ROCKS CONTAINING RADIOLARIA.

By WILLIAM HILL, F.G.S.

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I.—INTRODUCTION.

IT is only within comparatively recent years that Radiolaria have attracted the attention of geologists, and scarcely 100 years since the zoologist recognised amongst the minute creatures living in the sea a form so differentiated in its essential structure as to merit a place of its own in the animal kingdom.

In 1862 Hæckel published his well-known monograph on the Radiolaria, and though others had before this added considerably to our knowledge of these forms, this work is a convenient stepping-stone, and much of what follows in the opening paragraphs of this address is gathered from the Historical Sketch at the beginning of that volume.

Perhaps no other form of life so long escaped attention as Radiolaria. The earliest notes on them are scanty; observers seem to have mistaken fragments of their tests for mineral fragments or broken pieces of other organisms. The earliest observations which we may take as referring to Radiolarians are recorded in scattered essays having reference to minute light-giving animals of the sea, and are cited in Ehrenburg's comprehensive treatise.*

Tilesius, who accompanied Krusenstern on his voyage round the world in 1803-6, figures amongst many luminiferous animals several so-called "Infusionsthierchen," principally observed in tropic seas during great heat and continuous calm. These creatures, he says, are as shiny as molluscs, yet some of them are hard, almost gristly. One of his figures, which he calls *Leucophra eschinoides*, may be easily identified as *Acanthometra*. Tilesius gives other figures not definite enough for identification.

* "Das Leuchten des Meeres," *Abhandl. der Berlin Akad.*, 1834, p. 41.

Baird* in 1830 noticed minute jelly-like bodies which he thought were Macartney's *Medusa scintillaria*, but Baird's animalculæ were undoubtedly *Thalassicolla*.

The first accurate account of Radiolaria dates from Meyn's journey round the world in 1832-4. He observed three species and believed them at first to correspond to the Nostocs amongst plants (*i.e.*, simple collections or chains of similar cells); he called them *Palmellaria*, and with another family of Polypozoa he formed a new class of animals, the *Agastrica*.

These forms seem to have been subsequently recognised as *Sphærozoum fuscum* and *Physomatium atlanticum*.

Seventeen years later, Huxley published observations on certain jelly-like bodies which he had found floating in the sea during the cruise of the *Rattlesnake*, and from 1849 Müller's attention had been drawn to other forms which he had found in the Mediterranean. In the meantime, however, a large number of the fossil skeletons of Radiolaria had become known to Ehrenburg, who described them as *Polycistinæ* without thinking there was any connection between them and the nearly related *Sphærozoum* of Meyn.

Ehrenburg's first notice of Radiolaria is to be found in his work, published in 1838, on the formation of chalky rock and marls in Sicily. He there mentions certain forms which could be referred to the *Polythalamia*, *e.g.*, the *Nodosaria*, but whose test consisted of silica, was not dissolvable in acid, and had an appearance which to the eye was clear and glass-like. In the next year he describes a living Radiolarian from Cuxhaven (*Halionna radians*), which he had already found as a fossil in Greek marls. Later he found two living species at Cuxhaven which he identified with fossil forms in the Barbados earth.

In 1842 Forbes sent to Ehrenburg mud containing Radiolaria obtained from a depth of 1,020 to 1,200 ft. in the *Ægean* sea, which led Ehrenburg to think that the purer Radiolarian earths, like those of Barbados, and the *Nicobars*, had been always formed at great depths.

In 1857 Spratt obtained examples of mud from the Mediterranean, at depths varying from 1,500 to 9,720 ft., between Malta and Crete, in which Ehrenburg found thirteen different genera, and in 1860 Ehrenburg made a report on soundings obtained by Lieut. Brooke between the Philippines and Marianne Islands, and also on others obtained from great depths between the coast of California and the Sandwich Islands. He remarks that many of the genera were different to those already known to him either as fossils or from other seas, and leads him to suppose that these forms were typical of great depths.

In 1851 Huxley published (*Ann. and Mag. Nat. Hist.*,

* Baird, "On the Luminosity of the Sea." *London Mag. of Nat. Hist.*, vol. iii, 1830.

Ser. 2, Vol. VIII) an extremely careful description of bodies he had found, calling them *Thalassicolla*, not recognising their connection with the *Polycistinae* of Ehrenburg. His description was subsequently confirmed by Müller, and Huxley has the right to be considered the first who accurately investigated and recognised the structure of testless and test-bearing colony-forming *Radiolaria*, as well as a testless form, by his description of *Thalassicolla nucleata*.

Johannes Müller contributed not a little to our earliest knowledge of the *Radiolaria*, and between 1849 and 1858 he devoted much of his time to the study of these organisms. In 1853 he caught in a net, off the coast of Messina, *Radiolaria* with a spined skeleton, and while recognising their relationship with *Acanthometra*, *Thalassicolla*, and *Polycistina*, was at first doubtful whether they could be placed in one group, and of their connection with the *Thalassicolla* of Huxley. In 1855 Müller nearly lost his life in a shipwreck when coming home from Norway, whither he had been for the purpose of studying *Radiolaria*, and this seems to have given him a distaste for the sea. Though he continued to work for a time, and zoologists have now the benefit of his most careful observations and researches, after 1858 the literature of *Radiolaria* knows him no more.

In 1862 came Hæckel's monograph, which placed the great class of the *Radiolaria* and its sub-divisions on a firm foundation. Numerous papers published between that date and 1864, the majority of which are of German origin, added still further to our knowledge. But it is in the massive tomes of the Report on the *Radiolaria* found during the *Challenger* Expedition, and published in the year 1887, that one finds gathered together all the known information concerning these forms to that date. In this great work, a monument of painstaking research and patient study, Hæckel spent ten years of his life. Though a vast number of living as well as many of the older fossil forms are therein described, much however yet remains to be done, and a very wide field is open to the investigator. From this work and also from the report on Oceanic Deposits, I gather the following remarks, which will be useful in our discussion on ancient *Radiolarian* deposits this evening.

"*Radiolaria* occur in all the seas of the world, in all climatic zones and at all depths.*"

They may be found not only floating on the surface, but also at various, probably even in abyssal, depths of the ocean, certain species occurring in definite bathymetrical zones and adapted to the conditions found there. Those floating near the surface are generally to be distinguished from the abyssal forms by the more delicate structure of their skeletons. Some pelagic forms have no skeleton at all. As they seem incapable of move-

* *Challenger* Report : "*Radiolaria*," p. cxlvi, par. 226.

ment their dispersion must be dependent on the action of the wind, the waves, or of the ocean currents. The number of species found in widely separated localities is large, in few cases are species confined to a circumscribed area, but our knowledge of their general distribution is at present very incomplete. The greatest development of forms occurs in the tropics, and although abundant in the Arctic and Antarctic seas, the number of genera is not large, the number of species diminishing regularly towards the poles, more rapidly in the Northern than in the Southern Hemisphere.*

As in the case of the Foraminifera, the test of the Radiolarian after death gravitates to the ocean floor, and in some cases they have accumulated in sufficient abundance to give a definite character to the ooze; it is here that the greatest number and variety of forms occur.

Hæckel says deposits containing Radiolaria may be divided into two main divisions, terrigenous and abyssal, or, more shortly, muds and oozes.†

Terrigenous deposits (or muds) include all those sediments which are made up for the most part of materials worn away from the coasts of continents and islands, or brought down into the sea by rivers. Their greatest extent from the coast is about 200 nautical miles. They contain varying quantities of Radiolaria, but fewer than the next group.

The abyssal deposits or oozes usually commence at a distance from 100 to 200 miles from the coast. In general they are characterised by great uniformity, corresponding to the conditions under which they were laid down. They may be divided into true Radiolarian ooze, Globigerina ooze, and Red Clay.

One gathers that true Radiolarian ooze is found only in the greatest ocean depths. The purest example was obtained between Japan and New Guinea at a depth of 4,475 fathoms. The deposit was compact and laminated, red near the surface, but passing, in the three inches brought up by the sounding tube, to a yellowish colour. It was easily broken with the fingers when dry, though its component parts were not easily separable. Purified and decalcified, its appearance was that of a shining white powder. It consisted chiefly of Radiolaria and a few sponge spicules, together with some volcanic dust, minute mineral fragments, and a little calcareous matter. After treatment with acid the remains of the silicious organisms were estimated at 80 per cent. In other examples of Radiolarian ooze, silicious organisms, chiefly Radiolarians, but which include also spicules and a very few arenaceous foraminifera, range from 20 per cent. upwards, the average being 54.44 per cent., the

* See *Challenger Report*: "Radiolaria," chap. IX, par. 226-240.

† *Challenger Report*: "Radiolaria," p. clv, par. 236.

remainder consisting of fine washings, 39.88 per cent., mineral grains, 1.67 per cent., and carbonate of lime, 4.01 per cent.*

The tests of Radiolaria are also very abundant in Red Clay, and form, sometimes, an important constituent of it. In some localities Red Clay and Radiolarian ooze seem to pass into each other. Hæckel says: "A large portion of Red Clay appears to me to consist of broken-down Radiolarian shells in which a peculiar metamorphism has probably taken place."† "Futhermore, John Murray has called attention to the fact that in many deep sea deposits yellow and red particles remain which unmistakably present the form of Radiolarian shells . . . it seemed as if some substance had been deposited in and on these organisms. Similar transitions from well-preserved Radiolarian shells into amorphous mineral particles I have found in several other specimens of *Challenger* soundings."

Radiolaria are usually present in Globigerina ooze, but they add little to the mass of it, and are difficult to distinguish until the ooze has been decalcified by acid. In the residue after this operation silicious organisms, chiefly Radiolarians, but including spicules and arenaceous foraminifera, do not often exceed 10 per cent. of the mass of the original ooze.

The comparative abundance of Radiolaria in the deposit is indicated in the *Challenger* Report by the words "very few," "few," "many," "numerous," "very many" and "Radiolarian ooze." Red Clay, in which the quantity of Radiolarian tests exceeds 20 per cent. of the mass of the material, is included in Radiolarian ooze.

The boundaries of these various deposits are not distinctly marked, one graduating to the other. As a whole it may be said that the purest Radiolarian deposits and the Red Clay in which their remains are usually abundant are found in the deepest portions of the ocean floor, Globigerina ooze, in which they are common, forming at less depths, and this passes gradually into "mud" as land is approached and the water becomes shallower. Though Radiolaria become less common in this passage from ooze to mud as the depth lessens, there are one or two notable exceptions. Thus at station 200, in 250 fathoms ("green mud"), they are "numerous," while at station 201, in 82 fathoms (stones and gravel), at 219, in 500 fathoms (blue mud), at 232, in 345 fathoms (green mud), there are "many" Radiolarians in the deposit. In all other cases where the depth of water is less than 500 fathoms there are but "few" or "very few" Radiolarians present.

The explorations of the *Challenger* were, however, chiefly directed to the deeper parts of our existing oceans, and the occurrence of shallow water deposits containing a large number of Radiolaria may be more numerous than is at present known.

* *Challenger* Report: "Deep Sea Deposits," p. 206.

† *Challenger* Report: "Radiolaria," p. clviii, par. 239.

Hæckel divides the Radiolaria into legions—1. The Spumellaria; 2. The Acantharia; 3. The Nassellaria; and 4. The Pheodaria. Of these, only the Spumellaria and the Nassellaria, which have skeletons of pure silica, are likely to be found by the geologist, but one family in the Nassellaria (the Nassellida) and two in the Spumellaria (Thalassicollida and Collozoida) are devoid of skeletons. Amongst the Spumellaria are the Beloidea, the skeleton of which consists of disconnected portions closely resembling in appearance and shape minute sponge spicules. In the Acantharia, a legion almost wholly absent in the deep sea-muds brought up by the *Challenger*, the skeleton consists of Acanthin, which, though firm in the living organism, is easily destroyed, while that of the Phæodaria is a silicate of carbon, likewise easily destructible. There is, however, in the Phæodaria, the Dictyochida, a sub-family of the Cannoraphida, whose skeleton, like that of the Beloidea, is in detached portions. These free spicules are simple rings or hat-shaped pyramidal bodies with latticed cap over the ring; these are of pure silica, and the fossil remains of this form, as well as the Beloid skeleton of Spumellaria, have been recognised.

II.—THE PRESERVATION OF RADIOLARIAN REMAINS.

The test of the Radiolarian is a silicious network of great delicacy and beauty, and though easily seen and distinguished from all other minute organisms when free, there are few forms which can be more easily overlooked or lost when they have become included in a consolidated mass of an inorganic or organic deposit. This arises from the clear and glassy nature of the skeleton, for, until some change has taken place, there is nothing to catch the eye, while the open network often allows the fine matter to penetrate within it, and there appears to be no break in the homogeneity of the deposit.

Examination under the microscope between crossed Nicols shows that the silica of the skeleton is in an amorphous condition like that of sponge spicules, and is readily soluble in caustic potash. It is therefore clear that the Radiolarian skeleton may in process of time be dissolved and lost, but, like the spicules, traces of it may remain, and before going further I propose to say a few words on the general aspect of Radiolarian remains that I have seen in various rocks.

Recent Radiolarian ooze, when seen as a thin section, appears as a felted mass of their silicious skeletons, the outward form and the meshwork of those that are entire being more or less visible in a débris of broken fragments, the whole presenting a general uniformity of texture and appearance. As

the ooze becomes more calcareous, usually by the admixture of foraminiferal débris, or the proportion of fine inorganic matter increases, there is some difficulty in seeing the glassy skeletons, and they may be passed over easily until there occurs the section of one incompletely filled with the finer material, when a hollow appears, which draws attention to the fact of its presence.

The best known deposit of fossil Radiolaria is that of Barbados, and its study has given us useful information of the changes which occur in their skeletons after the consolidation and elevation into land of the oceanic oozes which contain them. These changes have been dealt with at some length elsewhere,* and I need only say that the silicious network gradually disappears, while the interior of the test sometimes becomes filled either with clear amorphous silica derived from the Radiolaria themselves, or in the more calcareous earths by granular crystalline calcite, so that only an outline of the original form with indistinct traces of the network or central capsule is visible.

This is perhaps the most common appearance presented by the Radiolarian when seen in thin sections of rocks, which are of such a nature as to be too hard to break up or disintegrate chemically. In some rocks of silicious nature, *e.g.*, the Jaspers and Hornstones of the Jurassic series in the Alps, as well as in other silicious rocks, the skeleton may be so well preserved in a silicious ground mass that the specific determination of the organism is possible.

In the most purely calcareous rocks, *e.g.*, the Chalk, the body of the test may become infilled with calcareous débris or minute calcitic crystals, and it is seen in section as a disc, or ball, or cap-shaped form, whiter and more translucent than the surrounding deposit, thus breaking its continuity, more rarely spines can be traced in the same kind of material.

Sometimes the infilling material is entirely silicious. Thus Prof. Rupert Jones, Mr. Holmes and myself have found casts of Radiolaria with indistinct traces of the network in clear crystalline chalcedony in flint meal. I have also found in chalk, after treatment with acid, casts of Radiolaria in minute silicious crystals, snow-white in colour. I have also met with casts of Radiolaria in greenish-grey mud, which could be broken up by pressure with a needle. These two last might easily be missed in sections of the rock which contained them. Mr. Shrubsole records Radiolaria in the London Clay preserved in iron pyrites. Except in the Tertiary Rocks—*e.g.*, the Radiolarian earths of Barbados and in those occurring in the Nicobar Islands or the marls of Cyprus, it is rare to find free and well-preserved skeletons of these forms, yet they do

* Hill and Jukes-Browne, "On the Occurrence of Radiolaria in the Chalk." *Quart. Journ. Geol. Soc.*, vol. II, p. 600.

occasionally occur in the Secondary Rocks, for, as will be presently mentioned, beautifully perfect tests, some of which are quite equal in their state of preservation to those from Barbados, occur in the Chalk. Taken as a whole, it will be seen in the sequel that Radiolaria are best preserved in such rocks as contain a considerable percentage of inorganic matter.

III.—RADIOLARIA IN TERTIARY DEPOSITS.

Barbados Earths.—The Oceanic Rocks of Barbados and their relation to other rocks of that Island have been described in some detail in a paper by Messrs. Harrison and Jukes-Browne.* By reference to that paper it will be seen that they rest unconformably on the Scotland Beds. They are described (from below upwards) as, first, chalky (foraminiferal) earths passing upwards to earths in which silicious organisms, chiefly Radiolarians, predominate (40 ft.), and these to the pure Radiolarian deposit (130 ft.). This, again, passes upwards into calcareo-silicious earths (with layers of pumiceous sand) (45 ft.), and ultimately to chalky foraminiferal earths and marls (25 ft.).

In the lowest and also the highest chalky deposits Radiolaria are rare or absent, but in the calcareo-silicious, and silicio-calcareous rocks there is a gradual increase in their number. In the upper and lower part of the deposits which contain a proportion of calcareous matter, the Radiolarians as a whole are recognisable in thin sections only by their outline, often feebly marked in the matrix of the rock, but in some cases the test has remained hollow and is infilled with a clear substance of the nature of colloid silica, or less commonly with crystalline calcite. In the purest silicious earths the tests are thickly packed in a matrix of Radiolarian fragments, and the details of their outward form and the meshwork can be closely followed and, as in the less pure earths, some of the tests may be hollow and filled with clear material. There is, however, even here evidence of the instability of the skeleton, for in some specimens of silicious earths they have suffered partial dissolution. It is indeed only by the study of a long series of these deposits that one comes to realise which may be and which are not the ghostly outline of these organisms.

The most silicious of these rocks are permeated with silica in the colloid state which forms the cementing material, and is probably derived from the Radiolaria, spicules, and other silicious organisms. Compared with recent deposits the central part is clearly a Radiolarian ooze, passing gradually upwards and downwards to a calcareous ooze containing "few."

* Harrison and Jukes-Browne, "The Geology of Barbados, Part II: The Oceanic Series," *Quart. Journ. Geol. Soc.*, vol. xlviii, p. 170.

Radiolarian deposits probably of Miocene age also occur in the Island of Trinidad. They are known as the Naparima marls. They have been described by Mr. L. Guppy* and later by Messrs. Jukes-Browne and Harrison.† In general character and succession they agree with the typical series of Barbados, though in the relative development of the various members of the series they differ greatly. The Globigerina marls and the representatives of the calcareo-silicious and silicio-calcareous beds are thicker, while the purer Radiolarian earth is thinner than in the Barbados. There is also a larger percentage of quartz and argillaceous matter, evidence of a closer approach to land; on the other hand there is less pumiceous material.

A small specimen of these marls was kindly sent me by Mr. Arthur Earland. It is a close grained, whitish, laminated marl. Seen in section the matrix is a fine isotropic material, apparently fine inorganic matter and Radiolarian débris with a few spicules. Scattered through this the tests of entire Radiolaria are discernible, with many foraminifera, chiefly Globigerina. Notwithstanding this latter fact the quantity of calcareous matter in the matrix is not very large, the foraminiferal tests are for the most part entire, and stand out clearly when the section is viewed with crossed Nicols. Mineral grains are few and small in this specimen. There seems to me some little difference in the predominating Radiolarian forms when compared with those in the Barbados earths, and diatoms are distinctly more numerous.

Mediterranean Area.—Rocks containing Radiolaria, probably of Miocene age, occur in the South of Europe (Calabria and Greece), in the Islands of the Mediterranean (Sicily and Cyprus), and in the northern coast of Africa between Oran and Tripoli, this latter being the well-known Tripoli earth. Hæckel described a specimen sent him from Oran as a pure Radiolarian deposit similar to the Radiolarian ooze found by the *Challenger* in the Central Pacific.‡

White chalky and silicious earths containing many Radiolaria occur in the island of Cyprus, in association with Globigerina oozes. Specimens coming from Nicosia, Paralimni and Goshi were kindly sent by Mr. Bellamy to Mr. A. J. Jukes-Browne, who forwarded them to me. Their actual succession and their stratigraphical position have not yet been fully ascertained, though they probably are of Miocene age; nor have I yet attempted a critical investigation of the Microzoa. They are Globigerina marls, but in the relative quantity of calcareous and silicious organisms which they contain they will certainly

* "On the Microzoic Formations of Trinidad." *Quart. Journ. Geol. Soc.*, vol. xlviii, p. 528.

† "On the Oceanic Deposits of Trinidad," *Quart. Journ. Geol. Soc.*, vol. lv, p. 177.

‡ See *Challenger* Report "Radiolaria," p. clxvi.

compare with the silicio-calcareous and calcareo-silicious rocks of Barbados. In some specimens the tests of the Radiolaria have undergone partial solution and the rock is permeated with silica in the amorphous colloid state. The tests of foraminifera (chiefly Globigerinæ) and also the hollow Radiolaria are also filled with clear amorphous silica, which, however, in some cases has assumed the form of crystalline chalcedony. Thus in the more silicious specimens the Radiolarians are only to be recognised by their outline, the silicious network having for the most part disappeared.

A specimen of white chalky rock from Paralimini when seen in thin section looks at first sight like a pure Globigerina ooze, large specimens of that foraminifera being common; it is only here and there that a Radiolarian can with difficulty be recognised. Yet on treatment with acid, the residue (14 per cent.) consists largely of Radiolarians which in their state of preservation and in variety of form rival, if not excel, those contained in similar rock from Barbados. I estimate the Radiolarians to form at least 6 per cent. of the mass of the rock, the remainder of the residue being amorphous silicious matter, with a few spicules and sand grains.

Australia.—A dull or yellowish white rather soft rock from Fanny Bay, Port Darwin, Australia, proved to be a deposit containing many Radiolaria when examined by Dr. G. J. Hinde.* This rock while made up chiefly of Radiolaria and their débris contains also minute grains which "appear to be quartz, while others are probably rutile." The Radiolaria appear as a whole as mere outlines, though in a few the structural details are preserved. The horizon is uncertain, but the rock is probably of Miocene age.

A later note of Dr. G. J. Hinde suggests the possibility of this being a deep sea deposit. I have seen this rock at Port Darwin; it forms a conspicuous band at the top of the cliffs, but I did not get specimens.

France and Belgium.—Radiolaria have been found by M. Cayeux† in the Eocene tuffeaux of the north of France and Belgium. These tuffeaux are usually sandy, glauconitic and spiculiferous, but in some localities, e.g., the tuffeaux of Lincent, contain a considerable proportion of calcite. They alternate with beds of sand, the one passing laterally into the other; the whole of them must be shallow water deposits and could not have been laid down in a deep sea. In some Radiolaria are wanting, but in others, e.g., the tuffeaux of Bouchavesnes, they are abundant; the hardness of the rock however prevents their isolation.

* "Note on a Radiolarian Rock, Fanny Bay, Port Darwin," *Quart. Journ. Geol. Soc.*, vol. xlix, p. 221.

† "Terrains Sédimentaires," p. 116, *et. seq.*

Thin sections show circular and ellipsoidal forms filled with chalcedony, but little trace of the skeleton remains. M. Cayeux refers them to the sub-order Prunoidea, and the families Ellipsida and Druppulida, but is doubtful if any can be referred to the Sphæroidea.*

Mr. W. H. Shrubsole† has recorded the presence of Radiolaria in the London clay. Their silicious skeleton seems to have undergone a complete pseudomorphic change to pyrites. Haeckel refers them to the families Sphæroidea, Discoidea, and Cyrtioidea.

A clay containing many Radiolaria, probably of Miocene age, occurs in the Nicobar Islands, but I have no further information of this deposit.

IV.—RADIOLARIA IN SECONDARY DEPOSITS.

Leaving the Tertiary rocks, we next come to the uppermost strata of the Mesozoic series, the Chalk. In a deposit so clearly oceanic in its origin one would imagine that Radiolaria, Sponge spicules and Diatoms would certainly occur, but it seems that when silicious organisms are sparsely scattered in a gradually accumulating calcareous ooze, there may be a general tendency for them to pass into solution and their silica to finally segregate in nodules. It is rare indeed to find the comparatively unaltered Radiolarian skeleton in the Chalk, yet they do occur occasionally in circumstances which show the general permeation of the deposit by silica, probably derived from organic sources, as well as a proportion of inorganic material. Evidence of their occurrence in the Chalk is rapidly accumulating.

Beginning with the Upper Senonian, Zietel has found six species in that division in North Germany.

The Arnager limestone, Calcaire d'Arnager, of the Island of Bornholm is referred by Dr. G. Ravn‡ to the Lower Senonian. It is a very sandy chalk much like some of our chalk marl, a comparatively shallow water deposit laid down within range of mud-bearing currents. In a thin section it can be seen to be full of Radiolaria, but their skeletons have to a great extent disappeared; most of them are filled with clear colloid silica and are seen in outline only. In quantity there are at least as many as in the calcareo-silicious earths of Barbados or the white limestone of Cyprus.

M. Cayeux§ says they are fairly numerous in the nodular chalk of the zone of *B. quadratus* in the South East of the Paris basin. Some are replaced by calcite, other by phosphate; he recognises the families of Spumellaria and Nassellaria. They

* "Terrains Sédimentaires," p. 130.

† "On Radiolaria in the London Clay," *Quart. Journ. Geol. Soc.*, vol. xlv, p. 121.

‡ "The Cretaceous Stratigraphy of Denmark."

§ "Terrains Sédimentaires," pp. 262, 330, 451.

also occur rarely in the chalk in the zone of *M. cor-testudinarium* in the Craie du Nord, and also in the Craie de Rouen in the zone of *M. breviporus*, and in the Turonian.

In the Smectique de Herve, Belgium, the zone of *Bel. quadratus*, M. Cayeux* has recognised twenty-seven genera of Radiolarians, and figured and described a considerable number of them. He remarks that while presenting a great variety of forms the number of individuals is restricted. Discoidea, chiefly Porodiscida and Cyrtoida are the predominant forms. He particularly draws attention to the fact that these Radiolaria are contained in an undoubted terrigenous deposit which includes also Foraminifera, Sponge spicules, and Diatoms, and which cannot be compared with an abyssal ooze.

Coming to our own Chalk, Mr. W. Murton Holmest† has described forty-one species belonging to twenty genera which he found in chalk-flints, probably from the zone of *Holaster planus*, near Coulsdon, Surrey. Mr. Jukes-Browne and I have recorded the presence of Radiolaria in the Chalk itself.‡ In the nodules of the Melbourn Rock the outlines of Radiolaria may be found replaced by crystalline calcite, and bodies which we refer to as Radiolaria occur also in the hard beds of the Chalk Marl in Norfolk, Lincolnshire, and Yorkshire. I have also found Radiolarian casts in the meal of flints, from the zone of *R. cuvieri*, at Hitchin.

Still more recently the investigation of chalk boulders found in the Boulder Clay near Aberdeen, has disclosed an extensive Radiolarian fauna. The boulders have at present proved otherwise unfossiliferous, so that the horizon of the Chalk is doubtful. The whole series of boulders collected seems to indicate a considerable thickness of Cretaceous strata, beginning with a glauconitic marly rock, which apparently passed upwards to a pure chalk. Nearly the whole of the specimens obtained contained Radiolaria preserved in different ways. In the glauconitic marl Cyrtoid casts in greenish grey mud were abundant, in company with sponge spicules. Some of the other specimens were practically sponge beds, containing a very large number and great variety of spicules. These are permeated with silica in an amorphous colloid, and largely in globular condition. They are full of the casts of Radiolarians, mostly of one form only (Cyrtoid) similar to those of the marl, though in rare cases the mesh is preserved. The casts are made up of minute silicious crystals, white in colour, which appear to have formed within the tests, sometimes the cast is of clear chalcedony. Many other specimens contain similar casts but of different species. Others again, also containing many spicules, and much

* "Terrains Sédimentaires," pp. 185 and 205—Plates vii and viii.

† "On Upper Chalk Radiolarians," *Quart. Journ. Geol. Soc.*, vol. lvi, p. 694.

‡ Hill and Jukes-Browne "On the occurrence of Radiolaria in the Chalk," *Quart. Journ. Geol. Soc.*, vol. li, p. 600.

colloid silica distributed through the mass of the rock, contain also Radiolarians in a perfect state of preservation; the delicate spines and processes are intact, and many are quite equal in preservation to those found in the Barbados earths. The forms have been partially worked out by myself and comprise at least 20 genera and some 30 or 40 species.

Many years ago Prof. Sollas* found Radiolaria in the coprolites of the Cambridge Greensand. In thin sections they are seen to be fairly common. Some are entirely replaced by opaque material, the mesh work and spines being well preserved, but the majority are filled with material clearer than the surrounding phosphate of lime, and though their outline and often the spines can be discerned the general details of the test is wanting. I have been unable to isolate any well-preserved test by the action of acid on the coprolites, which easily break down, but rounded forms which may be casts in semi-opaque granular material occurred in the residue.

Radiolaria occur in coprolites taken from a layer in the Gault 90 ft. below the Cambridge Greensand, at Arlesey, Bedfordshire. In some they occur in fair numbers, though in others they are absent.

Prof. Sollas† also found Radiolaria in the Upper and Lower Greensand; he says forms resembling *Haliomma* may be noticed of somewhat frequent occurrence. In Upper Greensand from a pit west of Puttenham, Surrey, are forms which I take to be Radiolaria in outline. Mr. G. E. Grimes‡ has described two forms from the Lower Greensand and two from the Upper Greensand of Surrey.

In the Paris Basin, in the Gaize of the Argonne, zone *Schl. inflata*, M. Cayeux§ recognises forms which he refers to the *Sphæroidea* and *Discoidea*, and in the Gaize of the Cher he also records *Spumellaria* and *Nassellaria*. They all appear to be casts, and as usual little more than the outline, with faint traces of the skeleton, can be seen in thin sections.

Mr. A. K. Coomaraswamy|| records the occurrence of Radiolaria in the Upper Gondwana Series (Jurassic), near Madras. The Radiolaria occur in white, cream or coffee-coloured shales which have a porcellaneous appearance and conchoidal fracture; they appear to be permeated by silica which, very locally, contains chaledonic patches. Thin slices show the rock to consist of a fine silicious paste containing also some small fragments of clastic quartz and (rarely) some carbonaceous specks. The Radiolaria are here associated with plant remains, and Mr. Coomaraswamy believes they "must have been

* *Quart. Journ. Geol. Soc.*, vol. xxix, p. 78 (1873).

† *Geol. Mag.*, vol. x (1873).

‡ *Geol. Mag.*, Dec. iv, vol. ii, p. 345 (1895).

§ "Terrains Sédimentaires," p. 37.

|| "On the Occurrence of Radiolaria in the Gondwana Beds near Madras," *Geol. Mag.*, p. 305, 1902.

deposited in comparatively shallow water, a state of things also indicated by the detrital character of the other beds included in the Sripurmatur group. The shales cannot, however, have been formed very near the shore.”*

Referring to these beds Mr. Foote† says “they show every evidence of having been deposited in perfectly tranquil water at sufficient depth probably to be beyond the agitation of the waves.”

In a gaize occurring in the Upper Oxfordian of France in the Ardennes, zone of *Cardioceras maria*, M. Cayeux‡ records the presence of many Radiolaria. They have, however, become so obscured in the general silicification of the rock that even generic determination is impossible.

The coprolites which occur in the mines from which iron ore is obtained in the Upper Lias at Ilsede, Hanover, have yielded a large number of Radiolarians. Rust§ described seventy-two species from this source, chiefly Sphæroidea and Cyrtoides. The coprolites, which are round, cylindrical or sausage-shaped, with smooth or slightly rough surface, vary in size from that of a lentil to a goose's egg. In thin section they are seen to consist of fine matter almost homogeneous in appearance, coloured from bright yellow to dark brown. In this matrix are embedded the Radiolaria, Sponge spicules, a few Foraminifera, particles of plants and spores, and “tintinoiden.” The preservation of these remains varies apparently according to the degrees of digestion they have undergone. In many cases the most delicate structure of the Radiolarian is preserved, in others they have been completely pulverised. Both Radiolaria and sponge spicules are often darkly coloured, sometimes they are brownish, sometimes carmine red, very occasionally they are uncoloured and water clear. The coloration is probably due to iron. Two species of Ammonites occur. *A. torulosus* (Zeiten) of the Lower Dogger, and *A. caprotinus* (Schlth) of the Upper Lias; the former not uncommon, the latter abundant, frequently occurring in the interior of the coprolites themselves. Material filling the hollow part of the Ammonites contained the same organic remains, though in less abundance, as those seen in the coprolites, so that there can be no doubt that both coprolites and Ammonites are of the same age.

In the upper part of the Jurassic System of the Alps are limestones known as the Tithonian Series. This division includes some marly or shaly limestones with more massively bedded rock sometimes coloured reddish or pink—the Aptychus beds. In the red limestone Radiolaria are abundant|| and well

* “On the Occurrence of Radiolaria in the Gondwana Beds near Madras,” *Geol. Mag.*, p. 306, 1902.

† *Mem. Geol. Surv., India*, vol. x, p. 64.

‡ Cayeux, “Terrains Sédimentaires,” p. 19, *et seq.*

§ Rust, “Beitrage zur Kenntniss der fossilen Radiolarien aus Gesteinen des Jura,” *Palæontographica*, Bd. xxxi (Oder iii, Folge vii, Band).

|| Rust, *Ibid.*

preserved. These rocks also include nodules described by Rust as hornstone and red jasper. The hornstones are of cryptocrystalline silica, perhaps not unlike our flint, grey to black in colour, and contain a proportion of carbonate of lime and rhombohedral crystals, probably dolomite; occasionally they may contain clay. The jaspers are coloured red by oxide of iron and also by red clay which fills their hollows; they may also contain white clay, or, like the hornstones, some lime. The hornstones consist chiefly of sponge spicules with foraminifera, amongst which Radiolarians occur sparingly; but in the jasper they are so thick as to press upon each other, while spicules and foraminifera are wanting. Rust says the jasper might well represent a silicified Radiolarian deposit like the true Radiolarian ooze of the *Challenger*.

In a Flysche from Teisendorf, in the Achthal, a greyish-white limestone with darker "particles" of Radiolaria occur in great numbers.* In the neighbourhood of the darker particles, they are especially numerous and well preserved. The "particles" seem to be small concretions of silica of the nature of flint; they also contain Radiolaria, though the details of their structure are less distinguishable.

A Flysche from Traunstein, in Upper Bavaria (horizon not mentioned) was, in outward appearance, much like the rock last noted, but it contained no Radiolaria, nor did a thick grey limestone from Urschlatt; but a similar rock from the Carpathians near Podbeil contained a number of fairly well-preserved forms. The two last are probably Neocomian, but their horizon is not definitely ascertained.

V.—RADIOLARIA IN PALÆOZOIC DEPOSITS.

Radiolaria occur in the Culm measures of Cornwall, Devon and Somerset. Sometimes they are crowded together, sometimes only sparsely distributed through the rock. Twenty-three genera have been recognised by Messrs. Hinde and Fox.†

The deposit which contains them seems to have been a fine mud, containing minute flakelets of mica and, in some instances, particles of quartz. Usually it is finely laminated, the laminations being due to regular lines of dark amorphous matter and fine granular particles, probably in part carbon and in part iron. Sometimes, however, the dark matter is so abundant that the rock is practically opaque. While some portions of this deposit are still so soft and unconsolidated as to disintegrate easily in water to a milky sediment, other portions are permeated with silica

* Rust, "Beiträge zur Kenntniss der fossilen Radiolarien aus Gesteinen des Jura," *Palæontographica*, Bd. xxxi (Oder iii, Folge vii, Band).

† "On a well-marked Horizon of Radiolarian Rocks in the Lower Culm Measures of Devon and Cornwall," *Quart. Journ. Geol. Soc.*, vol. II, p. 609.

(probably derived from the Radiolarians) and cherty beds have been formed. The softer parts contain many Radiolarian casts; in the harder cherty beds their skeleton has disappeared to a great extent, and as usual they are recognisable chiefly in outline. Radiolarian cherts also occur in the Carboniferous rocks of South Wales, the forms found in them closely correspond with those of the Culm.*

Perhaps one of the most remarkable discoveries yet made of a Radiolarian deposit is that in the Palæozoic rocks of New South Wales near Tamworth.† Radiolaria were first identified during the systematic examination of certain red jaspers in the Devonian Rocks, then in thin beds of silicious limestones and also in black cherts from Jenolan. But subsequently it "was found that Radiolaria were by no means restricted to the thin bands of lenticular silicious limestone, but were distributed in numbers so vast throughout the jointed clay stones, the prevalent sedimentary rock of the district (Tamworth), as to constitute perhaps half their bulk." "The thickness of the whole Radiolarian series was estimated at about 9,260 feet, inclusive of the submarine tuffs."‡ *Lepidodendron australe* occurs *in situ* in the Radiolarian series, and the authors of this paper "specially desire to emphasise the occurrence of the Radiolarian limestone only six inches above the stratum which contains so many examples of *L. australe*, and, moreover, in some examples from this horizon chalcedonic casts of Radiolaria abound in the same rock as that which contains *L. australe*."§ In some localities it would appear that limestones containing corals and crinoids are interbedded with that containing Radiolarian remains. At one point Radiolaria occur in abundance in soft clay shales. "These beds are minutely laminated, the laminæ of deposition being about 1 m.m. thick. . . ." "The base in which the tests occur is very fine grained, the particles being from 0.025 to 0.05 m.m. in diameter, and in places the clay-shales are streaked and spotted with finely divided carbon."||

From rock specimens taken from the neighbourhood of Tamworth, N.S.W., Dr. G. J. Hinde¶ has described 53 species belonging to 29 genera; few of the species are, however, common in rocks of Devonian age hitherto known, and the same want of affinity is shown when compared with those recorded from the Culm measures of Devon and Somerset.

A remarkable feature is the absence of Cyrtoid forms, and many Discoidal genera common in other fossil Radiolarian faunas.**

* Dr. G. J. Hinde, Swansea Memoir, p. 25.

† David and Pittman, "Palæozoic Radiolarian Rocks in New South Wales," *Quart. Journ. Geol. Soc.*, vol. lv, p. 16.

‡ *Ibid.* p. 17.

§ *Ibid.* p. 23.

|| *Ibid.* p. 25.

¶ "On the Radiolaria in the Devonian Rocks of New South Wales," *Quart. Journ. Geol. Soc.*, vol. lv, p. 60.

** *Ibid.* p. 62.

In the Ordovician or Lower Silurian strata of the southern uplands of Scotland, Prof. H. Alleyne Nicholson detected Radiolaria. They have been described by Dr. G. J. Hinde.* They occur in a well-marked zone bounded below by a thin band of black shale containing Glenkiln Graptolites of Sandeilo facies, and above it there is another mass of black shale with Lower Hartfell fossils having a Caradoc facies. The zone included between these two beds of graptolitic shale consists from below upwards of nodular red and green cherts, red and green mudstones, followed by massive grey mudstones, and cherts, mudstones, and shales, succeeded above by black flints and shales, with a few Glenkiln Graptolites. The mudstone accompanying the chert becomes in some places silicious and passes gradually into chert. In these transition beds casts of Radiolaria are present in the rock."†

The forms specifically identified by Dr. Hinde occur in the most silicious (cherty) portions of the rock. The greater part are mere casts recognisable as Radiolaria only in outline as nearly transparent spheres, sometimes with a visible central capsule; in some, however (specially where the rock has a red stain), the meshwork and spines are preserved by a dark material which has replaced the silica, though in respect to the details of their structure they are not to be compared in clearness with Radiolaria from more recent deposits. They are extremely abundant, and appear to be embedded in Radiolarian débris similar to that of the purely silicious deposits of Barbados, and such inorganic matter as occurs is of the finest description. Dr. Teall, who has examined sections of the cherts, thinks that some minute flakelets of mica may be present, while some very minute crystalline rods may be rutile.

With two or three doubtful exceptions, all the forms identified by Dr. Hinde belong to the legion of the Spumellaria. Amongst them are detached spicules which are referred to the sub-order Beloidea. The absence of all Cyrtoid forms is again a remarkable fact.

Radiolarian chert believed to be of Ordovician age occurs at Mullion Island, and on the mainland at Chippons Farm, Cornwall.‡ This chert very closely resembles that from Abington §

* "Radiolaria from the Lower Palæozoic Rocks of the South of Scotland," *Ann. and Mag. Nat. Hist.*, 1890, p. 40.

† *Ibid.* p. 47.

‡ See Fox & Teall "Notes on some Coast Sections at the Lizard," *Quart. Journ. Geol. Soc.*, vol. xlix, p. 199; also Dr. G. J. Hinde, *Quart. Journ. Geol. Soc.*, vol. lv, p. 214.

§ In my address last year on Flint and Chert I inadvertently included specimens from Mullion Island in the description of Culm Measure Cherts. These, however, are believed to be of Ordovician age. In a brief description of the Chert which I had examined I was influenced by their appearance, thinking they belonged to the Culm Measures.

VI.—SUMMARY AND INFERENCES.

Though there are many breaks in the chain in this summary of geological evidence, it is clear that Radiolaria have existed in the seas occupying portions of the earth's surface from Ordovician times to the present, frequently occurring in sufficient numbers to give a marked character to the rocks in which they occur. When they come upon the scene their development is such that it is fair to infer they have existed at a still earlier date; indeed evidence of progress in the form of their silicious skeleton is not entirely wanting, though our incomplete knowledge of fossil forms makes it impossible at present to draw any conclusion as to the development of the various groups. Hæckel says,* "The agreement of all Radiolaria in those consistent and essential characters of the unicellular body which distinguish them from all other Protista justifies the conclusion that all members of this class have been developed from a common undifferentiated stem form." . . . "The legion Spumellaria or Peripylea is to be regarded as the common stem group of the Radiolarian in its simplest form."

This conclusion published in 1887 seems supported by the later discovery of Radiolaria in the Palæozoic rocks; for almost all the species identified belong to the legion Spumellaria.

Thus, in 1900, Dr. G. J. Hinde† described twenty-three species from the Ordovician of Scotland. He remarks:—"With two or three doubtful exceptions the forms which I have been able to determine in this chert may be included in one of the four legions or sub-classes into which Hæckel has divided the Radiolaria, viz., that of Spumellaria."

Again in describing the Radiolaria from the Devonian Rocks of New South Wales the same author says: "The same features which distinguish the New South Wales Devonian Radiolaria from those of the Palæozoic deposits of other areas seem still more strongly to mark them off from the Radiolaria of Mesozoic and Tertiary rocks. In no respect is the difference more manifest than in the apparent absence of the Cyrtioidea. The evidence . . . from Scotland, France and Germany, and now from New South Wales, points to the conclusion that the predominant forms of the Palæozoic Radiolaria belonged to the Sphæroidea (Spumellaria) with medullary tests and radial spines, and that the Cyrtioidea were either not represented, or formed but a small part of these organisms in the earliest rocks."

But in the Lower Culm measures, the next earliest in our series, the Cyrtioidea appear, and Dr. Hinde refers four forms out of forty-seven described to this order of the sub-class

* "Report on Radiolaria in *Challenger Expedition*," p. cv.

† "On Radiolaria from the Lower Palæozoic Rocks of the South of Scotland," *Ann. and Mag. Nat. Hist.*, July, 1900, p. 43.

Nassellaria. From this point onward Cyrtoid forms are well represented and, in fact, form a large proportion of the recognised species of fossil Radiolaria.

Thus it seems possible that Radiolaria may eventually be found in still older rocks, and may prove to be among the earliest forms of life known.

Rocks containing Radiolaria may be compared with recent Radiolarian deposits, which vary from muds containing a few to Globigerina oozes, in some of which they are numerous ; but the chief interest perhaps centres in those which have been regarded as pure Radiolarian oozes, indicating abyssal depth in ancient oceans.

In comparing rocks containing Radiolaria with recent deposits we must not forget the instability of the Radiolarian skeleton ; in some cases many may have disappeared, in others circumstances may have favoured their preservation ; the material in which they have been surrounded and embedded may have become altered since it was deposited, while the conditions which prevailed before, during, and after the deposition of an extensive Radiolarian fauna must also be taken into account. Every case of their occurrence must be considered on its own merits, and no inference drawn from their mere abundance, which may be due to favourable condition of preservation.

Some of the rocks in which they occur may be dismissed with few words, for they are muds and fine sands laid down in very moderate depths at no great distance from land, and contain but "few" forms. To this class may be referred the London Clay, the Gault, and our Lower and Upper Greensands.

The Gondwana beds of the Upper Jurassic series of India may also be included among the shallow-water deposits ; the association of Radiolaria with vegetable matter may here be especially noticed.

The Eocene and Cretaceous Tuffeaux and Gaizes of the North of France and Belgium, and also the Gaize occurring in the Oxfordian in the Ardennes, M. Cayeux* regards as comparable with the shallow-water deposits of the *Challenger*, laid down either in less than 100 fathoms of water or beyond the 100 fathom line in the neighbourhood of the continents. This comparison must be taken broadly, for beyond the fact that shallow-water deposits containing Radiolaria do occur and are recorded in Hæckel's list, p. clx, of the *Challenger* Report, such deposits have not yet been carefully described. Though Radiolaria are not invariably present, in some of these deposits there are "many," while in the Tuffeaux of Bouchavesnes (Eocene) "numerous" is perhaps a term which could be applied in comparing them with recent deposits.

The coprolite-beds in the Lias at Ilsede, Hanover, cannot

* "Terrains Sédimentaires," p. 158.

be regarded as deep-water deposits. The general character of the rock, its fossils, together with the presence of particles of vegetable matter, leaves little doubt that it accumulated in water of no great depth. I do not gather from Rust's account that the Radiolaria are exceptionally abundant, but rather that they are well preserved, a fact that allows so large a number to be specifically identified. "Phosphatic nodules observed in existing deposits belong to the coast line," though they may occur "along the edge of the abyssal zone in deposits of pelagic type, which, however, from their nearness to land, still contain terrigenous elements."* No specimen described in the *Challenger* Report agrees closely with this deposit; from Rust's description there is nothing which suggests that it was of pelagic type, and it may possibly be compared to a mud containing "many" Radiolaria laid down at no great distance from a coast line.

We may now pass to the Chalk, which, while containing scanty evidence of the presence of Radiolaria, yet may have contained them in abundance. There can be little doubt that the conditions which prevailed during the deposition of the Chalk were favourable to the growth of Radiolaria; the Chalk itself is comparable with the foraminiferal oceanic oozes of the present day, in which Radiolaria are usually present often in some abundance.

The presence of so large an amount of silica in the form of flint suggests that much organic silica was once mixed with the deposit, to which Radiolaria probably contributed a share. Taking the Chalk of the Paris Basin and that of our own country together, there is scarcely a zone in which they have not been recognised, though in our own country their occurrence has not been noted in the highest beds. I think that a careful search in flint-meal would possibly reward the investigator.

It is curious that while evidence of the presence of Radiolaria is so scanty in the main body of the Chalk they should occur in numbers in localities which were probably near the confines of the Cretaceous ocean. Thus the Arnager Limestone of Bornholm, a glauconitic calcareous mud, though containing "numerous" Radiolaria, must have been laid down in comparatively shallow water within the reach of currents charged with inorganic matter. Again, in the case of the boulders of chalk which occur in the post-glacial clays near Aberdeen. These boulders were doubtless derived from the Upper Cretaceous Series, though, without fossil evidence, their horizon is doubtful. Taking a green-grey rock not unlike our Upper Greensand in appearance as evidence of the base followed by others containing 25 per cent. of insoluble matter, chiefly fine mud like our Chalk Marl, the series passes gradually to a pure Chalk containing less than 1 per cent. of insoluble material, the

* "Deep Sea Deposits," *Challenger* Report, p. 397

whole of the specimens displaying the broad general features which distinguish the Chalk. The presence of sand grains, fine inorganic matter and sponge spicules, shows, I think, that most of these boulders were derived from a Chalk laid down originally not far from land, the deposit becoming more purely calcareous as the subsidence during the latter part of the Cretaceous Epoch continued. All these boulders contain Radiolaria, except the two purest Chalks; in these no silicious skeletons were found in the residue after acid, nor could they be seen in thin sections. In those containing the most inorganic matter or sponge spicules they are "numerous," passing to "few" as the purer Chalks are reached.

The examination of a number of thin sections of flints gathered from the surface in Aberdeenshire, all of which contained casts of Cretaceous fossils, with one doubtful exception disclosed no traces of Radiolaria.

The Smectique de Herve, zone *Bel. quadrata*, is another instance of an impure calcareous deposit containing Radiolaria laid down not very far from the coast line of the Chalk sea. With this evidence of the existence of Radiolaria near its margins one may reasonably infer that they also lived in the central and clearer parts of the Cretaceous sea, but why they have preserved their identity in the muds of the shore line and not in the purer foraminiferal ooze is a question not easy to answer.

There will be no difficulty in the comparison of the calcareo-silicious and silico-calcareous marls and chalk of the Mediterranean area with the deep sea foraminiferal and Radiolarian oozes of the present day. Most of them are in fact fossil Globigerina oozes, passing in some localities to a true Radiolarian ooze. The Radiolarian ooze seems developed chiefly on the African side, for, judging by accounts already published, they stretch along the coast of North Africa from Tripoli to Oran, but it also occurs in Sicily, Calabria, Zante and Greece.*

The chalky deposits of Cyprus are not pure Radiolarian oozes; all contain a large proportion of calcareous matter, chiefly foraminifera and their débris, together with a little inorganic matter; they compare with chalky oozes in which Radiolaria are "numerous"; all, however, are deep-water deposits.

So much has been already written of the Barbados earth that it is unnecessary to discuss it here; there is a general consensus of opinion that the pure Radiolarian rock of this island, and also that of the neighbouring island of Trinidad, were laid down in water of abyssal depth. A point, however, to be noted is, that these pure Radiolarian deposits are intimately associated with foraminiferal oozes comparable with the oozes formed at less depths in the oceans of the present day; the succession, both in the Barbados and Trinidad, indicating quite clearly

* *Challenger Report*, "Radiolaria," p. clxxi.

a gradual depression and subsequent re-elevation of the ocean floor.

We have now arrived at the last four of our deposits containing Radiolaria, all of which have been claimed as representing abyssal depths in seas or oceans. Three of these occur in the earlier stages of our earth's history, the fourth is that which occurs in the upper part of the Jurassic Series in the Alps. In the last case the evidence on which this conclusion is based rests chiefly on the abundance of the Radiolaria, the homogeneous and extremely fine character of the deposit with which they are associated, its freedom from carbonates, and the general paucity of fossils, indicating an absence of life during the accumulation of the sediment. That Radiolaria occurred in sufficient abundance to justify the classification of the rock as a Radiolarian ooze I think must be taken as granted (Rust says that the tests press upon each other in some specimens which he has examined), and the fact that silicious nodules or beds of silicious rock occur indicate that the original deposit contained much organic silica which, as usual, has segregated either as chert or flint. The silicious rocks appear to be over and underlain by others, very largely calcareous; of their actual nature I am ignorant, though Steinman* says they contain a few pelagic foraminifera and Radiolaria. Our knowledge of the Jurassic Radiolarian deposits is, however, at present not large. The flints or cherts, or, as Hæckel calls them, crypto-crystalline quartzes, have not been studied in place in great detail, and what we know of the Radiolaria of these rocks has been largely gathered from fragments derived from the beds.

Next in order are the Radiolarian rocks of the Culm Measures of Devonshire and Cornwall; here, again, we have an undoubted Radiolarian deposit. Messrs. Hinde and Fox† say: "These organisms in some instances are thickly crowded in beds, in other places they are sparsely scattered in a silicious mass. Detrital minerals are, as a rule, absent in the Radiolarian beds, but in some instances they occur as microscopically minute fragments of mica and quartz. . . ." "Dark carbonaceous and ferrous materials, crystals of pyrites, rhombohedral crystals, or negative crystals of carbonate of lime or dolomite are also abundant in these rocks. . . ." "Radiolarian deposits of a similar character to these fossil beds are now known only from great oceanic depths, and we are justified in regarding these Culm Radiolarian rocks as laid down in deep water of an open sea at some distance from the shore." Mr. Jukes-Browne‡ dissents from this opinion, and says: "There is no good reason for supposing that the water in which

* Steinman, "Beobachtungen in den Alpen," p. 51.

† Hinde and Fox, "Radiolarian Rocks of the Lower Culm," *Quart. Journ. Geol. Soc.*, vol. li, p. 661.

‡ "Student's Handbook of Stratigraphical Geology," 1902 Ed., p. 269.

these Lower Culm Measures were accumulated was deeper than any other part of the Carboniferous Sea."

With regard to the rocks with which the Radiolarian deposits of the Culm are associated, there seems a division of opinion as to the true succession. Members of our Association saw what appeared to be a conformable junction between the Upper Devonian and the Lower Culm Beds. Our report* says that the Pilton Beds, which could be well made out, are followed by the Codden Hill (Lower Culm Chert) Beds. Next come the limestone of Venn and Swymbridge, and this succession was confirmed in a visit on the same day to the old limestone quarries at Swymbridge. On the other hand, Messrs. Hinde and Fox say there is a gradual passage from the shales and slates of the Upper Devonian rocks into black shales and limestones with an abundance of *Posidonomyæ*. "We think there is sufficient evidence for the view that these rocks occupy a lower position in the series than the Radiolarian (Codden Hill) Beds."†

In the discussion on Mr. F. G. Collins'‡ paper on the Culm of South Devon, Mr. Dewey remarks that in North Cornwall and east and west of Dartmoor the order of the Chert beds and limestones must be reversed, and suggests overthrust to account for it.

According to Mr. Clement Reid§ there are, west of Dartmoor, Upper and Lower Chert Beds separated by 250 ft. of black shales and lenticular limestones, and a lava bed of 50 ft. in thickness.

The examination of many specimens of the Chert and Shales of the Lower Culm Measures from quarries near Barnstaple, kindly sent me by Mr. Hamling, did not impress me with their resemblance as a whole to the Radiolarian ooze, or the Red Clay containing Radiolaria of the oceans of the present day, or with their analogue, the Radiolarian Earth of Barbados. Taking advantage of an opportunity which offered, I paid a visit to Barnstaple, Mr. Hamling most courteously accompanying me and directing me to such quarries as showed the best sections of the Radiolarian Chert as well as of the beds which appear to over and under-lie them. Later I went to Launceston and saw many of the quarries described in the paper by Messrs. Hinde and Fox.

From these quarries I collected a long series of specimens, and also some of the limestone from Marsh near Swymbridge and from Hearson's quarry near Barnstaple.

Some of the limestones from the above localities scarcely deserve the name, being, in fact, a slightly calcareous mud which,

* "Excursion to North Devon," *Proc. Geol. Assoc.*, vol. xxi, pp. 458 and 460.

† Hinde and Fox, "On the Radiolarian Rocks of the Lower Culm," *Quart. Journ. Geol. Soc.*, vol. ii, p. 656.

‡ *Quart. Journ. Geol. Soc.*, vol. lxxii, p. 413.

§ C. Reid. *Mem. Geol. Surv.*, "Summary of Progress, 1908," p. 26.

in its original condition, may perhaps be comparable with the Clay of the Upper Gault. Thin sections show that they consist largely of amorphous matter partly calcareous, through which is distributed minute calcareous particles, probably derived from Crinoids, Shells, and the like, together with minute mineral fragments. These particles, slightly coarser than the general mass, show some arrangement in layers, the longer axis of such particles usually lying in the same direction, and there are alternations of finer and coarser material. Some specimens, however, consist only of amorphous material and in section are dirty-looking from the admixture of opaque, probably carbonaceous, matter. Large fragments of Crinoids and of shell occur, but are not common.

These limestones will not break down in acid, but after its action a thin slice will be found to consist largely of amorphous matter, which I take to be silicate of alumina, and is very similar to the residue of the Gault after like treatment. Minute mineral particles are abundant.

The limestone from Hearson's quarry is seen underlying the Chert Beds which are visible above it. I cannot say whether this is an inversion of the strata or a true succession. Sections of this limestone show that it is practically identical with many of the cherts in the general character and arrangement of the material of which it consists. It is, moreover, permeated with silica and seems to indicate the passage of a calcareous to a silicious rock.

Other specimens from Swymbridge are, however, true limestones, consisting of rather small interlocking crystals of calcite showing cleavage planes. Foraminifera and fragments of calcareous organisms can be seen in them. They break down entirely and readily in an acid solution, the residue being dark-grey amorphous matter with a few sand grains, and many small thin flakes of silicified material.

Though the limestone has no striking characters, a careful comparison of sections of chert and limestone has convinced me that the Cherts and Shales are simply a silicified rock which had once the same character as the first-mentioned limestones from Swymbridge and Hearson's quarry, the silicification being probably due to the abnormal quantity of organic silica in the original deposit supplied by the Radiolaria, which has displaced the calcareous elements of the rock and segregated in the Chert beds. The general arrangement and appearance of the coarser particles in both chert and limestone seem to me not infrequently very similar, the chief difference being that the chert or shale usually contains traces of Radiolaria, and the limestone does not. The resemblance is sometimes more striking in the dull black chert than in the shales, though it can be followed in both. There appears to be some metamorphosis in the material due to

other causes than the silicification of the deposit. Crinoids occur in the chert beds; one fragment of the buff-coloured shale in Hannaford quarry, mentioned in the paper by Messrs. Fox and Hinde, was full of the casts of Crinoid stems.

The shales also appear to have been originally of the same matrix as the limestones, but are decalcified and less thoroughly permeated by silica. Though it is possible to cut some portions of the shales with a knife, experiment will show that they often contain lenticular masses of silicified material, which in places passes to what is practically chert. The soft yellowish bed at Hannaford quarry and the soft pale-grey shale at Baracadoes can be followed passing laterally into a silicious rock and to chert. Messrs. Hinde and Fox say*: "The soft shales in some instances appear to result from the partial decay of harder beds."

The Radiolaria are rather unequally distributed. Some of my sections of chert or shale contain hardly a trace of them; in others they are abundant, but in few I should describe them as closely packed. Besides the fine carbonaceous matter referred to by Messrs. Hinde and Fox, some of the cherts and shales contain many minute mineral particles which, in the case of an example from Ilington, are fairly coarse. On the whole there is a want of that homogeneity which is characteristic of a true deep sea Radiolarian ooze or clay, and I think the Radiolarian Rocks of the Culm may be classed with muds formed along the edge of a continental shelf rather than deep water oozes, though such muds may be laid down in water of considerable depth. In a recent paper, however, Messrs. Dixon and Vaughan† conclude that the Radiolarian deposits of the Culm, as well as those occurring in the Carboniferous series in South Wales, were formed in shallow water under lagoon conditions.

The most remarkable of all the Radiolarian deposits I have mentioned is that of New South Wales. Though "the upward and downward limit is yet undiscovered," for a thickness estimated at 9,250 ft. Radiolaria seem to be the chief constituent of the rock, their tests being estimated at about a million to the cubic inch. This enormous deposit shows the importance of Radiolaria as rock builders, and is also evidence that they may retain their form and be easily recognised from the very early stages in the earth's history. I have seen no examples of these rocks, and can therefore only give the opinions and draw conclusions from the remarks of those who have studied them.

Dr. Hinde,‡ in his paper on the Radiolaria, says:—"The Radiolarian clay stones of Tamworth, N.S.W., may be compared

* Hinde and Fox, "On the Radiolarian Rocks of the Lower Culm," *Quart. Journ. Geol. Soc.*, vol. lxxii, p. 628.

† Dixon and Vaughan, "The Carboniferous Succession in Gower," *Quart. Journ. Geol. Soc.*, vol. lxxvii, p. 511 *et seq.*

‡ "On the Radiolaria of the Devonian Rocks of New South Wales," *Quart. Journ. Geol. Soc.*, vol. lv, p. 62.

with the recent Red Clays with Radiolaria of the *Challenger* Report, and the Tuff Rocks with the same forms sparsely scattered in them also find their parallel in the volcanic fragmentary materials which were dredged by the *Challenger* from the depths of the Southern Ocean."

Messrs. David and Pittman,* who have studied these rocks in the field as well as in the micro-section, have come to the following, among other, conclusions: "(3) That the fact that a thick bed of coral limestone and plant beds, on three horizons, are interstratified with the Radiolarian Series, taken in conjunction with the previous conclusion—(viz. that the whole of the strata are remarkably fine-grained) shows that the radiolaria were deposited in clear sea-water, which, though sufficiently far from land to be beyond the reach of any but the finest sediment, was nevertheless probably not of very considerable depth."

Dr. Hinde,† however, remarks that it is not improbable that the plant fragments and the tuff may have been carried out by wind and wave currents, and deposited in deep water in the same manner as the masses of leaves, pieces of sugar cane and bamboo, and other débris, which Prof. A. Agassiz dredged from a depth of 1,000 fathoms at a distance of 10 or 15 miles from and off the Caribbean Islands. While this is possible, the conclusion arrived at by Messrs. David and Pittman seems the more probable.

Though some of the material of these rocks may have been derived from volcanic sources, and a portion of the fine clay be the result of the disintegration of volcanic and Radiolarian débris, after the manner in which red clay from abyssal depths is believed to have been formed, there seems to me more than a suspicion that extremely fine carbonaceous as well as terrigenous material was intermixed with this deposit during its accumulation. In the extraordinary number of Radiolaria it contains, it can hardly be compared with a typical "blue mud," though in one instance amongst the recent deposits brought up by the *Challenger*, Radiolaria were recorded as "numerous" in a green mud from 250 fathoms (see p. 8). Neither can it be compared with a "red clay" if the admixture of carbonaceous and terrigenous matter be admitted.

Agassiz‡ says: "It must be remembered that all bottom deposits merge into one another, and at times it is difficult to say whether a deposit shall be called a red clay, a Radiolarian ooze, a Globigerina ooze, or a 'blue mud.'"

Though this deposit is augmented by thin beds of volcanic material and limestone, having regard to the extremely slow rate at which it is generally agreed that the abyssal red clays

* David and Pittman, "On the Palæozoic Radiolarian Rocks of New South Wales," *Quart. Journ. Geol. Soc.*, vol. lv, p. 36.

† *Quart. Journ. Geol. Soc.*, vol. lv, p. 61.

‡ "Three Cruises of the *Blake*," vol. xiv, *Bull. Mus. Comp. Zool.*, p. 267.

accumulate, one gasps at the time which must be conceded if more than 9,000 feet of it were laid down without the help of any terrigenous material brought down by currents from some neighbouring land. The rocks which over- or under- lie the Radiolarian deposits of New South Wales have not yet been ascertained, so that we have at present no evidence of the depression or re-elevation of the land. I am inclined to think from what is before us that this deposit was "laid down sufficiently far from land to be beyond the reach of any but the finest sediment," but was practically a Radiolarian mud in contradistinction to an abyssal ooze.

With regard to our last Radiolarian deposit, that of the Ordovician series of Scotland, Dr. Hinde* remarks:—"The Ordovician chert may therefore be considered to be due to the accumulation of tests of Radiolaria, and is thus a pure Radiolarian rock equally as much as the Tertiary beds of Barbados and the Nicobar Islands, which according to Hæckel correspond with recent Radiolarian ooze and are certainly of deep sea origin, having been probably deposited at depths greater than 2,000 fathoms."

Against this Mr. Jukes-Browne† brings what seems to be a cogent argument, viz., that at Tannylaggie, west of Bladenock, grauwackes and grits are interbedded with the Radiolarian chert. He continues:—"Here, therefore, the cherts alternate with fairly coarse terrigenous deposits, clearly indicating an approach to the land which was the main source of supply, which the authors of the Memoir‡ admit. They omit, however, to explain how this association can be reconciled with the oceanic theory, and it seems to me that the facts are sufficient to disprove Dr. Hinde's contention. In justice to him it should be stated that the stratigraphical details were not known to him in 1890, when he very naturally compared the ancient Radiolarian material with modern deposits."

I am much indebted to Dr. J. Horne for a series of specimens of these Ordovician cherts and mudstones obtained from Abington, Scotland, by Mr. Macconochie, collector of the Geological Survey. From the aspect of the specimens when seen in thin sections I must agree with Dr. Hinde in believing they represent a pure or nearly pure Radiolarian deposit, for the tests, seen now for the most part only in outline, are often so crowded together that no other interpretation seems possible. The material filling the spaces between them gives little or no evidence of the admixture of terrigenous material; whatever there may be is of the finest possible description. The mud-

* Hinde, "On Radiolaria from the Palæozoic Beds of the South of Scotland," *Ann. and Mag. of Nat. Hist.*, July, 1890.

† "Building of the British Isles," 1900 Ed., p. 73.

‡ Messrs. Peach and Horne, "On the Silurian Rocks of Scotland," *Mem. Geol. Survey (Scotland)*.

stones interleaved with the chert are also extremely fine matter, and may be compared with abyssal clay of the present day. It is remarkable therefore to find west of Abington, at Tannylaggie and beyond, this chert with* "the normal character of the Radiolarian zone, being charged with recognisable Radiolaria," occurring "in constant association with greywackes," and "in such a way as to suggest the two types of rock are interbedded."

The changes from chert to greywackes are rapid, and are shown in fig. 96, p. 398. In some localities the alternating beds are of some thickness, in other places they are thin. Thus, at Dirneark layers of greywacke are intercalated between the cherts, and a thin layer of greywacke separates a band of chert, only a foot thick, from the overlying shale.

We have here in closest association and apparently without a passage bed two deposits, the one organic and hitherto looked upon as essentially a deep water formation, and the other a grit which can only be regarded as indicating comparatively shallow water with land at no great distance. The rapid transition from the one to the other is surprising; one cannot imagine that it was due to any oscillation of the ocean floor, but rather that these Radiolarian cherts were not formed in water of great depth, but only at such a distance from land as to be beyond the limit to which terrigenous material was being transported in that area at that period of the earth's history.

There are, of course, no recent deposits, nor are there at present known any comparatively recent rocks either of Tertiary or Secondary age with which these peculiar conditions of deposition can be compared. If we may, however, suppose at this early stage of the earth's history a pure Radiolarian deposit could be laid down so near a coast line as to be within range of fairly coarse terrigenous material, and therefore in presumably comparatively shallow water, it follows that ancient Radiolarian deposits do not invariably indicate abyssal depths. The fineness of the material constituting the mudstones and the purity of the Radiolarian deposit at Abington shows that only the lightest mud found its way into this locality, but one cannot, in view of the evidence near Tannylaggie, take this as altogether conclusive of abyssal depth of water.

I believe that I have now enumerated all or nearly all the most important rocks containing Radiolaria known at the present time, and have discussed the general character of most of them. In some cases the rocks enclosing these organisms are of distinctly shallow water type and show that Radiolaria could and did exist in considerable numbers within areas where fairly coarse terrigenous materials were accumulating; in other cases they occur in finer deposits which may be compared with muds laid down at some distance from the land. It is only in Tertiary times that

* "The Silurian Rocks of Britain," *Mem. Geol. Surv.*, vol. i, pp. 397-399.

we find Radiolaria associated with deposits comparable with the foraminiferal deep-sea oozes of to-day. As we proceed downwards to the older rocks the absence of such deposits becomes more and more marked.

In the Radiolarian deposits of Palæozoic age the remains of Radiolaria are associated with black mud, with the débris of crinoids, corals, shells, sometimes with plant remains, and in a few cases with sand and felspathic grit. Those of Mesozoic age are often associated with sand and glauconite, and even the Chalk, though a foraminiferal ooze closely resembling a modern deep sea ooze in its chemical and physical characters, differs from such an ooze in the fact that the dominant foraminifer is *Textularia* and not *Globigerina*. There is, in fact, no deposit of older date than the Miocene, which is quite comparable in its composition with the oceanic oozes of the present day.

It may be objected that a large part of the earth's surface is still geologically unexplored and that calcareo-silicious earths of modern and Miocene type may yet be discovered in older formations. One cannot deny the possibility of this, but since Radiolaria and foraminiferal deposits have been found in so many parts of the world, the probability is not great.

We know that Radiolaria did exist as early as Ordovician and Devonian times in sufficient numbers to form deposits analogous to Radiolarian ooze; we know, too, that the essential conditions of such a deposit was clear water at some distance from land, conditions which we should say to-day were equally favourable to the growth of foraminifera. Yet no pure compact limestones have been found in association with them which can be regarded as having been chalky foraminiferal oozes. Thus it would seem that in the early days of our earth's history the seas, while suited to Radiolaria, were not yet suited to foraminiferal life, and that the recent calcareous oozes are the result of a gradual evolution of such a fauna in the open oceans as the waters became more fitted for their development. Even to-day, according to Sir John Murray, Radiolaria are more abundant in those parts of the ocean which have relatively a low salinity.

Current action, too, may be an important factor in the determination of the position of a Radiolarian ooze. Though generally present in the waters of the open ocean their numbers may vary considerably, and their greater or less abundance in surface water may affect the nature of the bottom deposit. They appear to be especially numerous, together with foraminifera and pelagic mollusca, in the equatorial and counter equatorial current between the Sandwich Islands and Tahiti, a position which corresponds fairly with a deposit of Radiolarian ooze, and the position of the Radiolarian ooze on the eastern side of the Indian Ocean is very suggestive of the influence of current action.

It is the opinion of many biologists, such as Moseley and Heilpin, that all branches of early invertebrate life originated in shallow waters near the coast lines, and that the modern deep sea fauna has been derived from a littoral fauna. The earliest oceanic fauna may have been a surface and pelagic fauna mainly composed of Radiolaria, while the earliest foraminifera may have been such as lived on or near the sea floor, and obtained their food in shallow water near the sea shores. Even in carboniferous times the prevalent foraminifera are heavy solid forms, such as Fusulina, Endothyra, Valvulina, and Saccamina.

It is not improbable that the earlier condition and distribution of oceanic waters was not that of the present time; the great depths now attained in many localities, with the concomitant results affecting organic deposits, may be only an accident in the present physical condition of the earth's crust.

Mr. Jukes-Browne* in his short essay on the supposed permanence of Continents and Oceans, in the 2nd Edition of his "Building of the British Islands," surmised that "in the early Palæozoic times the total area of the sea was less than that of the land and possibly there was more equal general distribution of land and sea over the whole surface of the globe," and further "that the tendency of all subsequent changes has been to alter this arrangement by widening and deepening certain sea basins and depressions till they assumed the dimensions of oceans."

He informs me that if he were now revising this passage he would lay more stress on the comparative shallowness of the Palæozoic seas than on the possibility of their more limited extent; he thinks their area may have been as large, but that their depth was much less than that of Tertiary and modern oceans.

If we may suppose in the earlier stages of the earth's history there were no great oceanic depths, and consequently no abyssal deposits, the waters of the Palæozoic oceans may have shallowed very gradually and terrigenous material may have been carried to a greater distance from land than it usually is at the present time. There would then be a gradual but irregular passage from silicious and argillaceous terrigenous deposits to such a sediment as Radiolarian mud.

* "Building of the British Islands," 2nd Edition, p. 448.