MEMOIR 78

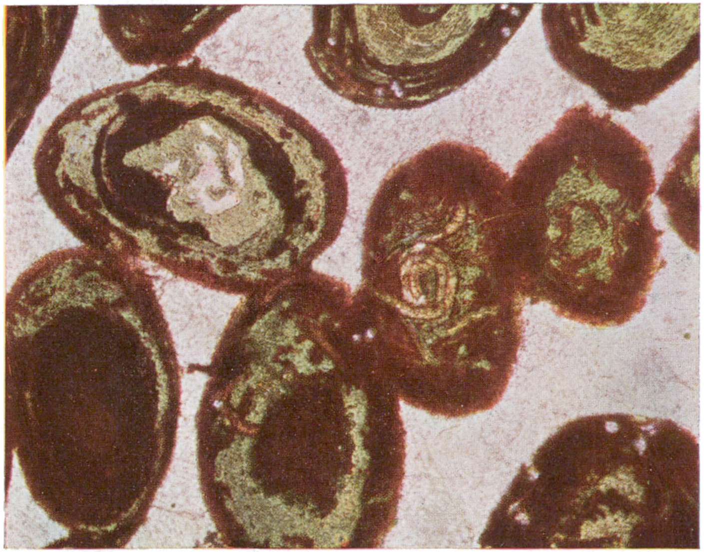
WABANA IRON ORE
OF
NEWFOUNDLAND

BY

ALBERT ORION HAYES

GEOLOGICAL SURVEY
DEPARTMENT OF MINES
OTTAWA
1915

Plate I.



EXPLANATION OF PLATE I.

Ore from upper part of Scotia bed, locality 215 D5, slide 21, microphotograph enlarged 127 diameters. Boring algæ in spherules composed of alternate concentric layers of chamosite (green) and hematite (brown) in siderite matrix. The coiled tubules are in a nucleus of chamosite and have crystalline hematite deposited on the exterior of their walls. Plate XV A illustrates ore similar to that from which slide 21 was cut. (Pages 17, 24, 40, 74.)

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GEOLOGICAL SURVEY

MEMOIR 78

No. 66, GEOLOGICAL SERIES

Wabana Iron Ore of Newfoundland

BY

Albert Orion Hayes

OTTAWA
GOVERNMENT PRINTING BUREAU
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Wabana Iron Ore of Newfoundland.

CHAPTER I.

INTRODUCTION.

An endeavour has been made in this paper to present the results of a detailed study of the petrology and chemistry of the Wabana iron ore. A discussion of the origin of the ore and short descriptions of deposits of similar character and age, are given in conclusion.

I had the pleasure of visiting the Wabana iron mines in November, 1911, in company with Mr. C. L. Cantley, assistant to the general manager of the Nova Scotia Steel and Coal Company. Many questions suggested themselves as to the exact nature of the oolitic iron ore and its origin, and a preliminary investigation was made by Mr. Cantley and the writer in December of the same year. The conclusion was then reached that only a most thorough investigation would serve to answer these questions satisfactorily. While carrying out this research I have been aided in many ways by the management of the Nova Scotia Steel and Coal Company, and desire to acknowledge especially the kindness of Messrs. Thomas Cantley, R. E. Chambers, C. L. Cantley, and A. R. Chambers, and to thank the company most heartily for its courteous co-operation in carrying out both field and laboratory work. I am also much indebted to Mr. Jas. P. Howley, Director, Geological Survey, Newfoundland, through whose kindness and personal interest this work has profited.

The field study of the ore deposits was made by the writer in the summer of 1912, after a general geological survey of the Cambro-Ordovician of Conception and Trinity bays had been carried on by Professor Gilbert van Ingen and the writer, with the assistance of Mr. B. F. Howell of the Department of Geology, Princeton university.

The microscopic examinations and some of the chemical analyses were made by the writer in the laboratories of the

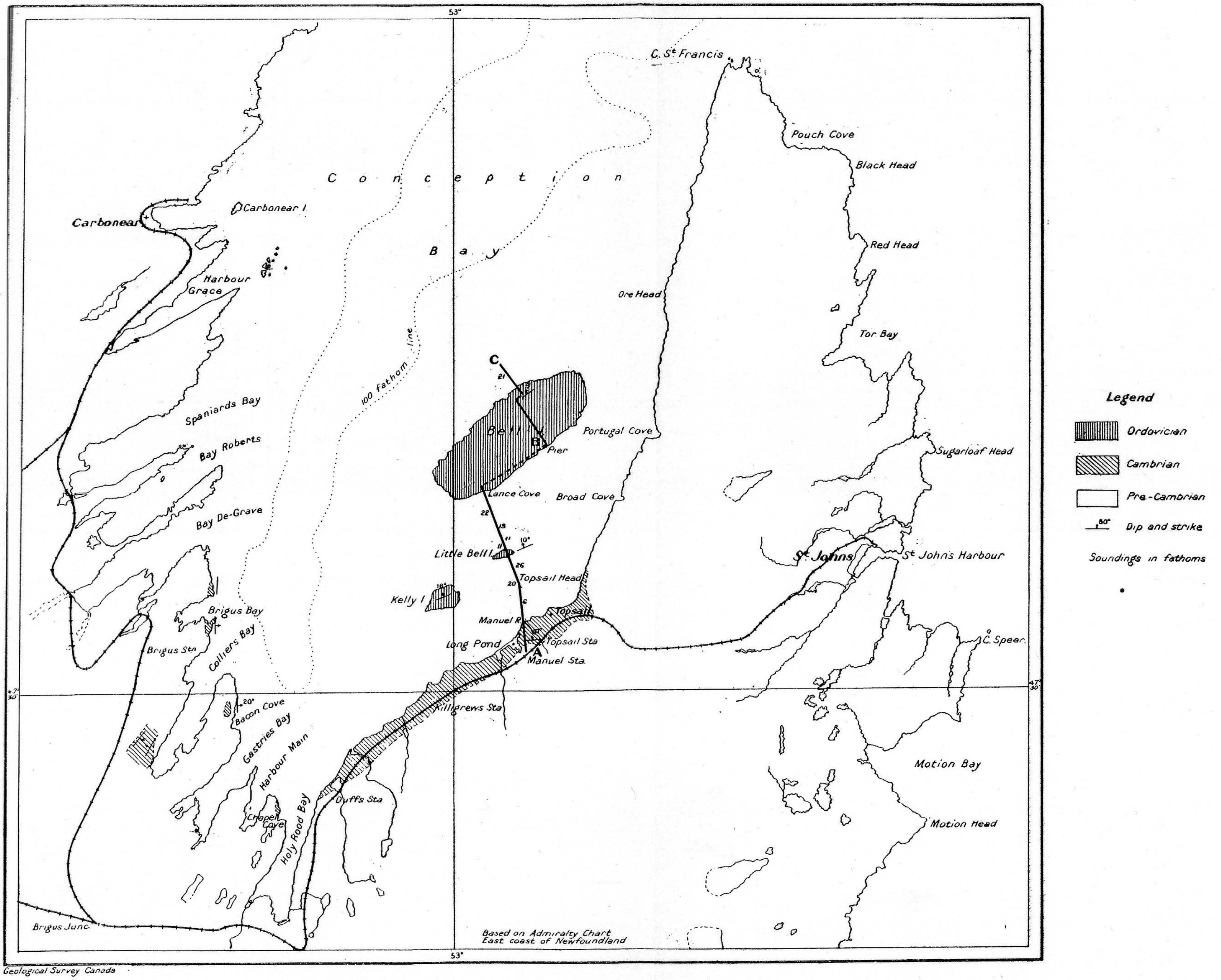
Department of Geology at Princeton university, and a number of the chemical analyses were also made by him at Wabana, Newfoundland, in the laboratory of the Nova Scotia Steel and Coal Company. This company has provided other analyses of the ore and accompanying rocks, which were made from time to time by its chemists, Messrs. T. G. McFarlane, W. L. Fraser, and A. V. Seaborn, whose work I desire to gratefully acknowledge.

It gives me great pleasure to express my deep gratitude to Professors C. H. Smyth, jun., and Gilbert van Ingen, of the Department of Geology, Princeton university, for their continued generous support throughout this investigation. It would be impossible for me to give them credit for each of the many suggestions by which they have aided this work. Professor van Ingen has also identified the fossils referred to in the text, supplied the material for a chemical analysis of the fossil brachiopod, *Lingula hawkei*, and prepared the photographs. I am especially indebted to Professor Smyth for many valuable suggestions regarding methods of investigation, and above all for giving me freely of his own experience in similar fields of research.

This thesis was accepted by the Faculty of Princeton university in partial fulfilment of the requirements for the degree, Doctor of Philosophy, and is the first of a series of contributions to the geology of Newfoundland by the graduate students and staff of the Department of Geology of the university.

The Wabana iron ore deposits are owned and mined by two Canadian firms, the Nova Scotia Steel and Coal Company and the Dominion Iron and Steel Company, operating steel plants at Sydney Mines and Sydney, in Cape Breton. According to the report of the Department of Mines, Mines Branch, on the production of iron and steel in Canada during the calendar year 1913, by John McLeish, page 7, the total quantity of Newfoundland ore shipped during 1913 from the Wabana mines was 1,605,920 short tons, of which 1,048,432 tons were shipped to Sydney and 557,488 tons to the United States and Europe. The Wabana mines furnished during 1912 and 1913 from 47 to 48 per cent of the total amount of iron smelted in Canada.

Since the Wabana ore is so closely connected with Canadian



Geological Survey Canada

Fig. 1. Key Map showing line of section A B C

Scale

1 0 5 10 Miles

industry, this thesis has been accepted for publication by the Geological Survey, Canada.

The Wabana iron ore forms part of a series of Ordovician sediments which are exposed on Bell island, in the south central part of Conception bay (Figure 1). The ore beds outcrop for about 3 miles along the northern shore of this island and dip to the northwest (Figures 2, 3, and 4). They are the highest beds of the northern limb of an anticline, the truncation of which has revealed an almost continuous series of unmetamorphosed sandstone and shale several thousands of feet thick, underlying the ore and ranging in age from Lower Cambrian to lower Ordovician.

An extraordinary concentration of ferruginous minerals occurs in five principal zones through the upper 1,000 feet of strata, which comprise, with the accompanying sandstone and shale, a fossiliferous series of shallow water deposits presenting problems of structure, stratigraphy, palæontology, petrology, and chemistry. Although this paper is restricted mainly to the petrology and chemistry of the ore series, the conclusions reached are based on the broader foundations of a general geological investigation of the vicinity.

The general and detailed stratigraphy of the ore zones is described first, and a summary of the palæontology follows. To demonstrate the composition of the ore and accompanying rocks, detailed descriptions of thin sections studied under the microscope are given. Each zone is taken in stratigraphical order, beginning with the lowest. Microphotographs illustrate the petrology of each zone and these are referred to by plate numbers in the text. Following the petrology, the chemistry of each zone is taken up, recalculations of important analyses made, and their significance stated. In conclusion, the bearing of the results of the investigation on the question of the origin of the ore and of the oolitic pyrite is considered, and the theories of origin of similar deposits discussed.

Certain names have been given to the various iron ore beds, and among others "Dominion bed" and "Scotia bed" to the principal workable beds. These names were applied before submarine mining commenced, when the Dominion bed was operated by the Dominion Iron and Steel Company, and the Scotia bed by the Nova Scotia Steel and Coal Company, on the land claims on Bell island. In the case of the submarine holdings, however, each company owns all of the beds within its respective areas, the boundaries of which are vertical. At the present time the Scotia Company is mining largely from the Dominion bed, as well as the Scotia bed, while the Dominion Company owns a part of the Scotia bed, as well as part of the Dominion, and other beds in their submarine property. Hence the names of the ore beds do not indicate the names of the owners.

PREVIOUS WORK.

During the years 1842 and 1843, J. B. Jukes made a general survey of the geology of Newfoundland and in his report (27: pp. 81-82)[1] the following descriptions are found:

"On the southeast side of Kelly island, a mass of gritstone, in many beds having a total thickness of 30 or 40 feet, rises into the middle of the cliffs. . . . . In Little Bell island, as well as in Bell island itself, several bands of similar stone exist, but none of such thickness nor in so favourable a situation for working as in Kelly island. In the upper beds of Bell isle, namely those on the northwest side, there is but little stone, although one bed of bright red sandstone about 8 feet thick was observed."

This is probably the earliest reference to the Wabana ore, as the only bright red strata of Bell island are beds of a ferruginous oolite whose colour is due to hematite; and a bed, of about the thickness noted, forms a striking feature of the northwest coast.

In his report for 1868, Alexander Murray (35: p. 157) described a section from Manuels brook across Kelly, Little Bell, and the west end of Bell islands, from Lance cove northwards. The highest stratum described in the section is a "mass of greyish granular white-weathering sandstone" which underlies the principal ore beds. Higher strata containing the

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[1] Figures in brackets refer to bibliography, p. 95

iron ore are exposed farther east, but as these are not included, they were probably not visited and one of the most wonderful accumulations of iron ore in the world remained unknown until many years later.

The ruins of old stone fireplaces at Lance cove point to an early settlement of Bell island, but no accurate history is at hand concerning the pioneers. Primitive farming was carried on during the latter half of the nineteenth century by Irish settlers who took their product to St. Johns in sailing vessels, their only means of communication. Anchors were frequently made by enclosing the heavy "red rock" in frames made from small fir trees, but no one realized the value of these particular rocks until many years had passed.

The nature of the iron ore was eventually recognized and its value being realized, the property was acquired by Messrs. Butler of Topsail, Newfoundland, from whom it was purchased by the Nova Scotia Steel and Coal Company in 1893. The difficult pioneer work of developing the property for this company was managed by Mr. R. E. Chambers, and we are indebted to him (8) for the first description of the deposit, published in 1896.

An historical sketch and a description of the development of mining operations were given in 1909 by Messrs. R. E. and A. R. Chambers (9), and in 1911 an article by Mr. Thomas Cantley (6) reviewed the history of the mines, and described the ore beds and methods of mining. The following interesting facts have been taken from Mr. Cantley's paper:

During the summer of 1895, when the mines on Bell island were being opened and preparations made for large shipments of ore, Mr. Thomas Cantley gave the locality the Indian name "Wabana," which means "The place where daylight first appears," an appropriate name for this eastern portion of the continent.

"In 1899 a portion of the areas was sold to the then recently formed Dominion Iron and Steel Company, the latter thus acquiring the lower bed while the Nova Scotia Company reserved for themselves the upper bed, the ore in which contains a higher percentage of iron than any of the other seams. This sale included a submarine area of 3 square miles adjoining the shore.

Subsequently, the Nova Scotia Company acquired outlying submarine areas which it was believed would be workable because of the increased thickness of cover. The well known persistence of the beds also led to the belief that this submarine area would contain all the beds outcropping on the land.

"Upon the submarine areas each company owns all the beds upon their respective claims, while on the land the Nova Scotia Steel and Coal Company operate the "Scotia" or upper bed, the Dominion Company working the underlying seam.

"As the work progressed, additional areas were secured, and at the present time, the Nova Scotia Steel and Coal Company own 32½ square miles of the submarine areas within the supposed limits of the basin, and the Dominion Iron and Steel Company, 5½ square miles.

"To reach the Scotia submarine areas, it was necessary to pass through the Dominion areas, which, adjoining the land, extend almost 4,000 feet to the deep. An agreement was made by which the slopes could be driven through these intervening areas and work was commenced accordingly in March, 1905. This work progressed favourably and the Scotia submarine areas were reached in 1909. As the slope proceeded it was ascertained by diamond drilling that the lower bed had increased very greatly both in thickness and richness. At the outcrop this seam was 11 feet thick, but gradually increased to over double that thickness—indeed, in places to over 30 feet; while analyses of the ore showed that the iron content was higher and the silica correspondingly lower."

Since the writing of the above quoted paper in 1911, additional submarine grants have been secured by the Nova Scotia Steel and Coal Company, their total holdings now being 83½ square miles. Many changes have also been made in their plant for facilitating the increased output of ore.

In a paper on the Iron Ores of Newfoundland (26: p. 751) Mr. James P. Howley gives an approximate estimate of the probable amount of ore, taking into consideration twelve bands of ore, ten of which range from 12 to 15 inches in thickness, and two large bands near the top of the series, the lower (Dominion bed, zone 2) averaging 10 feet and the upper (Scotia bed, zone 4) 8 feet. He says:

"By the aid of the dip and strike of the strata, where accessible, it is possible to form a fair idea of the extent of the trough, and unless some unforeseen disturbance takes place, whereby the ore may be greatly diminished or thrown out altogether, and provided the bands maintain their thickness and stratified character throughout, the result arrived at reaches the enormous total of 3,635,343,360 tons, I shall not hazard an opinion as to the amount that may be recoverable."

It is to be pointed out that a stretch of about 10 miles of water intervenes between Bell island and the Pre-Cambrian rocks on the north shore of Conception bay, towards which the ore dips, and that no outcrops of the Cambro-Ordovician series are found on the shore of Conception bay north of Brigus-North head, which lies about 10 miles to the southwest of the island. Any estimation of the total amount of ore present, depends largely on an interpretation of the structure of the ore strata, and hence must be largely hypothetical.

Mr. H. Kilburn Scott, M.I.M.M., of London, in 1909 (39: p. 39) estimated the ore in the Scotia property alone to total 652,500,000 tons, and total recoverable ore, deducting that lost in pillars by faults and poor zones, to total 395,525,000 tons.

Mr. Elwin E. Ellis and Mr. Edwin C. Eckel have each estimated the amount of the Wabana iron ore, and the results of their findings were given as testimony in a legal case, as follows, according to the "Iron Age" of October 16, 1913, in an article entitled—"The Steel Corporation Dissolution Suit."

"Edwin E. Ellis, of Birmingham, Alabama, a geologist, formerly with the United States Geological Survey, and now with the Tennessee Coal, Iron, and Railroad Company, testified regarding the iron mines which are being operated near Bell island, in the Conception Bay district, Newfoundland, of which he had prepared maps. He said that claims had been taken as far as 12 miles out from shore and that it is planned to operate workings of that length. He estimated the reserve at 3,250,000,000 tons allowing for workings 5 miles long. . . . . .

"Edwin C. Eckel testified . . . . . that in Newfoundland there were 3,500,000,000 tons of economically available ore within a radius of 5 miles of Bell island. Besides this there are billions of tons which are not economically available at this time. In one deposit alone in the Newfoundland district he said that the ore runs 30 feet thick and contains about 90,000,000 tons to the square mile."

No discussion of the geology of the Wabana ore with reference to its origin, has come to the writer's notice, but Professor C. K. Leith (29: pp. 99-100) and Dr. R. Beck (2) group them with the Clinton ores as primary sediments.

CHAPTER II.

STRATIGRAPHY.

GENERAL STRATIGRAPHY OF THE ORE ZONES.

From a study of the ore-bearing rocks, the conclusion has been reached that the ore beds are primary sediments which have been deposited on the floor of a marine sea of Arenig to Llandeilo age, and that their distribution was regulated by the same forces which have had to do with the formation of the sandstones and shales which accompany them. (Plate II A).

Several thousand feet of unmetamorphosed and slightly disturbed sediments accompany and underlie the ore beds and dip 8 to 10 degrees north-northeast. The distance across the strike of these strata from the basal Cambrian conglomerate on Manuels brook to the highest beds on Bell island is about 8 miles, of which about 3½ miles is covered by the water of Conception bay (Figure 2). Exposures occur on Kelly and Little Bell islands, about midway across this covered portion, and furnish a section over 1,000 feet in thickness, which reveals strata of a character very similar to that found on Bell island. The sediments are laid down in broad lenticular beds of varying thickness and extent, which occasionally begin at a point, spread and thicken, and then die away within a distance of 100 feet (Plates II B and III A), although usually they are much more continuous. Cross-bedding and ripple-marks are constantly met with. It is evident that these sediments were deposited on a sea bottom that suffered continual oscillation relative to the surface of the water. Zones of strata varying in thickness up to about 100 feet, and composed predominantly of sandstone or layers made up of beds of shale, are very persistent and can usually be traced as far as exposed above water. The individual layers constituting these zones are themselves continually thickening and thinning, being replaced by others of similar character. The ore beds display all the features peculiar to off-shore deposits, but were accumulated generally in thicker and more extensive individual layers than those of the accompanying rocks, and the thicker beds of oolitic hematite appear to be the most persistent of the series.

Oolitic iron ore and ferruginous rocks have been found in six zones on Bell island and these are given in stratigraphical order, beginning with the lowest (Figures 2, 3, and 4, and Plate IIIB).

Zone 0.—A thin ferruginous band occurs in the strata, forming the extreme southwest part of the island, outcropping from Lance cove westwards to the western shore near the "Clapper" (Figures 2 and 3).

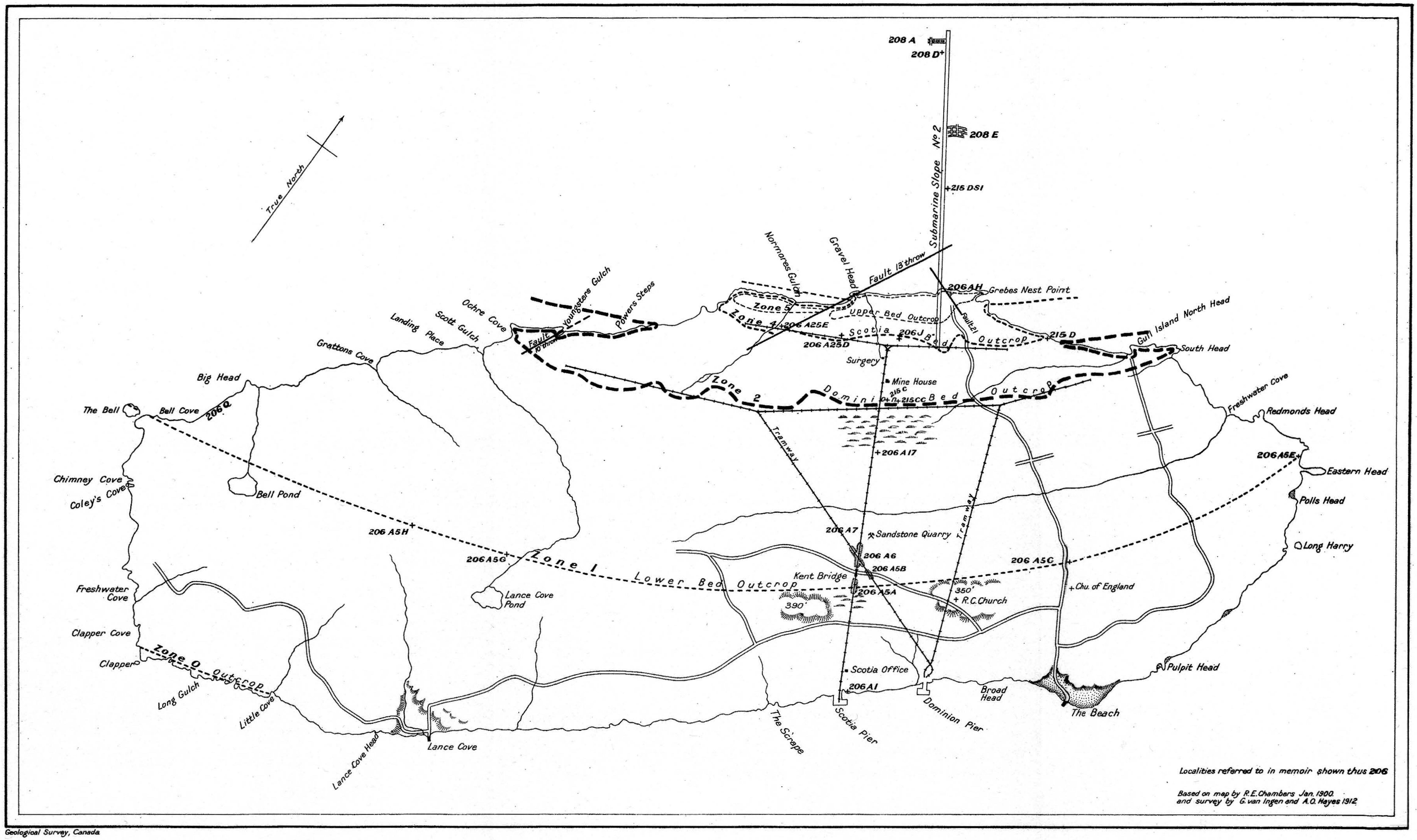
Zone 1.—This zone is partially exposed by shallow cuttings along the tramways of the Nova Scotia Steel and Coal Company and of the Dominion Iron and Steel Company near their intersection at Kents bridge. It may be traced by intermittent outcrops from Eastern head on the east coast of the island to the northwest coast between Big head and the Bell (Figures 2 and 3). It contains bands of oolitic hematite, two of which appear to be continuous, one attaining a thickness of about 2 feet.

Zone 2, Including the Dominion Bed.—The lowest oolitic hematite of this zone is about 600 feet stratigraphically above zone 1, and the whole zone consists of a series of bands of oolitic hematite alternating with shales and cross-bedded, fine-grained sandstones, comprising about 100 feet of strata culminating in the Dominion bed. The top 35 feet of strata are composed largely of oolitic hematite in thick beds with thin ferruginous sandstone and shale parting rocks (Figures 2, 3, and 4, and Plate IV).

Zone 3, Pyrite Beds.—Oolitic pyrite occurs in from one to three bands extending through strata from a few inches up to 4 feet in thickness, and found from 1 to 10 feet above the highest oolitic hematite of zone 2. (Figures 2 and 4, Plates IV and V).

Zone 4, Scotia Bed.—This zone commences 210 feet above zone 3 and is confined to about 15 feet of strata (Figures 2, 3, and 4, Plates IIIB, VI, VII, and VIII).

Zone 5, Including the Upper Bed.—The lowest band of this zone is separated from the top of the Scotia bed by about 40



Geological Survey, Canada

Fig 3 Outcrops of ore-beds on **Bell Island, Newfoundland**

feet of sandstone and shales, and the oolitic iron ore continues upwards through about 50 feet of strata (Figures 2, 3, and 4, Plates IIIB and IX).

DETAILED STRATIGRAPHY OF THE ORE ZONES.

Zone I.

This oolitic hematite is not being mined for ore, and consequently the ferruginous strata are exposed for study only in the perpendicular cliffs of the coast and along road and prospect cuttings. Ten exposures were found which serve to trace the outcrop nearly the entire length of the island, about 5¾ miles. Three sections will illustrate the stratigraphy of the zone, one from the east coast, another from the interior, and the third from the west coast. Lists of fossils are given on page 22.

Section at Eastern Head. Locality 206 A 5 E.

Number	Strata	Thickness[1]		Character
		Rock	Hematite	
10	Shale.........	Eroded	....	Purple-black, fine-grained, sandy.
9	Sandstone.....	2 ft.	....	Green, medium-grained.[2]
8	Hematite.....	....	2 ft.	Oolitic.
7	Sandstone.....	10 ft.	....	Green, medium-grained.
6	Hematite.....	....	1 ft.	Oolitic.
5	Sandstone.....	15 ft.	....	Green, medium-grained.
4	Shale.........	30 ft.	....	Purple black, fine-grained, sandy.
3	Sandstone.....	5 ft.	....	Medium-grained, green.
2	Hematite....	....	2 ft.	Oolitic.
1	Sandstone.....	20 ft.	....	Green, medium-grained.

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[1] Thickness estimated in steep cliff by eye.

[2] The green sandstone of this zone appears to be ferruginous, but no analyses of it have been made.

Section in Cutting South of Kents Bridge. Locality 206 A5A.

Number	Strata	Thickness		Character
		Rock	Hematite	
18...	Sandstone.....	5 ft. 0 in.	......	Dark to light green, fine.
17...	Sandstone and shale.......	1 ft. 6 in.	......	Gradual change with thin shales.
16...	Sandstone.....	2 ft. 4 in.	......	Green, coarse, granular.
15...	Sandstone and shale.......	4 ft. 5 in.	......	Gradual change with thin shales.
14...	Hematite.....	......	4 in.	Oolitic.
13 ...	Sandstone.....	8 in.	......	Ferruginous.
12 ...	Sandstone.....	4 in.	......	Ferruginous, coarse.
11...	Shales........	1 ft. 0 in.	......	Black, in thin layers, with thin sandstone layers. Dip 10 degrees north.
10...	No exposure....	1 ft. 1 in.	......	....
9...	Sandstone.....	2 ft. 0 in.	......	Dark green, medium-grained.
8...	Hematitic Sandstone...	9 in.	......	Coarse-grained with quartz pebbles.
7...	Hematite.....	......	1 ft. 6 in.	Oolitic.
6...	No exposure...	1 ft. 1 in.	......	....
5....	Sandstone.....	2 ft. 8 in.	......	Coarse, dark green.
4...	No exposure...	3 ft. 10 in.	......	....
3....	Shale.........	3 ft. 10 in.	......	....
2...	Sandstone with hematite bands....	1 ft. 3 in.	3 in.	Oolitic hematite in 3 bands each 1 inch thick.
1....	Sandstone.....	1 ft. 0 in.	......	Medium-grained, ferruginous.

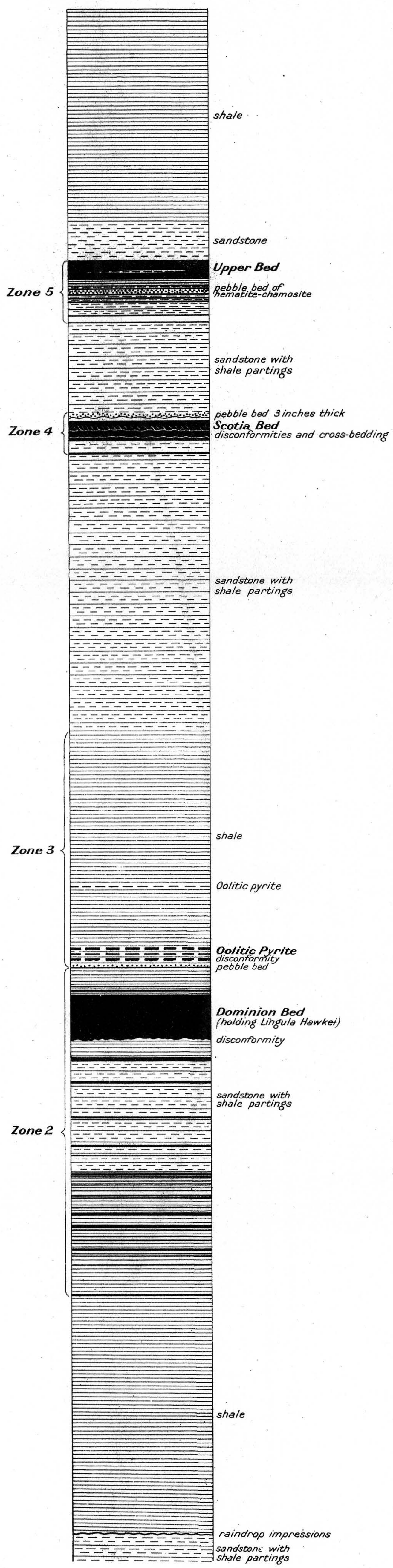

Fig 4. Generalized section through **Zones 2,3,4, and 5.**

Scale of feet

Big Head Section, Locality 206 Q.

Number	Strata	Thickness[1]		Character
		Rock	Hematite	
4.....	Sandstone.....	100 ft. top eroded .	......	Shaly at base.
3d....	Sandstone.....	4 ft.	......	Massive green beds.
3c.....	Hematite ?....	......	1 ft.	Two thin red bands each 6 inches thick. Not known if oolitic.
3b....	Sandstone.....	6 ft.	......	Massive green beds.
3a....	Sandstone.....	20 ft.	......	Thinner bedded. Beds less than 2 feet thick.
2.....	Shales........	15 ft.	......	....
1e....	Sandstone.....	10 ft.	......	Massive green.
1d....	Hematite.....	......	2 ft. 6 in.	Oolitic. Measured with rule.
1c.....	Sandstone.....	20 ft.	......	Massive green.
1b....	Hematite ?....	......	1 ft.	Red band. Not sure of character.
1a....	Sandstone.....	25+ft.	....	Massive green.

[1] All thicknesses except 1d, estimated by eye at a distance of about 500 feet.

Zone 2, Including the Dominion Bed.

This zone extends about 3¼ miles along the outcrop on the island from Gull island, South head, on the northeast coast to Ochre cove, its western limit on the north coast, and has been found to continue unchanged in general character to the face of the submarine workings over 1½ miles north of the island. The area exposed and exploited appears to comprise a very small part of its total extent.

The section on page 14 is taken from the record of diamond drill boring No. 5 and gives the succession of strata through the upper part of zone 2, upwards to the base of zone 4 (Figures 2, 3, and 4 and Plate IV).

Bore-hole No. 5 Section.

Strata.	Thickness.		Character.
	Rock.	Ore.	
Underlying Zone 4.			
Cross-bedded sandstone and fine grey argillaceous shale	124 ft. 0 in.	......	
Zone 3.			
Grey argillaceous shale holding graptolites in lower 60 feet	83 ft. 0 in.		Slightly pyritiferous
Oolitic iron pyrites	....	1 ft. 4 in.	
Sandstone, grey, cross-bedded	5 ft. 0 in.	......	
Zone 2.			
Oolitic hematite	......	1 ft. 7 in.	
Sandstone	0 ft. 1 in.	......	Ferruginous.
Oolitic hematite	......	0 ft. 6 in.	Ore.
Sandstone	0 ft. 3 in.	......	Ferruginous.
Oolitic hematite	......	1 ft. 11 in.	Ore.
Shale	0 ft. 2 in.	......	Fine grey.
Oolitic hematite	......	8 ft. 7 in.	Ore.
Shale and oolitic hematite	0 ft. 4 in.	......	
Oolitic hematite	......	1 ft. 0 in.	Ore.
Shale and oolitic hematite	0 ft. 4 in.	......	
Oolitic hematite	......	1 ft. 1 in.	Ore.
Shale and oolitic hematite	0 ft. 6 in.	......	
Oolitic hematite	......	5 ft. 2 in.	Ore.
Sandstone, thin-bedded	6 ft. 8 in.	......	
Sandstone with shale partings	2 ft. 0 in.	......	
Oolitic hematite	......	0 ft. 7 in.	
Sandstone	0 ft. 4 in.	......	
Oolitic hematite	......	0 ft. ½ in.	
Sandstone	0 ft. 2 in.	......	
Oolitic hematite	......	0 ft. 2 in.	
Sandstone	0 ft. 3 in.	......	
Underlying thick series of sandstone and shale beds with thin layers of oolitic hematite.			

Dominion Bed, Outcrop Section, 215 C (Plate IV).

No.	Slides.[1]	Chemical Analyses[2]	Thickness.	Description of strata.
7.....	......	L	......	Brownish black shales with some interlaminated hematite and nodules.
6.....	8	K	0 ft. 6 in.	Oolitic chamosite holding many brachiopod shell fragments.
5.....	......	J	1 ft. 6 in.	Hard, grey, fine-grained, ferruginous sandstone.
4.....	......	I	0 ft. 6 in.	Oolitic hematite ore holding many brachiopod shells and nodules.
a....	......	......	......	*Disconformity.*
3.....	......	H	4 ft. 0 in.	Oolitic hematite ore.
2.....	......	G	0 ft. 6 in.	Interlaminated parting rock similar to 0.
1.....	2	F	6 ft. 0 in.	Oolitic hematite ore.
0.....	1	E	Floor of stripping.	Interlaminated, fine-grained, greenish grey sandstone and purple black shale.
			Bottom.	

[1] Pages 30, 31
[2] Page 46

Zone 3, Pyrite Beds.

This remarkable occurrence of iron sulphide is found above zone 2, separated from it by from 1 to 10 feet of shales or sandstones. It has been found to be composed of pyrite, and where studied, is predominantly oolitic. The pyrite occurs in from one to three beds which vary in thickness from 1 inch to 1 foot or more (Plate V). The beds thicken and thin and die out within short distances, but the zone itself is very persistent, having a distribution, as far as known, equal to that of zone 2.

There has been a complete change in the nature of the iron-bearing minerals from the oolitic hematite of zone 2 to the oolitic pyrite of zone 3. Thin sections of the oolitic pyrite reveal no trace of hematite. Graptolites occur with the pyrite and accompanying shales, and furnish a means for the interpretation of the conditions obtaining during the deposition of the rocks containing this accumulation of iron sulphide (Plate XIIA).

The following section is taken from the upper part of zone 2 through zone 3, from a point in the submarine slope (Figures 2 and 3).

Pyrite Section, 208 D, through Zone 3.

No.	Strata.	Thickness.		Character.
		Rock.	Pyrite.	
7	Shale...........	85 ft. 0 in.	......	Graptolites in lower 60 ft.
6	Pyrite..........	......	1 ft. 0 in.	Graptolitic, oolitic (Slide 31).
5	Shale...........	0 ft. 8 in.	......	Graptolitic.
4	Pyrite..........	......	0 ft. 6 in.	Graptolitic, oolitic.
3	Shale...........	1 ft. 0 in.	......	Graptolitic.
2	Pyrite..........	......	1 ft. 2 in.	Graptolitic, oolitic (Plate V) (Slide 44).
1c	Shale...........	2 ft. 6 in.	......	Fine-grained, fissile.
1b	Pebble bed......	0 ft. 2 in.	......	Fine-grained sandy shale with phosphate nodules and shell fragments.
1a	Shale...........	4 ft. 0 in.	......	Fine-grained, fissile.
0	Underlying oolitic hematite with shale partings at top of zone 2 (Plate X).	......	......	Contains conglomerate of oolitic iron ore at top.

Zone 4, The Scotia Bed.

The iron ore of this zone is confined to about 15 feet of strata, and fewer layers of parting rock occur in the hematite than are found in the ore of the other zones. A thin ferruginous sandstone parting, found along the eastern surface outcrop and numbered in sections as 215 D4 on page 17 (Plate VIII), and as 206 J2c3 on page 18 (Plate VI) dies out; and at the point where section 206 A25 E is taken, this horizon is marked between the top of E7 and the bottom of E8 by a disconformity formed by wave erosion apparently contemporaneous with the deposition of the parting rock farther east. The eroded surface contains worm burrows and above this disconformity the oolitic hematite is cross-bedded, indicating that shallow water conditions obtained during the deposition of this zone.

The upper 3 to 6 inches is composed of a grey, oolitic ore and although similar in texture, a sharp colour line marks the change from the general red hematite of the lower ore. This grey layer is found everywhere over the Scotia bed and is due to the presence of oolitic chamosite instead of hematite.

Section 215 D, Zone 4 (Plate VIII).

No.	Slide.	Chemical[1] analyses.	Strata.	Thickness.		Character.
				Rock.	Ore.	
9	26, 27	......	Pebble bed	0 ft. 3 in.	....	Phosphate nodules and shell fragments.
8	25	Za, Zc	Sandstone	0 ft. 3 in.	....	Chamositic.
7	24	......	Shale......	0 ft. 1 in.	....	....
6	22, 23	Z	Ore.......	......	0 ft. 3 in.	Grey oolitic chamosite............
5	21, 86	Y	Ore.......	.....	4 ft. 4 in.	Oolitic hematite.
4	20	......	Sandstone..	0 ft. 2 in.	....	Ferruginous parting.
3	19	X	Ore.......	.....	2 ft. 3 in.	Oolitic hematite.
2	18	W	Ore.......	.....	0 ft. 6 in.	Oolitic hematite with three one-half inch shale partings.
1		V	Sandstone..	0 ft. 11 in.	....	Ferruginous, chamositic.
			Underlying beds of oolitic hematite, sandstone, and shale.			

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Section 206 J, Zone 4 (Plates VI and VII).

No.	Slide	Chemical analyses.[1]	Strata	Thickness.		Character.
				Rock.	Ore.	
6	.....	......	Slate......	2 ft. 3 in.	.....	Hard, grey.
5	.....	U	Pebble bed	0 ft. 3 in.	.....	Phosphate nodules and shell fragments in sandy shale.
4c	.....	......	Shale......	0 ft. 1 in.	.....	Sandy.
4 (b-a)	.....	T	Sandstone..	0 ft. 9 in.	.....	Green ferruginous chamositic.
3	.....	......	Shale......	0 ft. 2 in.	.....	Fissile.
2e	.....	......	Ore.......	....	0 ft. 3 in.	Grey oolitic chamosite.
2d	.....	S	Ore.......	....	3 ft. 6 in.	Oolitic hematite.
2c3	.....	R	Sandstone..	0 ft. 4 in.	.....	Ferruginous, green, with many shell fragments.
....	.....	......	Ore.......	....	0 ft. 1 in.	Oolitic hematite.
....	.....	......	Sandstone..	0 ft. 1 in.	.....	Ferruginous, green.
2c(1-2)	.....	......	Ore.......	....	0 ft. 4 in.	Oolitic hematite, with thin sandy partings.
2b	54	Q	Ore.......	....	1 ft. 11 in.	Oolitic hematite.
2a	51	P	Rock......	0 ft. 1 in.	.....	Shell fragments and sandy shale.
			Underlying beds of oolitic hematite, sandstone, and shale.			

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Section 206 A25 E, Zone 4.

No.	Strata.	Thickness.		Character.
		Rock.	Ore.	
11....	Shale............	......	......	Grey, fissile.
10.....	Sandy shale......	0 ft. 9 in.	......	Hard, green with trilobites.
9.....	Sandstone........	0 ft. 3 in.	......	Green, finely laminated chamositie.
8f....	Ore.............	......	0 ft. 6 in.	Oolitic chamosite with siderite, grey.
8 (a-c)	Ore.............	......	2 ft. 10 in.	Oolitic hematite with siderite, cross-bedded.
.....	....	......	......	*Disconformity.*
7 (a-h)	Ore.............	......	2 ft. 6 in.	Oolitic hematite. Disconformity at top shown by wave erosion and vertical worm burrows. (Plate XIV A).
6.....	Sandy shale......	0 ft. 3 in.	......	Green, ferruginous.
1-5...	Ore.............	......	1 ft. 0 in.	Oolitic hematite with thin shale partings.
	Underlying beds of oolitic hematite, sandstone, and shale.			

Zone 5. Including the Upper Bed.

This zone is the highest, stratigraphically, and outcrops along the north of the island in a series of bands of oolitic hematite separated by sandstone and shale partings, which contain lean, ferruginous oolitic layers composed of chamosite and siderite with smaller amounts of hematite.

Section 206AH, through this zone, described below, was measured on the north cliff. Its component layers are shown in Plate IX.

Section 206 AH, Zone 5. (Plate IX.)

No.	Thickness.		Description.
	Oolitic hem.	Rock.	
22	....	20 to 50 ft. top eroded.	Dark soft shales, top of bank.
21	....	....	....
20	....	6 in.	Carbonate, phosphate, pebbles, pyrite, hard band.
19	....	6 ft. 3 in.	Variable as follows:
19f	....	....	½ in. shale.
19e	....	....	7½ in. iron silicate carbonate bed.
19d	....	....	8 in. iron silicate rock.
19c	....	....	2 ft. 3 in. iron silicate rock.
19b	....	....	11 in. heavy slate with many pebbles.
19a	....	....	1 ft. 9 in. heavy layer. Base fills erosion channels in top of underlying hematite.
18	18 in.	....	Rhombic hematite.
17	....	12 in.	Slate with phosphate pebbles in upper 5 inches.
16	....	32 in.	Heavy bed, chamosite and hematite mixed. Bedding plane at base.
15	10 to 12 in.	....	East of fault (Slides 93 and 94).
14	....	13 in.	Slate.
13	....	12 to 15 in.	Heavy bed, red and green ferruginous at base, slaty at top.
12	5 in.	....	Rhombic hematite.
11	....	7 in.	Irregular slaty parting rock. Fossil trails at base.
10	4 in.	....	Irregular rhombic hematite.
9	....	35 in.	Heavy bed, variable, as follows:
9d	....	....	9 in. massive, homogeneous, lean ore.
9c	....	....	11 in. slaty, knotty.
9b	....	....	4 to 5 in. white-weathering pebbles. Lingula.
9a	....	....	11 in. mixed chamosite and hematite.

Section 206 AH, Zone 5—Contd.

No.	Thickness.		Description.
	Oolitic hem.	Rock.	
8.........	24 in.	....	Hematite with green rock partings, as follows:
8e......	....	....	7 in. hematite.
8d......	....	....	1 in. parting.
8c......	....	....	4 in. hematite.
8b......	....	....	2 in. parting.
8a......	....	....	10 in. hematite.
7.........	....	9 in.	Hard green rock and hematite intermingled.
6.........	1 ft. 8 in.	....	Platy rhombic hematite, as follows:
6c......	....	....	5 in. hematite.
6b......	....	....	½ inch. sandstone.
6a......	....	....	1 ft. to 2½ in. hematite.
5.........	....	1 ft. 1 in.	Hard bed of hematite and green slate.
4.........	4½ in.	....	Soft hematite, platy. Many brachiopod fragments.
3 (a-f)....	....	5 ft. 6½ in.	Heavy bed. Alternating hematite and green siliceous rock.
2.........	....	2 ft. 6 in.	Grey hard shale, with grey sandstone seams.
1.........	....	1 ft. 1 in.	Hematite at base of cliff.

GENERAL REMARKS ON THE ORE ZONES.

All of the ore bands are characterized by wave erosion indicated by ripple-marked surfaces (Plate XIA). Some portions of zone 4 are cross-bedded (Plate VIII). Worm burrows are splendidly preserved in the ore and accompanying rocks of all zones (Plates XIIIA, XIIIB, and XIVA), and comparatively fresh brachiopods are found in all the ore beds as well as in the accompanying sandstones and shales. The brachiopods are the most important marine fossils, and they are preserved in such a manner as to indicate that the animals lived in the loose material which eventually became compacted into the oolitic iron ore (Plate XIIB). Graptolites occur in the oolitic pyrite and fine fissile grey shales overlying the oolitic hematite and shale of zone 2 (Plate XII A).

CHAPTER III.

PALÆONTOLOGY.

A number of distinct faunal horizons which may be roughly correlated with the ore zones, occur in the ore measures. No accurate descriptions of the range of the faunas are here attempted. In the ferruginous sandstones and oolitic hematite beds of zone 1 (localities 206 A5A, 206 A5B, 206 A5E), the following fauna has been found: *Lingula affinis*, *Lingulella bella*, *Sphaerobolus fimbriatus*, *Obolus burrowsi*, *Cruziana similis*, *Arenicolites*, and *Sphaerobolus spissus*.

In the oolitic hematite of the Dominion bed, zone 2, *Lingula hawkei* occurs, and boring algæ are abundant. In the upper part of zone 2 above the Dominion bed, a pebble bed carries a Helmersenia-like brachiopod. This species is absent from the overlying shales of zone 3. (Plates I and XII B).

Above a disconformity at the top of zone 2, the pyrite beds, with the accompanying and overlying shales of zone 3, hold *Didymograptus cf. nitidus*, abundantly (Plate XII A). Thin-shelled orthoceratites are also found, and linguloid brachiopods occur in the pyrite layers.

From the oolitic ore of the Scotia bed and accompanying rocks of zone 4, the following fauna has been taken: trilobites including an asaphid, probably *Niobe*, a Pro-calymene, *Schizocrania* new sp., Lingula new sp., *Hymenocaris*(?) tail of an Eurypteroid crustacean, *Cruziana similis*, *Arenicolites*, and *Eophytum linneanum*. Boring algæ are abundant in the iron ore.

Zone 5 holds the following forms: *Schizocrania*, *Lingula leseueri*, *Lingula* sp., and *Orthis* sp. undet.

The trails known as *Cruziana similis*, *Arenicolites* (Plates XIII A, XIII B, and XIV A) and *Eophytum linneanum* are found throughout all zones. Raindrop impressions are found at locality 206 A17 between zones 1 and 2 (Plate XXVIII).

The Schizocrania occurring in the pebble bed 206 J3 of zone 4 and 206 AH section of zone 5, exhibit a peculiar feature.

The laminæ of the shells of these brachiopods and of lingula frequently have a thin coating of galena over their surfaces, giving them a shiny appearance. This remarkable association of lead sulphide and fossil shells is worthy of further study. Small concentrations of galena occur in the upper part of the Scotia bed and may be genetically associated with these fossils.

The general bearing of the presence of this fauna in the ore rocks and the special significance of the incursion of graptolites in zone 3 will be discussed in the chapter on the "Origin of the Ore."

CHAPTER IV.

PETROLOGY.

The study of the ore and accompanying rocks in thin sections has supplied much exact information regarding their composition and structure, and by combined microscopic and chemical analyses the important iron-bearing minerals have been identified.

There is considerable literature concerning iron ores of similar type and age occurring in France, Bohemia, and Wales; and of similar type but of younger age in the United States, England, and Germany. Comparisons of the results of this petrological investigation, with published descriptions of similar work in other fields, has aided greatly in securing a wider understanding of these bedded iron ores.

A general description of both the megascopic and microscopic characteristics of the ore and associated rocks will be followed by short descriptions of each zone. Illustrations of thin sections will be found at the end of the memoir.

MEGASCOPIC DESCRIPTION OF THE ORE.

The ore has the reddish brown colour typical of amorphous hematite, a fresh fracture presenting a reddish grey colour with a sub-metallic lustre. Along the weathered outcrop, or wherever shattered by blasting, the ore breaks up readily into parallelopiped-shaped blocks, along lines parallel to the principal fault systems of the region (Plates IV, VIII, XI B). These breaks are marked by minute veinlets of calcite and quartz crossing one another nearly at right angles and forming a reticulating meshwork throughout the ore beds. The weathered surface exhibits a fine granular appearance due to an oolitic structure. The concretions which will be referred to as spherules, are very small, varying in diameter from one-tenth to one-half of a millimetre, and are usually somewhat disc-shaped, having their shorter diameters at right angles to the bedding plane of the ore as though flattened by pressure in this direction.

The spherules are more flattened in the body of an ore band where they are closely packed together, than at the contacts with parting rocks where they are scattered through the rock matrix. The spherules of the Dominion bed are consistently smaller, about half the size, and more flattened than those of the Scotia bed, giving the Dominion ore a very much finer-grained appearance than the Scotia ore (Compare Plates XV A and XV B).

Small fragments of brachiopod shells are always contained in the ore and have usually been almost perfectly preserved. Many nodules occur, usually along lines parallel to the bedding of the rocks, but frequently scattered indiscriminately through the ore and varying in size from that of the spherules to one centimetre in length. They are usually somewhat elongated, irregular spheroids showing a dark green colour in cross section (Plate XIV B).

MEGASCOPIC DESCRIPTION OF ACCOMPANYING ROCKS.

The rocks accompanying the ore as partings are fine-grained ferruginous sandstones and sandy shales which have a thickness varying from a thin film to several inches (Plate X). The sandstone has a greenish grey colour and the shale is grey-black with a purple tinge. Both present shining faces when broken parallel to the bedding of the rocks, due to a chloritic mineral, similar in appearance to mica but without elasticity, breaking easily when bent. This mineral is probably crystalline chamosite.

MICROSCOPIC DESCRIPTION OF THE ORE AND ITS CONSTITUENTS.

The ore is composed of two principal iron-bearing minerals, hematite and chamosite, while a third, siderite, becomes locally abundant. Quartz is present in some quantity and occurs generally as detrital fragments, and locally in a recrystallized form. Small fragments of brachiopod shells are always present and minute boring algæ occur throughout the ore series.

Hematite is the most abundant iron-bearing mineral and occurs in a very finely divided form, arranged in concentric bands in small spherules. It is opaque and can be studied best in reflected light, when its natural colour is seen. In the denser ores, hematite frequently obscures the presence of other minerals which have been found to occur with it; therefore the spherules may be studied to the best advantage in the leaner ores. The spherules may be completely composed of hematite or they may have a distinct central portion, termed the nucleus, which is frequently a grain of quartz, quite often a small shell fragment, sometimes the ferrous green silicate, chamosite, or occasionally siderite. The other part is made up of an alternation of layers of hematite and chamosite. In many spherules the hematite obscures the layers of chamosite, but by digesting the spherules in hydrochloric acid, a banded residue of gelatinous silica, similar to that found on treating spherules of chamosite alone, is always obtained, indicating the presence of the silicate in all hematite spherules. Hematite occurs also to a limited extent, filling the interstices between the spherules. Crystals of hematite are frequently found enclosed in chamosite and recrystallized quartz, where they exhibit the typical hexagonal outline. These crystals are very minute and exceedingly thin, translucent and of a ruby red colour. It is probable that all of the hematite occurs in this micro-crystalline form.

Chamosite, an aluminous ferrous silicate, is found in all the ore bands and is second to hematite as an iron-bearing constituent. The composition of the green iron silicate as determined from chemical analyses T, W, Z, Za, Zc (pages 58-62) approximates the composition given by E. R. Zalinski (53: pp. 70-79) for chamosite. Similar minerals such as thuringite and uncrystallized silicates having no constant composition, may accompany the chamosite. A further discussion is given under "Chemistry." Chamosite occurs both in the spherules and in the interstices between them. In the spherules it appears to be mostly uncrystallized. Where non-oolitic it frequently exhibits a micro-crystalline structure, the crystals being grouped in clusters, revealed only by the higher powers of the microscope. It also occurs in larger crystals having a tabular structure. Its colour varies from light to deep green and its index of refraction is higher than that of quartz. Between crossed nicols the chamosite in the spherules is deep blue and shows the cross of aggregate polarization. The micro-crystalline mineral with crossed nicols exhibits a change from yellow to deep blue, the aggregates of minute crystals producing an exceedingly spotted effect.

In the leaner portions of the ore the spherules are composed of either a series of concentric layers of chamosite alone or of an alternation of concentric layers of chamosite and hematite, surrounding in either case a nucleus composed of quartz, a shell fragment, or a small area of hematite, siderite, or chamosite. In some parts of the oolitic ore the chamosite fills all of the interstitial spaces between the spherules, and it is exceptional to find a thin section which does not contain some of this mineral. Where the chamosite is not found, either the spherules are packed together very closely and a large development of hematite has masked other constituents, or the interspherular spaces are filled with quartz or siderite.

Siderite occurs in crystalline form as small rhombohedra, but usually it is difficult to recognize any crystalline form, a granular aggregate in which crystalline structure has occasionally developed, being the rule. It is usually found in the matrix of the ore, that is outside the spherules, sometimes forming all of this interstitial part. It also occurs within the spherules, occasionally forming the central portion or nucleus. In many instances this mineral has replaced chamosite, hematite, and quartz, both outside and inside the spherules, but no instance has been discovered where chamosite or hematite replaces siderite in the spherules. The siderite has an ash grey colour in thin section, exhibits a pearly iridescence between crossed nicols, and has a high index of refraction.

Quartz occurs in small fragments scattered throughout the ore, frequently forming the nuclei of the spherules. It is generally of detrital origin, but at some horizons it is found in recrystallized form and is apparently secondary to the spherules. The detrital quartz is white and frequently contains gas and fluid inclusions and small needles of apatite. In polarized light, each grain extinguishes as an individual crystal. The recrystallized quartz fills interstices between and is outlined by the curved exteriors of spherules. It is made up of aggregates of minute crystals.

Fossil shell fragments are present throughout all of the ore. They occur in varying shapes and sizes and are frequently so well preserved that the most minute structure of the shell can be seen. They are commonly found as nuclei of spherules, in larger rectangular fragments and in lath-shaped pieces usually lying parallel to the bedding of the ore. The material in natural light is pale lavender to light brown and between crossed nicols is almost isotropic. The fragments present a structure characteristic of inarticulate brachiopods, and consist in cross section of a series of lamellæ with minute pores traversing them at right angles.

Fossil Algæ.—Fossil tubules of minute boring algæ occur in shell fragments, spherules, phosphate nodules, and siderite. Their structure is revealed only by the higher powers of the microscope; frequently in the shell fragments a mat of minute tubules is found, while in the spherules sections of single tubules are ordinarily seen. Where abundant in the spherules their presence is indicated by a riddled appearance, as the cross section is nearly white and resembles a tiny hole. The tubules occur in different sizes varying from one-fifth to 4 microns in diameter, and they may represent several species of boring algæ.

MICROSCOPIC DESCRIPTION OF PARTING ROCKS.

These rocks are composed principally of very small fragments of detrital quartz and of chamosite together with small shell fragments and carbonaceous material. Spherules are characteristically absent, but sometimes occur locally, especially in the vicinity of a change from parting rock to ore. As most of the constituents of the parting rocks are similar to those of the ore, the descriptions already given for such need not be repeated here. The relations between them are somewhat different, especially in regard to quantity and form, and require brief consideration.

Quartz forms the largest proportion of the parting rocks, occurring in small angular fragments frequently lath-shaped, forming rude parallelograms much elongated relative to their width and rarely exhibiting evidence of rounding by erosion. While rounded forms are found among the larger quartz grains of the ore, at certain horizons, even the largest fragments in the parting rocks seldom exhibit this character. Their detrital origin is shown by inclusions of apatite and liquid and gas cavities in many of the fragments.

Chamosite occurs as cement to the quartz and gives to the thin sections the appearance of mosaics, the white quartz fragments being surrounded by the green ferrous silicate of higher refractive index. It occurs in small platy crystals in the microcrystalline form and is also sometimes uncrystallized. The larger crystals have a tabular structure and are rudely rectangular if cut parallel to the base, and long and narrow if cut at right angles to this plane. It is of a green colour, is pleochroic, and polarizes in light yellows.

Shell fragments are more plentiful in the parting rocks than in the ore, and some horizons have a phenomenal development, forming layers nearly an inch thick. They are composed largely of calcium phosphate and in all rocks and ore where chemical analyses have been made, the content of calcium phosphate varies with the amount of shell material contained. The fragments are frequently altered by chamosite-like silicates and in many instances the original structure is destroyed thereby, but all gradations are found in the alteration of the shell material. Between crossed nicols, the shell fragments appear dark or allow a very small amount of light to penetrate. This optical character is typical of calcium phosphate nodules and spherules as well.

Zircon and Sphene.—Minute grains resembling crystals of zircon and sphene are found in the sandstone layer, 215 D8, zone 4, and with nearly all the grains of sphene is associated a cloudy material, which is opaque in transmitted light and white in reflected light, resembling leucoxene.

DESCRIPTIONS OF SLIDES ILLUSTRATED BY MICROPHOTOGRAPHS.

Dominion Bed, Zone 2.

Plate XVI A, Slide 1, Magnified 34 Diameters, Locality 215 C0. This rock is from the floor of the Dominion bed and consists of alternations of ferruginous sandstone with siliceous shale. The fine-grained sandstone is a mosaic of quartz fragments set in a matrix of uncrystallized and micro-crystalline chamosite and many cross sections of crystalline chamosite are present. Many small shell fragments are found, generally in long narrow strips lying parallel to the bedding of the rock. A few spherules of chamosite are scattered through the thin section. The siliceous shale consists largely of an extremely fine-grained, semi-opaque, dark brown material containing small quartz fragments, chamosite, and shell fragments. Many small irregular patches and films of an opaque substance resembling carbonaceous matter are found in thin layers parallel to the bedding plane.

Plate XVI B, Slide 100, Magnified 34 Diameters, Locality 208 A7. This is a dense hematite ore, the oolitic nature of which can be seen only in reflected light and does not appear in the plate. The white areas represent the quartz fragments and between the closely packed spherules, a little green chamosite and brown phosphate occur. A chemical analysis shows that the iron in this ore totals 78·37 per cent weighed as Fe_2O_3 and 14·98 per cent SiO_2.

A chip of the ore from which this slide was ground was treated with hydrochloric acid. The hematite went into solution, but the spherules did not disappear. Instead of the spherules of hematite, there remained spherules of gelatinous silica, identical with those obtained by a similar treatment of a chip of the oolitic chamosite from Section 215 D6, Slide 22, Plate XXIII B.

Plate XVII A, Slide 11, Magnified 110 Diameters, Locality 215 CC9. Angular character of the fragmental quartz in the ore and parting rocks. The large fragment holds liquid and gas inclusions distributed along lines at right angles to one another, and the fragment has broken parallel to these.

Plate XVII B, Slide 2, Magnified 110 diameters, Locality 215 C1. The lower part of the figure shows oolitic hematite with quartz fragments, while in the upper part scattered spherules occur with many quartz fragments and lath-shaped shell fragments in a matrix of phosphatic material. At the centre of the figure, a mat of tubules of boring algæ occurs in a shell fragment. The tubules extend from the shell fragment into the surrounding rock matrix, indicating that the relative position of these constituents has not altered since the algæ were living in the unconsolidated sediments. When examined carefully under a magnification of about 2,000 diameters, the tubules are seen to be coated exteriorly with a relatively thick encrustation of microcrystalline hematite, the interiors being usually free of hematite. Thus the red colour of tubules, which appears black in the plate, is due to a deposit of hematite which was probably formed during the life of the organism, since such plants give off oxygen which would tend to oxidize the iron to hematite. (Plate I).

Plate XVIII A, Slide 13, Magnified 110 Diameters, Locality 215 CC.2 A ferruginous sandstone parting rock holding brachiopod fragments, a large one of which is shown in the plate. The laminated character of the shell is preserved and many opaque, worm-like bodies are seen along the left hand side. These are hematite-coated tubules of algæ which were apparently parasitic on the shell, having bored into it before the materials were hardened into a compact rock, either during the life of the brachiopod or when the shell fragment formed a part of soft sea bottom deposits.

Plate XVIII B, Slide 8, Magnified 34 Diameters (Slides 84 and 29 are similar), Locality 215 C6. This slide is also from the upper part of zone 2 from a bed of pebble ore made up of spherules of chamosite which appear to have been the first to form and to have been later cemented together by other chamosite. The siderite is not a primary constituent of the spherules or nodules and frequently replaces them, as shown in the bottom right hand part of the plate.

Summary of Petrology of Zone 2. The upper part of the zone consists of alternating thick layers of ore and thin bands of parting rock (Plate X). The ore is composed of hematite and chamosite, usually in the form of spherules, and while hematite occurs between the spherules in the denser ores, chamosite is always so found. Siderite occurs only in the upper 6 inches of the zone at 215C, and appears to be secondary to the chamosite and hematite. Fragmental quartz is always present forming up to about 10 per cent of the ore and up to 50 per cent or more of the parting rocks. The detrital origin of the quartz grains is indicated by their shape and by the apatite and the fluid and gas inclusions found in them (Plate XVII A). Some of these fragments appear to be partially replaced by the chamosite. The detrital quartz grains, which vary greatly in size, occur as nuclei of the spherules, and also scattered through the interstitial matrix. A small amount of recrystallized quartz is also found in the matrix of the ore.

The ferruginous sandstone parting rocks of the ore are made up principally of fragmental quartz, together with chamosite and a small variable amount of shell fragments (Plates XVIA and XVIIA).

Chamosite is the most persistent iron mineral and is found throughout all the ore and rocks examined (Plate XVIII B). It is intimately associated with the structure of the spherules, frequently forming their nuclei, and is apparently never absent; when invisible, as in Plate XVIB, it is indicated by the presence of gelatinous silica after treatment with hydrochloric acid. It is frequently hidden by opaque hematite in the denser ore.

The presence of abundant detrital quartz and unaltered shell fragments holding boring algæ, intimately associated with the iron-bearing minerals, and the bedded arrangement of these materials indicate a primary sedimentary origin (Plates XVII A and XVII B).

A band of magnetite about one inch thick was cut through by a diamond drill boring in the lower part of the Dominion bed, but was not found exposed in the workings.

Pyrite Bed, Zone 3.

Plate XIX A, Slide 44, Magnified 34 Diameters, Locality 208 D2b. This is a section from the lowest bed of pyrite. The spherules of pyrite occur in an extremely fine-grained siliceous groundmass suggesting an original siliceous mud or ooze. In some of the spherules concentric layers of a brown substance, resembling calcium phosphate, alternate with others of pyrite. Fragments of brachiopod and graptolite remains are plentiful and occur both fresh and in various stages of replacement by pyrite. In many instances nodules of pyrite occur made up of a number of pyrite spherules with fragments of quartz. The relation of a pyrite spherule to a shell fragment shown in the plate, indicates that they have been placed together by mechanical means. The shell fragment is practically unaltered and such associations of materials in various stages of pyritization suggest that the various constituents have been brought together by agitation on the sea bottom. The general aspect of the rock suggests that no constituents have been added epigenetically.

Plate XIX B, Slide 31, Magnified 80 Diameters, Locality 208 D6. This plate shows the character of a portion of the upper bed of pyrite. The material is similar in general character to the specimen illustrated by Plate XIIA. The groundmass is a clear, recrystallized quartz and appears to have had its origin in a pure form of siliceous material. Rectangular and rounded elongate masses of pyrite are pseudomorphs of brachiopod remains.

Summary of Petrology of Zone 3. The strata composing the zone are alternating beds of oolitic pyrite and fine-grained, fissile, grey black shale. Thin sections from the pyrite layers show them to be composed principally of pyrite in the form of spherules with nodules and irregular masses, quartz in small fragments, and other siliceous material, and brachiopod and graptolite remains. No hematite was found in this zone.

Some of the pyrite is clearly secondary to the organic remains (Plate XIIA), and also to some of the spherules which have been cemented together in the form of nodules of spherules. There remain, however, many unpyritized fossil fragments in contact and intimately associated with those which have been completely replaced by pyrite, indicating that these various constituents were brought together mechanically by agitation on the sea bottom after the formation of the pyrite.

The bedding planes of the original sediment in the beds of oolitic pyrite are perfectly preserved as shown in Plate V. The recrystallization of the siliceous groundmass in which the spherules occur, shown in Plate XIX B, probably marks a diagenetic change in original material. There is no evidence of the addition of any important constituents which were not present in the original sediment and it seems probable that the spherules and the nodules containing the spherules and the pyritization of shell fragments resulted from diagenetic changes occurring in the oceanic sediments.

Scotia Bed, Zone 4.

Plate XXA, Slide 18, Magnified 80 Diameters, Locality 215 D2. This is from the lowest band of the workable ore-bed. Spherules of hematite occur in a groundmass of chamosite. The nuclei of the spherules are also chamosite. Fragments of quartz occur in the groundmass. The chamosite appears to be largely micro-crystalline.

Analysis W, from which the composition of chamosite was determined, was made from material represented by this plate.

Plate XXB, Slide 20, Magnified 80 Diameters, Locality 215 D4. From the lower middle part of the workable bed, this plate shows a contact of the oolitic ore with a sandstone parting rock. In the lower half of the plate, spherules of hematite are shown closely packed together with translucent green chamosite filling the narrow interstices. The upper half is composed principally of angular quartz fragments in a matrix of chamosite and hematite. The change from ore to parting rock is abrupt and the contact sharp.

Plate XXIA, Slide 86, Magnified 110 Diameters, Locality 215 D5. This figure shows a part of the middle of the upper half of the Scotia bed where spherules of hematite are surrounded by siderite. Many minute round white dots are seen in the spherules, giving them a riddled appearance. These are cross-sections of boring algæ. The rhombohedral structure of the crystalline siderite is clearly exhibited. Quartz is present only rarely as nuclei of spherules and its absence from the upper part of the Scotia bed suggests a condition of formation differing from that of the Dominion bed, only in being increasingly more favourable to chemical deposition, when detrital sedimentation almost ceased.

Plate XXIB, Slide 21, Magnified 80 Diameters, Locality 215 D5. This plate illustrates an ore composed of spherules of chamosite bordered by an outer layer of hematite and with some concentric layers of hematite in the interior of the spherules. The spherules are well separated from each other and, though frequently touching, are usually nearly completely surrounded by siderite, which occupies all of the interstitial space. A few quartz fragments occur as nuclei of some of the spherules, but this mineral is remarkably scarce.

In some of the spherules minute areas of siderite are scattered through the chamosite and where these occur, the structure of the spherule is destroyed, indicating that the siderite invaded the spherule after it was formed. A closer examination of the alternating bands of hematite and chamosite, reveals the fact that while the hematite contains many tubules, the chamosite is almost free from them. Wherever a tubule of this organism is found in the chamosite, it is almost invariably surrounded by hematite. Frequently a cross-section of a tubule is found in the interior of the spherules, in chamosite, apart from a layer of hematite, and usually a small border of hematite surrounds this tubule, evidently secondary after the chamosite. Wherever the algæ are abundant in the chamosite of the spherules, hematite is plentiful. In Plate XXIA, where the spherules hold much hematite, the algæ are found with difficulty; but they are nevertheless present for they can be seen in a great many of the spherules. It is probable that with the increase of opaque hematite, the interior portions of these tubules may be also filled with hematite, so that they are obscured even when the walls of the tubules remain. Since plants give off oxygen while living, this association of hematite with the boring algæ suggests a source of oxidation which will be discussed further on pages 74 et seq.

Many tubules of algæ are preserved in the siderite matrix. This most important fact suggests that the decaying remains of dead algæ have supplied carbon dioxide to precipitate the siderite and that some of the partially destroyed tubules have been preserved in this iron carbonate. A further discussion will be given on pages 80 et seq. See also Plate I.

Plates XXIIA and XXIIB, Slide 21, Magnified 110 Diameters, Locality 215 D5. Plate XXIIA shows spherules composed of concentric layers of hematite and chamosite surrounded by siderite. The spherule at the centre has for its nucleus the remnant of a quartz fragment which has been partly replaced by siderite, which has divided the fragment into two parts and all but severed a third. A portion of the interior of the spherule has also been replaced and the concentric banding of the layers of chamosite and hematite destroyed. Plate XXIIB shows the same spherule between crossed nicols. The simultaneous extinction of the various quartz areas, indicates that all belong to the same individual crystal which has been partly destroyed.

Plate XXIIIA, Slide 23, Magnified 80 Diameters, Locality 215 D6. A nodule having a foot-shaped outline, is represented in the right central part of the plate. The upper part of the nodule consists of a mat of algæ and near the centre in its lower part, a shell fragment altered to chamosite, is preserved. About the nodule are spherules of chamosite surrounded by siderite, and in the upper half the outer portions of the spherules are shown to be partly replaced by siderite. Their original outline has not been entirely destroyed and pseudomorphs of siderite after chamosite spherules have been formed.

In contact with the phosphate nodules at its upper left border, a spherule has a nucleus composed of a shell fragment in which small tubules of a boring algæ occur. Analysis Z, from which the composition of chamosite was determined, was made from the material represented by this slide.

Plate XXIIIB, Slide 22, Magnified 80 Diameters, Locality 215 D6. This plate is of a thin section taken from the top of the Scotia bed, zone 4. Plate XXIII, A and B, is representative of a thickness varying from 3 to 6 inches at the top of this zone. The ore changes in colour abruptly from red to grey, due to the absence of hematite in this upper portion. The spherules shown in Plate XXIIIB are much broken up and also replaced in part by siderite. Their crushed and bent appearance suggests that they were disturbed while in a gelatinous condition. It is probable that they were agitated by the action of waves in a shallow sea and that the incursion of siderite also occurred before the consolidation of the ore.

Plate XXIVA, Slide 24, Magnified 20 Diameters, Locality 215 D7. This plate shows the change at the extreme top of the Scotia bed, zone 4, from oolitic chamosite in siderite matrix to a fine-grained shale containing also considerable siderite. The spherules are scattered sparsely through the shale as though stirred up and mixed through muddy material by the action of waves at a time when a change in conditions of sedimentation brought about a cessation of the formation of oolitic iron ore and introduced the deposition of fine mud and sandstones. A quartz veinlet lies nearly parallel to the bedding and is shown at the top of the plate.

Plate XXIVB, Slide 25, Magnified 80 Diameters, Locality 215 D8. The rock represented in this plate is composed almost entirely of equal parts of chamosite and quartz. Most of the quartz grains appear to be detrital, but a considerable number may have been crystallized diagenetically out of primary siliceous ooze. The quartz and chamosite are frequently so closely associated as to indicate a simultaneous formation. Much of the chamosite is micro-crystalline and some is crypto-crystalline or amorphous, similar in appearance to the chamosite composing the spherules in the ore. There is also a considerable amount of more coarsely crystalline chamosite which resembles the micro-crystalline variety in ordinary light, being light green, but polarizes in brighter colours, blue-green to yellow.

Minute grains resembling detrital zircon and sphene are scattered through the slide. A cloudy material is usually associated with the sphene, appearing black and opaque in transmitted light and white in reflected light, suggesting leucoxene. The rock is characterized by a laminated appearance shown in the plate as parallel, wavy dark bands, due probably to argillaceous and carbonaceous matter.

It is from such material as is represented in this figure that the chemical analyses Za and T were made for the purpose of determining the composition of the green iron silicate.

Plate XXVA, Slide 26, Magnified 20 Diameters, Locality 215 D9. A layer 3 inches thick, made up of phosphate nodules and shell fragments in a matrix of quartz grains and chamosite, occurs a few inches above zone 2. The plate shows these as dark coloured areas and under the microscope they present the optical properties of phosphatic material. They are light brown in transmitted light and remain dark between crossed nicols. Many quartz grains are usually present and are represented in the figure by small white dots. The rock contains 12·26 per cent P_2O_5 (Analysis U, page 52).

Plate XXVB, Slide 27, Magnified 80 Diameters, Locality 215 D9. This photograph is from the same horizon as that of Plate XXVA and is placed here to show the cross-section of a splendidly preserved fragment of an inarticulate brachiopod, together with spherules of chamosite all in a matrix of chamosite and quartz. The minute canals crossing at right angles to the layers of the chitinous material of the shell may be seen. These are typical of inarticulate brachiopods. Such fossil fragments furnish the phosphorus of the ore in the form of calcium phosphate.

Plate XXVIA, Slide 54, Magnified 34 Diameters, Locality 206 J2b2. This figure presents an exceptional feature which is confined to the lower part of the Scotia bed, zone 4. The same iron-bearing minerals are present, oolitic hematite predominating, chamosite forming an integral part of the spherules, and siderite rarely present. The material between the spherules is recrystallized quartz holding minute crystals of hematite. The spherules are corroded about their outside edges and it seems probable that the solutions from which the quartz has been recrystallized have been instrumental in this destructive action toward the spherules. If the dissemination of the hematite in this recrystallized quartz is a phenomenon secondary to the formation of the quartz, one would expect to find similar dissemination in the interstitial material in other parts of the ore, but this has not been found. The irregular outline of the spherules is due to their partial replacement by quartz. A calcite veinlet cuts the ore. This small veinlet is typical of a reticulating network of similar veinlets throughout the ore, and it is along these cracks, which have been filled sometimes with quartz, but most frequently with calcite and occasionally with both these minerals together, that the ore breaks up into blocks when loosened from the bed by weathering or by mining operations.

Plate XXVIB, Slide 51, Magnified 34 Diameters, Locality 206 J2a. The rock represented by this plate was taken from a one inch band in the lower part of the Scotia bed, zone 4. The lower part of this band is made up of thin films of sandy shale, and in the upper part a band of calcium phosphate rock is found about half an inch thick, The shale is composed of chamosite with small fragments of quartz and shells arranged in lines parallel to the bedding of the rock. The bedded arrangement is shown in the plate by films of black material probably composed of carbonaceous matter. The calcium phosphate band represented by the plate is composed of fragments having rectangular outlines and varying in sizes from very minute to one-half a millimetre. Most of these have been so highly altered that the original shell structure is obliterated. The fragments are closely packed together so that little interstitial space is left and this is occupied by chamosite. It is probable that this ferrous aluminous silicate has effected the alteration of the shell fragments, for every gradation has been found, from fresh shell fragments to material resembling chamosite though still retaining the shape of the shell fragments.

A subordinate amount of fragmental quartz is shown by minute white irregular areas in the plate. Siderite frequently surrounds these grains and appears to have partly replaced many of them. A platy mineral, seen as long, thread-like forms, parallel to the bedding, is probably crystalline chamosite.

Plate I, Slide 21, Magnified 127 Diameters, Locality 215 D5. The natural colours in transmitted light of a thin section of this ore show spherules composed of alternating concentric layers of green chamosite and reddish brown hematite in a siderite matrix. The coiled tubules are in a nucleus of chamosite. The reddish colour of the tubule is due to a deposit of crystalline hematite on the exterior walls of the tubules. See frontispiece and pages 17, 74.

Summary of Petrology of Zone 4. The general descriptions given for zone 2, Dominion bed, apply also for this zone; but some important variations occur in zone 4, Scotia bed, which will be summarized here. Crystalline quartz, secondary to the hematite, is found in the lower part of the Scotia bed, occupying interstices between the spherules (Plate XXVIA). This has not been found elsewhere. Only the lower few inches of the bed are free from siderite, this mineral being found throughout the larger part of the upper portion of the bed, and it is progressively more abundant upwards. It has replaced much of the chamosite, some of the hematite, and occasionally the detrital quartz fragments (Plates XXIIA, XXIIB, XXIIIA, and XXIIIB).

Through the upper 3 feet of the ore, fragmental quartz is almost absent and this fact may indicate an exceptional condition of sedimentation, since detrital quartz is usually present elsewhere in this series and generally forms a considerable percentage of the rocks. Some original quartz from this horizon has been replaced by siderite.

Chamosite is found in every stratum of the zone, and though not so abundant as hematite in the ore, it is distributed through a much wider range, forming a large part of both ore and accompanying rocks. Hematite is very intimately associated with chamosite in the same manner as described for zone 2. The association of hematite with boring algæ in chamosite spherules, as shown in Plates I, XXIA, and XXIB, indicates that in some cases at least, the hematite has developed after the formation of the chamosite. In the lower part of the zone a concentration of shell fragments has been recognized, which forms a layer about half an inch thick. By chemical analysis P, page 56, this was shown to contain 62·76 per cent calcium phosphate while the shells themselves contain 68·14 per cent calcium phosphate (Analysis Zd). Further microscopic and chemical study has revealed a very intimate relationship between the content of shell fragments and the percentage of phosphorus in the ore rocks, and the writer has concluded that these organic remains are the principal source of the phosphorus and calcium of the ore.

Small bodies of crystalline galena occur, rarely in the upper part of the Scotia bed, in aggregates of only a fraction of an inch in size.

Upper Bed, Zone 5.

Plate XXVIIA, Slide 93, Magnified 110 Diameters, Locality 206AH15. This plate illustrates the oolitic hematite and chamosite with siderite taken from a bed 6 feet thick at the very top of zone 5 (Plate IX). Spherules composed of alternating layers of hematite and chamosite are found, many of which have exterior borders of siderite. The siderite cuts across the original banding of the spherules and is found frequently in the interior portion of the spherules destroying their original concretionary structure.

Summary of Petrology of Zone 5. The ore and rocks of this zone are made up of constituents similar to those which compose zones 2 and 4; but siderite has a greater range, being found throughout the zone, and chamosite has a proportionately greater distribution. The general relationships between the minerals are the same.

SUMMARY OF PETROLOGY OF OOLITIC ORE FROM ZONES 2, 4, AND 5.

The ore from each of the workable beds is similar in general composition and texture. The iron-bearing minerals are hematite and chamosite, while siderite becomes locally abundant. Quartz and shell fragments are also important constituents. The ore is oolitic.

The rocks accompanying the ore are also similar throughout the series, varying from a ferruginous shale to a ferruginous sandstone. They are composed principally of detrital quartz and chamosite and some shell fragments. These rocks are non-oolitic.

Hematite is the chief iron-bearing mineral of the ore. It is seldom found outside the spherules and probably occurs in micro-crystalline form since minute crystals are found under the higher powers of the microscope wherever the hematite is thin enough to allow light to penetrate. The hematite is associated in the spherules with concentric layers of chamosite, frequently forming alternate layers. Hematite is sometimes found associated with fossil boring algæ in spherules of chamosite and frequently where so found the hematite is of apparently later formation than the chamosite through which the algæ have bored. This condition is probably due to the oxidation of some of the iron of the chamosite to hematite due to oxygen given off during the life processes of the boring algæ. These algæ occur at all horizons both in the Dominion and Scotia beds and in both beds are frequently found having their tubules coated exteriorly with micro-crystalline hematite. This fact has an important bearing on any interpretation of the chemical conditions of the sea bottom and will be discussed later under the origin of the ore.

Green iron silicates resembling chamosite occur as characteristic primary constituents throughout the ore and rock. Chamosite occurs as the spherules of the ore or fills the interstices between them, and forms much of the matrix surrounding the detrital quartz grains in the accompanying rocks. It assumes an amorphous form in the spherules and is very minutely crystalline elsewhere. It occurs also frequently in larger crystals in the parting rocks.

Siderite, which is found at the top of zone 2 and throughout most of the upper part of zones 4 and 5, is clearly of later formation than the chamosite and hematite. It is never found as a primary constituent of the spherules, but is frequently associated with them, sometimes forming their central portions. In every case of this sort, the original structure of the spherule appears to be partly or wholly destroyed, and the detrital quartz, shell fragment, or chamosite making up the spherule are replaced by the siderite.

The *quartz* is of three varieties: detrital quartz fragments holding inclusions of apatite, very fine-grained undifferentiated siliceous material, sometimes crystallized, and secondary quartz. The detrital quartz is similar in character to that found in granitic rocks and owes its origin to the disintegration of a former crystalline rock. The fine-grained siliceous material appears to have its origin in a siliceous ooze or mud, and to have in some cases corroded and replaced portions of hematite spherules, and crystallized about them, in small aggregates. The secondary quartz together with calcite fills fault cracks in the ore beds.

The *shell fragments* are comminuted remains of inarticulate brachiopods. They are found in every portion of the ore and rock, and in the ore frequently form the nuclei of the spherules. Thin layers, composed almost entirely of these remains, are found up to half an inch in thickness.

CHAPTER V.

CHEMISTRY.

A number of chemical analyses have been made to determine the composition of the ore and accompanying rocks, and to learn more exactly the nature and origin of certain important constituents such as the iron-bearing minerals, silica, and phosphorus. The analyses have been arranged in the stratigraphical order of the rocks from which they have been taken and tabulated separately for each zone. No analyses have been made from zone 1.

Analyses of Shale and Sandstone not in Ore Zones.

Analysis A (page 45) taken from the sandy shale occurring halfway up the cliff at the shipping pier of the Nova Scotia Steel and Coal Company on the south shore of the island, shows that these rocks contain considerable iron and alumina, but no lime. About 600 feet of strata intervene between this horizon and zone 1 (Plate IIB).

Analysis B, taken from the sandstone halfway across the island, shows a much smaller content of iron and alumina but no lime. This sandstone lies between zones 1 and 2.

Analyses from Zone 2.

Analyses A and B and twelve analyses from zone 2 are as follows:

Table of Analyses.

	A	B	C	D	M	N
SiO_2	57·00	76·50	11·98	12·59	8·39	12·66
Al_2O_3	15·98	6·05	5·13	5·71	....	......
TiO_2	....	....	....	0·27	....	......
P_2O_5	....	....	2·02	1·63	......	3·24
Fe_2O_3	8·83	2·14	75·90	75·12	78·38	48·60
S	....	....	0·03	0·00	....	......
CaO	0·00	0·00	2·71	1·49	....	......
MgO	....	....	0·21	0·42	......	......
MnO	....	....	0·23	0·06	....	......
CO_2	....	....	....	....	....	18·17
H_2O-	....	....	....	0·52	....	......
H_2O+	....	....	1·86	....	....	......
Loss on ignition	....	....	....	2·17	....	......
Total	....	....	100·07	99·98	....	......
Sp. Gr.	....	....	....	4·10	....	4·40

Analysis.	Slide No.	Locality.	Analyst.	Date.
N	84	206 A19D	A. V. Seaborn	1912.
M	..	208 H6–9	A. V. Seaborn	1912.
D	..	....	T. G. McFarlane.	1899.
C	..	....	....	Nov. 13, 1895.[1]
B	..	206 A7	M. L. Fraser	1911.
A	..	206 A1	M. L. Fraser	1911.

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[1] Analysed for Nova Scotia Steel and Coal Company.

Description.

N—Ore from upper part zone 2, Dominion bed, holding siderite, surface outcrop.

M—Ore from zone 2, submarine workings.

D—Average sample ore from zone 2, Dominion bed.

C—Average sample ore from zone 2, Dominion bed.

B—Sandstone halfway across Bell island.

A—Sandy shale from halfway up cliff at N.S.S. and C.Co. pier.

Table of Analyses.

	E	F	G	H	I	J	K	L
SiO_2......	36·61	14·80	49·21	18·80	17·64	46·90	16·99	34·48
P_2O_5......	0·08	2·29	0·48	0·94	1·11	0·20	1·25	0·11
Fe_2O_3.....	33·18	73·04	27·83	71·88	68·26	32·46	45·94	37·68
S.........	0·15	0·03	0·25	0·02	0·005	0·63	0·39	0·01
CaO......	0·00	3·24	0·64	1·12	1·16	1·38	1·76	0·18

Analysis.	Slide No.	Locality.	Analyst.	Date.
L..............	....	215 C7	A. V. Seaborn............	1911
K..............	8	215 C6	"	"
J..............	....	215 C5	"	"
I..............	....	215 C4	"	"
H..............	....	215 C3	"	"
G..............	....	215 C2	"	"
F..............	2	215 C1	"	"
E..............	1	215 C0	"	"

Description.

L—Shales above zone 2 ore, surface outcrop.

K—Oolitic hematite and chamosite ore, zone 2, surface outcrop.

J—Oolitic hematite ore containing much quartz. Zone 2, surface outcrop.

I—Oolitic hematite ore containing phosphatic pebbles and shell fragments. Zone 2, surface outcrop.

H—Oolitic hematite ore, zone 2, surface outcrop.

G—Parting rock of fine-grained ferruginous sandstone. Zone 2, surface outcrop.

F—Oolitic hematite and chamosite ore.

E—Fine-grained sandy shale on floor of workable bed. Zone 2, surface outcrop.

Analyses C and D are nearly complete and were made from average samples of iron from the Dominion bed. These two analyses resemble each other very closely, an average of their results giving:

Fe_2O_3	SiO_2	P_2O_5	CaO	Sp.Gr.
75·51	12·28	1·82	2·10	4·1

Since the content of ferrous oxide is not given, only an approximate recalculation of the mineralogical composition can be made. The average content of about 2 per cent of combined water and 5·5 per cent alumina, points to a chamosite content of about 24 per cent, and a recalculation of the average of analyses C and D may be made as follows:

Hematite			65·51
Chamosite	SiO_2	6·00	23·89
	Al_2O_3	5·42	
	FeO	9·99	
	MgO	0·32	
	Mn	0·15	
	H_2O+	2·01	
Calcium phosphate $(CaO)_3 P_2O_5$ in the form of shell fragments			4·43
Quartz			5·98
Hygroscopic water			0·52
			100·33

Analyses E, F, G, H, I, J, K, L, were made from a series of samples taken at intervals from bottom to top, from the surface outcrop of the Dominion bed (Plate IV) selected purposely from lean ore in order that the constituents associated with the hematite might be studied to better advantage. In an analysis Zd, described on page 56, the composition of the brachiopod shells taken from this zone is shown to be 68·14 per cent calcium phosphate, 9·68 per cent lime, and 9·69 per cent silica, iron, alumina, etc. The molecular proportion of lime to phosphoric acid is as 168 to 142 and in these analyses the percentages of lime and phosphoric acid are present in approximately these proportions, except in analyis E, where the content is negligible. Thin sections ground from chips of the same specimens from which the analyses were taken, reveal a shell fragment content, apparently proportional to that of calcium phosphate.

According to these analyses, the lime content in this zone varies from nothing to 3·24 per cent, and the phosphoric acid content, from 0·08 per cent to 2·29 per cent. There is usually an excess of lime over the amount necessary to combine with phosphoric acid to form calcium phosphate, but occasionally the phosphoric acid is in slight excess. This relation between lime and phosphoric acid is similar to that found in the analysis Zd of the brachiopod shell. The following table shows the excess of these constituents over the amounts of each required to form calcium phosphate:

Table of Analyses.

Analysis.	CaO	P_2O_5	$(CaO)_3 P_2O_5$	Excess CaO	Excess P_2O_5
L	0·18	0·11	0·24	0·05	....
K	1·76	1·25	2·73	0·28	....
J	1·38	0·20	0·43	1·15	....
I	1·16	1·11	2·13	....	0·14
H	1·12	0·94	2·04	0·02	....
G	0·64	0·48	1·04	0·08	....
F	3·24	2·29	4·99	0·54	....
E	0·00	0·08	....	....	0·08
D	1·49	1·63	2·69	....	0·43
C	2·71	2·02	4·28	0·45	....

Small veinlets of secondary calcite fill minute cracks in the ore everywhere, as has been stated in the petrographical descriptions. This calcite also tends to increase the free lime content. The excess of phosphoric acid may be due to concentrations of phosphorus in the form of salts of iron resulting from the alteration of shell fragments.

The small amount of sulphur shown by these analyses probably occurs in the form of iron sulphide as the thin sections reveal an occasional particle of pyrite.

Analysis M represents the upper 6 feet of ore mined at locality 208 A in the submarine workings.

Analysis N is from the upper part of the zone where the ore is made up largely of chamosite and siderite. This type of ore is only a few inches thick at the top of the zone.

Analysis from Zone 3, Oolitic Pyrite.

Analysis.	Slide.	Locality.	Analyst.	Date.	Description.
O.........	31 44	206 D6	A. V. Seaborn...	1911	Oolitic pyrite from upper part of zone 3 (Plate V).

SiO_2	P_2O_5	CaO	Fe	S	Total.
9·91	0·35	0·54	35·18	34·46	80·44

A sample from this zone was analysed by Dr. E. T. Allen of the Carnegie Geophysical laboratory, Washington, D. C., with a view to ascertaining the nature of the iron sulphide. Dr. Allen found "that more than 90%, possibly all of the iron is present as pyrite. Cobalt, nickel, copper and arsenic are not present in more than traces, but the small amount of carbonaceous matter and possibly a little hematite that could not be separated made a more exact determination impossible."[1]

The study of seven thin sections taken from this zone at regular intervals discloses no hematite whatever, and shows

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[1] Communication to the writer from H. E. Merwin, Feb. 27, 1913.

that as a general rule the pyrite exists principally in the form of spherules, nodules, and masses, but is not disseminated through the groundmass, this being almost free from pyrite. The groundmass makes up a considerable proportion of the rock and is nearly always an extremely fine-grained shale holding considerable chamosite. Plate XIXA illustrates the normal rock. The excess of iron in the analysis over that required to form iron pyrite is, therefore, present probably in the form of chamosite. The lime is present in slight excess of that necessary to combine with the phosphoric acid to form calcium phosphate, and both of these constituents are probably derived from shell fragments, as has already been shown for similar material in zone 2. Basing the composition of chamosite on analysis T1 page 59, the analysis may be recalculated as follows:

SiO_2	6·12%	Remaining silica after deducting for chamosite.
$(CaO)_3$ P_2O_5	0·76	
CaO	0·13	
FeS_2	64·53	Iron pyrite from spherules, nodules, etc.
FeO	6·57	Excess over iron necessary to form FeS_2.
SiO_2	3·79	Silica necessary to form chamosite with excess iron.
Al_2O_3, MgO, H_2O+,	6·77	Theoretical addition based on excess FeO and chamosite, analysis T1.
	88·67	

The balance of the rock is probably composed of aluminous materials making up the shale matrix.

Analyses from Zone 4.

Chemical analyses from this zone confirm conclusions arrived at from the study of its petrology, and demonstrate that the distribution of the iron-bearing minerals is somewhat different from that of zone 2, siderite becoming much more abundant. Two points have been selected for a special study, localities 206 J, Plates VI and VII; and 215 D, Plate VIII. Six analyses, P, Q, R, S, T, and U, are listed on page 52 from 206 J, and seven analyses, V, W, X, Y, Z, Za, and Zb, from 215 D, on page 53.

The methods outlined by W. F. Hillebrand (23) were employed by the writer except for determinations where special methods were required, and also by Mr. Seaborn for analyses Q and S. The writer has no record of methods for the other analyses.

Analysis Q was taken from the lower part of the ore zone and S from the upper part of the hematite ore at 206 J. A comparison of these shows a striking diminution in silica content in the upper ore and while the total amount of metallic iron is about the same, the amount of ferrous iron and carbon dioxide is much greater in the upper part of the ore. The lime and phosphoric acid content remain about constant in both.

Table of Analyses.

	Q, lower ore.	S, upper ore.
SiO_2	9·85	4·66
Fe_2O_3	67·79	52·08
FeO	10·03	21·17
CO_2	1·05	10·78
CaO	2·42	2·88
P_2O_5	2·26	2·11

Table of Analyses.

	P	Q	R	S	T	U
SiO_2	8·02	9·85	42·14	4·66	63·33	27·78
Al_2O_3	....	3·23	3·72	3·05	11·68	......
TiO_2	....	0·40	0·54	0·28	0·49	......
P_2O_5	28·76	2·26	13·01	2·11	0·07	12·26
Fe_2O_3	18·78	67·79	1·47	52·08	0·46	14·41
FeO	....	10·03	13·29	21·17	17·88	......
CaO	37·30	2·42	17·80	2·88	0·27	......
MgO	....	0·37	0·72	1·14	1·49	......
MnO	....	....	0·46	0·78	0·10	......
CO_2	....	1·05	5·08	10·78	0·30	0·95
H_2O-	....	0·32	0·30	0·27	0·26	......
H_2O+	....	2·35	2·60	1·72	4·90	......
Total	92·86	100·07	101·13	100·92	100·96	55·40
Sp. Gr.	....	4·34	2·72	4·23	2·86	......

Analysis.	Locality.	Slide No.	Analyst.	Date.
U	206 J5	81	A. V. Seaborn	1912
T	206 J4b	77	A. O. Hayes	1912
S	206 J2d5	66	A. V. Seaborn	1912
R	206 J2c3	60	A. O. Hayes	1912
Q	206 J2b2	54	A. V. Seaborn	1912
P	206 J2a	50	A. O. Hayes	1913

Description.

U —Pebble bed 1 foot above zone 4.
T —Middle part of sandstone layer, 9 inches thick, immediately above ore.
S —Upper part of bed, 2 feet below top of workable ore.
R —Parting rock in zone 4, 2 feet above floor of workable ore.
Q —Lower part of zone 4 ore, 6 inches above floor of workable ore.
P —Rock composed largely of shell fragments underlying ore of zone 4.

Table of Analyses.

	V	W	X	Y	Z	Za	Zb
SiO_2........	27·68	15·29	7·44	5·36	16·22	62·83	41·00
Al_2O_3.......	9·10	9·63	9·04	....	7·65	9·96	18·20
TiO_2.......	0·37	....	....	....	0·61	....	......
P_2O_5.......	4·77	1·07	1·63	1·54	4·91	0·30	......
Fe_2O_3......	2·39	44·17	59·89	84·96	2·99	5·37	19·57
FeO........	29·80	19·38	16·74	....	35·38	14·69	......
CaO.......	7·19	1·54	....	....	4·01	0·69	0·00
MgO.......	2·30	1·45	....	....	1·84	1·43	......
MnO.......	1·38	0·26	....	....	3·12	....	......
CO_2........	11·54	0·43	4·57	1·22	16·64	0·00	......
Na_2O.......	....	0·46	....	....	....	0·19	......
K_2O........	....	0·08	....	....	....	0·11	......
H_2O-......	0·51	0·83	....	....	0·78	0·27	......
H_2O+......	3·44	5·80	....	....	2·61	5·42	......
Total......	100·47	100·39	99·31	93·08	96·76	101·26	78·77
Sp. Gr.....	....	....	....	4·50	3·50	2·93	......

Analysis.	Locality.	Slide No.	Analyst.	Date.
Zb....................	....	....	M. L. Fraser	1911.
Za....................	215 D8	25	A. O. Hayes	1912.
Z.....................	215 D6	23	"	"
Y.....................	215 D5	38	A. V. Seaborn	"
X.....................	215 D3	19	A. O. Hayes	"
W....................	215 D2	18	"	"
V.....................	215 D1	37	"	"

Description.

Zb —Shale above zone 4, Scotia bed, locality not specified.
Za —Sandstone layer 3 inches thick, 4 inches above zone 4.
Z —From top of zone 4, 3 inches grey ore, oolitic chamosite.
Y —From upper part zone 4 ore about 2 feet from top, oolitic hematite.
X —From lower part zone 4 ore, oolitic hematite.
W —5½ inches ore, oolitic hematite and chamosite, lower part of zone 4.
V —11 inches dark green rock, lower part of zone 4.

The much lower content of silica in S appears to be due to an almost entire absence of fragmental quartz, as shown by the study of thin sections from the same horizon. The much higher content of ferrous iron and carbon dioxide in S, indicates that a large amount of iron carbonate occurs in the upper ore, which is absent from the lower. Analysis X is also from the lower ore, and Y from the middle of the workable bed, a little higher up, though not in the upper hematite-siderite ore, represented by analysis S. A reduction in silica content from 7·44 per cent in X to 5·36 per cent in Y, shows that a similar diminution in silica content takes place upwards.

Since the ore is essentially a primary sediment, and its constituent materials were brought together in the first instance by mechanical means, a heterogeneous mixture of constituents has resulted, and an exact mineralogical composition could be determined only with great difficulty. The petrographic and chemical analyses have demonstrated the presence and composition of the most abundant materials, however, and the following recalculations of Q and S serve to illustrate these with tolerable accuracy:

Table of Analyses.

	Q	S
Hematite	67·79	50·08
Chamosite[1]	18·05	17·65
Siderite	2·77	27·63
Vivianite[2]	0·83	....
Calcium phosphate in the form of shell fragments	4·46	4·61
Calcite	....	0·68
Hygroscopic water	0·32	0·27
	100·07	100·92

---

[1] Composition based on analyses Z1 and W1. See page 59.

[2] Presence not proved optically, but thought probable from chemical relations.

As already shown, in the Dominion bed, zone 2, so also in the Scotia bed, zone 4, lime and phosphoric acid are present in the ore and parting rocks in quantities proportional to the amount required to form the chitinous material of the fossil brachiopod fragments (See analysis Zd, p. 56). The following table shows the amounts of lime and phosphoric acid present in each analysis, with the corresponding excess of lime or phosphoric acid, over the amounts required to form calcium phosphate. In eight out of ten analyses, a slight excess of lime is found, agreeing with analysis Zd of the fossil brachiopod. The slight excess of phosphoric acid in analyses Q and Z, is probably due to a concentration of phosphorus in the form of a phosphate of iron, formed out of the decomposition products of organic remains and iron. Minute crystals resembling vivianite occur in Slide 2 (p. 133).

Table of Analyses.

	CaO	P_2O_5	$(CaO)_3\ P_2O_5$	Excess CaO	Excess P_2O_5
Zc	0·49	0·30	0·65	0·14	....
Za	1·43	0·30	0·65	1·08	....
Z	4·01	4·91	7·42	....	1·50
W	1·54	1·07	2·33	0·28	....
V	7·19	4·77	10·40	1·57	....
T	0·27	0·07	0·15	0·19	....
S	2·88	2·11	4·59	0·40	....
R	17·80	13·01	28·36	2·45	....
Q	2·42	2·26	4·47	....	0·21
P	37·30	28·76	62·76	3·30	....

Analyses P and R are of especial interest on account of their greater content of phosphoric acid and lime, and a comparison of the amount of calcium phosphate contained in the rock represented by P, with the analysis of a brachiopod shell, follows:

Analysis of Brachiopod Shell.

Locality.	Slide.	Plate.	Analyst.	Date.	Description.
P 206 J2a	51	XXVIB	A. O. Hayes	1913	From upper part of layer of sandy shale composed largely of shell fragments.
Zd 206 A 19	..	XIIB	"	"	Shell of brachiopod *Lingula hawkei* Rouault, Davidson, taken from oolitic hematite.

Analysis P.

SiO_2	8·02
Fe_2O_3, Al_2O_3, etc.	18·78
P_2O_5	28·76
CaO	37·50

Analysis Zd.

SiO_2, Fe_2O_3, Al_2O_3, etc.	9·68
P_2O_5	36·94
CaO	47·12

Analysis P Recalculated.

SiO_2	8·02
Fe_2O_3, Al_2O_3, etc.	18·78
$Ca_3(PO_4)_2$	62·76
CaO	3·30

Analysis Zd Recalculated.

SiO_2, Fe_2O_3, Al_2O_3, etc.	9·68
$Ca_3(PO_4)_2$	68·14
CaO	9·68

An examination of Plate XXVIB taken from a thin parting (206 J2a) from the lower part of zone 4 (Plate VI) revealed a layer of about half an inch in thickness composed of highly altered angular fragments of shell closely packed together. Chamosite accompanies the shells, has replaced many of them, and forms the cementing material of the rock. The original structure of most of the shell fragments is destroyed, but some are sufficiently fresh to establish the identity of the material, for every gradation from typical shell to typical chamosite retaining the rectangular outlines of the shell fragments is present. Analyses P and Zd were made to confirm the conclusion that a close relationship exists between the content of lime and phosphorus of the ore and accompanying rocks and the presence of brachiopod shell fragments.

The results of these two analyses show that the fossil brachiopod shell has a content of lime and phosphoric acid sufficient to make up 68·14 per cent calcium phosphate; while the parting rock holds 62·76 per cent calcium phosphate. The shell material (analysis Zd) was taken from one complete valve of the brachiopod, *Lingula hawkei* (Plate XIIB) by Professor van Ingen, who obtained the sample with the utmost care. It is probable that considerable ferruginous material has impregnated these fossil shells, as in many cases, they appear in thin sections to be altered by chamosite. Generally, however, the shell fragments have been remarkably preserved and frequently the most minute structure of the original shell is retained. In the case of the shell analysed, the original sculpture was preserved and it is probable that the analysis approximates very closely its original chemical composition. The hematite and possibly some of the calcite were introduced by mechanical means in obtaining the sample.

A definite relationship is thus established between the fragments of the Lingula shells and the content of calcium phosphate of these rocks and the conclusion has been reached that the phosphorus and the original lime content of the Wabana iron ore have for their source, the fossil remains which have been preserved in it.

Butschli (5) shows in an extensive series of analyses in his monograph on Organische Kalk Gebilde, Berlin, 1908, that different species of Lingula shells contain calcium phosphate varying from 48·92 to 88·32 per cent. Some of the brachiopods have a larger content of calcium phosphate than he has noted for any other organic remains.

Analyses of Chamosite.

Analyses Za, Zc and T have each been taken from a ferruginous sandstone separated from the top of the oolitic ore of zone 4 by a thin layer of shale (Plates VII and XXIVB). A petrographical description of this rock is given on pages 37 and 147, and the chemical analyses have been made to determine the composition of the widely distributed green iron silicate, which has been referred to as chamosite. These analyses with others will be described on the pages following.

The name "Chamosite" has been employed to denote one of the principal iron-bearing minerals of this series of rocks, and the term has been applied generally to a green iron silicate, whose optical properties have been described, and the chemical identification of which has been made from analyses listed on pages 59 and 62.

Materials for analyses were obtained from both the ore and the accompanying rock. The rock from which the composition of the green iron silicate was obtained, occurs in the form of a sandstone 3 to 9 inches thick at the top of zone 4, separated from the oolitic ore below by 1 to 2 inches of shale.

Table of Analyses.

	Za	Zc	T	Z	W
Soluble SiO_2	10·56	10·56	10·65	6·27	12·54
Insol. SiO_2	52·27	53·87	52·68	9·95	2·75
Al_2O_3	9·96	9·61	11·68	7·65	9·63
TiO_2	....	0·98	0·49	0·61	......
P_2O_5	0·30	0·30	0·07	4·91	1·07
Fe_2O_3	5·37	2·83	0·46	2·99	44·17
FeO	14·69	14·69	17·88	35·38	19·38
CaO	0·69	0·49	0·27	4·01	1·54
MgO	1·43	1·42	1·49	1·84	1·45
MnO	....	0·14	0·10	3·12	0·26
CO_2	0·00	0·13	0·03	16·64	0·43
Na_2O	0·19	....	....	....	0·46
K_2O	0·11	....	....	....	0·08
H_2O-	0·27	0·92	0·26	0·78	0·83
H_2O+	5·42	4·74	4·90	2·61	5·80
Total	101·26	100·68	100·96	96·76	100·39
Sp. Gr.	2·93	2·93	2·86	3·50	

Analysis.	Locality.	Slide No.	Analyst.	Date.
Za	215 D8	25	A. O. Hayes	1912.
Zc	215 D8	25	"	"
T	206 J4b	78	"	"
Z	215 D6	22	"	"
W	215 D2	18	"	"

Description.

Za —Sandstone layer, 3 inches thick, 4 inches above zone 4, Scotia ore.
Zc — “ “ “ “ “ “ “ “ “
T — “ “ “ “ “ “ “ “ “
Z —Oolitic chamosite, top 3 inches of zone 4, Scotia ore.
W — “ “ and hematite from bottom of zone 4.

Table of Analyses.

	Za1	Zc1	T1	Z1	W1
Sol. SiO_2	21·67	23·50	22·28	17·24	25·42
Al_2O_3, TiO_2	21·05	23·56	25·46	21·03	19·52
Fe_2O_3	11·03	6·30	0·96	....	....
FeO	30·17	32·62	37·41	49·50	39·28
CaO	1·41	....	0·31	....	....
MgO	2·93	3·16	3·12	5·06	2·94
MnO	....	0·31	0·21	....	....
Na_2O	0·39	....	....	....	0·93
K_2O	0·22	....	....	....	0·16
H_2O+	11·13	10·55	10·25	7·17	11·75
Total	100·00	100·00	100·00	100·00	100·00

Za1 —Analysis recalculated from Za to show composition of chamosite.
Zc1 — “ “ “ Zc “ “ “
T1 — “ “ “ T “ “ “
Z1 — “ “ “ Z “ “ “
W1 — “ “ “ W “ “ “

Analyses Za1 and Zc1 are from separate samples from the same locality (215 D9), while T is from the same sandstone horizon, but at a locality (206 J4b) about half a mile west of 215 D. Plate XXIVB taken from this rock is described on pages 37 and 147 shows that the rock is made up almost wholly of nearly equal parts of fragmental quartz and crystalline iron silicate. A separation of the green iron silicate from the detrital quartz was made by solution in hydrochloric acid until all iron was dissolved. The residue was treated with sodium carbonate to separate undissolved silica of combination from the quartz.

The solution was then analysed according to the procedure outlined by W. F. Hillebrand (23). After the determination of the quartz by treatment with hydrofluoric acid, in analyses Za and T, a residue of about one per cent of alumina was found. This may have been present in the rock as a silicate of alumina similar to the argillaceous material which forms the larger part of the series. The insoluble alumina of analyses Za, Zc, and T, is included with the alumina of green iron silicate, and the recalculations Za1, Zc1, and T1, have been made to compare with analyses of thuringite listed by Dana (13: pp. 657-8) and Hinze (24: p. 742). Analyses Za1, Zc1, and T1, fall within the limits of those given by Dana and Hinze for thuringite, and W1 resembles more closely the analyses they list for chamosite (Dana, p. 658 and Hinze, p. 738). The composition of the green iron silicate has also been recalculated from analysis Z, taken from a sample of the grey oolitic ore from the top 3 inches of the workable part of zone 4. Siderite cements the chamosite spherules together and hematite is found in small amounts in both the spherules and the matrix (Plates XXIIIA and XXIIIB). After eliminating the calcium phosphate, ferrous carbonate, manganese carbonate, and ferric iron, the remainder has the composition shown in analysis Z1. The number of constituents to be considered tends to depreciate the value of these results. A much higher content of ferrous iron is shown than in the other analyses from the sandstone layer, which may be due to reduction of hematite by carbonaceous matter. Similarly, analysis W was recalculated and the result is shown in W1. The sample from which this analysis was made, is composed of oolitic hematite and green iron silicate in a matrix of green iron silicate, together with a small amount of fragmental quartz (Plate XXA) and next to the ferruginous sandstone offers the best opportunity for a reliable analysis of this green iron silicate. Both the ferrous iron and silica are higher than in any of the analyses listed by Dana and Hinze for thuringite, and approach more nearly those given by them for chamosite.

The results of a thorough investigation of the chemical composition of thuringite and chamosite, made with minerals obtained from their type localities, by E. R. Zalinski (53: pp.

70-79) give a more exact standard of comparison than has hitherto been available. While Dana classes chamosite as a variety of thuringite, Hinze places it as a separate species. Zalinski also concludes that chamosite and thuringite are distinct mineral species and gives their chemical formulæ as based on the results of his work.

Analyses for alumina insoluble in hydrochloric acid were made from samples Zc and T and a little over 1 per cent found in each case. This alumina is probably present in the sandstone as finely divided particles of argillaceous material scattered through the rock. The titanium dioxide has also been estimated in these samples. Therefore, for a more accurate comparison with analyses of pure minerals, these constituents which are included with the alumina in Zc1 and T1, should be deducted. In Zalinski's analyses, lime, manganese oxide, and the alkali oxides are not present, hence for a comparison with his results, these constituents have also been deducted and recalculations made of Zc, T, and W. Since the analysis Za is from the same material as Zc, and the titanium dioxide and insoluble alumina have not been determined, this will not be recalculated here. Likewise, analysis Z which contains much siderite and carbonaceous matter, probably causing the amount of ferrous iron to be unreliable, is left out. The recalculation of analyses Zc, T, and W are given under Zc2, T2, and W2 as follows:

Table of Analyses.

	Zc2	T2	W2
SiO_2	24·87	23·23	25·64
Al_2O_3	19·45	22·85	19·75
Fe_2O_3	6·66	1·00	....
FeO	34·52	38·99	39·74
MgO	3·34	3·25	2·98
H_2O	11·16	10·68	11·89
	100·0	100·00	100·00

Zc2—Chamosite from sandstone.
T2 — " " "
W2— " " oolitic iron ore.

With these analyses those of Zalinski for thuringite and chamosite may be compared. They are as follows:

	Thuringite.		[3]Chamosite
	[1]Average of 1 and 2.	[2]Average of 3 and 4.	
SiO_2	22·30	21·35	25·19
Al_2O_3	16·81	17·70	19·74
Fe_2O_3	15·13	11·57	....
FeO	32·78	36·81	41·45
MgO	1·30	3·90	1·49
H_2O	11·04	8·78	12·13
	99·36	100·11	100·00

[1] Formulæ recalculated by Zalinski from these analyses, are as follows:
H_{18} (Fe, Mg)$_8$ (Al, Fe)$_8$ Si$_6$ O$_{41}$. For thuringite.
[2] H_{17} (Al, Fe)$_8$ (Fe, Mg)$_{10}$ Si$_6$ O$_{44}$. For thuringite.
[3] H_6 (Fe, Mg)$_3$ Al$_2$ Si$_2$ O$_{13}$. For chamosite.

A comparison of these results shows that all three analyses Zc2, T2, and W2 are very similar to Zalinski's analysis of chamosite, while they are all higher in silica and alumina and lower in total iron than his analyses of thuringite.

The presence of ferric oxide in the analyses Zc and T, may be due to the oxidation of chamosite, or both thuringite and chamosite may be present in the rock. The total amount of iron is strikingly constant, however, and this is again confirmed by analysis Za1, made from similar material as Zc2, although in this case 11·03 per cent of Fe_2O_3 is shown. Hence the writer has concluded that the green iron silicate of both ore and accompanying rocks occurs principally in the form of chamosite, and has used the term throughout this memoir to designate the green iron silicate.

From the petrographic study the writer was impressed with the variation in colour of the amorphous variety of this type of material, from light to deep green. It seems probable that chemical interaction between these green iron silicates and other constituents of the ore, has resulted in the formation of iron silicates of varying composition. The chamosite of the spherules, as shown by Plates XXIIIA and XXIIIB must have been in a soft gelatinous condition, and this may have been the original condition of the material out of which the crystalline chamosite developed.

While a large part of the chamosite of the ferruginous sandstone at the top of zone 4, represented by analyses Zc2 and T2, is crystalline and that of the oolitic green ore occurring below the workable bed, represented by analysis W2, is mostly micro-crystalline, that represented by analysis Z1 occurs in spherules apparently in the amorphous form. It seems probable that the crystalline material is the mineral and the amorphous material, analysis Z1, may not have a constant composition, but may vary within certain limits.

Analyses from Zone 5, Upper Bed.

The petrological study has shown that in this zone, as in zones 2 and 4, hematite, chamosite, and siderite are the iron-bearing minerals of the ore, and that detrital quartz is present in moderate amount.

The following incomplete chemical analysis is of a specimen taken from the workable bed in the submarine slope 2, about one-half mile north of the surface outcrop.

SiO_2	Al_2O_3	P_2O_5	Fe_2O_3	FeO	CO_2	Total	Sp. Gr.
8·60	4·82	1·22	72·70	8·37	1·38	97·09	4·20

Analysis.	Locality.	Analyst.	Date.
Zb	215 Dsl	A. O. Hayes	1912

A petrographical examination of the material analysed, with the chemical analysis, shows that hematite, chamosite, and siderite are present. The hematite forms 72·70 per cent of the ore, and chamosite makes up most of the balance, while siderite and fragmental quartz are much less abundant.

Kelly Island Chamosite.

A ferruginous sandstone occurs on Kelly island which has not been described. The principal bed is about 18 inches thick and the following partial analyses have been made from a specimen taken from Martin cove:

SiO_2	Fe	P_2O_5	CO_2
31·98	27·75	1·74	12·59

Analysis.	Locality.	Slide.	Analyst.	Date.
Ze	217 A13 c	41	A. V. Seaborn	1912

No determination of lime was made to discover whether the CO_2 is present as calcite or siderite. Since the rock does not effervesce with hydrochloric acid, it is probable that the calcite is absent and that the carbonate is present in the form of siderite. The thin sections reveal the presence of a green iron silicate allied to chamosite.

A recalculation of the analysis, assuming siderite, chamosite, and calcium phosphate to be present with the addition of a sufficient amount of alumina, water, and lime, gives the following:

Quartz	SiO_2	21·98	21·98
Chamosite	SiO_2	10·00	40·09
	FeO	15·09	
	Al_2O_3*	10·00	
	H_2O*	5·00	
Siderite	FeO	20·56	33·15
	CO_2	12·59	
Calcium phosphate	P_2O_5	1·74	3·80
	CaO*	2·06	
		99·02	99·02

* Hypothetical additions.

Summary of Chemistry of Ores.

The chemical analyses have confirmed those identifications which have been made by petrographic methods, given the exact composition of other constituents not determined optically, and established certain relationships indicative of the mineralogical composition of the ore and rocks.

Petrographic examinations have revealed the presence of three principal types of iron-bearing minerals in zones 2, 4, and 5, including an oxide, silicates, and a carbonate. The most abundant of these was easily identified as hematite, and chemical investigation has shown the others to be chamosite, and probably other green iron silicates, and siderite. The fossil shell fragments have a composition of between 60 and 70 per cent calcium phosphate, and the lime and phosphoric acid present in the ore are derived principally from this source. The ores and accompanying rocks appear to be free from any original lime content in excess of that which is found in combination with phosphoric acid in the shell fragments.

All of the constituents of the ore vary within certain limits at different localities and at different portions of the ore beds, as shown in the following table:

Hematite	50 to 70	per cent.
Chamosite	15 to 25	"
Siderite	0 to 50	"
Calcium phosphate	4 to 5	"
Calcite	0 to 1	"
Quartz	0 to 10	"

Zone 3 consists of layers of iron sulphide in the form of oolitic pyrite intercalated between beds of shale.

CHAPTER VI.

ORIGIN OF THE ORE.

PRIMARY NATURE OF ORE BEDS.

The iron ore occurs in strata forming an integral part of a series consisting principally of shales and sandstones. The series is of lower Ordovician age and since it exhibits closer relationships with European than with American geological formations, it is referred to the Arenig and Llandeilo of Wales, corresponding roughly with the Beekmantown, Chazy, and Black River of the Appalachian province.

A considerable number of detailed observations and experiments have been made and described, relative to the origin of the ore. As a result of this work, the writer has concluded that the iron ore occurs as a primary bedded deposit, and that the iron content was present in the sediments at the time that the series was laid down. It is probable that the spherules were formed out of the extremely fine-grained, unconsolidated, ferruginous sediments of the sea bottom, in water sufficiently shallow to allow of a certain amount of agitation due to the action of the surface waves. (Plate X).

In the course of the deposition of a thickness of about 400 feet of strata, in which the three workable beds are contained, records are found of a number of changes of sea-level relative to the sea bottom and shore. Ripple marked surfaces in all of the workable beds were formed by shifting of the bottom deposits by currents off a shore-line. These are beautifully shown on the floors of the workable beds of zones 2 and 4 (Plates XIA and XIB). A disconformity occurs above zone 2, varying at different localities from a few inches to a few feet above the highest hematite of the Dominion bed (Plates IV and V), immediately above which the oolitic pyrite and black shales, holding graptolites, were laid down. The incursion of graptolites signifies a modification of the sea bottom such as to allow the passage of continuous ocean currents, capable of bringing in these planktonic organisms. They are considered to have been transported as are similar forms of life existing to-day in the Sargossa sea, and it is thought that a considerable deepening of the sea took place at the close of the deposition of zone 2. Shallow water conditions again prevailed at the close of the deposition of zone 4, probably accompanied by vertical oscillations, as evidenced by a ripple-marked surface in the ore found at locality 206 A25 E7, 2 feet above the floor of the workable bed, and by the occurrence of a pebble bed, 206 J5, occupying erosion channels in the fine-grained sandstone, 206 J4, about 1 foot above the top of the Scotia ore (Plate VII). The ore above the erosion surface in the upper part of the ore bed is cross-bedded, indicating the progressive accumulation of the spherules at the edge of a submerged bar, arranged in lamellæ at a steep angle to the bedding plane (Plate VIII).

The Scotia bed, where examined at the surface outcrop, contains a relatively small amount of detrital quartz fragments and has an exceptionally high siderite content. The ore zone is confined to about 15 feet of strata, about half of which is composed of workable ore, occurring in a compact layer containing thin parting lenses of ferruginous sandstone at some localities, but entirely free from these layers over other areas.

CONDITIONS DURING DEPOSITION.

Considerable direct evidence is thus available on which to base a conception of the conditions obtaining during the deposition of the Scotia bed. The absence of detrital quartz in the ore, indicates that the ore was formed at some distance from a shore-line, while the ripple marked surfaces and cross-bedding of the spherules required shallow water for their formation. The upper bed also exhibits similar phenomena characteristic of such marginal deposits.

That the ore was deposited in marine waters is evidenced by their content of marine brachiopods (Plate XIIB). The graptolites in the shales and oolitic pyrite, also demonstrate the salt water origin of zone 3 (Plate XIIA).

It is evident that the spherules were formed before the final consolidation of the ore, since the ore is sometimes found to be made up of thin lamellæ of oolitic hematite, and earthy hematite in alternating layers arranged by the sorting action of water (Plates VIII and XXVIIB). There occurs also at the top of zone 2, a conglomerate holding pebbles of oolitic hematite-chamosite (Plate X). The spherules, where closely packed together in the denser portions of the ore, are much flattened by vertical pressure and lie like tiny discs placed horizontally, and where the spherules are disseminated more sparsely, they remain much more spherical. Spherules in certain layers parallel to the bedding of the ore are frequently much more flattened than others. This flattening probably occurred while the spherules were in a soft condition when variations in the thickness and density of overlying sediments would result in differing amounts of crushing.

EVIDENCE FROM FOSSILS.

Another most convincing fact is that worm burrows are found in all the ore zones, showing that the worms have burrowed from an erosion surface, removed the spherules, and formed cavities which became filled with mud in which few spherules occur (Plates XIIIA, XIIIB, and XIVA).

The fossil boring algæ are minute tubular organisms found splendidly preserved in brachiopod fragments, in spherules of hematite, and in chamosite and phosphate nodules. Similar boring organisms are known in modern seas and the presence of these fossil forms in both shells and spherules indicates that these materials were pierced while resting on the sea bottom. The tubules of these algæ, the delicacy of which may be appreciated by stating their dimensions which vary from one-fifth to four microns, often extend beyond the walls of the shells into the surrounding matrix. The portions of the ore in which these algæ occur in this fashion could not have been subjected to much mechanical rearrangement. It is evident, therefore, that not only the spherules, but the material which surrounds them, must have formed a part of the unconsolidated sediments (Plates I, XVIIB, XVIIIA, XXIB).

PRIMARY FORMATION OF SPHERULES.

It has been demonstrated that chamosite, hematite, and siderite are the important iron-bearing minerals and that siderite is in general secondary to the other two. Some hematite appears to be secondary to the chamosite, as has been described on pages 35 and 140. In the ferruginous sediments of both ore and parting rocks, chamosite was one of the earliest iron minerals to form. In the ore it built small concentric concretions of the amorphous material, and in the rocks a non-oolitic form, much of which is crystalline.

The alternating concentric layers of hematite and chamosite in the spherules, suggest that most of the hematite of the ore was formed contemporaneously with the chamosite.

The result of an experiment made by Professor C. H. Smyth, jun., (40: pp. 487-496) on the composition of similar spherules in the Clinton ores, is given as follows: "Everywhere the individual particles of the ore, when closely examined, have a marked concretionary texture, this being true of all varieties, but showing most clearly in the oolitic varieties. A spherule of the oolite or irregular fragment of the fossil ore, when lightly hammered, scales off in thin concentric shells, while thin sections under the microscope usually show concentric structure in spite of the opacity of the earthy hematite. But this structure is better shown, while at the same time another feature is brought out, by digesting spherules and fragments in hydrochloric acid. The result of the treatment is to dissolve the iron oxide, but the grains instead of disappearing or diminishing in size, retain their original size and shape, becoming white and translucent. Under the microscope they are seen to consist of concentric shells which may be pried apart by a needle. The material of these shells is either dark with crossed nicols or shows the cross of aggregate polarization. It is readily soluble in fixed alkalies, and though it has not been analysed, it is probably amorphous silica."

Similar experiments were made on the Wabana ore, one from oolitic hematite (Plate XVIB), another from oolitic chamosite (Plate XXIIIB), with like results in both instances.

The siderite has replaced both chamosite and hematite and, in many instances, detrital quartz as well. All of these operations appear to have taken place in the sediments while they were still unconsolidated, i.e., diagenetically, and no important introduction of iron seems to have been made since the beds were deposited (Plates XXIIA, XXIIB, XXIIIA, and XXIIIB). The only minerals found which have been introduced secondarily to the iron are calcite and quartz. These fill fault cracks which vary from microscopic veinlets to veins several inches in thickness (Plate XXVIA). The calcite and quartz frequently occur together and in one instance a 3-inch calcite vein is cut across by a quartz vein about one-quarter of an inch in thickness.

The phosphorus of the ore and rocks has been shown to be derived chiefly from fossil remains principally in the form of fragments of brachiopod shells. These furnish also the original lime of the ore series. A small amount of secondary lime has been introduced by the calcite veins. (Plates XIIB, XXVA, and XXVB).

SOURCE OF THE IRON.

Many questions present themselves regarding the source of the iron, and the various complex changes which it has passed through before reaching its present state. No direct evidence bearing on these questions is available and any statement must be necessarily theoretical.

F. Villain (49: pp. 1291-1293) proposed for the oolitic iron ores of Luxembourg and Lorraine, a juvenile source consisting of outflows of iron-bearing solutions from fissures in the earth's crust, but no evidence whatever has been found on which to base such an hypothesis for the Wabana ore.

It seems probable that the iron was derived by long continued weathering of earlier crystalline and sedimentary rocks, the solution of their iron content by mineral and vegetable acids and subsequent transportation of the iron salts by streams into the sea.

The Pre-Cambrian sedimentary and crystalline rocks contain much iron and these have furnished the iron of the Cambrian and Ordovician rocks underlying the Wabana ore.

The Upper Cambrian rocks of Manuels brook and the higher strata outcropping on Kelly and Little Bell islands, contain a considerable amount of disseminated iron-bearing minerals, including sulphides, silicates, and carbonates. Occasional concentrations of one or more of these minerals occur. The Upper Cambrian beds of Manuels brook hold considerable iron sulphide and some carbonate. Chemical analysis Ze of the ferruginous bed on Kelly island, described on page 64 gives 27·75 per cent of metallic iron. This occurs in forms resembling chamosite and siderite. The shale at the Nova Scotia Company's pier on the south shore of Bell island (Plate IIB) holds 8·83 per cent ferric oxide. The shales generally appear to be rich in iron, and as the greater part of this Cambro-Ordovician series is composed of shales, the whole series holds an unusually large amount of iron.

EVIDENCE FROM ABSENCE OF LIMESTONE.

There is a general absence of limestone from this Cambro-Ordovician series above the Middle Cambrian, and there is no evidence that any has ever existed, none having been found in the Upper Cambrian exposed on Manuels brook, or in the Ordovician measures on Kelly, Little Bell, or Bell islands. Chemical analyses A and B (p. 44) of shale and sandstone underlying the ore beds on Bell island, show an entire lack of lime, while many analyses of the beds and accompanying rocks, prove that the total content of about 2 per cent of lime occurs largely as a phosphate derived from fossil remains, and that little or no calcium carbonate occurs as an original constituent of the ore and accompanying rocks. The theory proposed by Professor L. Cayeux (7: pp. 284-285) for deposits of similar character and age in the Armoricain peninsula, France, and suggested for all similar Palæozoic deposits, that an original limestone has been transformed into an oolitic iron ore, is absolutely untenable for the Wabana ore, where every observation confirms the conclusion that the ore was originally formed in essentially the same condition, excepting induration, in which it is found to-day.

A much longer period is represented by the Wabana ore series than would be required merely for the continuous deposition of such a thickness of rocks. About 200 feet below the Dominion bed, the rocks were, when soft, exposed above water, for raindrop impressions are here preserved pointing to an emergence shortly after their deposition (Plate XXVIII). A change in fauna at the top of zone 2 occurs coincidently with a disconformity marked by an erosion surface (Plate V), and a deepening of the sea followed. The Scotia and Upper beds also give evidence of many oscillations in the relative level of land and sea. Professor Gilbert van Ingen has suggested that successive marginal tilting probably occurred contemporaneously with the deposition of the rocks of Bell island, causing the shore-line to advance and raising the underlying measures above sea-level. These soft sediments, with their large iron content, would then be available to further enrich the sea with iron solutions.

The chemistry of the processes involved in the formation of the ore must of necessity be very complex. I have concluded from petrological and chemical investigations that chamosite, with perhaps other similar green iron silicates, are the most generally distributed primary iron-bearing constituents of both the ore and their accompanying rocks. The hematite is intimately associated with the chamosite and is by far the most abundant iron-bearing mineral of the ore.

MODE OF PRECIPITATION OF THE IRON.

Since W. Spring (43: pp. 47-62) has shown that ferric hydroxide will become dehydrated in salt water and form ferric oxide, the view may be taken that some of the iron may have been precipitated as ferric hydrate and formed the ferric oxide directly. If so, both the silicates and oxide have formed together in a most intricate fashion to build alternate layers in the spherules. It appears probable that a considerable proportion of the iron was precipitated primarily as ferrous aluminous silicates similar to chamosite and thuringite, and while a small amount of hematite appears to have been formed about tubules of boring algæ, apparently secondary to the chamosite, most of the hematite may be of contemporaneous origin with the silicates. The siderite was the last iron-bearing mineral to form and it frequently replaces chamosite, hematite, and quartz. It may have been produced by the aid of decomposing organic matter acting on chamosite and hematite during a period of shallow water conditions such as prevailed during the formation of the top of the Dominion bed, zone 2, and of much of zone 5.

It has been shown that the ore of zones 2, 4, and 5, was formed as off-shore deposits on the bottom of a sea in which marine life was abundant, some organisms, such as worms, actually burrowing into the oolitic ferruginous sediments. The question regarding the mode of precipitation of the iron on the bottom of an open sea, still remains unanswered. It is possible that during the deposition of the hematite-chamosite ore, the sea was restricted by some means to a basin-like form, but was still sufficiently shallow to allow the migration of a fauna found in similar rocks in Europe. During the deposition of the material in which the oolitic pyrite is found in zone 3, a sufficient depth must have been attained for open currents to pass, carrying marine plankton, as is shown by the graptolites which occur in the oolitic pyrite and accompanying shales.

EVIDENCE FROM FOSSIL ALGÆ IN ORE.

The role which minute organisms such as algæ and bacteria play in the building up of such deposits, has not as yet been very thoroughly investigated and it is probable that many of the little known chemical processes may be due to the action of such organisms.

"According to Ehrenberg, the algæ, especially the so-called iron algæ, *Gallionella ferruginea* Ehrenb., are active ore precipitants coating their cell walls with ferric hydrate and opaline silica. This alga is abundant on the sea bottoms. According to the recent works of Mollisch and Winogradsky, these and most other supposed algæ are ciliated bacteria of different kinds, especially *Leptothrix ochracea*" (Beck 2: p. 102).

Tubules of algæ are found abundantly in the fragments of brachiopod shells in the ore, some of which extend out of the shells into the surrounding matrix, in such manner as to indicate that they pierced the material of the shells after the latter were deposited as fragments in the soft sea bottom. The algæ are also found plentifully preserved in ferruginous phosphatic nodules and many of them have been found in spherules composed of hematite and chamosite (Plates I and XXIA).

Most suggestive of all, however, in relation to the diagenesis of the ore, is their presence in siderite, in which, in the upper part of the Scotia bed, tubules of algæ have been preserved.

These fossil algæ have been studied by Professor Gilbert van Ingen, who refers them to the Schizophyceae, or blue green algæ. Dr. Marshall A. Howe of the New York Botanical garden, has examined the algæ and remarked (25) upon their close resemblance to species of modern blue green algæ of similar habits. When living such algæ take up carbon dioxide and water which are broken up by the action of light (photosynthesis), and oxygen is given off as a waste product (John M. Coulter 12: Pt. I, p. 150; Pt. II, p. 302).

The chemical reaction may be outlined as follows:

$$12\ CO_2 + 12\ H_2O = \underset{\text{Starch}}{2C_6H_{10}O_5} + \underset{\text{Oxygen}}{12O_2} + 2H_2O$$

The carbohydrate, starch, thus obtained by photosynthesis, and nitrogen, obtained by the process of osmosis, are converted into proteids which provide food for the organism to build up its protoplasm by the process termed metastasis (H. W. Conn, 11: p. 129).

The food of the plants consists of carbon dioxide, water, nitrates, phosphates, potash salts, and other minerals in small quantities (Conn, op. cit.). During the life of the algæ oxygen is their most abundant waste product, and a zone of oxidation would be found in the immediate vicinity of the flourishing plants. The decomposition products of the algæ, together with those of the brachiopods, trilobites, worms, and other animals present in this Ordovician sea, provided a large amount of carbon dioxide and ammonia together with small amounts of other gases and salts.

It is impossible to discover the exact nature of the sea water in which the ore beds were laid down, but it is thought probable that it differed only locally, and in degree of concentration of certain constituents, from the average composition of the waters of modern oceans. F. W. Clarke (10: p. 112), writing on the composition of oceanic salts, has listed 24 analyses of sea water from many parts of the globe and remarks regarding them: "They show a striking uniformity in the composition of sea salts, the only great variable, being that of concentration."

The mean of 77 analyses by Dittmar (15: p. 203) of ocean water from many localities, collected by the Challenger expedition is as follows:

Cl	Br	SO_4	CO_3	Na	K	Ca	Mg	Total
55·292	0·188	7·692	0·207	30·593	1·106	1·197	3·725	100·000

Salinity 3·365 per cent.

The tubules of the fossil algæ are frequently covered exteriorly with a layer of crystalline hematite (p. 35). This is especially noticeable where spherules of chamosite have been bored and it seems probable that the oxidation of the iron was in these instances at least, caused by the life processes of these algæ, and since by examination of only a small number of slides, the algæ have been found at many horizons in both the Dominion and Scotia beds, and evidently lived in great abundance throughout the time of deposition of the ore strata, it may be that sufficient oxygen was provided in this manner to account for the large proportion of the iron of the ore in the form of hematite.

The iron, brought into the sea by streams, in the form of salts of organic acids, chlorides, sulphates, ferrous bicarbonate, etc., having a higher specific gravity than sea water, would sink to the bottom, and ammonia formed on the sea bottom from decaying organic matter might produce, directly or indirectly, a precipitate of iron hydroxide.

The oxidizing action of the algæ above referred to would tend to oxidize the precipitated hydrate of iron to hematite. Since the oolitic ore occurs with argillaceous rocks, hydrated silicates of alumina were undoubtedly abundant, and the chamosite and other silicates of iron may have had their origin in the combination of the iron and hydrated aluminous silicates, the process taking place contemporaneously with the formation of hematite. As stated before (p. 74) Ehrenberg has found that certain unicellular plants coat their cell walls with ferric hydrate and opaline silica. This phenomenon suggests the possibility of a common source in the plant activities for the silicates as well as the oxide of iron. As I have found no evidence of organic influence in the building up of the concentric layers of hematite and chamosite, I think that this structure is probably due to physical causes.

The work of the late Dr. G. Harold Drew (19: pp. 139-141) on the marine denitrifying bacteria at Port Royal, Jamaica, and at Tortugas, Florida, gives data concerning conditions under which plants flourish or have their growth restricted in the ocean, and suggests also a means by which calcium carbonate may be precipitated with perhaps the formation of oolitic limestone. These experiments supply information suggesting an interpretation of certain conditions obtaining in the Ordovician sea while the Wabana ores were being deposited. Dr. Alfred G. Mayer, Director of the Department, writes as follows of Dr. Drew's work (32: pp. 123-124): "G. Harold Drew, Esq., carried out observations which justify the belief that he has probably discovered one of the most interesting facts yet revealed through the study of oceanography. He finds that the most abundant bacillus at depths between ten fathoms and the surface in the ocean off Jamaica and Tortugas is a form that possesses the capacity to convert all the nitrates of the water into nitrites and finally to expel the nitrogen from the sea in the form of gas, thus depriving the surface waters of the sea of nitrogen. This relative scarcity of nitrogen in the tropical ocean accounts for the paucity of plant life in warm seas as compared with the conditions seen in temperate regions, where great masses of fucus, etc., cover the rocks. Dr. Drew also showed that the formation of ammonia and the final liberation of nitrogen by this bacterium would leave the calcium free to combine with the dissolved carbon dioxide of the ocean, thus causing a precipitation of calcium carbonate. The vast areas of chalky mud of the Bahama-

Florida region and in the tropical Pacific, may have been formed in this manner. This denitrifying bacterium appears to grow best in a moderate light and to be most abundant at a depth of 10 fathoms, below which it gives place to another, non-denitrifying form, which appears to be characteristic of the deep sea and is readily killed upon exposure to sunlight."

Dr. Drew writes (Op. cit., 19: 139): "The formation of beds of fine unorganized chalky mud in certain places off the southern Florida Keys may possibly be explained in this way, and it is conceivable that some such bacterial action may have played a part in the formation of some chalk and oolitic limestone beds in geologic times." . . . (19: p. 140-1). "On August 7, 1911, two samples of water were collected in the lagoon of the Marquesas islands, 40 miles east of the Tortugas. These samples were obtained near the eastern entrance to the lagoon, while the tide was still ebbing, but nearly low. The bottles were sent to Plymouth, England, where they were studied . . ." A number of experiments were made and among other results, the following interesting phenomenon was observed: "Rapid growth in a medium consisting of calcium succinate 1·0 gram (soluble), potassium nitrate 0·5 gram, and sea water 1,000·0 c.c., with production of thick, milky appearance, due to extremely finely divided particles of calcium carbonate, so fine that they will not settle.

"To such a culture a trace of a very finely powered hydrated calcium sulphate or fine sand was added. This resulted in the formation of a precipitate which, on microscopical examination, could be seen to consist of finely laminated concretions, some of which appeared to have a particle of calcium sulphate or sand as a nucleus. The concretions were soluble in dilute hydrochloric acid with evolution of carbon dioxide. These concretions bear a resemblance to those of some oolitic limestones, and the experiment suggests the manner in which some oolites may have been formed.

"The bacteria which cause the formation of these concretions seem to be the same as those found at Tortugas and Jamaica."

The statement that "The relative scarcity of nitrogen in the tropical ocean accounts for the paucity of plant life compared with the conditions seen in temperate regions," is especially suggestive, for since plant life in the form of algæ was abundant when the ores were formed, we may perhaps conclude that no denitrifying bacteria were active there and if existing at that early geological time, the climate was probably temperate. The absence of limestone from the Upper Cambrian and lower Ordovician, also indicates an absence of such bacteria at functioning temperature.

THE FORMATION OF OOLITES BY PHYSICAL PROCESSES.

The experimental formation of "finely laminated concretions about a nucleus of sand or calcium sulphate" is especially interesting and suggestive. By means of bacteria, organic matter is decomposed and ammonia set free to form ammonium carbonate with the dissolved carbon dioxide in the water. The calcium sulphate is usually precipitated as a very finely divided powder and it seems probable that this material gathered about the nuclei by the force of surface tension rather than by the aid of organisms.

Dr. T. Wayland Vaughan (48: p. 303) has studied the processes which result in the formation of oolites composed of calcium carbonates, which are forming at the present time in shoal waters off the coasts of Florida and the Bahama islands and has announced the following conclusions:

"The empirical facts in the process of the formation of the Floridian and Bahaman oolites are demonstrated. They are as follows: (1) Denitrifying bacteria are very active in the shoal waters of both regions and are precipitating enormous quantities of calcium carbonate which is largely aragonite; (2) this chemically precipitated calcium carbonate may form spherulites which by accretion may become oolite grains of the usual size, or it may accumulate around a variety of nuclei to build such grains."

Similar physical methods were probably operative for the formation of the oolitic hematite-chamosite. The tendency of extremely minute particles to collect together under the influence of surface tension, is well known, and the micro-crystalline hematite and chamosite have together furnished such pulverulent material for the production of the spherules in this manner.

While oxidizing conditions obtained on the sea bottom, very different conditions were produced in the underlying sediments. Dr. John Murray and Mr. Robert Irvine (36: p. 483) say of blue mud deposits: "The deeper layers of the deposit are very stiff and compact, blue or black in colour, owing to the presence of organic matter and of sulphide of iron, while the immediate surface of the water in contact with the superincumbent water is thin, watery, and usually of a light brown or red colour from the higher oxidation of the iron. In the "Challenger" trawlings the bag of the net would frequently be filled with a soft red-coloured mud from the surface layers, while the iron frame supporting the beam was covered with patches of a stiff blue mud or clay from the deeper layers."

Professor Lindgren (30: p. 250) cites an occurrence on the south side of Molokai, Hawaiian islands, where hematite mud is spread out over a large area of shallow coral reef.

ORIGIN OF SIDERITE AND ITS RELATIONS TO HEMATITE AND CHAMOSITE.

Wherever, in the Wabana ores, siderite has been found in association with hematite and chamosite, it replaces them, but the tubules of the algæ are sometimes preserved in it. As has been shown above, it is probable that oxidizing conditions obtained upon and immediately above the sea bottom, due to the growth of algæ. At the same time some of the dead and decaying algæ, together with inarticulate brachiopods, worms, trilobites, and other organisms would be entombed by the upper portions of the newly formed sediments. Where sufficiently covered to make escape of the products of decomposition difficult reactions would take place somewhat similar to those outlined by John Murray and Robert Irvine (36: pp. 485-486), who have shown that the alkalinity of water in the blue mud is much higher than that of the water overlying the mud, and quoting from page 485 "At first we were inclined to refer the great increase of alkalinity to the excess of carbonate of lime derived from the solution of the dead shells of calcareous organisms by carbonic acid, the latter being much increased in sea-water through the deoxidation of the sulphates by organic matter, but the total lime present in the water filtered from the muds was found on determination not to have increased in any notable degree above that present in normal sea-water; indeed, the latter filtrates show a slight decrease of lime, which points, it may be, to the precipitation of carbonate of lime in the mud."

	Average sea water.	Mud water.
Sodium chloride, $NaCl$	77·758	79·019
Magnesium chloride, $MgCl_2$	10·878	11·222
Magnesium bromide, $MgBr_2$	0·217	0·220
Magnesium sulphate, $MgSO_4$	4·737	2·232
Potassium sulphate, K_2SO_4	2·465	2·506
Ammonium sulphate, $(NH_4)_2SO_4$	2·465	0·206
Magnesium carbonate, $MgCO_3$	2·465	0·909
Calcium carbonate, $CaCO_3$	0·345	2·686
Calcium sulphate, $CaSO_4$	3·600	2·686
	100·000	100·000

"The increase of alkaline ammoniacal salts points, however, to a further reaction, by which carbonate of lime is increased to a slight degree, for as ammonium carbonate ($(NH_4)_2CO_3$) is formed by the decomposition of the albuminoids present, the sulphates in the sea-water by this means are decomposed, sulphate of ammonia ($(NH_4)_2SO_4$) and earthy carbonates being the result."

There is a marked absence of the alkali carbonates from the Wabana ores and accompanying rocks, so that if any were formed they either remained in solution or were decomposed by syngenetic chemical processes. During the deposition of the ferruginous beds, it seems probable that a variety of iron salts were in solution in the sea water, and the ammonium carbonate resulting from the decomposition of organic matter, where entombed by overlying sediments, may have decomposed these iron salts, with the formation of the corresponding ammonium salts and the precipitation of the iron carbonate, siderite.

Quartz grains and chamosite, both in matrix and spherules, are frequently partly destroyed and replaced by siderite. Solutions of alkali carbonates and hydroxides have a considerable solvent action on quartz and dissolve non-crystalline silica very readily, and such a solvent may have been produced and concentrated locally in sufficient quantity to aid in the solution of these constituents, the iron carbonate being deposited. Thus it appears that while the hematite and chamosite were being deposited on the surface of the bottom deposits, siderite was contemporaneously formed in the underlying sediments, consisting of oolitic hematite-chamosite muds, quartz grains, and siliceous material, for a distance downward, the amount of siderite formed being dependent upon the quantity of decomposition products furnished under proper cover.

CHAPTER VII.

OCCURRENCES OF IRON ORES OF SIMILAR AGE AND CHARACTER.

Oolitic iron ores of approximately the same geological age have been found in Canada and Europe, and more recent deposits of similar character in Europe and the United States.

M. Y. Williams (51: p. 246) has correlated an occurrence at Arisaig, Nova Scotia, with the Wabana ore and refers it to the Upper Cambrian. He describes the deposit as follows: "Oolitic hematite beds are found in the James River rocks near the base of the Baxter Brook division and again at a lower horizon. The sedimentary origin of the ores is most probable from the consideration of the oolitic and sparingly fossiliferous character of the ore, its longitudinal extent, and its close association with the definite rock horizon. Some secondary concentration or transference of material, may, however, have taken place.

"So far as could be observed the two formations have entirely conformable relations to each other and on the evidence of *Obolus* (*Lingulobulos*) *spissus* and *Lingulella* (?) obtained from the upper iron ore horizon (both from the ore itself and the associated schist), these rocks are proven to be of the Upper Cambrian or Ozarkic age. The ore is likewise correlated with the Wabana ore of Bell island, Conception bay, Newfoundland; but because of low grade and faulted condition it has not yet been developed, although portions of it will probably be profitably mined sooner or later."

These ores are also described by Professor J. E. Woodman (52: pp. 15-23), as bedded hematites.

The abundant literature descriptive of the Clinton ores, has made them known to all interested in such deposits. Opposing theories regarding their origin were discussed and the facts supporting the theory of their sedimentary origin were concisely presented in 1892 by Professor C. H. Smyth, jun. (40: pp. 487-

496). Professor Smyth has more recently formulated his view of the formation of the iron ore as follows (42: pp. 33-52): "Assuming a rather complete analogy with modern lake ores, it is probable that the iron was deposited, for the most part, as limonite with, perhaps, subsidiary carbonate. The dehydration of the limonite may have followed soon after precipitation, since W. Spring (43: pp. 47-62) has shown that freshly precipitated ferric hydroxide undergoes spontaneous dehydration while still in contact with water, particularly if the latter is saline. On the other hand, dehydration may have been a slower process, aided, perhaps, by pressure of overlying rocks, and slight temperature increase."

Some of the other publications dealing with the Clinton iron ores, and of which full titles are given in the bibliographic list, are: Smyth, jun. (41) ; Burchard (3) ; Burchard, Butts, and Eckel (4); Newland and Hartnagel (37); Rutledge (38); and McCallie (33).

Professor Smyth (42) discusses the theory proposed by McCallie (33) that the iron was originally deposited not as limonite but as glauconite, and concludes that this hypothesis is untenable.

J. J. Rutledge (38) concludes that by far the greater part of the iron of the Clinton ores is due to replacement and concentration of the iron, but thinks that the intimately associated oxides and silicates of the spherules and the iron present as the carbonate in isomorphous mixtures with calcium carbonate may be due to original deposition.

Professor C. K. Leith (29: pp. 99-100, 1908) groups together the flax seed ores of the Clinton and other beds of the Appalachians and Wisconsin, the ores of the Torbrook and Nictaux areas of Nova Scotia, the Wabana ores of Newfoundland, and a recently discovered deposit in Missouri. He considers them to be sedimentary ores derived by weathering processes and deposited in the ocean as iron oxide rather than as ferrous salts, and that they have undergone no further concentration, being mined essentially in the condition in which they were deposited.

Ores comparable in character and extent, with the Wabana ores, occur in France, on the Armorican peninsula. These are described by L. Cayeux (7: 1909) who concludes that an oolitic limestone was replaced by siderite from which in turn the chamosite, hematite, and other iron-bearing minerals as well as the quartz of the ore have been derived.

Many of the descriptions and photographs of thin sections of ores taken from this locality in France, represent phenomena so similar to those of the Wabana ore, that they might serve to illustrate the latter. A fauna, similar to that described in this paper, occurs in these French ores and rocks, including boring algæ which are found also in the hematite spherules and in the siderite. Certain of the algæ of the Wabana ore are similar to the algæ-like fossils found by Professor L. Cayeux in the similar oolitic iron ores of Le Ferriers-aux-Etangs. He writes that these organisms seem to be endowed with a selective faculty for certain ferruginous constituents of the ores, including siderite and hematite. I have already outlined an explanation for this association, suggesting that, while living, the algæ gave off oxygen which oxidized the iron to hematite, and in their decomposition the ammonium carbonate given off precipitated siderite which formed a preservative for some of the undestroyed tubules. Professor Cayeux has also studied specimens of Clinton ores and concludes that these were derived from a limestone by a secondary replacement. The theory of a long series of replacement (7: p. 285) first from an original oolitic limestone to siderite and then through chlorite to hematite, the siderite and hematite so derived giving rise to quartz, goethite, pyrite, etc., appears to me to be unwarranted by the observations of fact which Professor Cayeux has so clearly described in his admirable monograph. A study of the descriptions and photographs has led me to suggest that the deposits at May-sur-Lorne, Saint Rémy, and Le Ferriers-aux-Etangs, may be primary bedded ores of character and origin similar to those of the Wabana iron ore.

Pisolitic iron ores are found in Wales and have been described by W. G. Fearnsides (21: pp. 170, 173; 1910), who places them in the Llandeilo, the next younger formation above the Arenig, and thought by Professor van Ingen to correspond very closely in age to the upper part of the Wabana series. The Ordovician slates of southeast Carnarvonshire in which the ore occurs, are much disturbed by igneous rocks, and, since the ore masses were observed to show no signs of crushing, and the largest ore bodies lie near the crushed zone where it abuts upon the metamorphic aureoles of the late intrusive dolorites, Mr. Fearnsides has been led to urge that the ore is of secondary or metasomatic origin, and owes its distribution to the position of the fault. It seems probable that this pisolitic ore has a mode of origin similar to other like deposits. The much disturbed condition of these rocks makes an interpretation of their origin difficult. I have seen no descriptions of slides of this ore and it may be that a thorough study of their petrographic character would reveal original constituents not otherwise discernible. The presence of oolitic hematite in strata holding a fauna closely related to the lower Ordovician of Bell island, suggests the probability of similar conditions of sedimentation.

The occurrence in the Ordovician of the Iberian peninsula of iron ore similar to that of the Amorican peninsula is referred to by Robert Douvillé (18: p. 13; 1911), but no detailed description is given.

In Bohemia and Thuringia (Germany) there are a number of bedded deposits of oolitic hematite-thuringite-chamosite-siderite ores, occurring in lower Silurian measures. In Bohemia the ore occurs in the so-called Komarauer Schichten (Barrande's Etage D) of Katzer (28: pp. 820, 844-852, 986-989) and is succeeded by an overlying graptolite zone. The ore closely resembles that at Wabana, several beds of oolitic hematite and chamosite occurring as primary sediments in a series consisting principally of quartzites with associated slates, greywacke, conglomerates, diabase amygdaloids, and diabase tuffs. An ore bed at Nucitz is 16 feet thick, shows stratification, and holds fossils. The ores are rich in phosphorus and also carry a little magnetite. A general absence of limestone from the measures, as is also the case with the Wabana sediments, is worthy of note since it indicates a condition of sedimentation unfavourable for the formation of an original oolitic limestone.

From the lower Silurian iron ores of Thuringerwald, Germany, a deposit at Schmiedefeld (Sachsen Meiningen) near Grafenthal in Thuringia, has been studied petrographically by H. Loretz (31: pp. 120-147; 1884), and found to consist of oolitic chamosite, as a dark grey compact aggregate of small concentric pellets, cemented together by siderite. Thuringite occurs in accompanying slates. The ores occur as lenticular beds as much as 7 feet thick.

The above-mentioned deposits from Bohemia and Thuringia are classed by Dr. R. Beck (2: pp. 82-84) as original intercalations in normal sediments. Professor W. Lindgren (30: p. 243) writes of these deposits: "Many believe that the iron is derived from the decomposition of the associated diabase tuffs. Be that as it may, these iron ores are certainly of sedimentary origin."

The extensive Minnette ores of Luxemburg and Lorraine, of Jurassic age, resemble the Wabana ores in their oolitic character and the content of green ferrous silicate. According to L. van Werveke (47) the oolitic iron ores of Lorraine were deposited on the bottom of a shallow coastal sea. "The iron was brought from the land to the sea by brooks and rivers, and was precipitated in very diverse forms as silicate (looking like glauconite), also as carbonate, sulphide, and sesquioxide in the upper strata, possibly also as ferric hydrate."

While many geologists propose a primary origin for the various minerals of the oolitic iron ores of North America and Europe, briefly referred to above, there is not as yet an unanimity of interpretation. The American geologists with few exceptions, agree with Professor C. H. Smyth regarding the primary origin of the iron minerals of the Clinton ores. Professor L. Cayeux (7) and Dr. A. Harker (22: pp. 273-275) hold that these ores are replacements of original limestone. Professor Cayeux also holds this theory for the oolitic ores of the Armorican peninsula which occur intercalated in strata where there is a general absence of limestone, and are composed of hematite with much chamosite, thuringite, and siderite. While Dr. R. Beck (2) and Dr. W. Lindgren (30) regard the oolitic iron ore of Thuringia and Bohemia to be of sedimentary origin, E. R. Zalinski (53: pp. 81-84) considers them to be alterations from other sediments.

In England, Alfred Harker (22) considers the valuable iron-stones of Rosedale (Dogger), the Cleveland main seam, and the Jurassic ores of Northampton and Rutland, to be formed by metasomatic changes from limestones.

J. E. Stead (44: pp. 75-117) also considers the Cleveland ores to be replacements and concludes that the original strata were siliceous and clayey limestones which have been removed by iron carbonate and silicate solutions.

H. H. Thomas and D. A. MacAlister (46), on the other hand, compare the Jurassic and Lower Cretaceous ores of England with those of continental Europe and say that they "seem to be due in part to original precipitation, and partly to metasomatic replacement. The pisolitic ores especially seem to have the characters of original sediments."

CHAPTER VIII.

ORIGIN OF THE PYRITE BEDS.

At the close of the deposition of the Dominion bed at the top of zone 2, a disconformity occurs (Plate V) immediately above which, layers of oolitic pyrite alternating with beds of fissile black shale are found, which hold an abundant fauna of graptolites identified by Dr. Rudolph Ruedemann[1] to be *Didymograptus* cf. *nitidus*. Associated with the graptolites are brachiopods, orthoceratites, and probably other fossils.

Since the graptolites were planktonic organisms drifted about by ocean currents, their presence indicates a sudden deepening of the sea at the close of the formation of zone 2. No hematite accompanies the pyrite and an entire change takes place from sediments containing oolitic hematite and chamosite with siderite, to oolitic pyrite, a few inches of shale intervening. With the deepening of the sea, the algæ would cease to grow, for they are shallow water plants depending on sunlight for their life processes. The oxidation produced by these organisms would therefore be lacking, and conditions similar to those found on modern sea bottoms where pyrite is forming, were probably produced. (Plates XIIA, XIXA, and XIXB).

Murray and Irvine (36: p. 496) explain the principal reactions which occur in mud waters, by the following formulæ:

(1) $RSO_4 + 2C = 2CO_2 + RS$,

where R is an earthy alkaline metal or an alkali.

(2) $RS + 2CO_2 + H_2O = H_2S + RCO_3CO_2$.

(3) $RS + RCO_3CO_2 + H_2O = 2RCO_3 + H_2S$.

On the hydrosulphuric acid meeting with ferric oxide (Fe_2O_3) present in the surface layer of these blue muds the following reaction occurs:

(4) $Fe_2O_3 + 3H_2S = 2FeS + S + 3H_2O$.

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[1] Personal communication to the writer in December, 1912.

While these reactions may outline in a general way some of the probable chemical equivalents, I have as yet insufficient data to apply them to zone 3. The fact that the iron sulphide is present in the form of FeS_2 raises the question as to whether it was deposited as this higher sulphide or as ferrous sulphide, FeS, and free sulphur, the higher sulphide forming by subsequent diagenetic processes. In either case the evidence indicates that the essential constituents were present in the original sediments and that the pyrite occurs as a primary bedded deposit.

The formation of ferrous sulphide in the bottom deposits of the Black sea is described by N. Androussow (1: p. 7). He has found that a micro-organism *Bacterium hydrosulfuricum ponticum*, liberates hydrogen sulphide not only from albuminoids, but also directly from sulphates and sulphides, and ferrous sulphide results from the action of the hydrogen sulphide on iron salts. Other micro-organisms as yet insufficiently studied, also occur in the Black sea. In depths of 300 to 717 fathoms, two varieties of mud were found, a viscous sticky black mud holding iron sulphide (FeS), and a less dense blue mud holding pelagic diatoms, a smaller quantity of FeS, and concretions of FeS_2. The blue mud is thought to underlie the black mud. Thus the fact is established that FeS_2, is produced in bottom deposits of the Black sea at depths of 300 to 717 fathoms.

The researches of Dr. Bruno Doss (16: pp. 662-713) on the formation of iron sulphide both in the bottom deposits of the Black sea and in Miocene sandy clays of Samara, are of the highest importance in their bearing on the origin of pyrite in sedimentary rocks. He found that hydrated ferrous sulphide and free sulphur are deposited in the modern muds on the sea bottom, through the agency of certain iron bacteria. In a study of the cores of eight bore-holes sunk on the property of the brothers Melnikow in Samara, a new iron sulphide was discovered by Doss (17).

The bore-holes were made to obtain water, but incidentally gas was found in sandy clays overlying the Miocene sediments. The following strata were bored through: 48 metres brown clay, 46-48 metres clayey sand, 11 metres sandy clay, and 1 to 2 metres of underlying sandy clay of Miocene age.

In these Miocene sediments black iron sulphide was found occurring in finely divided, microscopic particles, frequently clinging to such marine shells as *Cardium pseudoedule* and *Mactras* sp. By chemical analysis he found the black sulphide to be FeS_2, a form of ferric sulphide not previously identified, to which he gave the name "melnikowit." By microscopic study he found pyrite associated with the melnikowit in such fashion that he concluded that the pyrite was derived from the melnikowit. He dissolved the melnikowit in aqua regia and ignited the insoluble residue which turned a yellow colour. This residue, besides clay, consisted of material resembling amorphous silica penetrated by reddish coloured thread-like forms. He found these thread-like forms to resemble pictures of *Gallionella ferruginea* published by Mollisch, and in order to be more certain, sent them to Dr. Schorler in Dresden, who identified them to be the bacteria, *Gallionella ferruginea* of Ehrenberg.

Having found that hydrated iron sulphide and free sulphur are formed in modern deposits, Doss concludes that these constituents were formed in the Miocene deposits through the agency of desulphurizing bacteria and combined with the loss of water to form melnikowit. He does not know whether the bacteria actually precipitated iron sulphide or whether they produced the iron hydrate which, being acted upon by H_2S, produced the hydrated iron sulphide.

The Black sea communicates with the Mediterranean through the narrow strait of Bosphorus through which two currents flow in opposite directions, the surface water being carried into the Sea of Marmora while the deeper water moves toward the Black sea. The upper current, flowing toward the Sea of Marmora, consists of brackish water, while the lower carries salt water from the Mediterranean into the Black sea. Since the salt water currents do not reach the surface, marine planktonic organisms cannot be freely carried into the Black sea. Somewhat similar conditions, but with the access of surface currents of water, may have obtained in the Ordovician sea when the graptolitic pyrite beds of the Wabana deposits were formed. In such an enclosed sea, uplift would cause shallow water conditions suitable for the growth of algæ and the formation of the hematite-chamosite-siderite deposits. Subsidence would bring about the deeper water necessary for the production of the iron sulphide such as is found in zone 3.

Descriptions of deposits of oolitic pyrite are rare but the pyrite and barite of Meggen on the River Lenne in Westphalia, Germany, which occur in Devonian slates, may be noted here. Underlying the deposit, which averages 10 feet thick, are greywacke slates. Overlying it are dense nodular limestones carrying fossils, *Prolecanites* and inclusions of iron pyrite. The limestones are in part dolomitic and are overlaid by clay slates. The pyrite is distinctly stratified, occurring in fine layers and in some parts is oolitic. Dr. R. Beck (2: pp. 481-482) classes these deposits as epigenetic. Denckmann (14: p. 112) ref. quoted from Beck (2: p. 480) conjectures that the Meggen deposit is an alteration from the limestone which is thinned at this point. Stelzner (45: p. 342) thinks that it exhibits the characteristics of a bedded sediment, and Lindgren (30: p. 283) classes it as a sedimentary deposit.

CHAPTER IX.

CONCLUSION.

The oolitic iron ore with ferruginous shales and sandstones forms part of a series of sedimentary rocks of lower Ordovician age.

The ore beds are characterized by ripple-marked surfaces and cross-bedded layers, and contain remains of animals which lived in shallow water. The spherules of the ore vary in size from 0·1 to 0·5 millimetres and are composed of alternating concentric layers of hematite and chamosite. These spherules were pierced by living boring algæ, hence the iron minerals forming them were precipitated near the surface of deposition, while the algæ flourished on the sea bottom.

Siderite occurs in smaller quantity than hematite and chamosite, but becomes locally abundant. It replaces chamosite and hematite and in some instances detrital quartz in the ore. The algæ are found in all horizons in the ore beds and formed a very abundant marine plant life growing on the sea bottom. Tubules of the algæ are preserved in the siderite and are frequently coated exteriorly with hematite. The siderite was chemically precipitated, probably under cover of overlying sediments where concentrations of ammonia and carbon dioxide resulted from decaying organic matter. Thus while hematite and chamosite were forming at the surface of deposition, the siderite was contemporaneously formed in the immediately underlying sediments.

There is a total lack of limestone from the series, and igneous rocks are also absent. Practically all of the original calcium content of the ore, averaging about 2·5 per cent, is present in the form of fossil remains composed largely of calcium phosphate, or as calcium phosphate derived from such organic matter. The phosphorus of the ore is also derived from the remains of organic life preserved in it. No evidence of diagenetic transformation from an original oolitic limestone to an oolitic iron ore has been found and no concentration of iron has occurred since the deposition of these ferruginous sediments. They are primary bedded iron ore deposits, mined to-day in essentially the same condition except for induration, faulting, and the addition of small amounts of secondary calcite and quartz in fault cracks, as when they were laid down.

Oolitic pyrite also occurs as part of the same series of sediments, but is characterized by a planktonic fauna indicative of open ocean currents and deeper water. The layers of pyrite show distinct stratification and are probably similar in origin to modern deposits of pyrite now forming in the Black sea.

The pyrite spherules are composed of concentric layers of pyrite, frequently alternating with layers of phosphatic material. Pyritized and unpyritized graptolites and brachiopod remains occur together in contact with the spherules, indicating that some mechanical mixing took place on the surface of deposition.

CHAPTER X.

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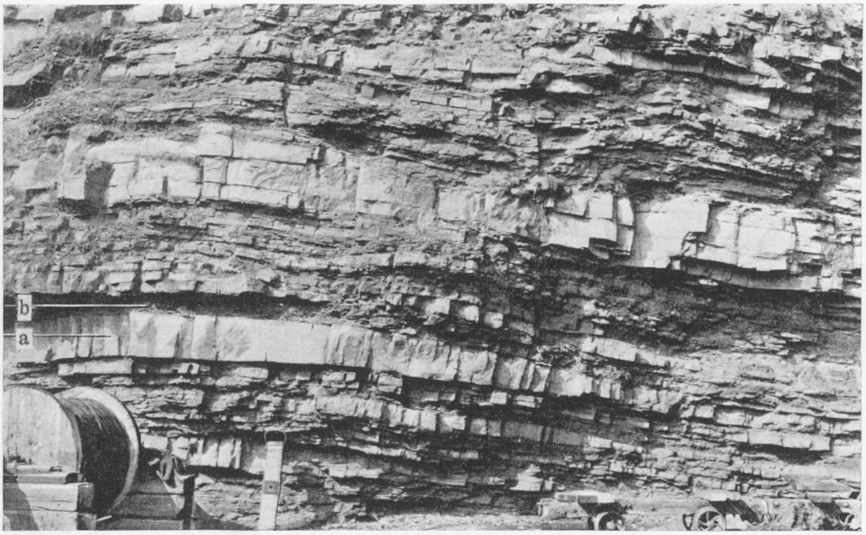
EXPLANATION OF PLATE II.

A. Lower Cambrian basal conglomerate 18 feet thick exposed at highway bridge of Manuels brook. Locality 210 A1. (Page 9.)

B. Sandy shales with intercalated lenticular sandstones at foot of cliff at Nova Scotia Steel and Coal Company's pier, locality 206 A1, on south shore of Bell island. (Pages 9, 44, 72.)

PLATE II.

A.



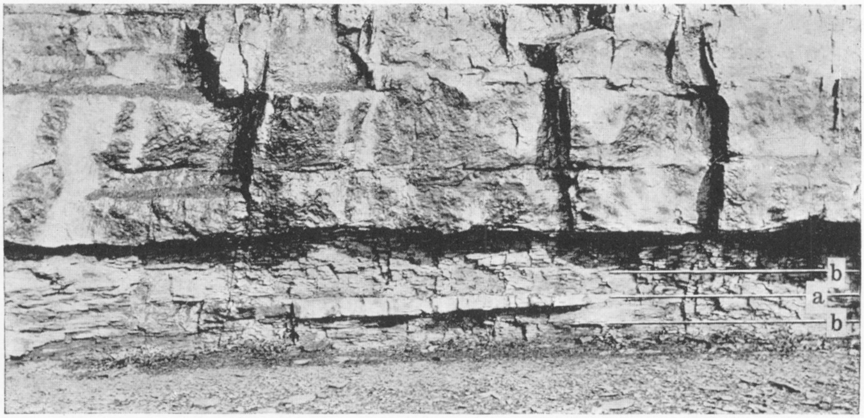
B.

Explanation of Plate III.

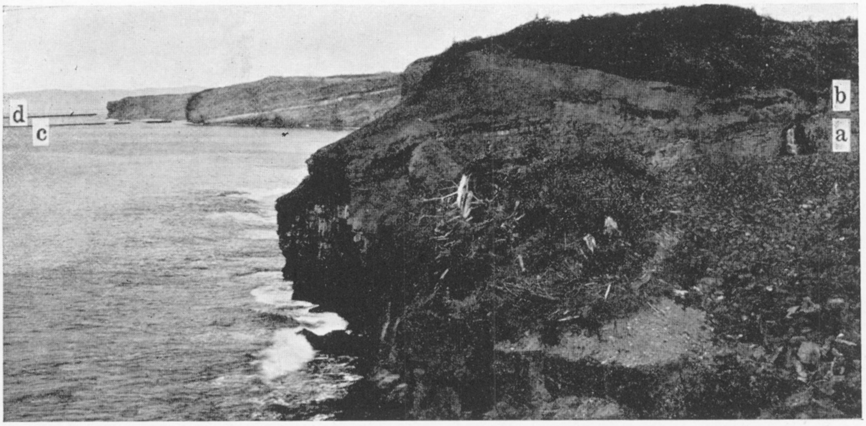
A. Lens of parting rock in midst of oolitic hematite-chamosite ore of zone 5, locality 206 AH18, on north cliff of Bell island about 500 feet west of submarine slope No. 2 of Nova Scotia Steel and Coal Company. a—parting rock; b—oolitic hematite. (Pages 9, 12.)

B. North coast of Bell island at Youngsters gulch looking northeast. Shows Dominion bed (a) with underlying measures, and with overlying pyrites zone (b); in the distance the Scotia bed (c) and the Upper bed (d) are seen dipping at about 9 degrees north-northwest into the sea. (Pages 10, 11.)

PLATE III.



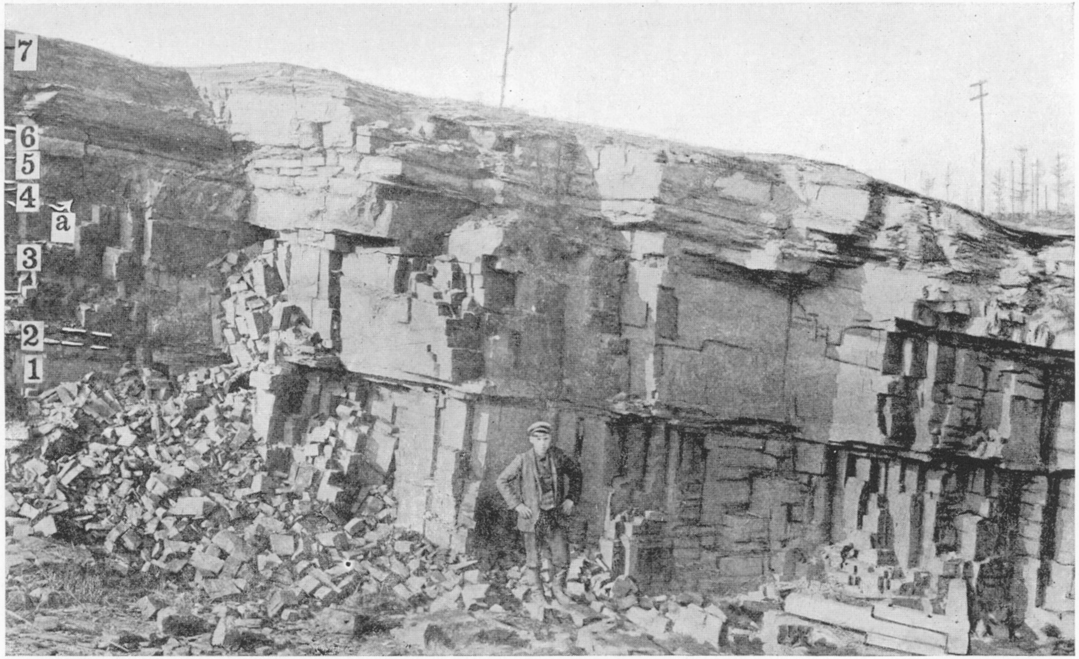
A.



B.

Explanation of Plate IV.

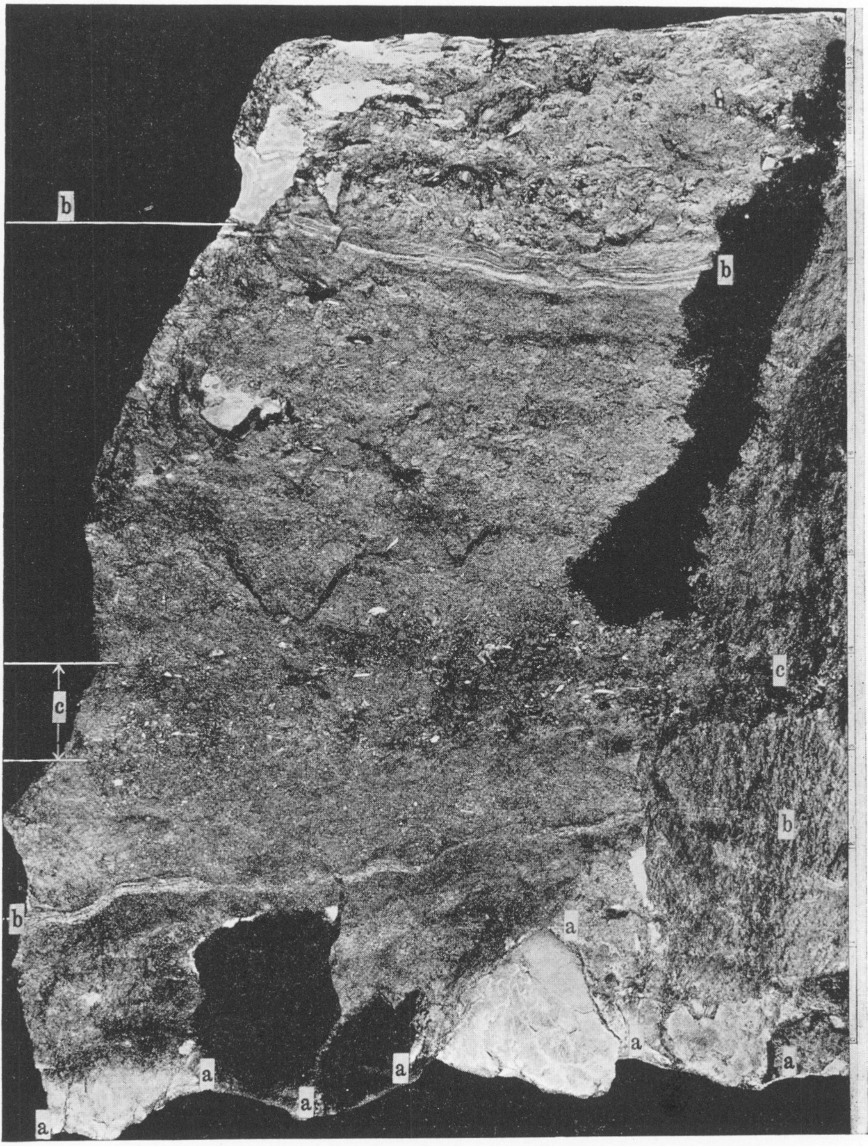
Dominion bed, face in surface stripping, locality 215 C, showing the characteristic blocks into which the ore breaks. The numbers are those of the section described on page 15. (Pages 10, 24.)


7
6
5
4
a
3
2
1

Explanation of Plate V.

A cross-section of a bed of oolitic pyrites about 14 inches thick. A disconformity is indicated by the line joining a, a, a, a; b—b are lines of stratification; c—c are nodular bands. Locality 208D (Pages 16, 73, 89.)

PLATE V.



Explanation of Plate VI.

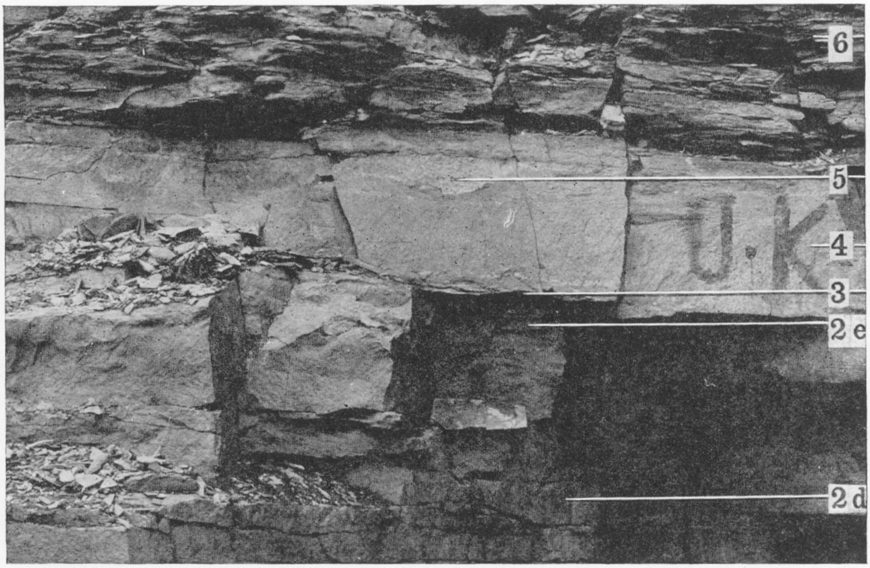
Scotia bed with overlying shales at the surface stripping, locality 206 J. The numbers are those of the section described on page 18.

PLATE VI.

EXPLANATION OF PLATE VII.

Detail of upper part of Scotia bed, locality 206J, showing pebble bed occupying channel in upper surface of chamosite sandstone. Numbers are those of section on page 18.

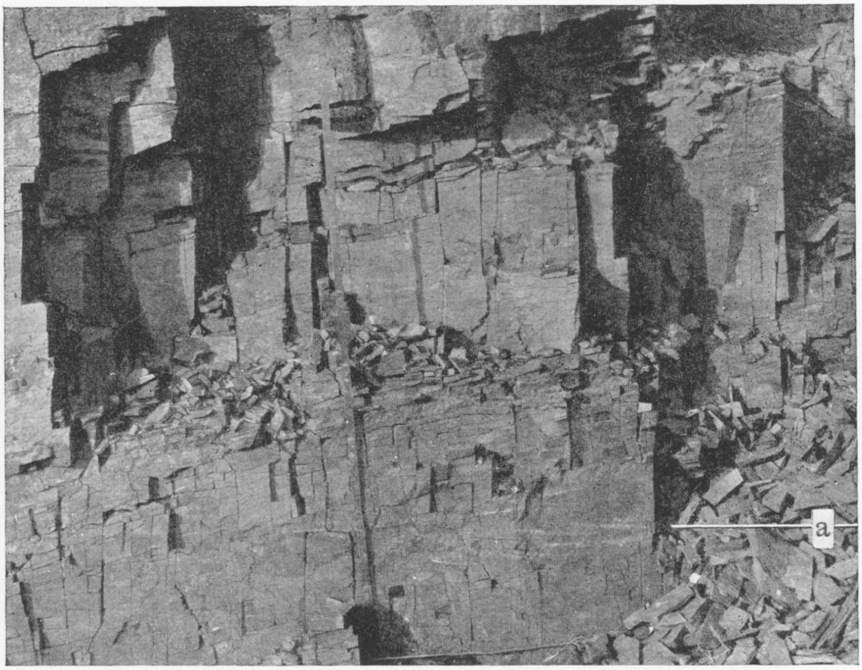
PLATE VII.



EXPLANATION OF PLATE VIII.

East stripping face of Scotia bed showing (a) cross-bedding in oolitic hematite-chamosite ore; note angular blocks into which ore breaks. (Pages 17, 24, 69.)

Plate VIII.



EXPLANATION OF PLATE IX.

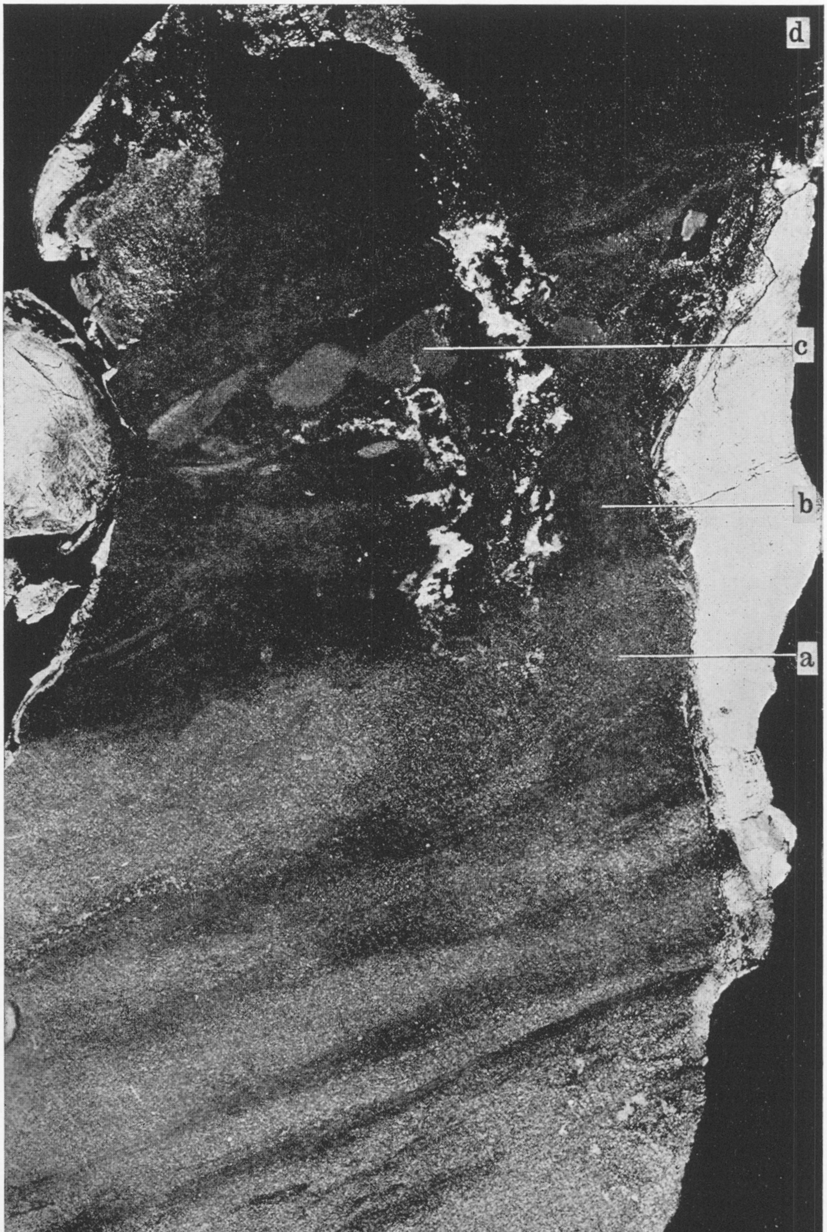
Face of north cliff at the fault, locality 206 AH, showing layers 3 to 21 of the Upper zone 5. The numbers are those of the section, pages 20, 21.

PLATE IX.

EXPLANATION OF PLATE X.

Section of upper part of Dominion bed showing rearrangement of materials, natural size, locality 208 D0. a—oolitic hematite-chamosite; b—parting rock of ferruginous shale; c—pebbles of oolitic hematite-chamosite; d—overlying shale. The hematite-chamosite spherules composing the pebbles of the inter-formational conglomerate formed a portion of an oolitic layer which has been broken up and recemented by argillaceous material. (Pages 25, 67, 69.)

PLATE X.

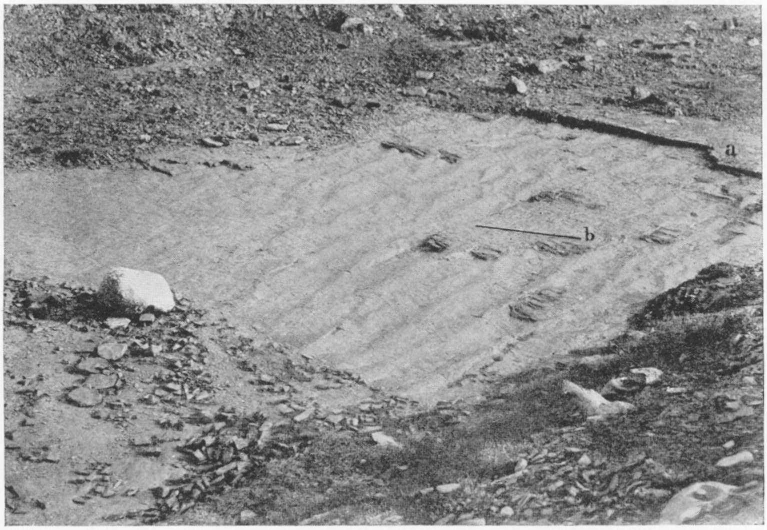


EXPLANATION OF PLATE XI.

A. Ripple-marked surface underlying the Scotia bed at its east stripping. a—overlying ore filling the channels of the ripples; b—the rule is 3 feet long. (Page 67.)

B. Nearer view of ripple-marked surface just below the Scotia bed showing the oolitic hematite filling the ripple troughs and the characteristic angular blocks of ore. (Pages 24, 67.)

PLATE XI.



A.

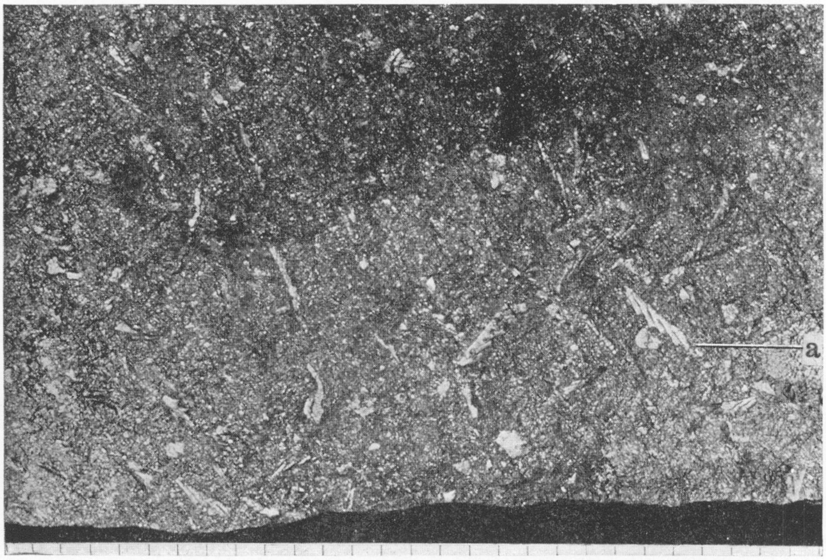
B.

Explanation of Plate XII.

A. Pyritized graptolites and fragments of brachiopods in oolitic pyrite, magnified 3 diameters, locality 208 D4. a—Didymograptus nitidus. (Pages 22, 33.)

B. *Lingula hawkei* from the Dominion bed, natural size, locality 206 A19x. a—dorsal valve; b—ventral valve. (Pages 22, 57.)

PLATE XII.



A.

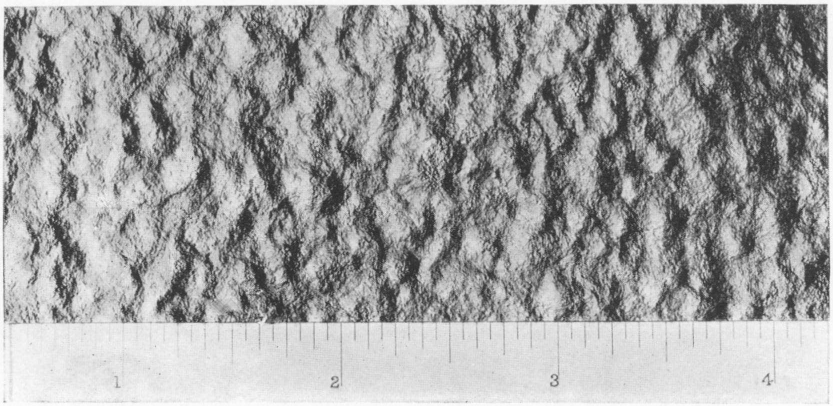
B.

EXPLANATION OF PLATE XIII.

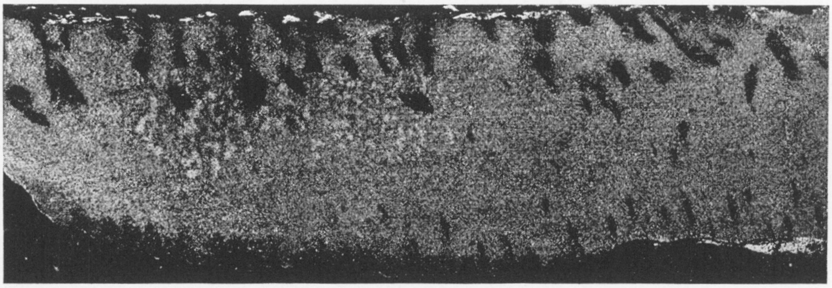
A. Upper surface of layer of ore with depressions marking the openings of worm burrows into the oolitic hematite-chamosite of the Dominion bed, locality 206 A19x, slightly enlarged. (Pages 22, 69.)

B. Vertical section of block shown in A. (Pages 22, 69.)

PLATE XIII.



A.



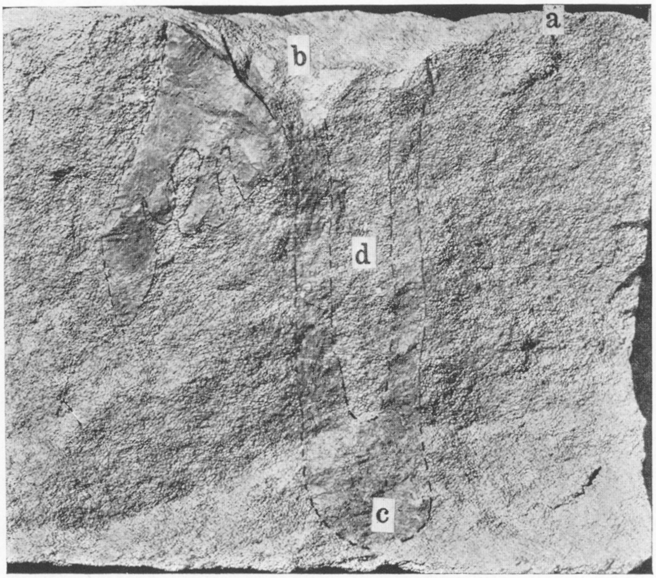
B.

EXPLANATION OF PLATE XIV.

A. Double worm burrow in oolitic hematite-chamosite of the Scotia bed, locality 206 A25 E7h. a—erosion surface of ore; b—mouth of burrow; c—bend at bottom of burrow; d—area of oolitic hematite between the two arms of the burrow. (Pages 19, 22, 69.)

B. Phosphate-chamosite pebbles and shell fragments in oolitic hematite-chamosite ore of the Dominion bed, natural size, locality 215 CC10. a—pebble; b—shell fragment. (Page 25.)

PLATE XIV.



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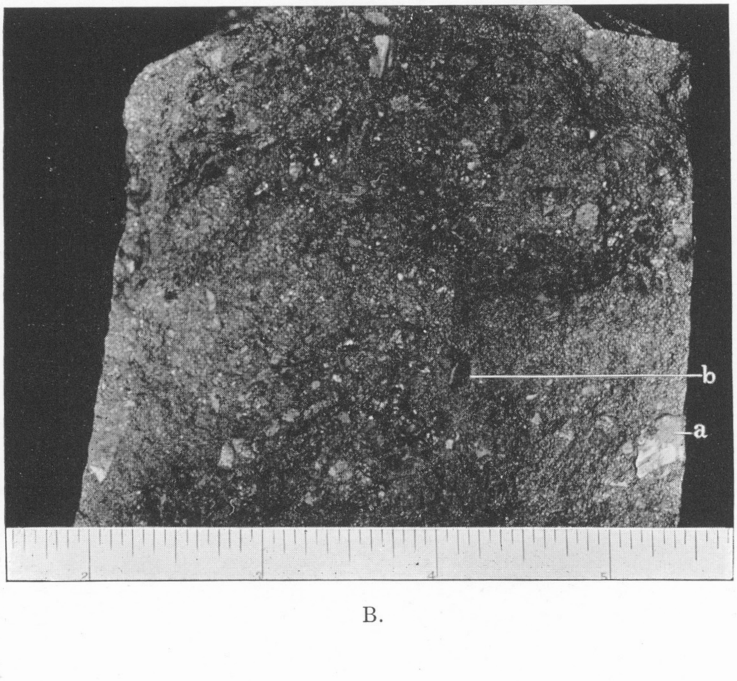


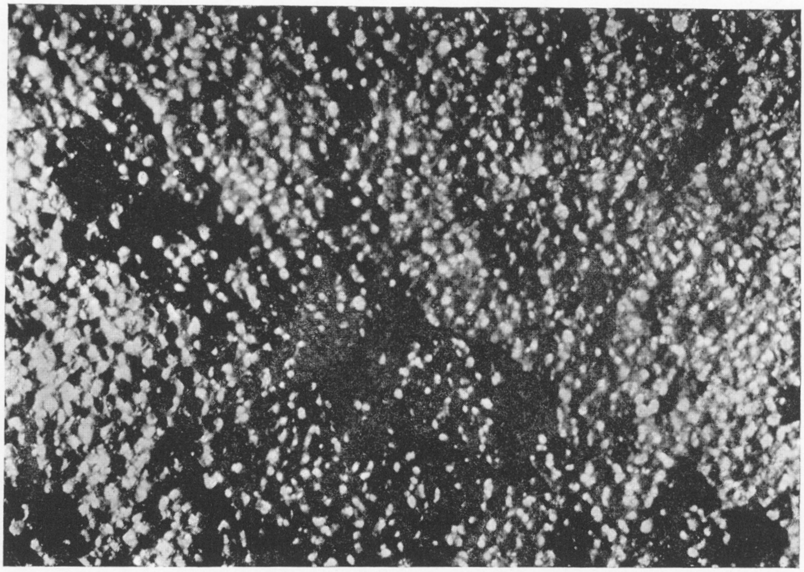
B.

EXPLANATION OF PLATE XV.

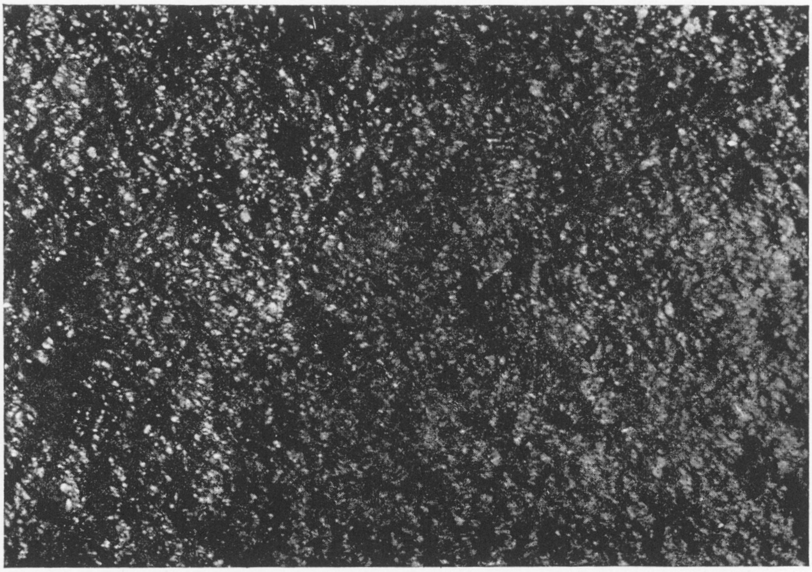
A. Scotia ore; oolitic hematite-chamosite, showing well formed spherules of larger size than those of Dominion ore, magnified 8 diameters, locality 206 A25 E7h. (Page 25.)

B. Dominion ore; oolitic hematite-chamosite showing flattened spherules of smaller size than those in Scotia ore, magnified 8 diameters, locality 208 H4. (Page 25.)

PLATE XV.



A.



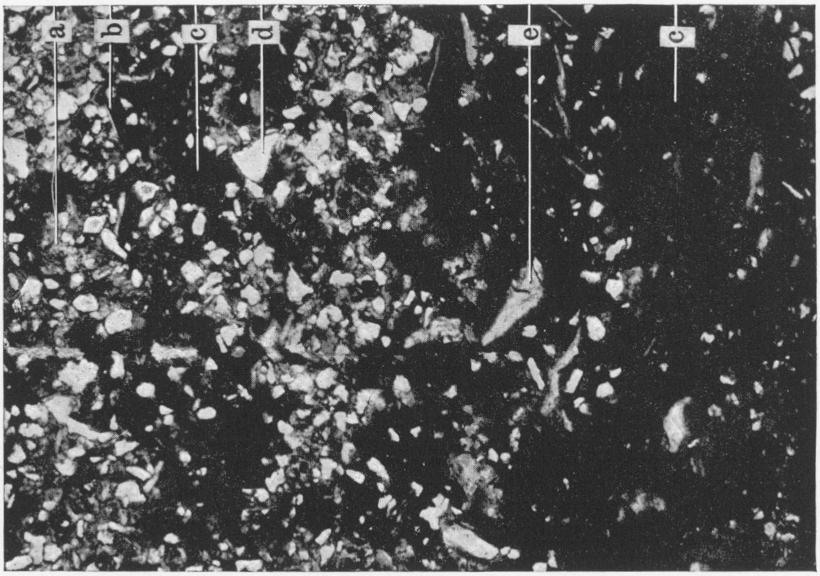
B.

Explanation of Plate XVI.

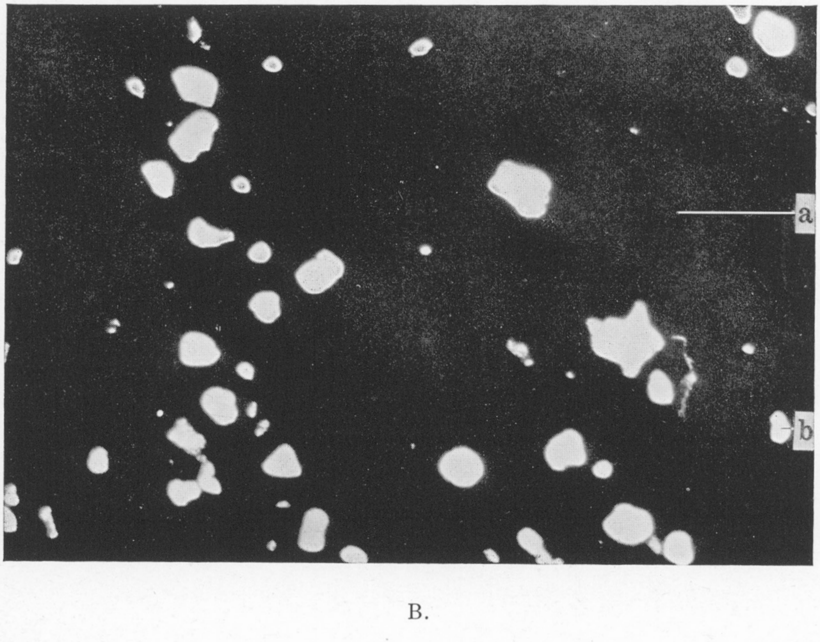
A. Ferruginous siliceous shale underlying the Dominion bed, zone 2, locality 215 C0, slide No. 1, microphotograph enlarged 34 diameters, natural light. a—chamosite matrix; b—crystalline chamosite; c—fine-grained carbonaceous? shale; d—quartz fragment; e—shell fragment. (Pages 15, 30.)

B. Oolitic hematite-chamosite ore from Dominion bed, zone 2; microphotograph enlarged 34 diameters, natural light, locality 208 A7, slide No. 100. a—dense hematite masking the chamosite; b—quartz fragment. The oolitic structure cannot be seen because of the opacity of the hematite matrix. (Pages 30, 70.)

PLATE XVI.



A.



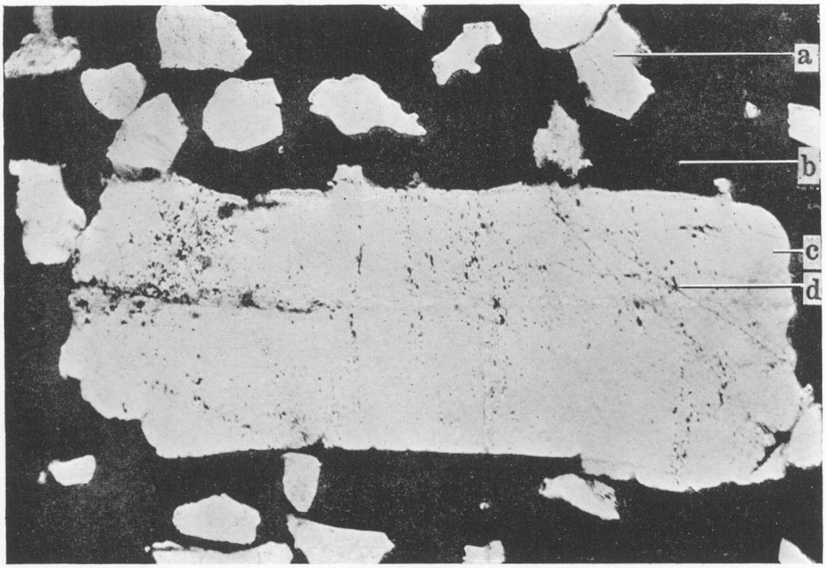
B.

EXPLANATION OF PLATE XVII.

A. Ferruginous sandstone parting rock from Dominion bed, zone 2, locality 215 CC9, slide No. 11, microphotograph enlarged 110 diameters, natural light. a—angular quartz fragment; b—hematite matrix; c—quartz fragment; d—liquid inclusions with gas bubbles arranged in lines approximately at right angles to each other and parallel to the sides of the quartz fragment. (Pages 27, 30.)

B. Ore from the Dominion bed, zone 2, locality 215 C1, slide 2, microphotograph enlarged 110 diameters, natural light. a—hematite matrix; b—chamosite matrix; c—spherule of hematite with border of chamosite; d—fragmental quartz coated with chamosite; e—quartz grain nucleus of spherule; f—shell fragment; g—shell fragment filled with boring algæ; h—large tubule coated exteriorly with micro-crystalline hematite; i—smaller tubule extending through shell fragment into hematite; j—tubules extending beyond wall of shell into chamosite matrix of rock, and coated exteriorly with microcrystalline hematite. (Pages 15, 31, 69.)

PLATE XVII.



A.

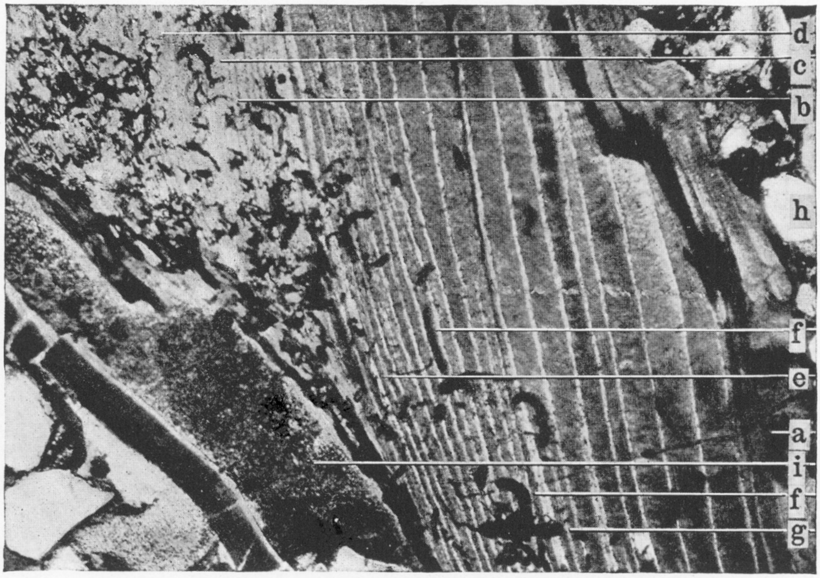
B

EXPLANATION OF PLATE XVIII.

A. Ferruginous sandstone parting rock from upper part of Dominion bed, zone 2, locality 215 CC11, slide 13, microphotograph enlarged 110 diameters, natural light. a—shell fragment; b—tubule of boring alga, uncoated; c—tubule of boring alga coated exteriorly with microcrystalline hematite; d—tubule partly bare and partly coated; e—smaller tubule; f—larger tubule; g—smaller tubule suddenly swelling to larger size; h—quartz fragment; i—chamosite matrix. Several sizes of tubules exist, varying in diameter from one-fifth to 4 microns. (Pages 31, 69.)

B. Chamosite ore from the upper part of the Dominion bed, zone 2, locality 215 C6, slide 8, microphotograph enlarged 34 diameters, natural light. a—spherule of chamosite; b—nodule composed of chamosite spherules with chamosite cement; c—matrix composed of chamosite; d—siderite replacing chamosite; e—quartz fragment. (Pages 15, 31.)

PLATE XVIII.



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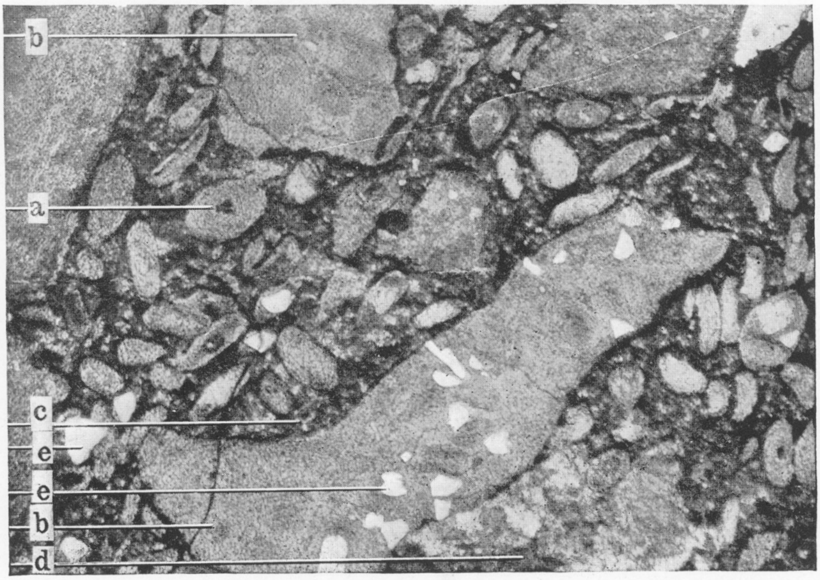


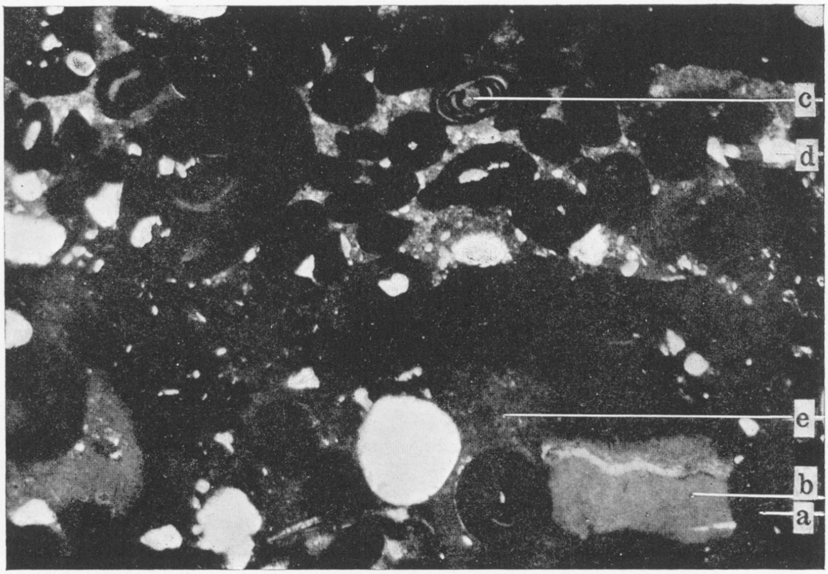
B.

EXPLANATION OF PLATE XIX.

A. Oolitic pyrite from zone 3, locality 208 D2b, slide 44, microphotograph enlarged 34 diameters, natural light. Spherules of pyrite occur with fossil graptolites and brachiopod fragments in a matrix of very fine-grained siliceous argillaceous material. a—spherule of pyrite; b—shell fragment; c—spherule of concentric layers of pyrite and brown material resembling calcium phosphate; d—quartz fragment; e—matrix of very fine-grained siliceous material. (Pages 16, 32, 89.)

B. Oolitic pyrites from locality 208 D6, slide 31, microphotograph enlarged 80 diameters, natural light. Spherules of pyrite with pyritized brachiopod and graptolite remains surrounded by quartz which has crystallized and replaced portions of both spherules and fossils. a—pyrite spherules; b—pyritized shell fragment; c—crystalline quartz matrix, which has partially replaced fossil fragments and pyrite; d—quartz in spherule; e—quartz in pyritized shell fragment. (Pages 16, 32, 89.)

PLATE XIX.



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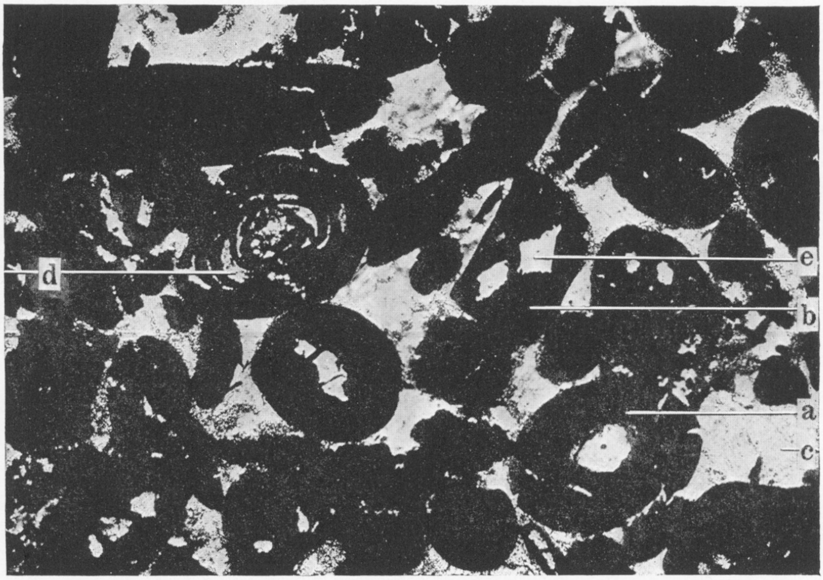


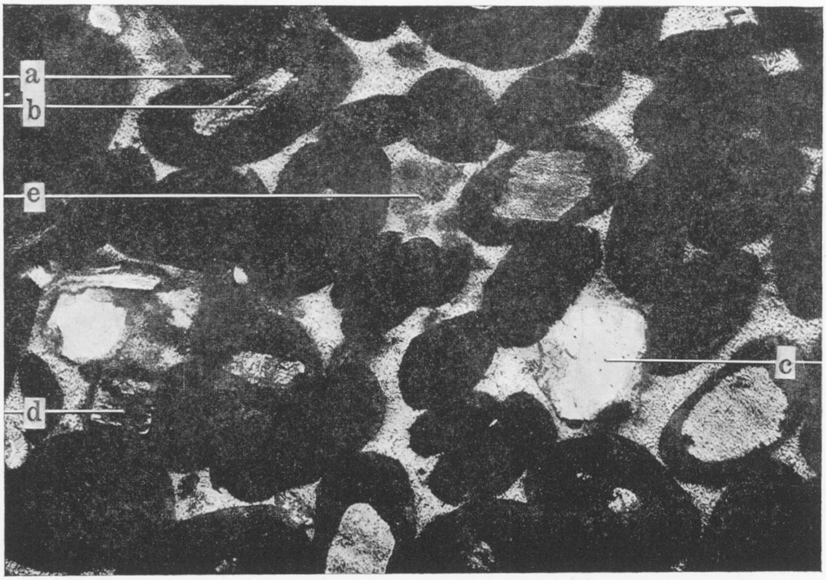
B.

EXPLANATION OF PLATE XX.

A. Oolitic hematite-chamosite from zone 4, underlying the Scotia bed, locality 215 D2, slide 18, microphotograph enlarged 80 diameters, natural light. No siderite is present in this specimen. a—hematite spherule; b—chamosite nucleus; c—quartz fragment; d—shell fragment; e—matrix of microcrystalline chamosite. (Pages 17, 34.)

B. Contact of oolitic hematite-chamosite ore with overlying ferruginous sandstone parting rock, middle of Scotia bed, locality 215 D4, slide 20, microphotograph enlarged 80 diameters, natural light. Siderite is absent. a—hematite spherule; b—chamosite matrix between spherules; c—contact of ore and parting rock; d—quartz grain; e—chamosite in sandstone; f—hematite in sandstone. (Pages 17, 34.)

PLATE XX.



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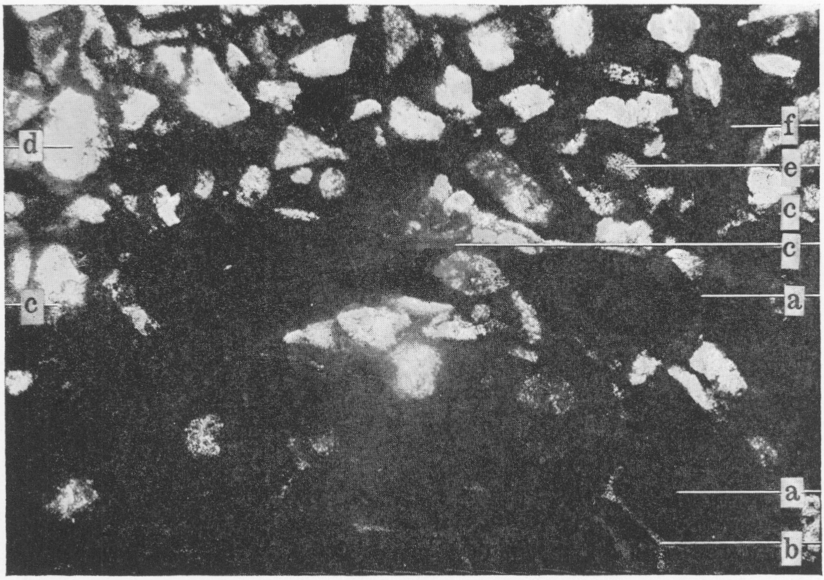


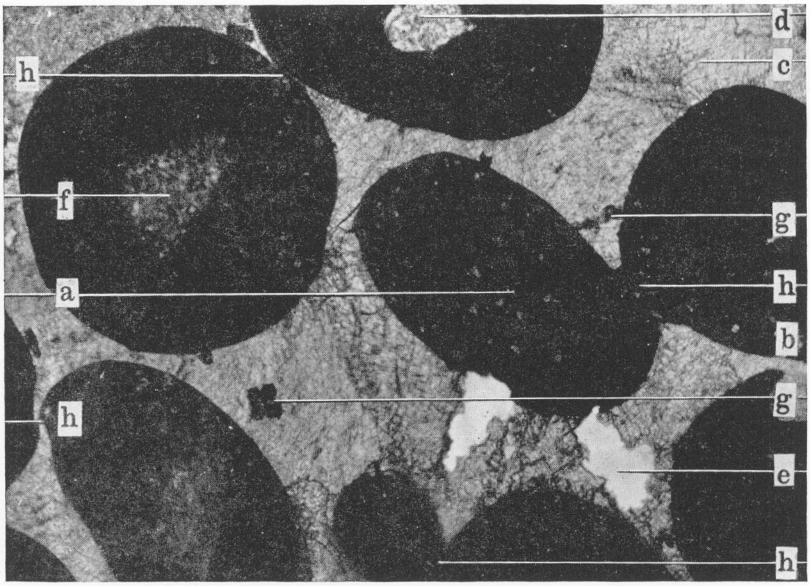
B.

EXPLANATION OF PLATE XXI.

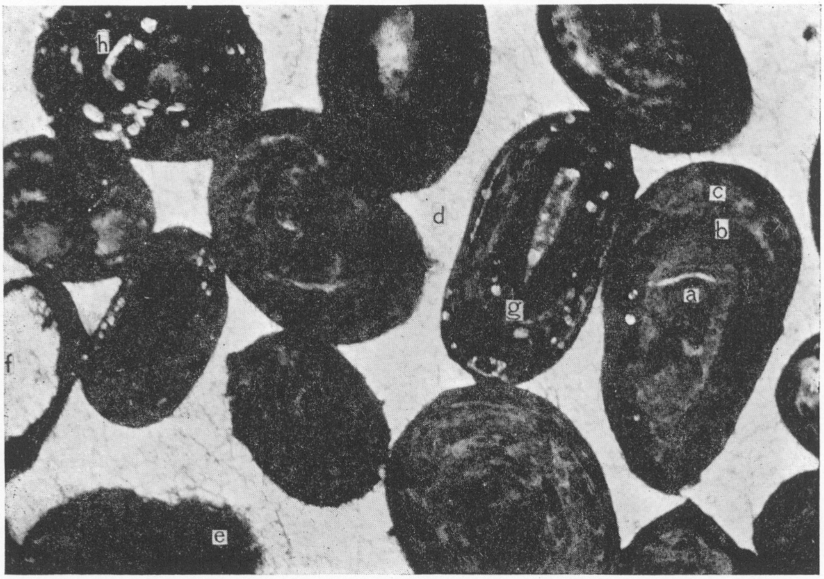
A. Ore from upper part of Scotia bed, locality 215 D5, slide 86, microphotograph enlarged 110 diameters, natural light Hematite spherules containing boring algæ. Ore contains abundant siderite between spherules a—hematite spherule containing cross-section of algal tubules; b—cross-section of tubule; c—siderite matrix; d—siderite at centre of spherule; e—hole in slide; f—chamosite nucleus; g—microcrystalline hematite developed around tubules preserved in the siderite matrix; h—hematite developed about tubules between spherules, joining the spherules together. (Pages 17, 34, 75.)

B. Ore from the upper part of Scotia bed, locality 215 D5, slide 21, microphotograph enlarged 110 diameters, natural light. Hematite-chamosite spherules containing boring algæ. Contains much siderite which also holds boring algæ. The spherules are partly replaced by siderite. a—spherule of alternating layers of hematite and chamosite; b—hematite; c—chamosite; d—matrix of siderite; e—hematite spherule replaced exteriorly by siderite with destruction of structure; f—interior of spherule replaced by siderite with destruction of structure; g—cross-sections of tubule of boring algæ in chamosite spherule showing surrounding development of hematite; h—longitudinal section of tubules also showing development of hematite. (Pages 17, 35, 69.)

PLATE XXI.



A.



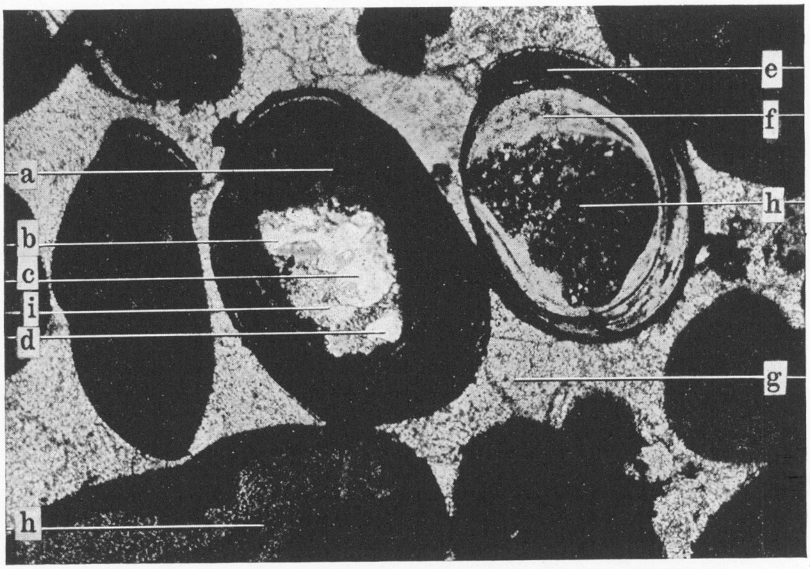
B.

EXPLANATION OF PLATE XXII.

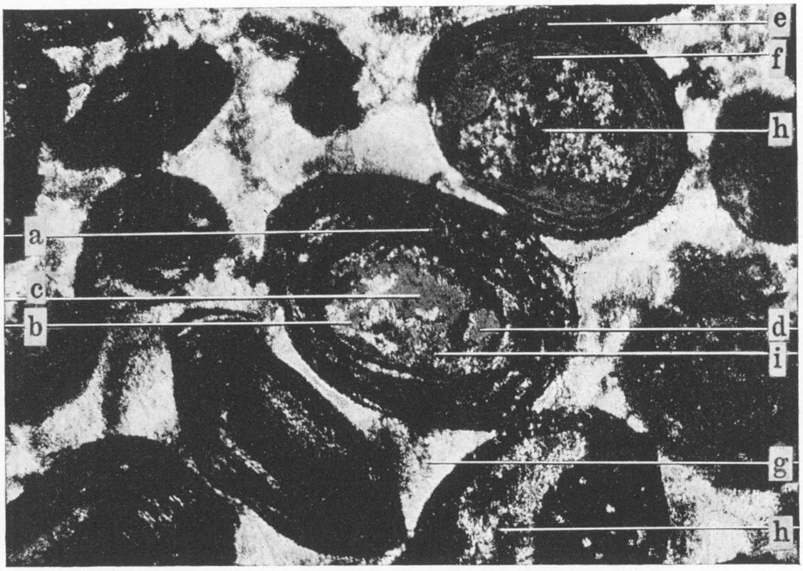
A. Upper part of Scotia ore, locality 215 D5, slide 21, microphotograph enlarged 110 diameters, natural light. Quartz, hematite, and chamosite replaced by siderite. a—spherule of concentric layers of hematite and chamosite; b, c, d—remnants of quartz nucleus replaced by siderite. These irregular quartz grains appear to have originally formed a part of a single crystal, portions of which were replaced by siderite. The siderite divides the individual into several parts and gives it a very irregular outline. These quartz grains contain gas and fluid inclusions similar to those shown in Plate XVIIA, d. e—layer of hematite; f—layer of material resembling calcium phosphate; g—matrix of siderite; h—siderite in interior of spherule where the original concentric banding has been partially destroyed through replacement by siderite; i—siderite replacing detrital quartz grain. (Pages 17, 36, 71.)

B. Upper part of Scotia ore, locality 215 D5, slide 21, microphotograph enlarged 110 diameters, crossed nicols. This is from the same area as A. a—spherule of concentric layers of hematite and chamosite; b,c,d—remnants of quartz nucleus showing simultaneous extinction between crossed-nicols. e, f, g, h, i—same as in A. (Pages 17, 36, 71.)

PLATE XXII.



A.



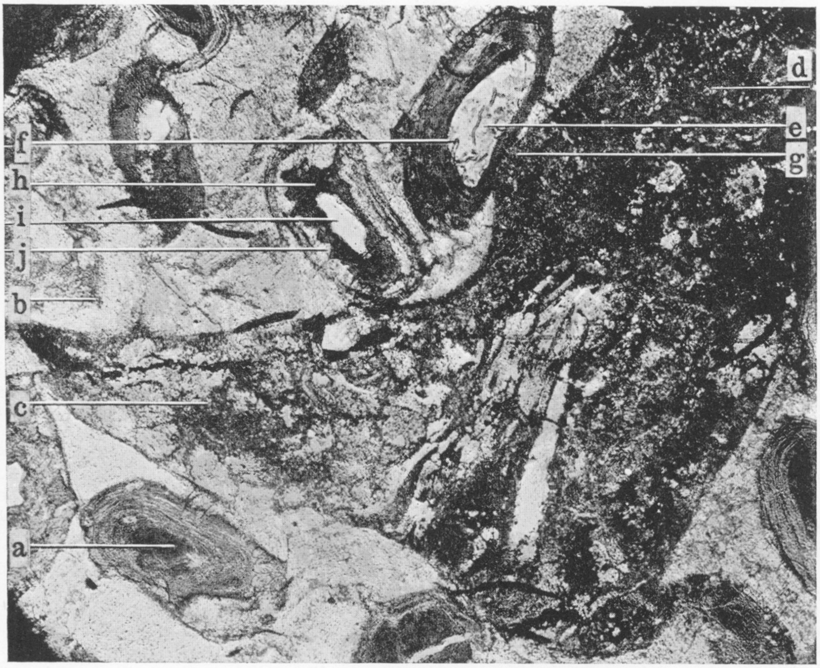
B.

Explanation of Plate XXIII.

A. Oolitic chamosite from near top of Scotia bed, locality 215 D6, slide 23 microphotograph enlarged 80 diameters, natural light. Pseudomorphs of siderite after chamosite spherules and boring algæ in siderite and in phosphate nodules. a—spherule of chamosite; b—matrix of siderite; c—phosphate nodule; d—mat of tubules of boring algæ in nodule; e—phosphatic material, probably a shell fragment forming nucleus of spherule; f—boring algal tubules in nucleus; g—tubule of boring alga extending beyond nodule into chamosite spherule; h—chamosite spherule; i—quartz nucleus; j—pseudomorphs of siderite after chamosite spherule. (Pages 17, 36, 71.)

B. Oolitic chamosite from near top of Scotia bed, locality 215 D6, slide 22 microphotograph enlarged 80 diameters, natural light. Broken and crushed chamosite spherules in matrix of siderite. a—chamosite spherule; b—siderite matrix; c—quartz grain, nucleus of spherule. (Pages 17, 36, 71.)

PLATE XXIII.



A.

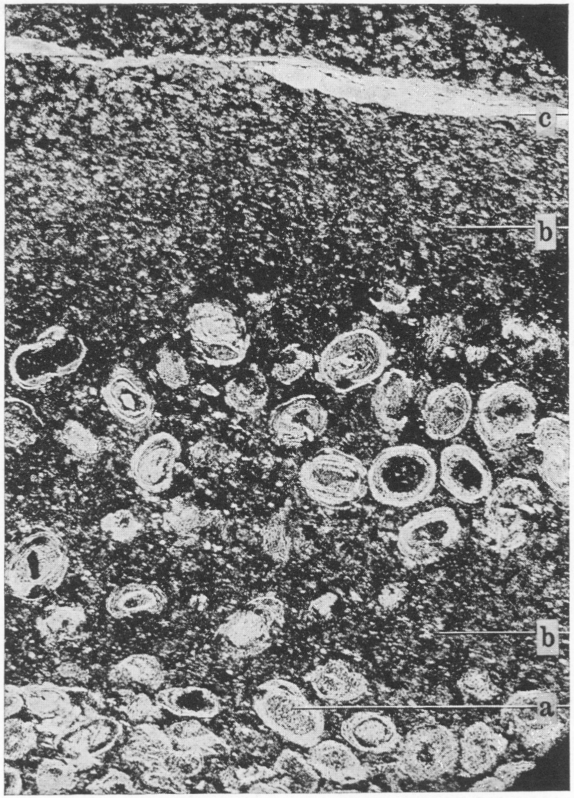
B.

EXPLANATION OF PLATE XXIV.

A. Contact of Scotia ore with overlying shale, locality 215 D7/6, slide 24, microphotograph enlarged 20 diameters, natural light. Scattered chamosite spherules in shale forming top of Scotia bed. a—chamosite spherules; b—shale composed of argillaceous matter, siderite, and chamosite; c—quartz veinlet. (Pages 17, 37.)

B. Fine-grained chamositic sandstone from above Scotia bed, locality 215 D8, slide 25, microphotograph enlarged 80 diameters, natural light. The ferruginous sandstone here figured was used for a chemical determination of the chamosite. a—quartz grain; b—crystal of chamosite; c—microcrystalline chamosite; d—fine-grained material probably composed of carbonaceous and argillaceous matter. (Pages 17, 37).

PLATE XXIV.



A.

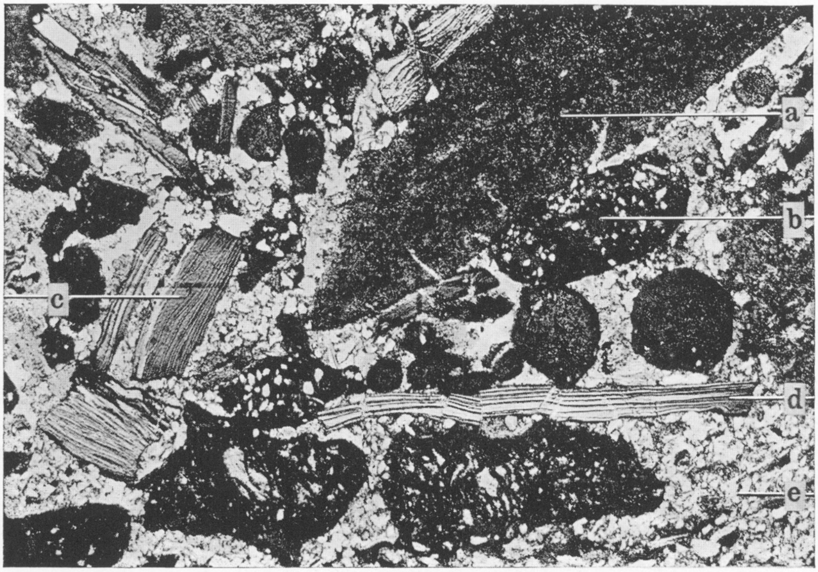
B.

EXPLANATION OF PLATE XXV.

A. Nodular layer from above the Scotia bed, locality 215 D9, slide 26, microphotograph enlarged 20 diameters, natural light. Phosphate nodules and shell fragments in matrix of quartz grains and chamositic and argillaceous material. a—phosphate nodule of very fine-grained material; b—nodule containing quartz grains; c—shell fragment; d—broken shell fragment; e—matrix of quartz grains and chamosite. (Pages 17, 38, 56, 71.)

B. Nodular layer above Scotia bed, locality 215 D9, slide 27, microphotograph enlarged 80 diameters, natural light. Scattered chamosite spherules, phosphate nodules, and shell fragments in matrix of quartz grains, chamosite and argillaceous material. a—brachiopod fragment; b—chamosite spherule; c—argillaceous phosphate nodule; d—quartz fragment in matrix; e—chamosite in matrix. (Pages 17, 38, 56, 71.)

PLATE XXV.



A.

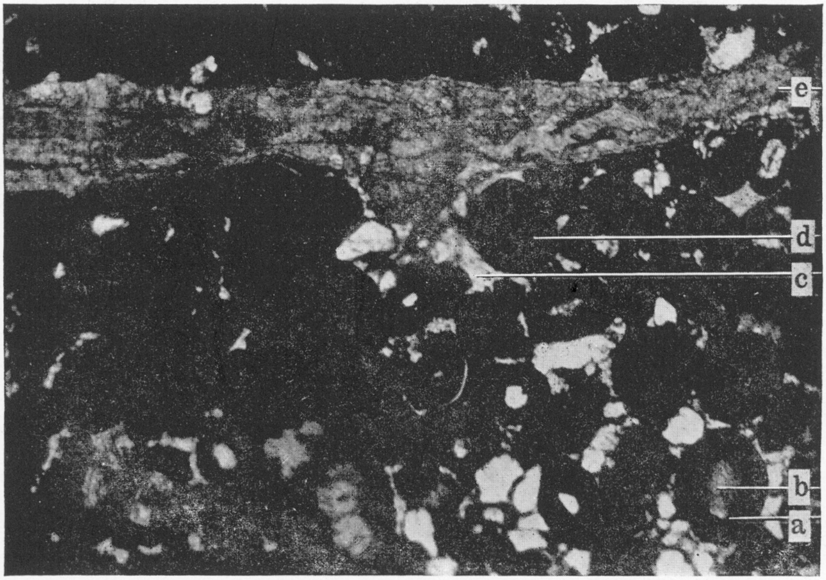
B.

Explanation of Plate XXVI.

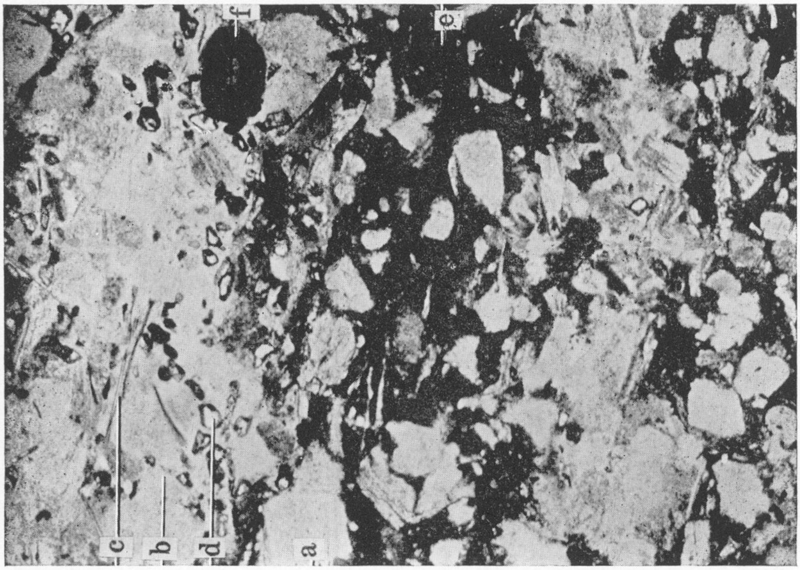
A. Ore from the lower part of the Scotia bed, locality 206 J2b2, slide 54, microphotograph enlarged 34 diameters, natural light. Figure shows oolitic hematite-chamosite ore in a matrix of crystalline quartz. The quartz has corroded the exterior portions of the spherules and contains many individual micro-crystals of hematite. A minute calcite veinlet crosses the ore. a—hematite spherule; b—chamosite nucleus; c—crystalline quartz between spherules; d—hematite spherule with ragged edge, showing replacement by quartz; e—veinlet of calcite. (Pages 18, 38, 71.)

B. Rock composed of shell fragments from beneath the Scotia bed, locality 206 J2a, slide 51, microphotograph enlarged 34 diameters, natural light. Shell fragments closely packed together, are highly altered and cemented by chamosite. Argillaceous material, quartz grains, and crystalline chamosite, also occur. a—shell fragment; b—shell fragments cemented by chamosite; c—individual crystal of chamosite with long axis parallel to bedding of rock; d—quartz grain; e—argillaceous material arranged in bands parallel to bedding of rock; f—chamosite-hematite spherule. (Pages 18, 39, 56.)

PLATE XXVI.



A



B

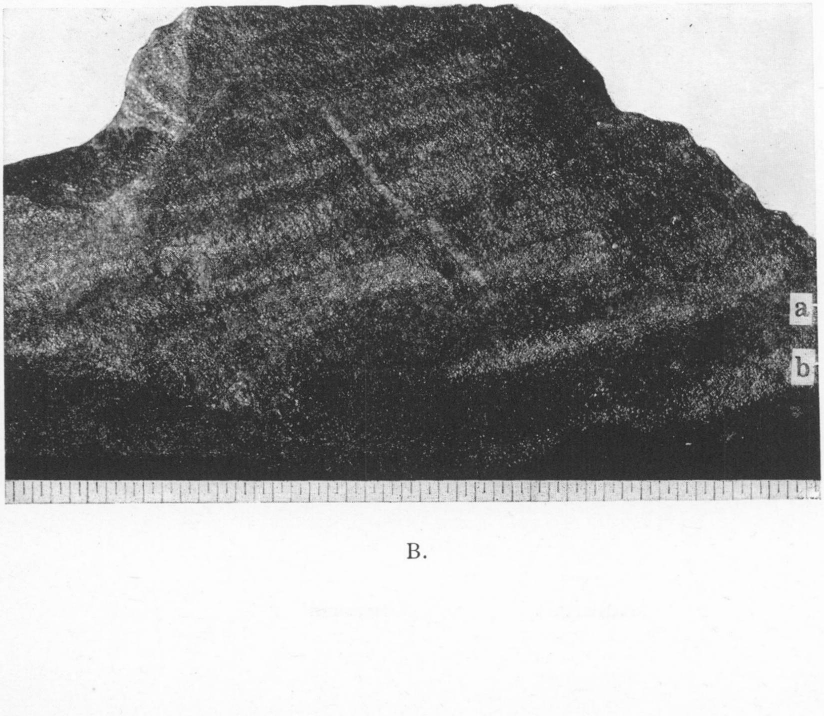
EXPLANATION OF PLATE XXVII.

A. Oolitic chamosite-hematite with siderite, locality 206 AH15, slide 93, microphotograph enlarged 110 diameters, natural light. Spherules composed principally of concentric layers of chamosite with a little hematite, partially destroyed and replaced by siderite. a—spherule of hematite-chamosite in concentric layers; b—outer border of siderite, cutting across spherule; c—spherule of hematite-chamosite partially destroyed by siderite; d—siderite which has replaced the chamosite both in spherule and matrix. (Pages 20, 41, 80.)

B. Cross-bedded and laminated ore from Scotia bed, east stripping locality 206 A25x, reduced to about three-quarters natural size. Consists of cross-bedded alternating laminæ of earthy hematite (a) and oolitic hematite (b). (Page 69.)

PLATE XXVII.

A.



B.

EXPLANATION OF PLATE XXVIII.

Fossil raindrop impressions on sandstone surface at locality 206 A17, about 75 feet below the lowest oolitic hematite of zone 2. A surface area of about 12 square feet is shown in the photograph. Each joint of the folding rule is 6 inches long. (Page 73.)

Plate XXVIII.

INDEX.

A.

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