ON THE GEOLOGICAL HISTORY OF IRON-ORES.

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*(Read March 1st, 1889.)**Introductory.*

There is no intention on the present occasion of going very deeply into scientific questions, nor will it be possible within the limited time at our disposal to treat the matter at all thoroughly. A glance here and there at some of the most noteworthy developments of iron-ore is all that can be expected. In doing this we must avail ourselves of the assistance of the chemist in a few elementary matters, and we must also consult the statistics of the various mining records to enable us to arrive at some estimate of the nature and the quantity of iron-ore in the several formations. Beyond this, there is no intention whatever of treating the subject from an economic point of view.

PART I.

Definition of an Iron-Ore.

And first of all let us define what is an iron-ore. Without going into minute particulars we may say that an iron-ore is a mixture of iron oxide or of iron salt, or of both, with certain earthy or carbonaceous impurities. Hence an iron-ore will present every gradation from a highly crystalline body to an extremely earthy one, and its percentage of metallic iron may range from about 72 per cent. to any figure which the smelter deems worthy of his consideration—say about 30 per cent. Excluding the sulphur compounds, there are only four iron minerals of first class importance. These four are *Magnetite*, *Hematite*,* *Limonite*, and *Chalybite*.

The Four Iron Minerals

Magnetite (cubic) has an iron percentage of 72.4; oxygen 27.6. It consists of one molecule of protoxide of iron and one molecule of peroxide, and has the formula Fe_3O_4 . Portions of this ore possess polarity and are natural magnets or “load-stones.” G. 5.

Hematite (rhombohedral) has an iron percentage of 70;

* Or *Hæmatite*, not *Hēmatite*.

IRON MINERALS AND ORES.

Rutley del. F.H. Michael lith.

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oxygen 30. This is the peroxide, or sesquioxide of iron, the formula being Fe_2O_3 . Varieties are Specular Iron, Red Hematite, Red Ochreous Hematite, Argillaceous Hematite, etc. G. 4.5-5.

Limonite has an iron percentage of 60; oxygen 25.6; water 14.4. It consists of two molecules of peroxide of iron and three of water, and has the formula $2(\text{Fe}_2\text{O}_3) \cdot 3(\text{H}_2\text{O})$. Varieties are Compact ore (Brown Hematite), Ochreous yellow ore, Brown clay-ironstone, Pisolitic and some Oolitic ores. Bog ore, Laterite, Limnite, etc., are closely associated. G. 3.6.

Chalybite (rhombohedral) has an iron percentage of 48.2; oxygen 13.8; carbonic acid 38. It consists of one molecule of protoxide of iron and one of carbonic acid, and has the formula FeOCO_2 (FeCO_3). Varieties are Spathic ore, Clay-ironstone, and some Oolitic ores. G. 3.8.

Iron in Kosmos.

In one form or other iron is a very abundant element; indeed, I strongly suspect that it is the prevailing element of our solar system. In the native state it exists as disseminated grains in basaltic and other rocks, and has been found in large masses in Greenland, where probably it has been derived from basalt which has been subjected to reducing agencies. Prof. Rupert Jones has recently called my attention to an article in 'Le Naturaliste,' 15th April, 1888, where a figure is given of a mass of scoriaceous rock, about three inches across, containing lumps and filaments of native iron. This mass was collected by Dr. Johnston Lavis from the summit of Vesuvius. If we are to take a hint from extra-telluric bodies the meteorites speak in favour of an abundance of iron in Kosmos, since one class, the sky-irons, consist simply of metallic iron alloyed with some nickel. Another class, the sky-ironstones, consist mainly of iron, whilst the third class, or sky-stones, consist of stony matter in which iron and kindred elements, such as magnesium, play a part not dissimilar to their functions in the more basic lavas of our own planet.

Iron Minerals and Silicates in Rocks.

If the deductions I have drawn from the proportion of iron in meteorites be correct, it follows that there must exist an

immense store of iron in the interior of the earth, whilst the portion which exists in the crust is comparatively small. There it occurs chiefly in combination with silica or as magnetite grains. It is not probable that any portion of the primeval crust of our globe is actually the same as the very oldest rocks known to the geologist, but these oldest rocks have been constructed out of the materials of the primeval crust, and they contain abundance of iron silicates. Moreover, from time to time throughout geological history there has been a tendency to a reaction of the interior upon the exterior, whereby immense quantities of fluidal rocks have been brought in proximity to the surface. These are the plutonic and volcanic rocks, many of which contain large stores of iron silicates together with what I may term primary magnetite and other iron oxides.

Before proceeding with the main argument, viz., the accumulation of iron-ores, it may not be unprofitable to direct your attention to some of these iron silicates, to their mode of occurrence in the crystalline rocks, and to their relation with the disseminated grains of iron oxides, more especially magnetite. The most abundant iron silicates are mica, hornblende, and augite. To these may be added the rarer, but still more ferruginous olivine and hypersthene of the ultra-basic rocks. Whilst the clays of the sedimentary beds are made up largely of fragmental felspar more or less kaolinized, and the sandstones chiefly of fragmental quartz, both clays and sands are enriched with iron by the iron silicates, already partially modified by chemical action. Some interesting experiments are recorded lately in the 'Transactions of the Geological Society of Edinburgh'* on the action of carbonic acid on these minerals. It was found, for instance, that muscovite, which is not a highly ferriferous mica, was not chemically dissolved, whilst biotite lost some of its ferric oxide and magnesia. Hornblende and augite decomposed at the same rate as biotite: they became hydrous, and lost by solution magnesia, lime, and iron. The felspars yielded more slowly.

Transparencies.

I will now proceed to exhibit by way of illustration a few

* Vol. v, Pt. ii.

rock-sections, the point being to demonstrate the occurrence of iron-minerals.*

Iron, Oxygen, and Carbon.

Starting, then, with the iron silicates and iron oxides, especially "primary magnetite" as the source of our iron-ores, if we wish to know how these are accumulated we must, first of all, study the peculiar relations of iron to oxygen, and, secondly, the action of carbon products upon these results. In the end we shall be driven to admit that a large proportion of our iron-ores are due to processes engendered by vegetable decomposition, such processes acting as collectors or accumulators of the ore itself. In the case of the large deposits of magnetite and hematite in the Archæan or very oldest rocks, their accumulation by organic agency may be open to doubt, since even if due to the action of carbonic acid, such carbonic acid may easily have formed part of the Earth's atmosphere in these early times.

It is now necessary to reflect a little upon the peculiar behaviour of iron with regard to oxygen and carbon. The whole process may be described as a battle between iron and carbon for a molecule of oxygen. This is admirably illustrated

* The following were exhibited on this occasion :—

1. *Olivine basalt* (Pl. II, Fig. 3).—Cut from a specimen in the possession of Mr. Geo. Smith, from the drift of Finchley. The structure here is partly ophitic, with a fair amount of lath-shaped feldspars and but little augite; primary or idiomorphic magnetite very conspicuous. The olivine, though fresh, is cracked, and these cracks have strings of fine magnetite dust of secondary origin, either derived from the mineral itself or the result of infiltration.

2. *Hornblende-andesite* (Pl. II, Fig. 1).—From a slide in the possession of Dr. Hatch. The chief feature of interest here is the partial replacement of the edges of the hornblende crystals by secondary magnetite.

N.B.—It is said that in the formation of actinolite from hornblende, the change is accompanied by a copious separation of granular magnetite.

3. *Serpentine*, Cadgwith (Pl. II, Fig. 2).—Cut from the well-known black serpentine. See analysis by myself in appendix to Prof. Bonney's paper, "On the Serpentine, etc., of the Lizard District," 'Q. J. G. S.,' Vol. xxxiii, p. 925. Here the process of conversion from olivine to serpentine is accompanied by the separation of magnetite dust beginning in the centre of the fissures.

4. *Hematite in Serpentine*.—Also from the Lizard district, another case of serpentinized olivine where nearly the whole of the iron appears as indefinite blotches of hematite. The veins contain both magnetite and hematite.

5. *Nepheline Rock*.—Nepheline associated with feriferous augite. There is a fine skeletal crystal of primary magnetite, and numerous radiations of magnetite disposed in accordance with some peculiarity of the nepheline.

6. *Paulite*, Banff (Polarized).—Labradorite and hypersthene with some ilmenite.

by what occurs during the formation of bog-ore. Iron as bicarbonate disseminated in the waters of a pond, on reaching the surface, seizes on an additional molecule of oxygen, in the proportion of two of iron to three of oxygen. This causes it to lose its carbonic acid, but being desirous of having a companion, the sesquioxide of iron thus formed immediately combines with water, forms a hydrate, and sinks to the bottom. Portions of such accumulations are from time to time redissolved owing to the abstraction of the extra molecule of oxygen by the carbon of decomposing vegetation. This extra molecule of oxygen helps to form the carbonic acid or other humus compound which dissolves the iron now reduced to protoxide. In this way the game of solution and precipitation is kept up indefinitely, and where the balance is in favour of precipitation an accumulation of ore will occur.

The main lesson to be deduced from these considerations is that the agencies of reduction by rendering the iron soluble endow it with locomotion, whilst the agencies of oxidation are amongst these which tend to arrest that locomotion and to fix it in one spot. Doubtless there are other causes besides oxidation, as, for instance, the loss of the second molecule of carbonic acid in the bicarbonate without further oxidation. In this case the iron will be deposited as carbonate and not as hydrated peroxide.

These points are well stated by Pumpelly, who observes that iron is a base with a strong affinity for the acids most frequently circulating in the upper crust of the earth, and especially for the humus acids and their ultimate term, carbonic acid. It also has a strange affinity for oxygen, and in the presence of this it forms the nearly indestructible, and in the absence of organic matter almost insoluble, sesquioxide. As sesquioxide, in the presence of organic matter, it provides the oxygen for decay, and its residuary protoxide is itself dissolved by the resulting organic acid and enters into circulation.

Colour of the Rocks.

It is not too much to say that the principal colouring matter in nearly all rocks is due to disseminated iron oxide, and it sometimes happens that the most highly coloured rocks are most deficient in workable iron-stone. We have a good instance of this in the variegated strata of the New Red Sandstone, a subject very exhaustively treated by Mr. Maw, of Broseley,

some years ago in the 'Quarterly Journal of the Geological Society.' He found that the colouring is effected by films both of the anhydrous and hydrated sesquioxides investing the individual grains of sand. In many of these cases of intense colouring it is the degree of dissemination rather than the amount of iron which produces such a striking effect. The intermediate colours are due to the blending of the anhydrous and hydrated peroxide. It is probably owing to the deficiency of organic matter in these red rocks that they remain red rocks still. They have been coloured in the first instance by solutions of ferrous carbonates and sulphates depositing the insoluble peroxide, and, for lack of reducing agents in sufficient amount, the iron of these beds has not been rendered soluble, and therefore remains disseminated instead of being concentrated. In clays and shales the iron is mostly ferrous, and the colour of these rocks is a greyish blue. The iron in this case is partly protected from removal by the comparative impermeability of clay. Most blue clays will contain iron in various forms to the extent of about four per cent. of the metal. A grey clay of the Coal Measures was found to contain FeO 3·88, FeS_2 1·716. Some of the Skiddaw Slates contain up to eight per cent. of ferrous oxide.

Mode of Deposition.

We must now proceed to consider the evidence afforded by the iron ores themselves as to the causes which have determined their deposition. And let it be remembered that there is one important difference between iron ores and the ores of the heavy metals generally, viz., that the former occur for the most part in beds which form part of a series, in the same way as do limestones, clays, and sandstones. It is true that there is also abundance of iron ore in mineral veins and "flats," but still the bulk of the iron ores must be regarded as bedded accumulations.

Statistics.

Since the more recent deposits are on the whole less obscure in their nature than the more ancient ones, it will be convenient to commence our study with the newest rocks and to proceed downwards in the geological scale. Before doing so I would direct your attention to a summary of the output of iron ores

in the early part of the present decade, as shown in the following table:—

THE WORLD'S PRODUCTION OF IRON-ORES IN 1882.

	Tons.
Great Britain	18,622,000
United States	10,080,000
Germany	8,981,000
Spain	5,510,000
France	3,857,000
1881 Austria-Hungary	1,157,000
1880 Russia	1,128,000
1881 Sweden	910,000
Other countries, about	1,500,000

We cannot help noting that our ferruginous little island accounted for more than one-third of all the iron-ore mined at that date, viz., six years ago. However, we have nothing to do with the economics of the question; what we are concerned with is the geological information which such a table helps to convey. In order further to test the case I submit a table of the iron-ores mined in Great Britain in the previous year, arranged according to their respective geological formations:—

IRON ORES RAISED IN GREAT BRITAIN IN 1881.

	Tons.	Tons.
A. Tertiary iron-ores (Ireland)		200,000
B. Iron-ores of Jurassic age—		
Cleveland	6,538,000	
Northants	1,270,000	
Lincolnshire	1,020,000	
Other districts	148,000	8,976,000
C. Iron-ores of Permian age—		
Lancashire	1,190,000	
Cumberland	1,615,000	2,805,000
D. Coal-Measure iron ores—		
England	2,540,000	
Wales	278,000	
Scotland	2,600,000	5,418,000
E. Iron-ores older than Coal Measures		238,000
Total in tons of ore		17,537,000

It is not possible to state exactly the nature of the ore in each case. Under E. most of the ores are crystalline. Some of the Cornish lodes yield fine crystals of hematite and göthite. Some of the fissures of the Carboniferous Limestone yield very pure spathic ores. The total, however, is very small, and the bulk of the ores mere vein-products. D. The iron-ores of the

Coal Measures are principally Clay-ironstone and Black-band ironstone, which must be classed as Carbonates, and also some brown ore, which must be classed as Limonite. C. The Permian ores of Cumberland and Lancashire consist almost entirely of Hematite. B. The Jurassic iron-ores are mainly Carbonates and Limonites.

Let us now turn to the United States by way of comparison, and here I am able to submit a very elaborate table by Mr. Pumpelly, which shows at a glance, by means of columns, the iron-ores mined during one year (1880) according to geological horizons and kinds of ore. Taking the Coal-Measures as our dividing line, we at once perceive that an enormous proportion of the iron-ore is found below these strata, whilst an extremely small amount is obtained from the beds above. In fact the conditions are exactly the reverse of what obtain in this country. At the same time it should be pointed out that, owing to the superior richness of the magnetites and hematites of the older rocks, the total yield of metallic iron for the two countries is by no means in proportion to the amount of ore raised.*

IRON-ORES RAISED IN THE UNITED STATES IN 1880.
AFTER PUMPELLY.

	Limonite.	Carbonate.	Hematite.	Magnetite.	Total (tons).
Tertiary ...	29,000	—	—	—	29,000
Mesozoic ...	—	74,000	—	—	74,000
Carboniferous...	30,000	824,000	—	—	854,000
Devonian...	39,000	—	—	—	39,000
U. Silurian	95,000	—	615,000	—	710,000
L. Silurian	1,626,000	—	323,000	403,000	2,352,000
Huronian...	332,600	—	1,574,000	161,000	2,067,600
Laurentian	—	—	24,000	1,800,000	1,824,000
	2,151,600	898,000	2,536,000	2,364,000	7,949,600

* The three years 1880-2 saw the maximum average of about 18,000,000 tons raised in the United Kingdom. Last year (1888) the iron-ore raised in

PART II.

We will now proceed more directly to the consideration of the "Geological History of Iron-Ores," commencing with the newest formations.

Recent Iron-Ores.

Everyone knows how quickly an iron pan forms towards the base of gravels and other porous beds under certain conditions of peaty soil and forest litter. It is hardly necessary to explain this further than to remark that the humus acids have been busily at work reducing and dissolving existing iron combinations. Such solutions are transported by underground percolation until arrested by an impervious bed or from some other cause, when they deposit an impure limonite which sometimes converts the base of a gravel into an iron conglomerate. This often happens in our Pleistocene gravels, and is well illustrated in the Bagshot district.

A very interesting instance of a recent deposit of iron-ore in large quantities is mentioned by Mr. Postlethwaite,* who says that when the Woodend Mine, near Threlkeld, was reopened, after having been closed for 13 years, it was found that where the mineralized water enters the level large masses of limonite had been deposited on the sides, and were hanging from the roof in the form of stalactites, filling up more than half the width of the level. In this case the source of the iron is attributed to the oxidation of pyrites.

Macadam† gives an interesting account of the deposits of meadow ore (limonite) now going on in Ross-shire. The Erradale deposit occupies a flat strath formed by the "red burn." Slabs several inches thick are thus being formed, and are used by the inhabitants for boundary walls. This is a really rich ore, some portions containing 50 per cent. of metallic iron. It is such meadow ores which probably afforded iron to the earliest metallurgists. Hence Linnæus, who was fond of a joke, named this species *Tophus*‡ *Tubalcaini*, in honour of the first the United Kingdom had fallen to 14,166,000 tons, but the imports from foreign countries, chiefly Spain, amounted to 3,552,000 tons. (*Josiah T. Smith*: Address to the British Iron Trade Association, 1859.) At present I have no particulars as to the latest yield in the United States, but it is well known that the deposits there are enormous.

* 'Trans. Cumberland and Westmoreland Assoc.,' No. 11, "Mineral Springs near Keswick."

† 'Mineralogical Magazine,' Vol. vii, p. 72.

‡ A grain.

smith whom history has recorded, and also in allusion to the frequently granular character of the ore.

Lake Ores.

By far the most interesting of recent iron-ores are the deposits taking place in lakes, of which those in Sweden afford a notable example. In that country the rocks are generally well charged with iron silicates and other iron minerals, which undergo slight reduction and solution from the decay of forest litter, etc. In fact it is the old story on a large scale. The streams carry proto-salts of iron into the lakes, where the shuttlecock game between decomposing carbonaceous matter at the bottom and oxygen at the top results in the gradual accumulation of a large quantity of hydrated sesquioxide of iron (limonite) mixed with humus compounds, and too often with phosphates to a prejudicial extent. These ores may, in fact, be said to grow, and the proprietor can reap a crop, perhaps half a foot thick, every quarter of a century.

There is one point in connection with these lake ores of especial interest to naturalists, viz., to what extent diatoms are instrumental in the formative process. A general impression exists that they are in some way agents in this work. It was Ehrenberg who alleged that certain fresh-water infusoria or diatoms had the power of separating iron from water, and depositing it as hydrated peroxide in their siliceous coverings. *Gaillonella* (*Didymohelix*) *ferruginea* is believed to be more particularly active in this work. I have not been able to obtain an authentic account of this somewhat mythical diatom, but submit an enlargement of a drawing extracted from the Berlin Zeitschrift (1866) professing to represent this species. (Fig. 1.)

FIG. 1. *Gaillonella ferruginea*, Ehrenberg. *b* is magnified 2,000 times.

There are, no doubt, plenty of microscopic organisms, including diatoms, which are associated with lake ores, simply from

the fact of their remains being mixed with materials which go to form such ores. Also, it is by no means improbable that iron oxide, in some cases, replaces the opaline silica of the diatoms. But the question is—Do these diatoms really co-operate in the formation of lake ore in the sense of secreting from the water large quantities of iron? Or is it not rather that in their decay they contribute like any other group of organisms to the formation of compounds which are favourable to these accumulations. Samples of some of these ores abound with confervoid fragments, some of them coloured with oxide of copper or phosphate of iron, and many diatoms, such as *Spongolithis*, *Pinnularia*, *Navicula*, *Eunotia* occur. Nevertheless, it seems highly probable that lake ore could be formed without the assistance of a single diatom, and that the story of *Gaillonella ferruginea* secreting iron is more or less of a myth.

Referring for a moment to a much older formation, we might quote as a parallel case the encrinite iron-ore of the Lower Limestone Shales in South Wales. There is a statement in a well-known publication ('Iron-Ores of Great Britain') that "these [encrinites] seem to have the power of secreting iron to a great extent with the lime necessary for their support." On the other hand, Mr. Wethered ('Q. J. G. S.,' 1888, p. 190) remarks that the calcareous skeletons of corals and polyzoa in the Lower Limestone Shales are generally well preserved, but with the remains of encrinites the whole skeleton appears to be replaced by oxide of iron. However difficult it may be to account for this peculiarity, the replacement theory is to be preferred to the secretion theory, and this, I think, must be the explanation with reference to ferruginous diatoms in lake ore, if any such exist. It is only fair, however, to admit that certain heath plants do contain a considerable quantity of iron in their ash, and such plants also appear to favour the deposit of iron oxide. Hence it may be said if heath plants do this, why not diatoms likewise? *

* Since the reading of the paper my attention has been called to a pamphlet by C. W. Sjögrén 'On the Swedish Lake Ores' (Ekesjö, 1862, printed by A. Nilsson). He gives the following account of appearances at the bottom of a partially-drained lake:—

"And here a strange and wonderful spectacle was exhibited. On the bottom of these hollows, some of which were from 6 inches to 3 feet in diameter, ores of different shapes were lying motionless, on the top of which might be seen little beings of different sizes, some visible to the

Cascade Range.

It is mentioned by an American writer* that the basaltic rocks of the Cascade range, exposed to the immense rainfall and luxuriant vegetation of the Northern Pacific coast, have contributed to the formation of very extensive deposits of bog ore.

Tertiary Iron-Ores.

The same author says that similar deposits were forming also during the Tertiary period, as is shown by the Prosser Mine, near Portland, in Oregon. Here a body of limonite, from six to eight feet thick, still showing in places more or less the texture of bog ore, and containing roots and trunks of trees of a former forest growth, lies upon a bed of basalt, and is covered by many hundred feet of recent basalt. This contains up to 50 per cent. of metallic iron, with much phosphorus. Part of the bed is altered to a compact mineral like brown pitchstone, containing 30 per cent. of metallic iron.

Antrim.

The most noted Tertiary ores in the British Isles are those of Antrim, which, like the ores just mentioned, are also associated with basalt.

These deposits were described in the 'Q. J. G. S.' for 1869, when considerable difference of opinion was expressed as to their true origin. Their general position and nature may be inferred from Messrs. Tate and Holden's section on Island Magee. (Fig. 2. See next page). The ferruginous series is as much as 60 feet thick in some places, and is sandwiched between two masses of basalt, each about 300 feet thick.

No. 1 represents the hard columnar basalt of the upper series; at the base are a few inches of a steatitic (?) kind of rock.

No. 2. The upper portion of this is a pisolitic ore, some of

naked eye, and some so small as to be invisible without a magnifying glass, all actively engaged at their work, viz., to *spin* around themselves, like the caterpillar, their *metallic shell*." This apparent spinning he then proceeds to describe, and on the ground of these observations Herr Sjögrén was of opinion that the lake-ore is generated by these infusoria.

He professes to draw a distinction between the origin of "Lake-ore" and of "Bog-ore."

* Pumpelly, 10th Census Report.

the black pisolites having the appearance of graphite. These are more or less magnetic, many of them consisting chiefly of magnetite. This ore is rich in iron and nearly free from

FIG. 2. Section at Belunford (after Tate and Holden).

1. Columnar basalt with 2 or 3 inches of decomposed rock below.
2. Pisolitic iron ore, 2ft. 6in., chiefly magnetite.
3. Bole—an indurated, red, ferruginous ochre, passing into and alternating with 3ft.
4. Yellow ochre, which graduates into
5. Blue lithomarge, base not seen.

phosphorus, but is often contaminated with titanitic oxide; the lower part is an aluminous ore of considerable value, not so rich in iron, but equally free from phosphorus. Small partings and seams of a siliceous lignite are sometimes found in the aluminous as well as in the pisolitic variety.

Nos. 3 and 4 are red and yellow ochres.

No. 5. Lithomarge, a variegated argillaceous rock, with a predominating blue colour. This graduates downwards into a basalt exhibiting a concretionary structure, the outer coats not distinguishable from the lithomarge, whilst the kernel is a compact basalt. The lithomarge usually rests upon an irregular flooring of basalt, which in places is eroded into deep holes.

The source of the iron oxides in the ore bed is no doubt primarily the iron in the decomposing basalt, the ochres representing a sort of intermediate stage. The alumina is due to the same source. It only remains to suggest the agency of concentration. It is not unreasonable to suppose that these ores are of lacustrine origin, probably on somewhat different horizons. In other parts of the county an aluminous limonite in association with plants and lignite clearly point to the action

of decomposing vegetation—similar to what we have already seen. The present anhydrous condition of the pisolitic ore, and possibly, also, its freedom from phosphoric acid, is most probably due to the action of hot overlying basalt, which brought the original limonite into its present condition.

It is worth noting that when Tate and Holden's paper was read before the Geological Society there must have been a general belief in the ferruginating power of diatoms. Tate himself only once found diatoms of the *Coscinodiscus* type, and "not of the genera which form the bog ore." Hence it is evident he did believe in diatoms forming bog ore. In the discussion which followed the late David Forbes spoke of the pisolitic ore of the Swedish lakes as "still in course of formation by means of confervoid algæ," and Mr. Etheridge inquired if there were any traces of *Gaillonella*.

Iron-Ores of Cretaceous Age.

The Chalk of the British Isles does not, as far as I am aware, contain any noteworthy accumulation of iron-ore; but to the age of our Upper Chalk belongs the famous deposit of Somorostro, near Bilbao, where red hematites, associated with some calcite, and practically free from phosphoric acid, occur between sandstones and limestones. The special features of this deposit are unknown to me.

The Lower Cretaceous series of our own country affords a few unimportant localities not much worked at present. The Tealby iron-ore occurs in Judd's Middle Neocomian, as does that at Claxby. The latter ore is described as a brownish-yellow hydrated peroxide, very oolitic, the grains being mostly of a shiny black, and hollow.* On this horizon we notice a feature very characteristic of the iron-stone series of our Secondary rocks, viz., the abundance of large Monomyaria, and especially of Pectens. At Tealby *Pecten cinctus* abounds. It is the same with the iron-ores of Jurassic age. In the Supracoralline deposit of Westbury are large specimens of *Pecten di-striatus*. The iron-stones of Dogger age, especially at Northampton, contain abundance of large Limas, whilst the Cleveland ore and its equivalents contain *Pecten equivalvis*, which is perhaps the biggest of them all.

* Kendall, 'Iron-Ores of the English Secondary Rocks.'

Iron-Ores of Jurassic Age.

The deposits at Westbury and Abbotsbury between the Corallian and the Kimeridge Clay are of considerable interest, but not important in comparison with other ore beds of this system. Practically there are three horizons in the Jurassic rocks, which have recently yielded large quantities of iron-ore, the highest of these being the Yorkshire Dogger and its equivalents. This is mainly within the *opalinus* zone, and for the most part rests on the Upper Lias. The next is the Marlstone, or *spinatus* zone of the Middle Lias, in which occurs the Cleveland main seam. Thirdly, there is an exceptional development of iron-ore in the *semicostatus* zone of the Lower Lias at Frodingham, in Lincolnshire.

(a) The Dogger.

Situated at the junction of the Inferior Oolite and Lias, this ferruginous horizon can be traced throughout a large part of N.E. Yorkshire, where it is known as the "Top Seam." This is very unequally charged with iron, and is only worked when trade is brisk, but there are many features of interest to which I would briefly direct attention before proceeding to consider the Northamptonshire iron-ore, which is situated on the same horizon.

The Dogger in Yorkshire.

Without attempting to describe the features of the "Top Seam" in the districts where it has been chiefly worked, I may remark that the development of the Dogger at the Peak has the most interest for geologists. It there consists of a chocolate-coloured sub-oolitic irony grit, the series being about 30 feet thick, and it immediately underlies the carbonaceous shales and sandstones of the Yorkshire Lower Estuarine. The *Nerinea* bed, which contains so many of the fossils of this horizon, appears originally to have been a marly grit. Now the shells are more or less ferruginated, and exist either as spathic iron or as limonite. These facts were pointed out by Sorby more than 30 years ago. Sometimes when the shell is very thick, as in the case of *Astarte*, an inner layer of calcite may yet be noticed. In the year 1874, being at that time unacquainted with what Sorby had written, I drew the attention of the Association to these facts, and arguing from what I had observed both in the Yorkshire and Northamptonshire Dogger, came to the conclusion that the

whole of this iron was the result of substitution, and that the element which had been mainly removed was calcium; in other words, that a sandy sub-oolitic limestone had become a sandy sub-oolitic ironstone.*

Rosedale Magnetic.

Before dealing with the structure of the Peak ironstone let us direct our attention to the celebrated Rosedale magnetic ore, which presents features of exceptional interest. There are two deposits of this peculiar ore, occurring in parallel troughs in the Upper Lias Shale. The horizon is that of the Blue Wyke Sands, and hence rather below the Dogger proper. Mr. Kendall, who is our chief authority, says that small denuded areas in the Upper Lias Shale of Yorkshire are not uncommon, and that they are frequently occupied by siliceous limestones of the Dogger series.

The ore is very oolitic and, when unweathered, strongly magnetic, owing to its large charge of magnetite, an unusual circumstance for ores of the Secondary rocks in England. This is probably due to the partial peroxidation of the carbonate in the oolitic grains, where the magnetite entirely resides. The unaltered blue-black ore contains :

Ferric oxide	...	...	28 per cent	} Iron 48 per cent.
Ferrous oxide	...	...	37 „	

It is, in fact, Mr. Kendall thinks, a compound of magnetite and clay ironstone. The section exhibited (See Pl. II, fig. 4) might in some respects pass for the section of an ordinary oolite, where there are concentric ova of fine granular matter in a paste, which is largely composed of calcite, the chief difference here being the absence of fibrous structure. This was probably a highly calcareous rock originally, remarkably free from grit, consequently the percentage of iron is now high. Though different portions of the mass yield varying results, the above percentage may be taken as a fair average. The interspaces consist mainly of carbonate of iron, intermixed with fine granular matter of the nature of mud (hydrous silicate of alumina). The subtranslucent granular matter in the interior of the ova is also probably of the nature of mud mixed with some ferrous carbonate. The richest part of the ore, therefore,

* 'Proc. Geol. Assoc.,' Vol. iv, p. 123, *et seq.* "Excursion to Northamptonshire."

resides in the outer part of the grains, which may be regarded as consisting of nearly pure magnetite. The calculated amount of magnetite is 40 per cent., and that of the ferrous carbonate 24 per cent. This still leaves about 9 per cent. of iron protoxide for combination with silica, phosphoric acid, etc. Several flakes of mica may be noted in the slide, whilst there is scarcely any quartz grit.

Peak Ironstone

We are now in a position to compare the rich Rosedale ore with a ferruginous grit of the Top Seam series from the Peak—a sample, in fact, of the true Dogger as there developed. In this slide the angular clear spaces are mainly sections of quartz grains, whilst the opaque portion represents a paste of limonite, in which they are embedded. But the numerous ill-defined ova show that this possesses oolitic structure, and when we examine the rock closely we find that greenish gray granules constitute a considerable portion of the mass. The case of the shells, before quoted, is proof enough of substitution, but in this case there has been secondary action, and much of the carbonate of iron has been oxidized to limonite, with possibly some admixture of hematite. Like the so-called Northampton Sand, and other gritty ores, oxidation is favoured by the highly granular character of the rock, just as it is checked in the closer-fitting particles of the more argillaceous ironstones. The question of the source of the iron will be discussed in connection with the Duston ore.

Northampton Ore.

Proceeding southwards, the Dogger is found to possess a varying charge of iron throughout the East Midlands, having been worked on a small scale near Lincoln, and at Cottesmore, in Rutland. In the county of Northampton the ore-bed, says Mr. Kendall, is of a quality suitable for metallurgical purposes over a very large area, and has been worked at many places.

There are probably no more interesting sections anywhere than those in the neighbourhood of Northampton, where the ore-bed in some cases is nearly 30ft. thick. It consists largely of limonite, and contains *en masse* from 25 to 40 per cent. of metallic iron. The lowest beds are very rich in phosphoric acid, and contain cores of greyish-green carbonate, mixed with

silicate. Some of them even have a bluish tinge, which may be due to the amount of hydrated ferrous phosphate. Although these lower blocks are not prized by the smelter, they are interesting, from a scientific point of view, as affording evidence of the origin of the Northampton ore. (Fig. 3.)

FIG 3. Northamptonshire Iron-Ore (after Maw).

a and a'. Friable portions, yellow to brown in colour, containing about 21 per cent. of Ferric oxide.

b. Hard brown strings, layers and shells of iron-ore, containing about 75 per cent. of Ferric oxide.

c. Nodules of compact Carbonate of Iron, containing about 80 per cent. FeCo_3 .

d. Green ores, occurring near the base; mostly Carbonate, with some Silicate of Iron, and 2 per cent. of Phosphoric Acid.

This may be said to exist in three conditions—(1) as a brownish-yellow soft mass, full of oolitic granules, and containing a variable proportion of quartz grains. When the quartz grains predominate to any extent the ore is merely a ferruginous grit, like the specimen from the Peak. This portion of the ore contains about 21 per cent. of sesquioxide of iron, 1 per cent. of ferrous oxide, and 1 per cent. of phosphoric acid. Its colour and appearance are due to the admixture of disseminated limonite, with much earthy and marly matter. (2) The second condition is that of strings or shells of dark brown oxide; these consist of nearly pure limonite, and are, of course, very rich in iron, 76 per cent. of the sesquioxide having been calculated. (3) The third condition is that of the greenish-grey cores already mentioned. These represent the unoxidized residue of the rock; their structure being oolitic or gritty in variable proportions. These greyish-green layers are very much like the Cleveland ore both in composition and physical condition, being, on the whole, somewhat more sandy. A specimen analyzed by the late David Forbes was estimated to contain 40 per cent. of protoxide of iron, chiefly as carbonate, but also with much silicate and phosphate. The phosphoric acid alone was estimated at 2 per cent.

The conditions under which the Northampton ore occurs in the neighbourhood of that town are so well known that a study of them helps to throw considerable light on the origin of iron-ores of Jurassic age in this country. It should be borne in mind that the calcareous equivalents of this ore are worked as building stones, both at the Duston stone-quarry, and at Bass' pit, in Northampton. The species of fossils are identical, but their mineral condition is quite different. It is perfectly clear, therefore, that whilst some portions of the Dogger, in this district, have been ferruginated, other portions have not, or, at least, only to a small extent. The Dogger, whether calcareous or ferruginous, rests directly on the Upper Lias Clay; and above the ore and its calcareous equivalents occur a series of sands and sandy clays, with plant-remains, known as the Lower Estuarine of Northamptonshire. That the entire mass of the Northampton Dogger was originally a sandy oolitic limestone is pretty clear from the fact of the fossils being of the same kinds both in the ore and in the equivalent limestones. The relative position of the ore and limestone, with respect to the underlying Lias and

overlying Estuarine, is a further proof that both ore and limestone form parts of one series. It may, then, be taken for granted that no one doubts the Northampton iron-ore being the result of replacement, but opinions differ—1st, as to the mode of replacement; 2nd, as to the source of the iron.

Mr. Kendall has summed up the various opinions expressed on these subjects in his able paper entitled 'The Iron-Ores of the English Secondary Rocks.' He agrees in the main with the views announced by Sorby many years ago with reference to the origin of the Cleveland ironstone, and by myself more recently with reference to the Northampton ironstone, viz., that, in the first instance, carbonate of iron has replaced carbonate of lime. Carbonate of iron dissolved in carbonic acid, or, in other words, bicarbonate of iron, has permeated and saturated these rocks for a considerable period. These rocks were originally marly and arenaceous oolites, like so much of the Inferior Oolite elsewhere. Where the grains of quartz sand originally existed in the rock these still remain, and thus it happens that iron-ores on this horizon are often lean and sandy. This view of the case by no means harmonizes with the explanation offered by Professor Judd, who considered that the waters containing carbonate of iron dissolved portions of the "siliceous and other materials," which were in part redeposited in the rock in the form of oolitic grains. That the oolitic grains may, in some cases, be of secondary origin is very possible, but it is perfectly certain that the solvents in operation would attack carbonates more readily than they would silica and silicates. Hence it is only reasonable to suppose that all the carbonate of lime must have disappeared before any considerable quantity of siliceous matter could have been attacked. Judd has, no doubt, saved himself by making use of the phrase "other materials," but the prominence he gives to the solution of siliceous materials is decidedly misleading.

Oxidation of Northampton Ore.

The conversion of carbonate of lime into carbonate of iron implies a diminution of volume, or an increase of porosity, and this favours the second operation which the Northampton ore has undergone, viz., oxidation, whereby, through the action of surface waters the carbonate of the protoxide is converted into the ordinary hydrated peroxide, or limonite. In this way a

peculiar distribution of the iron is brought about, which may be described as centrifugal. Argillaceous ironstones are, for the most part, protected from this secondary action by the inferior permeability of the material.

Source of the Iron.

We now come to the question as to the source of the iron in the so-called Northampton Sand. On this point we may freely admit that there has been more than one source, so that the various and conflicting views may all have some degree of truth.

Mr. Kendall, speaking of the iron-ore in our Jurassic rocks generally, considers that it has been derived from the interbedded clays, which were themselves made up out of the Permian and Trias of the north-west. He ought also to have added the Coal-Measure shales as a source of the Jurassic clays. He gives analyses, showing as much as 9 per cent. of protoxide of iron in a Lias clay, and about 7 per cent. of the combined oxides in Kimeridge clay from Westbury. Undoubtedly clays and shales contain a considerable amount of iron—about 4 per cent. in most blue clays. But the very fact that the iron is now there is more or less a proof that such massive clays have not been seriously leached by acid percolations. The beds which are apt to be thoroughly leached by organic acids are porous micaceous sands and their shales, such as those constituting the Lower Estuarine, which immediately overlies the ironstone in the neighbourhood of Northampton. The pale colour of these sands and shales tells of exhaustion, whilst the quantity of woody matter readily suggests the agent.

Some of you may, perhaps, have noticed how ferruginous quartzose sand is rendered colourless round decaying roots. It has been proved that the action of a root one-sixth of an inch in diameter whitens the sand to a distance of from one to two inches round it. This, of course, means the removal of the iron, probably as ferrous carbonate. I merely quote this as a sample of the nature and not of the extent of the agency. The amount of iron removed will depend largely upon the permeability of the beds. But whether from sands or clays, or from both, the motor in all cases must have been the products of organic decay, which, rendering the iron soluble by reduction, also supplied the carbonic acid which combined with and con-

veyed the individual molecules of iron from point to point until they found a suitable resting place. Hence it was the decay of life, and mostly of vegetable life, which set the machinery in motion, and thus the study of Natural History becomes in a way connected with such phenomena as the aggregation of iron-ores.

(b) *Marlstone Series.*

By far the most important development is the Cleveland ironstone.

Cleveland Iron-Ore.

The problem of the origin of the large charge of iron in the deposits of the *spinatus*-zone in Cleveland is less clear. There is no necessity for me again to insist upon the replacement theory. Practically everyone is agreed as to the introduction of iron by replacement subsequent to the formation of the rock. I must remind you that the Cleveland main seam has an extent of between 300 and 400 square miles, but that it is only the north-eastern part of the area which contains really good ironstone. The ore is usually rather thickly bedded, and towards the base has a somewhat greenish-grey tinge. Except at the outcrop the ore is mainly in the condition of ferrous carbonate, with a small admixture of the peroxide. Silicate of iron is present, especially in the granules. The structure is occasionally oolitic, the ova being very small, but much has simply the appearance of a mudstone. Organic remains are abundant, and *Pecten equivalvis* is especially characteristic of the horizon both in Yorkshire and elsewhere. The abundance of animal matter is, no doubt, one cause of the large charge of phosphoric acid in the stone.

Analysis shows that the main block of the Eston ore contains only a trace of lime, whilst there is $2\frac{1}{2}$ per cent. of phosphoric acid. In this case the charge is equal to about 35 per cent. of metallic iron. Taking the average of Cleveland ore, the earthy constituents amount to about 28 per cent. of the whole in the following proportions—silica $11\frac{1}{2}$, alumina $8\frac{1}{2}$, lime 5, and magnesia 3 per cent.* Much of this silica exists in a somewhat soluble condition, and it has been found that the small oolitic concretions, or fig-seed-like grains, after parting with their carbonic acid, yield a skeleton of silica, which readily dissolves

* Kendall, *op. cit.*

in caustic potash. It is quite possible that the agencies which supplied the charge of iron may at the same time have introduced a certain quantity of "soluble" silica, since the products of decomposing vegetation are known to have the power of dissolving silica to a considerable extent. On the other hand, this excess of "soluble" silica may be due to silica-secreting organisms which have been buried in the bed itself, though this is the least probable supposition. We shall see further on the remarkable connection which exists between dissolved silica and iron-ores in the case of the ferruginous schists of the Lake Superior region. In an abstract notice of these schists, etc., in the 'Mineralogical Magazine,'* Mr. Teall alludes to the silica in the oolitic grains of the Cleveland ore.

Occasionally these granules favour a partial oxidation, and thus we find small quantities of iron oxide deposited concentrically. The transparency (Pl. II, fig. 5) shows this feature, but the opaque granular mass at the corner of the slide better represents the bulk of the ore, which may be regarded as a massive and earthy ironstone, which was originally a marl or marlstone rock, like so much of the *spinatus*-zone in other parts of England. This zone is also ferruginous in other places, as at Caythorpe, in Lincolnshire, Holwell, in Leicestershire, Adderbury, on the borders of Oxfordshire and Northamptonshire, and Fawler, in Oxfordshire. But this is nothing compared to the enormous extent of the ferruginated area in Cleveland, and some explanation of this peculiarity may be demanded.

After what has been said with regard to other iron-ores, I need scarcely dwell upon the subject of leaching by means of organic acids as a process for conveying solutions of iron to beds affording facilities for substitution, whereby iron replaces some other element, generally calcium. But, as before stated, the source whence the iron of this horizon was derived is much less clear to my mind than in the case of the Dogger ores. There, in the majority of cases, the requisite machinery is supplied by an Estuarine series above. Mr. Kendall remarks that, usually, where the Dogger series is highly ferruginated the Marlstone series is not, and *vice versa*. In the case of the Cleveland ore, he is disposed to look to the Upper Lias Shale as the source of the iron. Undoubtedly the Upper Lias of Yorkshire is ex-

* Vol. vii, p. 236.

tremely rich in iron, but this looks as though its beds had not been leached to any great extent for the benefit of other horizons. Still, the Upper Lias may have been so rich in iron as to have supplied the materials for the ferrugination of the Cleveland main seam without evincing many symptoms of exhaustion. The abundance of wood in some places rather favours the notion. At the same time, there is just the possibility that a large portion of the iron in the Cleveland main seam has been derived from beds of an estuarine character, which have either been removed, or are at present inaccessible to observation.

(c) *The Frodingham Iron-Ore.*

I must do no more than allude to the very interesting development of ironstone in the *semicostatus*-zone of the Lower Lias at Frodingham, in Lincolnshire. This consists of rather thin-bedded alternations of iron-ore (limonite) and ferruginous limestone, and affords good evidence of the truth of the replacement theory.

Iron-Ores of Permian Age—Hematites of Cumberland and Lancashire.

If we continued to adopt the order of geological position merely, the ironstones of the Coal-Measures would next come in for consideration. But the deposits to which I will now draw your attention, although they lie below the Coal-Measures, are mainly of Permian age, and ought to be considered in connection with that formation.

To Mr. Kendall's admirable papers we are indebted for most of our knowledge of these important iron-ores, which are found in the Eskdale Granite, the Skiddaw Slate, and Coniston Limestone, but principally in the Carboniferous Limestone. It is the latter only which we need consider, and I will direct your attention principally to the Hematites of West Cumberland.

Structure of the District.

A brief summary of the local geology may be useful. In that district the Carboniferous Limestone series rests progressively on the older rocks. It consists of alternations of

limestone, sandstone, and shale, and in the Whitehaven district the number of limestones is six. These contain the bulk of the hematite. In the overlying Millstone Grit there are merely strings of hematite running up into it from the Top Limestone. The Coal-Measures, 1,100 feet thick, are made up of alternations of sandstones and shales of the prevailing dark colour, amidst which occur numerous bands of fire-clay, coal (26 seams), and clay-band ironstone.

The Upper Coal-Measures are apparently represented by a deposit known as the "Whitehaven Sandstone," which is alike unconformable to the main Coal-Measures below and to the basal Permian breccia above. It is important to note the existence of a bed of hematite in connection with red shales in this Whitehaven Sandstone. On the other hand, the basal Permian breccia contains iron gravel derived from the denudation of rocks containing hematite. These facts appear to fix the date of the ore deposits as between the end of the Upper Coal-Measures and the beginning of the Permian.

Mode of Occurrence.

The hematite occurs in all the six beds of limestone, but the deposits are most numerous in the first and third limestones. Their form is variable, being sometimes bed-like, sometimes vein-like; elsewhere filling dish-like hollows in the limestone immediately below the drift.

The bed-like deposits occur mostly in the first or Top Limestone. The Parkside iron-ore deposit is an excellent example. This extends over an area of thirty-four acres. The roof is of Millstone Grit, which is even and regular, whilst the sole of the ore, which rests upon Carboniferous Limestone, is subject to such undulations that its thickness ranges from 40ft. and upwards to as little as 4ft. In this case it is only the upper part of the Top Limestone which has been completely ferruginated. In another locality (Bigrigg) it is the lower part of the limestone which has been ferruginated; consequently the roof is uneven, whilst vein-like extensions of hematite pass upwards through siliceous portions of the limestone.

All the most important deposits of the Whitehaven district are by the side of faults, and this brings us to the consideration of vein-like deposits, such as those of Salter Hall and

Eskett mines, as depicted by Mr. Kendall. (Fig. 4.) This section almost tells its own story. Here there is a combination of the vein-like deposit and the bed-like deposit, and we

FIG. 4. Salter Hall and Eskett Mines, Whitehaven (after Kendall).

f. Hematite.

s. Shales.

have no difficulty in understanding how the process of ferrugination is dependent upon faulting. This section also helps one to understand the geology of the district.

Composition, etc.

As a sample of the composition of West Cumberland hematite, the Salter Hill ore contains the following:—

Fe_2O_3	...	...	...	86.37	per cent.
Al_2O_3	...	...	...	1.21	"
SiO_2	...	...	...	9.56	"
CaO, aq. etc.	...	...	...	2.57	"
				99.71	

This yields $60\frac{1}{2}$ per cent. of metallic iron, and there is only $\frac{3}{10}$ of phosphate of iron. The kidney structure so often seen is formed in open spaces in the interior of the ore called "loughs." Quartz and other minerals are also abundant in these "loughs." Much of the limestone is in the cherty condition known as "whirlstone," so that siliceous matter may be said to abound in connection with these West Cumberland ores.

It is worthy of notice that when the ore is in contact with either shale or sandstone, there is a distinct line of demarcation between the ore and the rock. This is rarely so when it is in contact with limestone or "whirlstone;" in this case the ore and the stone are grown together, and the passage from one to the other is by regular gradations. Another point of importance to be noted as bearing upon the question of the mode of formation of the ore is the occurrence of partings and nests of shale. In many cases such shale partings may be traced into the adjacent limestone, showing that all originally formed part of one series, and that the shale has been only slightly affected by the agencies which changed the limestone into ironstone. Mr. Kendall appeals to these cases of shale partings in the ore as conclusive proof that the hematite could not have been deposited in caverns, since this would imply the stretching across such caverns of thin beds of shale—an obvious impossibility. There can be no other explanation than that of replacement, and this is further exemplified by the presence of corals of Carboniferous Limestone species in the hematite ore.

Summary of Facts and Conclusions.

Briefly, then, we may sum up what may be regarded as more or less certain with regard to the history of the hematites of Cumberland, and presumably of Furness.

1. That the ore bodies are the result of the replacement of carbonate of lime by what is now hematite in portions of the Carboniferous Limestone series.

2. That the evidence is unfavourable to the supposition, maintained by some, that the hematite has been deposited in caverns and open fissures.

3. That faulting has greatly determined the position of the deposits.

4. That the ferrugination took place between the period of the deposition of the "Whitehaven Sandstone" (Upper Coal-

Measures) and the basal Permian conglomerate, *i.e.*, in the interval between the close of the Carboniferous and the beginning of the Permian.

Source and Mode of Introduction of the Iron.

The original source of the iron and the mode of its introduction are much less obvious. Of course the iron must have been in a state of solution, but whether as perchloride or bicarbonate, or in any other soluble combination, is not so easy to determine. Mr. Kendall, as quoted by the late Mr. J. A. Phillips, suggested the Coal-Measures as the probable source from which this metal originally came. He further remarked that the sandstones and shales belonging to that formation contain a large percentage of iron. Since these rocks probably at one time everywhere overlaid the Carboniferous Limestone of the hematite districts, he thought it not improbable that a large proportion of the iron in the limestones had been the result of the percolation of carbonated waters through super-incumbent beds. There can be no doubt that the Coal-Measures constitute an enormous store-house, both of iron-ore and of disseminated iron, as all estuarine deposits must do upon the principles already laid down in this paper. It is highly probable that the "churns" of brown hematite (limonite) in the upper beds of the Carboniferous Limestone of the Forest of Dean originated in this way. But in Cumberland we have to deal with red hematite, or anhydrous peroxide of iron, and the origin may possibly be different.

On the whole, Mr. Kendall now prefers what he calls a volcanic origin for the original iron salt. The replacement, it is true, is due to percolation from above, as is shown by the gash-like form of the veins, the ore generally becoming less and less as it goes deeper. But he considers that perchloride of iron was introduced in the gaseous form through the moving fractures of that uneasy period, and was dissolved in the waters of the "reddened Permian sea." Such irony water would then circulate freely in the Carboniferous Limestone along lines of faulting, but not otherwise. Hence, where there is no faulting there is no iron-ore.

In concluding this subject I am inclined to believe that the temperature of the solution, whether perchloride or bicarbonate, was high; partly because the ore body is now anhydrous, and partly because of the abundant deposit of rock crystal in

association with some of this ore. These facts rather point to hot springs, but beyond this I venture on no conjecture.

Other Permian Ores.

Although there is no time to deal with other iron-ores of Permian age in this country, we must bear in mind that the Permian horizon is essentially a ferruginous one. Fossiliferous hematite nodules are by no means rare in the Permian breccia of Leicestershire (Gresley, 'Mid. Nat.' ix, 1886). There is a remarkable instance of a compact hematite ore resting unconformably upon dolomitic limestone of the Carboniferous series at Mwyndy in South Wales. The ore itself is stated to be of Permian age; and a section is given in the 'Iron-Ores of Great Britain.'

Iron-Ores of the Coal-Measures.

We now come to the consideration of the Clay-ironstones of the Coal-Measures, with which must be included those of the shales in the Millstone Grit and the Yoredale series. The subject is so vast that it is impossible to give it adequate treatment if we are even to glance at any of the older formations. The question of concretionary action is one which, alone, might occupy an evening. The solid sheets of argillaceous ironstone, sometimes continuous over large areas, and elsewhere represented by nodules abundantly spread over plane surfaces of equal dimensions, are well known to the inhabitants of South Yorkshire and Derbyshire.

In many cases it seems to me that these bodies are not the result of replacement, but are original concretions in strata where carbonate of iron was more plentiful than carbonate of lime. The usual process of all "estuarine" beds, such as those of the Wealden in Sussex, or the Lower Oolites in East Yorkshire, was here effected on an immense scale. An abundant supply of decomposing carbonaceous matter yielded solvents such as I have before described, which served to leach the more permeable beds. It is not at all improbable that some of these clay-ironstones owe their existence, in the first instance, to lagoons or slight hollows in alluvial flats where peaty matter accumulated, though not in sufficient quantity to form a good coal. But it has been pointed out that the phenomena of coals, especially gas-coals, blackband-ironstones, and ordinary clay-ironstones, seem to wait upon each other very much. I merely

quote this as a suggestion, and pass on to the consideration of other formations.

Iron-Ores older than the Coal-Measures.

In the United Kingdom there are no ironstones largely worked in beds below the Coal-Measures except those of Permian age, which have been already noticed. But many interesting iron-minerals are obtained from these older rocks, such as the stalactitic limonite of the Forest of Dean, locally known as "brush ore." The well-known ironstone lode near Lostwithiel, in Cornwall, contains crystallizations of remarkable interest. Small hand-specimens exhibit hematite, göthite, and limonite in such close proximity that an excellent opportunity is afforded for comparing these three oxides. The Devonian rocks generally contain considerable quantities of hematite, chiefly in association with limonite and spathic ores. Hence it is by no means intended to imply that the older rocks in the United Kingdom are devoid of iron-ores. Yet a glance at the Table of statistics (*supra*, p. 110) shows that, as compared with the formations already described, they do not tempt the iron-miner to any great extent.

American Iron-Ores.

In America the case is quite different. In that country big things are, of course, the order of the day. But their "iron mountains," as well as the more ordinary deposits, occur in rocks which are certainly older than the Coal-Measures, and are for the most part of high antiquity. The so-called Archæan rocks contain a large proportion of the iron-ores now mined across the Atlantic, whilst the formations above the Coal-Measures, as we have already gathered from an inspection of the Table, contribute next to nothing. Omitting the clay-iron-stones of the Carboniferous in America, I will endeavour to give a very brief sketch of the ore deposits in the beds below the Carboniferous.

Archæan.

The base of the Archæan system, according to Pumpelly, is the Laurentian, to which succeeds the Huronian, the latter being covered in places by an eruptive series.

In the States of New York and New Jersey, the Laurentian rocks have yielded a large amount of iron-ore. Magnetites occur in the gneiss and limestones of that series, much twisted and tilted at high angles. It should be noted that these

gneisses, especially in New Jersey, are rarely free from magnetite, and are often sufficiently impregnated with it to form beds of lean ore, and in places workable deposits. Magnetite ore bodies also occur occasionally in the crystalline limestone. In many of the mines there is no sharp demarcation between the ore and the wall-rock, the ore and the gneiss both carrying the same minerals in inverse proportions.

The so-called Huronians are, however, the most ferri-ferous rocks in North America. In the Lake Superior region the ores are entirely derived from them. These beds are represented as resting, almost conformably, on Laurentian gneiss. (Fig. 5.)

FIG. 5. Generalized Section of the Michigan Iron-Ore (after Pumpelly).

Pumpelly gives a very generalized section, representing a sequence, which in most regions is much complicated by folding and fracture. A bed of quartzite resting on the Laurentians is succeeded by a bed of limonite, the upper portion of which is hematite with intercalated quartzite. Then ensues an eruptive bedded mass, above which occur the richer portions of the deposit, good hematites with some magnetite in association with certain peculiar Huronian schists and jaspers, etc. This represents the more complex phase of the iron country: in other parts the sequence is more simple. What I particularly wish to point out is the association of these ores with quartzite, schist and jaspers, since it will be necessary to return to this subject when dealing with the views of the late R. D. Irving on this remarkable district.

In Minnesota the iron-ore consists of enormous bodies of hematite in connection with Huronian schists and quartzite, the whole being overlain, as in Michigan, by lavas of the uppermost Archæan. These are not worked at present.

In Missouri the three remarkable masses known as Iron Mountain, Pilot Knob, and Shepherd Mountain are referred to the Huronian. No beds of Laurentian age are found here. Pumpelly observes that the Missouri ores are associated with porphyries and conglomerates which are supposed to be of Huronian age. The ores are represented as being chiefly hematites. Magnetic ores and martite occur in porphyry in a true vein at Shepherd Mountain with 65 per cent. of iron and scarcely any phosphorus. These ores also occur in an immense irregular vein or mass, in places 60ft. thick, in decomposed porphyry at Iron Mountain, where the great ore body sends out into the porphyry countless anastomosing veins of ore, abounding in crystals of apatite, so as to form a reticulated mass of ore and rock. Through the atmospheric removal of the decomposed porphyry the heavy and indestructible ore-veins have been left to form an accumulating mantle of ore-detritus. The ore has lost nearly all its phosphorus through the weathering of the apatite crystals. Pilot Knob is similar. These ores are free from manganese.

Silurian Ores.

The next great ferriferous horizon in the United States occurs in the Trenton and Canadian groups of the Lower Silurian. In the Appalachian region from Vermont to Alabama

is a limonite-bearing belt associated with limestones and schists of this age. Numerous hypotheses, says Pumpelly, have been advanced to explain the origin of these limonites. Dana thought they resulted from the leaching of beds either of iron carbonates, or of a limestone carrying iron carbonates. Somewhere I remember having seen the suggestion that these limonites had resulted from the oxidation of immense beds of pyrites. However, we have very little time left to investigate their origin. The most interesting fact to note is—that the Alleghany Mountains contain such important ferruginous horizons in ranges which constitute a sort of framework to the great interior Coal-basin.

There is yet another horizon, in the Upper Silurian of the Alleghanies, where hematite-ores of Clinton age are known as “fossil” or “dyestone” ores. These have the following features in common:—(1) Association with olive shales which owe their green colour to ferrous silicates; (2) The occurrence of the ore only above drainage level, changing from ore to ferruginous limestone below that level.

The Views of R. D. Irving.

Sufficient has now been said with respect to the principal horizons for iron-ore in the United States. A short notice of Mr. Irving's views as to the origin of the iron-ores of the Lake Superior region must conclude this brief reference to trans-Atlantic deposits. Recalling the generalized diagram of the sequence before folding took place in that region (Fig. 5), we must also remember the amount of siliceous matter associated with these ores. Two distinct theories have been brought forward, one implying a sedimentary, the other an eruptive or volcanic origin. Owing to the amount of bedded igneous rock between the two series, and also to the fact that in some districts the Huronian beds are succeeded by great sheets of Archæan lavas, the latter theory has been held by many.

Mr. Irving criticizes the several points of the igneous theory, referring especially to the views of Mr. Wadsworth. He observes that the occurrence of fragments of banded jasper in the overlying quartzite indicates that these substances had reached their present condition at an early date.

He first studied the formation in an unfolded district, and became convinced that not only the banded-jasper schists, but several other forms of ferruginous rocks, such as magnetite and

hematite schists, etc., must and have had a common origin with the ordinary ore and jasper. This was in 1883, after which year he undertook much microscopic work in this connection. The silica which is so abundant in the ferruginous schists presents every evidence of chemical origin; fragmental quartz being seen, but always sharply distinguishable from the water-deposited silica.

Rejecting the metamorphic as well as the igneous theory, Irving refers to the fact that the least altered forms of ferruginous schists contain a considerable portion of some carbonate. This favours the notion of the replacement of a rock originally dolomitic or calcitic by siliceous and ferruginous substances.

In the uncontorted district certain regularly-bedded hematites could be traced directly into one of the carbonate-bearing beds, showing the gradual replacement of the rhombs by red oxide of iron. He does not appear to offer any suggestion as to the source of so much silica and iron.

His general conclusions as to these ores may be stated briefly as follows:—

(1). That the original form was a series of thinly-bedded carbonates interstratified with carbonaceous shaly layers, also often impregnated by the same carbonate. This carbonate was usually ferriferous, though probably there were intermediate forms between it and dolomite. Such a series finds parallels in the carbonates of the Coal-Measures and the so-called "black-band ores."

(2). The change was effected by a process of silicification, which varied in degree up to complete substitution.

(3). The iron thus removed at the time of silicification passed into solution in the percolating waters to be re-deposited in various places as it became oxidized, thus making the ore bodies and impregnations, and providing the colouring-matter for the jasper. Some of the hematite bands were formed by direct oxidation from iron-carbonate seams.

He quite allows that the bodies of rich ore may have had different origins, and that for some cases there is at present no satisfactory explanation. This affects both magnetite deposits and specular ore. He also thinks that some of the silicifying processes went on before the folding, but that the larger bodies of crystalline ore belong to the period of crumpling and shattering.

These views are valuable as being the conclusions of a man who spent his best days in this remarkable region, though they leave us completely in the dark as to the origin of the iron-carbonate itself. If we may judge from a recent paper, 'On the Crystalline Schists of Lake Superior,' contributed to the last session of the International Geological Congress, these views are also shared by his colleagues, who seem prepared to accept the most wholesale substitutions as secular processes taking place under ordinary conditions, and without the aid of exceptional heat or pressure.*

We must now recross the Atlantic, and since there are no Archæan iron-ores of note in our own islands, I propose to give a short account of the "Iron Mountains" in Swedish Lapland.

Gellivara, etc.

The information is derived from the official report of Torell and his associate surveyors, and was published at Stockholm in 1877. The Swedish and Norwegian Railway Company (formerly the Northern of Europe Railway Company) have constructed a line from Luleå, on the Gulf of Bothnia, to Gellivara, the distance being about 120 miles. This place was first heard of, as an iron locality, in 1704, and in 1735 a concession was granted to Lieutenant Tingwall, who ceded his rights to one Steinholtz. The first furnace was built in 1742. To cut a long story short, I may state that all attempts at profitable working failed for upwards of a century.

There is something so attractive in the idea of an "Iron Mountain" that it seems almost a pity to qualify the allusion in any way; but the prosaic Swedes tell us that the deposit of iron-ore really occupies only about $\frac{1}{20}$ of the surface of the mountain—say about 160 acres—though from the high angle at which the beds are inclined the ore, in most places, reaches too great a depth to be ever bottomed. The hill itself rises with a

* Since the reading of the paper my attention has been drawn by Prof. Rupert Jones to a recent article by Van Hise, in the 'American Journal of Science' (Vol. xxxvii, Jan., 1889), who observes that Irving's fundamental conclusions have been borne out by late investigations, viz., that the original rock of the iron-bearing formation is a cherty iron-carbonate, from which the various phases of rock and of the ore found in it have been produced by a complex series of alterations. These ores are not the results of carbonates of iron which have altered in place, but it is almost certain that such iron carbonates have been the source whence the iron oxides for these ores have been derived. The origin of this cherty iron-carbonate, Van Hise says, is one of great interest, but at present we are left in the dark upon this point. Possibly we may hear something further ere long.

gradual slope some 500 or 600 feet above the surrounding country. A plan with two sections showing the principal outcrop is submitted. This outcrop, according to scale, has a length of 18,000 Swedish feet—say three miles—with a mean width of about 250 feet. (Figs. 6, 7, 7a. For fig. 6 see p. 140).

FIG. 7. Nearly East and West Section at the east end of the Mountain.

FIG. 7a. North and South Section (along the line A B), towards the west end of the Mountain.

The ore occurs in a gneissic series, which is compared to the so-called "red gneiss" of southern Sweden. This gneiss varies greatly within the area both in colour, texture, and mineral composition, but, taken as a whole, it is the principal constituent of Gellivara's "Iron Mountain." It frequently contains hornblende and black mica in considerable quantities, so as to assume a greyish colour. In some places it is strongly foliated, with much hornblende and iron oxide impregnated in the mass. The gneiss is also much seamed by veins of granite, the principal outcrop being close to a large mass of granite. The report expresses an opinion that this granite has uplifted the gneiss, compressed the beds and the ore, and brought the latter to day by numerous folds. It should, however, be noted that the greater part of the ore is not actually exposed on the surface, its presence where there is no uncovered knob being indicated by the compass.

The ore forms distinct and constant beds in the gneiss. In some cases the ore and rock pass into each other, so that the ore contains hornblende, felspar, and other minerals, whilst grains and even thin beds of ore appear here and there in the gneiss over considerable distances. This is exactly what occurs with respect to the magnetite ores in the Laurentian gneiss of New Jersey and New York, and there also granite is close at hand.

As a rule the ore is magnetite, with a central core of hematite in places; the latter, according to the views of Torell, being the unreduced residue of the principal ore. The ores are extremely rich, ranging up to 70 per cent. of metallic iron, the minimum analysis giving 50 per cent. Phosphorus is

W.

FIG. 6. Plan of Gellivara's Iron Mountain (after Torell).

E.

abundant, crystals of apatite being numerous. There is very little sulphur or manganese, and an average of about one per cent. of titanitic acid. Torell reckons only about 20 acres to contain "Bessemer metal."* If these statements are correct it is evident that the antiquity of an ore is no guarantee of its freedom from phosphorus, whilst we have seen, on the other hand, that the Bilbao ore of Upper Cretaceous age is almost free from that impurity.

Kirunavara.

One other notable development of iron-ore in Lapland may be mentioned. This is Kirunavara, or the Hill of Ptarmigans. The hill, which rises about 700 or 800 feet above Luosojaur (Salmon Lake), consists mainly of a porphyry-like petrosilex (quartz-felsite), in which a seam of magnetite occurs, extending through the hill, it is estimated, to the level of the Lake. The conditions and quality are very much the same as those of Gellivara. The surface of ore is represented as 76 acres, and the quantity above the level of the lake is estimated at 260 million tons.

General Conclusions.

It may be asked, What are the general conclusions to be drawn from the facts and interpretations which have been briefly indicated in the preceding pages. We must all admit that the origin of iron-ores in the oldest rocks is still enveloped in considerable obscurity. This is the more impressed upon us when we find that the Archæan iron-ores of Swedish Lapland are regarded as hematites which have been reduced to magnetites, whilst there seems to be a contrary impression regarding many of the Archæan ores of the United States. In fact, the presence of large masses of martite affords conclusive proof that much of the red ore results directly from the oxidation of the black ore without change of crystalline form.

Again, if there is anything to be learnt from the behaviour of iron in erupted rocks, it would seem that magnetite is the original form of iron-ore. But it may be urged that this applies only to the case of small grains, and cannot be predicated of large masses. Moreover, the presence of these same masses indicates concentration of some sort, and the

* In a letter dated 17th March last, Mr. Henry W. Trinder informs me that he has heard, on good authority, that the Gellivara ore containing so much phosphorus is the portion next the igneous rocks, "and that a few feet from such rocks the phosphorus ceases."

question really resolves itself into this—not what is the origin of the iron, but what have been the causes of its concentration.

There is a growing impression amongst geologists that many of the old gneisses are really not the result of ordinary sedimentation, but that they represent a modification of rocks having more or less of an igneous origin, the basic igneous rocks being represented by the hornblendic gneisses, and the acidic igneous rocks by silico-felspathic gneisses, etc. If this view be the correct one there can be no room for the action of decayed carbonaceous matter such as finds a place in the imagination of a certain school, founded on the presence of graphite, which may have had a very different origin. It should be mentioned in this connection that the latest views of some American geologists are to the effect that the Laurentian rocks may be newer than the beds which repose upon them, having been more or less reduced to a state of igneous fluidity or, at least, of plasticity so as to have been completely re-composed at a period subsequent to the deposition of the overlying beds.

But what has all this, you may say, to do with concentrations of iron-ore? Merely that the theory of the leaching of beds by acids of organic origin, generated in the beds themselves, can scarcely be applicable to the explanation of the masses of iron-ore in the very oldest rocks. How far acids of organic origin are accountable for the immense substitution which, according to the late R. D. Irving, has taken place in forming the Huronian iron-ores of the Lake Superior region we cannot say. In this case it would seem to have been silicic acid which helped to decompose the original iron-carbonate, but as to the origin of such an ancient iron-carbonate or the sources of so much silicic acid we obtain no information.

But whatever may have been the principal causes of concentration in the older rocks, which were probably formed under physical conditions as regards atmosphere, very different to those which afterwards obtained, there seems to be little doubt that from Carboniferous times down to the present day we owe most of our accumulations of iron-ore, whether of original deposition or of substitution, to the leaching of beds by acids, which were in the main the result of the decomposition of organic matter, chiefly of vegetable origin. Reduced and dissolved by carbon-products, iron moves about in all directions; its solutions permeate the rocks and impregnate many a

spring. Sometimes it collects into lumps and concretions, which obey the laws of segregation like any other crystallizable matter in solution: sometimes it takes the place of limestones more or less completely, and tarries for a while as carbonate in a series of massive beds. Then comes the rival element in oxygenating waters, whose entry is facilitated by fissures, shrinkage, denudation, and all the conditions which favour percolation. The resulting oxides are more or less fixed bodies, stones, in fact, of an indestructible character, which often constitute some of the most enduring elements of the rocks in which they are enclosed.

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EXPLANATION OF PLATE II.

(*Rock-sections enlarged by a two-inch objective.*)

FIG. 1.—*Hornblende-andesite* from America. *b.* Crystal of hornblende passing on the exterior into secondary magnetite. Some of the smaller crystals of hornblende have already passed into magnetite. *c.* Crystal of andesine.

FIG. 2.—*Black Serpentine* from Cadgwith. The process of conversion from olivine to serpentine is accompanied by the separation of magnetite dust (secondary magnetite), *b*, beginning in the centre of the fissures.

FIG. 3.—*Olivine Basalt* from the Drift of Finchley. *a.* Crystal of primary (idiomorphic) magnetite. *b.* Magnetite dust in the fissures of the olivine.

FIG. 4.—*Magnetic Iron-ore* from Rosedale. The ground mass consists mainly of carbonate of iron, slightly argillaceous. The magnetite resides in the concentric bands of the spherules, especially towards the exterior, Percentage of metallic iron about 48.

FIG. 5.—Oolitic portion of *argillaceous carbonate of iron* from the Cleveland main-seam at Guisborough.