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R.J.B. KENNA

GRADE CONTROL IN RELATION TO LITHOLOGY AND CHEMISTRY

IN THE NORTHAMPTON SAND AND FRODINGHAM IRONSTONES

M.Sc. THESIS, 1965



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INTRODUCTION

Among the most recent detailed accounts of the Northampton Sand Ironstone and the Frodingham Ironstone are those of the Geological Survey, published as Memoirs by Taylor (1949) and Hollingworth and Taylor (1951), and Whitehead et al (1952), respectively. These Memoirs deal with the ironstones from many aspects, and provide much useful information for companies engaged in mining them. Variations in lithology and chemistry within the Northampton Sand Ironstone have been related to stratigraphical subdivisions within the Ironstone, and to rock types within these subdivisions. The Frodingham Ironstone has been less fully described as far as chemical and lithological relationships are concerned, although the principal types of ores have been recognised by Davies and Dixie (1951).

Taylor (1949) makes the following statement, when referring to the Northampton Sand Ironstone, and it can well be applied to the Frodingham Ironstone also: "As the exploration and development of the ironstone field proceeds by boring and by the opening of new workings it is most essential that full and accurate data - both chemical and petrographical - should be collected". Recent drilling, together with data obtained from opencast and underground



mining operations within the properties of the United Steel Companies Limited, has yielded further information relating to the Northampton Sand and Frodingham Ironstones. Of particular interest is that information relating to chemical and lithological variation.

The present thesis is an essay in economic geology in that it seeks to show how lithological and chemical data, and their inter-relationships, can be used to control the grade of iron ore mined by opencast and underground methods. Reliable control of the quality of ore supplied to the blast furnaces is fundamental to the economic success of an industry based on low-grade ironstone. The aim of the present work is to show how this is and can be achieved in the operations of the United Steel Companies Limited.

Information of academic value which has emerged from the United Steel Companies Limited drilling and mining operations is also referred to, this including the more recent interpretations of structure, relating to both ironstone fields, the presence of calcite conoliths in the Northampton Sand Ironstone, the apparent decrease in the proportion of Type A Ironstone (Davies and Dixie, 1951) in the present Frodingham Ironstone workings, and the fact that the Frodingham Ironstone is less variable in nature than indicated by Elliot (1945).

Mining methods are described and techniques of grade control are discussed, including drilling, sampling, assaying, presentation of data, and control during mining.

To avoid disclosing confidential information, the exact geographical location of grade maps is not shown.

Data in the text and in diagrams drawn from other works is acknowledged in the text.

SKETCH MAP ~ NORTHAMPTON SAND IRONSTONE FIELD.

Based on Hellingworth and Taylor 1951.

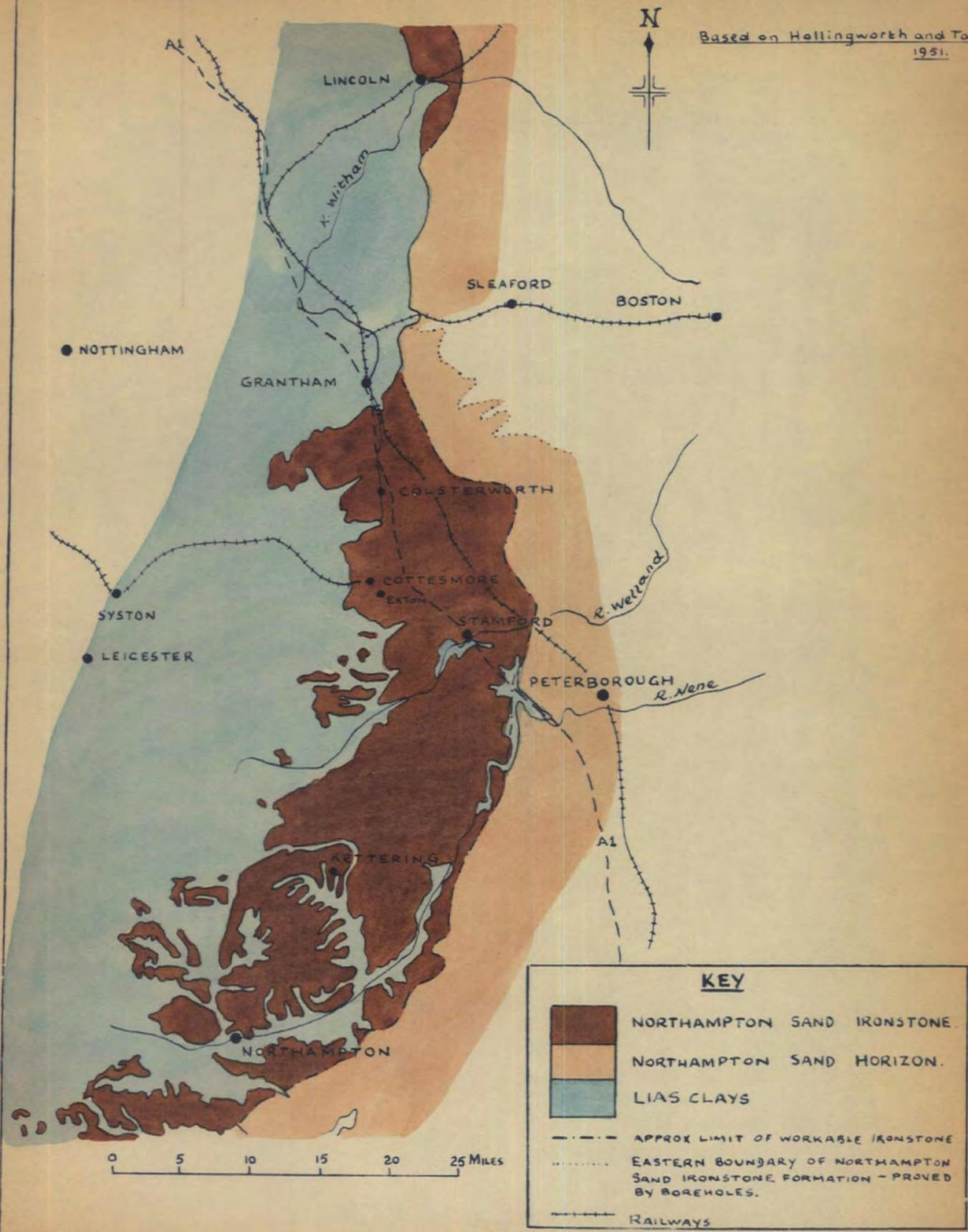


FIG 1.

NORTHAMPTON SAND IRONSTONE MINING
OPERATIONS

The United Steel Companies Limited mining operations are centred in South Lincolnshire, close to the village of Colsterworth, eight miles south of Grantham, and in Rutland, at Exton Park bordering on the village of Exton, six miles north-west of Stamford (Fig. 1). Apart from one underground mine at Colsterworth, all the mining is opencast. Opencast mine faces and the location of the underground mine are shown in Fig. 3.

Much of the area around Colsterworth, north to Little Ponton and east to Burton Coggles and Bitchfield has been explored with boreholes spaced on a 400 feet grid, as has much of the area around Exton and Cottesmore. To the east of the A.1 road the remaining area in Fig. 3 has been explored with boreholes spaced on a one kilometre grid coincident with that of the Ordnance Survey.

2.A GEOLOGY OF THE NORTHAMPTON SAND IRONSTONE FORMATION

I. Review of Previous Work

Previous accounts of the Northampton Sand Ironstone Formation have been given by Hallimond (1925), who demonstrated its sedimentary

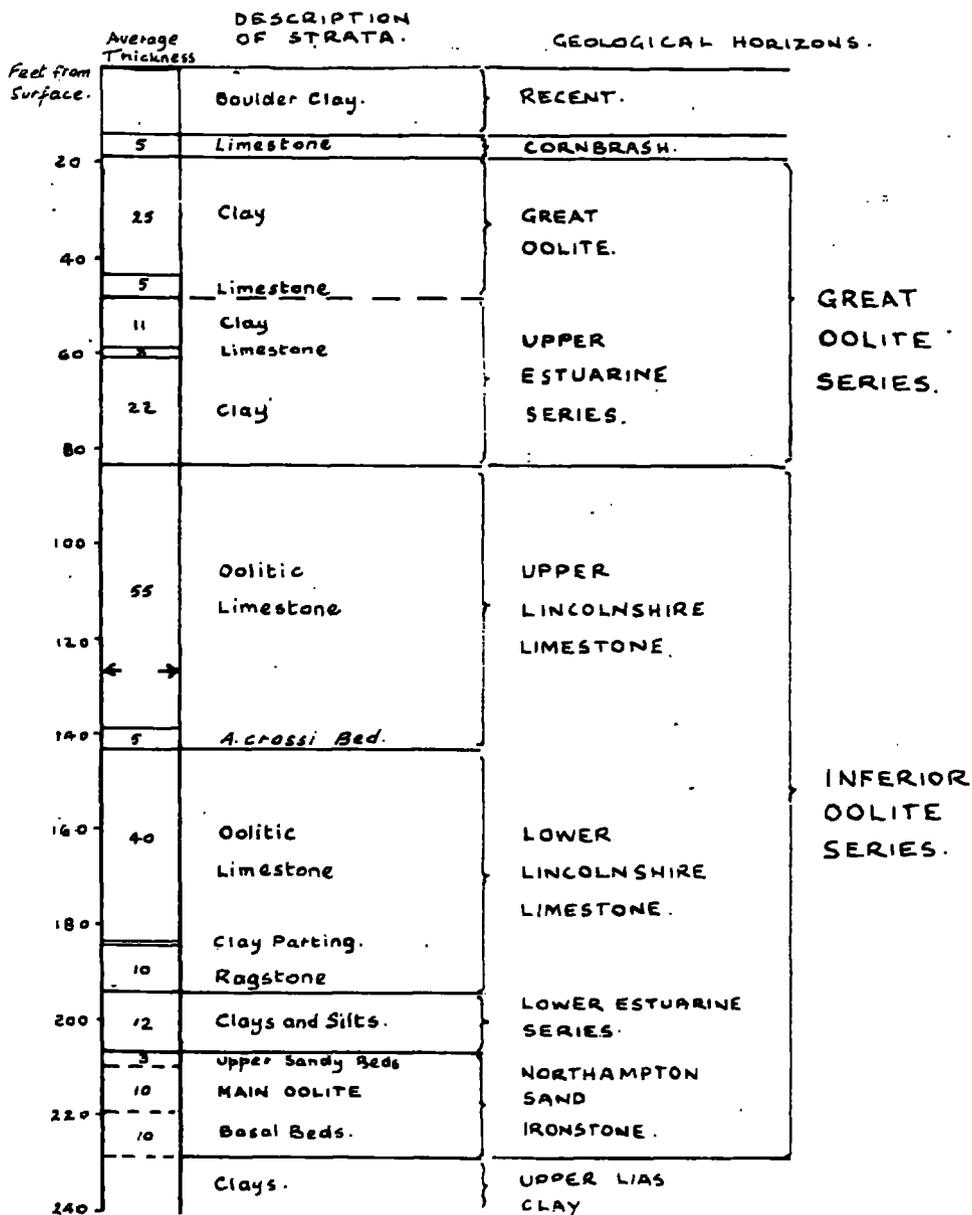
origin. Detailed petrological and stratigraphical accounts have been given by Taylor (1949) and Hollingworth and Taylor (1951) as Geological Survey Memoirs. General accounts of petrology and beneficiation problems were presented at the Geological Congress, Algiers, by Taylor, Davies and Dixie (1952). Particular mineralogical aspects of the ironstone have been elucidated by Andrews (1950), Cohen (1952) and by Youell (1948 and 1958). Several reports relating to petrology, lithology and chemistry have been written by United Steel Companies Limited geologists, including the writer; these are unpublished.

Under the headings Stratigraphy, Structure, Lithology and Mineralogy, the writer has included certain fundamental observations similar to those made by previous workers.

II. Stratigraphy

The Northampton Sand Ironstone Formation, generally oolitic, is present throughout most of Northamptonshire, Lincolnshire and the adjacent parts of Leicestershire and Rutland (Fig. 1). The writer has also observed pockets of the Formation in boreholes near Appleby, Scunthorpe, where it occurs as a ferruginous sandstone or sandy oolite. The Formation is located at the base of the Inferior Oolite Series (Jurassic) (Hollingworth and Taylor, 1951, p.3), and its position in the Geological Sequence is shown in Fig.2. Within the arc extending from Northampton, through Wellingborough and Stamford to Grantham, the horizon is often of economic value as a low-grade iron ore. At its margins, the ironstone becomes more siliceous

COLSTERWORTH AREA.
TYPICAL GEOLOGICAL SUCCESSION
EAST OF THE RIVER WITHAM.



← → Maximum overburden encountered in present opencast mines

Vertical Scale: 1 inch = 40ft.

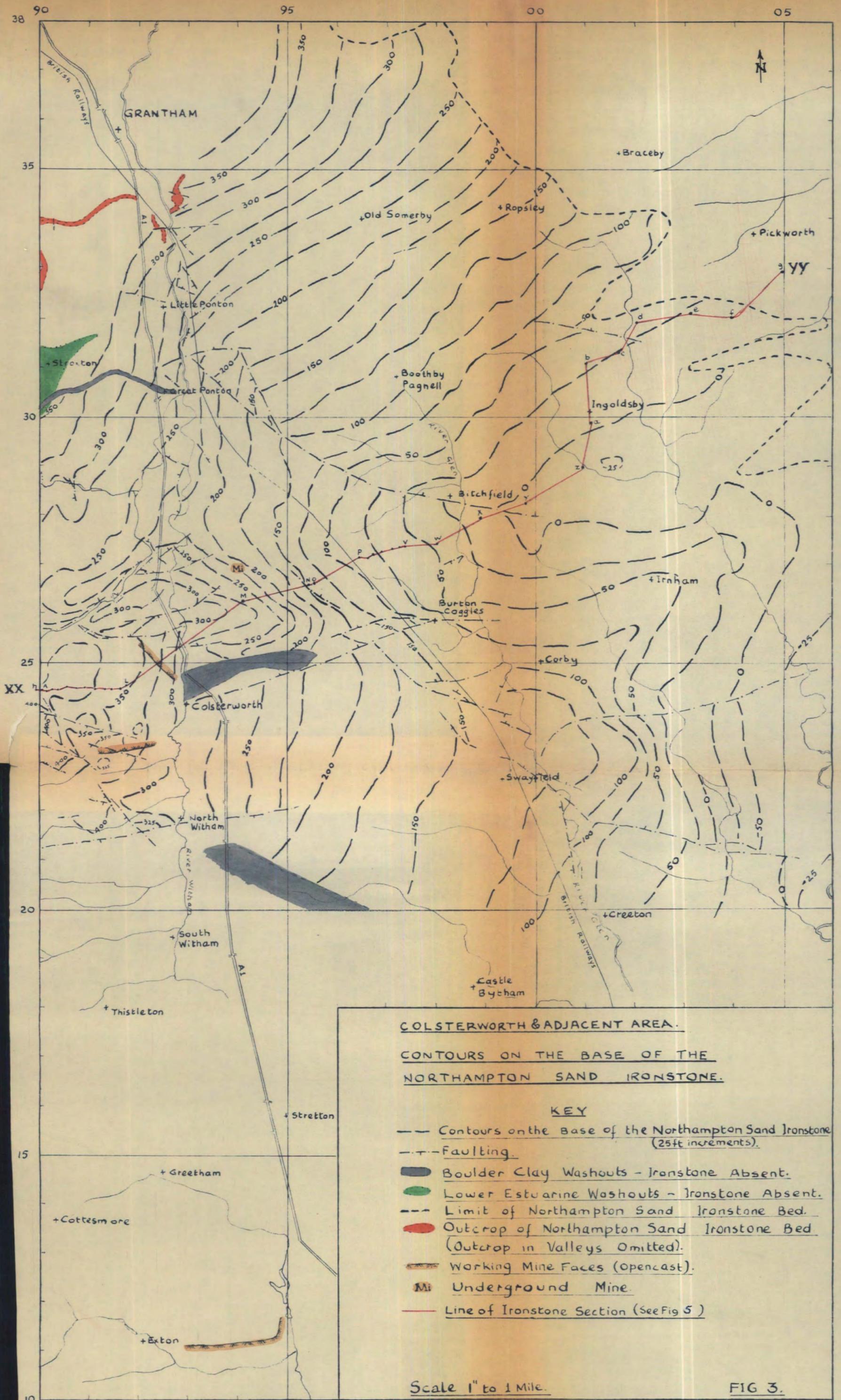
FIG 2.

and sand grains may predominate over ooliths. The eastern boundary of the ironstone in part of the area being considered is shown in Fig.3, and here Lower Estuarine clays and sands rest directly on Lias clays.

In the area about Colsterworth and Exton the ironstone may be superceded by topsoil only, however, in the present workings it may be overlain by various thicknesses of Lower Estuarine clays and silts, Lincolnshire Limestone and boulder clay - in places boulder clay may rest directly on the ironstone. To the east of Colsterworth the depth of the overlying strata may exceed 250 feet. The ironstone may be absent due to Lower Estuarine washouts or boulder clay washouts.

The Ironstone Formation is made up of a series of beds and lenses composed of various mineralogical types of ironstone, differing in chemistry. The most important mineralogical type is a sideritic chamosite oolite. Whereas the full thickness may be of economic importance, generally beds of substandard ironstone occur at the top or at the base.

The Geological Survey has divided the Formation into five main stratigraphical groups (Table 1), and it is emphasised by Hollingworth and Taylor (1951, p. 39) that a continuous succession is never found: erosion, non-deposition and leaching are some of the factors responsible for this. The groups reflect major differences caused during sedimentation, principally differences in physico-chemical environments. Variations in physico-chemical environment may give lateral as well as vertical variations in mineralogy and chemistry.



THE GEOLOGICAL SURVEY SUB-DIVISION OF THE NORTHAMPTON SAND IRONSTONE FORMATION

(After Taylor, 1949, and Hollingworth and Taylor, 1951)

	SUB-DIVISION	THICKNESS	GENERAL LITHOLOGY
5	UPPER CHAMOSITE-KAOLINITE GROUP	0 - 7 feet	Kaolinite and chamosite oolites and sandstones and mudstones
4	UPPER SIDERITE MUDSTONE-LIMESTONE GROUP	0 - 8 feet	Siderite mudstones, variably oolitic or sandy. Occasional sideritic sandstones or sideritic limestones.
3	LOWER CHAMOSITE-KAOLINITE GROUP	0 - 5 feet	Chamosite and kaolinite oolites. Locally secondarily sideritised. Infills washouts in beds beneath and interbedded with the main oolitic ironstone group.
2	MAIN OOLITIC IRONSTONE GROUP	0 - 14 feet	Mostly oolites and shelly oolites. Oolites of chamosite or limonite. Matrix mostly siderite but accompanied locally by calcite or chamosite. Lenses of siderite mudstone may be present. The uppermost beds are commonly shelly and carry pellets and other detrital fragments.
1	LOWER SIDERITE MUDSTONE-LIMESTONE GROUP	0 - 10 feet	Sideritic mudstones, siltstones and sandstones, sideritic limestones, calcareous sandstones and sandy limestones - shelly: phosphatic nodules at base.

TABLE 1

At the present time, most of the ironstone of economic importance is won from the Main Oolitic Ironstone Group of the Geological Survey. In the vicinity of the United Steel Companies Limited workings, the ironstone can be split conveniently into three main stratigraphical units, being equivalent to some of the Geological Survey's groups. These units reflect the economic value or grade of the ironstone.

III. Structure

The Jurassic strata, including the Northampton Sand Ironstone Formation, has a gentle dip to the east or south-east, although locally these directions may vary. The contours on the base of the ironstone are shown in Fig. 3, and the information is plotted from the United Steel Companies Limited borehole data.

Small faults and folds are present locally, and in the present workings one fault with a throw of 20 feet has been encountered. Much jointing is present in the Lincolnshire Limestone and in the ironstone, and, in the more disturbed areas, clay- and debris-filled gulls may contaminate the ironstone; the latter condition is particularly evident in areas affected by cambering or valley bulging (Hollingworth and Taylor, 1951, p.31).

2.B GENERAL LITHOLOGY AND MINERALOGY OF THE IRONSTONE

I. Lithology

Unoxidised ironstone is generally grey, dark bluey-grey and green; the upper and lower beds are generally light grey.

PLATE 1



Unweathered Northampton Sand Ironstone

Upper half of mine face south-west of Colsterworth village.
The foot rule is resting on a 3 inch bed of siderite mudstone
- the marker band separating the Upper Beds from the Main
Oolite of United Steel Companies Limited subdivisions.

PLATE 2



Box-structures in Oxidised Northampton Sand Ironstone

Part of mine face south-west of Colsterworth village - shell beds close to the top of the United Steel Companies Limited Main Oolite subdivision. Note shell casts below the right hand edge of the foot rule.

Oxidised ironstone is characterised by its rich brown colour. A face of ironstone is often massive-bedded and generally blocky in appearance, the boundaries of the blocks being formed by joints and bedding planes (Plate 1). In the middle and upper beds the blocks are 2 to 3 feet across, whilst in the lower beds the blocks are more massive, and may be 10 feet across, or more. In the oxidised ironstone, (generally under shallow cover), box-structures are characteristic; these have been formed as a result of percolating rainwater (Plate 2). The boxes, with weathered layers of compact and friable ironstone, frequently have an unoxidised core, and other lithological features are often obliterated.

II. Mineralogy

The better quality ironstone is generally an oolite, in which ooliths with an iron content of about 30 per cent. are set in a matrix of siderite with an iron content of about 40 per cent. In the poorer quality ironstone, quartz grains, shell fragments and less iron rich ooliths (e.g. kaolinite and calcite) take the place of iron-rich chamosite ooliths, and chamosite or calcite may replace the matrix siderite. The main mineralogical constituents of the ironstone are shown in Appendix I, together with their chemistry, and their mode of occurrence is shown in Table 2.

In unoxidised ores, the main minerals are chamosite, siderite, calcite and quartz; kaolinite and limonite may also be important. The main minerals of oxidised ores are goethite, limonite, kaolinite and quartz. Taylor (1949, p. 53) has detailed the main chemical

MINERALS AND MICROSTRUCTURE WITHIN THE NORTHAMPTON SAND IRONSTONE

MATRIX

DETRITUS

MINERAL

Unweathered Ores

<p><u>SIDERITE</u></p>	<p>May replace chamosite of oololiths, quartz in sand grains and calcite in shell fragments. In places is spherulitic.</p>	<p>Often most important iron-bearing mineral - various textures. May form a siderite mudstone. May replace other constituents of matrix.</p>
<p><u>CHAMOSITE</u></p>	<p>Dominant constituent of oololiths; diameter of oololiths 0.2 mm. - 0.5 mm., ellipsoidal, concentric structure (re-worked oololiths at base - structureless), green, greeny-brown.</p>	<p>Common - may be interstitial to siderite.</p>
<p><u>LIMONITE</u></p>	<p>Grains, nuclei of oololiths, part of oololiths.</p>	
<p><u>KAOLINITE</u></p>	<p>In places part or main constituent of oololiths, mainly in Upper and Basal Beds.</p>	<p>Quite common.</p>
<p><u>QUARTZ</u></p>	<p>Particularly abundant in Upper and Basal Beds, usually 0.1 mm. - 0.3 mm., in Basal Beds 0.05 - 0.25 mm. in diameter. Rather angular.</p>	
<p><u>PYRITE</u></p>	<p>Nodules at base.</p>	<p>Finely disseminated.</p>
<p><u>MAGNETITE</u></p>	<p>Mainly fine grains in shells and oololiths.</p>	
<p><u>COLLOPHANE</u></p>	<p>Nodules and pebbles - particularly at base.</p>	
<p><u>MICAS & FELDSPARS</u></p>	<p>In poor quality types.</p>	
<p><u>CALCITE</u></p>	<p>Shell fragments, oololiths at base.</p>	<p>Finely crystalline - particularly at base.</p>
<p><u>CLAY MINERALS</u></p>		<p>In poor quality ironstone.</p>
<u>Weathered Ores</u>		
<p><u>HAEMATITE</u></p>		<p>Rare - as a result of oxidation of siderite mudstone bands.</p>
<p><u>QUARTZ</u></p>	<p>Abundant in Upper and Basal Beds, size as above. Residual.</p>	
<p><u>CLAY MINERALS</u></p>		<p>Present.</p>
<p><u>CALCITE</u></p>	<p>May be redeposited locally, in the form of veins, filling joints.</p>	
<p><u>LIMONITE & GOETHITE</u></p>	<p>Oololiths brown, size as above.</p>	<p>Common, replacing chamosite and siderite. (In intensely weathered parts, box structures may consist entirely of clayey limonitic ironstone).</p>

changes resulting from weathering, and these are summarised thus:

- (i) An increased iron and slightly increased silica content due to a general decrease in volatiles, particularly carbon dioxide.
- (ii) Oxidation of iron from the ferrous to the ferric state.
- (iii) Decrease in lime and alumina contents, ascribed to leaching and solution, accompanied by some redeposition of calcite and alumina-bearing minerals (allophane and aluminium sulphates) on joint faces and cavities. Analyses by the United Steel Companies Limited do not show conclusively that alumina is removed on oxidation.
- (iv) Iron redistribution - particularly in box-structures.

2.C PETROLOGICAL CLASSIFICATION OF THE IRONSTONE

I Detailed Mineralogical Classification

For detailed mineralogical work, the method of description used by the Geological Survey (Taylor, 1949, p. 5) should be adhered to. Adjectival prefixes are used for the groundmass minerals, and substantival prefixes for the minerals of the ooliths. For example, a sideritic chamosite oolite is a rock consisting of chamosite ooliths enclosed in a sideritic matrix.

The Geological Survey's classification attaches much importance to groundmass, and it is on the variation of groundmass constituents that the Geological Survey has based its stratigraphical groupings.

A complete classification, more comprehensive than that of the Geological Survey, is based on the following (after Davies

et al., 1964, unpublished):

- (i) State of oxidation,
- (ii) Proportion of detrital constituents to matrix: based on modern sedimentary petrology classifications, values of 10 per cent, and 50 per cent. are used to differentiate between rock types, e.g. a rock with less than 10 per cent. detritus of sand or silt grade (0.01 - 2.0 mm) is classified as a mudstone, whilst rocks with up to 50 per cent. of detritus are referred to as mudstones with a prefix indicating the most abundant type of detritus present, e.g. oolitic mudstone.
- (iii) Nature of matrix (e.g. sideritic, chamositic, calcitic, kaolinitic, clayey).
- (iv) Nature of detritus (e.g. ooliths, shell fragments, sand or silt)
- (v) Nature of ooliths (e.g. chamosite, limonite, kaolinite, calcite)
- (vi) Other characteristics (e.g. replacement textures, such as spherulitic siderite, etc.).

II Simplified Classification of the Ironstone - Log Types

The previously described classification systems, which can only be applied with accuracy after microscopic examination, tend to be cumbersome when logging mine faces and large numbers of borehole cores. A simplified classification system, shown in Table 3, was introduced by Davies and Dixie (1948, unpublished). Their system places an emphasis on the detrital constituents, and particular types of ironstone are classified by letters; it is seen from Table 3 that there is much variation in the matrix constituents within each type.

The system now used by the writer is based on that of Davies

THE CLASSIFICATION OF THE NORTHAMPTON SAND IRONSTONE (SHOWING VARIATION IN

DETRITUS AND MATRIX OF UNWEATHERED IRONSTONE)

(From Davies and Dixie - 1948, unpublished)

M A T R I X

<u>Normal</u>	<u>Calcareous</u>	<u>Chamositic</u>
Almost all Siderite	Siderite with Calcite	Siderite with Chamosite

	TYPE X	
	TYPE XY	
	TYPE Y	
	TYPE Z	

Chamosite ooliths

Chamosite ooliths
with some sand grains

OOOLITHS AND
DETRITAL
CONSTITUENTS

Sand grains

Kaolinite bearing
chamosite ooliths

and Dixie (1948), and the ironstone types are again classified by letters, referred to by the writer as 'Log Types'. Whereas Davies' and Dixie's classification refers to unweathered ironstones, that of the writer caters for weathered ironstones; for example, type X of Davies and Dixie (1948) refers to a chamosite oolite, whilst type X of the writer refers to a limonite or a chamosite oolite. The writer's classification, shown in detail in Table 4, allows for more types to be distinguished, it also allows for reference to other distinguishing features within types. For borehole core and face logging, colour keys relating to the log types and to the state of oxidation are also useful.

Detrital constituents, apart from silt-grade quartz and crystalline calcite present towards the base of the ironstone, are easily visible with a hand lens. Visible calcite or obviously limey bands are referred to by the letter C. The presence of silt-grade quartz with calcite towards the base can be inferred with experience. It has been found convenient by the writer to combine reference letters to give further information; for example, XKy would represent a sandy, kaolinite oolite, XB would represent a dominantly oolitic rock with easily visible lenses of blue siderite mudstone. The dominant characteristic always appears first in the combination, and capital letters help to emphasise major characteristics. Pebble beds and shell beds are also recorded, as is the state of oxidation.

Table 5 shows a borehole logged in accordance with this simplified classification, together with the partial chemical analysis and a more detailed mineralogical description of ore

SIMPLIFIED CLASSIFICATION SYSTEM OF THE NORTHAMPTON SAND IRONSTONE

LOG TYPES

X,XX	Abundant or very abundant ooliths*
Xk	Abundant pale (kaolinitic) ooliths* (Z of Davies and Dixie)
Xy	Ooliths and quartz grains present*
Y	Abundant visible quartz grains*
C	Calcite (detrital or as matrix)
V	Few or no ooliths or visible quartz grains - clayey appearance, Upper Beds
W	Few or no ooliths or visible quartz grains - clayey appearance, Basal Beds
MIT	Basal transitional beds, much mica, no ooliths
B	Siderite mudstone - often 'flinty'
Sph	Sphaerosiderite present
P	Pebbles or nodules
Su	Visible pyrite
∪ ∪ ∪	Markedly shelly
(CY)	Calcite and/or inferred silt grade quartz shown in brackets - generally Basal Beds
□	Unoxidised
□	Oxidised

The above symbols may be used separately or in combination.

* Based on Davies and Dixie, 1948, unpublished.

BOREHOLE LOGGED IN ACCORDANCE WITH THE SIMPLIFIED CLASSIFICATION SYSTEM. THE STATE OF OXIDATION, PARTIAL CHEMICAL ANALYSIS AND DETAILED MINERALOGICAL DESCRIPTION IS SHOWN.

FT.	LOG TYPE	OXIDATION	TOTAL				DETAILED MINERALOGICAL DESCRIPTION
			Fe	CaO	SiO ₂	S	
0-53							Sphaerosiderite.
1	XKY + Spn		31.2	1.2	22.6	1.25	Chamositic sandy chamosite kaolinite oolite.
2			29.0	1.7	31.0	0.22	Sphaerosideritic sideritic chamositic kaolinitic sandy oolite.
3	Y		20.3	1.6	49.5	0.07	Oxidised sideritic kaolinitic sandstone.
4			23.8	2.9	33.6	0.04	Sideritic chamositic kaolinitic sandstone.
5			23.5	3.7	34.1	0.08	
6	YX		25.4	2.0	29.0	0.01	
7	YK		29.8	3.9	20.3	0.04	Sideritic oolitic sandstone.
8	XK		34.4	4.8	10.1	0.07	Sideritic chamosite oolite.
9	X		35.0	4.9	9.7	0.01	
10			34.8	5.3	8.8	0.01	
11	+ XK		34.8	4.8	9.5	0.01	
12			35.8	4.5	10.2	0.29	Sideritic chamositic chamosite kaolinitic oolite.
13			33.0	5.7	12.0	0.15	Chamositic sideritic chamosite oolite.
14			32.8	4.0	16.5	0.74	
15	YCK + B		20.0	15.5	21.6	0.17	Calcitic sideritic chamositic oolitic shelly sandstone.
16			15.4	20.3	22.6	0.23	
17	Y(C) +		16.1	13.0	32.0	0.41	
18	YC		11.4	22.1	27.7	0.51	
19	Wc		20.7	16.5	14.8	0.93	Calcitic sideritic chamositic calcarenite. (some calcite oolites)

CN71.

SEE TABLE 4 FOR EXPLANATION OF SYMBOLS & COLOURS

TABLE 5

types. The mineralogy of the oolites is not always clear, neither is the mineralogy of the matrix when this system is used, and the variation of matrix and detritus within the main types has been illustrated in Table 3. Generally, however, in unoxidised ore, log type X is a sideritic chamosite oolite; type W is fine grained and very variable in composition.

Photomicrographs of sectioned ironstone are shown in Plates 3, 4, 5 and 6. They are classified in detail, and log types are also shown.

2.D IRONSTONE SUBDIVISIONS IN ACCORDANCE WITH UNITED STEEL COMPANIES LIMITED CRITERIA

I General

In the Colsterworth area, the United Steel Companies Limited subdivide the ironstone into three main units which are generally easily recognised and reflect the ore grade. They are (1) Basal or Lower Beds, (2) Main Oolite, and (3) Upper or Sandy Beds. Davies and Dixie (1948, unpublished) refer to three subdivisions, but do not comment on the recognition of boundaries. The relationship of these subdivisions to those of the Geological Survey is shown in Table 6, together with their normal thickness range and grade characteristics in the Colsterworth area.

Subdivisions can be determined by using the simplified classification system, marker bands and other characteristics. Boundaries between subdivisions may be transitional and, in places, less clearly defined. This is true for the area north

RELATIONSHIP BETWEEN GEOLOGICAL SURVEY SUBDIVISIONS OF THE NORTHAMPTON SAND IRONSTONE AND UNITED
STEEL COMPANIES LIMITED SUBDIVISIONS (COLSTERWORTH AREA)

<u>Geological Survey Subdivisions (Hollingworth and Taylor, 1951)</u>	<u>United Steel Companies Limited Subdivisions</u>	<u>Usual Thickness</u>	<u>Grade Characteristics</u>
Upper Chamosite-Kaolinite Group			
Upper Siderite Mudstone- Limestone Group	Upper or Sandy Beds	3 - 4 feet	Generally poor.
Lower Chamosite-Kaolinite- Group			
Main Oolitic Ironstone Group	Main Oolite	7 - 12 feet	Good.
Lower Siderite Mudstone- Limestone Group	Basal or Lower Beds	5 - 10 feet	Usually poor.

of Great Ponton, the area south of Thistleton, and the area east of Bitchfield and Burton Coggles, where the Main Oolite may be difficult to separate from the Upper or Sandy Beds. In the Exton area, demarcation between the Main Oolite and the Upper or Sandy Beds is often difficult. Furthermore, in places it is difficult to separate accurately the Upper or Sandy Beds from the overlying Lower Estuarine sands and silts, and Basal or Lower Beds may be transitional with Lias clays.

The following occurrences may affect easy demarcation of the boundaries:

- (i) transitional beds, or facies,
- (ii) phases of non-deposition,
- (iii) intercolations of other typical lithologies,
- (iv) redistribution of some constituents after deposition - diagenetic,
- (v) erosion of beds,
- (vi) washouts, for example overlying beds may channel downwards, and Lower Estuarine and boulder clay washouts occur locally.

II Demarcation between the Ironstone and Underlying and Overlying Beds

(a) Basal Boundary

In the normal succession, the basal boundary separating the ironstone from the blue Lias clay is marked by a pebble or nodule bed (Hollingworth and Taylor, 1951, p.12) and in places by a mudstone conglomerate. These normally underlie generally hard limestones (including calcarenites) or calcareous mudstones. Where

transitional type beds occur, micaceous clays and mudstones (in places sideritic) may be interbedded with the hard limey beds, and phosphatic nodules and pebbles may be present throughout the transitional beds, but they frequently occur in greater abundance at the base of the transition zone. Pyrite nodules may occur throughout the transitional beds but are again more abundant at the true base. Oolitic debris may also be present within the transitional beds, as may lenses of chamositic clayey oolite.

(b) Upper Boundary

Whilst the junction between the Lower Estuarine Series and the ironstone is often easily apparent, there are places where accurate separation is difficult. Sideritic sandstones of the ironstone may have a leached appearance and may easily be confused with the light-coloured sands and silts of the overlying Lower Estuarine Series. In places it is difficult to distinguish between the limonite stained sandstones and siltstones, which may occur at the base of the Lower Estuarine Series, and the oxidised upper sandy and silty beds of the ironstone. Hollingworth and Taylor (1951, pp. 14 and 39) state that demarcation between Northampton Sand and Lower Estuarine Series may be locally indefinite, and that kaolinitic oolites and sandstones of the ironstone may pass gradually upwards into sands and silts of the Lower Estuarine Series.

In the workings west and north-west of Colsterworth village and in boreholes to the north and east, the dark blue and grey Lower Estuarine shales and clays which may have a thin shelly band

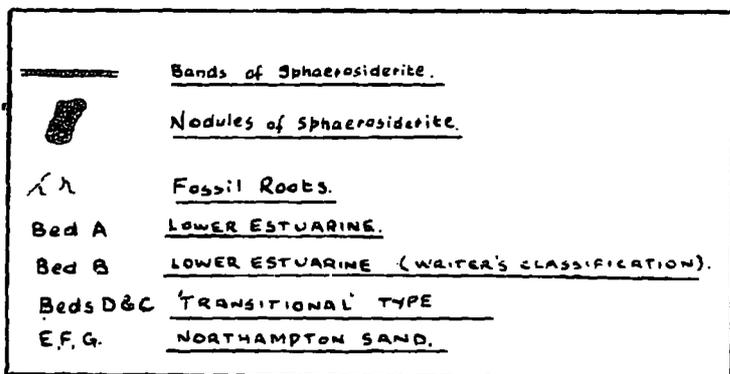
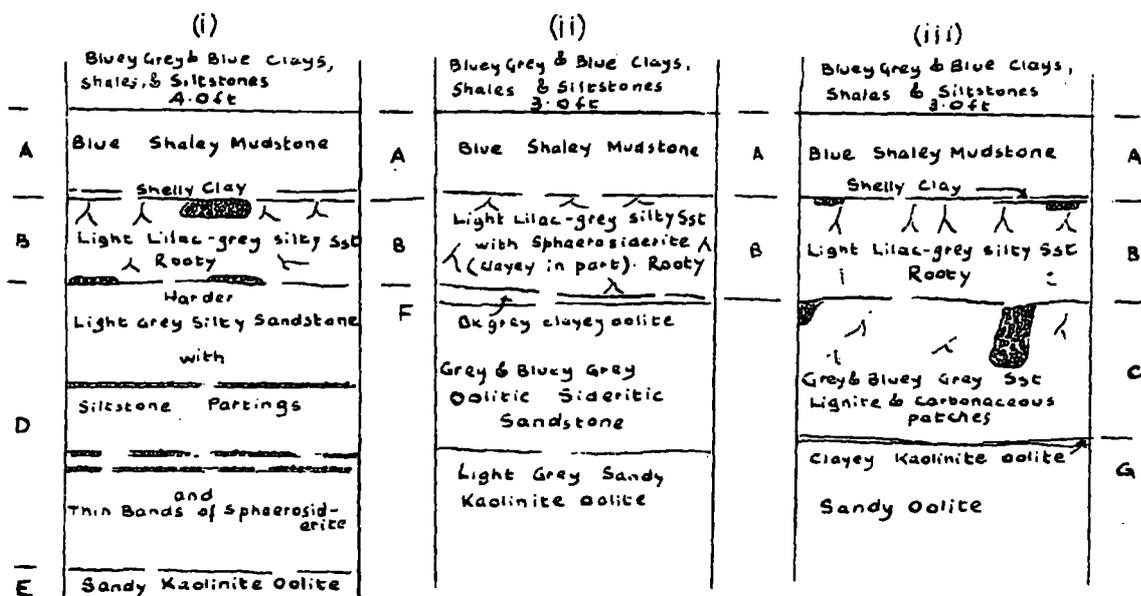
at the base, are underlain by a lilac-grey bed, generally between 9 inches and 2 feet thick, which the writer and other United Steel Companies Limited geologists consider to be related to the Lower Estuarine Series. The nature of this bed varies, it may be essentially a sandstone or a siltstone and often it becomes clayey. It generally contains fossil roots and spherulitic siderite (Fig.4). The spherulitic siderite may be scattered irregularly, particularly in the clayey rock, but it is more often found concentrated in nodules. Taylor (1949, pp.33 and 88) suggests that sphaerosiderite occurs in rocks of the Chamosite-Kaolinite Groups, or below the Lower Estuarine white sand, extending down into these beds; however, sphaerosiderite would appear to be present within the Lower Estuarine Series also.

This lilac-grey bed may overlies oolites, or sandstones which in places are sideritic or kaolinitic, and where sandstones occur demarcation may be difficult. In fact, these sandstones may be transitional Lower Estuarine-Northampton Sand facies. Examples of sections showing an indefinite boundary between the Lower Estuarine Series and the Northampton Sand are shown in Fig.4, and it is seen that beds underlying the lilac-grey bed may be rooty and contain spherulitic siderite; these beds may represent part of Taylor's Chamosite-Kaolinite Groups (1949, pp. 29 - 35).

South towards Exton Park the lilac-grey bed is absent, and the Lower Estuarine Series becomes sandier, particularly towards the base where it is softer, and separation is generally simple. Now that some or all of the top beds of the ironstone are discarded and most of the ore is won from the Main Oolite subdivision,

COLSTERWORTH AREA

VERTICAL SECTIONS - MINE FACE, N.W. OF COLSTERWORTH VILLAGE
SHOWING INDEFINITE LOWER ESTUARINE/NORTHAMPTON SAND BOUNDARY.



Vertical &
Horizontal Scale: $\frac{1}{2}$ " to 1 FT.

FIG 4.

these transitional beds and obscure boundaries present fewer problems.

III Demarcation of the Ironstone Subdivisions, and Marker Bands

(a) Criteria Used

The simplified classification system previously referred to (pp. 10 - 12) is useful when subdividing the ironstone, but a more effective subdivision is possible in the Colsterworth area by using 'Marker Bands' in conjunction with this. Other characteristics such as colour and hardness are also useful. Table 7 shows how the subdivisions and boundaries may be recognised.

(b) Basal or Lower Beds

These massive beds are equivalent to the Geological Survey's Lower Siderite Mudstone-Limestone Group (Taylor, 1949, and Hollingworth and Taylor, 1951), and their normal thickness is between 5 and 10 feet. They may, however, be thicker or thinner, or even absent, and the thickness of this subdivision bears no apparent relationship to the thickness of the overlying beds. The main log types would be Y, C and W, and the subdivision is uneconomic when considered as a separate unit.

The beds are generally obvious by their light bluey-grey colour and their hardness. They may take the form of limestones (including calcarenites), shelly sandstones, siltstones and mudstones, and they are less affected by oxidation than the overlying beds.

COLSTERWORTH AREA

NORTHAMPTON SAND IRONSTONE SUBDIVISIONS (UNITED STEEL COMPANIES LIMITED)

ROCK TYPES AND BOUNDARY MARKERS

United Steel Cos. Ltd. SUBDIVISION	MAIN ROCK TYPES	LOG TYPE	NOTES	BOUNDARY MARKERS AND NOTES
LR. ESTUARINE SER. (basal)	Grey silty clay and lt. grey siltstones or sandstones		May contain sphaerosiderite in nodules and lenses. Often rooty.	
<u>NORTHAMPTON SAND IRONSTONE</u>				
UPPER OR SANDY BEDS	Grey sideritic or kaolinitic sandstone Grey-green oolitic sandstone Blue siderite mudstone	Y Yx, Yxk B	Current bedded in places, may be rooty. Brown when oxidised. 'Flinty'.	Colour change, may be erosion surface. Continuous over considerable distances.
MAIN OOLITE	Grey kaolinite oolite Green - brown-green chamosite oolite Grey-green sandy kaolinite oolite in places	Xk X Xky	Pebble bed at top (pebbles of oolitic ironstone, kaolinitic mud and sideritic mud). Shelly beds near top May be current bedded Brown when oxidised - box structures.	Continuous over considerable distances, lt. grey when unweathered - pebbles white when oxidised. Shell beds continuous over considerable distances. Slight colour change
BASAL OR LOWER BEDS	Blue-grey sandy kaolinite oolite Blue-grey sideritic sandstone Lt. and dk. grey fine-grained rock - varying composition. Mostly sideritic calcitic chamositic shelly sandstones and sandy limestones. Micaceous shelly sandstones, clays and siltstones Pebble bed - phosphatic nodules and pyrite nodules and cubes	Xky Yx W, or Wc, (Y)c, (C)y, Etc. MIT P	Relatively soft Blue patches of sideritic mud. May be oolitic Ooliths of kaolinite and calcite may be present. May contain pebbles. Mudstone conglomerate in places may contain derived Liassic fossils & pebbles	Thin siderite mudstone in eastern area. Colour change and bedding plane. Harder beds and massive. Becoming softer, except where hard mudstone. Continuous over considerable distances.
UPPER LIAS CLAY	Blue clay			

The upper part of the subdivision may be less hard than the lower beds, since it is often a sandy oolite. Lenses and bands of siderite mudstone may be present, and more oolitic bands may occur locally. In places, particularly east of Colsterworth, a fairly persistent, thin, dark blue siderite mudstone band runs immediately below the Main Oolite. Towards the base of the subdivision, thin bands of mudstone or conglomerates of mudstone may be interbedded with micaceous clays. As previously mentioned, the base is marked usually by a mudstone conglomerate or a pebble and nodule bed, which may also be markedly pyritic.

In greater detail, microscopic examination will show that the matrix of some rocks may be composed of considerable amounts of siderite, together with some chamosite. Where the beds are partly oolitic, ooliths may be of chamosite, kaolinite or calcite. Plate 3(i) shows calcite replacing chamosite ooliths, and similar occurrences have been observed within the Basal Beds in the Colsterworth area. This might be regarded as evidence against theories suggesting that the ooliths in these ironstones were originally calcitic (Cayeux, 1909, 1922, and Deverin, 1940, 1945). A photomicrograph of a calcarenite from the Basal Beds is shown in Plate 3 (ii).

(c) Main Oolite

This subdivision is equivalent to the Main Oolitic Ironstone Group of the Geological Survey (Taylor, 1949, and Hollingworth and Taylor, 1951), but may include part, or all, of their Lower Chamosite-Kaolinite Group. The normal thickness is between 7 and

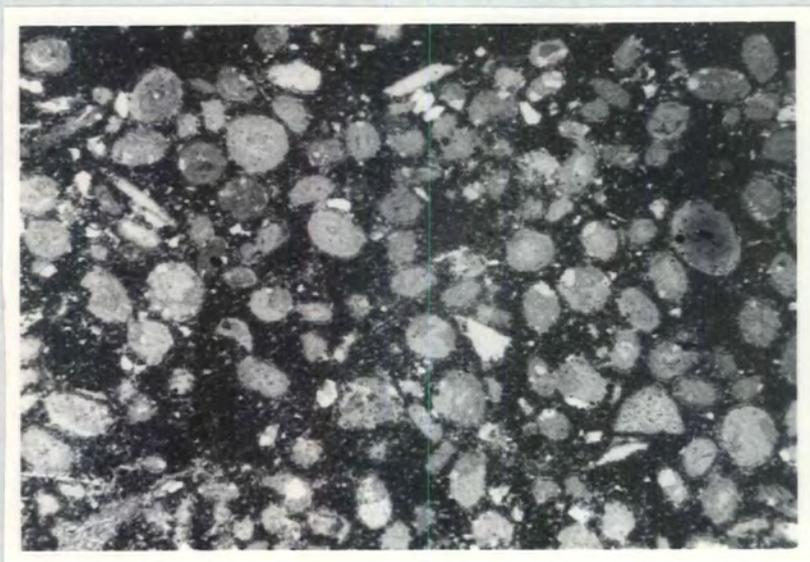
PLATE 3

NORTHAMPTON SAND IRONSTONE

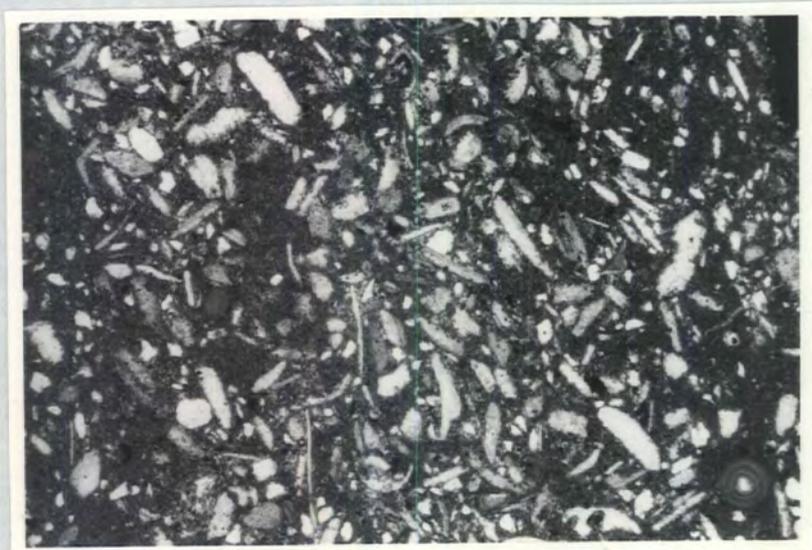
Photomicrographs from rocks in United Steel Companies Limited

Basal Beds

(Ordinary transmitted light X 15; depths are from top of ironstone).



(i) Borehole C, 18.0 feet, Chamositic sideritic sandy oolitic calcarenite (Wxc). Some of the ooliths, of relatively coarse calcite, have cores and layers of pale green chamosite, suggesting replacement by calcite of this mineral.



(ii) Borehole V, 18.0 feet, Sideritic chamositic calcarenite (Wc). The detritus is mainly of comminuted shell material, although there is some quartz sand and a few pale chamosite ooliths.

12 feet, but the beds may be thicker or thinner or absent. The Main Oolite consists often of five or six massive beds which may be traced over considerable distances laterally. Lensing is evident, and current bedding may be present in the upper part. When unoxidised, the upper and lower beds of this subdivision range in colour from grey to green and brown. When oxidised, these beds are rich brown in colour and exhibit box-structures. The beds would normally be logged as type X.

The base of the Main Oolite may be marked by an obvious bedding plane, and the lower greeny-brown or bluey-green beds of the Main Oolite are generally easily separable from the grey Basal Beds below the bedding plane.

The top of the Main Oolite can be separated from the overlying subdivision by using two important marker bands. The Main Oolite is generally overlain by a quite persistent bluey-grey, 'flinty' siderite mudstone, (probably the compact massive siderite mudstone at the base of the Geological Survey's Upper Siderite Mudstone-Limestone Group, Hollingworth and Taylor, 1951, p.39), generally between 1 inch and 6 inches thick, and this is often underlain by a pebbly or conglomeratic bed about 9 inches thick, (the pelley, shelly oolite or detrital rock at the top of the Geological Survey's Main Oolitic Group, Taylor, 1949, p.14, and Hollingworth and Taylor, 1951, p. 39). The pebbles may be of kaolinite or siderite mudstone, and may be oolitic. In the unoxidised state the pebble bed is generally light grey and the ooliths are often pallid. When oxidised, the pebble bed has a

mottled appearance, the pebbles weathering out as light grey or reddish blobs. In places, a thin, non-pebbly bed of oolite may occur between the overlying siderite mudstone and the pebble bed. Towards Great Ponton in the north and Bitchfield in the east the pebble bed becomes less evident, and between North Witham and Exton in the south, it is rarely well developed.

The pebble bed is generally shelly, and the beds below it are often markedly shelly to a depth of 3 to 4 feet, (Taylor refers to these shelly beds in which the fossils are preserved as casts, 1949, p.14). Where the overlying siderite mudstone is absent, the pebble bed alone will indicate the top of the Main Oolite, and where both these marker bands are absent, the top of the shell beds will be close to the top of the Main Oolite. The shell beds appear less evident in the areas mentioned above, where the pebble bed is less evident also, although there is no apparent reason for this.

In the absence of the overlying siderite mudstone, the pebble bed and the shell beds, demarcation can be made where the density of ooliths appears to increase, and where visible quartz is absent, as in the areas about Great Ponton in the north and Exton Park in the south.

At Exton Park a fairly persistent siderite mudstone band occurs within or at the top of log type X ironstone. Where type X beds overlie this siderite mudstone, it is suggested that there has been a return to a Main Oolite type of sedimentation in the upper subdivision (i.e. the Upper or Sandy Beds).

The main rock types in the Main Oolite subdivision are

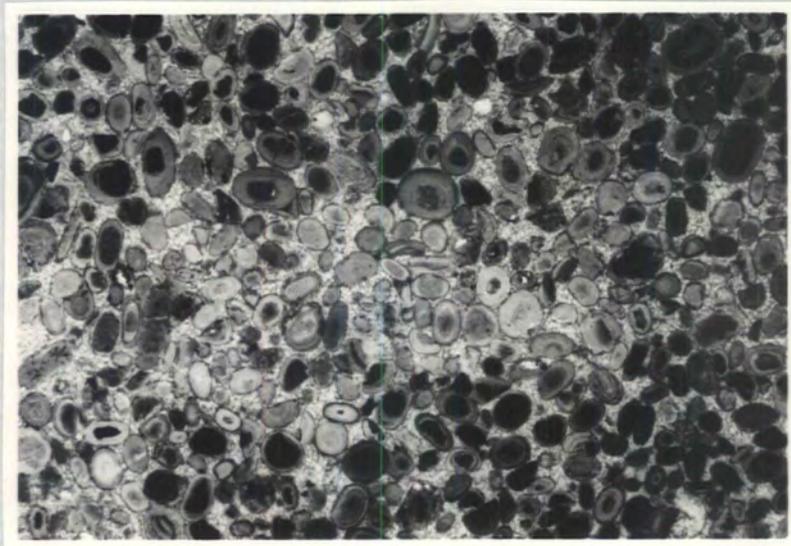
PLATE 4

NORTHAMPTON SAND IRONSTONE

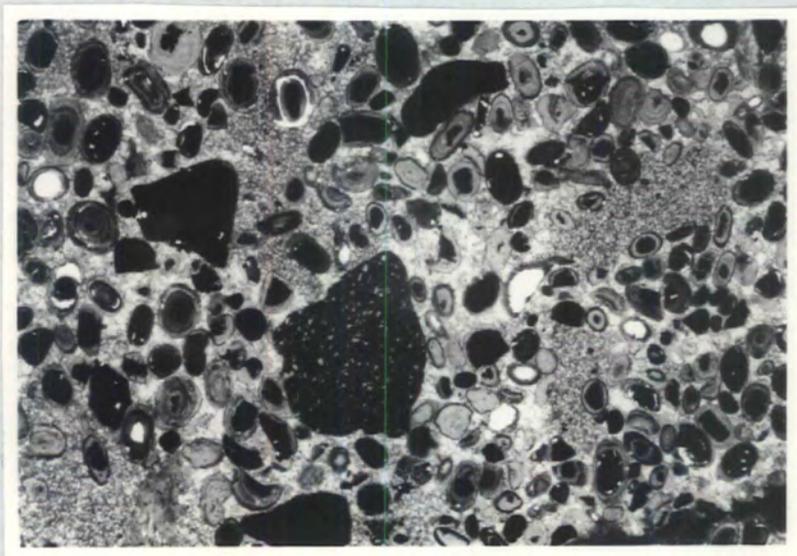
Photomicrographs from rocks in United Steel Companies Limited

Main Oolite

(Ordinary transmitted light X 15; depths are from top of ironstone).



- (i) Mine face south-west of Colsterworth. Sideritic chamosite limonite oolite (XX). Chamosite and limonite ooliths are set in a predominantly sideritic matrix.



- (ii) Borehole P, 7.8 feet, Chamositic sideritic oolitic mudstone (XP). The ooliths are of chamosite and limonite and there are occasional pebbles of oxidised chamositic mudstone and silty mudstone.

sideritic chamosite oolites (Taylor, 1949, p.14 refers), and the uppermost and lowermost beds may contain considerable amounts of chamosite in the matrix, and in places they may be quite sandy; they may also contain kaolinite ooliths. Towards the base of the Main Oolite, primary limonite ooliths (i.e. the ooliths were incorporated in the rock in their present state - the limonite not being due to subsequent weathering) may be present, and lenses of siderite mudstone are more abundant. Other variations may include an increase of calcite or kaolinite in the matrix, and lenses containing more detrital quartz may be present. When oxidised, both ooliths and matrix may be converted to limonite and goethite. Two photomicrographs of types occurring in the Main Oolite are shown in Plate 4.

(d) The Upper or Sandy Beds

These beds represent the upper three groups of the Geological Survey. In thickness and petrology this is the most variable subdivision. The beds are generally about 3 or 4 feet thick, but may be thicker or thinner, or even absent; evidence of current bedding may be present. The base of the subdivision in the Colsterworth area is usually marked by the bluey-grey 'flinty' siderite mudstone referred to above in (c), and in some areas this mudstone apparently splits into an upper and lower portion, separated by about 6 inches of sideritic sandstone. Demarcation between this subdivision and the Lower Estuarine Series has already been mentioned (p. 14). Over much of the area the beds appear lighter in colour than the underlying Main Oolite and overlying Lower Estuarine Series.

The main rock types are sandy oolites, sideritic sandstones,

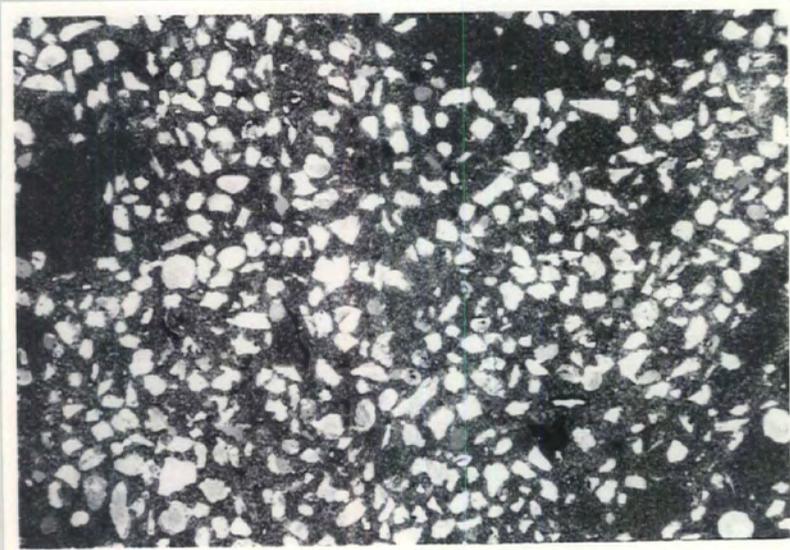
PLATE 5

NORTHAMPTON SAND IRONSTONE

Photomicrographs from Rocks in United Steel Companies Limited

Upper Beds

(Ordinary transmitted light X 15; depths are from top of ironstone)



(i) Borehole S, 2.7 feet, Sideritic sandstone (Y).
There are some sideritic mudstone pockets.



(ii) Borehole C, 5.5 feet, Siderite mudstone (B).
Some sand grains are present.

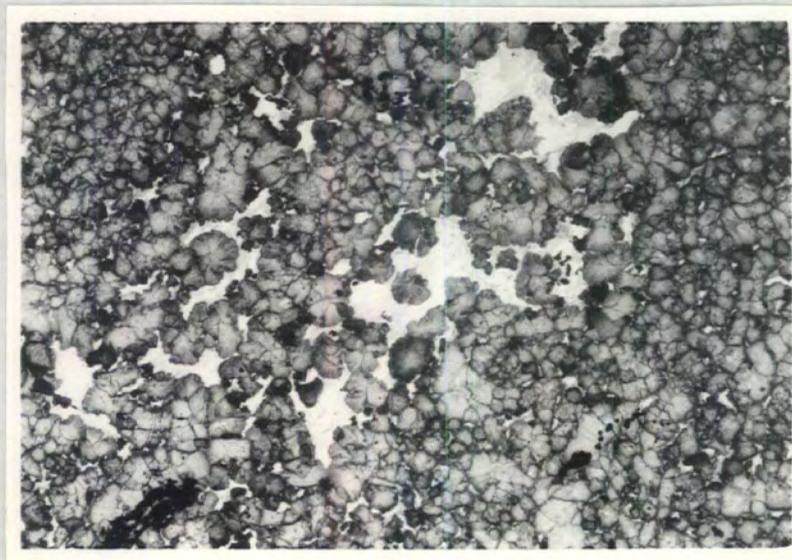
PLATE 6

NORTHAMPTON SAND IRONSTONE

Photomicrographs from rocks in United Steel Companies Limited

Upper Beds

(Ordinary transmitted light X 15; depths are from top of ironstone).



- (i) Borehole N, 0.2 feet, Sphaerosiderite (Sph).
There are interstitial pockets of colourless kaolinite and some secondary pyrite.



- (ii) Borehole M, 0.5 feet, Sideritic kaolinite oolite (XK).
The kaolinitic ooliths have been partly replaced by siderite, which also forms the coarse mosaic of the matrix. There is some quartz, and on the upper right side there is a pocket of sphaerosideritic kaolinitic mudstone.

kaolinitic oolites and sandstones, and the main log type would be Y. Lenses and bands of blue siderite mudstone also occur, and the uppermost beds may contain sphaerosiderite. Photomicrographs of some of the rock types are shown in Plates 5 and 6.

IV Example of Lithological Correlation of the Ironstone

The simplified classification system together with marker bands is useful in correlating the ironstone over considerable distances. Fig. 5 shows a generalised vertical section through the ironstone, over a distance of 12 miles, and the line of section is shown in Fig. 3. The section is based on information obtained from United Steel Companies Limited borehole cores, and it gives some indication as to how the ironstone varies both vertically and laterally; the section should not be regarded as being completely representative. The three main subdivisions (United Steel Companies Limited) have been recognised throughout the length of the section, except where the Main Oolite and Upper Beds are obviously absent in the north-east. The top of the ironstone on the section is taken as datum.

Samples from the borehole cores have been examined microscopically, and photomicrographs of some of these samples are shown in Plates 3, 4, 5 and 6; a detailed description of the samples is given in Appendix II.

(a) Ironstone = Total Thickness

At the eastern edge, the ironstone is only 14.5 feet thick, whilst in the west-central part (N) it reaches a thickness of

25.5 feet, and then there is a gradual thinning to the north and east, until eventually the Lower Estuarine Series rests on Upper Lias clays.

(b) Basal or Lower Beds

From a minimum of 4 feet (E) in the east, the beds thicken to 10 feet or more in the west-central part. In the extreme north-east, Basal Beds are the only representative of the Northampton Sand Ironstone, and they may be 12 to 14 feet thick before thinning out completely further to the north-east. The reason for assuming that the beds between (c) and (f) are Basal Beds is based on the following: it is assumed that the siderite mudstone band at 7.8 feet in borehole (W) is the sand band occurring in (X) at 5 feet and in (Y) at 2.8 feet, i.e. the depth to the top of the Basal Beds is decreasing. This reasoning is substantiated by the related lithological and chemical data in Fig. 7, and by samples that have been examined microscopically.

The most persistent remaining representative of this subdivision in the extreme north-east is the pebble bed or mudstone of the transitional beds, and in some surrounding boreholes it is found wedged between Lower Estuarine clays and sands and the Upper Lias clays.

(c) Main Oolite

Demarcation of the Main Oolite is based on the criteria cited under III (c), pp.17 - 20. It is seen from the section that the siderite mudstone and the pebble bed at the top of the subdivision are frequently encountered, and the underlying shell beds are

often recognisable. In the central and eastern areas, a blue siderite mudstone at the top of the Basal Beds is useful in determining the base. Substantiating evidence that this mudstone is relatively persistent has been obtained from underground mining operations in close proximity to (M) and (O).

In the extreme south-west, the Main Oolite is only 6 feet thick at (h), but it increases to 12 feet around (K) and (N). It then thins out to the north-east until it is absent, although a thin representative apparently occurs at (b).

(d) Upper or Sandy Beds

These are generally thicker in the south-west and west, and throughout range from 0 to 7 feet.

2.E

CHEMISTRY OF THE IRONSTONE

I General

The Chemistry of the ironstone has been described by Taylor (1949) and Hollingworth and Taylor (1951). Taylor (1949, pp. 8, 9 and 50) is critical of the ordinary commercial analysis, and emphasises the need to evaluate chemical and petrological relationships. The analytical procedure adopted in the United Steel Companies Limited mining and ironmaking operations is considered to be the best possible at the present time.

At the mining operations, the procedure is to analyse each one foot increment of ironstone for the following constituents (in weights per cent., dried at 105°C.): total iron, silica, calcium oxide and sulphur (silica is determined as a perchloric

acid insoluble and graphically corrected to 'true' silica); this applies to all boreholes and mine face samples. Composite analyses for alumina and magnesia are made for various thicknesses, and in certain instances analyses for alumina, magnesia and ferrous iron might be made on each foot. Loss on ignition at 950°C. is determined for the total ironstone thickness and anticipated working thickness and, at irregular intervals, for each foot of a borehole. The narrow limits of alumina and magnesia variation are not considered to be too significant in present blast furnace control, but in the future more importance may be placed on these constituents, and further analyses will be necessary. An average chemical analysis for the total thickness of ironstone in the immediate area around Colsterworth is:

Total Fe	31.8%	} — Dried, at 105°C.
SiO ₂	17.5%	
CaO	6.2%	
Al ₂ O ₃	6.4%	
MgO	1.2%	
S	0.29%	
Moisture	15.0%	

N.B. All further quoted analyses are on a dry (water-free) basis.

II Vertical Chemical Variation and the Inter-relationship between Lithological Subdivisions and Chemical Subdivisions

The Geological Survey has shown the chemical composition of its stratigraphical groups and of the various types of ironstone (Taylor, 1949, p. 57).

Table 8 shows the vertical variation of the main chemical constituents for four selected borehole cores; their log types are also shown, and three of the borehole cores (C, N and Z) are from the section shown in Fig. 5, and the other (CLP 80) is from an area three-quarters of a mile due west of Great Ponton.

Throughout the Colsterworth area the chemistry of the three lithological subdivisions shows characteristic differences, and these are summarised in Table 9. It is seen that the ironstone can be subdivided into three main subdivisions based on chemical data, and these subdivisions are coincident with the lithological subdivisions: variation in total iron, lime and silica contents of the one foot increments alone enables easy recognition of the subdivisions.

(a) Basal or Lower Beds

One foot increments of this subdivision have total iron values less than 30 per cent., silica values 20 per cent. or more and, where transitional beds occur, the silica content may be in excess of 40 per cent. Values for lime are usually more than 5 per cent., and in certain beds exceed 20 per cent. Beds with a sideritic matrix are usually responsible for the iron value being in excess of 20 per cent. High sulphur contents (in excess of 1 per cent.) frequently occur towards the base.

(b) Main Oolite

Iron values for one foot increments are generally in excess of 30 per cent. and silica values are below 20 per cent. (frequently less than 15 per cent.). A higher silica value may be present at the base, due either to an increase of chamosite in the matrix,

COLSTERWORTH AREA VERTICAL CHEMICAL VARIATION,

FOUR SELECTED BOREHOLES (C, N & Z ~ see figs 3&5), OXIDATION & LOGGED TYPES ARE
ALSO SHOWN.

REF: → CLP 80.

FT	OXID	Total Fe	CaO	SiO ₂	Al ₂ O ₃	MgO	Loss	S
1	Y _k	24.8	1.8	29.4	17.30	15.2	0.06	
2	X _k Y	27.3	0.6	28.0	14.35	14.4	1.11	
3		37.9	1.6	14.5	6.32	18.3	4.72	
4		39.4	1.8	15.2	8.69	12.0	0.38	
5		38.2	3.4	12.2	9.33	16.0	0.27	
6		37.0	4.7	9.6	5.93	20.3	0.18	
7		38.0	2.9	13.0	8.54	18.0	0.23	
8		43.2	2.1	11.0	8.27	11.9	0.05	
9		44.0	2.1	11.4	9.19	10.5	0.01	
10		39.4	2.9	11.3	9.68	15.1	0.01	
11		40.6	3.5	9.0	9.11	15.8	0.01	
12		44.0	2.2	7.6	5.52	17.3	0.04	
13		40.3	2.2	7.9	5.46	19.3	0.04	
14		42.2	1.8	9.1	4.85	17.8	0.08	
15		37.0	3.4	12.9	4.52	15.8	0.19	
16	Y(O _k)	28.8	5.2	22.5	6.52	18.7	1.20	
17	W _k	20.2	20.5	11.7	4.60	27.5	0.54	
18	W _k (CY)	22.2	16.5	14.2	5.60	23.6	0.56	
19		24.8	10.9	15.6	5.55	25.0	0.88	
20		20.0	6.6	21.7	7.12	16.3	0.65	
21		11.2	4.4	5.1	8.02	6.6	0.60	
22	Y MIT	14.4	3.8	44.6	10.26	12.7	0.71	
23		16.5	3.4	26.6	12.37	14.2	1.47	

FT	OXID	Total Fe	CaO	SiO ₂	Al ₂ O ₃	MgO	Loss	S
1	Y _k	30.2	10.5	1.3	21.7	16.7	6.51	0.45
2	Y _k X	31.0	6.9	1.0	33.5	27.1	4.23	0.88
3		24.3	14.4	1.5	4.01	37.9	4.38	1.78
4		24.3	18.8	1.3	37.8	36.2	4.70	2.31
5		33.6	16.1	1.1	38.1	30.8	6.02	2.99
6		30.4	22.1	5.4	15.3	8.4	5.38	2.42
7		37.2	25.1	2.9	11.3	0.8	7.67	2.60
8		36.8	31.3	3.4	10.4	0.2	7.17	2.87
9		36.4	31.8	3.5	9.2	0.2	6.56	2.95
10		36.8	31.9	3.9	9.0	0.5	6.48	3.12
11		39.6	21.8	5.2	9.6	0.4	6.42	2.41
12		36.2	30.9	3.3	10.4	0.1	6.84	3.40
13		29.0	23.2	6.2	15.1	2.1	9.15	3.15
14		30.0	23.7	8.5	20.3	11.6	6.33	3.74
15		28.4	18.2	2.2	26.4	20.2	6.07	3.24
16		13.0	7.5	8.4	37.1	31.9	5.49	1.83
17		8.4	7.3	26.8	25.1	22.7	3.07	1.38
18		24.8	19.8	19.1	12.0	4.8	5.94	2.47
19		26.0	23.1	13.1	10.2	3.0	5.51	2.60

FT	OXID	Total Fe	CaO	SiO ₂	Al ₂ O ₃	MgO	Loss	S
1	X _k Y	34.0	33.0	1.6	13.1	4.6	7.22	12.4
2	XY	32.0	28.8	2.5	16.0	9.7	6.15	2.98
3	X _k Y P	27.2	25.3	2.4	25.8	20.7	5.29	2.64
4	X _k Y P	25.6	23.4	7.4	21.8	16.3	5.59	2.48
5	X _k Y P	33.8	30.3	5.1	10.6	1.7	7.41	2.10
6	X _k Y P	36.2	33.3	5.2	8.0	0.3	6.05	2.65
7	X _k Y P	38.6	27.2	3.6	7.6	0.3	6.39	2.91
8	X _k Y P	36.2	28.9	4.9	7.8	0.2	6.21	3.33
9	X _k Y P	37.2	30.0	3.7	8.4	0.2	6.42	3.24
10	X _k Y P	39.0	28.4	6.2	7.7	0.1	6.25	3.02
11	X _k Y P	39.0	31.0	2.4	7.2	0.1	6.30	3.37
12	X _k Y P	37.6	32.8	3.8	7.2	0.1	6.79	3.17
13	X _k Y P	36.2	35.1	3.0	9.7	0.1	7.17	3.59
14	X _k Y P	35.6	39.1	3.0	11.4	0.2	8.56	3.60
15	X _k Y P	34.6	25.1	4.2	12.2	0.9	8.49	3.53
16	X _k Y P	30.8	25.4	2.8	17.8	3.5	10.64	4.04
17	X _k Y P	27.0	24.1	3.7	23.6	14.4	6.87	3.83
18	X _k Y P	25.6	22.8	4.3	25.4	17.3	6.53	3.68
19	X _k Y P	23.4	20.4	14.2	11.7	4.7	5.50	2.67
20	X _k Y P	23.2	19.8	15.6	13.4	5.9	5.04	2.40
21	X _k Y P	19.2	15.2	16.8	20.7	12.5	5.66	2.65
22	X _k Y P	15.6	12.0	13.8	30.5	23.0	6.07	2.36
23	X _k Y P	23.6	20.7	7.8	22.2	11.4	7.32	3.53
24	X _k Y P	10.4	7.2	5.8	52.8	41.6	8.90	1.35
25	X _k Y P	6.2	3.5	15.7	45.9	38.3	6.42	1.31

Z

FT	OXID	Total Fe	CaO	SiO ₂	Al ₂ O ₃	Loss	S
1	Y	24.9	24.7	2.4	31.5	3.13	1.98
2	Y	18.2	16.5	3.5	43.8	4.72	1.50
3	Y	19.6	18.7	4.9	37.2	4.24	1.80
4	Y	27.5	26.7	5.9	19.5	4.26	2.43
5	Y	22.2	21.4	5.5	32.4	3.30	1.96
6	Y	15.5	14.8	6.5	43.6	4.18	1.62
7	Y	14.1	13.6	11.7	34.7	2.84	2.17
8	Y	15.8	15.0	4.5	45.5	4.97	1.53
9	Y	14.8	14.3	9.0	39.8	3.43	1.80
10	Y	9.0	8.4	13.0	43.7	3.05	1.89
11	Y	9.4	8.6	13.0	43.6	3.80	1.77
12	Y	15.6	14.3	12.9	29.6	5.64	2.02
13	Y	13.5	10.6	18.0	32.6	6.55	1.68

KEY:
 FOREXPLANATION OF SYMBOLS
 SEE TABLE 3.
 OXIDISED } Visual
 UNOXIDISED } Estimate.
 TOP OF LOGGED MAIN OOLITE.
 BASE OF LOGGED MAIN OOLITE.

○ THIN SECTIONS, PLATES 3-6.
 ■ DETAILED MINERALOGICAL DESCRIPTION IN APPENDIX II.

or to quartz grains, or both.

A change from high iron values and low silica values to lower iron and higher silica values is frequently close to the base of the Main Oolite, but this change may not be coincident, and in the area west of Colsterworth, out of 110 boreholes, 27 showed a marked rise in silica (a rise from about 15 per cent. to 23 per cent.) to be coincident with the marked drop in iron (from more than 30 per cent. to less than 30 per cent.); 49 showed the marked rise in silica content to be one foot above the marked drop in iron, and 19 showed the marked rise in silica to be two feet above the marked drop in iron. The drop in iron is often coincident with, or one or two feet above the marked change in lime content (from about 5 per cent. to 10 per cent.).

Generally the pebble bed and the siderite mudstone at the top of the Main Oolite are either within or immediately above the 30 per cent. iron, 20 per cent. silica zone. The colour change at the base of the Main Oolite is usually coincident with the marked drop in iron.

(c) Upper or Sandy Beds

The chemistry of these beds is variable, and reflects the variable mineralogy. Where massive siderite mudstone is present, iron values in excess of 30 per cent. may occur and silica values may be less than 20 per cent; where oolitic sandstones and kaolinitic sandstones occur, iron values are usually less than 20 per cent. Silica values, frequently over 20 per cent., may exceed 50 per cent. in these Upper Beds, while lime values are generally less than 5 per cent.

CHEMISTRY RELATED TO LITHOLOGICAL SUBDIVISIONS FOR THE NORTHAMPTON SAND IRONSTONE IN THE COLSTERWORTH AREA - SHOWING MOST FREQUENT CHARACTERISTICS OF ONE FOOT INCREMENT ANALYSES

WITHIN LITHOLOGICAL SUBDIVISIONS

Sub-division	Total Fe	CaO	SiO ₂	Al ₂ O ₃	MgO	S
Upper or sandy Beds	Frequently -30%, (higher where siderite mudstone).	Generally -5%.	Frequently +20%, often +30%, (lower where siderite mudstone).	+8%, +10% where kaolinite.	-3%, often -1%	Some beds +1% in places.
Main Oolite	+30%, may be +40% (especially where oxidised).	Generally -5%, may be +6% where shelly top.	-20%, -15% often. Higher in basal foot in places.	Variable, depends on amount and composition of chamosite. Frequently 6 - 9%.	Frequently 2 - 4%.	Frequently -0.05%.
Basal or Lower Beds	-30%, +20% where sideritic lenses in matrix.	+5%. Frequently some beds +20%.	+20%, +40% in Transition zone.	Low, except in Transition Beds, +10%.	-3% often.	+1% near base.

These beds generally show, then, a marked increase in silica and decrease in iron when related to the underlying Main Oolite beds. Where these beds are kaolinitic there is a marked rise in alumina, and this is seen from the core analysis of the borehole east of Great Ponton (Table 8).

(d) Effect of Oxidation

With oxidation there is generally an increase in the iron and the silica contents, with a corresponding decrease in lime. The average analyses for the ironstone total thickness and the Main Oolite have been plotted graphically in Fig. 6 for boreholes (h), and (A) to (L) (as in Fig. 5), together with a row of boreholes east of the River Witham. The estimated amount of oxidation has also been plotted.

Table 10 shows the relationship between the alumina content of the Main Oolite and the extent of oxidation. Where known, ferrous iron figures have also been shown. This and other available evidence does not support Taylor's conclusion that some alumina is removed on oxidation (Taylor, 1949, p.55).

Oxidation rarely masks the separation of the Main Oolite from overlying and underlying beds when chemical data is used to demarcate.

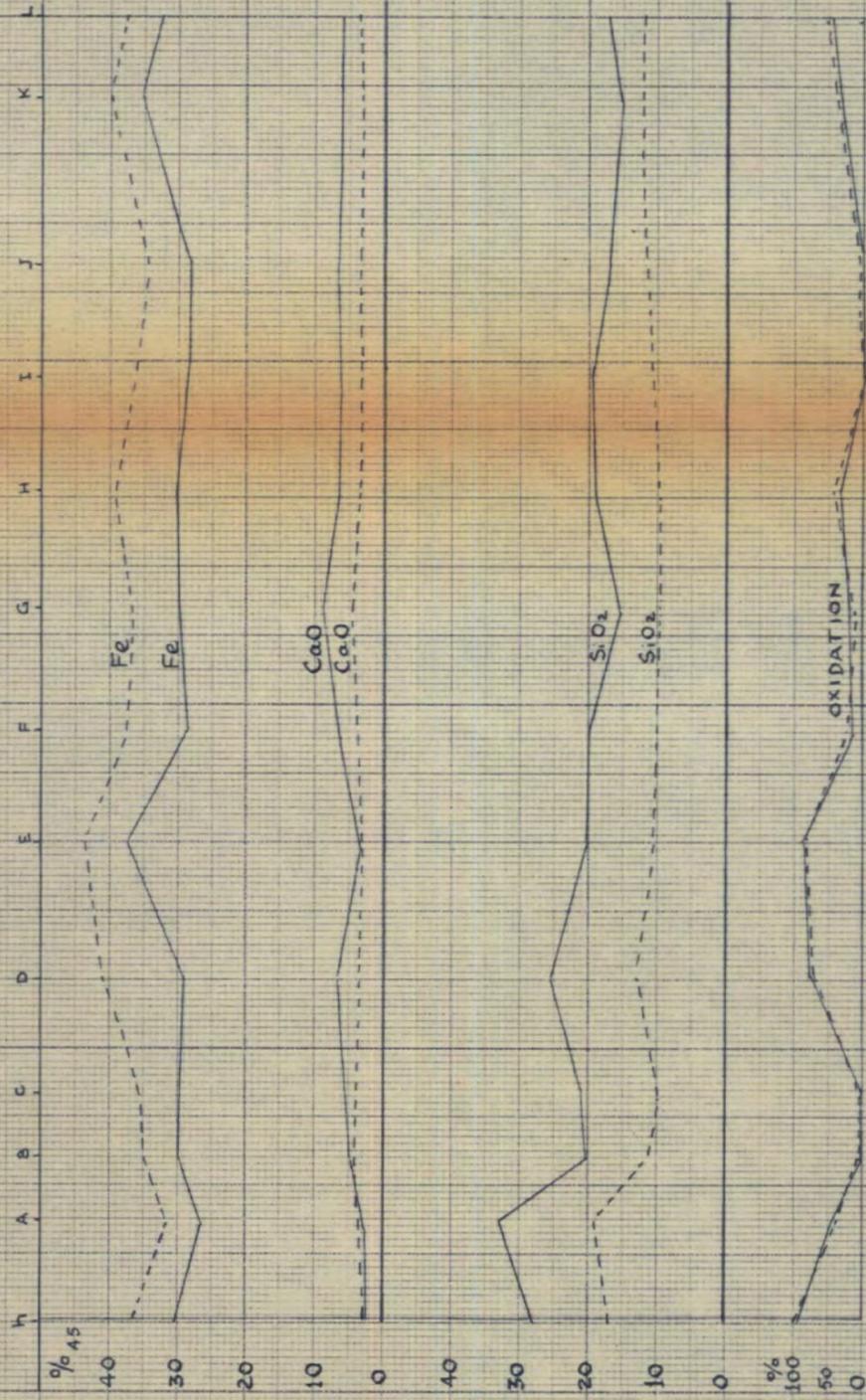
III Lateral Variation in Chemistry

Borehole core data plotted in Fig. 6 shows how the main chemical constituents, (when taking the average analyses for given thicknesses between constant upper and lower horizons) and the extent of oxidation vary over distances of 6,600 feet and 1,775 feet. Generally, it is seen that high iron and silica values reflect a higher percentage of oxidation. It is clear that the iron is more affected by oxidation than the silica.

COLSTERWORTH AREA

LATERAL VARIATION IN CHEMISTRY AND OXIDATION, FOR IRONSTONE, TOTAL THICKNESS AND LOGGED MAIN OOLITE

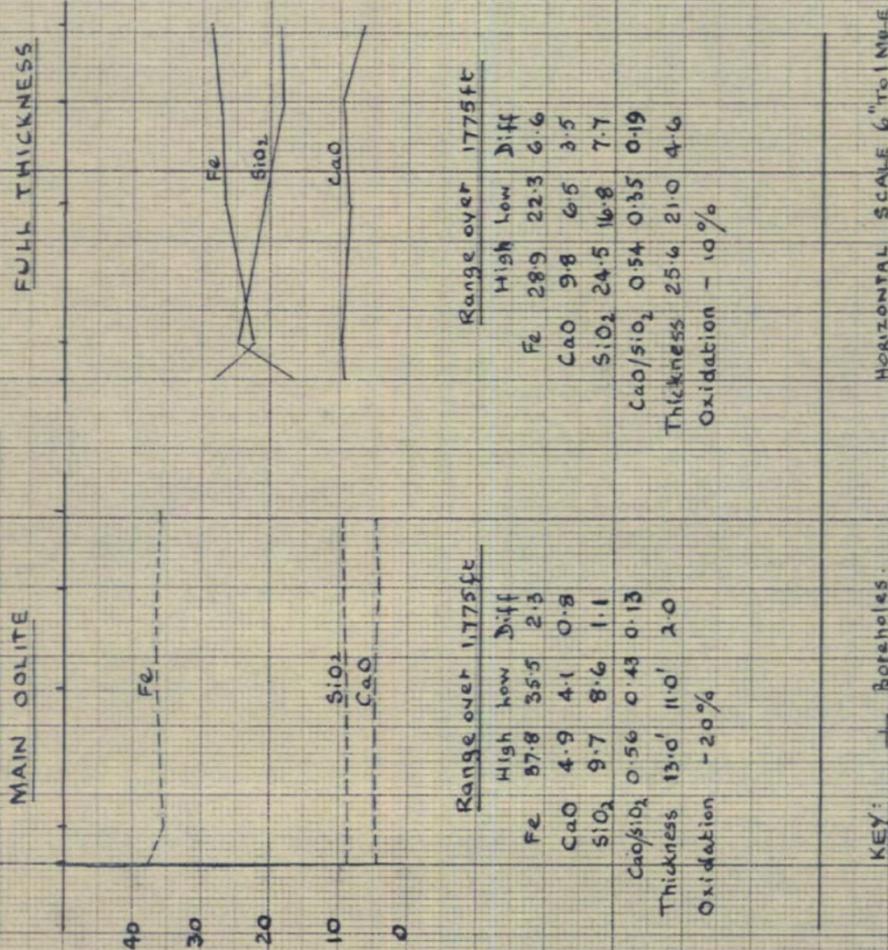
a) WEST OF RIVER WITHAM (See figs 385)



LOGGED MAIN OOLITE

Range over 6,600ft	
High	Low Diff
Fe	43.7 31.7 12.0
CaO	4.9 2.7 2.2
SiO ₂	19.0 9.5 9.5
CaO/SiO ₂	0.51 0.17 0.34
Thickness (nearest foot)	12.0' 6.0' 6.0'

b) EAST OF RIVER WITHAM.



KEY: — FULL THICKNESS
 - - - MAIN OOLITE
 A Boreholes

HORIZONTAL SCALE 6" TO 1 MILE

KEY: — Boreholes

HORIZONTAL SCALE 6" TO 1 MILE

ALUMINA CONTENT RELATED TO VISUAL ESTIMATED AMOUNT OF OXIDATION

IN THE MAIN OOLITE PORTION OF THE NORTHAMPTON SAND IRONSTONE

Mine Area	Borehole Reference	Total Fe	Fe++	Al ₂ O ₃	Estimated Visual Oxidation %
NW of Colsterworth (after Goldring, 1964, unpublished).	89	41.8	1.5	7.4	100
	95	39.0	16.2	7.2	+ 50
	167(C)	35.5	27.5	7.1	- 15
	165	33.6	29.5	7.0	0
	119	40.7	6.0	6.6	+ 75
	169	38.5	14.7	6.6	- 25
	57	33.7	29.0	6.5	0
	116	31.7	12.5	5.2	30
East of River Witham	NW 256	37.1	1.1	8.1	100
	NW 30	32.8	30.6	7.4	0
	CH 157(N)	36.2	29.2	7.2	12
	CH 97	37.8		6.6	8
	CH 181	34.8		6.0	0
	NW 251	39.8	0.3	5.9	100
	NW 216	33.1	25.4	5.0	- 20
	NW 178(Z)	27.5	26.7	4.3	0
Great Ponton Area	CLP 31	37.6		9.9	20
	CLP 80	40.2		7.6	52
	CLP 57	34.6		7.6	100
	CLP 121	42.1		7.3	100
Exton Park	CEP 76	37.3		8.4	- 25
	CEP 78	39.1		8.1	66
	CEP 75	34.4		6.8	19
	CEP 82	36.1		6.7	64
	CEP 81	37.4		6.0	50

TABLE 10

Chemical variation of the logged Main Oolite thickness is generally less than that of the overall thickness of the bed which, in Fig. 6b, includes several feet of basal transitional beds. In Fig. 6a, however, the iron variation of the Main Oolite is, when taking all the boreholes into account, greater than the variation of the overall thickness: this is due to variable oxidation and to the particularly heavy oxidation at boreholes (D) and (E), and to the low average iron content in borehole (A) where the Main Oolite has deteriorated.

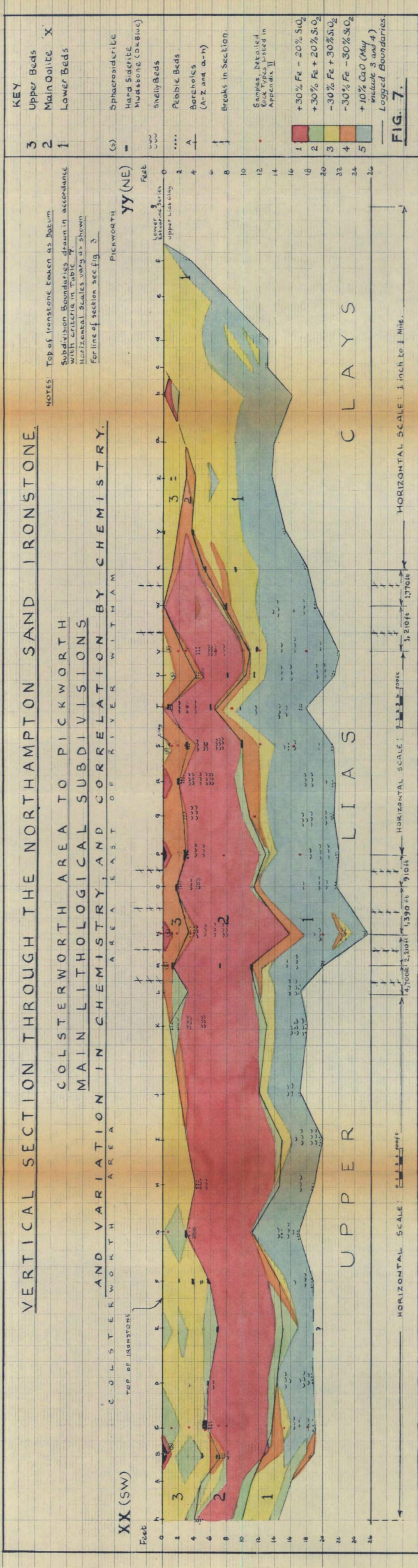
Where the Main Oolite is mainly unoxidised (Fig. 6b), there may be little chemical variation over considerable areas. Conversely, where the Main Oolite is oxidised throughout its vertical thickness and over a considerable area, there will be less chemical variation. (The Main Oolite, referred to in Fig. 13, is heavily oxidised throughout much of its thickness).

Variation in chemistry over a distance of 12 miles is illustrated in Fig. 7, and this is related to the logged subdivisions of the ironstone. Using the criteria mentioned in Table 9, it is seen that the logged Main Oolite coincides with the Main Oolite based on chemistry, i.e. for consecutive one foot increments with 30 per cent. or more of iron and 20 per cent. or less of silica. Where the Main Oolite logged subdivision is not coincident with this, it is generally because of deterioration either at the top or at the base of the Main Oolite, and, of course, the chemistry is for each foot, and logged subdivisions may have their boundaries within an analysed foot.

Lateral chemical variation for one unoxidised bed within the

VERTICAL SECTION THROUGH THE NORTHAMPTON SAND IRONSTONE.

COLSTERWORTH AREA TO PICKWORTH MAIN LITHOLOGICAL SUBDIVISIONS AND VARIATION IN CHEMISTRY, AND CORRELATION BY CHEMISTRY.



KEY
 3 Upper Beds
 2 Main Oolite
 1 Lower Beds

(s) Spherosiderite
 Hard Siderite
 Mudstone (dark blue)
 uuu Singly Beds
 Pebble Beds
 A Boreholes (A-Z and a-h)
 | Breaks in Section.

Samples, Detailed Rock Types listed in Appendix II
 1 +30% Fe - 20% SiO₂
 2 +30% Fe + 20% SiO₂
 3 -30% Fe + 30% SiO₂
 4 -30% Fe - 30% SiO₂
 5 +10% CaO (May include 3 and 4)
 — Logged Boundaries.

FIG. 7.

NOTES: Top of Ironstone taken as Datum
 Subdivision Boundaries drawn in accordance with criteria in Table 7
 Horizontal scales vary as shown
 For line of section see fig 3

PICKWORTH
 YY (NE)

Feet
 0
 2
 4
 6
 8
 10
 12
 14
 16
 18
 20
 22
 24
 26

XX (SW)

Feet
 0
 2
 4
 6
 8
 10
 12
 14
 16
 18
 20
 22
 24
 26

Feet
 0
 2
 4
 6
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 10
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 18
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 22
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 26

Feet
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Lower Lias clay

Upper Lias clay

Upper Lias clay

Upper Lias clay

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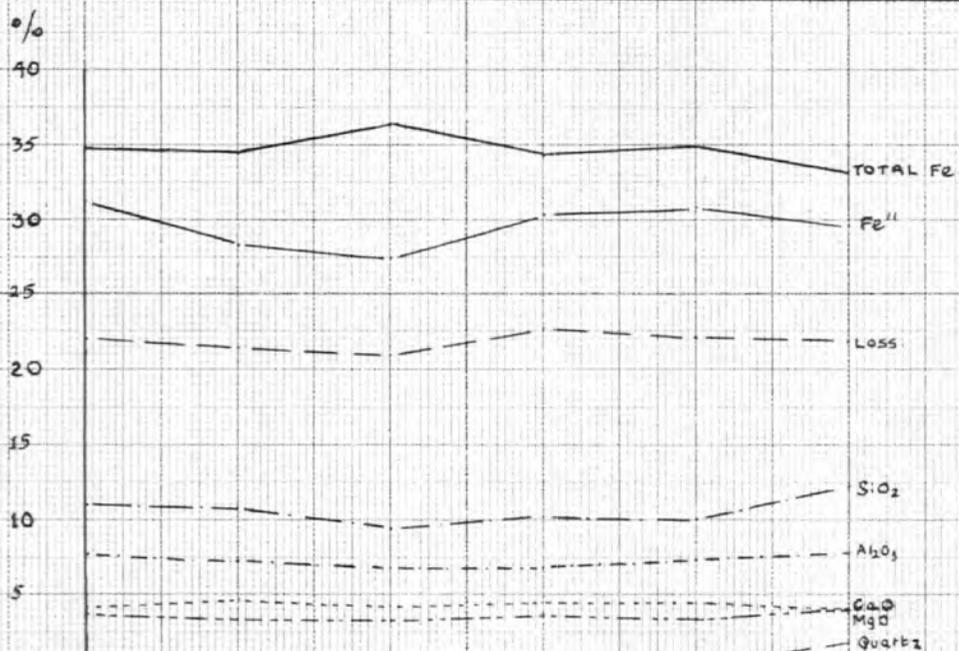
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LATERAL VARIATION IN CHEMISTRY
 ZONE BED WITHIN MAIN OOLITE,
 MINE FACE N.W. OF COLSTERWORTH.



60'	25'	10'	5'	500'	DISTANCE BETWEEN SAMPLES - FEET.
2.1'	1.6'	1.6'	1.6'	2.0'	1.8'
					THICKNESS OF SAMPLED BED - FEET.

DATA PLOTTED FROM CHANNEL SAMPLE ANALYSES.

ROCK = SIDERITIC CHAMOSITE OOLITE.

FIG 8.

Main Oolite is shown in Fig. 8. Variation is seen to be within narrow limits, and each sample is characteristically similar.

2.F THE RELATIONSHIP BETWEEN CHEMISTRY AND MINERALOGICAL TYPES

It will be realised that similar chemical analyses may relate to rocks of different mineralogy and microstructure. The relationship between chemistry and mineralogical types is particularly important in the study of sintering, blast furnace reactions, slags and techniques of beneficiation.

Given complete analyses and with knowledge of the composition of the minerals comprising the ironstone, it would be possible to calculate mineral compositions of samples and evaluate petrological variations. Taylor (1949, p.9) suggests that a routine chemical analysis does not supply the necessary data to determine the mineralogical composition; however, using the United Steel Companies Limited analyses, i.e. for total Fe, CaO, and SiO₂, mineralogical rock types can be determined reasonably accurately and the presence of certain minerals can be inferred. Taking proportions of Fe, CaO and SiO₂ rather than percentage weights, chemical differences due to oxidation are considerably reduced. These proportions, when plotted on three-component diagrams, fall into groups representing their particular rock types (c.f. Taylor, 1949, p.67). Fig. 9 shows a three-component diagram on which the analyses of Taylor (1949, pp. 60, 61 and 62) have been plotted as Fe, CaO and SiO₂ ratios and descriptions of the related thin

Based on Davies et al, 1964 (Unpublished).

No's as quoted by Taylor. ANALYSES PLOTTED AS Fe, CaO, SiO₂ RATIOS.

- 1-5, 20, 21, Sideritic Oolites. (1 oolites kaolinitic) } MAIN OOLITIC IRONSTONE GROUP OF SURVEY.
 - 6, 7, 22, 23, Sideritic Calcitic Oolites. }
 - 8, 10, 24, Sideritic Chamositic Oolites. (10 Magnetite Abdt). }
 - 11, 12, 25, 26 Sideritic Mudstones. }
 - 13 Sideritic Chamositic Mudstones (local shell debris) } SIDERITE MUDST. LST GROUP OF SURVEY.
 - 14 Sideritic Limestone. }
 - 15 Limestone. (Sdy) }
 - 16, 17, 27 Chamositic Oolites (Sdy) } CHAMOSITE-KAOLINITE GROUPS OF SURVEY.
 - 18 Kaolinitic Oolites (Sdy) }
 - 19 Sphaerosiderite. (Sdy) }
- (20-27 = weathered).

UNITED STEEL COS LTD. ANALYSES PLOTTED AS Fe, CaO, SiO₂ RATIOS.

(ALL ROCKS HAVE ~50% MATRIX BY VOLUME : Samples from various Subdivisions).

- x Oolites, Matrix mostly Sideritic, } United Steel Cos Ltd. Main Oolite Subdivision.
- ch x chamositic sideritic Matrix }
- c x calcitic sideritic Matrix }
- K x Kaolinite oolites. }
- Sandy &/or Shelly Oolites } Mainly United Steel Cos Ltd, Upper & Basal Subdivisions
- ch x chamosite in Matrix }
- c x calcite in Matrix }
- △ Limestones, Shelly sandstones, sandstones & Siltstones. } United Steel Cos Ltd Upper & Basal Subdivision

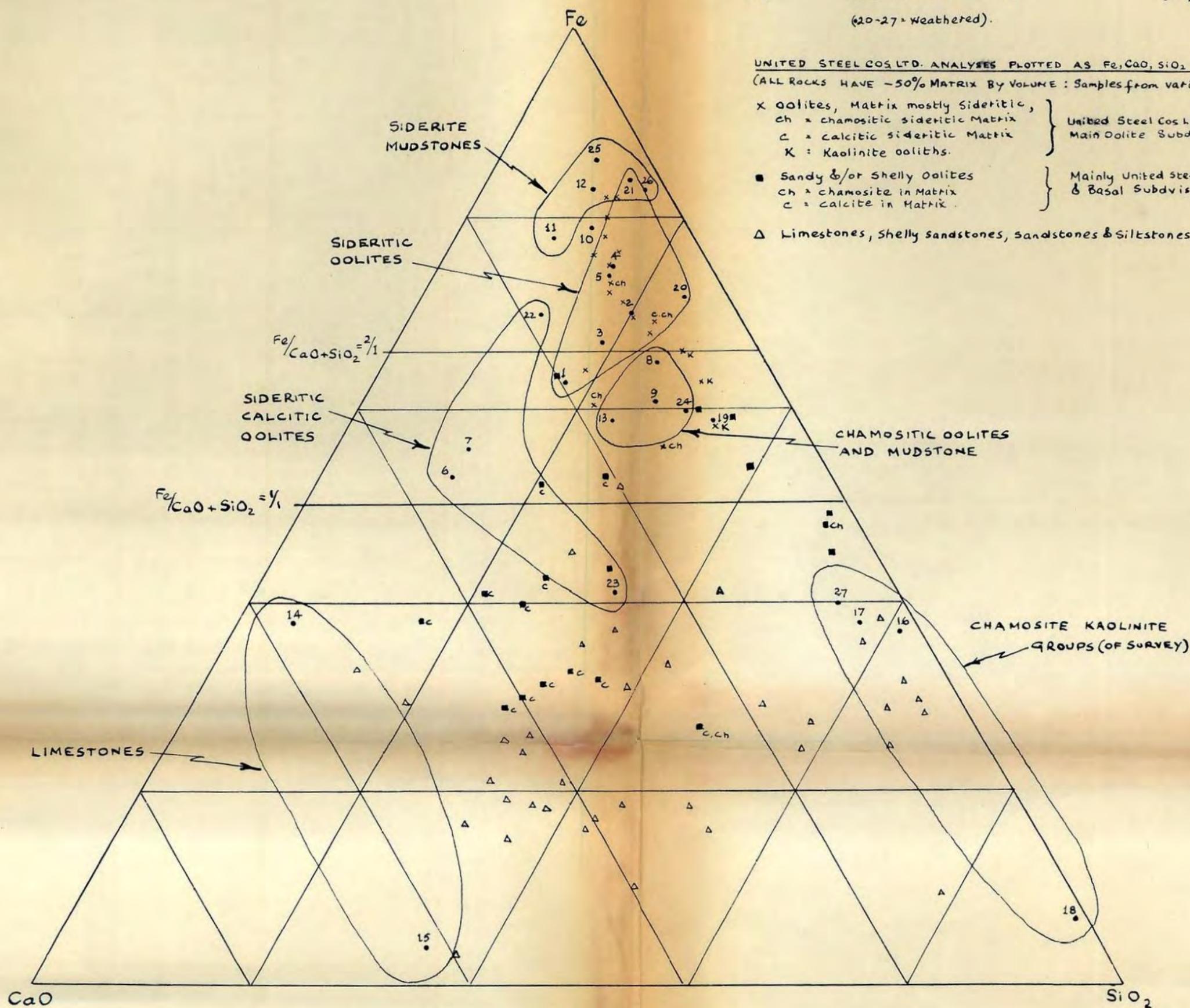


FIG. 9.

sections (Taylor, 1949, pp.58 and 59) are given; the rock type boundaries are drawn from these descriptions. United Steel Companies Limited workers (Davies et al., 1964, unpublished) have also investigated the relationship of rock type to chemistry and have differentiated between rocks containing less than 50 per cent. matrix by volume in microscopic section, and rocks containing more than 50 per cent. matrix by volume: their analyses, plotted as Fe, CaO and SiO₂ ratios for rocks with less than 50 per cent. matrix by volume, are plotted also on Fig. 9, and notes on the related thin sections are included.

Amongst the conclusions reached from this diagram are:-
Siderite mudstones with the following composition (in terms of ratios), Fe +75 : CaO -15 : SiO₂ -15, may overlap with sideritic oolites, i.e. Fe 63-86 : CaO -20 : SiO₂ -25.

Limestones and shelly sandstones have an Fe to CaO + SiO₂ ratio of less than 1 : 1.

Rocks with a CaO to Fe ratio up to 14 : 86 should not contain calcite, since CaO should occur in solid solution in siderite. On analysis, when CaO values are more than 6 per cent., calcite is probably present, when CaO values are less than 3 per cent., calcite is probably absent.

Davies et al. (1964, unpublished) suggest: "Rocks with a ratio of SiO₂ to Fe of more than 45 : 55 are either kaolinite or quartz bearing. On analysis, rocks with more than 30 per cent. SiO₂ probably contain quartz or kaolinite; however, if much siderite is present in the matrix, a value between 20 per cent. and 30 per cent.

SiO₂ may indicate quartz or kaolinite. Where the SiO₂ content is less than 15 per cent. it is unlikely that quartz or kaolinite are present."

Whilst chemical data can often be related to mineralogy, it is obvious that a one foot increment borehole analysis may include more than one rock type, and this will reduce the accuracy of such relationships. The simplified system of logging will help to show where lithological variations occur within a separate foot, and hence allow chemical data to be interpreted in terms of mineralogy, with discrimination.

2.G GRADE CONTROL - GENERAL, AND OUTLINE OF MINING PRACTICE

I Importance of Grade Control

The ultimate aim in grade control is to reduce variability in the chemistry of the blast furnace sinter feed, necessary for economic and satisfactory blast furnace performance. The lime and silica contents in the sinter are particularly important in blast furnace control.

Grade control is also necessary to ensure that, at a given time, only the most economic portion of the ironstone is mined, and that, whenever a change in grade is required, the demand can be satisfied. An appreciation of the inter-relationship between lithology and chemistry allows for grade variations to be better understood.

II Obtaining the Data

(a) Drilling

Whereas, in the past, most mining companies relied on trial-pits (where overburden was shallow) and mine face samples to obtain much of their grade information, the present policy in the United Steel Companies Limited Ore Mining Operations is to analyse borehole cores. Hollingworth and Taylor (1951, pp. 51 - 53) discuss boring and examine the merits of core and slurry sampling; whilst they conclude slurry sampling to be ideal in friable and weathered stone, they point out that the ironstone cannot be examined and that there is a danger of contamination from beds overlying the ironstone (Lower Estuarine Series), or from soft sandy or clayey material from the ironstone on either side of the bore. They also state that core sampling is useful in massive or unweathered beds.

Since the mid 1950's, all the United Steel Companies Limited drilling has been by 'Craelius X.H.50' Machines (Plate 7), and ironstone cores of either 101 mm. or 116 mm. are obtained. Whilst the ironstone in the United Steel Companies Limited areas is frequently massive, weathered areas are present and weathered beds may be interbedded with massive strata; core recovery is generally between 95 per cent. and 100 per cent. except in some heavily oxidised outcrop areas. Core sampling has proved to be more advantageous than slurry sampling where there is loss in volume, especially as the rock types and lithological relationships can be more accurately correlated with analyses and marker bands.

PLATE 7



'Craelius X.H. 50' Drilling Rig.

Drilling is divided into two categories, (i) Exploration Drilling, and (ii) Grade and Structure Drilling.

(i) Exploration Drilling

Apart from areas where boreholes have been spaced on a one kilometre square grid, most exploration drilling is on a 1,600 feet square grid. All boreholes are cored from the surface to 6 feet below the ironstone.

(ii) Grade and Structure Drilling

Where exploration drilling has indicated a workable ore reserve, as far as possible, before mining commences, the area is drilled on a 400 feet square grid, and thus boreholes previously drilled on the 1,600 feet grid will be included. Where faulting or washouts are located, extra boreholes are drilled to determine the full extent of the occurrence. Except where boulder clay is present, the entire thickness of strata is cored.

(b) Treatment of Ironstone Cores and Analyses

(i) Cores

Ironstone cores are split longitudinally; one half is boxed in one foot increments, and the other half is crushed in one foot increments to pass through a 100 mesh British Standard sieve. The solid portion is logged in accordance with the simplified classification system, and notes are made relating to the state of oxidation. The writer has found it advantageous to photograph the core in colour, and transparencies or photographs of the cores are useful for future reference - the main subdivisions and the extent of oxidation can often be recognised. After photographing,

samples for petrological study are removed, and cores are held in storage until all data has been correlated (or, in some cases, until the area concerned has been mined); apart from representative samples and cores relating to representative sections, they are then scrapped.

(ii) Analyses

The powdered portions of the core are dried at 105°C. Exploration samples are analysed in one foot increments for Total Fe, CaO, SiO₂, S, and often for Al₂O₃, MgO, ferrous iron and loss on ignition at 950°C is determined (silica is reported as a perchloric acid insoluble and graphically converted to true silica).

Cores on the 400 feet grid, apart from the exploration cores on the grid, are analysed in one foot increments for Total Fe, CaO, SiO₂ and S. As stated on p. 24, one foot increment analyses for Al₂O₃ and MgO are not at present considered essential. On occasion, however, more complete analyses may be made on each foot. Composite analyses for Al₂O₃, MgO and Loss are made for the full thickness and anticipated working thickness, and, from time to time, for other thicknesses.

Up to the present, it has not been found necessary to analyse cores in relation to bedding or rock type increments, especially as mining machinery cannot always follow precise boundaries. However, some face samples and occasional cores have been analysed in rock type increments.

III Correlation of Data

(a) Data Obtained from Exploration Drilling

The decision as to whether or not the area has a future economic potential can be decided.

Among the six-inch maps produced are those showing: Depth of Cover, Contours to the Base of the Ironstone, Full Thickness Isopachytes, Isopachytes of Thickness according to given grade criteria, and Variation in Fe, CaO and SiO₂ Contents for given thicknesses (generally Full Thickness and Proposed Working Thickness).

Criteria used in assessing the economic potential of an area may vary from time to time, and are influenced by trade conditions and beneficiation and mining techniques. For example, in the past, possible ore reserves have been calculated from maps showing:

Maximum thickness of ore averaging +30% Fe.

Maximum thickness of ore averaging +30% Fe at a given lime/silica ratio.

The thickness of ore where
$$\frac{\text{Average Fe}\%}{\text{Average Al}_2\text{O}_3\% + \text{CaO}\% + \text{SiO}_2\% + \text{MgO}\%}$$
 is more than a given Constant.

(b) Data Obtained from Grade and Structure Drilling

Besides giving additional ore reserve information, it is this data which is used to determine the method of mining, and the grade of ore to be produced at various times.

Apart from such maps showing contours on the top and bottom of the ironstone and depth of cover, the remainder are

particularly related to grade, and these are maps showing:

Extent of Oxidation - for various thicknesses.

Isopachytes - for thicknesses relating to ironstone grade, in accordance with various criteria; amongst the isopachyte maps at present drawn are those showing:

(i) The maximum thickness of ironstone averaging 30 per cent. iron or more with 20 per cent. silica or less. (This includes the Main Oolite, with some of the Upper or Basal Beds, or both).

(ii) The maximum consecutive thickness of ironstone with one foot increments of 30 per cent. iron or more and 20 per cent. silica or less, (a lesser thickness than (i)). This thickness represents the Main Oolite logged thickness, apart from occasions when the top or bottom foot of the Main Oolite does not conform with the above-mentioned criteria.

Grade variation - together with sections relating to Fe, CaO and SiO₂ contents, and the ratio of lime to silica, etc. (sulphur is no longer considered important, as all ore is sintered) for the full thickness, the proposed working thickness, and for beds to be discarded or left in situ. For opencast mines, selective mining may require grade variation maps to be drawn for the logged Main Oolite, and the advantages of mining this portion selectively are discussed under Suggested Future Practice, page 44.

Block grade - i.e. the average Fe, CaO, SiO₂, S, Al₂O₃ and MgO contents, together with the loss, and CaO/SiO₂ ratio for a

400 feet block (based on the average analyses of four borehole cores) relating to the present or proposed working thickness.

On opencast mine plans, the ironstone face is shown divided into 100 feet increments along its length, and, as the rail track in the mine is similarly divided up, the position of the loading machine in the mine can easily be found on the map.

Maps are generally drawn to the scales of 1/2,500, or 6 inches to 1 mile. Examples of such maps are shown in Fig. 10, and further examples of grade maps are shown in Figs. 12 and 13.

Borehole core sampling of the ironstone is considered to be less affected by human bias than is face sampling, where equal volumes for separate feet are rarely obtained, and, due to the human element, hard beds are frequently insufficiently sampled and soft beds are over-sampled.

IV Outline of Mining Practice

(a) General

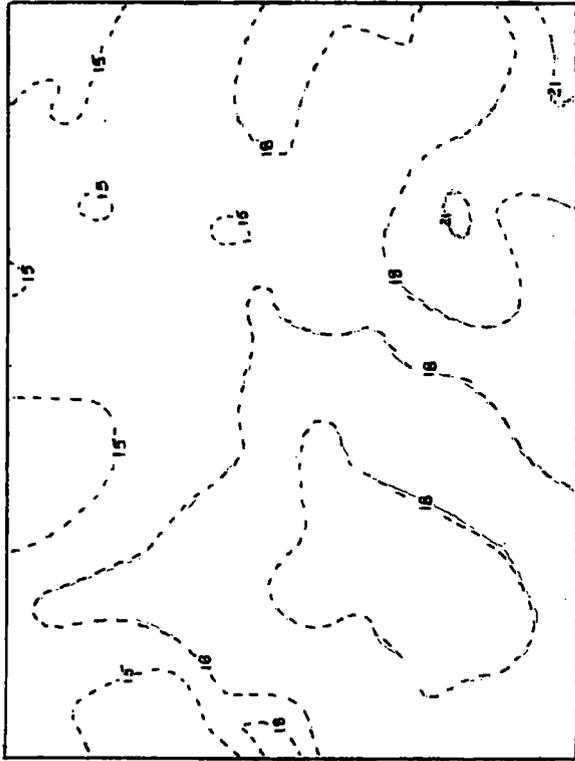
Where the overburden is less than 100 feet, mining is at present by opencast methods. In an area east of the River Witham at Colsterworth, experiments in underground 'room-and-pillar' mining are taking place.

(b) Opencast Mining

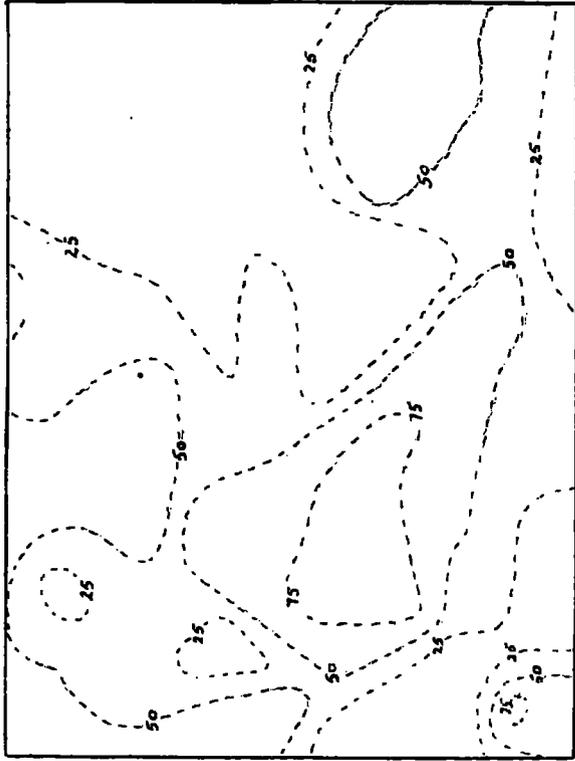
The ironstone is mined in longitudinal cuts or gullets, generally parallel to the outcrop and working away from it.

TYPICAL EXAMPLES OF MAPS DRAWN FROM INFORMATION OBTAINED AFTER 400' GRID DRILLING - COLSTERWORTH

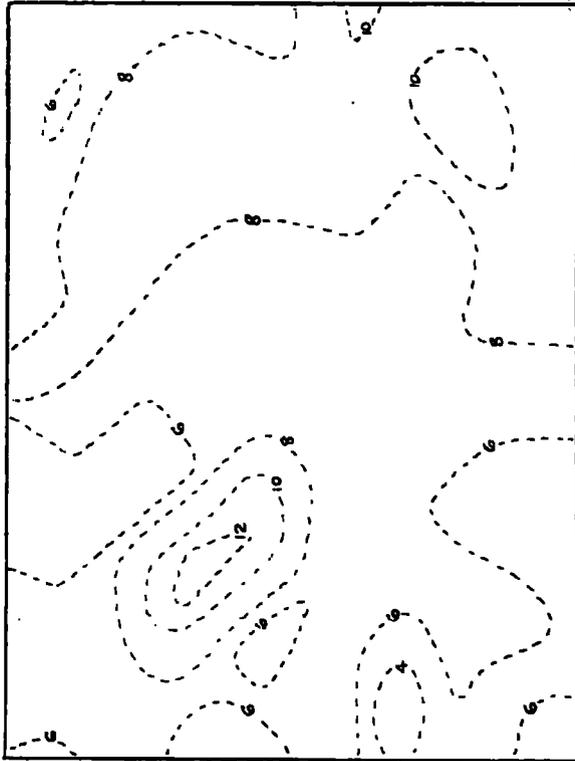
b.c.8d After Geology 1964 (Unpublished)



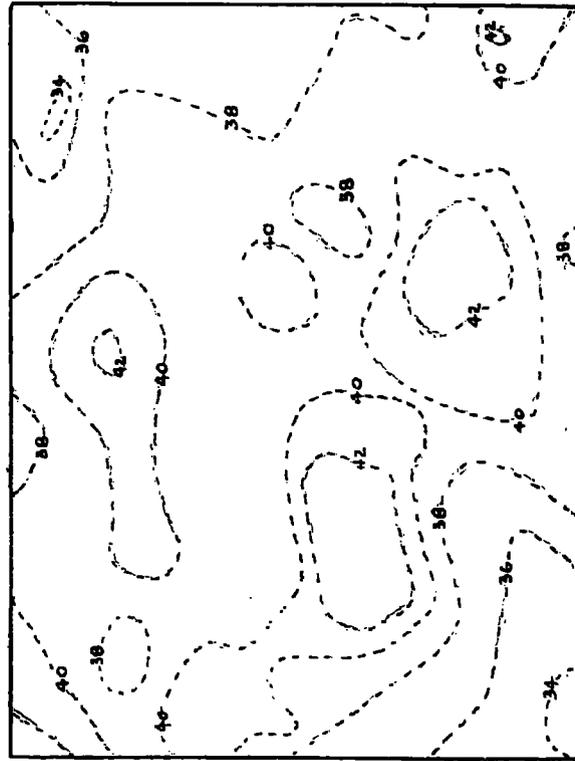
a. TOTAL THICKNESS OF NORTHAMPTON SAND IRONSTONE



c. EXTENT OF OXIDATION OF MAIN OOLITE.



b. THICKNESS OF MAIN OOLITE - BASED ON $Fe+30\%$ & $SiO_2-20\%$ FOR CONSECUTIVE ASSAYED FEET



d. VARIATION IN THE AVERAGE IRON CONTENT OF THE MAIN OOLITE, BASED ON THICKNESSES & ASSAY CRITERIA SHOWN IN b

NOTE, ISOPACHYTES OF THICKNESS, OXIDATION & IRON VARIATION MAPS, ARE DRAWN FOR THE SAME AREA.

SCALE: 6" TO 1 MILE.

As far as possible, the cuts are also parallel to the main dip direction to allow for as much natural drainage as possible. These cuts usually have a 'dead-end', and in such cases may be over 1 mile long; however, one of the Companies' mines has a cut 8 miles long, encircling the mining area.

Overburden composed of Lincolnshire Limestone, Lower Estuarine Series, and sometimes part or all of the low grade Upper Beds of the ironstone, is removed after drilling and blasting, by large stripping machines. These may be electrically powered walking draglines, with 20 cubic yard buckets and a 260 feet dump radius, which stand on the limestone overburden, or else large face shovels, with up to 17 cubic yard buckets, standing on the ironstone they have previously uncovered. (Plates 8(a) and 8(b)).

Overburden is tipped clear of the bared ironstone on the opposite side of the cut, where it has a characteristic 'hill and dale' appearance. After drilling and blasting, the ironstone is loaded by electrically powered face shovels with a $3\frac{1}{2}$ cubic yard bucket, into rail wagons. The rail track at the foot of the bared ironstone face connects up with railway sidings outside the mine area.

The loading machine progresses along the bared ironstone face, and, when the ore is loaded out, the rail track is moved away from the dump side, thus giving space for the dumping of more overburden as the next benching of ironstone is bared. One of the mines working for two loading shifts per day (16 hours) has a daily output potential in excess of 6,000 tons.

PLATE 8



(a) Opencast Mining Operation north-west of Colsterworth. Face shovel with a 17 cubic yard bucket is removing overburden ahead of smaller shovel ($3\frac{1}{2}$ cubic yard bucket) loading ironstone into rail wagons.



(b) Walking Dragline with a 20 cubic yard bucket for removing overburden at Exton Park standing on Lincolnshire Limestone. The ironstone face is oxidised throughout.

The tips of overburden are levelled out by bulldozers, and topsoil from the undisturbed side of the cut is removed by tractor scrapers and spread on the levelled area, thus restoring the area for agricultural use.

(c) Underground Mining

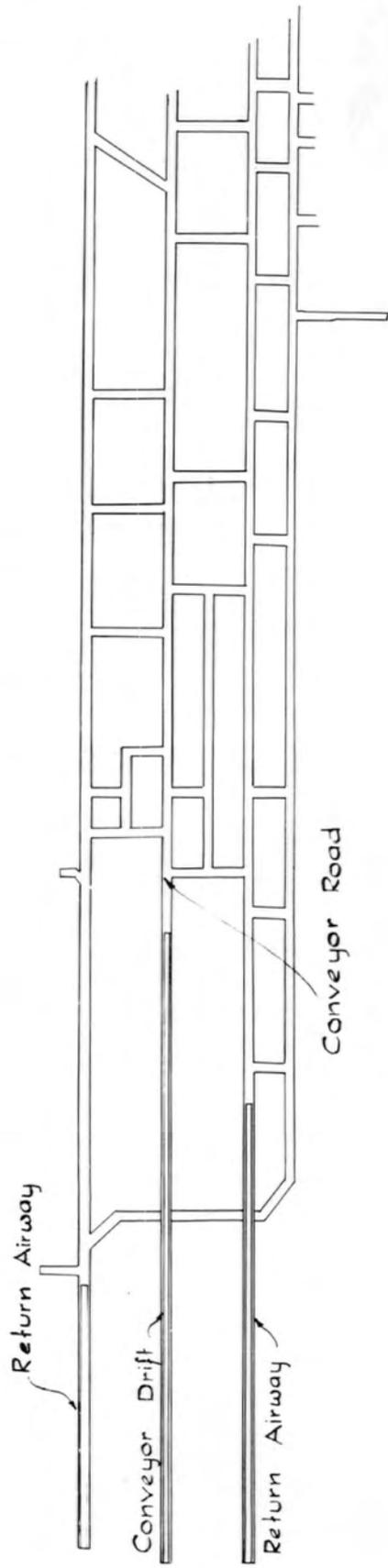
In the experimental underground mine, three entrance tunnels from the surface connect up with the main down dip roadways; the central roadway houses a belt conveyor.

Roadways are at present being driven down-dip towards the eastern boundaries, which are determined by the thickness and grade of ore. These roadways have an average width of 20 feet, and are between 12 and 15 feet high. At regular intervals, roadways are set off at right angles to the main dip roads, thus forming a linkage with the other dip roads. The resulting pillars may be up to 530 feet long and 180 feet wide. The total width of the down dip workings is 560 feet (Fig. 11).

During development, ore is won from the advancing roadways, and, on the retreat from the boundaries, ore will be won from the pillars. To maintain a good roof, a 3 to 4 feet thickness of ironstone is left in place, thus supporting the less competent Lower Estuarine clays and silts.

Roadways are extended by drilling and blasting, and the ore is loaded into shuttle-cars via 'Joy' loading machines. Shuttle-cars transport the ore to the conveyor belt on the central road for conveyance to the surface. A specially developed continuous mining machine is also being used for driving and loading out

EASTON MINE.
PLAN OF DEVELOPMENT DRIFTS.



SCALE

100 200 300 400 500 600 FT.

FIG. 11.

FIG. 11

roadways without the need for blasting.

2.H GRADE FORECASTING AND CONTROL DURING OPENCAST MINING

- PAST, PRESENT AND ALTERNATIVE PRACTICE

I Past Practice - (United Steel Companies Limited) - and the 400 feet Block System

For a period prior to 1962, six widely separated opencast mines were being worked in the Colsterworth and Exton areas, together with an experimental underground mine. In the opencast mines, the full thickness of the Northampton Sand Ironstone was mined. Based on the Ore Preparation Department's estimates of iron units and lime to silica ratio, the required tonnages and expected grade for each mine were calculated from the 400 feet block grade maps, on a yearly, monthly and weekly basis. The grades of mined ore were also assessed from the maps.

Over the period of one year, the analyses figures from the block grade maps compared favourably with the average yearly analyses made for the ore received at the Ore Preparation Plant; weekly comparisons of analyses showed anomalies from time to time. The weekly block of ore mined represents only a small proportion of the 400 feet block or blocks, and if the mining face is near the edge of a block, the average of the two analyses of the boreholes on the extremities of the edge will tend to be more accurate than the block average. There is often a relatively sharp rise or

fall in analysis when passing from one block to the next. Day to day variation will also be masked, due to the small area of the block affected. The use of data shown in the grade variation maps would have given more accurate grade estimates. Comparative block and grade variation maps are shown in Fig. 12, and the average iron content is shown for two hypothetical weekly outputs on each map.

The 400 feet block system was introduced so as to have grade and structural data for an area available well in advance of its being mined, and to reduce the amount of face sampling. Previously, experiments were made with 200 feet blocks, but it was suggested that any greater accuracy resulting from more boreholes could not justify the extra drilling costs, and, furthermore, the large number of boreholes required would have prolonged the exploration and grade drilling programmes. However, it has been shown that, whilst a 400 feet block analysis gives a fair overall assessment of grade, there is much variation at times within the block. Data obtained from additional boreholes may, in certain areas, alter grade variation and block grade maps considerably. Anomalies may occur if boreholes penetrate local oxidation zones, close to joints, where the surrounding rock is relatively unoxidised. At the present time the United Steel Companies Limited Research and Development Department is making studies to determine the degree of reliability of 400 feet borehole spacing, and the amount of reliance to be placed on any individual borehole core.

TYPICAL GRADE MAPS

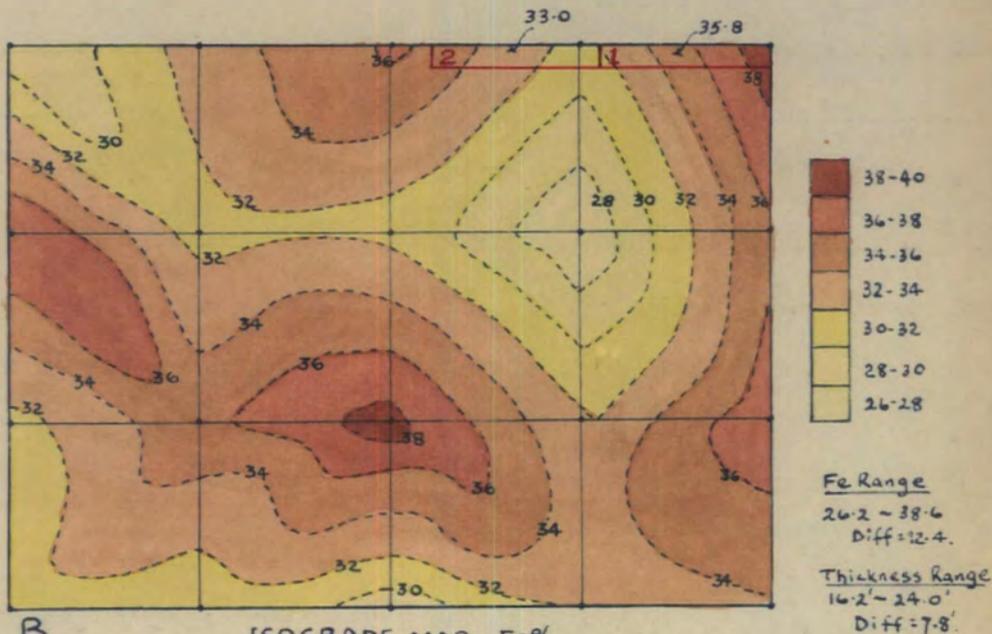
FOR SE CORNER OF EXTON PARK OPENCAST MINE

BASED ON ANALYSES (DRY) OF CORES, FROM BOREHOLES ON 400' GRID.

Th 17.8 Fe 32.6 CaO 6.0 SiO ₂ 19.7 S 0.19	19.3 32.9 6.4 19.1 0.19	20.2 31.4 31.2 7.1 21.6 0.17	20.2 32.9 32.9 6.9 20.1 0.17
19.2 33.8 5.3 20.2 0.13	20.2 34.2 5.5 19.5 0.14	20.1 32.1 7.1 20.9 0.12	19.6 32.7 7.1 20.6 0.13
19.9 31.9 6.6 22.1 0.10	19.7 33.4 6.0 21.1 0.08	19.5 33.2 5.9 21.5 0.06	Th 19.0 Fe 33.8 CaO 5.7 SiO ₂ 20.6 S 0.13

A BLOCK GRADE MAP (Full Thickness of Bed).

Showing Full Thickness of Bed, Total Fe%, CaO%, SiO₂%, S%
 Analysis for each block = Average of 4 Cores from each corner



400'

• Boreholes.

1

2

Hypothetical Face
 Positions after one
 & two weeks Loading.
 Av. Fe content shown.

FIG 12

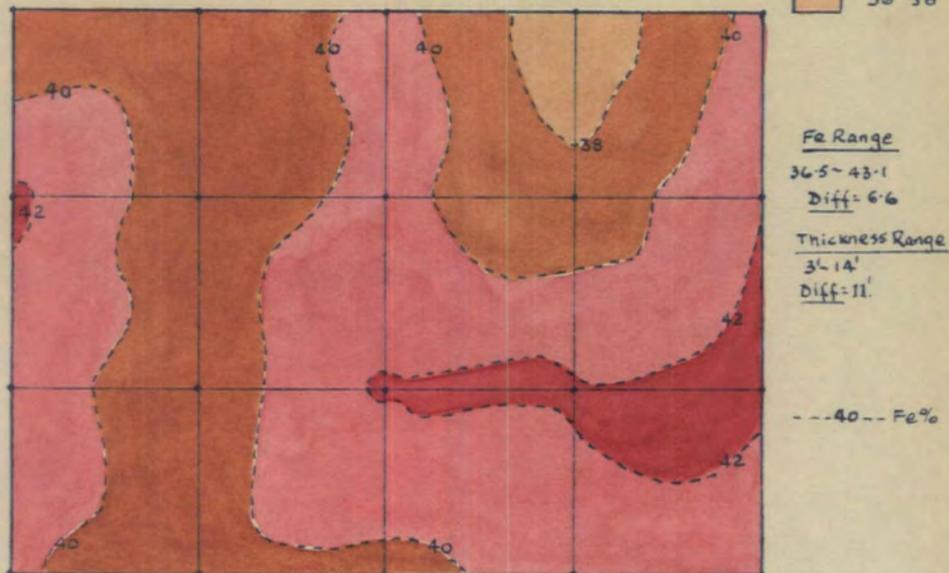
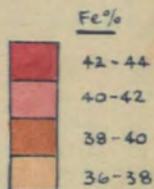
TYPICAL GRADE MAPS (contd.)

FOR SE CORNER OF EXTON PARK OPENCAST MINE

BASED ON ANALYSES (DRY) OF CORES, FROM BOREHOLES ON 400' GRID.



C ISOGRADE MAP - Fe% & SiO₂%
 TOTAL Fe% Variation & SiO₂% Variation, For Main Oolite



D ISOGRADE MAP - Fe%
 TOTAL Fe% Variation, Main Oolite - Minus Sandy Top Beds.

← 400' →
 • Boreholes

The analytical data obtained from cores on the 400 feet grid does, however, enable lateral variation to be better assessed from grade variation maps, drawn in conjunction with graphical grade variation diagrams for mine face sections, than from block grade maps.

II Present United Steel Companies Limited Practice

Due to the irregular mining rates at each opencast mine, caused by varying demands in tonnage, often as a result of trying to achieve a particular overall grade, there was a low utilisation of man-power and machinery, and this resulted in the need to reduce the number of opencast mines. At the present time, only three opencast mines are continuously worked, two are immediately west of Colsterworth, and the other is at Exton Park (Fig. 3). In order to improve the overall ore grade, so as to give a richer blast furnace burden and to reduce the cost in ore transport to the iron works at Scunthorpe in terms of cost per iron unit, the Basal Beds in each of the mines are left in situ. This reduces the amount of lime and silica transported per ton of ore, and correspondingly more iron units per ton are transported.

In one of these mines, the Upper Beds, with low iron and high silica contents, are removed and discarded; this further improves the iron content of the ore being transported, and further reduces the cost per unit of iron. Long term grade forecasting is still based on 400 feet block averages, but grade variation diagrams for face sections are now being used more in weekly grade forecasting.

The reduction in the number of mines, and the reduced thicknesses which are now being mined at a more constant rate, have together helped to reduce the overall variability in grade, but there is still some variance between forecast analyses and the analyses of ore received at the Ore Preparation Plant.

Variations in grade of the Northampton Sand Ironstone in the sinter mix can be evened out to some extent with stocked Northampton Sand ore of known grade at the Ore Preparation Plant, and variations can also be evened out by varying the proportions of known grade Frodingham ore added to the sinter mix.

III Alternative Practice of Grade Forecasting and Control

Another company, mining the Northampton Sand Ironstone from twelve or more opencast faces, uses a computer for assessing the weekly and daily grades and tonnage to be mined from each mine face, and the loading position at the faces.

Here, the faces are divided into 22 yard sections, each containing three boreholes, and the powder obtained from the holes is analysed. Twenty-four hours prior to mining the ore, each mine is instructed as to the number of wagons it will load from a particular portion of the face. The ore from these wagons is selectively crushed and bedded, and thus variability is reduced.

Because boreholes are not cored, and only slurry or powder samples are used to represent the total thickness of the worked portion, some doubt must be expressed as to how much reliance can be placed on the analyses, and hence on the overall reliability of the control procedure.

This procedure is unsuitable within the United Steel Companies Limited operations because railway wagons from the various mines have always arrived at the Ore Preparation Plant at irregular intervals, due to the greater rail haulage distances involved and lack of Companies' control during conveyance; also, sufficient bedding capacity has been lacking, and incoming Frodingham ores have to be considered in addition.

Sporadic loading at various mines results from the method of grade control mentioned above, and this would presumably have an adverse effect on mining costs.

2.J SUGGESTED FUTURE OPENCAST MINING PRACTICE

I Selective Mining

It has been shown that the Main Oolite subdivision of the ironstone is the least variable in grade, and that grade variation laterally is reduced when this subdivision is considered separately. Lateral variation in chemistry for the total ironstone thickness and logged Main Oolite have been compared in Fig. 6, and when considering the logged Main Oolite separately, the range between the high and low values of the average analyses is reduced by the following ratios (except for Fe in Fig. 6(a)):

Fig. 6(a)	Fe 0.9 : 1	CaO 3 : 1	SiO ₂ 1.9 : 1
Fig. 6(b)	Fe 2.9 : 1	CaO 4.4 : 1	SiO ₂ 7 : 1

Reduced chemical variation when considering the Main Oolite separately is seen also when relating Fig.12B to Figs.13A and 13B.

(The Main Oolite in this instance being consistently oxidised). Thus, to achieve a less variable grade, the Main Oolite alone could be mined.

Selective mining to win the Main Oolite would, however, further diminish the ore reserves (approximately 50 per cent. of the total ironstone thickness would be mined). Also, the stripping ratio (depth of overburden in relation to depth of ore) would increase, and thus increase the stripping cost per ton of ore. Against these disadvantages, however, is the fact that the ironstone drilling and explosives costs would be reduced, as less ore drilling would be required, and, still more important, transport costs in terms of cost per iron unit would be further reduced, as less silica (and lime) would be conveyed to Scunthorpe. These factors are particularly important when relating the economic value of the 'home ores' to high grade foreign ores and concentrates.

If, at the present time, the Main Oolite only was mined, the overall grade mined from the Colsterworth and Exton operations would be: +35% Fe, -12% SiO₂, -5%CaO

This grade can be obtained if the consecutive feet are in the +30% Fe, =20% SiO₂ range, in other words, the logged Main Oolite.

II Future Opencast Grade Forecasts for Selected Thicknesses

Grade forecasting for the Main Oolite thickness alone would be more accurate, since chemical variation is less than for greater thicknesses. It has been shown that the Main Oolite is readily recognised from lithological and chemical data, and precise

grade variation maps and diagrams can be compiled from borehole data for this subdivision.

At Exton Park, where sandy beds may occur in the upper portion of the Main Oolite, below the fairly persistent siderite mudstone, and where better grade beds overlie the apparent top of the Main Oolite (i.e. above the fairly persistent siderite mudstone), greater care is necessary in determining the mining thickness. The improvement of grade by mining the Main Oolite alone in the Exton Park vicinity is seen by comparing Fig. 12B with Figs. 13C and 13D.

Grade variation along the mine faces can be shown graphically as in Fig. 6, and, in opencast mines, graphs drawn from the grade variation maps along the centre line of two adjacent ironstone benchings should be sufficient, i.e. each graphical grade variation diagram will relate to two ironstone benchings, (a total width of 80 to 100 feet). The daily position of the loading machine would also be shown on such diagrams.

At certain times, for example during furnace re-lines, the highest grade ore available might be required. The thickness necessary to give the highest grade can be predetermined from the borehole information and the relevant graphs and maps can be made; also, the depth from the marker band at the top of the Main Oolite to the top and bottom of the higher grade ore should be plotted. The highest grade portion occurring along a mine face could be held in reserve for such occasions, if mining techniques permit.

III Operational Control in Selective Opencast Mining

The siderite mudstone marker band at the top of the Main Oolite.

is useful to the operators, and stripping machinery can remove all strata to the base of this marker band; this is at present being done in the mine where the Main Oolite only is being won. Although the hard, 'flinty' siderite mudstone has a high iron content, it must be removed, as it is difficult to commence blasthole drilling in this rock. It is only when the marker band is absent over distances of 50 feet or more that geological advice is essential. Washouts of inferior grade Upper Beds can be bulldozed away, should they occur. On occasions, when a higher grade of ore than that of the overall Main Oolite thickness is required, it might be possible to bulldoze the unwanted Main Oolite overlying the higher grade ore to one side, and the depth to be bulldozed away could be related to the position of the marker band. At Exton Park, due to the more variable upper portion of the Main Oolite, geological advice will more frequently be required.

The base of the Main Oolite is obvious to operators in all mines, and the loading machine finds its own level on the top of the hard grey Basal Beds, which have not been blasted and are unaffected by basal explosive break. In the present operations, oxidation rarely affects Basal Beds to such an extent that the horizon is completely lost for any great distance. Mining to achieve higher grades within the Main Oolite thickness will require greater geological control, although bedding planes will be helpful to operators in determining machine levels. (Plate 1).

2.K UNDERGROUND GRADE FORECASTING AND SELECTIVE MINING TO GRADE

In underground mining, where at least three feet of ironstone must be left in the roof to support the less competent Lower Estuarine beds, the use of the 'flinty' marker band or the pebble bed is less reliable. The Upper Beds may thin or channel into the Main Oolite, and such occurrences are not always apparent from boreholes, also using the marker bands at the top of the Main Oolite would present roof hazards in areas of thinning or washouts, and this has an important bearing on mine safety.

At present, the ironstone has to be worked for some distance below the base of the Main Oolite in order to accommodate the mining machinery, thus increasing grade variation and dilution.

Whilst, in the development stage, forecast and mined grade is being assessed from 400 feet block grade maps based on the anticipated working thickness, more accurate control should result from graphical grade variation diagrams drawn for sections close to the main roadways. The working thickness should be related to the colour change or the siderite mudstone marker band at the base of the Main Oolite, i.e. a certain number of feet above and below the colour change or marker. The thickness will generally be constant over considerable distances laterally, except where thinning or channelling is present.

The colour change and siderite mudstone marker at the base of the Main Oolite can readily be recognised by operators, and the light grey shelly beds below the siderite mudstone marker at the top of the Main Oolite are a useful guide in preventing overmining of the roof. Geological advice will still be essential in ensuring

that the correct thickness is being worked. Some control channel and belt sampling is in progress during development.

Whilst grade variation maps and diagrams are considered desirable during the retreat mining of pillars, block grade maps related to the anticipated mining thickness would probably be more reliable than in opencast mining. At a particular time, as pillars are being mined, a higher tonnage would come from a much larger portion of the 400 feet block than in opencast mining.

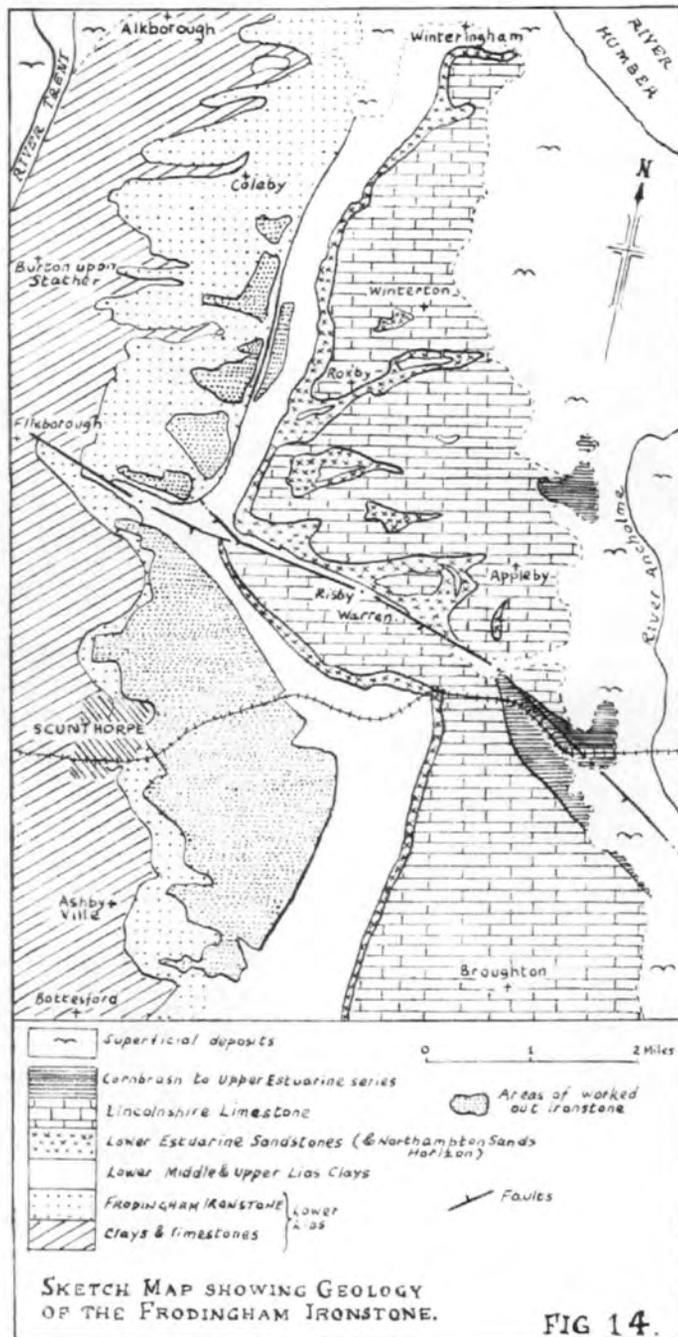
The underground mining thickness is relatively constant, but, because some of the upper beds of the Main Oolite may be left in the roof and because some of the Basal Beds are mined, so as to accommodate machinery, the variation in grade is greater than if the Main Oolite alone were mined. Automated mining machinery, capable of winning the Main Oolite thickness alone, would help to reduce grade variation and grade dilution.

2.L

SUMMARY

Throughout the United Steel Companies Limited mining areas, consistent lithological and chemical characteristics within the Northampton Sand Ironstone are useful in borehole and mine face correlation, and, because chemistry can be related to lithology, grade variation can readily be assessed and accurate grade forecasting comes closer to being a reality. In the existing mining areas and over a large part of the ironstone reserves, easily recognised marker bands allow for selective mining within given limits of grade, and reduced grade variation and improved ore grade can be achieved by mining selectively to win the Main Oolite

thickness of the ironstone. Grade variation in the Main Oolite will be less under deeper cover, where the ironstone is less affected by oxidation, or where oxidation has affected the Main Oolite over its vertical thickness and over a considerable area.



FRODINGHAM IRONSTONE MINING
OPERATIONS

The United Steel Companies Limited mining operations are located along the eastern and north-eastern town boundaries of Scunthorpe, extending from Roxby village in the north to Ashby Ville in the south, a distance of 6 miles (Fig. 16). Other companies are also mining in this area. The United Steel Companies Limited are at present operating three opencast and two underground mines in this region.

3.A GEOLOGY OF THE FRODINGHAM IRONSTONE

I Review of Previous Work

Previous accounts of the Frodingham Ironstone have been given by Hallimond (1925), and its sedimentary origin, petrography and chemistry were discussed. Elliot (1945) discussed the variability of the ore, and Davies and Dixie (1951) classified the ironstone into four principal petrological types, representative of different conditions of accumulation. Detailed stratigraphical and petrological accounts have been given by Whitehead et al. (1952) as part of the Geological Survey Memoir on the Liassic Ironstones.

Under the headings Stratigraphy, Structure, Lithology and Mineralogy, the writer has included certain fundamental observations, similar to those made by previous workers.

II Stratigraphy

The Frodingham Ironstone bed of north-west Lincolnshire, an oolitic, lime-rich, low-grade ironstone, occurs in Lower Lias strata and the geology of the area is shown in Fig. 14, whilst a Dip section (Fig. 15) shows its position in the Geological Succession.

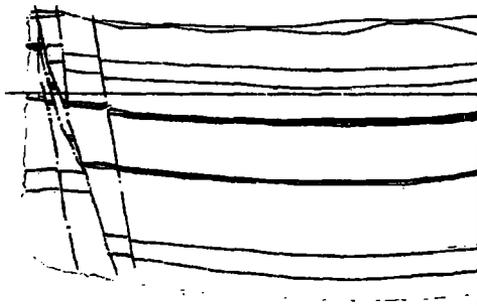
The northern boundary of the bed is close to the River Humber and the ironstone outcrops southwards, through Scunthorpe to Holme in the south, a distance of $10\frac{1}{2}$ miles (Whitehead et al., 1952, p.68). In the Low Santon area, the bed reaches its maximum thickness of 32 feet, whilst near Winteringham in the north it is 13 feet thick, and between Bottesford and Holme in the south it thins to 12 feet (after Whitehead et al., 1952, p.74).

Most of the outcrop area is covered by blown sand, but east of Appleby to the River Ancholme, where the ironstone is over 400 feet deep, strata ranging from Lower Lias Clays to Cornbrash Limestone may be present, and blown sand and peat may overlie all other strata. The ironstone is known to extend eastwards beyond the village of Appleby for a distance in excess of 4 miles, and east of the River Ancholme it is still considered to be workable.

At the present time, economic working limits in the north are expected to be close to Winterton, and deterioration and thinning of the bed in the Ashby Ville area will prevent any further working to the south. Between these places, the ironstone is being won by opencast methods where, at Roxby, the depth of cover now exceeds 120 feet, and between Roxby and Appleby, and

GEOLOGICAL

NE
W



HORIZONTAL SCALE:



VERTICAL SCALE:



Risby, Warren and Low Santon, the ironstone is won from underground mines (Fig. 16).

The ironstone is made up of a series of beds or lenses, generally 1 to 2 feet thick, and certain beds are continuous over several miles, across the north-south extent of the United Steel Companies Limited mining area. The ironstone is generally considered to consist of two main stratigraphical subdivisions, i.e. an Upper Clayey Subdivision and a Lower Limey Subdivision. Beds and lenses in both subdivisions are oolitic, and shell matter is present throughout both subdivisions, but is more abundant in the Lower Limey Subdivision. Between the central mining area and Roxby, the writer has found it convenient to refer to basal ferruginous clays and limestones as 'Transition Beds'. As in the Northampton Sand Ironstone, differences in mineralogy and chemistry reflect differing conditions of sedimentation.

III Structure

Whilst there is a general dip of beds to the east, there is a major deflection of outcrop between Low Santon and Dragonby, where the dip is deflected to the north-east, and this is due to a monoclinical structure affected by a major fault zone, with an approximately W.N.W.-E.S.E. direction, on the north side (Whitehead et al., 1952, p.73 refer). The main fault has a throw to the south of up to 100 feet (Figs. 14, 15 and 16). In the Memoir (Whitehead et al., 1952, p.72, and Plate IV) a roughly parallel

north-throwing fault is shown to the south; close drilling has shown that the fault is, in fact, absent, as is apparently the N.E.-S.W. connecting fault. The Memoir also shows some major N.W.-S.E. faulting in the Low Santon area; further boreholes have been put down in this area since the Memoir was published, and, on the results, there is no direct evidence of such faulting. The maximum dip of 6° to the north-east, and the packing of the contours in the Low Santon area, shown in Fig. 16, are no greater than the packing in the Risby Warren area, where three N.E.-S.W. sections have been drilled with a 200 feet borehole spacing, and have shown no evidence of faulting. Also, the immediate area around Low Santon has been drilled on a 400 feet grid, but, south of the railway, drilling has been less concentrated.

Faults in the ironstone, with throws up to 20 feet, are found throughout the working areas, and typical examples are seen in the Santon Mine area (Fig. 16), where the main direction of faulting varies between N.-S. and N.W.-S.E; and the other direction is mainly N.E.-S.W. North of the monoclinial region, and between it and Roxby, the main direction of faulting is N.W.-S.E.

The N.E.-S.W. direction faults in the Santon area generally have their fault-plane filled with calcite; the N.-S., N.W.-S.E. direction faults are generally marked by a fault zone, consisting of a series of faults and joints, extending laterally up to 30 feet, and often there are open gouges at the main break. The N.E.-S.W. direction faults apparently occurred first, as in places they are offset or broken by the N.-S. and N.W.-S.E. direction faults.

WINTERTON

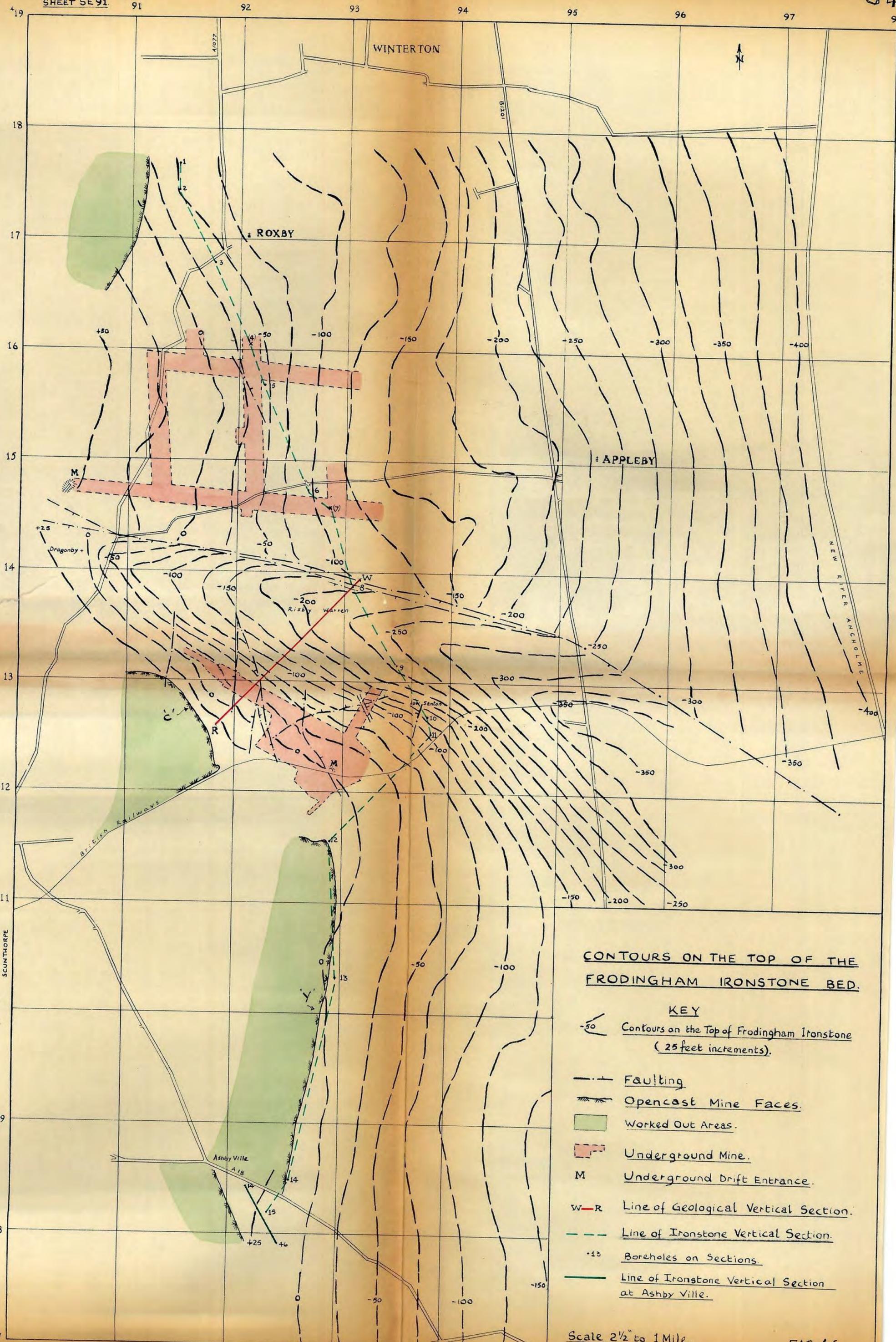
ROXBY

APPLEBY

NEW RIVER ANCHOLME

BRITISH RAILWAYS

Ashby Ville
A/B



CONTOURS ON THE TOP OF THE FRODINGHAM IRONSTONE BED.

KEY

-  Contours on the Top of Frodingham Ironstone (25 feet increments).
-  Faulting
-  Opencast Mine Faces.
-  Worked Out Areas.
-  Underground Mine.
-  Underground Drift Entrance.
-  Line of Geological Vertical Section.
-  Line of Ironstone Vertical Section.
-  Boreholes on Sections.
-  Line of Ironstone Vertical Section at Ashby Ville.

Scale 2 1/2" to 1 Mile.

FIG 16.

+10000
SE 90

SCUNTHORPE

09

08

07

19

18

17

16

15

14

13

12

11

10

09

08

07

Jointing in the Santon Mine area is mainly in a N.N.W.-S.S.E. direction, and the joints may be open or closed; in the Dragonby area, jointing is N.W.-S.E. in direction.

3.B GENERAL LITHOLOGY AND MINERALOGY OF THE IRONSTONE

I Lithology

Most of the ironstone being worked at the present time is unweathered, and is composed essentially of limonite ooliths with calcite shells, in a matrix essentially of calcite, or of siderite and chamosite. Current bedding may be developed, and lensing may be seen in individual beds or groups of beds.

The Lower Limey Subdivision of the ironstone consists mainly of light bluey-grey beds with interbedded brown and dark bluey-brown beds. Quite often, particularly along the middle portion of the mining area, some beds in the Lower Limey Subdivision are markedly pink; beds with densely packed limonite ooliths in the subdivision may appear brown, and whilst some of these beds are composed of clayey ironstone, close examination will show others to have a calcitic matrix. Thick lamellibranch shells (or fragments), mainly Cardinia and Gryphaea, are present throughout these limey beds, and, in certain beds of the subdivision, are noticeably more abundant. Towards Ashby Ville, clayey ironstones are more abundantly interbedded in the Lower Limey Subdivision, and the remaining limey beds are less oolitic and are often rich in pyrite. The base of the Frodingham Ironstone, between the middle working

area and Ashby Ville, is usually marked by the presence of a silty clay or claystone; however, clays and shales below this, together with thin limey beds, may be sparsely oolitic.

In the Roxby area, where the Lower Limey Subdivision has apparently thinned, the underlying series of claystones, shales and limestones, referred to by the writer as Transition Beds, contain ooliths; however, the ooliths become scarcer with depth, and eventually disappear.

The top of the ironstone is quite well-defined, although the first two or three inches of overlying Lias clay or shale may contain sparsely scattered limonite ooliths. The Upper Clayey Subdivision is essentially a brown limonite oolite, but may contain thin beds of limey ironstone and dark blue beds of oolitic mudstone; near outcrop, some of the upper beds tend to be browner as a result of weathering. Shells are present throughout the upper subdivision, and certain layers are more abundantly fossiliferous. Pyrite is visible in some of the more clayey beds of the Upper Clayey Subdivision, and shell fragments may be replaced by pyrite.

Particularly between the central working area and Roxby, there are some beds containing brown pebbles of ironstone and ochrous lenses; these pebbles are composed of re-worked ironstone (Whitehead et al., 1952, p.75). With these pebble beds, or in separate thin bands, pisoliths may be present. Dark blue to black, thin bands or lenses of ferruginous mudstone (usually less than 2 inches thick) are present at various levels, and, whilst

often discontinuous, they can be found at similar horizons, but are more frequently encountered in the Lower Limey Subdivision.

II Mineralogy

The unweathered mineralogical constitution of the Frodingham Ironstone, taken from Davies and Dixie (1951, p.89), is shown in Table 11. The chemical composition of the component minerals of the Frodingham Ironstone is similar to that of the Northampton Sand Ironstone. (Appendix I).

The nature of the ooliths and the shell fragments has been described by Davies and Dixie (1951, pp. 89 and 90), and the following is summarised from their work: The majority of the ooliths are ellipsoidal, with major axes about 0.30 mm. long, and pisoliths up to 5 mm. across are found in thin bands; subangular quartz grains, up to 0.25 mm. across, are present in some of the clayey ironstone.

The writer has found silty quartz to be present in the Basal Transition Beds between the central working area and Roxby, and silty quartz becomes more abundant throughout the ironstone sequence towards Ashby Ville, particularly in the upper 6 feet. Whilst limonite or limonite-chamosite ooliths are more common, kaolinite ooliths may be present at particular horizons, mainly in the upper portion of the Upper Clayey Subdivision.

Where the Upper Beds are oxidised, chamosite and siderite may be replaced by limonite, producing a limonitic limonite oolite.

Davies and Dixie (1951, p.91) have classified the ironstone according to its microstructure into four principal types.

THE MINERALOGICAL CONSTITUTION OF UNWEATHERED FRODINGHAM IRONSTONE

(After Davies and Dixie, 1951, p. 89)

Principal Constituents	Calcite Matrix	Chamosite-siderite Matrix
Limonite - mainly as ooliths	30	35
Quartz - as small grains	-	0-10
Calcite - as shells	20	20
- as matrix	30	-
Siderite	10	17
Chamosite	0-5	18-23

Minor Constituents

Sericite	1	3
Collophane	1.5	2.0
Pyrites	0.4	0.5 (locally up to 7.0)
Rutile	-	0.1

Manganese is present as carbonate, possibly in solid solution in calcite, (Andrews, 1950, Min. Mag., vol.xxix, p. 85).

TABLE 11

I Davies' and Dixie's Classification (1951)

This classification, based on mineralogy, with particular reference to microstructures, is also referred to by Whitehead et al. (1952, p.77). The ironstone is classified into 4 principal types, viz. A, B, C and D, (types A, B and C are 'clayey' ironstones, whilst type D is a 'limey' ironstone). These types are recognisable in thin section and are easily discernible in the hand specimen, although type A, as described by Davies and Dixie (1951), is now rarely found.

Because the types are recognisable from hand specimens, they have formed the basis for core and face logging within the United Steel Companies Limited operations. The principal types are referred to in Table 12, together with the writer's sub-types, again discernible in the hand specimen as well as in thin section, and the main distinguishing features are indicated.

Davies' and Dixie's work gives the impression that type A is widely distributed, both laterally and vertically. This is assumed, particularly, from their mine face sections (1951, pp.92 and 95, and Plate XII). The writer, however, has found that the occurrence of type A, in accordance with its original definition, is relatively scarce. It is sometimes found in the Roxby and Dragonby areas, generally within 3 feet of the top of the ironstone. Other occasional occurrences have been found in the Lower Limey Subdivision. This observation on the now apparent scarcity of type A has also been made by colleagues of the writer,

CLASSIFICATION OF THE FRODINGHAM IRONSTONE

PRINCIPAL TYPES
(Davies and Dixie, 1951)

DETRITUS

MATRIX

HAND SPECIMEN

B	-	Rhomb-shaped crystals of siderite distributed between linearly arranged flakes of chamosite.	Dense dark bluey-grey, granular fracture.
A	Limonite-chamosite oololiths (closely packed), calcite shells - all coated with a thin film of chamosite.	Dominantly granular siderite.	Highly polished brown oololiths in a green sponge-like mass of dark green chamosite.
C	Limonite-chamosite oololiths, and calcite shells partly replaced by chamosite.	Very fine-grained, of chamosite and siderite, some quartz grains at times.	Highly polished brown oololiths scattered irregularly through dark bluish grey matrix.
D	Calcite shells, limonite-chamosite oololiths.	Coarse crystalline calcite (some siderite and chamosite).	Hard light bluey-grey, may be pink or limonite stained. Includes fragments of other types.

SUB-TYPES (Kenna)

CA	Pallid oololiths of chamosite and/or kaolinite with bands of limonite. Oololiths often spastic, lithic, high proportion of oololiths to matrix. Calcite shells - may be replaced by siderite.	Dominantly chamosite.	Pale green or greyish white oololiths - closely packed.
C(b)	Limonite-chamosite oololiths. Shells in places.	High proportion of matrix to oololiths. Finely crystalline siderite and chamosite. Chamosite usually predominant.	Dark blue 'muddy', brown oololiths sparsely scattered.
CM	Limonite-chamosite oololiths and occasional shells and shell fragments.	High proportion of matrix to oololiths. Micaceous iron poor clay minerals, silty quartz.	Dark blue, clayey, shaley and micaceous, oololiths sparsely scattered, some visible quartz.
M	Occasional shells and occasional oololiths.	Opaque clay minerals and silty quartz in places.	Dark blue, shelly and clayey - oololiths rare.
C	Limonite-chamosite oololiths - high proportion to matrix constituents.	Chamosite and siderite.	Generally brown, due to closely packed limonite oololiths.

-sh

Shelly representatives of above.

<u>DL</u>	Shells and shell fragments, limonite oololiths sparsely scattered.	Much calcite.	Hard light grey, sparse limonite oololiths.
L	Shells and shell fragments, very occasional limonite oololiths.	Calcite.	Hard, light grey, resembling limestone.
LM	Some shells - very few limonite oololiths	Some clay and calcite.	Dark blue and light grey, patchy.
Lm		Very fine-grained calcite and clay minerals - patchy.	Hard light-grey mudstone - useful for logging purposes in the Ashby Ville area.
D	Limonite-chamosite oololiths (quite dense) - shell fragments and fragments of other limestone sub-types.	Coarsely crystalline calcite.	May appear brown if oololiths are closely packed.
DC and CD	Limonite-chamosite oololiths, shells.	Chamosite and/or siderite with calcite 50:50.	Difficult to distinguish with certainty, may be brown due to densely packed oololiths.

-sh

Markedly shelly representatives of above.

including Davies and Dixie. There is no obvious explanation for this scarcity of type A, although it is of interest to note that, when Davies' and Dixie's work was written, the ironstone workings were nearer outcrop, and that the larger part of their research was centred on the Roxby area.

Amongst Davies' and Dixie's criteria distinguishing type A from type C is that shells in type A are only coated with a thin film of chamosite, whereas in type C chamosite partly replaces calcite shells (1951, p.91). Whitehead et al. (1952, p.77) place less emphasis on this criterion, and the writer considers that in some cases at least, the coating of shells by chamosite could be an early stage in the replacement of shell calcite by chamosite. Perhaps the main criterion is that closely packed limonite oolites are coated with a thin film of chamosite, with the interstices filled with siderite. In the hand specimen, highly polished limonite oolites are set in green 'spongey' chamosite. Whitehead et al. (1952, p.77) state that the ratio of oolites and fragments to matrix is high in type A.

Because all the criteria indicative of type A are rarely encountered in one specimen, and because Davies' and Dixie's criterion is considered to be too rigid, the writer prefers to refer to all clayey oolitic ironstones under a principal type C.

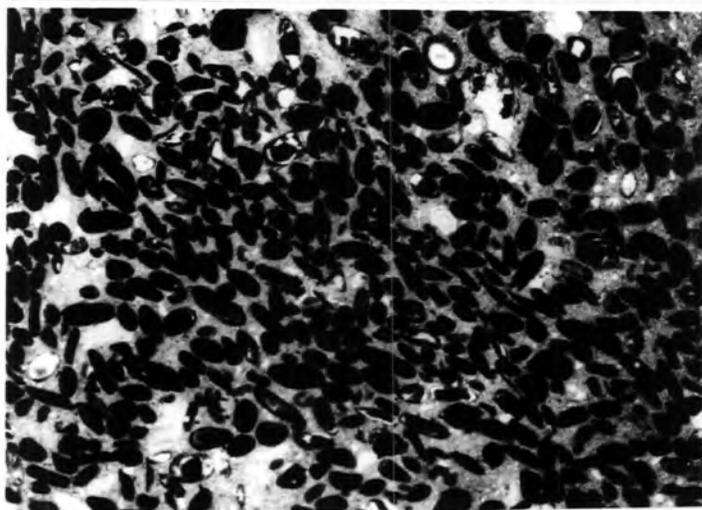
II Ironstone Sub-types

In practice, the writer has found that the principal types C (including ironstones with type A characteristics of Davies and

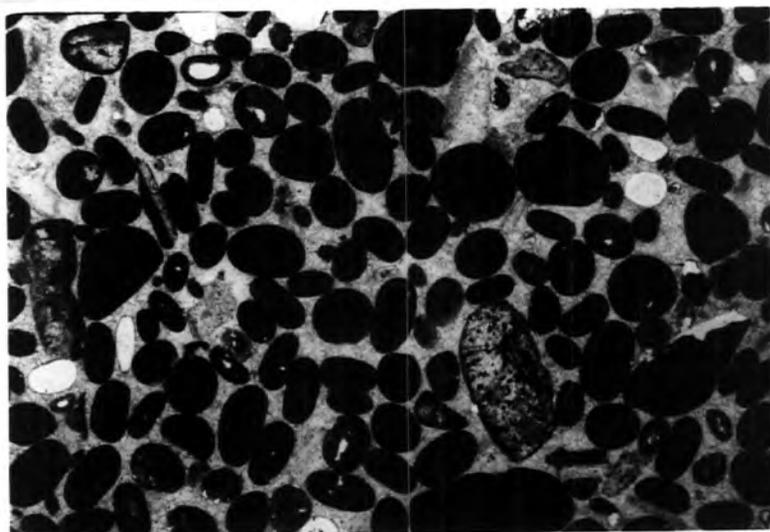
PLATE 9

Photomicrographs of FRODINGHAM IRONSTONE

(Ordinary transmitted light; where shown, depths are from the top of the ironstone).



(i) Mine Face C, Chamositic sideritic limonite oolite (C).
Limonite ooliths in a fine-grained matrix - the ratio of ooliths to matrix is relatively high. Magnification X 20.



(ii) Borehole 6, 8.8 feet, Calcitic limonite oolite (D).
Limonite ooliths in recrystallised calcite matrix, some shell material. Some pisoliths. Magnification X 15.

Dixie, 1951) and D ironstones have certain variable characteristics, very useful in logging and correlating borehole cores and face sections. It is convenient to describe all clayey oolitic ironstones under a principal type C, and, where necessary for logging and correlatory purposes, this principal type can conveniently be sub-divided into the more common sub-types of the writer, distinguishable in the hand specimen and in thin section. Where sub-types are referred to, a brown, densely oolitic clayey ironstone as shown in plate 9(i) is designated as C (this may include Davies' and Dixie's type A), whilst other obviously clayey oolitic ironstones, with various distinguishing features, can be sub-typed and the relevant suffix can be added.

Principal type D can also be sub-typed; when referring to sub-types, a relatively densely oolitic ironstone, with a calcitic matrix, as shown in Plate 9 (ii), is designated D. Whilst there are variations within the principal types C and D, there is every form of gradation between these two types.

The most important sub-types are described below, and it is pointed out that silt-grade quartz (0.01 - 0.05 mm.) is for convenience included with matrix constituents.

(a) Clayey Sub-types

- (i) Sub-type CA, (Plate 10 (i)). Clayey ironstone with green or pallid ooliths, often spastolithic, is typical of this sub-type. The densely packed ooliths are composed of chamosite or kaolinite, (or both), often surrounding a limonite core, or else they are made up of concentric layers of limonite alternating with chamosite or kaolinite. The matrix, which surrounds the ooliths, is dominantly of

chamosite; however, the hand specimen rarely has the dark green spongy appearance of Davies' and Dixie's type A (1951, p.91), the matrix is more often dark blue, and shell material is usually replaced by siderite.

Rocks with pallid kaolinite or chamosite ooliths occur most frequently in the Upper Clayey Subdivision and, in many cases, close to bands containing visible iron pyrites, (Whitehead et al., 1952, p.76, refer to the presence of green chamosite ooliths near to the Sulphur Bed).

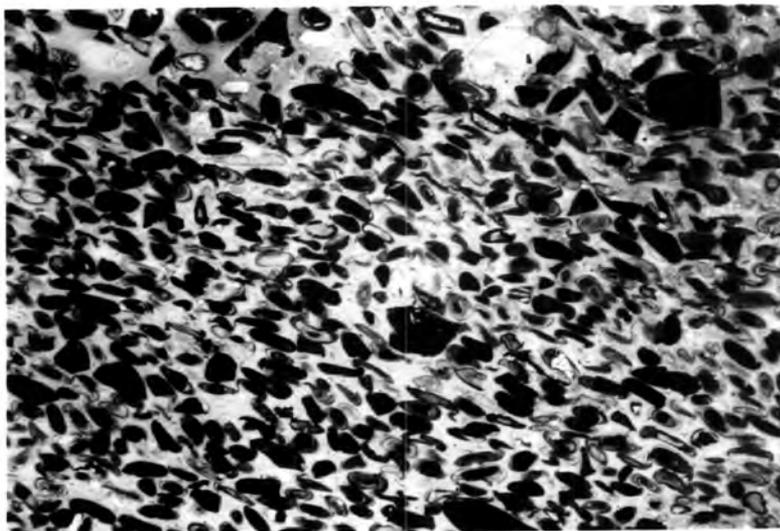
(ii) Sub-type C(b), (Plate 10 (ii)). Rocks of this sub-type are essentially chamositic sideritic oolitic mudstones. The best example of this sub-type is found in the Upper Clayey Subdivision between Roxby and the central mining area, and between 7 and 9 feet from the top of the ironstone, where it forms a continuous bed which may pass laterally into sub-type CM. It is recognised by its dark blue colour, and by the more sparsely scattered brown ooliths. Whilst the ratio of matrix to ooliths is high, gradations occur (Plate 10 (ii)). Microscopic examination shows that limonite ooliths are set in a fine-grained matrix of chamosite and siderite, and the matrix frequently contains a higher proportion of chamosite than siderite, often in excess of a two to one ratio. Silt grade quartz and other clay minerals may also be present. The blue colour in the hand specimen appears to be due to the high ratio of matrix chamosite and siderite to ooliths.

This sub-type is also found at other horizons in the ironstone. South of the central working area to Ashby

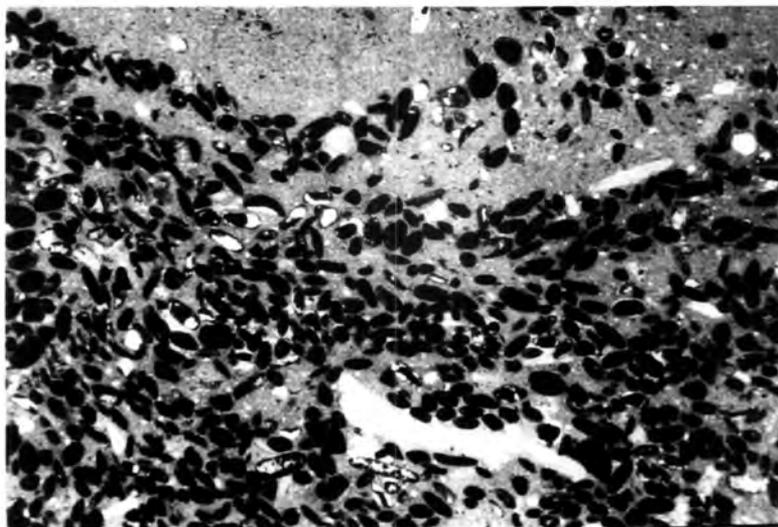
PLATE 10

Photomicrographs of FRODINGHAM IRONSTONE - Clayey Sub-types

(Ordinary transmitted light X 15; where shown, depths are from top of ironstone).



(i) Borehole 8, 0.8 feet, Chamositic sideritic kaolinite-limonite oolite (CA). Extremely spastolithic kaolinitic limonitic ooliths (note limonitic cores) are surrounded by a chamosite matrix with interstitial siderite.



(ii) Mine Face C, Chamositic sideritic oolitic mudstone (C(b)). Limonite ooliths in a fine-grained matrix of chamosite with siderite. Small amount of quartz and shell material. There is a high ratio of matrix (particularly in the upper portion), with a high ratio of chamosite.

Ville, less limey beds come into the Lower Limey Subdivision, and such beds occur in the Santon area, between 2 and 4 feet from the ironstone base. The colour of these beds is brown and blue, the blue portions being formed by lenses and thin layers of sub-type C(b).

(iii) Sub-type CM, (Plate 11 (i)). This sub-type is again dark blue, and sparsely oolitic. It may be difficult to differentiate between sub-types C(b) and CM as seen in the hand specimen, and the suffix can only be added with certainty after microscopic examination. However, as the horizons are continuous, the suffix can often be added by inference. Sub-types C(b) and CM may, at times, be interbedded.

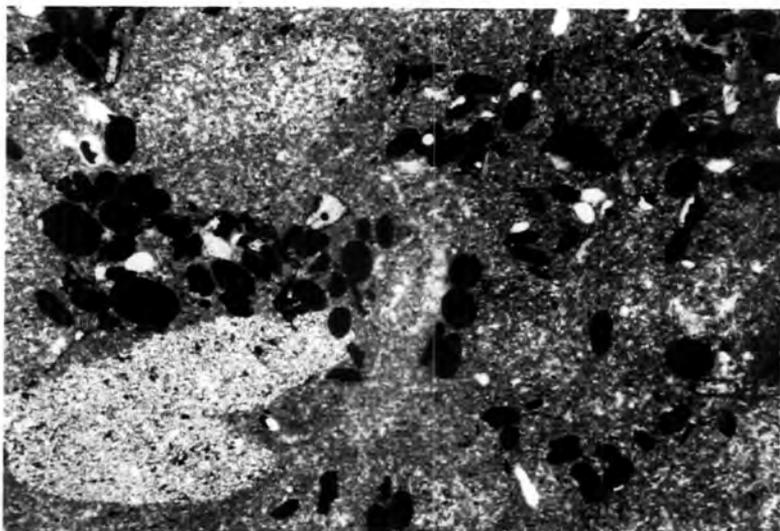
In thin section, the rock is seen to be generally composed of more than 75 per cent. matrix, more than 50 per cent. of which is made up of micaceous clay minerals and silty quartz (which is, at times, in pockets), the remainder is essentially chamosite, and sometimes calcite is present. The detrital constituents are essentially limonite-chamosite ooliths; some sand grade quartz might be present.

In the Roxby area, this sub-type, a dark blue oolitic micaceous claystone or siltstone, occurs in the Transition Beds below the Lower Limey Subdivision, and to achieve a good floor parting the upper parts of the Transition Beds are mined in the underground mine north of the main fault. Beds or intercalations of this sub-type are also present in the Ashby Ville area at several levels.

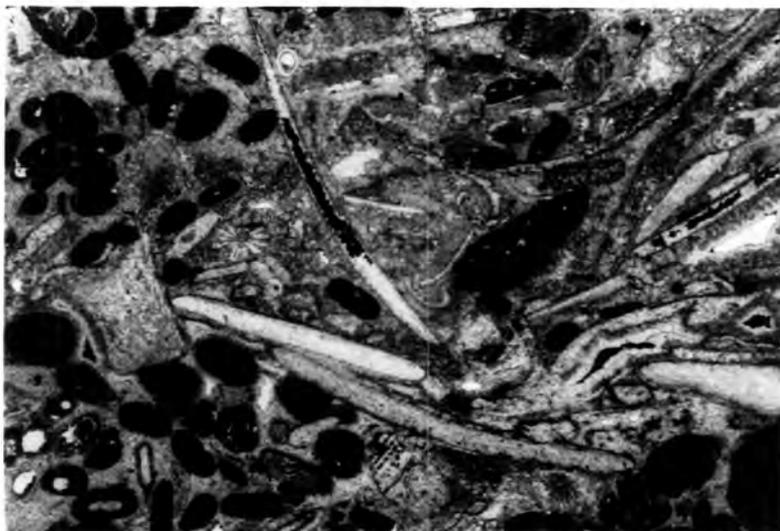
PLATE 11

Photomicrographs of FRODINGHAM IRONSTONE - Clayey Sub-types

(Ordinary transmitted light X 15; where shown, depths are from the top of the ironstone).



(i) Borehole 8, 29.5 feet, Oolitic silty claystone (CM). Sparsely distributed limonite ooliths are set in a matrix mainly of iron and poor clay minerals, with silty quartz (mostly in siltstone pockets) - possibly some chamosite.



(ii) Shelly sideritic calcitic chamositic oolite (C(sh)). There is much matrix siderite with subsidiary calcite, pockets of chamosite mudstone are present. Siderite is replacing shell material, limonite ooliths are sparse in this specimen. (From roof marker band in Santon Mine).

- (iv) Sub-type M refers to the clays, shales and clayey and silty mudstones within the ironstone and below the workable portion. Detrital constituents are rare, and the matrix is composed essentially of non-ferruginous micaceous clay minerals and silty quartz. In the Ashby Ville area, between 4 and 6 feet from the top of the ironstone (Fig. 18), there is a well-marked bed of this sub-type, which represents the 'snap band' referred to by the Geological Survey (1951, pp. 91, 92 and 93), it is often pyritic, and it probably represents deteriorated sub-types C(b) and CM.
- (v) Sub-type C,sh (Plate 11 (ii)). The suffix 'sh' is added when principal type C ironstone and its sub-types are markedly shelly, complete shells may be abundant in some ironstones of this type and shell fragments are easily distinguished in the hand specimen.

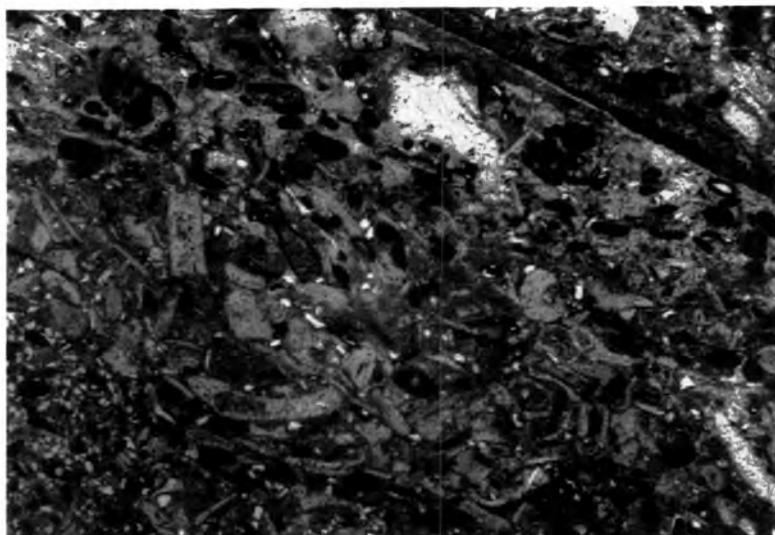
(b) Limey Sub-types

- (vi) Sub-type DL refers to a very limey type D, and the ooliths, usually composed of limonite, are patchy or sparse. The proportion of calcitic matrix is high, and shell detritus may be abundant. In Fig. 17, reference to this sub-type is omitted for clarity; it is, however, referred to in the section in Fig. 18.
- (vii) Sub-type LM (Plate 12 (i)). Clayey limestones, often with comminuted shell material, sparsely oolitic (limonite ooliths) and silty, are typical of this sub-type, in which matrix siderite and chamosite are very sparse. Representatives of this sub-type are found in the Transition Beds of the Roxby area.

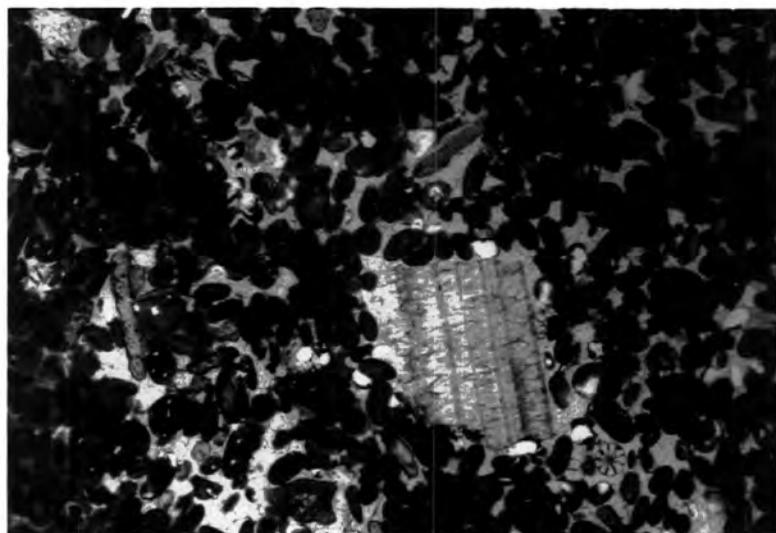
PLATE 12

Photomicrographs of FRODINGHAM IRONSTONE - Limey Sub-types

(Ordinary transmitted light X 15; where shown, depths are from the top of the ironstone).



(i) Borehole 8, 30.3 feet, Calcitic clayey silty oolitic calcarenite (LM). Comminuted shells with limonite ooliths in a matrix mainly of calcite, with clay minerals and silty quartz.

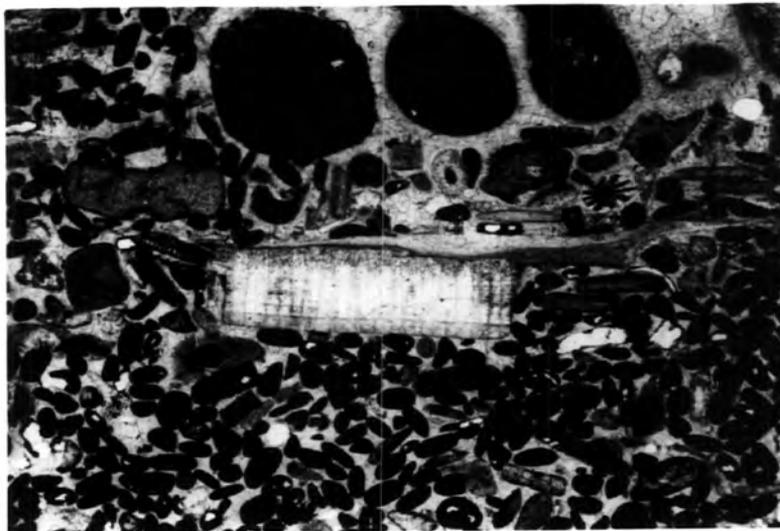


(ii) Borehole 8, 26.4 feet, Calcitic chamositic limonite oolite (DC). Banded limonitic ooliths with some shell material set in a matrix composed of calcite - and chamosite - rich pockets (in nearly equal amounts) with smaller pockets of siderite. Pyritic.

PLATE 13

Photomicrograph of Limey FRODINGHAM IRONSTONE

(Ordinary transmitted light X 15; depth is from top of ironstone).



Borehole 6, 18.2 feet, Shelly calcitic limonite oolite (D,sh).
Limonite oolites and shell material in a matrix of calcite, with
opaque limonitic pockets (possibly oxidised siderite).
Oxidised chamositic mud infills some of the shells (c.f. size of
oolites with those in Plate 9 (ii)).

- (viii) Sub-type Lm is a limey mudstone (useful for logging in the Ashby Ville area - Fig. 18).
- (ix) Sub-type L, limestones with few or no ooliths, usually within or below the Transition Beds.
- (x) Sub-types CD and DC (Plate 12 (ii)). In rocks of this sub-type, sometimes difficult to distinguish in the hand specimen, the matrix is composed of chamosite or siderite, or both, with calcite in nearly equal amounts. In Figs. 17 and 18 this sub-type is included under type D for clarity.
- (xi) Sub-type D,sh (Plate 13). The suffix 'sh' is added when principal type D ironstone and its sub-types are markedly shelly - shells and shell fragments are easily visible in the hand specimen.

NOTE: Other designatory letters or abbreviations which can be used separately or in conjunction with the principal types and sub-types are:

P - where pisolite or pebble beds and bands occur, (the latter being found mainly within principal type D ironstone)

Su - where pyrite is visible.

The predominant colours of the hand specimens and core samples are often referred to in logging.

III Application of the Writer's Classification System

The above data, which is co-ordinated in Table 12, has proved useful, not only in correlating mine face sections, but also in logging and correlating the many borehole cores obtained in the United Steel Companies Limited drilling operations. Where hand specimens or borehole cores have been classified with little or no reference to thin sections, it is useful to apply the term 'log

type' or 'as logged'.

Table 13 shows five boreholes logged in accordance with the classification, together with their chemical analyses: selected samples, examined in thin section, from Borehole 8 are described in Appendix III, and one of the boreholes has been split and analysed in relation to the log types present.

The basic chemistry of the principal types and sub-types is shown on a three component diagram in Fig. 19, where the analyses for selected samples have been plotted as Fe, CaO and SiO₂ ratios.

3.D

CORRELATION BY ROCK TYPES AND MARKER BANDS

I General Correlation

Davies and Dixie (1951, pp. 94, 95, and Plate XII) have referred to the ironstone being a lensed deposit, and the beds being composed of lenses of types A, C and D, with very discontinuous lenses of type B. They have shown the continuity of beds across the Roxby mining area, (1951, p.95), and they have also shown (1951, Plate XI) a correlation of quarry sections from Thealby to Ashby Ville; from the latter, whilst lateral variation is apparent, continuity of beds is not clearly shown, although in the northern sections continuity of certain beds can easily be inferred.

In Fig. 17, the writer has attempted to show the vertical and lateral variation of rock types within the ironstone between Roxby and Ashby Ville. This is a generalised correlation, and lensing of particular beds may be more severe, and intermediate borehole data, where available, has been omitted for clarity. The character of a particular bed or horizon may vary in differing degrees laterally; because of this, and the effects of lensing, continuity of such beds and horizons, and thinner beds, is inferred from the continuity in

lithology of the overlying and underlying beds. Apparent continuity of type or sub-type may indicate continuity of horizon rather than actual bed continuity. It is seen that certain beds are continuous over considerable distances, and particular horizons can be traced across the length of the section. Selected samples from boreholes 6 and 8 are described in Appendix III.

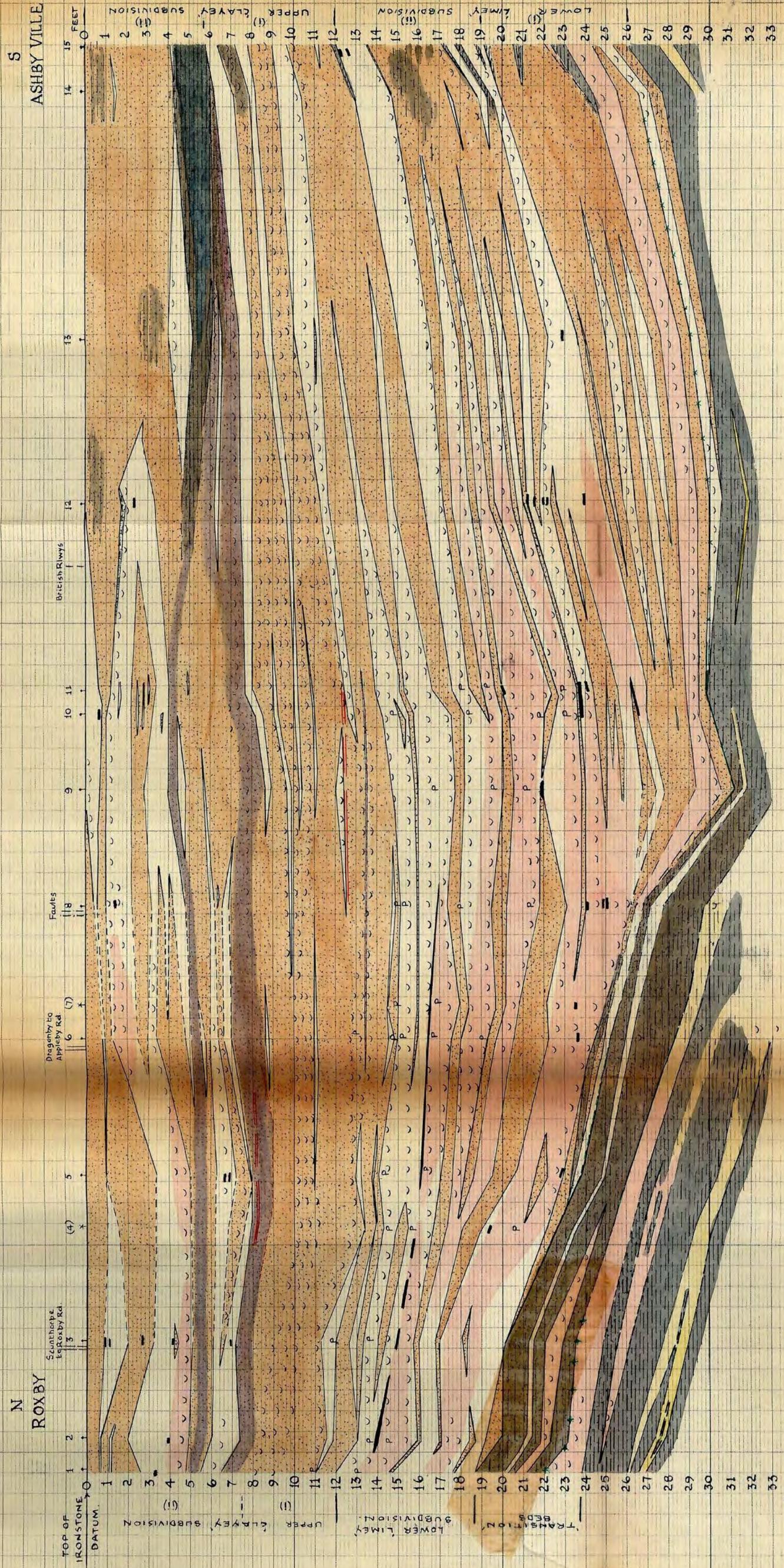
From the section in Fig. 17 it is seen that the bed of dark blue sub-type C(b) at 7 feet from the top of the ironstone in borehole 1 is continuous as far as Ashby Ville, where the horizon becomes shaley and the rock is classified as sub-type M. Other beds, for instance the types C below this, are continuous across the section, although lenses of type D are present. Continuity of shelly types C and D is also evident, as is the continuity of pink types D.

Between Roxby and borehole 8 (Fig. 17), the CM beds underlying the main limey sequence of the Lower Limey Subdivisions are easily recognised when mapping; however, between boreholes 8 and 9, correlation of CM beds is not clear, and whilst all the evidence at the present time suggests the correlation as shown, it infers that the combined thickness of the Lower Limey and Upper Clayey Subdivisions has thinned by 4 feet in a horizontal distance of 2,800 feet. Further, accepting this correlation, the CM beds appear to pass laterally southwards into sub-type M shales and clays. The alternative correlation would be to assume that the CM beds between 27 and 30 feet in borehole 8 are related to the C and D beds in borehole 9, between 27.8 feet and 31.2 feet. This would suggest a more marked facies change than in the previous case, within the horizontal distance of 2,800 feet. In the case of the preferred correlation, the suggested thinning of the bed towards borehole 8

VERTICAL SECTION THROUGH THE FRODINGHAM IRONSTONE.

ROXBY TO ASHBY VILLE.

SHOWING GENERALISED CORRELATION BY ROCK TYPES.



KEY:

- | | | |
|--|---|--|
| <p>C Brown, blue and green clayey oolitic, includes sub-types.</p> <p>C(b) Main dk blue, chamositic sideritic oolitic mudstone & chamosite horizons of upper clayey subdivision.</p> <p>CM Dk blue oolitic claystone & siltstone of transition beds, and 'snap band' of upper clayey subdivision.</p> <p>M Shales & clays, only main horizons within the transition are shown, eg 'snap band'.</p> <p>B Dk blue and black, non-oolitic chamositic sideritic mudstone.</p> | <p>D Light grey-wakes & pink limey oolitic beds.</p> <p>L Limestone, & clayey limestone - few or no oolites.</p> <p>P Pisolite bands & pisolite bands.</p> <p>)) Shelly representatives of types C & D.</p> | <p>--- Roof Markers, underground Mines.</p> <p>— Roof Position, "</p> <p>— Floor Markers, "</p> <p>— Floor Position, "</p> <p>X X X Floor Position & 'Marker' in Open-cast Mine in South, (Old man rack).</p> <p>+ + + Floor Position & 'Marker' in Open-cast Mine at Rosby.</p> |
|--|---|--|

HORIZONTAL SCALE:
0/1 = 100ft
0/1 = 50ft

Boreholes:
x Underground face log point.
- - - Boundaries not seen or floor.
- - - Boundaries difficult to determine.

NB. For line of section see Fig 16.
Selected samples from Boreholes 6 & 8 are described in Appendix III.

and the thickening of the base at borehole 9 could have been caused by channelling and greater subsidence in the region of borehole 9 and to the south of it. The progress of the underground mining operations north and south of the main W.N.W.-E.S.E. fault zone will eventually provide further evidence as to the correct correlation.

It will be seen from the section that type B, although thin, occurs at similar horizons in various boreholes. In practice, whilst type B may show much discontinuity, it can be used as a marker band in certain areas, and one band (i.e. at 16 feet from the top of the ironstone in borehole 5) in the Dragonby mining area is useful when considering the behaviour of beds above and below it. At various consistent horizons, particularly in the north, P bands (pebbles and/or pisoliths) are also useful when correlating borehole cores and face sections and in determining the behaviour of adjacent upper and lower beds. Pyritic bands (not indicated in Fig. 17) are useful in places as an aid in borehole and face correlation, and this is illustrated in Fig. 18.

Weathering prevented Davies and Dixie (1951, p.94) from accurately correlating the Ashby Ville ironstone with the northern sections. It is seen from the section in Fig. 17 that the ironstone sequence at Ashby Ville can be correlated with the sequences to the north.

II Marker Bands and Mining Horizons

(a) Underground Mining Operations

In the underground mining operations north of the main fault

zone, the blue sub-type C(b) between 7 and 9 feet (Fig. 17) from the top of the ironstone is used to locate the mine roof position, the roof being located approximately 6 to 9 inches up from its base, where there is frequently a parting.

The sub-type CM sequence in the Transition Beds is useful as a 'floor' marker, and the floor position is usually 2 to 3 feet below the top of the CM sequence; the floor is usually a hard pink type D or sub-type DL.

Plates 14 (a) and (b) are of underground face sections in the Dragonby underground mine, and represent faces 2,000 feet apart, and the strata shown in Plate 14 (b) is represented on the section in Fig. 17 (face log point (4)). It is seen that there is a relationship in lithology and log type between the two faces; the blue C(b) bed in the roof and the basal CM beds are clearly visible. Below the roof, at the base of the blue C(b) bed, thin bands of pyrite are frequently encountered in the Dragonby area, and these are marked W in the plates. Some very local lensing is seen in Plate 14 (b) between 11 and 12 feet and between 5 and 6 feet from the floor, (the stave is resting on the floor).

In the underground mining operations south of the main fault zone in the Santon area, where a thicker sequence of ironstone is left in the roof, the thin C,sh band, between 13 and 14 feet from the ironstone top, is a useful marker in determining the roof position normally located about 1 foot above this band (Fig. 17). This marker band is generally less than 3 inches thick and is a shelly sideritic calcitic limonite oolite, often with pockets of chamosite mudstone (Plate 11(ii)); it has a distinctive yellowy-

PLATE 14

DRAGONBY UNDERGROUND MINE

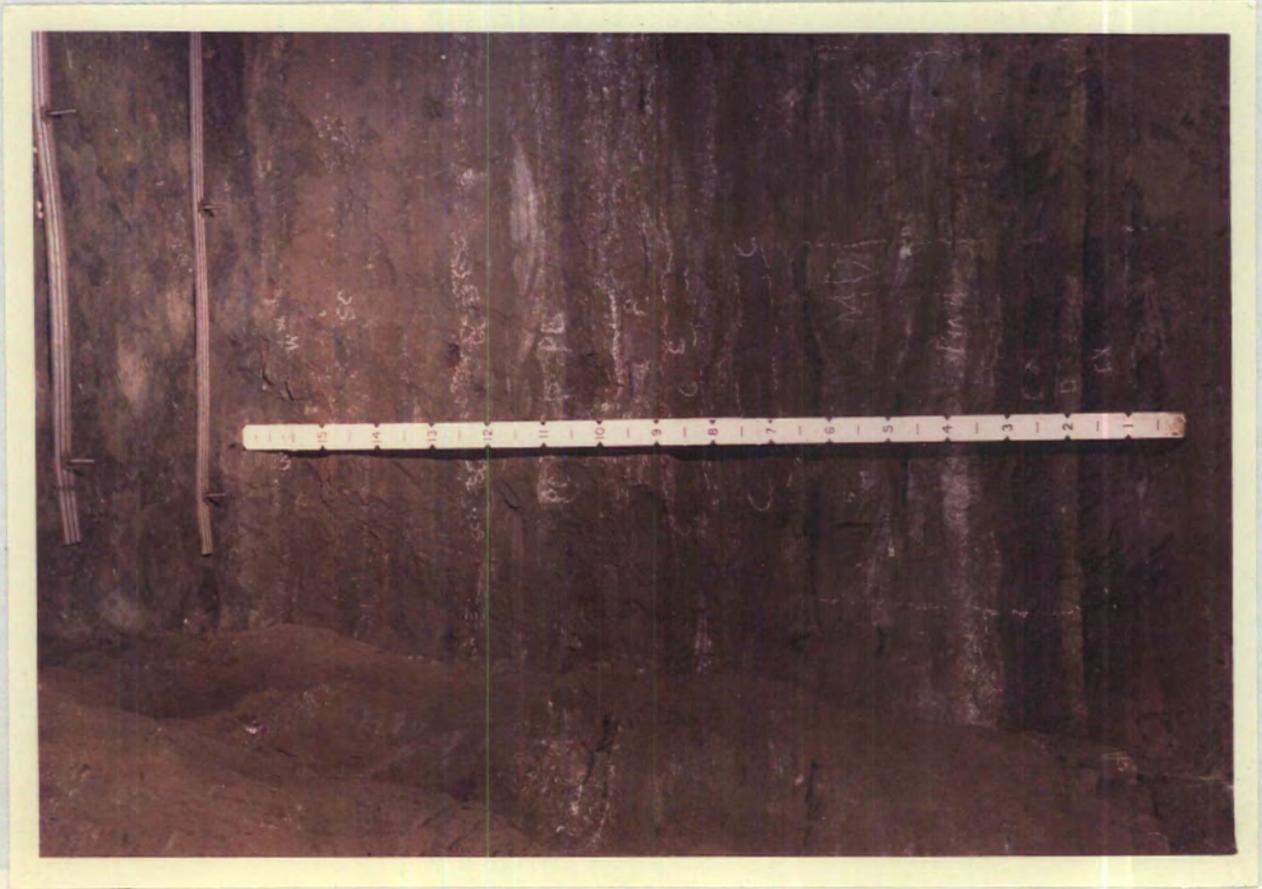
Face Sections 2,000 feet apart

Showing continuity of strata and lensing

(a)



(b)



C(b)
 C+Su
 C
 Csh
 C
 Csh
 C+D
 Csh+P
 C
 DCsh
 Dsh+P+B
 C
 D Pink
 C
 D Pink
 B
 D Pink
 (Banded)
 +B lenses
 Dsh Pink
 +DL
 C+E(b)
 CM
 D
 CM
 D+LM Pink

white appearance, apparently due to re-crystallised calcite, and it may contain some ankerite. It has a remarkably rich fossil fauna, including the following (identified by J. Potts - United Steel Companies Limited Research and Development Department):-

Lamellibranchs - Cardinia sp., Pleuromya sp., Pseudopecten cf aequivalvis, Pecten sp., Gryphaea sp., and Pholadomya sp.;

Brachiopods - Spiriferina sp., Rhynchonella sp. and a Terebratula type; Gastropods - long- and short-spined types, and microfossils.

This band is recognised as far east as Appleby, although not in every borehole. Its northern and southern extents are not accurately known, and in the north in borehole 5 (Fig. 17) it is possible that the type D at 13 feet from the top of the ironstone is a lateral derivative of the C,sh band, recognised at approximately the same level in borehole 6.

In Fig. 17, the brown and blue type C beds (which include sub-type C(b)), seen for instance in borehole 9 between 27.8 feet and 29.3 feet from the ironstone top, are useful in determining the depth to the floor. In the underground mine south of the main fault zone, the top of these beds is generally 4 feet above the floor in the western part of the mine, but to the north and east the depth is nearer 3 feet, and it is seen from the section that the top of these beds is still well-defined towards Ashby Ville where the beds are thicker. The behaviour of these beds to the north is less clearly defined; the correlation shown on the section suggests that they are of a much reduced thickness in the vicinity of borehole 8. The mine floor is often on a thin D type ironstone; however, presumably as a result of lensing, it is on clay (sub-type M) in borehole 10.

(b) Opencast Mining Operations

In the opencast mine west of Roxby village, the floor position is located in the Transition Beds on a hard limey parting within the CM sequence, and in borehole 1 (Fig. 17) the floor is at 20.5 feet from the top of the ironstone, where it is at the top of a hard pink D,sh bed.

In the opencast mines to the south, the floor is at the top of a type D ironstone, in places shelly, (Fig. 17), which may be equivalent to the 'Old Man Rock' referred to in the Memoir (Whitehead et al., 1952, p. 92).

III Vertical Section - Ashby Ville Area

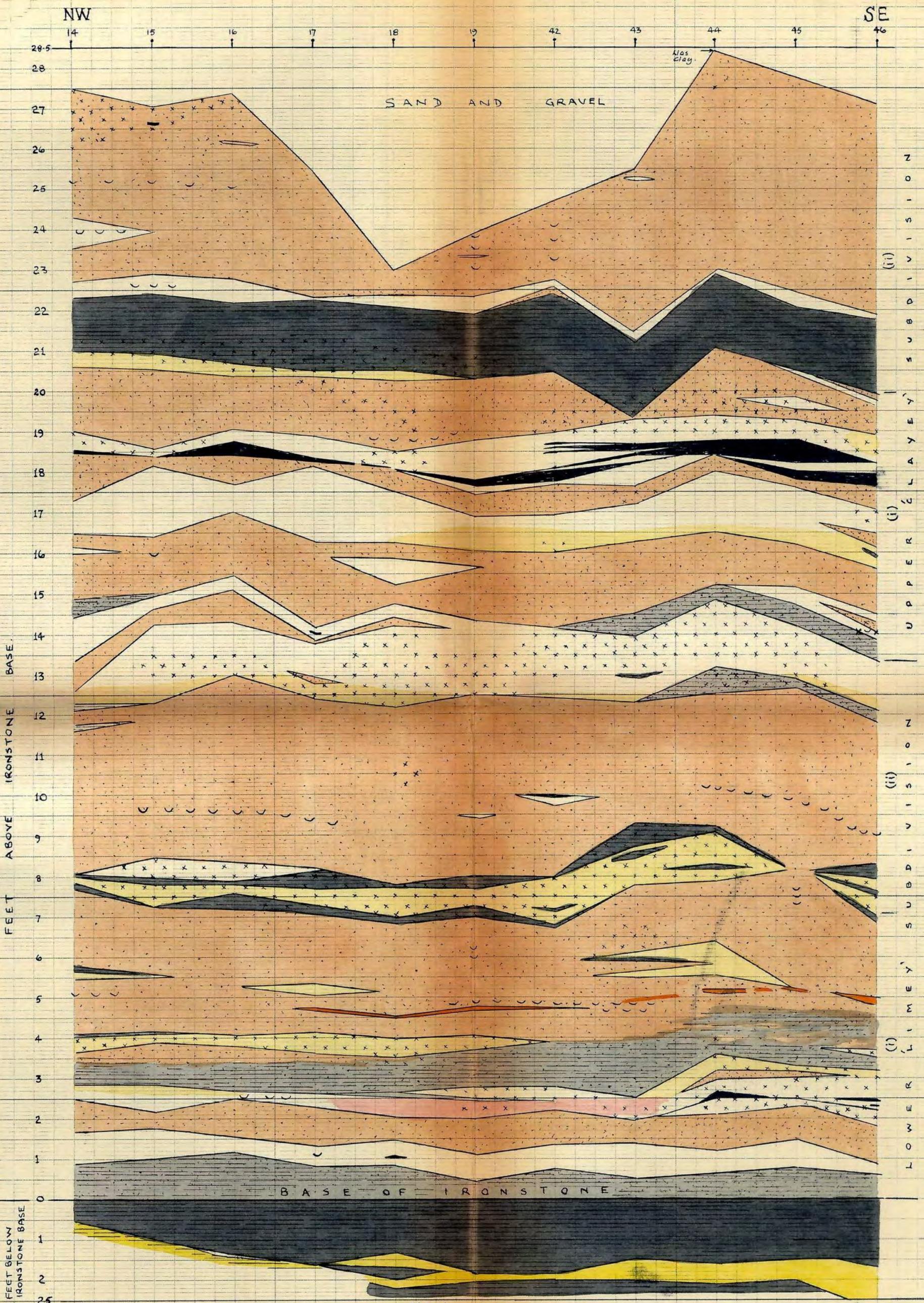
Fig. 18 shows a vertical section in the Ashby Ville area, and the information has been plotted from boreholes at 200 feet spacings. This section again shows the continuity of particular strata, and a good example of small scale lensing is shown. The principal type C has not been fully sub-typed in this section, and whilst lenses and intercalations of sub-types CM and C(b) are relatively abundant, only the main CM beds are shown.

3.E IRONSTONE SUBDIVISIONS AND LATERAL VARIATION

I General

As previously stated, the ironstone can be divided into an Upper Clayey Subdivision and a Lower Limey Subdivision. These subdivisions reflect the proportions of the principal rock types C and D, except in the Ashby Ville area. In the northern area, a third main subdivision can be recognised, i.e. Transition Beds,

ASHBY VILLE AREA
SHOWING MAIN ROCK TYPES (AS LOGGED)



KEY:

	C	Brown, Blue, Pink, clayey oolite, includes sub-types		D	Limey oolite, light grey and some pink.		Visible Iron Pyrites
	CM-M	Blue & Dk Blue-grey oolitic claystone, shale & siltstone. (ooliths sparse) - Main Horizons only shown.		DL	Very Limey oolite (ooliths sparse).		Main shelly Horizons.
	M	Blue Grey Shales, Clays & siltstones.		L	Limestone including LM, clayey Limestone.		Boreholes - (200ft grid)
	B	Non-oolitic Chamositic Sideritic Mudstone. Dk Blue-black, 'frinty'.		Lm	Light grey Limey mudstone.		HORIZONTAL SCALE 0 100ft 200ft

NB FOR LINE OF SECTION SEE FIG 16

FIG 18.

below the Lower Limey Subdivision. Further subdivision into sub-units is possible within the Upper Clayey and Lower Limey Subdivisions. Similar rock types occur in varying proportions within the Upper Clayey and Lower Limey Subdivisions, whereas, in the Northampton Sand Ironstone, particular subdivisions reflect particular rock types. The subdivisions are shown on the sections in Figs. 17 and 18.

II Transition Beds

In the Roxby and Dragonby mining areas in the north, these beds occur below the Lower Limey Subdivision and above the lower clays and limestones. The basal boundary is not always clearly defined as the lower clays and limestones are at times sparsely oolitic. The upper junction of these dark blue oolitic claystones (sub-type CM) with interbedded ferruginous limey oolites (sub-types DL and LM) is well marked by a colour change, as the overlying type D beds are usually light grey (sometimes pink) except for places where a thin brown type C may be present. South of borehole 8 (Fig. 17), the correlation suggests that these beds pass laterally southwards into more sparsely oolitic clays and shales.

III The Lower Limey Subdivision

The base of this subdivision is readily recognised from the underlying Transition Beds in the north, and the underlying clays and shales in the south. This subdivision is essentially composed of type D, with sub-types D,sh and DL ironstones, and in the north it is often pink; thin beds of type C ironstone are also present, and in the south type C is predominant over type D. The

subdivision can be further subdivided in the south into an upper and lower sub-unit (Figs. 17 and 18). The lower sub-unit (i), consisting essentially of type C ironstone, thickens to the south where it becomes more clayey and silty. The sub-unit is often bluey in colour due to the presence of sub-type C(b), and in the south sub-type CM may be present. The upper sub-unit (ii) is composed essentially of type D ironstones, except in the south where type C ironstones are predominant.

In the central and northern mining areas, the upper sub-unit may contain continuous P bands (of pebbles and/or pisoliths), and lenses and bands of type B ironstone are present in the upper and lower sub-units.

The top of the Lower Limey Subdivision in the north is generally more readily recognisable than in the south; however, mixed clayey and limey CD and DC ironstones, often shelly, may be present. A pisolitic band is generally found at the upper boundary in the north. In the south, for convenience, the top of the subdivision is taken at a lower horizon than in the north, as lensing has introduced more type C ironstones into the sequence in the south. The true boundary, as seen in the north, represents a horizon 2 feet higher than the boundary at Ashby Ville, hence the upper boundary for this subdivision, across the mining area, is not in stratigraphical continuity (Fig. 17).

IV The Upper Clayey Subdivision

This subdivision consists essentially of type C ironstones, including sub-types C(b), CA and C,sh; however, lenses of type D are present, particularly in the north. The base of the

subdivision from north to south is not in stratigraphical continuity. This subdivision can be divided into two sub-units (Figs. 17 and 18); the lower sub-unit (i) is taken from the base of the blue sub-type C(b) in the north and the base of the blue shale M in the south, to the top of the Lower Limey Subdivision. In the south, this sub-unit contains a higher proportion of type D ironstone, and in the north there are several thin pyritic bands, which are useful for underground face correlation in areas north of the main fault zone. The upper sub-unit (ii) is easily separable from the overlying clays, although the first two or three inches of the clay are sparsely oolitic. Type D is abundant in this sub-unit in the north and central mining areas, and kaolinite and chamosite ooliths are found at some horizons, (generally near pyritic horizons); thin pyritic bands or accumulations of pyrite are found at various horizons within the sub-unit.

V Lateral Variation of the Ironstone

Lateral variation within the ironstone between Roxby and Ashby Ville is shown in Fig. 17. Excluding Transition Beds, the ironstone is 19 feet thick at Roxby, and in the central mining area around borehole 9 the ironstone reaches a thickness of 31 feet. To the south, the bed thins to 26 feet at Ashby Ville. Thickening in the central part of the mining area reflects an increased thickness in the Lower Limey Subdivision, with some thickening of the Upper Clayey Subdivision. Variation of the beds and rock types within the subdivisions and sub-units, from north to south is readily seen in Fig. 17. East of a line between Low Santon and Appleby, boreholes have shown that the ironstone

maintains a thickness of between 27 feet and 30 feet as far as the New River Ancholme.

3.F

THE CHEMISTRY OF THE IRONSTONE

I General

The chemistry of the ironstone has been referred to by Elliot (1945) and in the Memoir by Whitehead et al. (1952, pp. 78 - 81).

Since 1958, many boreholes have been drilled close to, and to the east of, the present United Steel Companies Limited opencast and underground workings. Ironstone core recovery from these boreholes is frequently between 95 and 100 per cent. (core diameters are 101 mm. or 116 mm.) and as a result, more reliance can be placed on the analytical data obtained from these cores than on that obtained from previous drilling operations.

As in the United Steel Companies Limited operations in south Lincolnshire, each foot of the ironstone core, after drying to 105°C., is analysed for total iron, lime, silica, and sulphur (silica is determined as a perchloric acid insoluble and graphically converted to 'true' silica). At times, more detailed analyses may be made for such constituents as alumina, magnesia, manganese, quartz and ferrous iron. Composite analyses for alumina, magnesia and, at times, manganese are made for varying thicknesses, e.g. the opencast mining thickness, or underground mining thickness.

An average chemical analysis for the total thickness of the ironstone (30.6 feet) close to mine face C (Fig. 16) is:

Total Fe	23.4%	} Dried at 105°C.
SiO ₂	7.3%	
CaO	23.4%	
Al ₂ O ₃	4.4%	
NgO	1.7%	
S	0.44%	
Moisture	11.0%	

N.B. All further analyses are on a dry (water free) basis.

II Vertical Chemical Variation within the Ironstone

Vertical chemical variation within the ironstone has been shown by Elliot (1945, p.22). His analyses are for individual strata which, although not stated, will to a large degree reflect the different ironstone types and sub-types.

In Table 13, the chemical analyses and log types are shown for five selected borehole cores (four of which are on the section in Fig. 17). Normally, borehole and face analyses are for each foot from the top of the ironstone, and in Table 13 this is the case in four of the boreholes, however, in the fifth borehole the chemical analyses are related directly to the log types; subdivisions and sub-units are also indicated. Vertical variation in chemistry, principally in terms of variation in lime content, is shown in Fig. 20.

From the data shown in Table 13, the Upper Clayey Subdivision is seen to contain generally higher iron values than the Lower Limey Subdivision, and generally higher silica values occur in the upper sub-unit (ii) of the Upper Clayey Subdivision than in the lower ironstone sequence, except where Transition Beds

are present. At Ashby Ville, however, high silica figures are also found in the Lower Limey Subdivision, and in the central mining area towards Ashby Ville there is a tendency for high silica values to be found in the lower sub-unit (i) of the Lower Limey Subdivision (Table 13 and Fig. 20).

The data shown in Table 13 and Fig. 20 shows, as might be expected, that higher lime values are typical of the Lower Limey Subdivision; however, particularly in the central mining area towards Roxby, high lime values occur at several horizons in the upper sub-unit (ii) of the Upper Clayey Subdivision. Sulphur values in excess of 0.5 per cent. are found at various horizons in the Upper Clayey Subdivision in both clayey and limey ironstones. In the south, towards Ashby Ville, sulphur values in excess of 0.5 per cent. are frequently encountered within the Lower Limey Subdivision also (Table 13 and Fig. 20).

Manganese values are generally higher (more than one per cent.) in the pink type D ironstones of the Lower Limey Subdivision, and Davies and Dixie suggest that manganese is present as a carbonate, possibly in solid solution in calcite (Davies and Dixie, 1951, p.89, q.v. Andrews, 1950, Min. Mag., Vol. xxix, p.85). The higher silica and alumina values are associated mainly with C(b), CM and B ironstones.

There is considerable chemical variation within the subdivisions and sub-units, but chemical data can be broadly related to the lithological subdivisions and sub-units.

III The Relationship between Chemistry and Ironstone Types and Sub-types

Using the Companies' analyses for Total Fe, CaO and SiO₂, the

relationship between chemistry and rock types and sub-types can be shown. In Fig. 19, the analyses of selected rock specimens, the majority of which have been examined in thin section and classified into types and sub-types, have been calculated as proportions and plotted as Fe, CaO and SiO₂ ratios: more detailed chemical and petrological data is shown for some of these specimens.

Also plotted proportionately on the three component diagram are some analyses for one foot increments of borehole cores, and the log type is shown; whilst there is a general masking effect, due to variation in mineralogy over the foot thickness, the analyses plot closely to those for similar types of ironstone, classified from thin section examination.

It is seen that the principal types and sub-types fall into quite well-defined groups, and from the data plotted in Fig. 19, they show the following ranges in composition:

Principal Type	Sub-type	Fe	CaO	SiO ₂
D-----	DL, sh.	15 - 17	77 - 84	0 - 6
	D and D, sh	20 - 44	49 - 78	0 - 12
C-----	CD and DC CA, sh and C, sh (except no. 35)	42 - 58	30 - 46	10 - 23
	C and CA	47 - 73	15 - 34	8 - 34
	C(b)	35 - 55	11 - 20	29 - 53
	CM	15 - 30	1 - 14	57 - 79
	M	9 - 23	2 - 13	71 - 89

ANALYSES (UNITED STEEL COMPANIES LTD) PLOTTED AS Fe, CaO, SiO₂ RATIOS.

CHEMICAL & PETROLOGICAL DATA ~ SELECTED SAMPLES.

NO. TYPE SUB-TYPE	ANALYSIS			MATRIX CONSTITUENTS				DETRITUS ooliths/shells	DESCRIPTION		
	Total Fe	CaO	SiO ₂	Approx % Calcite	Siderite	Chamosite	Quartz				
19 C	29.5	7.1	8.5	4.5	70	30	-	75	25	Sideritic Chamositic Oolitic Mudstone	
5 Csh	26.5	17.2	18.0	6.6	30	55	5	70	30	Sideritic chamositic chamositic shelly oolite.	
13 C(b)	28.8	6.4	20.0	9.6	60	5	90	70	30	Chamositic Oolitic Mudstone	
23 C(b)	19.0	10.5	22.0	9.7	80	5	80	85	15	Chamositic Sideritic oolitic mudstone (some chamositic oolites)	
1 CAsh	20.6	22.8	6.2	2.8	30	20	50	60	40	Sideritic Chamositic oolitic shelly kaolinitic oolite.	
32 CMsh	17.7	8.1	34.9	10.0	65	5	45	50	60	Chamositic shelly oolitic siltstone	
15 DC	23.0	23.5	7.9	4.3	35	50	30	70	30	Calcitic Sideritic Chamositic shelly oolite.	
9 O	18.4	29.2	6.5	3.9	35	100	-	80	20	Calcitic Oolite (some shells)	
17 DLsh	7.6	7.550	3.1	1.9	30	5	5	30	70	Calcitic Oolitic kaolinitic oolites	
37 Msh	11.5	1.9	44.4	16.3	95	-	20	45	30	50	Chamositic shelly oolitic siltstone.

Nos 1-42 Analyses for rock specimens classified from thin sections.
 @ 43-55 Analyses for 1ft borehole core increments, and log types.

> 20% Quartz in Matrix
 Kaolinitic oolites present.
 Some Chamositic oolites present.

Higher Proportion of siderite in matrix than is normal for C.A.
 C with shells and more than 20% Quartz in an oxidised matrix (constituents difficult to distinguish).

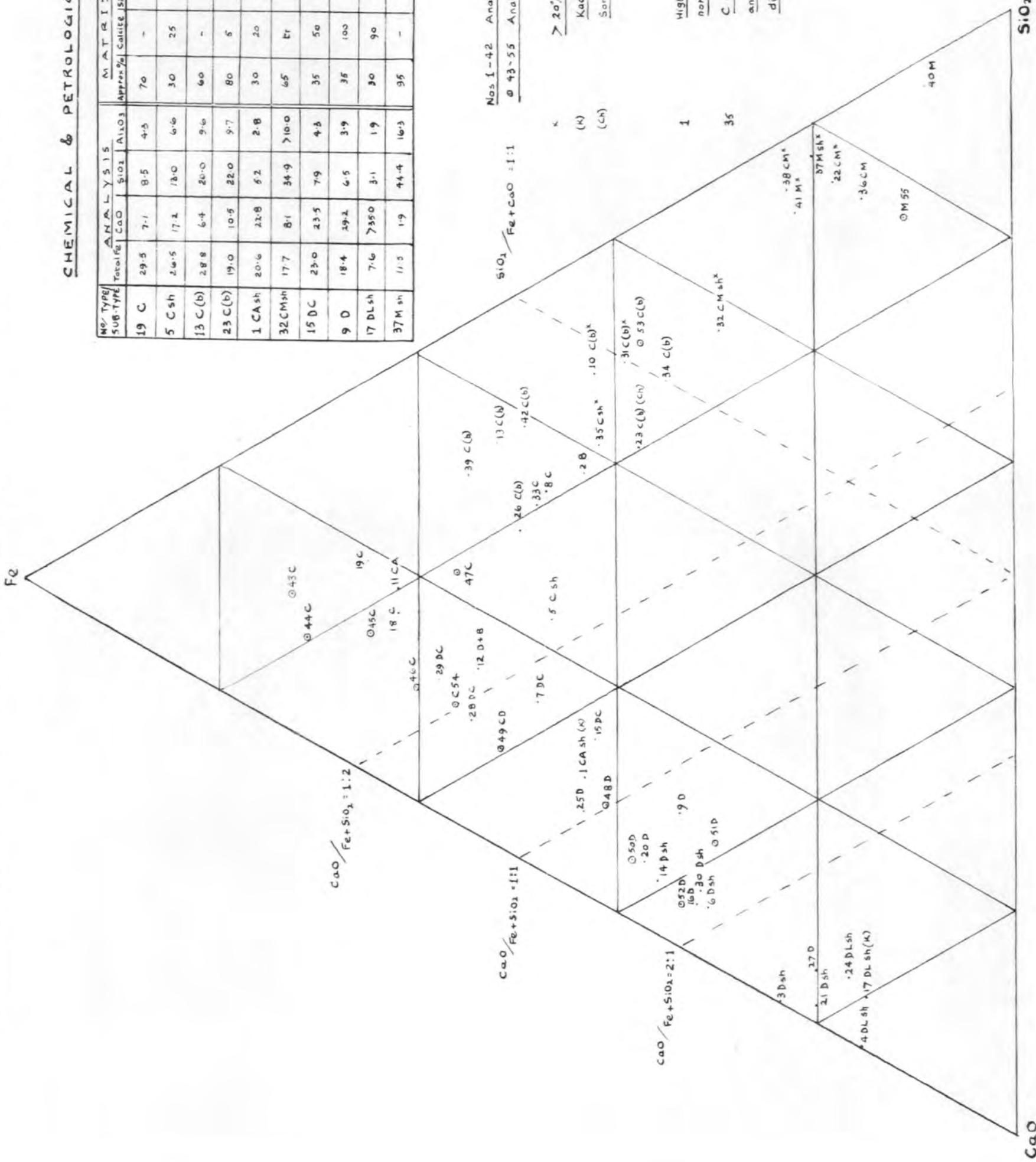


FIG 19.

Type D ironstones have a CaO to Fe + SiO₂ ratio in excess of 1 : 2 (frequently in excess of 1 : 1), and the more limey ironstones, such as sub-type DL have a CaO to Fe + SiO₂ ratio in excess of 2 : 1. In normal core analytical records, when the CaO to Fe ratio is more than 1 : 1, type D is indicated.

When the SiO₂ to Fe + CaO ratio exceeds 1 : 1, quartz (mainly of silt grade), or much clay with or without chamosite, or a combination of these is present; the sub-types would be silty C(b), CM (perhaps silty), and M.

Using normal analytical data for one foot borehole core increments, a lime content of more than 25 per cent. usually indicates the presence of type D ironstones; with a lime content of 30 per cent. or more, type D is definitely indicated. Although more than one type, or several sub-types, may occur within the individual foot of the borehole, the analysis will generally indicate the predominating type or sub-type present. At times, however, sub-type C,sh may have a lime content in excess of 25 per cent. The presence of type C ironstones can often be inferred where silica values in excess of 5 per cent. occur for an analysed one foot increment of core. Silica values in excess of 20 per cent. frequently indicate the presence of quartz.

Fig. 20 shows that when taking the lime values from core analyses, the chemistry reflects, and generally coincides with, the rock types across the mining area, even though there is a masking effect due to the analyses being for one foot increments.

IV Lateral Variation in Chemistry

Variation in the chemistry of the ironstone across the mining

area is shown in terms of lime variation in Fig. 20, and the general decrease in lime, with the corresponding increase in silica for the ironstone total thickness towards Ashby Ville is clearly seen from the figure. Sulphur contents in excess of 0.5 per cent. and silica contents in excess of 30 per cent. are also indicated.

Lateral variation in chemistry when considering the average analyses for different vertical cuts has been discussed by Elliot (1945, p.22), and he quotes the following figures for such variations along a 3,600 feet quarry face, sampled at 75 feet intervals.

Moisture %	Iron %	SiO ₂ %	CaO%	Sulphur %
10.0-14.1	18.3-24.5	3.8-7.1	19.8-26.7	0.04-0.36

Elliot also suggests that the next benching in the same quarry will show similar variations, but the location of maximum and minimum figures for any of the constituents will almost certainly be very different.

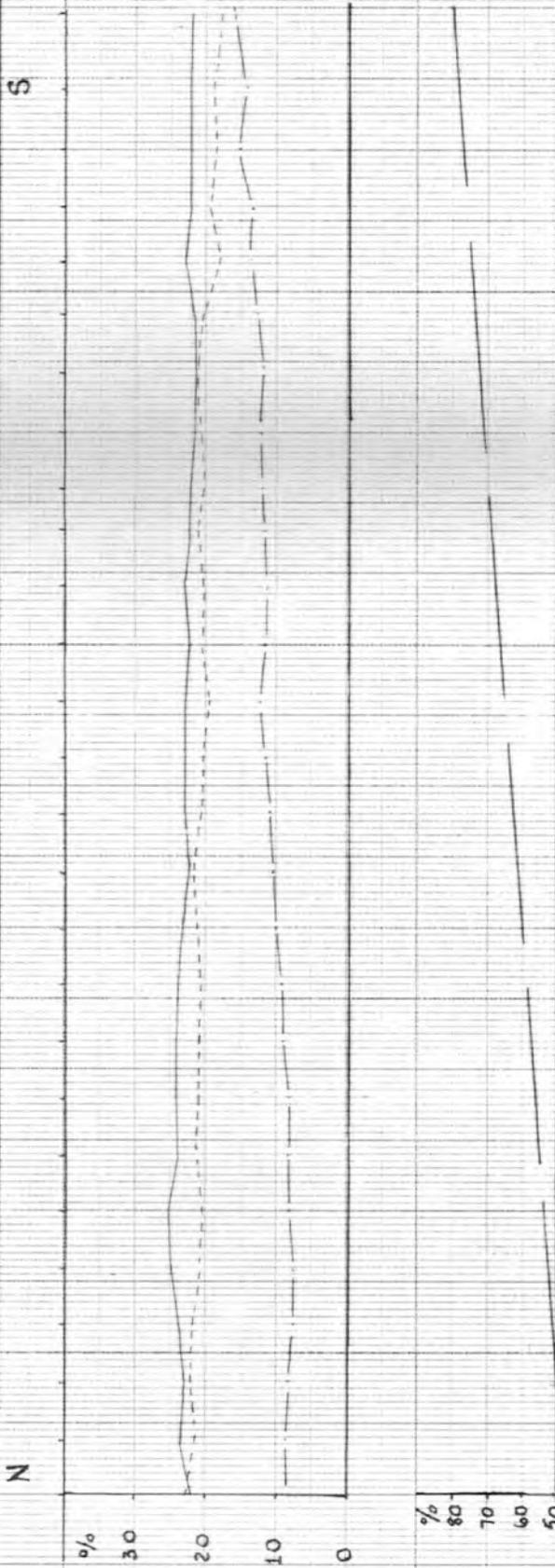
Information based on the data obtained from the United Steel Companies Limited recent drilling programme suggests that the variation is less, and often less random, than implied by Elliot. Fig. 21 shows the lateral variation in chemistry (using the average analyses for given thicknesses) across two opencast mine faces, based on data obtained from the 400 feet drilling grid, and these figures are compared with Elliot's figures in Table 14. Variation in the average analyses for given thicknesses, for three different areas (Figs. 22, 24 and 26) are also compared with Elliot's figures in Table 14.

Figs. 21, 22, 24 and 26 show that, when the average analysis for a mine face or mine area is between constant upper and lower

SCUNTHORPE AREA

SHOWING: LATERAL VARIATION IN CHEMISTRY OF THE IRONSTONE & PERCENTAGE OF CLAYEY IRONSTONE IN FULL THICKNESS.

(i) SECTION CLOSE TO MINING FACE 'Y' (SEE FIG 16) NOTE INCREASED SiO₂ & TYPE C TO SOUTH.



(a) FULL THICKNESS

Ranges over 10,450ft	
High	Low Diff
Fe	25.4 21.6 3.8
CaO	23.0 17.8 5.2
SiO ₂	16.0 7.9 8.1
CaO/SiO ₂	2.76 1.11 1.65
Thickness	31.5' 27.0' 4.5'

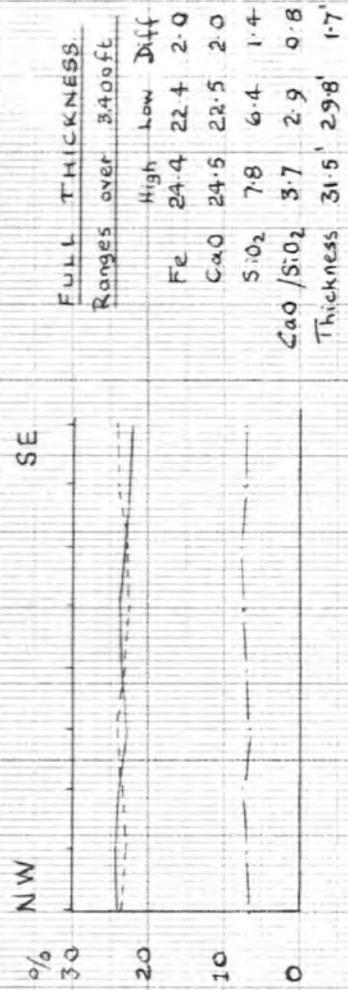
(b) PERCENTAGE TYPES C+M+C(B)+CM+B IN FULL THICKNESS (Mean Line Shown).

(c) REDUCED THICKNESS - OMITTING UPPER SUB-UNIT (i) OF UPPER CLAYEY SUBDIV. (ALTERNATE BOREHOLES ON 400ft GRID).

Ranges over 10,450ft.

High Low Diff	
Fe	24.8 22.0 2.8
CaO	26.1 20.0 6.1
SiO ₂	14.9 6.3 8.6
CaO/SiO ₂	4.15 1.34 2.81
Thickness	24.1' 21.0' 3.1'

(ii) SECTION CLOSE TO MINING FACE 'C' (SEE FIG 16)



(a) FULL THICKNESS

Ranges over 3400ft	
High	Low Diff
Fe	24.4 22.4 2.0
CaO	24.5 22.5 2.0
SiO ₂	7.8 6.4 1.4
CaO/SiO ₂	3.7 2.9 0.8
Thickness	31.5' 29.8' 1.7'

KEY: — Boreholes
 — Fe%
 - - - CaO%
 . . . SiO₂%
 - · - · TYPES C+M+C(B)+CM+B %

HORIZONTAL SCALE 0 400 800ft

horizons, the variation in chemistry is less than suggested by Elliot. In certain areas, and along particular faces, trends in chemistry can be recognised. In Fig. 21 (i)(a), for the full thickness of ironstone, there is a trend showing increased silica and decreased lime along the face from north to south. These trends, reflecting the increase in clayey types of ironstone, are also seen in the figure for a thickness less than the total thickness. In Fig. 22 the grade variation maps relating to the full thickness for part of the area at the back of this face, indicate that north-south faces would frequently show similar chemical variation, benching to benching. Hence, benching to benching, the positions of maximum and minimum figures for the chemical constituents will be closer than suggested by Elliot (1945). In Fig. 24, the variation in chemistry is again within narrow limits.

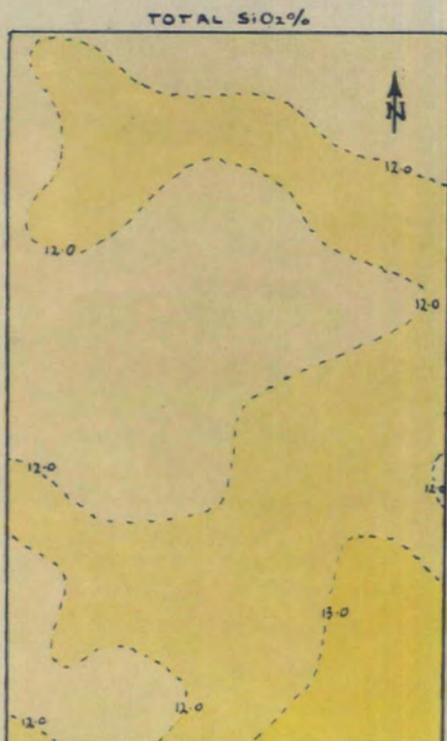
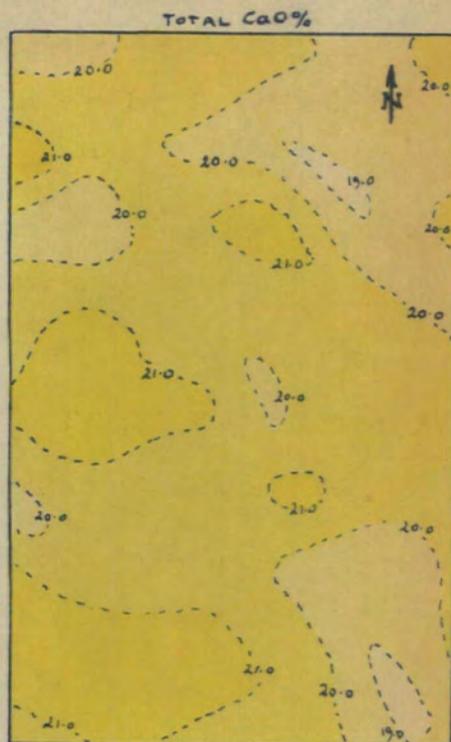
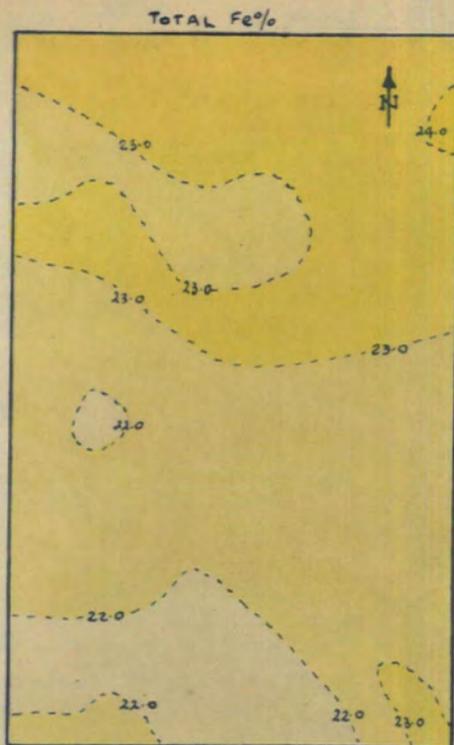
Quite often, the variation in chemistry for thicknesses less than the full thickness is greater, and this is seen from the lime and silica values shown in Fig. 21 (i)(a); this is probably due to lensing, the effect of which may be more exaggerated in the smaller thickness.

The chemical analyses for a particular bed in the lower sub-unit of the Lower Limey Subdivision, in the vicinity of borehole S.9 (Fig. 17), are shown in Fig. 23: chemical variation is again seen to fall within narrow limits, in this case particularly the silica content.

The narrow limits of variation in the average iron content for the total ironstone thickness in the concealed area north-east of Scunthorpe have been referred to in the Memoir by Whitehead et al. (1952, p.80), and the recent drilling programmes (covering the area

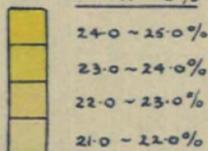
EXAMPLES OF GRADE VARIATION
MAPS - AREA EAST OF MINE FACE 'Y' (CENTRAL). BASED ON
INFORMATION OBTAINED AFTER 400FT GRID DRILLING.

FULL THICKNESS.

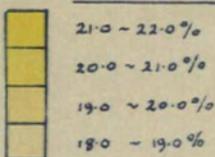


KEY:

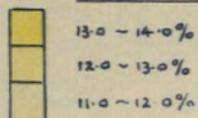
TOTAL Fe%



TOTAL CaO%



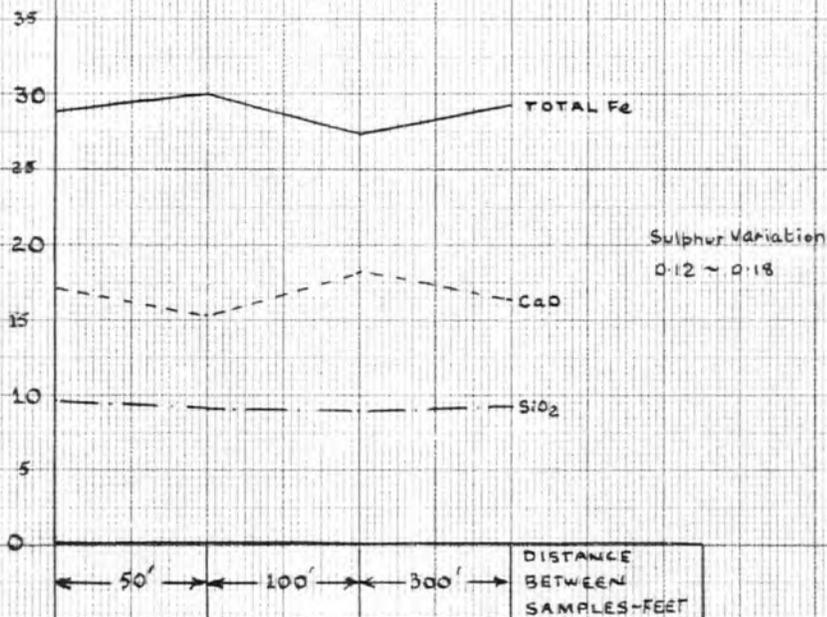
TOTAL SiO₂%



SCALE: 6" TO 1 Mile.

FIG. 22

LATERAL VARIATION IN CHEMISTRY
ONE BED IN LR LIMNEY SUBDIV^N
[SUB-UNIT (I)] SANTON MINE.



DATA PLOTTED FROM UNDERGROUND CHANNEL SAMPLE ANALYSES

Thickness of bed sampled: 1-ft (upper and lower portions of bed not sampled to avoid contamination).

Rock = TYPE C & C(b)

FIG 23

between the present workings and the New River Ancholme in the east, Fig. 16) substantiate these remarks and show that variation in the iron, lime and silica contents is very small between given upper and lower horizons.

The limits of variation for the main chemical constituents have been shown to be narrower than previously supposed by Elliot (1945), and this may be due to the fact that the writer's analyses relate to thicknesses between constant upper and lower horizons in an area less affected by weathering. Also, the writer's analyses are for borehole cores, where each foot of core is constant in volume and diameter.

3.G GRADE CONTROL - GENERAL, AND OUTLINE OF MINING PRACTICE

I Introductory Note

Grade control in the Frodingham Ironstone operations is equally as important as in those of the Northampton Sand Ironstone. In making the blast furnace sinter mixture, the ore feed is composed of Northampton Sand Ironstone and Frodingham Ironstone in an approximate ratio of 1 : 2. The larger proportion of the Frodingham Ironstone is won from three opencast mines, whilst the remainder is obtained from two underground mines. Variability in grade, due to oxidation, is less in the Frodingham Ironstone, than in the Northampton Sand Ironstone, and when taking the average analyses for the total ironstone thickness, lateral grade variation is less in the Frodingham Ironstone. The drilling and analytical procedure, together with the methods of correlation of data, are essentially similar to those applied at the Northampton Sand mining operations, and they are briefly described below.

II Ironstone Drilling and Analysis, and Face Sampling

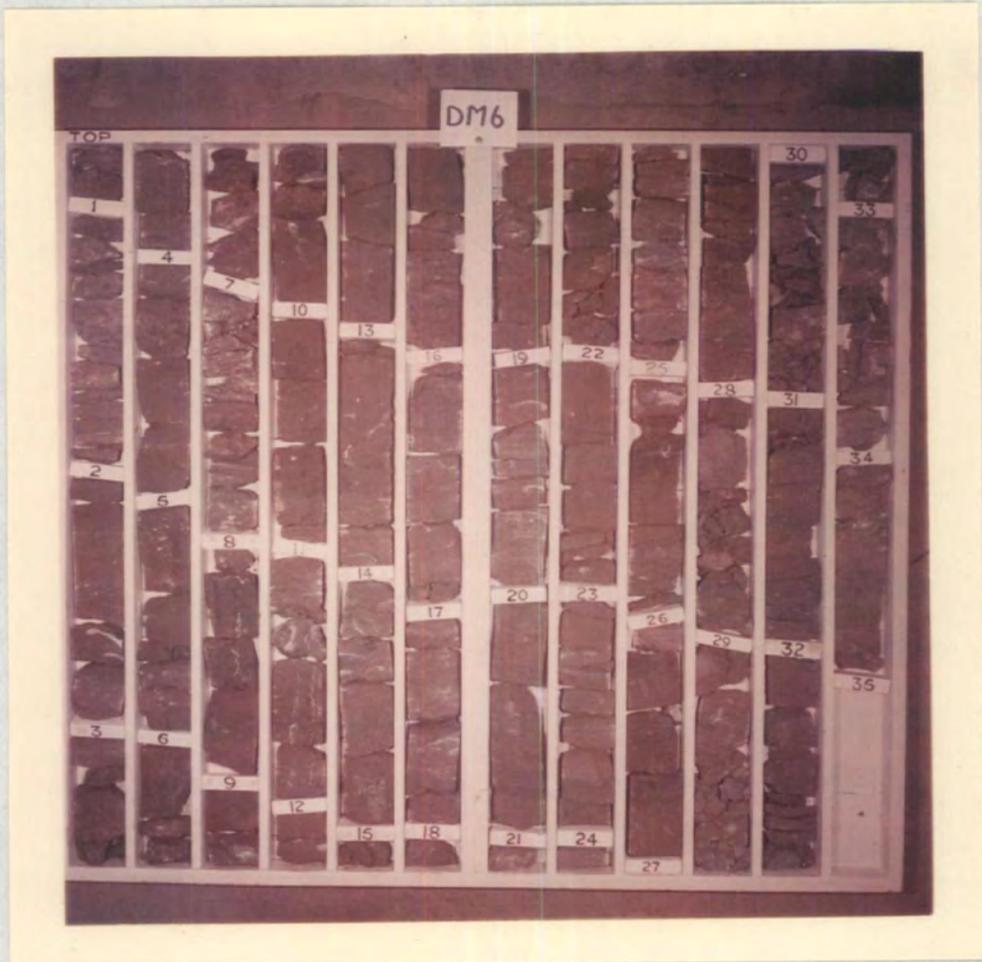
Most of the information used in grade control is again obtained from core drilling, using 101 mm. or 116 mm. drilling crowns, and core recovery is in the region of 100 per cent. Exploration drilling on a 1,600 feet grid usually precedes drilling to a 400 feet grid for grade and structure. Ironstone cores are split longitudinally, and one half of the core is boxed in 1 foot increments and, after logging, is photographed (Plate 15), whilst the other portion is crushed in 1 foot increments for analysis. Photographs of Frodingham Ironstone cores are even more useful for reference purposes than photographs of the Northampton Sand Ironstone, the various ironstone types (or sub-types) and horizons being more readily recognised. Cores are again held in storage until all logging and analytical data has been correlated; for opencast mining areas, representative cores are kept, and for underground mining areas, all cores are kept until the workings have reached the vicinity of the borehole.

Analyses for one foot increments are for total iron, lime, silica and sulphur on all cores; at times, additional analyses may be made for other constituents. Composite analyses for alumina, magnesia and loss are made for the anticipated working thickness on all cores, and loss on ignition is determined at 950°C.

It is not considered necessary to split cores according to type or sub-type for analysis, one reason being that different geologists might split at different levels and frequencies, particularly where types or sub-types occur in thin bands.

Whilst face sampling has been discontinued in opencast mining

PLATE 15



FRODINGHAM IRONSTONE

Typical reference photograph of split core.
(The top of the Transition Beds is 2 inches below block 26).

operations, underground face sampling is carried out to a set pattern, which is described on page 92. The upper and lower three feet of each underground face sample are analysed in separate one foot increments, whilst the intermediate portion is composited, and analyses are for total iron, lime, silica and loss. This data, together with the borehole core data, will be particularly useful during the retreat mining stage.

III Correlation of Data

The methods used for correlating borehole core and analytical data are again essentially similar to those used in the Northampton Sand Ironstone. For opencast mining areas, grade variation maps are drawn for the full ironstone thickness and the anticipated working thicknesses. In underground mining areas, grade maps are drawn for the anticipated working thickness, the opencast working thickness, and the roof thickness, in order that the economics are fully appreciated. Block grade maps showing the average analyses for the blocks are again drawn for underground and opencast working thicknesses. Grade variation maps are no longer drawn for sulphur content, as the sinter process no longer requires the removal of high sulphur content ironstone. Graphical grade variation diagrams may be drawn for various thicknesses.

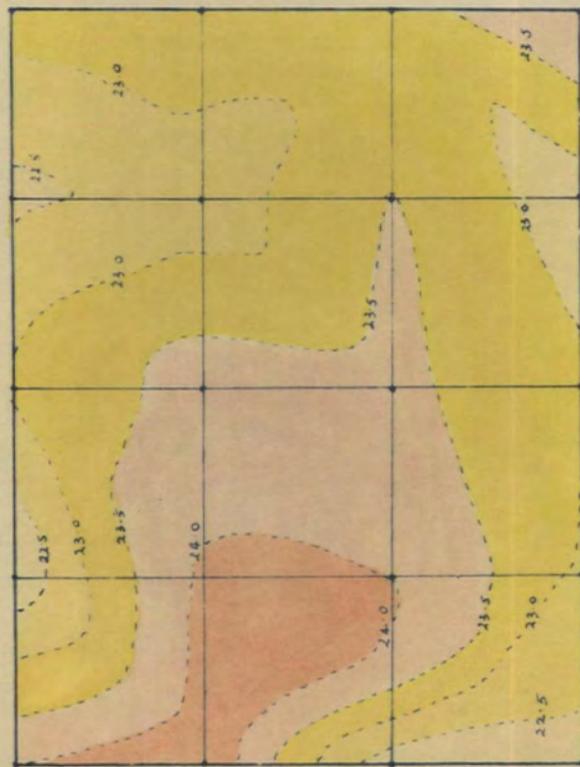
Examples of typical grade maps are shown in Figs. 22, 24 and 26, and lateral grade variation for opencast mine faces has been shown graphically in Fig. 21, where variation in type has been related to chemical variation.

TYPICAL GRADE MAPS.

FOR AREA AT BACK OF MINE FACE 'C' (fig 16).



A TOTAL Fe% ISOGRADE MAP, FULL THICKNESS 28.8 ~ 31.8 FT.



B TOTAL CaO% ISOGRADE MAP, FULL THICKNESS 28.8 ~ 31.8 FT.

SiO₂ Range
 6.3 ~ 7.5
 Diff: 1.2

Th	30.0	30.9	31.1	31.2
Fe	23.6	24.1	24.2	24.3
CaO	23.5	23.0	23.0	22.9
SiO ₂	6.63	6.92	6.78	6.81
	30.4	30.4	30.9	31.3
	23.5	23.5	23.9	23.9
	23.5	23.8	23.4	23.2
	7.06	6.82	6.90	7.14
	30.5	30.5	30.7	Th 30.7
	23.7	23.5	23.8	Fe 23.6
	22.8	23.4	23.2	CaO 23.4
	7.45	7.14	7.10	SiO ₂ 7.16

C BLOCK GRADE MAP FOR FULL THICKNESS.

Showing: Thickness, Total Fe%, CaO % & SiO₂ %.

1" = 100ft
 • Boreholes.

BASED ON ANALYSES (DRY) OF CORES FROM BOREHOLES ON 400' DRILLING GRID.

IV Outline of Mining Practice

(a) General

Harrison (1961) has given a comprehensive account on 'Mining Frodingham Ironstone'. Whilst there are two underground mines operating in this area, it is likely that opencast mining will continue longer than previously anticipated by Davies and Dixie (1951, p. 85). This is because improved opencast techniques, together with larger opencast mining machinery, will keep costs competitive with underground mining.

(b) Opencast Mining

The ironstone is mined in longitudinal cuts or gullets, parallel to the outcrop; the longest cut is approximately two miles in length, whilst the deepest overburden at the present time is 120 feet. Overburden, consisting essentially of Lias clays, requires no blasting before removal to the worked-out side of the cut by the large, electrically powered walking draglines standing on top of the bared ironstone. One of the largest walking draglines in Europe, with a 303 feet boom and a 25 cubic yard bucket is being used in stripping overburden in the Roxby area, and this machine can remove up to 100 feet of overburden (Plate 16). Where overburden is present in excess of the stripping machine's capabilities, the upper portion, which may include 'blown' sand, is removed by fleets of tractor scrapers. Due to the swell of the dumped clay, and in order to prevent clay slips, smaller draglines on the worked-out side of the cut re-handle some of the dumped material, and, by placing it further back from the cut, reduce the upper slopes of the heaps from 38° to approximately 25°.



Opencast Mining Operation - large walking dragline with a 303 feet boom and 25 cubic yard bucket, standing on top of Frodingham Ironstone. Note loading machine in background. (The rail track has now been removed).

Provided that satisfactory economics can be maintained, future opencast mining under deeper overburden could probably continue by using a combination of walking draglines and bucket-wheel excavators.

After drilling and blasting, the ironstone is loaded by electrically powered shovels, with a bucket capacity of up to $4\frac{1}{2}$ cubic yards, into 30 ton capacity rear dump trucks, for conveyance to the steel works (until 1963, the ore was loaded by the loading machines into rail wagons, a similar procedure to that in use at the Companies' Northampton Sand Mining Operations). The largest opencast mining operation, with two stripping draglines and three loading machines, can produce over 30,000 tons of ore per week (two working shifts per day), and the three loading machines can operate in sections of different grade along the face. The dumps on the worked-out area are levelled, and where cultivated land was present prior to mining, the area is restored for agricultural use.

(c) Underground Mining

Harrison (1961) has described underground mining in detail, and the following description is based on his work. The two underground mines, one north of the main W.N.W.-E.S.E. fault and one to the south, were positioned to win the ore from areas where the overburden exceeds 150 feet. Both mines are in the development stages, and mining is by the 'room-and-pillar' method; the present production is obtained from faces in the advancing roadways and cross-cuts, and after development to boundaries, pillars will be extracted.

A plan view of the Dragonby Mine layout is shown in Fig.25. From the entrance drift, roadways (20 feet wide tapering to 15 feet at the roof, and between 18 and 20 feet high) are driven to the east. Seven of these roadways are driven parallel, and are joined by cross-cuts, forming 160 feet by 70 feet pillars. During development, roadways progressing eastwards to the boundary form a production district, and at regular intervals production districts are developed to the north, where they meet with another east-west production district. Hence, development of north-south and east-west districts will continue until the boundaries are reached, and the large pillars of ore between north-south and east-west production districts, together with the supporting pillars in the development production districts will be mined on the retreat. To allow for a competent roof, 6 to 9 feet of ironstone is necessarily left in situ in the Dragonby area, and in the Santon area the roof thickness is greater, but on retreat some of this roof ore may be extracted.

After drilling and blasting, the headings are charged with explosive and each heading blast produces up to 300 tons of ironstone. The roof and sides of the heading are trimmed before loading out, and corrugated roof bars, anchored by $3/4$ inch wedge and sleeve bolts, are set hydraulically; girders may be necessary in broken ground. 'Joy' loading machines load the ore into shuttle cars (in the Santon Mine, where steep gradients occur, dump trucks are used), by which it is conveyed to a belt loading point for conveyance to rail wagons on the surface.

In Dragonby Mine, water is made at the rate of about 650 gallons

per minute, and most of this is from fissures. The water is confined to one district as far as possible, and the headings of that district are advanced at such a rate that the fissure is cut at the lowest point before other headings or districts reach the same fissure (in Dragonby Mine this is the southernmost east-west district). Horizontal and angled boreholes in advance of the working face pre-drain the area, and water is pumped to underground catchment lodges to allow for silt settlement before pumping to the surface.

3.H OPENCAST GRADE FORECASTING AND CONTROL DURING MINING

Long- and short-term grade forecasts and mine tonnages are based on the ironworks' estimates of pig-iron production. The tonnages to be loaded from each mine will depend on the ore grade, together with the stripping and loading capacity available. Having determined the economic weekly ore output, the approximate grade and tonnage to be won from each mine can be assessed at the beginning of the mining year.

The average yearly grade expected from each opencast mine is determined from the 400 feet block grade maps. These maps are used at present to assess the expected grade for short term forecasting, e.g. on a weekly basis, and in determining the grade of ore as mined. The mine face, together with the position of the loading machine, is also shown on these maps.

Whilst the variation in grade along opencast mine faces has been shown to be within narrow limits, the writer is of the

opinion that graphical grade variation diagrams for mine faces, as in Fig. 21, are more reliable than block grade maps in grade forecasting. Grade variation diagrams, for sections parallel to the face, at 100 feet increments, would be more accurate, particularly towards the edges of a 400 feet block and when crossing the boundaries between blocks.

During mining, it has been found that there is little need for geological control, as the top of the ironstone is definite and the floor position in individual mines is usually easily distinguished (Fig. 17). Because of the narrow limits of variation in the average analyses for the working thickness, which have been proved by boreholes and face sampling, very little face sampling is now carried out.

Whilst the most economic level of production for each mine has been assessed at the beginning of the year, it must obviously be reviewed monthly and weekly. As far as possible divergencies from the forecast tonnage are avoided to allow for economic mining, however circumstances may necessitate the adjustment of the forecast production from one or more mines, for example, the ironworks' demands may decrease or increase suddenly for various reasons, the ironworks may require a sudden grade change which cannot be catered for by using stock, breakdowns may occur in a particular mine, and unforeseen circumstances affecting overall grade occurring in the Northampton Sand mining operations might have to be catered for.

Minor adjustments to grade may require additional or lower tonnages to be obtained from a particular mine face, and as grade variation within a particular mine and over the area is not excessive, small swings in grade can readily be corrected. Major

adjustments in grade may be necessary from time to time, due to unforeseen circumstances or when a blast furnace is being re-lined, and different grades and tonnages may be required from certain mines so as to achieve an increased iron output from the remaining blast furnaces. Because marker bands and ore types are easily recognised, it is suggested that major grade corrections can be made by selective mining.

3.J

OPENCAST SELECTIVE MINING

I Lateral Selective Mining

At times, when grade adjustments are necessary, e.g. a demand for increased silica, an increased rate of mining at the south end of mine face Y (Figs. 16 and 21) may be necessary. Mining at different rates in various positions along mine face Y would be useful in grade balancing, and because there are three loading machines in this mine, this is made easier. In mine face C (Figs. 16 and 21), it is obvious that mining at different face positions could have little effect.

II Vertical Selective Mining

In the past, particularly in the southern mining area around Ashby Ville, the upper beds of ironstone with a high sulphur content were discarded, and the high silica values in the upper beds were an added factor to their removal. At the present time, the total thickness of ironstone south of the A.18 road (Fig. 16) is considered to be an uneconomic proposition because of its poor quality in relation to the ironstone north of this area.

Whilst at the present time in opencast mining no beds are discarded and very little ironstone is left in situ, it is possible that in the future some of the upper beds could be removed, and some of the lower beds might be left in situ. The reason for this would be to increase the iron content of the sinter mixture composed of Northampton Sand and Frodingham ores, and hence the blast furnace burden, at times of re-line or repair. At such times, much of the increased iron content would be obtained by using the highest grade Northampton Sand ore; however, to do this, and to maintain the same basicity, means that not only must higher grade Northampton Sand ore be used (with higher iron and lower silica contents), but the silica content of the Frodingham ore must also be decreased and, where possible, the iron content increased. The effect of removing the upper sub-unit (ii) of the Upper Clayey Subdivision along mine face Y has been shown in Fig. 21 (i), and here, whilst there is a slight decrease in iron content, there is a decrease in silica content together with an increase in lime content. In Fig. 26, the opencast working thickness grade is compared with that of the underground working thickness, and it is seen that, when leaving the roof portion - most of the Upper Clayey Subdivision - in situ, silica values are again decreased and lime values increased. In opencast mining, these beds of the Upper Clayey Subdivision could be removed by stripping machinery.

Selective mining could be easily controlled, as continuous beds or horizons can be recognised and borehole data could easily be adjusted to provide grade maps relating to the selected thickness.

GRADE VARIATION ~ SANTON AREA.

SHOWING OPENCAST ~ FULL THICKNESS GRADE, RELATED TO UNDERGROUND GRADE.

BLOCK GRADE

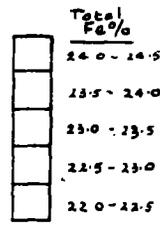
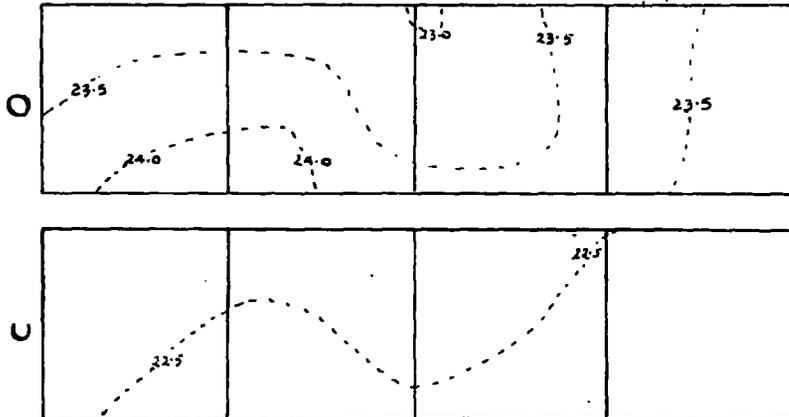
	O	U	O	U	O	U	O	U
Th	30.9	18.5	30.9	18.6	31.1	18.6	31.2	18.8
Fe	23.3	22.5	23.2	22.4	23.2	22.4	23.4	22.6
CaO	22.9	26.2	23.0	26.4	22.8	26.5	23.1	26.5
SiO ₂	7.2	5.1	7.1	5.2	7.3	5.1	7.3	5.1

Data drawn from analyses of 400' grid cores.

O = Opencast
U = Underground.

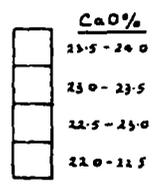
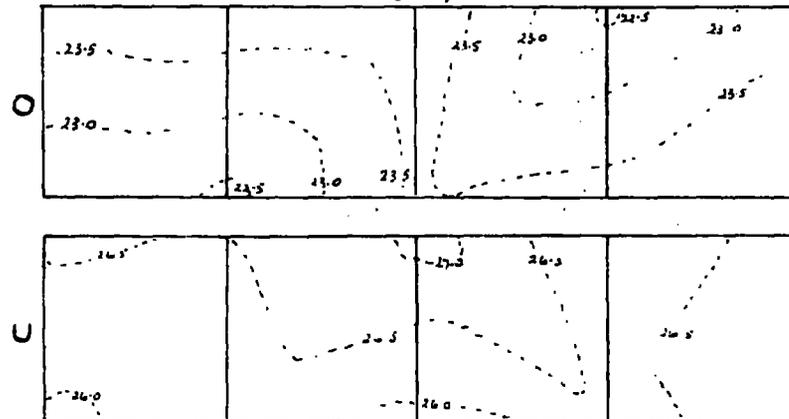
← 400' →

TOTAL Fe%



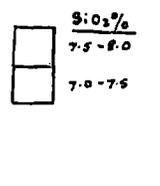
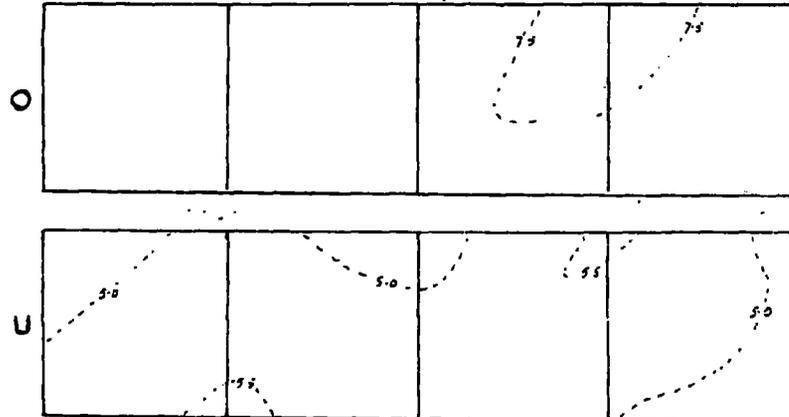
<u>Fe% Range</u>	<u>Diff.</u>
O 22.9 - 24.4	1.5
U 22.0 - 22.8	0.8

CaO%



<u>CaO% Range</u>	<u>Diff.</u>
O 22.4 - 23.8	1.4
U 25.8 - 27.1	1.3

SiO₂%



<u>SiO₂% Range</u>	<u>Diff.</u>
O 7.0 - 7.8	0.8
U 4.7 - 5.6	0.9

Mining less than the total thickness in the Frodingham Ironstone does not necessarily reduce grade variation, and this is illustrated in Figs. 21 and 26.

3.K UNDERGROUND GRADE FORECASTING AND CONTROL DURING MINING

The average yearly grade expected from the underground mines is determined from the 400 foot block grade maps, based on the estimated underground mining thicknesses - the upper and lower horizons being readily recognised. These maps, on which the advancing headings and cross cuts are shown, are also used at present to assess monthly and weekly expected grades.

For the underground mining thickness, because grade variation is within narrow limits (Fig. 26), block grade maps are most valuable for short term grade forecasting and in determining mined grade, as, in the development stage of mining, a block will include several advancing headings and cross-cuts, and hence a greater portion of the block is being considered than in the open-cast case (advancement of main roads and cross-cuts is at a higher rate than in the underground mine in the Colsterworth area and the portion of the block affected is greater). Block analyses will again be useful on retreat when pillars are mined out, as a considerable portion of a block or blocks will again be affected. Grade variation diagrams, drawn parallel to developing headings and based on borehole core and face sample data, should be used in conjunction with the block grade maps, they are particularly useful in determining trends and local grade variation.

Originally belt samples were obtained to determine mined grades at underground mining operations. Face samples were also taken at regular intervals to post check mined grade and borehole data, and to give added grade data for retreat mining. Analytical data obtained from belt sampling showed anomalies when related to face sample and 400 feet block analyses. As a result, belt sampling has been abandoned, also the frequency of face sampling has been reduced, since the 400 feet block analyses alone have proved to be equally reliable, and they compare favourably with analyses of ore received at the Ore Preparation Plant.

In the Dragonby Mine, face samples are taken at 180 feet intervals on the corner of every pillar on the two outside roadways and on the corner of every pillar on one side of the central roadway (i.e. three roadways) of a development district. In the Santon Mine, where pillars are smaller, the outer and central roads are again sampled but only for alternate pillars; the interval is again 180 feet. These face samples are analysed for total iron, lime, silica and sulphur, the top three feet and bottom three feet being analysed in separate one foot increments, while the remaining portion is composited; the average analysis for the face can thus be determined.

These face sample analyses enable a check to be made with block average grades and grade variation maps and they will be useful for giving added grade data when the pillars are extracted in retreat mining.

Whilst the roof and floor strata in the underground mines are generally easily recognised (Fig. 17), geological control is

necessary when lensing occurs, cutting out the normal roof or floor beds and marker horizons. Where lensing occurs in the roof it is at times necessary to mine to a higher or lower horizon, and hence some adjustment is necessary to grade data. The face sample analyses will indicate whether or not there has been over- or under-mining of the normal roof and floor, and remedies can be made to bring the floor or roof position up to its normal horizon. From time to time, the face sample positions are logged by a member of the geological staff to check that the correct mining thickness is being maintained and to ensure that unforeseen changes in lithology are recorded.

3.1

SUMMARY

Borehole cores and face sections of the Frodingham Ironstone can readily be correlated by chemical and lithological data, and ironstone types and sub-types are often continuous in beds or at similar horizons, and can be used as marker bands. The easily recognised types and sub-types have their own chemical characteristics.

Whilst chemical trends can be recognised, lateral chemical variation for given working thicknesses between constant upper and lower horizons is frequently within narrow limits, and this fact, together with the presence of marker bands, allows for easily controlled mining to grade and possible future selective mining.

C O N C L U S I O N

Logging and correlation of the many ironstone cores and opencast and underground mine faces within the United Steel Companies Limited operations is made easier by using simple classification systems, based on mineralogical and lithological differences readily discernible in the hand specimen. The simplified classification system used in logging the Northampton Sand Ironstone places an emphasis on the detrital constituents, whilst that used for the Frodingham Ironstone places more emphasis on the nature of the matrix.

In both the Northampton Sand and the Frodingham Ironstones, the proportion and position of ironstone types referred to in the classification systems allows for the ironstones to be subdivided into lithological subdivisions, useful in mining. Again in both these ironstones, at certain horizons, particular ironstone types are continuous over considerable distances laterally, or, as in the Frodingham Ironstone, similar rock types may occur at similar horizons but are not necessarily continuous. Particular types of ironstone may form continuous beds which can be used as marker bands, useful for correlating purposes and in selective mining; certain marker bands or horizons may form well-defined boundaries to the lithological subdivisions.

Abrupt vertical changes in chemistry, particularly in the Northampton Sand Ironstone, are usually coincident with vertical

changes in lithology, and both ironstones can be subdivided vertically from chemical data, particularly the Northampton Sand Ironstone. Subdivisions based on lithology are generally coincident with subdivisions based on chemistry, and ironstone correlation by lithology can often be substantiated by chemical data.

A relationship between chemistry and mineralogy can be shown in the Northampton Sand Ironstone, and taking proportions of iron, lime and silica, rather than percentage weights, the mineralogical ironstone type can be inferred from normal analytical data. Similarly, in the case of the Frodingham Ironstone, principal types and the writer's sub-types, identifiable from the hand specimen or from the thin section, can be recognised from normal analytical data (i.e. when proportions of iron, lime and silica are used).

Although average chemical analyses for the full thickness of the Northampton Sand Ironstone show considerable lateral variation, the average analyses for the Main Oolite portion when considered alone show much less chemical variation, particularly if it is either unoxidised, or heavily oxidised throughout its vertical thickness and over substantial areas.

When considering the average analyses for given thicknesses between constant upper and lower horizons, the Frodingham Ironstone has been shown to display less lateral variation in chemistry than was previously thought: lateral variation is generally less than in the Northampton Sand Ironstone (in the Colsterworth area), even though the former is a thicker and more abundantly lensed deposit.

Whilst for both ironstones the average analyses for 400 feet blocks (i.e. the average analyses of borehole cores at the corners of a 400 feet square) have been used for long- and short-term grade forecasting and in determining mined grade in opencast mining operations, greater accuracy can be obtained from grade variation maps and graphical grade variation diagrams parallel to working faces. In underground mining operations, particularly in the Frodingham Ironstone, more reliance can be placed on the average analyses of 400 feet blocks, when assessing mined grades and in grade forecasting; however, grade variation maps and diagrams enable trends and local grade differences to be better assessed.

Because lateral variation in lithology and grade, and mined grades can be determined from the data obtained from the 400 feet square borehole grid in both these ironstone fields, and because of the narrow limits of lateral grade variation in the Frodingham Ironstone and in the Main Oolite portion of the Northampton Sand Ironstone, the amount of face control sampling can be reduced.

Besides giving a better understanding of the chemical and lithological variations and their inter-relationship within the Northampton Sand and Frodingham Ironstones, the recent drilling and mining operations have given added information relating to the structure of these ironstone fields. Amongst other points of geological interest is that evidence contradictory to theories which suggest that the ooliths in the Northampton Sand Ironstone were originally of calcite.

It is possible that if, in the future, these ironstones are to compete with higher grade and better structure imported ores and concentrates, this knowledge concerning chemistry and lithology and their inter-relationship, allowing for easily controlled selective mining, will be even more important. Mining in both ironstone fields to achieve higher ore grades, and thus reduce transport, and iron-making costs might become more selective and the need for accurate grade control more critical.

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Plates 14 and 16 and Fig. 25 have been reproduced by permission of Appleby-Frodingham Steel Company (branch of The United Steel Companies Limited).

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APPENDIX

(i) THE MINERALOGY OF THE NORTHAMPTON SAND IRONSTONE

MINERAL	FORMULA	COMPOSITION (wt. %)										
		Fe	SiO ₂	CaO	Al ₂ O ₃	MgO	MnO	P	S	+H ₂ O	CO ₂	
Goethite	α -FeOOH	62.9	-	-	-	-	-	-	-	10.0	-	Calculated
Limonite	α -FeOOH with absorbed water	-	-	-	-	-	-	-	-	-	-	Composition variable
Siderite	FeCO ₃	39-41.5	-	4.2-5.9	-	2.2-3.2	0.1-0.2	-	-	-	33-35	From Taylor, 1949
Chamosite	(Al,Fe,Mg) _x (Al,Si) ₂ O ₅ (OH) ₄ x = 2.6 to 2.9	25-30	22-30	-	23-24	2-3	-	-	-	10.0	-	From Youell, 1958
Pyrite	FeS ₂	46.6	-	-	-	-	-	53.4	-	-	-	Calculated
Hematite	α -Fe ₂ O ₃	69.9	-	-	-	-	-	-	-	-	-	Calculated
Magnetite	Fe ₃ O ₄	72.4	-	-	-	-	-	-	-	-	-	Calculated
Quartz	SiO ₂	-	100	-	-	-	-	-	-	-	-	-
Calcite	CaCO ₃	0-2	-	56	-	0-1	0-0.5	-	-	-	44	From Graf, 1960, and Andrews 1950, (Mn is likely to enter into solid solution with Ca but Mg and Fe are unlikely to in calcite as old as that in Northants. Ironstone).
Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	-	46.5	-	39.5	-	-	-	-	14	-	From Grim, 1953, there may be very small substitutions of Fe and Ti for Al.
Collophane	Ca ₃ P ₂ O ₈ H ₂ O	-	-	36	-	-	-	20	-	5	-	Composition variable.
Alkali Feldspar	(Na,K) Al ₂ Si ₃ O ₈	-	65	-	20	-	-	-	-	-	-	Calculated. Alkalis = 10-16%.
Mica	K Al ₂ (AlSi ₃)O ₁₀ (OH,F) ₂	-	45	-	38	-	-	-	-	5	-	Calculated. Potash = 12%.
Rutile	TiO ₂	-	-	-	-	-	-	-	-	-	-	-

After Davies et al. (1964, unpublished)

A P P E N D I X

(ii) MINERALOGICAL DESCRIPTION OF ROCK SAMPLES FROM BOREHOLES IN
FIGS. 5 & 7

(Depths from top of ironstone)

Bore-hole	Depth	Mineralogical Description
h	3.0 ft.	Oxidised sphaerosideritic chamosite kaolinite oolite (ooliths of yellowish brown chamosite and kaolinite. Matrix - yellowish brown chamosite and kaolinite with pockets of goethite - after siderite).
C	1.2 ft.	Sideritic oolitic sandstone (chamosite ooliths).
	3.5 ft.	Sideritic kaolinitic shelly and sandy kaolinite oolite.
	5.5 ft.	Siderite mudstone (Plate 5 (ii)).
	7.0 ft.	Sideritic chamosite oolite.
	8.0 ft.	Sideritic chamosite kaolinite oolite.
	15.0 ft.	Chamositic sideritic shelly oolitic mudstone (ooliths mainly of coarse calcite, cores of chamosite).
	18.0 ft.	Chamositic sideritic sandy oolitic calcarenite (calcite ooliths, some with cores and layers of chamosite) (Plate 3 (i)).
G	0.5 ft.	Sideritic oolitic sandstone (chamosite and kaolinite ooliths - some sideritised shell material).
M	0.5 ft.	Sideritic kaolinite oolite (with a pocket of sphaerosideritic kaolinitic mudstone). (Plate 6 (ii)).
N	-	Sphaerosiderite - Lower Estuarine Series.
	0.2 ft.	Sphaerosiderite (Plate 6 (i)).
	1.0 ft.	Shelly sideritic oolitic mudstone (kaolinite ooliths sparse, some quartz).
	1.9 ft.	Sideritic chamositic kaolinitic sandy chamosite kaolinite oolite.
	3.3 ft.	Sideritic calcitic kaolinitic pebbly sandy kaolinite chamosite oolite (kaolinite and pale chamosite ooliths partly replaced by calcite. Pebbles of kaolinitic chamositic chamosite oolite and phosphatic mudstone).
	3.9 ft.	Chamositic kaolinitic pebbly sandy kaolinite chamosite oolite (pebbles of silty mudstone).
	20.0 ft.	Chamositic sideritic shelly oolitic mudstone (kaolinite ooliths partly replaced by calcite).
P	0.0 ft.	Siderite mudstone (small amount of kaolinite ooliths and quartz).

APPENDIX (ii) (Continued)

Borehole	Depth	Mineralogical Description
P	1.0 ft.	Sideritic oolitic sandstone. (Ooliths and pseudo-ooliths of pale green chamosite and kaolinite, much replaced by siderite).
	7.8 ft.	Chamositic sideritic oolitic mudstone (chamosite-limonite ooliths). (Plate 4 (ii)).
	17.0 ft.	Chamositic sideritic shelly sandy mudstone.
Q	11.6 ft.	Chamositic sideritic sandy limonite chamosite oolite and oolitic sandy mudstone.
S	1.1 ft.	Sideritic sandy mudstone (with some kaolinite ooliths).
	1.8 ft.	Sandy sideritic chamositic mudstone (with some chamosite ooliths).
	2.7 ft.	Sideritic sandstone (some sideritic mudstone pockets). (Plate 5 (i)).
	5.5 ft.	Shelly pebbly sideritic chamosite oolite (green ooliths with magnetite, calcitic shell material, pebbles of phosphate and claystone).
	12.0 ft.	Chamositic sideritic oolitic sandstone (pale green chamosite and kaolinite ooliths).
	16.2 ft.	Sideritic chamositic kaolinitic shelly oolitic mudstone (kaolinite ooliths being replaced by calcite, some quartz).
	18.0 ft.	Sideritic chamositic calcarenite (the detritus is mainly comminuted shell material, there is some quartz sand and a few pale chamosite ooliths). (Plate 3 (ii)).
T	2.9 ft.	Sideritic chamosite oolite (some magnetite in ooliths, some shell material, and mudstone pebbles).
	8.5 ft.	Sideritic chamositic oolitic sandstone, (pallid ooliths and pseudo-ooliths of chamosite and kaolinite).
V	1.9 ft.	Sideritic sandstone (sparse chamosite ooliths).
	2.9 ft.	Sideritic sandy kaolinite oolite (some ooliths spastolithic).
	6.5 ft.	Sideritic chamosite oolite, (some replaced shell material).
	9.9 ft.	Sideritic chamositic chamosite limonite oolite.
	12.0 ft.	Sideritic chamositic oolitic sandstone.

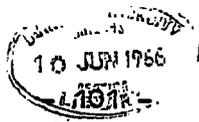
A P P E N D I X

(iii) MINERALOGICAL DESCRIPTION OF ROCK SAMPLES FROM BOREHOLES

IN FIGS. 17* and 20*, and TABLE 13*

(Depths from top of ironstone)

Bore-hole	Depth	Mineralogical Description
* 6	8.0 ft.	Chamositic sideritic oolitic mudstone (there is some shell material partially replaced by chamosite).
	8.8 ft.	Calcitic limonite oolite (some shell material and pisoliths). (Plate 9 (ii)).
	18.2 ft.	Shelly calcitic limonite oolite (Plate 13).
	25.5 ft.	Oolitic silty claystone (shell material 20% of detritus, matrix 60%).
	27.0 ft.	Calcitic oolitic silty claystone (ooliths sparse, calcite present sporadically in matrix).
	27.3 ft.	Sparsely oolitic claystone (90% matrix - mainly micaceous clay minerals).
**8	0.8 ft.	Chamositic sideritic kaolinite-limonite oolite (spastolithic kaolinite limonite ooliths surrounded by a chamosite matrix with interstitial siderite). (Plate 10 (i)).
	2.8 ft.	Chamositic sideritic limonite oolite.
	7.2 ft.	Chamositic sideritic oolitic mudstone (limonite ooliths)
	15.3 ft.	Calcitic shelly pisolitic limonite oolite and chamositic sideritic mudstone (includes fragments of limonitised oolitic mudstone).
	24.7 ft.	Calcitic shelly limonite oolite.
	26.4 ft.	Calcitic chamositic limonite oolite. (Banded limonite ooliths in matrix of nearly equal amounts of calcite and chamosite. (Plate 12 (ii))).
	27.2 ft.	Calcitic oolitic claystone (limonite ooliths, 85% matrix, mainly micaceous clay minerals, sporadic calcite and silty quartz).
	27.9 ft.	Calcitic oolitic shelly siltstone (limonite ooliths, 60% matrix, of silty quartz, finely granular calcite and clay minerals).
	29.5 ft.	Oolitic silty claystone, (limonite ooliths, 70% matrix, of iron-poor clay minerals with some silty material - possibly some chamosite) (Plate 11 (i)).



APPENDIX (iii) Continued

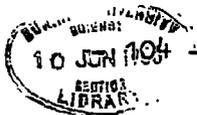
Bore- hole	Depth	Mineralogical Description
	30.3 ft.	Calcitic clayey silty oolitic calcarenite (the detritus is mainly comminuted shell material and the limonite ooliths comprise 30% of this. The matrix 30%, is silty quartz, calcite and clay minerals).

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