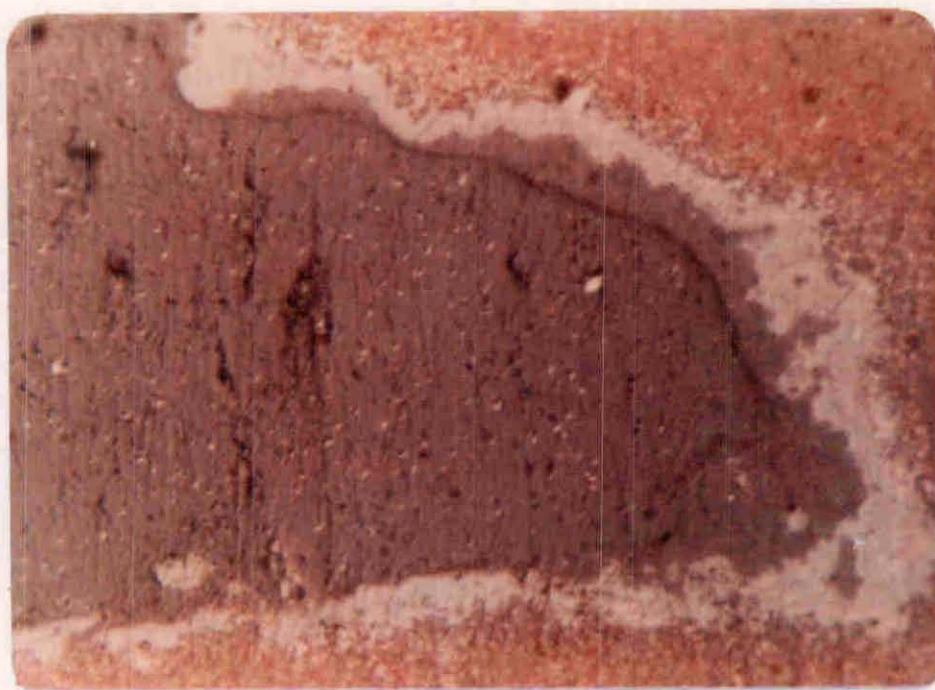


Figure 16. Goethite (light gray) concentrated in rims 5-125 μm thick around pisolites (dark gray). Typical of some pisolitic ferruginous bauxites. In other specimens goethite is concentrated within the pisolites.



20 μm

Figure 17. Goethite (light gray) lining small vugs (now filled with impregnation plastic (dark gray)). Tiny hematite grains (white) 1-3 μm across occur at the base of the goethite and are disseminated throughout the bauxite. Red internal reflections are due to the fine-grained hematite.



20 μm

Figure 18. Tiny, irregularly shaped goethite grains, 1-10 μm across, disseminated in bauxite. Such grains are commonly scattered throughout ferruginous bauxites.

Rare grains of goethite occur in the form of cubes about 110 μm across. Such grains are probably pseudomorphic after original pyrite crystals.

c. Hematite

Hematite is the principal iron mineral in the irony bauxite, high-iron bauxite, and pink streaky kaolin ore. It is an important iron phase in the greenish bauxite and siderite-bearing bauxite. Hematite occurs as a minor iron mineral in the red ore, some pyrite-bearing bauxites (Didier-Taylor specimen number 4), some high-grade bauxites, and yellow kaolin ore.

Hematite occurs in a variety of grain sizes and shapes. Unlike goethite which commonly exhibits abundant inclusions of bauxitic material, hematite grains typically lack bauxite inclusions. A common form of hematite is that which occurs in irony bauxite as grains about 20-60 μm across. Most of the grains are roughly spherical to ellipsoidal in shape, but some exhibit crude six-sided shapes. The grains are disseminated throughout the bauxite.

A second type of abundant hematite grain is that which is mostly 1-2 μm across and irregular in shape. The grains are disseminated throughout irony bauxite, high-iron bauxite, greenish bauxite, siderite-bearing bauxite, some high-grade bauxite, and pink streaky kaolin ore. In some specimens the grains range to 30 or even 50 μm . In the irony bauxite the tiny grains are more abundantly clustered near the larger hematite grains discussed in the previous paragraph (Figure 19). They are very abundant in an area 100-200 μm from those larger grains.

A third variety of hematite observed in polished thin sections is that of round concretionary hematite bodies. These are abundant in irony bauxite and high-iron bauxite. They commonly are 15-85 μm across, but may be larger and presumably are the microscopic extension of the size range of the megascopic concretions. They may contain abundant tiny bauxite inclusions throughout.

A fourth variety of hematite grains are those which exhibit euhedral six-sided platy shapes. Although they are abundant in irony bauxite they are less abundant in red ore and only a minor iron phase in siderite-bearing bauxite and pink streaky kaolin ore. Most of these crystals have formed their own euhedral shapes, but some of those in the pink streaky kaolin ore may be six-sided sections through pyritohedrons pseudomorphic after pyrite.

Rarely hematite is intergrown with goethite. Crudely cubic grains in high-iron bauxite consist primarily of goethite containing irregular patches of hematite. Irregularly shaped areas of goethite in red ore locally exhibit thin rims of hematite.

d. Lepidocrocite

Lepidocrocite and goethite are the two mineral phases which constitute limonite. Although they have the same chemical composition, they differ from each other in the nature of the H-O bond. In lepidocrocite, $\text{FeO}(\text{OH})$, the hydrogen is held as hydroxyl, whereas in goethite, HFeO_2 , the hydrogen acts as a cation in two-fold coordination between oxygen (Palache, et. al., 1944).

Lepidocrocite is distinguished with some difficulty in polished section and it is possible that more lepidocrocite is present than recognized in this study. Lepidocrocite was recognized to occur only as a minor phase in one specimen, the red ore. Thin bands, 4-5 μm across, of lepidocrocite occur intergrown locally with goethite.

Lepidocrocite is more easily distinguished by X-ray diffraction. Only one sample, that of iron bauxite, contained faint lines that indicated the possible presence of lepidocrocite. Most of the iron in that sample, however, is present as hematite. No lines belonging to lepidocrocite were detected in any of the other bauxites, neither in the bauxite ores nor in iron concentrates prepared from the bauxites.

e. Pyrite

Pyrite is the dominant iron mineral in pyrite-bearing bauxites, it may be present in some high-grade bauxite ores (Didier-Taylor specimen number 3), and it forms a minor iron phase in siderite-bearing bauxite. Pyrite-bearing bauxites contain iron sulfide concretions as large as two or three inches across. The concretions consist almost entirely of pyrite with only small amounts of bauxite in triangular concave patches outlining centers of pyrite crystallization. Most of the pyrite consists of anhedral to subhedral grains averaging about 125 μm , but the grains are tightly clustered together. The centers may consist of more euhedral pyrite of pyritohedral to cubic form. The outer portions of some concretions consist of coatings of coarser crystals.

Smaller pyrite concretions can be observed under the reflected light microscope to occur in pyrite-bearing bauxite (PTS-APG-5) and some high-grade bauxites (PTS-DT-11). Those present are 75-150 μm in diameter, exhibit round exterior margins, consist predominantly of fine-grained pyrite, and exhibit all stages of oxidation to goethite. (Figure 20). The concretions are locally clustered together.

A second form of pyrite in pyrite-bearing bauxite and some high-grade bauxites (PTS-DT-11) is that of spheres averaging about 12 μm in diameter. These spheres can be observed under high magnification to be comprised of clustered smaller spheres with diameters of about $\frac{1}{2}$ -1 μm . This type of pyrite has commonly been called "framboidal pyrite".

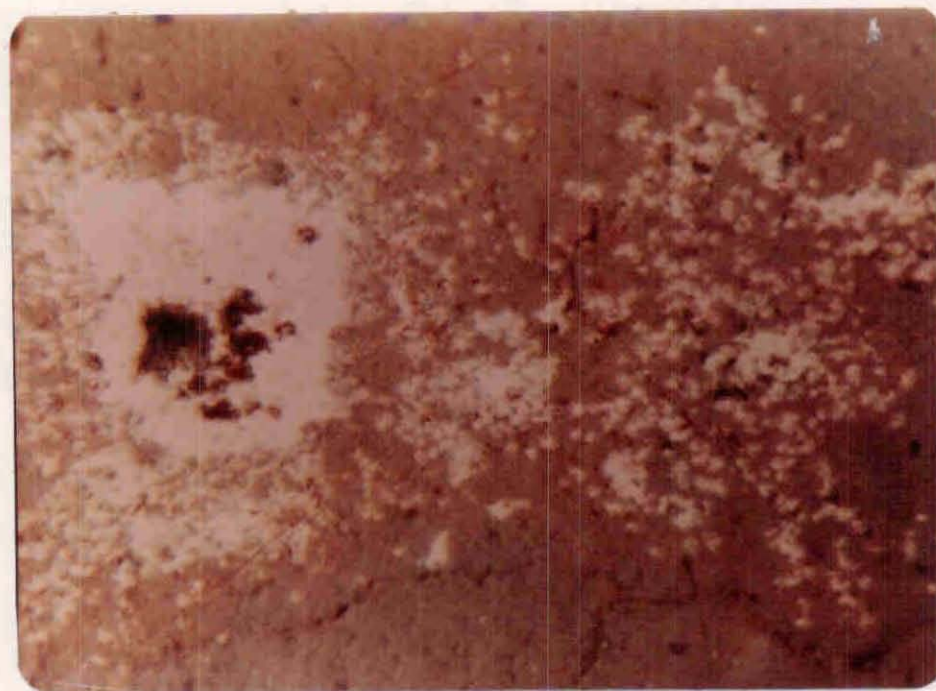


Figure 19. A hematite grain $37\ \mu\text{m}$ across surrounded by smaller (less than $5\ \mu\text{m}$) disseminated hematite grains. These hematite grains are common in ferruginous bauxites.

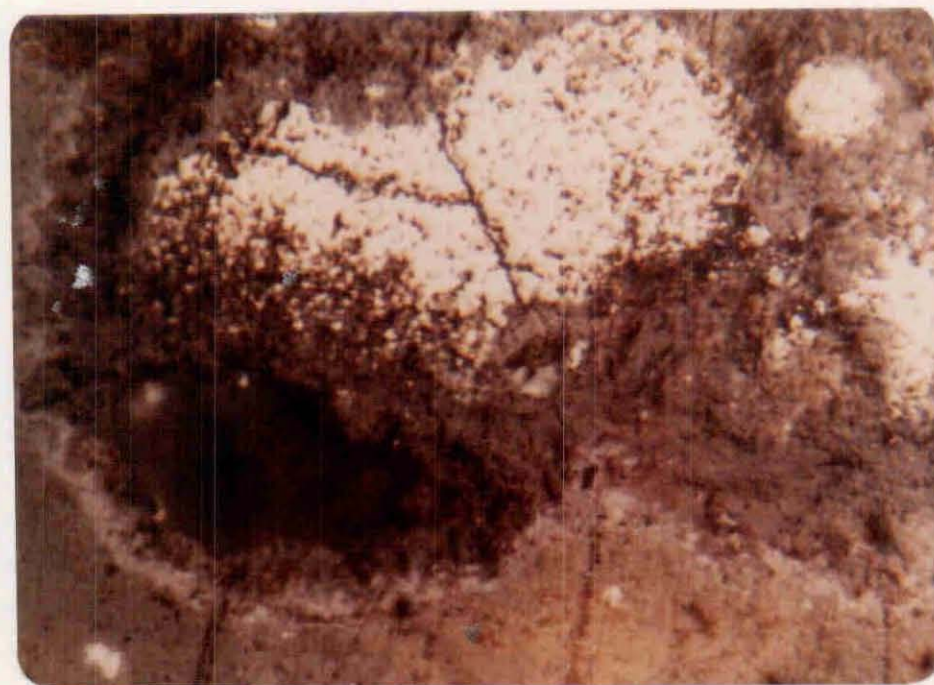


Figure 20. Pyrite (yellow) concretions, originally $75\text{-}150\ \mu\text{m}$ across, altering to goethite (light gray). Typical of pyrite-bearing ferruginous bauxites.

Tiny, pyrite grains are disseminated throughout portions of some pyrite-bearing bauxites (PTS-DT-10) and siderite-bearing bauxite. The grains are irregularly shaped and one to ten μm across.

f. Marcasite

Marcasite, the orthorhombic form of iron sulfide, occurs together with pyrite in some bauxites. In pyrite-bearing bauxite (PTS-APG-5) some of the concretions contain marcasite rather than pyrite. These marcasite concretions also are round and have diameters of 75-150 μm . In high-grade bauxites (PTS-DT-11) marcasite occurs in minor amounts with framboidal pyrite where it has crystallized after the pyrite.

g. Siderite

Siderite is an important iron mineral in two of the bauxite specimens studied: the greenish bauxite (PTS-DT-13) and the siderite-bearing bauxite (PTS-APG-7). Although siderite was not observed microscopically in either specimen, X-ray diffraction yielded a strong peak for siderite in greenish bauxite. Siderite was detected in heavy liquid concentrates prepared from the siderite-bearing bauxite.

h. Ilmenite

The iron-titanium oxide, ilmenite, occurs as a rare constituent in irony bauxite and red ore. The grains tend to show euhedral crystal outlines. They are commonly partly to strongly altered to hematite and especially anatase.

2. Suggestions on beneficiation

There are several processes by which the iron content of Eufaula ferruginous bauxites can be decreased or the effect of the iron content diminished. The first of these involves screening. Because a large amount of the iron in irony bauxite and high-iron bauxite is present in the form of relatively large iron concretions, screening is a simple and effective means to reduce their total iron content. Such screening results in a significant elimination of iron from those ferruginous bauxites (Gerald V. Sullivan, U.S. Bureau of Mines-Tuscaloosa, 1980, oral communication). Negative aspects of screening involve the expense and need to add water to the bauxite.

Secondly, those mining companies utilizing a slurry process find that some of the largest iron sores drop out by gravity during the slurry process.

Thirdly, with regard to treatment of the finer grained goethite and hematite, it would appear that high gradient magnetic separation (HGMS) might offer some potential. HGMS has been indicated to satisfactorily treat materials as fine-grained as that of the iron minerals in the Eufaula bauxites (Dobby, et al., 1979).

The weakly magnetic character of goethite and hematite, which are the principal iron minerals in those ferruginous bauxites that form the principal reserves in the district, should be sufficient for their removal by HGMS. A type of HGMS is currently being successfully employed to separate both Fe and Ti minerals from clays in Georgia (Ovellette, et al.,

Fourthly, the effect of the iron present in ferruginous bauxites can be diminished, without removing it, by fine grinding to disperse iron concretions into fine particles. If the iron is sufficiently dispersed throughout the final brick product it will not cause the brick to fail and generally will not discolor the brick too strongly.

Finally, some combination of the above processes may be the optimum manner to treat the Eufaula ferruginous bauxites for their iron contents.

D. Other Minerals

In addition to the iron minerals previously described in detail, other minerals which occur in or were sought in the bauxite specimens include those which: 1) dilute the bauxite grade, 2) occur as minor trace minerals, or 3) constitute a health or environmental hazard.

Quartz and kaolin are the principal diluent minerals. Quartz occurs as clastic subrounded to subangular grains. Although they constitute one or two percent of some specimens, they are entirely lacking from other specimens. The quartz grains are commonly about 50 to 400 μm across, but some are smaller and some are as large as 750 μm in some pyrite-bearing bauxite (PTS-APG-5). The largest quartz grains contain fluid inclusions. Kaolin was detected by X-ray means in all of the bauxite samples.

Fine-grained sericite and coarser grained muscovite occur as minor trace constituents in many of the bauxite specimens. They were detected primarily by petrographic transmitted light microscopy. Rare zircon and tourmaline subhedral grains were observed.

Small amounts of titanium minerals are also present in the bauxites. Anatase is the most common titanium mineral. Rutile and ilmenite are less common. Rare grains exhibit ilmenite in the process of altering to anatase.

No minerals which form a potential health or environmental hazard were identified in the Eufaula bauxite deposits. No asbestos minerals were identified during the course of this microscopic and X-ray study.

III. FURTHER WORK RECOMMENDED

The present research has fully disclosed the character of the phosphate grains which occur in the Birmingham iron ores. Further work might take three forms: 1) Similar microscopic examinations of the lower grade ferruginous sandstone protoses which in the Red Mountain Formation above the Big Seam would be useful to determine the nature of its phosphate grains and their potential separability. Except for the Big Seam, the ferruginous sandstone has the largest iron reserves in the Birmingham district (Simpson, et.al., 1978).

2) Similar microscopic examinations should be conducted on cores from a larger number of drill holes in order to better assess the phosphorous mineral varieties within specific blocks of the remaining ore reserves.

3) Future beneficiation research should be monitored by accompanying microscopic examinations of the beneficiation products to determine the extent of separation achieved for the various phosphate mineral varieties. Such microscopic studies could be a great aid to the mineral dressing efforts.

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V. STATEMENT OF PATENTS OR INVENTIONS

There were no patents or inventions under the grant.

VI. CONCLUSIONS

Intensive study by microscopic and microbeam techniques has shown that phosphorous occurs in the Birmingham, Alabama iron ores as 15 types of carbonate-fluorapatite (collophane), each distinguished by its size and shape. The largest type is not intergrown with hematite and will be liberated by fine grinding. Most of the other 14 types exhibit varying degrees of intergrowth with hematite and will not be liberated or only partly liberated from hematite by fine grinding. Modal analyses have shown that the proportions of the various carbonate-fluorapatite types differ significantly between four varieties of iron ore. These results, together with the fact that the proportions of those iron ore varieties vary in the district, have shown that about 27% of the phosphorous can be removed by beneficiation of iron ores in that portion of the district formerly mined and 60% from the iron ore reserves which remain in the central and eastern portions of the district. Fine grinding, selective flocculation, and flotation, similar to the technique utilized at the Tilden mill in northern Michigan, is recommended for additional beneficiation research and as a technique which may effectively treat the very fine-grained character of the Birmingham hematite and liberate the maximum amount of carbonate-fluorapatite.

Ore microscopic and petrographic studies have shown that Eufaula, Alabama ferruginous bauxites contain seven iron-bearing minerals. Goethite and hematite are the most abundant iron-bearing minerals, but pyrite, marcasite, and siderite are the principal iron minerals in some varieties of ferruginous bauxite. Lepidocrocite and ilmenite occur in minor quantities. The coarsest hematite grains are concretions which can be removed from the ferruginous bauxites by screening. For the finer grains of goethite and hematite, research is recommended on the utilization of high gradient magnetic separation which has been found elsewhere to be successful in removing fine-grained iron and titanium minerals from clay deposits.

Descriptions of Selected Polished Thin
Sections of Birmingham Iron Ores

1. Mine Bulk Iron Ore Sample: PTS-1
2. Fossiliferous Iron Ore: PTS-78-65
3. Oolite Iron Ore: PTS-78-77.5
4. Sandy-Flaxseed Ore: PTS-3249
5. Flaxseed Iron Ore: PTS-3530
6. Sandy Ore: PTS-3538
7. Fossiliferous-Sandy Iron Ore: PTS-78-72.5

Mine Bulk Sample: PTS-1

Megascopic Description-

The section is medium dark red with about 40-50% of the area consisting of hematite. Coarse sand grains constitute about 15-20% of the section. Calcitic fossils form the remainder of the specimen.

Petrographic Description-

This specimen consists of abundant fossil fragments and sand grains together with lesser amounts of hematite, oolites, and flattened hematite concretions, cemented by hematite and some sparry calcite. The sand grains are subrounded and average about $1\frac{1}{4}$ mm across. Irregular fractures in quartz are filled by hematite. The most abundant fossil fragments are bryozoa. Crinoids, brachiopod fragments, and echinoids also are common. Brownish iron-stained trilobite fragments are scattered through the specimen.

The principal occurrence of phosphorous in this section is in the form of collophane. Fourteen collophane grains can readily be distinguished. These grains are rather large and most are about $\frac{1}{4}$ to $\frac{1}{2}$ mm across, the size of medium sand grains. The largest grain is $2\frac{1}{2}$ mm across, slightly larger than very coarse sand grains. The collophane grains are subrounded in shape to rarely ellipsoidal. Most of the grains exhibit little intergrowth with adjacent iron minerals, but two exhibit slight marginal replacement by hematite. The collophane grains contain varying amounts of small inclusions of mostly quartz and minor feldspar. The inclusions are subangular to subrounded; they range from about 60 μm to 350 μm and average 200 μm . Although some collophane grains are free or almost free from quartz inclusions, others consist of as much as 65% inclusions. The collophane grains are tan or light yellow to medium brown in color. Most collophane grains are microcrystalline with tiny anisotropic areas 5-15 μm long, but some grains are isotropic. The origin of the collophane grains probably is that of vertebrate faecal pellets. Many of the larger grains exhibit a degree of rounding similar to that of the sand grains and appear to be transported clastic grains. These grains exhibit sizes similar to adjacent sand grains and their size tends to vary with that of sand grains from place to place in the section. Other collophane grains may represent faecal pellets which have not been transported or were transported lesser distances.

Two of the collophane grains are different from the faecal pellets described above. They are 100 to 1600 μm across and exhibit a distinct internal light yellow light brown and orange banded texture. These grains probably are vertebrate bone fragments.

Several methods of modal analysis have been applied to this section in order to evaluate the contribution of phosphorous by collophane to the total phosphorous content of the specimen. Measurements of the length and width of each of the 14 collophane grains were multiplied and added to obtain the total area represented by collophane ($7.165 \text{ mm}^2 - 2.07 \text{ mm}^2$ quartz inclusions) and this figure was divided by the total area of the thin section. The respective figures were 5.095 mm. and 924.5 mm., indicating 0.551% collophane of sand type in the section. A total of 0.126% phosphorous occurs in the specimen in this form, and it appears to present about one-third of the total phosphorous present.

The percent collophane also has been determined by automatic image analysis, which indicated an area of 8.36 mm^2 (minus 2.07 mm^2 for quartz inclusions) for the

14 collophane grains, 896.128 mm^2 for the entire thin section, and that 0.1056% phosphorous is present in the specimen in the form of the 14 large collophane grains. Thus, these grains constitute about one-quarter of the 0.40% phosphorous determined by chemical analysis to be present in core from which this specimen was taken.

Scattered trilobite fragments exhibit varying degrees of brown colors which are somewhat similar to that of the collophane grains. Echinoid fragments which are partially replaced also exhibit a spotted medium to dark brown color somewhat like that of the collophane grains.

Inclined Light Examination-

Examination of the section under transmitted and inclined light simultaneously shows that red hematite is the principal iron mineral and that blue hematite also is abundant. Minor goethite is present in some fossils. Most of the red and blue hematite occurs in this section as replacements of fossil fragments. Bryozoa are the most common fossils replaced by iron, but crinoids, echinoids, and trilobite fragments also are replaced. Hematite also occurs as oolites and flattened concretions.

Reflected Light Examination-

Hematite is the only opaque mineral present in the section. It occurs principally as very fine-grained (1-10 μm) coatings, replacements, and chemically deposited grains. Oolites and flaxseed are common and consist of alternating bands of hematite of varying grain sizes. Fine-grained hematite also forms coatings on fine sand quartz grains to develop surficial oolites. Fine-grained hematite is very abundant as coating on fossil fragments and as partial replacements of those fossils. Locally, hematite forms a cement between oolites, flaxseed, fossil fragments, and sand grains.

Luminoscope Study-

The same polished thin section which has been studied by the petrographic (transmitted light) and ore microscopic (reflected light) methods also was examined under the luminoscope. The calcite fossil fragments exhibit bright yellow cathodoluminescence. This feature helps to distinguish fossil fragments from sparry calcite cement which luminesces a darker reddish yellow. Even more useful is the fact that calcite fossil fragments which appear to be completely replaced or nearly so under ordinary light can be observed fully under the luminoscope. Apparently sufficient calcite remains to form the luminescence. For many fossils their full outline becomes visible under the luminoscope, whereas under the ordinary petrographic microscope those areas simply appear black due to the high degree of replacement by hematite.

All of the 14 grains of collophane observed under the petrographic microscope exhibit a light blue luminescence under the luminoscope. The light blue color is somewhat difficult to distinguish from the darker blue exhibited by the quartz grains, but can be readily distinguished after some practice and under optimum operating conditions of the luminoscope (12 KV and 0.9 ma). The significant aspect of collophane luminescence is that grains not visible by normal petrographic technique can be observed under the luminoscope. Many of these collophane grains occur in areas of the section consisting mainly of hematite and the collophane

grains are partly to substantially replaced by hematite. The most abundant of the additional collophane forms observed under the luminoscope are: 1) ovate to very elongate faecal pellets which form the nuclei of hematite oolites and flaxseed. Many of these collophane-bearing nuclei consist entirely of collophane, but more commonly they contain varying amounts of partly replaced calcite. 2) clustered tiny collophane grains which occur in some hematite areas. These grains are about 10 μm across. 3) small grains disseminated in hematite. These grains are about 20-30 μm across, equant to irregular in shape, and more evenly distributed throughout the section. 4) tiny grains of collophane scattered mostly throughout hematite areas but partly also through calcite areas. They occur partly within the edges of hematite oolites. Under the luminoscope their color is slightly more blue than that of collophane in sand grains, faecal pellet nuclei in hematite oolites, and rings of collophane in hematite oolites. Although some exhibit platy shapes, most are irregular in form. 5) collophane locally has formed as grains partially filling spaces between the walls of bryozoa fossil fragments and portions of some bryozoa are partly replaced.

Minor forms of collophane which are detected under the luminoscope include:

- 1) partial replacements of calcite grains other than bryozoa fossil fragments,
- 2) thin films of collophane on small quartz and feldspar clastic grains. The film on quartz have smooth inner margins, whereas those on feldspar exhibit ragged inner replacement boundaries. The films are less than 10 μm thick.
- 3) Collophane has locally formed as rings of chemically precipitated collophane which alternate with hematite in some oolites and flaxseeds. The rings are about 20 μm thick or less.

Collophane modal analysis was accomplished under the luminoscope by counting collophane grains of each type, multiplying by their average grains size (determined by measurements under the luminoscope), and dividing by the total area of the section (896.128 mm^2 ; determined by automatic image analysis). The size of each collophane grain present as hematite oolite nuclei and bryozoa replacements were measured individually rather than using an average figure. The amount of sand type collophane grains was determined by automatic image analysis as described under the section on petrographic analysis. The total amount of collophane in the section is 2.28%. Allotting 15.03% phosphorous to collophane (determined by electron probe), the total amount of collophane accounts for 0.34% phosphorous in this section. This value is very close to the 0.40% phosphorous determined for the mine bulk sample from which this section was taken. In summary, these data indicate that all of the phosphorous present in this specimen occurs in the form of collophane.

The abundance and size of each collophane grain type is given below:

<u>Collophane Type</u>	<u>Size</u>	<u>Percent</u>
Sand	.77 mm diam.	30.73
Nuclei in hematite oolites:		
Calcite replacements	100 x 60 μm	18.07
Faecal Pellets	150 x 110 μm	8.33
Clustered tiny grains in hematite	5 μm diam.	12.59
Small grains in hematite	10 μm diam.	5.30
Scattered tiny grains in hematite	5 μm diam.	8.20
Fossil fillings	30 μm diam.	9.84
Fossil replacements	Irregular	2.74
Calcite grain replacement	30 μm diam.	0.27
Spots of calcite replacement	20 μm diam.	1.48
Films on quartz grains	5 μm thick	1.71
Films on feldspar grains	10 μm thick	0.69
Rings in hematite oolites	5-10 μm thick	0.07
		<u>100.02</u>

Electron Microprobe Analyses-

Four collophane grains were analyzed quantitatively for P_2O_5 , CaO , and F. One of the grains was very small and yielded poor results. The other three grains were sand size and showed a small range of P_2O_5 from 34.08 to 34.66% with an average of 34.41. These three grains together with four similar sand size grains from PTS-3249 provided an average figure of 34.43% P_2O_5 which was utilized for all specimens to calculate from modal analyses the phosphorous contribution of sand size collophane grains.

Analyses for CaO vary from 48.55% to 49.53% and average 49.17%. Their fluorine content ranges from 2.85% to 3.06% and averages 2.95%.

X-ray Diffraction Analyses-

One collophane sand-size grain was analyzed in PTS-1 by X-ray diffraction to determine if it has a submicroscopic crystallinity. Although the grains are isotropic under ordinary transmitted light, the x-rayed grain yielded weak peaks.

Three other sand size grains in additional polished thin sections of the bulk sample (PTS-BS-2 and PTS-BS-6) were also analyzed by x-ray diffraction and found to give $29.3^\circ 2\theta$, $32.1^\circ 2\theta$, and $40.3^\circ 2\theta$ peaks for francolite. These x-ray results indicate that the optically isotropic sand size grains have a submicroscopic atomic structure consistent with that of francolite.

X-ray diffraction also indicated the presence of chamosite. Two low peaks for chamosite, $12.7^\circ 2\theta$ and $25.8^\circ 2\theta$, were detected.

PTS 78-65 Fossiliferous Iron Ore

Megascopic Description-

The section is light red with about 20-25% hematite. Crude banding results from a tendency of hematite to concentrate in darker red bands. Light pink bands are slightly broader and consist primarily of calcitic fossil fragments. Scattered quartz sand grains constitute less than 5% of the section.

Petrographic Description-

This specimen consists of calcitic fossil fragments, sand grains, hematite, and collophane grains. This specimen exhibits the character of fossil fragments especially well. Bryozoa are the most abundant fossil fragments. Brachiopod, crinoid, echinoid, and trilobite fossil fragments also are common. Bryozoa and echinoid fragments are especially susceptible to replacement by hematite. Trilobite fragments typically exhibit a brown color somewhat similar to that of the collophane grains. Most trilobite fragments are light brown in their interior portions and are darker brown locally, especially at their margins. A few round to subround quartz sand grains about 3/4 to 1½ mm in diameter are scattered throughout the specimen. Hematite occurs as partial to nearly complete replacements of certain calcitic fossil fragments together with scattered hematite oolites. Fossil replacement seems largely to be controlled by access of the iron solutions to a given fossil fragment, although certain fossil shells are more readily replaced than others. Several large intraclasts of calcite with quartz grains are present.

Three large collophane grains are present. The grains are about the same size as the quartz sand grains and may be as large as 1.5 mm long. One is medium to dark brown in color; the other two are light tan. They contain only a few quartz inclusions. One is a banded invertebrate fragment. The collophane grains exhibit slight replacement by hematite and commonly are rimmed by additional hematite. Automatic image analysis and grain measurement have shown that the three large collophane grains have a composite area of 1.6 mm², comprise 0.2% of the section, contribute 0.028% phosphorous to the specimen and account for about 9% of the total phosphorous present (0.36%) in the specimen. One bryozoa is almost completely replaced by collophane.

Inclined Light Examination-

Blue and red hematite are present as fossil fragment replacements and oolites. Bryozoa are the most commonly replaced fossils and replacement typically appears to be nearly complete. Bryozoan interiors are replaced by a mixture of red and blue hematite which tends to reveal their internal structures. Their marginal portions are replaced by and rimmed by blue hematite. Brachiopod fragments less replaced by hematite, but blue hematite locally accumulates at their margins as a coating. Oolites are comprised of alternating bands of predominantly blue hematite and lesser red hematite. Some are flattened flaxseed type oolites. Blue hematite forms veinlets filling fractures in some quartz sand grains. Blue hematite also forms rims or coatings around collophane grains. The interior portions of some collophane grains exhibit partial replacement by blue hematite, particularly at the margins of quartz inclusions.

Reflected Light Examination-

The hematite oolites consist of bands with hematite of various grain sizes. Many of the oolites contain very thin (about $\frac{1}{2}$ μm) bands of non-opaque minerals which separate the hematite bands. The nuclei of some oolites are partially replaced by disseminated specular hematite.

Reflected light examination of hematite oolites known from luminoscope study to contain rings of collophane show a variety of relationships. Some contain only a single collophane ring, others contain two or three collophane rings. Interbanding of thin collophane and hematite rings as thin as $\frac{1}{2}$ μm thick is prevalent in some oolites.

Hematite replacements of fossils are in the form of very fine grains, 1-15 μm across. The hematite is disseminated to vein-like.

Luminoscope Study-

No additional large sand-size grains of collophane can be detected by luminoscope study, but a variety of other collophane grains are present. Several large grains which have an appearance very similar to that of collophane with quartz silt grains and with a dark cement, can be observed under the luminoscope to be calcite. One intraclast does contain small grains of collophane together with abundant calcite grains.

Collophane occurs as rings in oolites, elongate faecal pellet nuclei in the centers of oolites, partial replacements, and fillings of fossil fragments, partial replacements of other calcite fragments, as rare coatings of clastic quartz and feldspar grains, and as abundant tiny grains about 10-20 μm across. Bryozoa fossils are particularly susceptible to replacement by collophane and some are nearly entirely phosphoritized. Some elongate ellipsoidal fossil fragments of bryozoa are entirely replaced by collophane and hematite. Collophane also forms partial fillings of the spaces within some bryozoan colonies. Although oolites are not abundant in this specimen, some of those oolites exhibit one or two rings of collophane interbanded with hematite. This chemically precipitated collophane may form coatings about bryozoa fragments which form the nuclei of many oolites and themselves may be partly or completely replaced by collophane. Although collophane forms thin films on feldspar and other grains, feldspar is not as abundant in this specimen as in oolitic ores. Tiny grains about 10-20 μm across are disseminated and locally clustered throughout the specimen and can be observed only under high magnification. These grains are mostly confined to areas of abundant hematite. In fact, most of the collophane forms described above occur in the hematite areas where they form intimate intergrowth with hematite.

Modal analysis was conducted under the luminoscope by counting collophane grains of each type, multiplying by their average grain size (determined by measurements under the luminoscope) and dividing by the total area of the section (799.81 mm^2 ; determined by automatic image analysis). The grain size of collophane in hematite oolite nuclei and that occurring as bryozoa replacements were individually measured for each grain rather than using an average. The amount of sand-type collophane grains was determined independently by automatic image analysis as previously described in the petrographic description. The total amount of collophane of all types present in the section is 1.7855%. With a phosphorous content of 15.03% in collophane (determined by electron probe), collophane accounts for 0.268% phosphorous in the specimen. This corresponds approximately with a chemical analysis of 0.36% phosphorous for the core. Thus, the modal ana-

lysis for collophane abundance indicates that this mineral accounts for nearly all (probably all) of the phosphorous present.

The abundance and size of each collophane type is given below: PTS 78-65

<u>Collophane Type</u>	<u>Size</u>	<u>Percent</u>
Sand	1.4 mm diam	10.09
Nuclei in hematite oolites	200 x 125 μ m	28.76
Small grains in hematite	15 μ m diam.	10.49
Scattered tiny grains in hematite	("plates") 5 μ m diam.	13.05
Fossil fillings	30 μ m diam.	27.58
Fossil replacements	Irregular	5.33
Calcite replacements	30 μ m diam	3.52
Films on quartz and feldspar clastic grains	5 μ m thick	<u>1.18</u>
		100.00

PTS-78-77.5 Oolitic Iron Ore

Megascopic Description-

The section is medium dark red with about 40-45% hematite. The specimen is characterized by especially well-developed banding with dark red hematite bands alternating with light tan calcite bands. A large fossil about one centimeter long occurs at one end of the section.

Petrographic Description-

This specimen consists of very abundant hematite oolites, calcite fossil fragments partly recrystallized to sparry calcite, and quartz fine sand grains. The oolites are round to ovate in shape and average about 300-350 μm across. They are composed primarily of hematite, but may contain concentric bands and nuclei of other minerals. The latter oolites show all gradations into superficial oolites in which large nuclei, usually quartz fine sand grains, are encased in a relatively thin hematite oolite coating. The oolites are clustered together in those bands in which they are most abundant. Calcitic fossils are most common in certain bands and consist of abundant crinoid fragments, and lesser amounts of bryozoa, echinoids, brachiopods, and trilobites. Most of the sparry calcite appears to have formed by recrystallization of calcitic fossil fragments. The large fossil at one end of the section is a bryozoan. Fine sand grains are scattered through the specimen and are most abundant in the oolite-rich bands. The sand grains are dominantly quartz. Most fine sand grains have moderate to heavy coatings of oolite hematite. The fine sand grains average about 200 μm across.

Tiny brown collophane grains are present throughout the section. Most of these grains are distinctly brown in color. Their typical shape is elongate with lengths two or more times that of their widths. The collophane grains are rather uniform in size. The larger grains are about 360 μm long and 210 μm wide, but these grains average about 240 μm long and 120 μm wide. Most of the collophane grains occur as nuclei in hematite oolites. The grains originated as faecal pellets. A total of 93 faecal pellets can be observed in the section by petrographic means. Calculations indicate that they contribute approximately 0.24% phosphorous to this specimen.

Inclined Light Examination-

Under inclined light the oolites can be observed to consist primarily of concentric bands of blue and red hematite. The outer bands are commonly blue hematite, and red hematite is abundant in the inner portions. The collophane grains are distinguishable by their strong brown to white internal reflections which are uniformly distributed across the grains.

Reflected Light Examination-

The only opaque mineral present is hematite. Hematite occurs primarily as oolites which vary in shape from ellipsoidal to flattened flaxseed. They also vary in the character of their nuclei. Whereas some lack any foreign

nuclei others consist only of a hematite coating on a quartz grain or calcite fragment nuclei forming superficial oolites. The hematite portion of oolites is comprised of bands of varying grain sizes, about one to ten μm in diameter. The hematite bands may lack intergrowth with gangue minerals or they may be interbanded with very thin bands of quartz, calcite, chamosite, and collophane. Such bands vary in thickness from $\frac{1}{2}$ to 10 μm . Certain oolites may contain as much or more collophane than hematite.

Luminoscope Study-

Luminoscope examination has contributed substantially to the recognition of additional collophane grains in this section. A total of 364 faecal pellets (including the 93 recognizable in ordinary light) were distinguished by their light purple luminescence. These grains may be entirely collophane of ovate to more distinctly elongate shapes and they may contain varying amounts of unreplaced calcite. Calculations indicate that about 0.09% phosphorous is present in the section in the form of these collophane grains.

Some oolites can be observed under the luminoscope to contain concentric bands of collophane. The bands are as much as 20 μm thick and some oolites contain two such bands. Although a number of oolites contain these collophane rings the total contribution of phosphorous in this form does not appear to be large. Collophane grains of this type are smoothly concave about quartz of fossil fragments. Such coatings on clastic feldspar grains have smooth outer margins but exhibit highly irregular inner margins against the feldspar. The irregular intergrowth is the result of partial replacement of feldspar margins by collophane. With progressive replacements the deep blue luminescence of the feldspar is destroyed. Collophane of this type shows a light blue luminescent color in contrast to that of a light purple luminescent color for collophane present as faecal pellet nuclei in oolites and that are present as complete rings in oolites.

The smallest collophane grains which can be observed under the luminoscope are tiny grains which locally appear to be plate-like with dimensions about 10 μm wide and 20 μm long. These tiny grains are abundantly scattered throughout the specimen and locally clustered together. These grains occur particularly within hematite oolites where their light blue luminescence contrasts with that of the light purple luminescence of collophane rings. Slightly larger grains of collophane, about 20 μm by 30 μm , also occur in hematite areas.

Collophane also forms as a replacement of fossil fragments. Most replacements are partial but some fossils are nearly completely replaced by collophane. Star-shaped bryozoa are most commonly replaced by collophane. Patchy replacements of selected calcite grains form irregular to about 30 μm across rather evenly disseminated throughout those grains.

Scanning Electron Microscope Study-

The scanning electron microscope-energy dispersive system was used to analyze several grains in this section. One of the oolites which appear to contain two ring of collophane was selected for analysis. SEM-EDS analysis showed that the rings are collophane as indicated by strong peaks for calcium and phosphorous. The SEM was also used to analyze the tiny grains 10 by 20 grains which were detected under the luminoscope to luminesce light blue. Although these grains

are very difficult to locate under the SEM, two grains were analyzed and both proved to be collophane. One of the grains analyzed occurred in an area dominated by quartz. The other grain occurred within the edge of the oolite previously analyzed. Furthermore, at high magnifications, 1000X and more, under the SEM those tiny collophane "grains" which luminesce light blue and occur within hematite oolites can be observed to occur as partial rings intergrown with the hematite. Under the SEM there appears to be a continuum from light purple luminescent collophane in the central portion of the oolite into light blue luminescent collophane in the outer portions of the oolite.

Electron Microprobe Analyses-

Four types of collophane in this section were analyzed for their chemical composition by electron microprobe technique. A total of 31 analyses were obtained on six collophane faecal pellets which occur as nuclei in hematite oolites. These results, together with eight analyses on a single grain in PTS-3249, are given and averaged below.

			CaO	P ₂ O ₅	F	Sum
PTS 78-77.5	Grain 1	6 Analyses	50.85	36.69	2.79	90.32
PTS 78-77.5	Grain 2	4 Analyses	49.82	35.86	2.42	88.11
PTS 78-77.5	Grain 3	6 Analyses	53.25	39.43	3.12	95.80
PTS 78-77.5	Grain 4	8 Analyses	51.94	37.38	3.37	92.69
PTS 78-77.5	Grain 5	5 Analyses	53.53	39.52	3.32	96.37
PTS 78-77.5	Grain 6	2 Analyses	50.56	33.90	2.35	86.81
PTS 3249	Grain 9	9 Analyses	51.80	38.46	3.09	93.35
Averages			51.68	37.32	2.92	91.92

Thus, the average phosphorous content is 16.29 in faecal pellet hematite oolite nuclei.

A total of nine electron probe analyses were carried out on three of the tiny disseminated collophane grains (blue "plates") in hematite and calcite. The results and averages are given below.

			CaO	P ₂ O ₅	F	Sum
Grains in Hm Oolite	6 Analyses		51.78	37.51	3.56	92.85
Grains near Hm Oolite	2 Analyses		53.23	37.05	3.13	93.41
Grain in Calcite	3 Analyses		50.92	35.88	3.15	89.96
Averages			51.98	36.81	3.28	92.07

Blue "plates" contain 16.07% phosphorous.

A total of six analyses were made on collophane rings in hematite oolites. The resulting averages are 45.70% CaO, 32.71% P₂O₅, 2.74% F and 81.15% sum. This amounts to 18.02% P in this form of collophane.

A total of five microprobe analyses were made on collophane partial replacements of calcite. The resulting averages are 51.89% CaO, 36.10% P₂O₅, 4.01% F, and 92.00% sum. This amounts to 15.76% P in this form of collophane.

PTS-3249 Sandy-Flaxseed Ore

Megascopic Description-

The section is dark red and contains about 60% hematite. It appears to contain some calcitic fossils and minor sand grains.

Petrographic Description-

This specimen consist of a mixture of fossil fragments and scattered sand grains enclosed in abundant hematite. The most abundant fossil fragments are bryozoa; less common are brachiopod, crinoid, and echinoid fragments. Trilobite fragments are rare.

Ten collophane grains are readily identified by transmitted light. The grains are large and average about $\frac{1}{2}$ mm across, the size of medium to coarse sand. This compares closely to a mean diameter of 0.66 mm measured by automatic image analysis for 100 quartz grains in the specimen. They exhibit a wide range in color from dark brown to light tan. Their shapes are subround to crudely rectangular. Most exhibit little to no intergrowth with hematite, but the margins of several are partly replaced by red and blue hematite. They are crypto-to microcrystalline.

Automatic image analysis equipment was used to determine the area represented by the ten large collophane grains and the area of the rock section. The grains total an area of 5.03 mm^2 . The collophane grains contain quartz inclusions which total an area of 0.6576 mm^2 ; subtracted from the collophane leaves 4.372 mm^2 . The entire section is 625.056 mm^2 . These figures indicate that the section contains 0.70% collophane in the form of the ten large grains and that these grains contribute 0.105% phosphorous to the specimen. Chemical analysis of the section of drill core from which this sample was taken indicated 0.35% phosphorous. Thus, 30% of the total phosphorous present in this specimen occurs in the form of large collophane grains.

Inclined Light Examination-

The opaque mineralogy is primarily blue hematite, with minor amounts of hematite. Hematite occurs as replacements of fossils, especially bryozoa, as oolites, flattened concretions and areas of iron oxide cement.

Reflected Light Examination-

Hematite is the only opaque mineral present. It occurs abundantly as oolites and flaxseed grains. Individual bands in oolites and flaxseeds contain hematite of varying grains from about $10 \mu\text{m}$ and down to the limit of resolution of the microscope. Some of the chemically deposited oolites and flaxseeds have nuclei quartz grains of fine sand size. Hematite also occurs as fine-grained, relatively thin coatings on quartz and feldspar sand grains. Hematite partially replaces

calcitic fossil fragments and commonly forms fine-grained coating around those fragments.

Specular hematite partially replaces the gangue nuclei in some hematite oolites. Rare hematite oolites contain multiple collophane rings one to 30 μm thick. Other hematite oolites contain silicate gangue rings one to five micrometers thick which alternate with hematite.

Luminoscope Study-

Many additional forms of collophane, beyond that of the sand grains, can be detected under the luminoscope. The majority of the collophane forms occur in hematite areas where they are concealed under ordinary light by partial replacement. Due to their partial replacement by hematite and their occurrence in areas of abundant hematite, the majority of these collophane grains will form locked hematite - collophane grains even at a very fine grind.

The more abundant types of collophane grain observed under the luminoscope are: 1) faecal pellets forming nuclei in hematite oolites, 2) fillings and replacements of bryozoa fossil fragments, and 3) small grains of collophane (20-30 μm) in hematite. Less abundant forms include: 1) scattered tiny grains in hematite, 2) calcite replacements, 3) films on small quartz and feldspar clastic grains, and 4) rings of collophane chemically deposited in hematite oolites.

Modal analysis of the various collophane grain types was carried out under the luminoscope by counting collophane grains of each type, multiplying by their average grain size (determined by measurements under the luminoscope), and dividing by the total area of the section (625.056 mm^2 ; determined by automatic image analysis). The size of each collophane grain present as hematite oolite nuclei and bryozoa replacements were measured individually rather than using an average grain size figure. The amount of sand type collophane grains was determined by automatic image analysis as described under the section on petrographic description. The total amount of collophane in the section is 2.24%. Alloting 15.03% phosphorous to collophane (determined by electron probe), the total amount of phosphorous in the form of collophane calculates to be 0.34%. This amount matches closely the 0.35% phosphorous detected by chemical analysis to be present in the core from which this specimen was taken. In summary, these data indicate that collophane accounts for all of the phosphorous present in this specimen.

The abundance and size of each collophane grain type is given below: PTS-3249

<u>Collophane Type</u>	<u>Size</u>	<u>Percent</u>
Sand	0.47 mm diam.	27.43
Nuclei in hematite oolites	180 x 140 μm	16.93
Small grains in hematite	15 μm diam.	18.88
Scattered tiny grains in hematite	5 μm diam.	4.99
Fossil fillings	30 μm diam.	12.78
Fossil replacements	Irregular	10.74
Calcite replacements	30 μm diam.	3.18
Films on quartz and feldspar grains	5 μm thick	3.13
Rings in hematite oolites	5-10 μm thick	0.94
		99.99

Scanning Electron Microscope Analyses-

Five of the large collophane grains present in this section were analyzed with a scanning electron microscope - energy dispersive analysis system. The analyses showed strong peaks for calcium and phosphorous for all five grains confirming their identity as collophane. Utilizing a 100 second counting time the phosphorous peaks were similar for the five grains suggesting no great variation in phosphorous content from grain to grain.

Electron Microprobe Analyses-

Five collophane grains in this specimen were analyzed quantitatively for their P_2O_5 , CaO , and F contents. Four of the grains are large sand size grains (two of which had previously been analyzed by SEM-EDS) and one is a faecal pellet which forms the nucleus of a hematite oolite. These grains were analyzed to determine their average phosphorous content and the variation from grain to grain. The sand size collophane grains show only a small variation from 33.44 to 34.90% P_2O_5 , and have an average of 34.44 P_2O_5 . The average of these four grains and three similar grains in PTS-1 is 34.43% P_2O_5 and this figure has been utilized for all specimens to calculate from modal analyses the phosphorous contribution of sand size collophane grains. The single faecal pellet analyzed contains a larger amount of phosphorous - 38.46% P_2O_5 . There is a substantial variation in color among the fine grains analyzed. The color variations are probably related to small amounts of organic matter present and are not a function of variations in phosphorous content.

Analyses for CaO vary from 45.82 to 49.97% and average 47.09% for the four sand size collophane grains. The faecal pellet analyzed 38.46% CaO .

The grains were also analyzed for their fluorine content so as to aid in mineral nomenclature. Fluorine varies from 2.93% to 3.75% and averages 3.14% for the four sand size grains. The faecal pellet contains 3.09% fluorine. Both collophane types are carbonate-fluorapatite (>1% F) rather than carbonate-hydroxylapatite (<1% F), (McConnell, 1973, p. 10).

PTS-3530 Flaxseed Iron Ore

Megascopic Description-

The section is dark red with about 60-70% hematite. Sand grains and fossil fragments are scattered throughout the specimen. Banding is mostly lacking from the specimen.

Petrographic Description-

This specimen consists of very abundant hematite, quartz sand grains, and calcitic fossil fragments. No oolite shapes are evident in the hematite areas due to its great abundance. Quartz sand grains are about 0.6 to 3 mm in diameter and subround to round. Fossil fragments are principally bryozoa, with less abundant crinoid, brachiopod, echinoid, and trilobite.

This section contains six large collophane grains, about one to three millimeters across, the size of very coarse sand and granules. Two are round sand grains, the third is distinctly elongate. Twenty smaller grains, 150 to 650 μm across, the size of fine to medium sand, also are present. These grains more commonly are elongate but some are rounded. Some of the collophane show marginal replacement by hematite, and one of the larger is strongly replaced.

Inclined Light Examination-

Examination of this section under inclined light contributes substantially to the visibility of the forms of hematite present. Flattened oolites or flaxseed grains are very abundant and constitute one of the principal hematite forms. They consist primarily of blue hematite, but some contain red hematite cores coated by blue hematite. Much of the hematite area consists of highly replaced fossil fragments. Typically the fossil fragments are replaced predominately by red hematite with local patches of blue hematite. Blue hematite also commonly coats the fossil fragments. Light yellow colors locally within fossils may be very fine-grained goethite.

Reflected Light Examination-

Hematite is the only opaque mineral present. It occurs primarily within flaxseed oolites as bands of various grain sizes from about 10 μm down to less than one μm . Some oolites are comprised entirely of hematite. Others are superficial oolites with nuclei of the gangue minerals, quartz, and calcite. Some oolites exhibit bands of chemically precipitated gangue minerals which alternate with hematite bands.

Locally, quartz sand grains are traversed by hematite veinlets 25 μm wide. No opaque minerals occur as nuclei in the oolites, but some disseminated hematite grains, commonly platy crystals, occurs as replacements of some nuclei.

Luminoscope Study-

The most important feature that the luminoscope study of this section brings out is the presence abundant fine-grained collophane in much of the hematite.

The collophane grains are about 5 μm in diameter, irregular in shape, and abundantly disseminated through those hematite areas which form a matrix or cement between hematite oolites, flaxseed, quartz sand grains, and calcitic fossil fragments. These hematite areas contain about 30% collophane and are clearly distinguishable from hematite oolites and flaxseed which lack this type of collophane. The individual collophane grains range from about 20 μ down to the limit of microscope resolution. Their angular shapes together with their association with fine-grained clastic feldspar grains suggests that this form may represent very fine-grain clastic collophane. However, at least some of the collophane in these areas has formed as thin films of collophane chemically deposited upon clastic feldspar grains. These tiny grains of collophane are restored to hematite areas where they are intimately intergrown with hematite and essentially all would be carried into the hematite concentrate during beneficiation. Other less abundant forms of collophane include that which is associated with fossil fragments, particularly bryozoa. Small collophane grains are locally caught within the open spaces of bryozoan colonies. Collophane also locally replaces portions of the cell walls of bryozoa. Faecal pellets form the nuclei of some hematite oolites or flaxseeds; light brownish, banded vertebrate bone fragments form the nuclei of others. Spots of collophane occur as replacements in calcite grains other than bryozoa. Thin films of collophane occur around some small quartz and feldspar clastic grains.

Minor forms of collophane include rings of collophane within hematite oolites and flaxseed and rings of collophane deposited around bryozoa fossil fragments.

Collophane modal analysis was accomplished under the luminoscope by counting collophane grains of each type, multiplying by their average grain size (determined by measurements under the luminoscope), and dividing by the total area of the section (702.27 mm^2 ; determined by automatic image analysis). The size of each collophane grain present as hematite oolite nuclei and bryozoa replacements were measured individually rather than using an average grain size figure. The amount of sand type collophane grains was determined by automatic image analysis as described under the section of petrographic description. The total amount of collophane in the section is 2.42%. With 15.03% phosphorous in collophane (determined by electron probe), the total amount of collophane accounts for 0.36% phosphorous in this section. Although no chemical analyses were available for the core from which this section was prepared, chemical analyses of iron ores of similar lithology and stratigraphic position run 0.38-0.42% phosphorous. In summary, these data indicate that all of the phosphorous present in this specimen probably occurs in the form of collophane.

The abundance and size of each collophane grain type is given below: PTS-3530

<u>Collophane Type</u>	<u>Size</u>	<u>Percent</u>
Sand	0.7 mm diam.	34.70
Nuclei in hematite oolites	150 x 90 μm	5.67
Clustered tiny grains in hematite	5 x 5 μm	30.95
Small grains in hematite	10 μm diam.	10.68
Fossil fillings	30 μm diam.	6.86
Fossil replacements	Irregular	3.06
Calcite replacement	30 μm diam.	5.29
Films on clastic quartz grains	5 μm rims	0.45
Films on clastic feldspar grains	10 μm rims	2.35
		<hr/> 100.01

Modal Analysis-

A modal analysis was conducted under the luminoscope by counting collophane grains of each type, multiplying by their average grain size (determined by measurements under the luminoscope) and dividing the area of the section (975.4 mm²; determined by automatic image analysis). The total percent collophane in the section is 1.495. If the phosphorous content of the collophane is 15.03% (as determined by electron probe), then collophane accounts for 0.225% phosphorous in this section. Chemical analysis for this core gave 0.27% phosphorous. Thus, the modal analysis of collophane abundance suggests that collophane accounts for the phosphorous present.

The abundance and size of each collophane in polished thin section 3530 is given below:

<u>Collophane Types</u>	<u>Percent</u>
Sand Size	34.70
Nuclei in Hm Oolites	
Calc Replacements	} 5.67
Faecal Pellets	
Clustered Tiny Grains in Hm	30.95
Small Grains in Hm	10.68
Scattered Tiny Grains in Hm & Gg	0
Fossil Fillings	6.86
Cossil Replacements	3.06
Calcite Grain Repl.	} 0
Spots of Calc. Repl.	
Films on Qz Grains	0.45
Films on Fd Grains	2.35
Rings in Hm Oolites	0
	<u>100.01</u>

Prediction on Locking-

The various types of collophane grains would be expected to behave somewhat differently during beneficiation and can be considered in three groups: 1) Some grains, such as the oolite nuclei, would form partly free collophane (or collophane plus calcite) and partly grains of locked collophane-hematite. At a grind material through about 400 mesh perhaps about one-fifth would be free and four-fifths would be locked. The films on quartz grains would form locked particles, perhaps about one-half with quartz and one-half with the surrounding hematite. 2) Other grains would form almost entirely locked collophane-hematite particles and these include: a) plates, b) grains in hematite, c) films on feldspar grains, d) rings in hematite oolites, and e) fossil replacements. 3) The calcite grain replacements and spots of calcite replacement would form mainly locked collophane-calcite grains.

The distributions of these eleven types of collophane in polished thin section 3530 into a heavy liquid sink concentrate and a float tail using a liquid of Sp. G. 2.94 would be expected to partition about two-thirds of the collophane into the sink fraction and about one-third into the float fraction as shown on the next page:

<u>Collophane Type</u>	Percent of Collophane in:	
	<u>Sink</u>	<u>Float</u>
Nuclei of hematite oolites:	34.58	8.65
Calcite replacements	34.58	8.65
Elongate faecal pellets	2.44	0.61
Ovate faecal pellets	2.02	0.51
"Plates"	10.72	
Grains in hematite	3.53	
Films on quartz grains	11.40	11.40
Films on feldspar grains	2.97	
Rings in hematite oolites	1.76	
Fossil replacements	3.82	
Calcite grain replacements		3.51
Spots of replacement in calcite		2.11
TOTALS	<u>66.73</u>	<u>33.29</u>

PTS-3538 Sandy Ore

Megascope Description-

The section is light red with about 40% hematite. It contains very abundant sand grains comprising about 40-50% of the section.

Petrographic Description-

This specimen consists of abundant sand grains disseminated throughout a matrix of hematite. The sand grains are predominately quartz, but an occasional partly altered feldspar grain is present. A few fossil fragments are present.

Nine large collophane grains are readily detected. Several are partly replaced by hematite. The collophane grains show a wide range in color from dark brown to light tan. They also exhibit wide variations in quartz grain inclusions from that of a rare grain to that of very abundant quartz inclusions. The quartz inclusions are subangular to subround. A few smaller collophane grains also can be observed petrographically. One collophane grain consists of two rings of collophane separated by hematite and with a core and surrounding hematite.

Examination of the nine collophane grains by automatic image analysis shows that they have nominal diameters which average 1.06 mm and these compare rather closely with nominal diameters of 100 measured quartz grains in the same section which average 0.92 mm. These figures are near the boundary (1mm) between coarse and very coarse sand.

Inclined Light Examination-

The hematite areas consist of replaced calcite fossil fragments, oolites, and hematite cement. Bryozoa and echinoid fossil fragments have been almost completely replaced by hematite, but their relict forms can be discerned under inclined light. They constitute the major portion of the hematite-rich areas. Many of the fossils consist of red hematite with a coating of blue hematite, but others have been replaced partly or almost entirely by blue hematite. Oolites also are abundant. They consist primarily of blue hematite but some also contain bands of red hematite. Most oolites exhibit little flattening, but some are distinctly flattened. Some are surficial oolites. Some collophane grains are partially replaced by blue hematite, and two grains completely replaced by hematite may have been collophane. The two rings of collophane described under petrography occurs in the central portion of a flattened oolite. Both blue and red hematite form a cementing agent between quartz sand grains, fossil fragments, and collophane grains.

Reflected Light Examination-

Hematite is the only opaque mineral present. It occurs as very small grains in banded oolites, partial replacements of fossil fragments, fracture fillings in quartz sand grains, and as cement between clastic grains. Hematite oolites are characterized by bands of varying grain size. The coarser-grained bands exhibit greater polishing hardness and reflectance. Although some hematite grains are as large as 130 μm , most are 13 μm and less. Rare oolites contain hematite nuclei. Fossil fragments partly replaced by hematite appear very dark in transmitted light, but under reflected light exhibit only scattered patches of re-

placement and mostly fine disseminated hematite plates about 10 μm long and less than one μm thick. Occasional quartz grains are fractured with hematite filling the fractures. Rare clastic feldspar grains are partially replaced by hematite. No other opaque phases, in addition to that hematite, are detectable in the section.

Luminoscope Study-

In addition to the nine large sand size grains of collophane described under petrography, six more grains of about the same size can be observed under the Luminoscope to occur in hematite. The grains are entirely clouded by hematite so that their presence is entirely unsuspected prior to luminoscope study. Examination under high magnification shows that some of these grains consist of two types of collophane: one is light purple and the other light tannish purple in luminescence.

Very abundant collophane is present in tiny grains concentrated in the hematite-rich areas between sand grains. Such areas appear to consist of a very fine hash of quartz, feldspar, etc. which have been invaded by hematite and collophane. The collophane, which can only be seen under the luminoscope, forms thin chemically deposited films on feldspar and quartz grains and occurs as very abundant grains of 10 μm and less (average about 5 μm) and disseminated throughout these areas. Much of the collophane may represent very fine-grained clastic fragment. This type of collophane is intimately intergrown with hematite. This collophane constitutes about 10% of the hematite cement areas between sand grains.

Collophane also occurs in less abundant but larger forms. Although hematite oolites are not as abundant in this ore as compared with some other types, some of the oolites exhibit distinct concentric bands of collophane and rare oolites consist almost entirely of collophane with only minor hematite rings. Some of the sand grains exhibit thin coatings of collophane, about 5-10 μm thick, especially those of feldspar composition. Collophane rarely forms veinlets crossing fractured quartz sand grains. Collophane commonly is associated with some fossil fragments, particularly bryozoan. Such collophane usually is contained within the open chamber of the fossil internal structure, but collophane may also partly replace the bryozoa wall and rare bryozoa are completely replaced by collophane. Collophane modal analysis under the luminoscope was accomplished by counting collophane grains of each type, multiplying by their average grain size (determined by measurements under the luminoscope) and dividing by the total area of the section (695.77 mm^2 ; determined by automatic image analysis). The size of each collophane grain occurring as hematite oolite nuclei and bryozoa replacements were measured individually rather than using an average grain size figure. The amount of sand-size collophane grains was determined by automatic image analysis as described under the section on petrographic description. The total amount of collophane in the section is 0.7511%. Utilizing a figure of 15.03% phosphorous in collophane (determined by electron microprobe), the total amount of collophane accounts for 0.21% phosphorous in this section. Although no chemical analyses were available for the core from which this section was prepared, chemical analyses of iron ores of similar lithology and stratigraphic position run 0.27 to 0.30 phosphorous. In summary, these data indicate that probably all of the phosphorous present in this specimen occurs in the form of collophane.

The abundance and size of each collophane grain type is given below:

<u>Collophane Type</u>	<u>Size</u>	<u>Percent</u>
Sand	1.06 mm diam.	86.44
Nuclei in hematite oolites	210 x 90 μ m	3.53
Small grains in hematite	15 μ m diam.	1.58
Scattered tiny grains in hematite ("plates")	5 μ m diam.	4.21
Fossil fillings	30 μ m	3.27
Fossil replacements	Irregular	0.24
Calcite replacements	30 μ m	0.21
Films on quartz and feldspar clastic grains	5 μ m thick	0.51
		<hr/> 99.99

PTS-78-72.5 Fossiliferous-Sandy Iron Ore

Megascopic Description-

The section is light to medium red with about 35% hematite. One end of the section is pink due to abundant fossils and only a small amount of calcite. Scattered quartz grains constitute about 5% of the section.

Scanning Electron Study-

A single large collophane grain was analyzed to confirm that it and similar grains are calcium phosphate. Additional collophane grains were not analyzed because numerous similar grains in other sections had previously been analyzed.

This section and other sections contain fossil fragments which exhibit a brownish color which is somewhat similar to but distinguishable from the brown color of many of the collophane grains. Trilobite fragments especially show the brown coloration and the marginal portions are darkest brown. This section was selected to analyze such grains for possible phosphorous content. Twelve brownish fossil fragments were analyzed. All of the fragments are calcite and their brownish color is due to partial replacement by hematite as indicated by Ca and Fe in the SEM-EDS. No phosphorous was detected in any of the fossil fragments analyzed.

The very tiny grains of collophane observed beneath the luminoscope to be abundantly scattered through portions of the hematite areas were examined with SEM to determine their shapes and with the SEM-EDS to determine their chemical compositions. Because sericite luminesces light purple somewhat similarly to that of collophane, it was uncertain whether some or even much of what appeared under the luminoscope to be very fine-grained collophane could be sericite. Initially, a large hematite area containing the tiny grains in question was scanned with SEM-EDS. This showed the presence of both phosphorous and potash. Secondly, platy crystals about five micrometers long and black in SEM absorbed current images were analyzed by SEM-EDS and found to be sericite. However, these platy crystals were observed under the SEM at 3000 X to be relatively uncommon. Thirdly, areas of medium gray tone in SEM absorbed current images were analyzed by SEM-EDS and found to be collophane. Examination with the SEM at 3000X shows that such collophane grains are very irregular in shape and are abundantly distributed throughout these hematite areas. In summary, the SEM studies indicate that although some of the very tiny luminous grains are sericite, most are collophane and that very tiny grains of collophane are perhaps even more abundant than those which are detectable with the luminoscope.

Thin coatings about 5-10 μ m thick are commonly present around clastic feldspar grains of sand size and less commonly such feldspar grains exhibit veinlets of collophane traversing them. These occurrences of collophane were detected primarily under the luminoscope but locally can be observed under ordinary light. Because this occurrence is very similar to that of feldspar alteration to sericite and the two minerals exhibit similar luminescent colors, they were examined by SEM-EDS which confirmed that both rims and coatings are calcium phosphate. The veinlets are anisotropic crystalline apatite.

Electron Microprobe Analyses-

The electron microprobe was utilized to study the very fine-grained clustered collophane. Both x-ray scans and spot analyses were performed. Hematite areas which contain the abundant very fine-grained collophane were scanned for their phosphorous distribution. Such scans conclusively showed that the tiny luminescent grains observed under the Luminoscope are collophane and illustrated especially well that they are abundantly distributed throughout those hematite areas.

The chemical composition of the fine-grained clustered collophane also was determined with the electron microprobe. Eight probe analyses of collophane of this type yielded an average of 45.32% CaO, 31.78% P₂O₅ (13.87% P) and 3.19% F.

Descriptions of Polished Thin
Sections of Eufaula Ferruginous Bauxites

1. Irony Bauxite - A.P. Green Sample 1 PTS-APG-1
2. High-Iron Bauxite ("Pink Ore") Harbison-Walker Sample 1 PTS-HW-3
3. Iron Concretion - A.P. Green Sample 8 PTS-APG-6
4. Greenish Bauxite - Didier-Taylor Sample 1 PTS-DT-13
5. Ferruginous Bauxite ("Red Ore") A.P. Green Sample 4 PTS-APG-2
6. Yellow Kaolin Ore - A.P. Green Sample 3 PTS-APG-8
7. Pink Streaky Kaolin Ore - A.P. Green Sample 2 PTS-APG-9
8. Pyrite-Bearing Bauxite - A.P. Green Sample 5 PTS-APG-5
9. Lignite and Pyrite-Bearing Bauxite Didier-Taylor Sample 4 PTS-DT-10
10. Siderite-Bearing Bauxite - A.P. Green Specimen 7 PTS-APG-7
11. High-Grade Bauxite Ore - Didier-Taylor Sample 3 PTS-DT-11
12. Medium Grade Bauxite Ore - Didier-Taylor Sample 2 PTS-DT-4
13. Roasted Irony Bauxite - A.P. Green Sample 1 P.S. 1, 2, and 3
14. High Grade Bauxite Ore - Didier-Taylor Sample 5 PTS-DT-12
15. Iron Concretion - A.P. Green Sample 8 PTS-APG-15
16. Iron Sulfide Concretion - Didier-Taylor Sample 6a PTS-APG-14

Irony Bauxite
A.P. Green Sample 1
McLeod Pit
PTS-APG-1

I. Character of Sample:

This sample is a high iron bauxite from the edge of the best bauxite zone at A.P. Green's McLeod Pit. It is called "irony bauxite" by the mining company, and said to represent as much as 80% of the reserves of the ferruginous bauxite present in the Eufaula bauxite district.

II. Ore Microscopy:

The polished thin section is light yellowish grey with cream, pink, and especially red bands in about 50% of the area. Pisolites are lacking.

The pinkish and red bands contain abundant disseminated grains of hematite. The grains are commonly about 20-60 μm . Most are roughly spherical to ellipsoidal in shape, but some exhibit crude six-sided shapes in polished sections. The grains are dense in the sense that they contain only small amounts of intergrown bauxite. Some of the grains seem to have served as nucleation centers for additional hematite deposition. They exhibit areas of up to 100-200 μm in which finer grained (2 μm) hematite occurs as disseminated grains constituting about 40-50% of those areas.

Hematite also occurs as very tiny grains one to two micrometers across. Although they are very tiny, the wide distribution and abundance (about 2%) makes this form of hematite an important iron mineral variety in this irony bauxite. These tiny grains constitute the red bands along with the 20-60 μm hematite grains, and they are the only form of iron mineral variety present in the pink bands. Many portions of the pink bands contain a much smaller number of disseminated hematite grains about 1-20 μm .

III. Petrography:

Only a few clastic quartz grains can be observed to be scattered through the bauxite. The grains are 120-300 μm across and they are subrounded in shape.

IV. X-ray Diffraction:

Gibbsite and kaolinite are the principal mineral constituents in this bauxite sample. Hematite is the principal iron mineral. Although the x-ray pattern shows a distinct line at $21.6^{\circ}2\theta$ for goethite, this iron mineral is not evident by microscopic examination. No pyrite lines are present.

High-Iron Bauxite
("Pink Ore")
Harbison-Walker Sample 1
Stockpile
PTS-HW-3

I. Character of Sample:

This sample is a high-iron bauxite from the "U" stockpile at the Harbison-Walker plant near Eufaula, Alabama. The ore is called pink ore by the company and it is said to be a typical of much of the ferruginous bauxites in the Eufaula district. It contains 4% Fe.

II. Ore Microscopy:

This section is pink to light reddish in color with a uniform color distribution.

The principal iron grains in this specimen are small disseminated grains of goethite and hematite from one to $13\mu\text{m}$ across. Hematite is the more abundant of the two minerals. Most grains are irregular in shape but some hematite grains are distinctly platy.

Goethite is more abundant in the form of bands $3\text{-}20\mu\text{m}$ thick which coat the inner surface of small vugs which are $15\mu\text{m}$ across. At the base of the goethite bands, goethite gives way to thin bands of hematite and especially to tiny disseminated hematite grains. The hematite grains are up to $6\mu\text{m}$ across, but most commonly only $1\text{-}2\mu\text{m}$ across. They are densely clustered in areas $15\text{-}25\mu\text{m}$ thick about the goethite-lined vugs.

III. Petrography:

Only small clastic grains can be detected in this section. The grains are $60\mu\text{m}$ and less. Identifiable minerals include quartz, some zircon, and rare tourmaline.

IV. X-ray Diffraction:

Gibbsite and kaolinite are the main mineral phases present in this bauxite. Goethite is the only iron mineral detected.

Iron Concretion
A.P. Green Sample 8
Davis Property Stockpile
PTS-APG-6

I. Character of Sample:

This sample is an iron concretion or "iron sore" typical of those present in much of the high-iron bauxites in the Eufaula district. The concretions vary in size from about $\frac{1}{4}$ inch or less up to several inches across. Their shapes are crudely spherical, ovate, elongate tubular, and irregular. This form of iron accounts for much of the iron present in ferruginous bauxites in the Eufaula district.

II. Ore Microscopy:

This section consists of a single large pink to dark red iron concretion which is about $\frac{1}{2}$ -1 inch in diameter. A large part of the concretion was ground away during section preparation. The pink areas contain abundant very fine-grained hematite about 1-2 μ m across. Veinlets, 30-65 μ m across, composed of hematite and goethite traverse the pink area also.

The dark red portions of the concretion are comprised of dense hematite. Although the individual hematite grains are very small, they are concentrated together to form large dense areas which contain only a small amount of bauxite.

III. Petrography:

No large clastic grains are present within the concretion.

IV. X-ray Diffraction:

Several concretions were x-rayed and three portions of one concretion were analyzed separately. The only iron mineral detected in all of the concretions was hematite. The $14.15^{\circ}2\theta$ line for lepidocrosite was absent from all of the x-ray patterns. Hematite constitutes the tiny central crystals as well as the finely granular material throughout the concretion. The outermost portions of the concretions consist of kaolinite, dickite, gibbsite, and boehmite, as well as some hematite.

Greenish Bauxite
Didier-Taylor Sample 1
PTS-DT-13

I. Character of Sample:

This sample is a greenish gray bauxite obtained from a stockpile on the Didier-Taylor property. The bauxite ore in this stockpile analyzes 45-55% Al_2O_3 , 30% SiO_2 , and 2.4% Fe. This ore may run as high as 10% Fe. The company believes that the iron is present in a combined form, i.e., in silicate form, rather than being present as oxides or hydroxides.

II. Ore Microscopy:

The polished thin section is tan to light brown with areas and crude bands of darker yellowish brown color. Pisolites are lacking.

Small grains of goethite, hematite, and pyrite are present. Goethite, the most abundant iron mineral, occurs as tiny grains disseminated throughout the bauxite. Although some grains are as large as 200 μm , most are less than 40 μm and by far the most abundant are only a few micrometers across. Most grains are irregular in shape, but some exhibit cubic shapes relict from pyrite. Hematite is much less abundant. Some hematite grains exhibit elongate crystal forms, but most are irregular in shape. Hematite grains are less than 50 μm and down to the limit of resolution of the microscope (about one micrometer). Some iron grains are an intergrowth of hematite and goethite, with hematite generally constituting the inner portions.

Small pyrite grains also are disseminated throughout the bauxite. They are less abundant than goethite and hematite, but yet they are rather common. The largest pyrite grains are 160 μm across, but more commonly they are 50 μm or less. Most pyrite grains are irregular in shape. No pyrite was observed to form replacement remnants in hematite or goethite grains.

Although siderite is detected by X-ray diffraction, it cannot be detected in the polished thin section.

III. X-ray Diffraction:

Kaolinite and gibbsite are the major minerals present. A strong peak for siderite at $32.0^\circ 2\theta$ and other peaks indicate that it is an important iron constituent in this bauxite. Peaks are present for both goethite and hematite. Weak peaks also are present for pyrite.

Ferruginous Bauxite
("Red Ore")
A.P. Green Sample 4
Davis Property
PTS-APG-2

I. Character of Sample:

This sample was collected from a deposit on A.P. Green's Davis Property. The deposit is a ferruginous bauxite called "red ore" by the company. Although the deposit has a high Al_2O_3 content (70%) has been extensively drilled, and the surface cleared of vegetation, it has not been mined because of its high iron content (nearly 5%). It is said to be typical of about 5% of the reserves of ferruginous bauxite in the Eufaula district.

II. Ore Microscopy:

The section is light reddish brown in color due to the presence of very abundant iron. Pisolites are moderately abundant and many are darker than the groundmass.

Goethite is the principal iron mineral but some hematite, lepidocrocite, and pyrite are present. Goethite occurs in six different forms: 1) Much of the goethite occurs in grains about 35 μm to 130 μm across. Most of these grains are equidimensional in shape but some are distinctly elongate. The grains exhibit a wide variety of degrees of intergrowth with bauxite. Some grains are almost entirely goethite, with only small (about 3-6 μm) inclusions constituting about 5% of each grain and scattered especially toward their edges. Other grains of about the same size and shape contain many more bauxite inclusions, commonly constituting 30-60% of the goethite grains. 2) These, in turn, grade into grains or wispy irregularly shaped areas of goethite that are composed predominantly of bauxite and small percentages of exceedingly fine-grained, from about 5 μm down to the limits of resolution of the microscope (about $\frac{1}{2}$ - 1 μm). 3) Goethite also occurs as thin coatings of small vugs. The coatings are about 7 μm thick and form around areas about 65 to 130 μm in diameter. 4) Goethite also forms rims (5-125 μm thick) and veinlets (5-50 μm wide) around and across pisolites, which are about 1-10 μm across. Some pisolites contain sponge-like goethite distributed through most of the pisolite. 5) Very fine-grained (1-5 μm) dull goethite occurs densely clustered in the central portions of some pisolites. 6) Less commonly, goethite occurs in the form of distinct cubes, a form which it probably has retained by pseudomorphic alteration of original pyrite crystals.

PTS-APG-2

The cubes are about 110 μm on a side and are readily distinguished from the previous five forms of goethite by the absence of bauxite inclusions.

Hematite is much less abundant than goethite and occurs only as solid grains lacking bauxite inclusions. The hematite grains are mostly irregular in shape, but some appear to be platy crystals. The hematite grains average about 30-80 μm , but some are as large as 120 μm and others are only 1-2 μm across.

Thin bands of lepidocrocite (4-5 μm across) occur locally intergrown with goethite.

Very fine-grained (1-4 μm across) pyrite is present but it appears to have been introduced during impregnation and/or polishing. It is disseminated in areas of impregnation plastic.

III. Petrography:

No clastic quartz grains are present in this bauxite. Tiny platy crystals of muscovite are scattered throughout the specimen. The largest is 150 μm long and 50 μm wide, but most are about 15 μm wide. Rare euhedral crystals may be rutile. They are difficult to detect due to the abundant iron present in this specimen. Pisolites are exceedingly abundant in this specimen. A few of the pisolites exhibit well-developed radial acicular textures.

IV. X-ray Diffraction:

Gibbsite and kaolinite are the principal mineral constituents. The presence of goethite is shown by a very strong peak at $2\theta = 21.5^\circ$. The presence of minor hematite is suggested by peaks at 36.4 and 54.5. No pyrite peak is present for the non-impregnated bauxite sample.

Yellow Kaolin Ore
A.P. Green Sample 3
McLeod Pit
PTS-APG-8

I. Character of Sample:

This sample is a yellow kaolin ore from A.P. Green's McLeod Pit. It is representative of a peripheral shell that is present around most all of the bauxite deposits in the Eufaula district. Similar yellow material may run as high as 70% Al_2O_3 where the clay content is lower.

II. Ore Microscopy:

The polished thin sections are yellow to yellowish brown in color. Distinct thin bands are present throughout the specimen. Pisolites are lacking.

Goethite is the principal iron mineral present in this yellow kaolin ore. The goethite grains exhibit a wide range of size from one to 32 μm . Grains from one to 6 μm are the most common. The grains are sparsely distributed throughout the specimen and grains of all the various sizes may be present in any given area. Most of the goethite grains exhibit an irregular shape. An occasional grain exhibits a straight edge belonging to a crystal face. Rare grains have the cubic form of former pyrite from which those grains have altered. The grains do not have inclusions of clay.

Minor hematite grains are present. Some hematite grains exhibit platy shapes.

III. Petrography:

A few subangular quartz grains are scattered throughout the section. The grains are about 50-300 μm across.

IV. X-ray Diffraction:

Kaolinite and gibbsite are the principal phases. Goethite is the only iron mineral present. The typical peaks for hematite at $35.7^\circ 2\theta$ and $49.6^\circ 2\theta$ are very weak. No lines for pyrite are present.

Pink Streaky Kaolin Ore
A.P. Green Sample 2
McLeod Pit
PTS-APG-9

I. Character of Sample:

This sample is a pink kaolin ore from A.P. Green's McLeod Pit. The coloration occurs as pink streaks in a yellowish mass of clay. The sample is a 45% Al_2O_3 kaolin ore that occurs in zones peripheral to bauxite ores in the Eufaula district.

II. Ore Microscopy:

The thin section is mostly light yellow or tan with thin bands one to two mm thick that are pink in color. No pisolites are present.

The principal iron mineral present in this pink kaolin ore is hematite. The hematite grains are sparsely scattered through the specimen in the both the pink bands and in the yellow clay areas. The grains range in size from one to 50 μm . The most abundant grains are one to 7 μm across. Most hematite grains are irregular in shape, but some are euhedral plates about 20 μm long and 3 μm across. Rare grains have 6-sided shapes perhaps relict from pyrite pyritohedrons.

Goethite occurs as minor disseminated grains.

Tiny pyrite grains, 1-13 μm across, are present in local clusters.

III. Petrography:

This specimen is almost completely free of larger clastic grains. Only an occasional quartz grain is present.

IV. X-ray Diffraction:

Kaolinite is the only non-iron phase detected. Although strong peaks for both hematite and goethite would suggest that the two minerals are present in about equal proportions, microscopic examination detects only very small amounts of goethite.

Pyrite-Bearing Bauxite
A.P. Green Sample 5
PTS-APG-5

I. Character of Sample:

This sample is a pyrite-bearing 60% Al_2O_3 bauxite from a stockpile on A.P. Green's Davis Property. Pyrite-bearing concretions are present on the surface of the pile. Ores of this type are said to represent less than 5% of the Eufaula district's bauxite reserves.

II. Ore Microscopy:

The thin section is tan with local small dark brown spots. The specimen is exceedingly porous.

Pyrite, marcasite, and goethite are the iron minerals present in this bauxite specimen. The dark spots are small iron sulfide concretions which have been partly altered to goethite. The central portions of some concretions consist of fine-grained pyrite clustered together to form masses 75 μm or more across. The pyrite contains only a little bauxite. The iron sulfide comprising other concretions is marcasite. Rare spherical masses about 12 μm across exhibit framboidal textures. Both pyrite and marcasite occur as remnants in the cores of concretions which have altered to goethite in the outer portions. Although as much as 70% iron sulfide may remain in some concretions, most have about 10-30% pyrite or marcasite, with remaining portion consisting mainly of goethite.

Goethite also occurs as irregularly shaped small grains disseminated throughout the bauxite. The grains may be as large as 20 μm , but most are 1-3 μm .

Coal macerals are abundantly distributed throughout the specimen. All of the macerals have very low reflectance, and are not distinguishable by variations in reflectance. Some of the macerals are elongated stem-like fragments. Others exhibit cellular internal textures, similar to those typical for fusinite, but they are much less reflective.

III. Petrography:

A few large clastic grains of quartz are present. The largest is 750 μm across. Some of the quartz grains contain very tiny (1-3 μm) fluid inclusions. Scattered tiny plates of sericite are present locally.

IV. X-ray Diffraction:

Gibbsite and kaolinite are the principal phases. The presence of goethite is shown by a strong peak at $21.6^\circ 2\theta$. The typical hematite peaks at $35.7^\circ 2\theta$ and $49.6^\circ 2\theta$ are totally lacking. Pyrite and marcasite were not detected.

Lignite and Pyrite-Bearing Bauxite
Didier-Taylor Sample 4
PTS-DT-10

I. Character of Sample:

This sample is different from most bauxite ores in the Eufaula district in that it contains appreciable lignite and is black in color. Pyrite concretions are said to be abundant in this ore, although we could find none on the dump despite a prolonged search. The ore analyzed 72% Al_2O_3 and contains 0.79% Fe (but it is said to commonly run 2% Fe or more). Mr. Joel Wilson indicated that this ore is unique to the district and that its occurrence is restricted to the one pit which he owns. It was, however, one of the fine-grained iron-rich bauxites which he previously sent to the U.S. Bureau of Mines in Tuscaloosa, Alabama to study for beneficiation testing to decrease the iron content.

II. Ore Microscopy:

Most of the thin section is black in color. Narrow black veinlets traversing the specimen have taken a better polish than the intervening areas. A small portion of the section is lignite-free bauxite.

This section contains a large number of various coal macerals. Cellular-textured forms are very common. Other forms include elongate stem-like forms, dark uncollapsed spores (sporinite), swollen plant wall material (ulminite) and brighter semifusinite particles.

Very few iron mineral grains can be observed under the microscope. Small scattered pyrite grains are locally present and are perhaps the most common of the iron minerals. Rare small grains of hematite and goethite are present, the largest of which is 9 μm across.

III. Petrography:

The bauxite portion of this section contains scattered small clastic quartz grains, some sericite plates, and rare zircon grains.

IV. X-ray Diffraction:

Gibbsite and kaolinite are the principal phases. Lines for goethite and probably for hematite are present. A very low peak, if any, is present at $56.3^\circ 2\theta$ for pyrite.

Siderite-Bearing Bauxite
A.P. Green Specimen 7
Davis Property Stockpile
PTS-APG-7

I. Character of Sample:

This sample was obtained from a stockpile on A.P. Green's Davis Property. This ore was believed to contain the iron mineral, siderite, because tiny rhomb-shaped crystal can be observed megascopically to occur in the bauxite.

II. Ore Microscopy:

The polished thin sections are tan to light brown in color. The bauxite exhibits a blocky fracture pattern with the edges of the blocks showing a medium brown color. Several small black spots are present locally.

No siderite is present in either of the two thin sections of this specimen. Hematite is the most abundant iron mineral. It occurs in grains of a wide variety of sizes. Most common are tiny irregularly shaped hematite grains about 1-6 μm . Other hematite grains are platy or exhibit elongate euhedral shapes and are as large as 45 μm . Irregularly shaped goethite grains, less than about 8 μm across, are less common. Tiny irregularly shaped pyrite grains are present but not common.

III. Petrography:

Several siderite plates are present in this section. The specimen lacks large quartz grains. This bauxite contains abundant dark pisolites, 50-600 μm , which are scattered throughout. Such pisolites are not formed under reflected to contain more goethite grains than the surrounding bauxite groundmass but only show a general slightly brighter reflectance over the entire pisolite.

IV. X-ray Diffraction:

Kaolinite and gibbsite are the principal phases. Goethite has the most distinct lines for any iron mineral, and the characteristic hematite peaks at $35.8^{\circ}2\theta$ $46.9^{\circ}2\theta$ are not well pronounced. No siderite lines were detected in X-ray analyses of hand picked grains, but siderite was detected in X-ray analyses of heavy liquid concentrates prepared from this sample.

I. Character of Sample:

This sample is a 70% Al_2O_3 and 30% SiO_2 bauxite ore which was estimated to contain about 1½% Fe (the estimate may be on the high side). This high-grade bauxite ore was examined to compare the character of its low iron content with that of the ferruginous bauxites.

II. Ore Microscopy:

The thin section exhibits a light tan or buff color. Tiny red brown spots are scattered throughout most of the specimen.

Small disseminated goethite and hematite grains are present throughout the bauxite specimen as relatively minor constituents. The irregularly shaped grains are mostly 1-15 μm across, but some are as large as 30 μm .

Pyrite is locally present as tiny grains and as concretions 75-160 μm across. They exhibit all stages of alteration to goethite. Pyrite also occurs as framboidal clusters. The nearly spherical framboids are 25-35 μm in diameter and are clustered together with other pyrite spheres and minor amounts of subsequently crystallized marcasite.

A few quartz sand grains about 100-400 μm across are scattered through the bauxite specimen.

III. Petrography:

Scattered quartz grains are present but not especially abundant in the bauxite. They range in size from about 25 μm to 400 μm . The grains are subrounded.

IV. X-ray Diffraction:

Gibbsite and kaolinite are the principal phases. Goethite is the principal iron mineral, but weak peaks at $35.9^\circ 2\theta$ and $49.8^\circ 2\theta$ indicate that hematite also is present. Peak heights suggest that the goethite: hematite ratio might be 2:1 or more.

I. Character of Sample:

This sample is a medium grade bauxite ore typical of those with which little problem with iron content is experienced. The bauxite ore in this stockpile analyzes 55-62% Al_2O_3 , and 0.78% Fe. This ore is said to commonly run as much as 3% Fe.

II. Ore Microscopy:

The polished thin sections are tan with dark veinlets which can be observed megascopically. The principal iron mineral observable under ore microscope is goethite. Goethite occurs in three forms. Most commonly it is present as tiny disseminated grains about 2 μm across. Some goethite forms discontinuous veinlets about 1 μm wide. Least commonly, goethite forms six-sided euhedral crystal shapes, about 25 μm across, probably relict from crystalline pyrite.

Pisolites are mostly lacking from this bauxite sample. Those pisolites present contain disseminated goethite, and rare specular hematite grains.

Very tiny grains (1-4 μm) of pyrite are present in portions of this section, but their character suggests that they have been introduced during impregnation and/or polishing of the section. All of the pyrite grains appear to be fragmental and they are very much concentrated near "veinlets" of impregnation plastic which contain larger fragmental particles of polishing grit and rare larger pyrite.

III. Petrography:

Rare rounded clastic quartz grains as large as 300 μm across are sparsely scattered through the specimen. Muscovite plates are scattered throughout as a minor constituent.

IV. X-ray Diffraction:

Gibbsite and kaolinite are the principal mineral constituents in this bauxite sample. The principal iron mineral is goethite. The presence of minor pyrite is shown by a very small peak at $56.7^\circ 2\theta$.

Roasted Irony Bauxite
A.P. Green Sample 1
P.S. 1, 2, and 3

These polished sections were prepared from a roasted specimen of irony bauxite taken from the edge of the bauxite zone at A.P. Green's McLeod Pit. The specimen is equivalent to that described under PTS-APG-1. The specimen was roasted at 650° C for 20 hours to reduce the iron minerals iron oxides that might take a better polish and better exhibit their textural character.

The roasted specimen contained iron primarily in the form of hematite. The roasted hematite has been converted to metallic iron and wüstite. Metallic iron is the most common form. It occurs as tiny bright grains 1-2 μm across. The grains are clustered in areas 30-50 μm across, some of which exhibit 6-sided shapes. Wuestite occurs in grains about 15 μm across. Smaller grains, about 1-6 μm , of metallic iron and wuestite are scattered throughout the specimen.

This roasted product does not provide an improved means of studying the textures of the iron minerals in this irony bauxite sample.

High-grade Bauxite Ore
Didier-Taylor Sample 5
PTS-DT-12

I. Character of Sample:

This sample is 75% Al_2O_3 and 11% SiO_2 bauxite ore which was estimated to contain about 0.5 to 1% Fe_2O_3 . This high grade bauxite ore was examined for the purpose of comparing its iron mineralogy with that of the ferruginous bauxites.

II. Ore Microscopy:

The thin section exhibits a gradation in color from tan to pinkish or light brown. Local areas are outlined by thin white rims.

Pyrite and goethite are the principal iron minerals. Pyrite occurs as a few scattered concretions about 125 μm across. Pyrite also has an important occurrence as framboidal spheres. The spheres range from 7 to 42 μm in diameter and consist themselves of smaller spheres about 1 μm across. They exhibit all stages of alteration to goethite. A large portion of the spheres have gone entirely to goethite.

Goethite also occurs as tiny grains disseminated throughout the bauxite. The grains are 1-20 μm across. Most appear to be irregular in shape, but some are spherical and others are elongate.

III. Petrography:

Several quartz grains and one zircon grain are present in the bauxite. The grains are subangular to subround. The largest is 140 μm across.

Iron Concretion
A.P. Green Sample 8
Davis Property Stockpile
PTS-APG-15

I. Character of Sample:

This sample is an iron concretion or "iron sore" typical of those present in many of the high-iron bauxites in the Eufaula district. Concretions vary in size from about 1/4 inch or less up to several inches across. Their shapes vary from crudely spherical to elongate and tubular. Concretions account for an important portion of the iron present in ferruginous bauxites in the Eufaula district.

II. Ore Microscopy:

This section consists of a single large concretion. Megascopically the concretion consists of three zones: 1) an interior porous portion with blue gray hematite and many small areas of red hematite and many small areas of red hematite, 2) an exterior portion of dense blue hematite, and 3) reddish brown bauxite outside the concretion. Under the microscope, areas one and two differ only in the amount of dense blue hematite. The hematite occurs in a feathery to cellular texture with elongate areas oriented in a radial fashion extending from the center towards the edges of the concretion. The areas consist of very fine-grain hematite.

Minor goethite occurs as a thin coatings (25 μm thick) on the outside of the hematite concretions and as local yug-fillings within the concretion. Part of the goethite radial fibrous and exhibits yellow internal reflections.

III. Petrography:

Although portions of the concretion exhibit a very low reflectance indicative of bauxite(?), none of these areas transmit light.

Iron Sulfide Concretion
Didier-Taylor Sample 6a
PTS-APG-14

I. Character of Sample:

This sample is an iron sulfide concretion or "iron sore" typical of pyrite-bearing bauxites in the Eufaula district. The concretions commonly are an inch or two across. Their shapes are quite variable from crudely spherical to more elongate. Some consist of thick coarsely crystalline coatings partially enclosing finer grained portions in a tubular form.

II. Ore Microscopy:

This section consists entirely of pyrite. The pyrite occurs as a massive intergrowth of mostly anhedral to partly subhedral grains average about 125 μm across, but show a wide range of grain size with the largest grains generally occurring toward the outer margins. Most pyrite grains are anhedral and form a granular texture. Locally, the pyrite grains exhibit six-sided shapes, mostly cuts through the pyritohedron, and some four-sided cuts through euhedral cubes. Most of the euhedral to subhedral pyrite crystals developed as early crystallization centers and they were coated by subsequent pyrite rims. The coarsest pyrite grains are elongate and as much as 1 3/4 cm long. Locally, thin coatings 25 μm thick, form a layered sequence with texture somewhat similar to that of colloform texture.

III. Petrography:

Very little material is present in this specimen that transmits light. Bauxite occurs only locally between the centers or groups of pyrite grains and tends to form triple point - like areas that are triangular and concave.

The Luminoscope and Cathodoluminescence

Because the Luminoscope is a relatively new instrument and its previous utilization has been primarily limited to certain types of geologic studies, a brief discussion is included here to acquaint the reader with the general nature of the Luminoscope and cathodoluminescence (CL). Although it has long been known that the electron beam of the electron microprobe causes certain materials to luminescence, and that property has been utilized to locate and center the beam, only in the last ten years or so has there been commercially available an instrument which exploits that property. The instrument at UMR is manufactured by Nuclide Corporation in Acton, Mass., but similar instruments are available elsewhere (e.g., Leitz). An electron beam is produced by a cathode tube, and, in contrast to the normal use of the electron microprobe, the beam is spread out sufficiently to cover the entire area viewed under the microscope. An evacuated sample chamber will accept two normal size thin sections or polished thin sections. Polished sections must be about one-quarter inch thick or less to be examined with the Luminoscope. Loose fragmented material also can be studied, but it is generally better to mount the material in a plastic and prepare a polished thin section.

For some minerals (e.g., calcite, dolomite) a voltage of 8 KV is adequate to cause their CL, other minerals (e.g., quartz) require about 12 KV. Magnetic deflectors are used to focus the beam. It was found that the collophane luminesced best at 12 KV or higher. The sample chamber is mounted on the stage of a normal petrographic or reflecting microscope. Because the intensity of luminescence is much less than that of transmitted or reflected ordinary light, exposure times required for photography are much longer. The CL photomicrographs included in this report required 3 to 7 minutes for low magnifications and 12 minutes or longer for the higher magnifications. Furthermore, the exposures must be taken by repeated one-minute segments to avoid burning the specimen. These exposure times are for a fast film (Ektachrome ASA 400) "pushed" to ASA 1600 for development.

Previous investigations with the Luminoscope have involved primarily the study of porosity reduction in limestones by the petroleum industry. In this application, the Luminoscope provides the means to distinguish sparry calcite or dolomite which has filled pores from clastic and fossil carbonate grains. Luminescent study of sedimentary rocks also commonly helps distinguish crystalline overgrowths from the clastic grains they coat, and appears to constitute a unique means to distinguish authigenic feldspar (nonluminescent) from clastic feldspar. Other geologic applications have involved the recognition of apatite, zircon and feldspar grains in igneous and metamorphic rocks. Recent studies of dolomite in Mississippi Valley-type ore deposits have shown that fine-banding resulting from repeated periods of deposition can be distinguished under the Luminoscope. The writer knows of no previous studies of beneficiation problems with the Luminoscope.

It is important to realize that the CL of a mineral is usually a function of its trace element content rather than being due to its major constituents. This means that one usually cannot predict whether a given mineral in a given ore deposit or rock will luminesce. Only by actual study of a specimen does one determine if CL will help in a given research project. In the writer's experience, the luminoscope has proved useful in three of ten research projects for which its use was attempted. Furthermore, because the color of luminescence is a function of the trace elements present and their ratios of abundance, the color also is not predictable in advance of actual study. Thus, although some of the collophane in the Birmingham iron ores luminesces light purple, other collophane types luminesce light blue. The different colors probably reflect variations in ratios of various rare earth elements and possibly manganese. Despite the above restrictions on predictability, some minerals contain certain trace elements commonly enough that they often exhibit certain CL colors. For example, calcite and dolomite usually exhibit yellow-orange and orange-red CL due to Mn^{2+} . Potash feldspar commonly luminesces bright blue due to Ti^{4+} and apatite usually luminesces light blue due to rare earth elements. No studies previous to the present one have noted luminescence in collophane. Some minerals, have an intrinsic CL due to defect structures or the host crystal structure. Zircon always exhibits an intrinsic white CL.

Most of the ore minerals do not exhibit CL. Those ore minerals which do exhibit CL include: cassiterite, scheelite, powellite, diamonds, collophane, and bastnaesite.

Additional details regarding instrument design and operational procedure can be obtained by writing Donald J. Marshall, Nuclide Corporation, 916 Main Street, Acton, Mass. 01720.

D.

Appendix D.

Selected X-ray Diffractograms of Eufaula
Ferruginous Bauxites

1. Irony Bauxite - A.P. Green Specimen 1
2. High-Iron Bauxite - Harbison-Walker
Specimen 1
3. Greenish Bauxite - Didier-Taylor Specimen 1
4. Ferruginous Bauxite ("Red Ore") A.P. Green
Specimen 2

