

No. VIII.—A STUDY OF OIL SHALES AND TORBANITES. By  
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INTRODUCTION.

THE oil shales and torbanites form a group of materials which have in common the characteristic that on distillation they yield a product consisting typically of paraffins and olefines, and this feature is the source of their industrial importance.

The Boghead coal or Torbanehill mineral of Armadale and Bathgate, Linlithgowshire, is the type of the torbanites or Boghead coals, and is the material originally distilled in Scotland for the manufacture of mineral oil. For oil-making this coal was exhausted in ten years, and for the past fifty years the Scottish industry has had to rely on the oil shales which occur in the Lothians, Fife, and Lanarkshire.

Two varieties of torbanite occur in Linlithgowshire in the one seam—one brown, the other black. The former is the richer of the two, and of more restricted occurrence. It is very light in weight (sp. gr. about 1·2), tough, almost structureless megascopically, breaks with a conchoidal fracture, thin splinters being translucent and red in colour at the edges, has a light brown streak, and is most resistant to the weather. The black variety differs mainly in being of a dense black colour, with glossy fracture and brownish-black streak.

The Lothians oil shales are heavy, laminated rocks (sp. gr. 1·7 to 2·3), brown to black in colour, with pronounced bedding, which is particularly obvious after weathering or burning. Of the oil shales there are also two varieties—plain shale and “curly.” The former is the more usual, and the latter seems to be produced from it by the effect of movements under pressure resulting in contortion of the bedding and the development of numerous slickensides.

At Armadale the torbanite occurs at the base of the Scottish Coal Measures (immediately above the Millstone Grit), and is associated with typical Coal Measures deposits of sandstone, fireclay, ironstone, and common coal. Closely similar or identical material is known from elsewhere in British Carboniferous rocks, and torbanites of Carboniferous or Permian-Carboniferous age also occur under similar conditions in various parts of Europe; America (Jeffrey, 1910); Africa (Hatch & Rastall, 1913, p. 136); and Australia (James R. M. Robertson, 1892, p. 88; Carne, 1903).

The oil shales of the Lothians occur on a lower horizon than the torbanite, in the upper part of the Calciferous Sandstone series, underlying the Carboniferous Limestone. The associated strata consist of sandstone, fresh-water limestone, so-called marl, fireclay, one or two thin coals, and black shales, only portions of which rank as oil shales.

From the fact that the basis of the Scottish oil industry is a shale, that term is frequently applied to other materials capable of yielding oil by destructive distillation, including such diverse materials as torbanites, bitumens, and limestones, &c., soaked with petroleum, irrespective of whether or not they are laminated clay rocks, which are the essential features of a shale. This use of the term is, of course, quite incorrect.

In September, 1913, the late Mr. W. Fraser, then managing director of the Pumpherston Oil Company, Limited, suggested to the writer that a study of oil shales by means of the microscope would probably yield useful and interesting results, and a beginning was at once made with a series of samples previously collected for megascopic study. The general bearings of the question very quickly emerged, but at the same time it became evident that the comparison of micro-sections with the results of tests of material from the same seam made at different times by various hands was unsatisfactory, not only on account of the varying results got by different workers, but also because of the natural variations in the seam. It therefore became necessary to undertake a series of tests, and these were carried out by a standardised method on samples selected as showing in the highest degree the special qualities of the particular material under test and on quantities as small as possible in order to

reduce the disparity in size between the sample distilled and that submitted to the microscope. A portion of the sample tested was retained for reference and micro-sections were cut from it. As a guide to the quality of the crude oil produced by distillation, a setting point was determined by observing the temperature at which a drop of oil suspended on the bulb of a thermometer ceased to be fluid, and the specific gravity was determined by means of a 10-gram bottle (or, in the case of very small samples, by suspension of a drop in another liquid, the specific gravity of which was then found by means of the bottle).

The micro-sections made and examined number about two hundred finished sections, while a great many temporary preparations have been made of the spores, &c., of existing cryptogams, and, in view of the algal theory of the origin of the materials under discussion, much attention has been paid to microscopic algæ, and the phenomena of the growth and decay of several species have been kept under regular observation for the past two years.

The samples examined have been personally collected, and their modes of occurrence studied, from various places in the counties of Linlithgow, Midlothian, Lanark, Fife, Stirling, Renfrew, Ayr, Sutherland, Caithness, Inverness, Sussex, Hampshire (Isle of Wight), Dorset, Antrim, while others have been obtained, through the kindness of various friends, from France, Spain, Bulgaria, Siberia, China, Canada, United States, West Indies, Victoria, New South Wales, Tasmania, Iceland. The age of the samples ranges from Ordovician to Recent.

#### PREVIOUS WORK.

The lawsuit arising out of the Torbanehill mineral lease (1854) brought forth much evidence, both microscopic and chemical, as to the origin of the "Torbanehill mineral," but little assistance is to be got therefrom, and the same can be said of various vague theories to be found in the publications of the Royal Physical Society of Edinburgh and the Edinburgh Geological Society, and elsewhere during the next thirty or forty years.

Dr. J. R. M. Robertson (1892, p. 110), after discussing the

various occurrences of torbanite in New South Wales, says, "I see no reason for believing that the origin of this mineral differs essentially from that of other coal seams. It has in all probability been formed by deposition of a particular description of plant life that only flourished in limited areas where the conditions of soil, temperature, and protection existed."

In 1892, Bertrand and Renault published "*Pila Bibractensis* et le Boghead d'Autun," which was followed by a series of papers dealing with the allied rocks of Scotland, New South Wales, and America. They sought to prove that the Boghead coals or torbanites were composed of accumulations of microscopic gelatinous algæ, preserved by a hypothetical anti-septic solution, which gave to oil shales and torbanites their peculiar characters. They based this theory on the presence in these deposits of enormous numbers of yellow or red bodies showing internal structures remotely resembling the cells of certain recent free-floating microscopic algæ, and assigned the forms found in the torbanites of various countries to definite algal species. This theory was supported by Potonié (1910).

Jeffrey (1910; 1914, p. 735; 1915, p. 220) attacked the algal theory, and urged that the supposed algæ were the deeply sculptured coats of the spores of vascular cryptogams.

David White (1906, p. 26; 1909, p. 50) accepted the algal theory, but according to a later publication (1913, p. 3) he has transferred his support to the spore theory.

Seward (1898, p. 178) expresses doubt as to the organic nature of the structures described by the French investigators, and adds, "It is by no means impossible that further research might lead us to accept the view that the brightly coloured organic-like bodies may be inorganic in origin."

H. M. Cadell (1910, p. 23-24) refers to the "grey shale" of West Calder as being "composed almost entirely of entomostracan remains squeezed together like grains of linseed in a piece of oil cake," and goes on to say, "In this connection it may be noted that entomostraca are exceedingly common in many of the shales, together with fish and plant remains, and it is probable that the large quantity of ammonia in some beds is due to the high percentage of nitrogenous animal matter that they originally contained." But he remarks, "Other

shales again are almost totally devoid of fossils, although rich in oil and ammonia, and this probably points to the presence of organisms with soft bodies, and no shell or hard covering capable of preservation in the fossil state." At another place (1901, p. 29) he suggests that the numerous fossil fish in a part of the Pumphreston shales have something to do with their unusual richness in nitrogen. In "The Story of the Forth" (1913, p. 8) he suggests that oil shales are derived from an extremely macerated peat embedded in estuarine mud.

D. R. Steuart (1912, p. 164) details some experiments designed to determine the nature of the organic matter of the shales, and comes to the conclusion that it is not of the nature of resin or bitumen, because it is not extracted by solvents of these substances, but that it may be derived from vegetable or animal matter altered by special bacterial action.

W. Scheithauer (1913, p. 12) says, "It would appear that a large number of marine animals perished on certain occasions, probably as the result of volcanic outbreaks, the Scottish shale deposits having been shown to belong to the volcanic region."

John B. Robertson (1914) examined a number of shales and torbanites chemically, and his conclusions are, "There is but little resinous matter in oil shales, the main bulk of the organic material being insoluble in organic solvents," and "the organic matter in oil shales is a decomposition product of vegetable matter (originally algæ, spores, or simply concretions of macerated organic material) similar in nature to that found in peat and in cannel coal, and produced by a definite combination of external conditions." He also says, "There would seem to be no experimental ground for concluding that animal remains are mingled with this vegetable product." The paper contains a most useful series of complete analyses.

E. H. Cunningham-Craig (1916) argues that the oil shales are simply the last stage in the drying up of petroleum-charged strata, and that certain portions, because of their more absorbent nature and greater affinity for oil, have retained a larger proportion than others, and have become oil shales, while the structures regarded by other authors as alternatively algæ or spores are simply globules of oil solidified on an inorganic or other nucleus.

Thus there are three distinct theories respectively ascribing the source of the hydrocarbons to—

- (1) Animal matter ;
- (2) Vegetable remains ;
- (3) Natural petroleum ;

with a fourth which makes a blend of Nos. 1 and 2.

Megascopic examination of the Lothian shales gives little guidance as to their origin. In some, shells of ostracods are abundant, while carbonised plant remains—stems, twigs, leaves, roots, cones, &c.—are common enough, but make up a quite inappreciable proportion of the shale.

The microscope reveals a great variety of material—

- (1) Very minute carbonised fragments of plants, frequently showing traces of cellular structure, with occasional small spores.
- (2) The yellow bodies regarded as algæ, spores, or oil globules.
- (3) Shells of minute crustaceans, and bones, teeth, and scales of fish.
- (4) Mineral matter consisting of sand grains, crystals of pyrites, &c.

A first survey of this varied collection of *débris* produces an impression that it is hopeless to attempt to make anything definite out of it. The yellow bodies are of a rather indefinite, rounded, brain-like form, and their identification with the algæ of Bertrand and Renault as seen in the Boghead coals of Scotland, France, and Australia depends rather on colour and outline than on internal structure, as this is rarely well seen in the Lothian shales. The spores generally present in the Lothian shales are not at all of the type found in, say, the Kiltongue, Lillie's, the cannels, the spore bands of the coalfields, or in tasmanite; they are much smaller and more transparent, but bear the tri-radiate ridge typical of the tetraspore (Bennie and Kidston, 1886). They have not been noticed elsewhere, and are so comparatively scarce in the shales that their exact determination seems unimportant.

At the outset a series of sections was prepared from well-known seams (Fraser, Fells, Broxburn, Dunnet, Pumpherstons)

from various localities, the samples sectioned being taken in some cases from definite positions from top to bottom of the seam and from a number of scattered parts of the workings. The examination of these sections showed that the mixture of ingredients is a fairly constant feature of all the shales, but the constituents occur in varying proportions, not only from seam to seam but in different parts of the same seam. The variations, however, seemed to be on so comparatively small a scale as to make it difficult to assign to each constituent its part in giving to the shale its peculiar properties, and it therefore became necessary to seek for allied materials containing the various ingredients in more definite proportions. In previous megascopic study of the subject a collection of such materials had already been accumulated which much simplified matters, and others have been added. In the course of identifying the frequently very fragmentary organic remains and in seeking for the links in the chain of evidence, many blind alleys have had to be followed, but it is not proposed to re-traverse these in the course of the present discussion.

#### THEORY OF ANIMAL ORIGIN.

1. *Levenseat Shale*.—This is a strong bluish-black shale containing the usual megascopically visible plant and fish remains, with a few ostracods, and a portion which is crowded with the shells of lingula. The microscope shows that the two materials differ only in the presence of a great mass of shells in the lingula portion (Plate VIII., Figs. 1 and 2), and it might therefore be expected that if animal matter has any bearing on the production of oil shales this part should be richer, and might give an oil of different quality. On distillation the following results are got:—

|                          | Crude Oil.<br>Gals. per Ton. | Sp. Gr. | S.P.   |
|--------------------------|------------------------------|---------|--------|
| Normal Shale, - - - -    | 44·7                         | ·895    | 30° C. |
| Lingula Portion, - - - - | 31·7                         | ·892    | 31° C. |

The lingula portion is thus the poorer in yield, while there is no difference in the quality of the product. It must therefore be assumed that the very large numbers of animals, of whose presence the shells are the visible evidence, have contributed nothing to the oil yield, and their shells have simply constituted

a dilution of the matter forming the normal shale. This comparison becomes still more striking if the yields of the two materials are referred to an ash-free basis, *i.e.*, the effect of the mineral matter on the yield per ton of shale is eliminated and the comparison restricted to the organic matter. It is then found that the yields are identical. (See Table II., at end.) It may be noted in passing that one-half of the ash of the lingula portion is soluble in hydrochloric acid. This, representing probably the calcium carbonate of the shells, is some measure of the part which animal matter might have been expected to play in the formation of this shale. (See Tables II. and III.)

2. *Thorntonhall Shales*.—These shales occur in the neighbourhood of the Hurlet Limestone at Thorntonhall. The upper one is a tough, blue-black shale, of a somewhat cancelloid nature, showing in micro-section both animal and vegetable remains, while the lower shale is crowded with ostracod shells, and contains also fish remains, but no noticeable vegetable matter (Pl. IX., Figs. 1 and 2). On distillation the yields are—

|                      | Crude Oil.<br>Gals. per Ton. | Sp. Gr. | S.P.   |
|----------------------|------------------------------|---------|--------|
| Black Shale, - - - - | 29                           | ·910    | 30° C. |
| Grey Shale, - - - -  | Trace only.                  | —       | —      |

3. *Edmondia Shale*.—This shale, occurring below the Arden Limestone, is crowded with the shells of crustaceans, gastropods, lamellibranchs, and possibly cephalopods. Many layers of the shale are completely covered with overlapping shells, most of which are pyritised. The microscope shows a quantity of the usual kinds of vegetable matter lying between the shells. The result of distillation is—

|                    | Gals. per Ton. | Sp. Gr. | S.P.         |
|--------------------|----------------|---------|--------------|
| Crude Oil, - - - - | 9              | 949     | Below 18° C. |

As the vegetable matter present is bound to have yielded oil, and its quantity would have led one to expect more oil than is actually got, it seems necessary to credit the low yield to the vegetable matter, and to attribute its small quantity, evil smell, and poor quality to the action of the sulphur present as pyrites.

4. *Craigie Glen Shale*.—This shale occurs about midway between the Hurlet Limestone and the Hosie, and exactly fits



Mr. Cadell's description as being crowded with ostracod shells crushed together like grains of linseed in an oil cake. On distillation the yield is—

|                    | Gals. per Ton. | Sp. Gr. | S.P.   |
|--------------------|----------------|---------|--------|
| Crude Oil, - - - - | 43             | ·880    | 33° C. |

At first sight this seems to be an exception as to origin, but the sections show an abundant supply of the typical vegetable matter lying between the shells. The sample tested came from beside a fault, and was intensely slickensided; in view of other similar occurrences, it seems that this may have improved the quality of the oil.

5. *Kimmeridge "Blackstone."*—This is another apparent exception. Many of the bedding planes are covered with the shells of ammonites of considerable size and of other molluscs, while the mass of the rock shows very numerous seed-like bodies, in shape and size closely resembling ostracods, and it has therefore been supposed that the peculiar properties of this material are due to animal matter. The microscope shows that the supposed ostracods are minute lenses of calcite or siderite—purely mineral segregations—while the other genuine evidences of animal life are so relatively scarce and so irregularly distributed as to be quite inadequate to account for the yield of 58 gallons per ton which the material gives.

The mass of the rock is made up of vegetable matter very similar to that found in some of the other materials, plentifully dusted over with minute crystals of iron pyrites. Probably the presence of the last-named is the cause of the comparatively low yield and the poor quality of the oil (sp. gr., ·996; s.p., below 16° C.).

Unfortunately the optical evidence as to the presence of animal matter is limited to those animals possessing hard parts capable of preservation, and it may be argued that such evidence is not conclusive as soft-bodied animals may have contributed to the shales without leaving any visible trace, but it would certainly be strange if those instances in which animal remains are so prominent to the eye should be just those in which their perishable parts had not influenced the essential characters of the oil shale.

The cholesterol and phytosterol test is of no value when

applied to shale *oils*, and no one seems to have applied it yet to the shale itself. There remains apparently only the method of investigation just described, and it has been applied to all the material available which seemed to give support to the idea that animal remains are an important contribution to the formation of an oil shale.

In view of the results obtained, and the fact that the richest oil-yielding materials known (the torbanites) give only the rarest sign of the former existence of animal life, it must be assumed, until fresh evidence is available, that animal matter has contributed in no material way to the formation of oil shales and torbanites.

#### THEORIES OF VEGETABLE ORIGIN.

It now remains to determine the nature of the vegetable matter present, and whether it is capable of conferring on the shale its distinctive character. For this purpose it is necessary to give attention to coals of various kinds and to some of the allied shales of the coalfields.

For convenience in the foregoing the yellow bodies—the supposed *algæ*—have been included as vegetable matter, but their exact nature will now be discussed.

That these yellow bodies have some close connection with the yield of oil from the various typical shales is shown by the fact that they occur in similar form in more or less abundance in all the materials so far examined (with the exception of those from New Brunswick, Utah, and Colorado), which yield an oil comparable with that from the Lothian shales. Various other ingredients may or may not be present, but these yellow bodies are a constant feature. (See Tables 2 and 3.)

In the case of the brown Boghead coal, the microscope shows that practically nothing but the yellow bodies is present; there is in addition only a small proportion of opaque amorphous matter\* filling the interstices, an occasional streak of bright coal,

\* The application of the terms “opaque amorphous matter” and “opaque groundmass” to this constituent is a survival of the early stages of this inquiry, when it defied all attempts to render it transparent, but in thinner sections lately produced it is often revealed as a red structureless material in which is frequently embedded minute *débris* of spores, &c.

or a sand grain. The same holds good of the black Boghead, but the percentage of opaque matter is greater, and a series can be made up, with an increasing proportion of opaque ground-mass and a diminishing proportion of the yellow bodies, through such materials as the Lillie's Shale, Wheatrigg Gas Coal, Brora Cannel, Cadder Cannel, &c. Comparison of the yields shows that there is a simple connection between the proportion in which these constituents are present and the quantity and nature of the yield; the greater the percentage of the yellow bodies the higher the yield of oil and the larger the proportion of opaque matter the higher the gravity of the oil. It seems that this opaque matter is of the nature of the amorphous groundmass of ordinary coal, and that from it is derived by distillation such products as are characteristic of coal tars (even low-temperature tars), while the yellow bodies are the source of the typical shale products. Although low-temperature distillation brings the products of ordinary coal nearer to the character of the shale product, yet the difference between the two products, even when obtained under identical conditions, is very marked.

From a study of sections of coals and a consideration of recent investigations into the subject, it seems that this opaque matter represents the liquid putrefaction products of vegetable matter, the whole of the cellular structure having been obliterated in the process of decay in water.

This opaque matter in its typical form is absent from the Lothian shales, being apparently represented there by the minute carbonised vegetable fragments (while the brown tinge of the sections may be due to its presence in a dilute form), but it is present to an important degree in the shales of the coalfields (such as the Kiltongue Musselband shale) and in the cannel coals (like the Wheatrigg, Brora, Darnley Parrot). Evidently it is this material that yields the tarry products of distillation, some paraffins, and possibly the bulk of the nitrogenous compounds (including ammonia and the nitrogen combined with hydrocarbons).

As already mentioned, there is division of opinion as to the nature of the all-important yellow bodies. Bertrand and Renault regard them as algæ, Jeffrey considers them to be spores, Cunningham-Craig classes them simply as globules of

oil—the last relics of dried-up petroleum. It is not proposed to spend time on the full criticism of these theories, but they will be briefly dealt with.

(1) Cunningham-Craig's theory (the most recent) is a resuscitation in a complete and developed form of the vague views put forward at intervals from the time of the Torbanehill trial as to a "bituminous enrichment" of certain beds. It may simply be mentioned that it is difficult to understand how, as in the case of the best torbanites, 10 or 20 per cent. of mineral matter could absorb and hold 80 to 90 per cent. of "inspissated petroleum," and the study of sections of what are unquestionably rocks soaked with inspissated petroleum from various parts of America and Russia fails to reveal anything whatever comparable with the bodies typical of the torbanites, but simply streaks of oil spread through the rock.

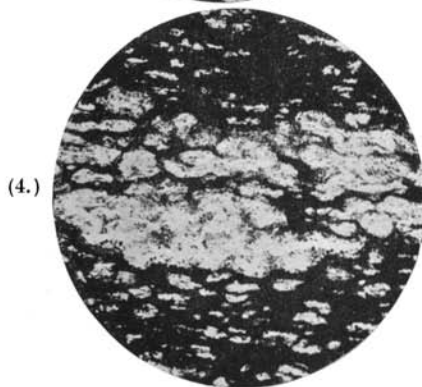
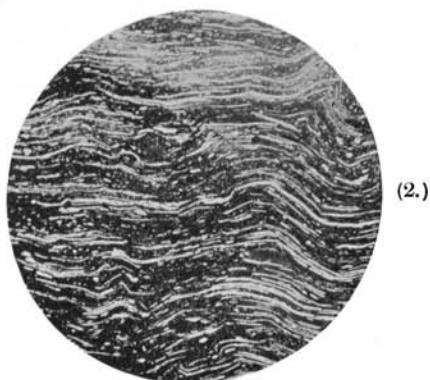
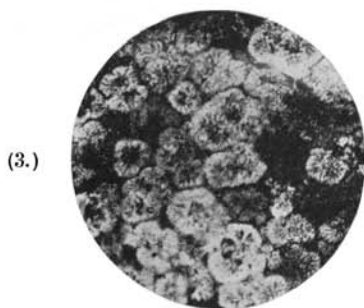
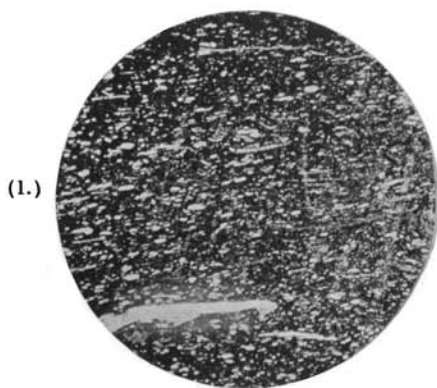
In connecting oil shales and torbanites with petroleum, Cunningham-Craig discovers a relationship between the occurrence and richness of the shales and torbanites and the existence of anticlinal structures in the strata. This idea seems to have been first suggested by D. R. Steuart (1912, p. 144) so far as the Lothian shales are concerned, and he gives figures bearing on the point. That the quality of both oil shales and torbanites is capricious is well known, and it is to be expected that a rich part should occasionally coincide with the summit or upper parts of an anticline, but it has yet to be demonstrated that the variation in quality in the direction of the dip is greater than in the direction of the strike.

(2) *Spore Theory*.—In the case of the Wolgan (New South Wales) torbanite considerable support can be found for the spore theory in the existence of a central cavity in almost every individual yellow body, and the resemblance is better appreciated after making a comparison with undoubted spores from other sources. Certain differences exist, however. Spores are very familiar objects in coals (Lomax, 1911, 1913; Bennie and Kidston, 1886, p. 82) and certain shales (*e.g.*, Lillie's), while tasmanite is simply a sandstone containing a very large proportion of these bodies (Twelvetrees, 1912, p. 4; Newton, 1875, p. 339). Originally approximately spherical, as found in coals, tasmanite, &c., they have been so deformed by pressure that the walls are crushed together, and the contents of the cell

have disappeared (Pl. IX., Fig. 3), while its site may be partly invaded by the embedding material which has found entry through the micropyle or the ruptured spore wall. The originally spherical space is thus reduced to a mere line, which may sometimes ramify, through the folding of the spore coat, but which does not penetrate to the outer boundary (except at the micropyle). In the case of the bodies in the Australian torbanites, the central line generally ramifies considerably, and very frequently traverses the whole length of the body (Pl. VIII., Fig. 4), while in the case of those occurring in the French and Scotch torbanites and in the Scotch and some other shales and cannels, it is totally absent, and its place is frequently taken by a reticulated system of lines wholly inconsistent with the spore idea (Pl. VIII., Fig. 3).

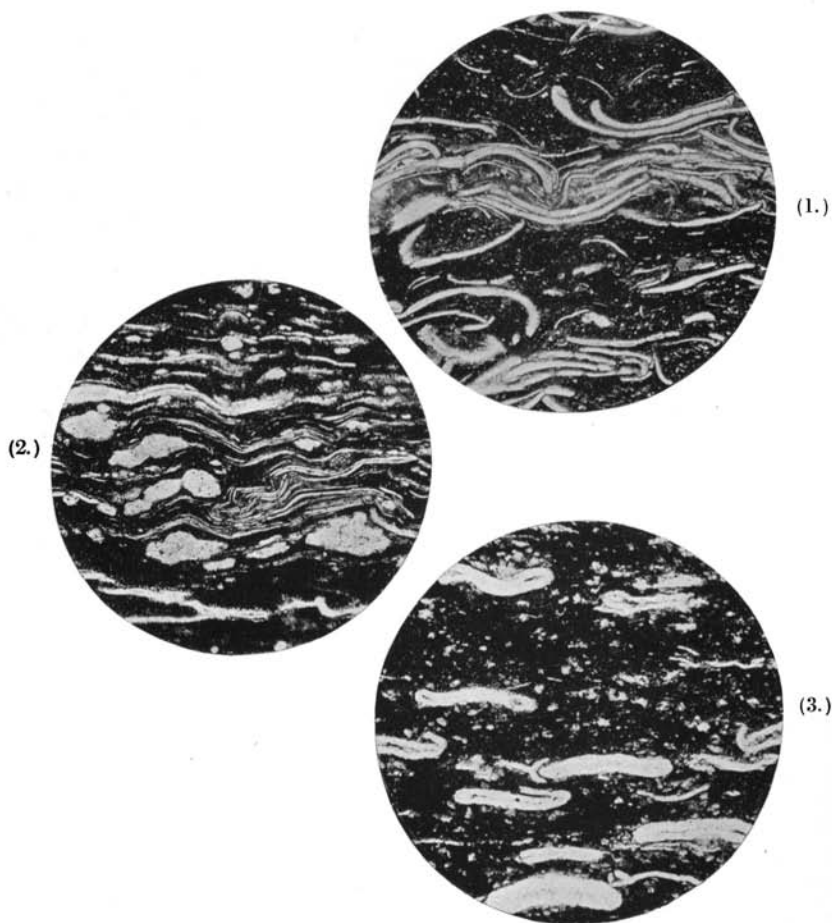
(3) *Algal Theory*.—Bertrand and Renault ask us to suppose that algæ, consisting of water to the extent of about 90 per cent., and of most fragile structure, have been preserved by the action of a hypothetical antiseptic solution, produced possibly from their own decay, and have been enabled to resist pressures which have reduced to discs the robust spherical spores lying beside them, and have flattened branches and trunks of trees to thin sheets of carbonised material, and to escape processes of decay that have converted woody material to a structureless mass. The nature of existing free-floating microscopic algæ—and it is by them that we must judge their ancestors—is such that a slight change of temperature or some other unfavourable circumstance will cause the death and almost instant complete dissolution of the organisms. So rapid is this process that a tubeful of water strongly coloured by the presence of immense numbers of these algæ becomes visibly clearer under the influence of sunlight and the accompanying rise of temperature.

The theory attributes the preservation of the algæ to the action of the antiseptic solution, now represented by the opaque enveloping material, and it might therefore be supposed that the greater the proportion of that groundmass the more perfect would be the preservation of the characteristic structures, but this is by no means the case. In such materials as the Kiltongue shale, the Brora and the Wheatrigg cannels, in which the groundmass is the preponderating constituent, it is rarely



*Photos. by S. Fingland.*

Photomicrographs of Oil Shales.



*Photos. by S. Fingland.*

Photomicrographs of Oil Shales.



that the "algal" structure can be traced in the yellow bodies. On the other hand, it might be urged that it is in the richest materials that the best structures will be found, but in the Hartley Vale torbanite (the richest material known) they are much less perfect than in the Wolgan torbanite (both from New South Wales).

Further, the yellow bodies are to be found with other materials (such as spore cases, ostracod, and other shells) bent around them in a way that shows conclusively that they can never have been the fragile bodies which the algal theory requires (Pl. IX., Fig. 2).

(4) "*Resin*" Theory.—From a study of the mode of occurrence of these bodies in a variety of materials the conclusion has been reached that they are simply grains and fragments of resin, and the supposed cell structures are merely the effects of physical and mechanical processes incident to geologic action.

The work of David White and Reinhardt Thiessen (1913, 1914) has shown the prevalence of resin in the vegetation of the Carboniferous period as well as of later times, and that the decay and elimination of the more perishable and woody parts results in a concentration of the resins in the residue. Resins occur in plants as secretions from wounds, and also in definite canals and cells in stem, leaves, and fruits, and vary in consistency from brittle solids to viscous liquids. When occurring in canals they are set free as minute needle-like rods on the decay of the tissue, when in cells they are set free as more or less spherical or subangular grains, and when derived from wounds they are in irregular lumps.

Early in the examination of the shales material was noticed which, from its colour, form, and cracked appearance, and occasional occurrence within the cells of carbonised wood, was tentatively regarded as resin, and a careful study of such occurrences has resulted in the construction of a series of stages in the development of the typical "algal" structures. It seems that in such cases as the French and Scotch torbanites we have simply an accumulation of resin grains (possibly derived from rods or wound lumps by attrition) originally containing a proportion of volatile matter in their constitution, and the evaporation of this, with consequent internal shrinkage and strain, caused the development of a series of cracks, radial and



reticulated, similar to what is produced in ironstone nodules under a similar process. Sometimes, also, the yellow bodies occurring in these materials present what appears to be a minute cone-in-cone structure, arranged radially with the apices towards the centre and with a small pit where the base of each series of cones rests on the outer boundary of the body, and probably this structure owes its origin to the same inorganic causes, as the more familiar occurrences in ironstones, &c. It is easy to see that sections of such structures at varying angles to their axes would give rise to such appearances as have been regarded as evidence of cellular structure. In studying fossilised tree stems which had been flattened and reduced to a tithe of their original diameter by pressure, it was found that in some cases a complete line of division had been opened from bark to bark through the pith and extending longitudinally through the stem, while in others, more firmly built, a line of incipient fracture had been developed in the same directions. It appears that this is a result of the pressure causing spreading of the timber at right angles to the direction of the force, with consequent rupture along the line of greatest strain. It is conceivable that pressure has acted in the same way on more or less plastic resin fragments to produce the central line ramifying through the yellow bodies of the Australian torbanites and of some of the Scotch shales. The same yielding under pressure seems to have caused the flow of the resin around resisting particles within or adjacent to them (crystals of pyrites are known to occur in recent resins), and has resulted in the formation of the alveolar and cellular structures described by the French authorities in the fossil "algæ." Minute gas bubbles are frequent in resin, being the cause of the cloudiness of some specimens of amber, and it seems probable that the distortion of such gas bubbles and vacuoles has given rise to some of the "algal" structures.

It will be noticed that this view as to the origin of torbanites and oil shales is in conflict with the conclusions reached by D. R. Steuart and John B. Robertson as a result of their chemical work on the question. Their opinion that resins are absent is based solely on the absence of material extractable by the ordinary solvents of resin, but against this it may be

pointed out that the effect of these solvents is variable. K. Dieterich (1901) says that the results of examination of resins are often very contradictory for various reasons connected with methods of working, &c., and proceeds—"This is especially true of such resins as dammar, copal, and sandarach, which exhibit oftentimes remarkable differences of solubility, even in the hands of unimpeachable authorities, according to the age and origin of the sample and the length of time it has been exposed to air and light after exuding from the parent tree." Further—"The age of the resin and time it has lain on the ground or covered up in the soil exercise great influence on its solubility. When quite fresh both dammar and sandarach are more readily soluble than after a long sojourn in the place of discovery. Thoroughly fossilised resins . . . are in consequence of their age either soluble with great difficulty or almost entirely insoluble."

The resin from the American coals was examined by the U.S. Bureau of Plant Industry, who found that only traces were extracted by chloroform, that alcohol took several weeks to remove one-third of the material in the extractor, and that only small quantities were removed by toluene and ether (White, 1914, p. 81).

It therefore does not seem that the failure to obtain an appreciable amount of extract in the experiments of D. R. Steuart and John B. Robertson is final proof of the absence of resinous material.

The following analyses are interesting as showing the close agreement between the C/H ratios of torbanites, oil shales, and resins, and the divergence in the case of other coals:—

|  | C.    | H.   | O.   | Ratio<br>C/H. | Authority.                         |
|--|-------|------|------|---------------|------------------------------------|
| Resinous vessel-casts,   |       |      |      |               |                                    |
| Montana Coal, - - -  | 76.4  | 9.3  | 14.3 | 8.2           | White<br>(1914, p. 68).            |
| Fossil Resin, - - -  | 78.6  | 9.5  | 11.8 | 6.6           |                                    |
| Torbanite, - - -   | 84.6  | 11.0 | 4.4  | 7.7           |                                    |
| „ (Black Boghead), - -   | 65.72 | 8.27 | 6.7  | 7.95          | J. B. Robertson<br>(1914, p. 196). |
| „ (Wolgan), - - -  | 63.58 | 7.81 | 4.41 | 8.14          |                                    |
| Dunnet, Camps, and Broxburn Shales (average of 9 samples), - - - | 16.69 | 2.3  | 4.17 | 7.27          |                                    |
| Coniferous Resin (average), - - -                                | 80    | 11   | —    | 7.2           | Thiessen<br>(1913, p. 293).        |
| Coal (Welsh) from - - -  | 90.01 | 6.71 | 1.67 | 13.41         | Pollard<br>(1915, pp. 14-31).      |
| „ „ to - - -   | 95.68 | 3.04 | .51  | 14.56         |                                    |

In the distillation of resin the products obtained do not resemble shale oil, but E. J. Mills (1892, p. 15) remarks that in the process "an approximation is continually in progress towards the composition of the paraffin series," so that it does not appear unreasonable to suggest that the processes which so profoundly alter the nature of woody material in the lapse of geological time (*e.g.*, in the production of anthracite) may bring the resins to a state to yield paraffins on distillation.\*

Resin in general contains no nitrogen, and therefore torbanite derived from it should be low in that element. This is indeed the case, as is well known industrially, and is well brought out by the nitrogen contents of the various materials examined by John B. Robertson (1914, p. 196), when recalculated to an ash-free basis—

|                               | Nitrogen Per Cent. |                    |
|-------------------------------|--------------------|--------------------|
|                               | On Total Shale.    | On Ash-free Shale. |
| Dunnet Shale, - - - -         | 49                 | 2.30               |
| " - - - -                     | 53                 | 2.58               |
| " - - - -                     | 61                 | 2.48               |
| " - - - -                     | 67                 | 2.62               |
| " - - - -                     | 69                 | 2.52               |
| " - - - -                     | 60                 | 2.40               |
| Camps Shale, - - - -          | 65                 | 2.11               |
| " - - - -                     | 53                 | 3.13               |
| Broxburn, - - - -             | 68                 | 1.78               |
| Torbanite (Black Boghead), -  | 63                 | .77                |
| " Wolgan, - - - -             | 81                 | 1.05               |
| " "Burnt Shale" (Maybrick), - | 75                 | 4.75               |
| " (Curly), - - - -            | 1.23               | 8.4                |

Incidentally, the above table brings out another point of interest, viz., that the nitrogen contents (or a portion of them) are left behind on liberation of the oil-forming constituents—a point well recognised in practice, but emphasised in the case of the two "burnt" shales mentioned above—and are therefore probably derived from a different source.

The percentage of nitrogen in ash-free coals is given by Brame (1914, pp. 60-61) as from 1.02 to 1.85; by Carrick Anderson (1897, p. 81), as from 1.65 to 2.11; and by Pollard (1915, pp. 14-31), as from .19 to 2.22. It will be noticed that the upper limit of these figures is somewhat less than the

\* In the discussion of this paper Mr. C. R. Cowie mentioned that on distillation under pressure resins do yield paraffins, a fact which supports the above suggestion.

average of the figures quoted above for the oil shales, but, if a portion of the organic matter of the shale is resin containing no nitrogen, it might be expected that the nitrogen contents of the shale would be less and not more. The explanation seems to be that certain of the nitrogen compounds are very stable, and resist decomposition, so that they become concentrated along with the resin. Brame (1914, p. 42) remarks, "It is evident that certain of the nitrogen compounds (in coal) are very stable since they do not break down at the high temperature of the gas retort," and ". . . of the nitrogen . . . usually 50 per cent. remains in the coke." In nature the effect of this stability is shown by the increase in the percentage of nitrogen in peat with increase in depth and age, which is remarked on by Brame (1914, p. 23) and by D. R. Steuart (1912, p. 165), and the following figures (Björling & Gissing, 1907, p. 21) illustrate this:—

|                                 |       |       |       |
|---------------------------------|-------|-------|-------|
| Depth, . . . . .                | 2·5'  | 3·6'  | 4·5'  |
| Percentage of Nitrogen, . . . . | 1·715 | 2·509 | 3·067 |

It therefore seems that in the production of oil shales and torbanites a double process of concentration goes on which results in the accumulation (1) of the resistant resinous material, and (2) of the stable nitrogen compounds, but while the accumulation of the former material is steadily progressive, a stage is reached with the latter when they break up, and the remaining material then tends towards the composition of a torbanite with reduced nitrogen contents.

With regard to the ash in the brown and black Boghead coals, if these are the result of the elimination of perishable materials, it should follow that there would be a greater percentage of ash in the brown variety, in the case of which the process has proceeded further, but, in fact, the black variety has usually the higher proportion of ash. This apparent anomaly seems to be due to the black torbanite having been formed where it received a larger quantity of detrital mineral matter, a view which is supported by the larger proportion of comparatively coarse material which can be detected in its ash by means of the microscope.

While apparently resin as such is the chief oil-yielding ingredient, it seems likely that resinous matter, such as spores,

may also be capable of playing the part, but probably to a less extent. D. R. Steuart (1912, p. 164) describes some experiments on this point, distilling lycopodium spore dust mixed with Florida fuller's earth, but apparently overlooks the fact that in the recent material he was dealing with the complete spore, while in the fossil state only the spore coat persists, and this differs in composition from the contents. Accumulations of undoubted spore remains occur in nature, and the results of distillation of two of these can be quoted—tasmanite and a spore coal from Canderrigg, Larkhall. In the former case the product is so polluted with sulphur that no reliance can be placed on the result, while in the latter, although spore coats appear to be the predominant constituent, the product does not seem to have much in common with shale oil, and therefore more evidence is needed to enable an opinion to be formed.

There remain two or three materials tested which are somewhat exceptional—the Kimmeridge "blackstone," the Skye shale, and the brown coals from Victoria and the Isle of Wight, and the "Surturbrand" from Iceland. The first two are of Mesozoic and the three last of Cainozoic age. The products of "blackstone" and Skye shale are characterised by high percentage of sulphur accompanied by a low grade of oil, and in both cases the source of the oil seems to be vegetable. Sections of the "blackstone" show great numbers of lenticular, bright reddish-yellow bodies, flattened along the bedding, showing no hint of internal structure, but plentifully dusted with iron pyrites. Fuller investigation may show these to be resin grains also. In the case of the Skye shale similar reddish material lies in definite bands, also well supplied with pyrites, but it is not quite certain that the granular structure so prominent in the "blackstone" is present here.

The Victorian brown coal approximates to the condition of a peat, containing a very large percentage of water, and the odours released on distillation and the nature of the product also resemble those from peat. It was therefore expected that the distillation of the sample of similar age from the Isle of Wight would yield somewhat similar results, and its relatively high quantity and quality came as a surprise. On account of its very fragile nature no satisfactory section has yet been made

from it, but megascopic examination reveals the presence of numerous yellow specks which fuse when touched with a hot needle; normally they are brittle, and have every appearance of resin, and it seems likely that this material owes its character to the large proportion of resin present, not only as megascopically visible fragments, but also well distributed through the mass as microscopic particles. In general aspect the material is of a somewhat waxy lustre, devoid of structure, but cubically jointed, and very suggestive of an immature cannel coal. On distillation or burning in the open it gives out a fragrance which is a welcome change from the rank odours of most of the other materials.

The "Surturbrand," although of Cainozoic age, has a very Carboniferous aspect, and on megascopic examination would be classed as very coaly blaes. The small sample appeared to be made up mainly of leaves, and yielded a forked stem several inches long and over 1 inch in diameter in its crushed state. The friability of the material as a whole seems to make successful sections impossible, and only one attempt has yet been made, but the piece of wood has yielded several very interesting sections, which reveal the extremely crushed and collapsed cells of the wood, with medullary rays and resin cells, and lenticels in the bark. A competent botanist to whom the sections were submitted had no hesitation in identifying the wood as coniferous. The inference is that there is a fair amount of resinous matter in the "Surturbrand."

A sample of a black massive material from New Brunswick was distilled; practically the whole mass came over as a heavy tar, leaving a light, shining, porous coke in the retort. Megascopically, the material showed intensely plicated dull and bright bands about  $\frac{1}{8}$  inch or less broad, very suggestive of those seen in a streaky, viscous fluid. Micro-section showed distinct flow structure, with a small amount of vegetable and mineral matter arranged in accordance therewith. Quite clearly this is a dried-up petroleum which has picked up sand and plant fragments in its passage through sedimentary strata.

Oil rocks from America and Russia proved to be finely crystalline limestones, entirely devoid of any trace of animal or vegetable matter, with the exception of two or three possible

ostracods and a doubtful wormcast. In them oil is present in streaks lying along the bedding, but no sign whatever could be detected of the structures typical of the torbanites, and which, if Cunningham-Craig's theory be correct, should be present. On distillation there is considerable difference in the quality of the products, which may have been due to variations in the temperature of the experiments or to differences in the degree of inspissation.

#### MODE OF FORMATION.

While the probable mode of formation of torbanites and oil shales need not here be discussed at length, some reference to the matter will not be out of place.

The Boghead coal of Linlithgowshire occurs as a lenticular deposit of small area (about 2500 acres), entirely cut off to the east by outcrop, and in other directions thinning out or becoming replaced by common coal, which also sometimes underlies it. It forms part of a normal sequence of coal-bearing strata, and it seems probable that it represents a deposit formed in a swamp fringed with vegetation, but with open water towards the centre sufficiently deep to prohibit the growth of plants. Towards the margins accumulations of plant remains undergoing the normal processes of partial decay were converted into common coal, but such drifted vegetable matter as reached the central area became so completely oxidised as to leave practically only the resistant resin. Where this process had the fullest effect the resulting deposit became converted, in course of time, into brown Boghead coal, while the materials of the black variety were accumulated nearer the fringe of vegetation, where the process of elimination of woody material was less complete. The fringe of growing vegetation, acting as a filter, excluded from the open water towards the centre all but the very finest of the sediment washed into the swamp, and such as did penetrate to the open water would tend to be deposited in the median zone, this accounting for the higher percentage of ash in the black Boghead. Both varieties of Boghead coal contain numerous stigmata, but these seem to be the evidence of a subsequent phase, when reduction of the water level again permitted plant growth.

Probably similar conditions gave rise to the torbanites of New South Wales, France, and elsewhere.

In the case of the Lothian oil shales conditions were somewhat different. It is clear that they accumulated as the widespread mudflats of an estuary, and apparently the river which carried the mud brought also a proportion of extremely macerated vegetable matter—possibly, as H. M. Cadell (1913, p. 10) has suggested, the wash from a peat-covered land surface—and the ebb and flow of the tide would aid in the elimination of the woody materials and the concentration of the resin. Occasionally in time of storm a few branches, cones, or leaves were drifted into these back waters to be buried in the mud, and sometimes, as in the Fraser Seam at Tarbrax, trees were able to grow and spread their roots across the ooze.

The conclusions therefore are—

- (1) Animal matter has played no appreciable or essential part in giving to either oil shales or torbanites their valuable properties.
- (2) The oil-yielding material consists of resin fragments which owe their external form either to their site of origin in the plant or to attrition in transport, modified by subsequent pressure, while the internal structures have been developed (*a*) as shrinkage or pressure cracks; (*b*) by flow around resistant grains; (*c*) by distortion of vacuoles or gas cavities; or by other inorganic processes.
- (3) The nitrogen is present wholly or mainly in vegetable débris other than resin.
- (4) There is no evidence to support the view that petroleum has played any part in the production of either torbanites or the Lothian shales, or the canneloid shales of the coalfields, but it rather seems that the reverse is the case.
- (5) It seems probable from a number of instances that dynamic metamorphism has some influence—other things being equal—on the yield and quality of oil, but this point has not been fully investigated.

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*Note.*—Since the foregoing was written a paper on “The Constitution of Coal,” by D. T. Jones and R. V. Wheeler (1916), has been brought to the writer’s notice. These investigators report that, by extraction of common coal with pyridine and re-extraction of this extract with chloroform, coal can be resolved into cellulosic and resinic portions, the former yielding almost entirely phenols on distillation, while the latter yields paraffins, olefines, and naphthenes. This change in the nature of the products of the resinic constituents they ascribe to polymerisation of the resins under pressure.

It may be pointed out that the result of the present investigation is to show that oil shales and torbanites are derived from the same “mother-substance” as coal by the action of natural processes which segregate the resistant resin portions and alter them dynamically, and that on distillation of the resulting material the paraffins and olefines are mainly or wholly derived from the altered resins, while the relics of the cellulosic substances yield the products more characteristic of coal tar, which conclusions are supported by the chemical work of Jones and Wheeler.

TABLE I.

*Yields, &c., from various Materials Tested.*

| Material.  | CRUDE OIL.        |                          |             |
|--|-------------------|--------------------------|-------------|
|  | Gals.<br>per Ton. | Sp. Gr.                  | S.P.<br>°C. |
| Brown Boghead, - - -                             | 130               | ·890                     | Below 20    |
| Black Boghead, - - -                             | 110               | ·895                     | 30          |
| Wolgan, N.S.W., - - -                            | 130               | ·883                     | Below 20    |
| Lillie's, - - - - -                              | 74                | ·910                     | 29          |
| Kiltongue-Musselband Shale, -                    | 35                | ·890                     | 33          |
| Levenseat (Normal), - - -                        | 44·7              | ·895                     | 30          |
| Levenseat (Lingula), - - -                       | 31·7              | ·892                     | 31          |
| Wheatrigg, - - - - -                             | 51                | ·944                     | 31          |
| Chapel, - - - - -                                | 28                | ·946                     | 31          |
| Brora, - - - - -                                 | 32                | ·924                     | 27          |
| Craigen Glen, - - - - -                          | 43                | ·880                     | 33          |
| Thorntonhall (Black), - - -                      | 29                | ·910                     | 30          |
| Thorntonhall (Grey), - - -                       | —                 | —                        | —           |
| Edmondia, - - - - -                              | 9                 | ·949                     | Below 18    |
| Darnley Parrot, - - - - -                        | 30                | ·986                     | 31          |
| Cadder Cannel, - - - - -                         | 55                | ·982                     | 33          |
| Skye, - - - - -                                  | 17                | 1·006                    | Below 18    |
| Kimmeridge, - - - - -                            | 58                | ·996                     | Below 16    |
| Isle of Wight Brown Coal, -                      | 32                | ·937                     | 40          |
| Feeland, - - - - -                               | 28                | ·933                     | 25          |
| Braidwood, - - - - -                             | 5                 | ·930                     | Below 20    |
| Victorian, - - - - -                             | 5                 | Heavy tarry<br>products. |             |
| Canderrigg Spore Band, - - -                     | 27                |                          |             |
| Canderrigg Bright Coal, - - -                    | 31                |                          |             |
| Peat, - - - - -                                  | 29                | —                        | —           |
| Oil Rocks (U.S.A., Canada,<br>Russia), - - - - - | 8                 | From                     | From        |
|  | 10                | ·898                     | 21          |
|  | 40                | to                       | down-       |
|  | 52                | ·913                     | wards.      |

TABLE II.

*Yields, &c., from various Materials Tested calculated to  
Ash-free Basis.*

| Material.                   | Gals.<br>per ton.<br>Total. | Ash %. | Gals.<br>per ton.<br>Ash-free<br>Basis. | Sp. Gr. | S.P.<br>° C. |
|-----------------------------|-----------------------------|--------|---|---------|--------------|
| Brown Boghead, -            | 130                         | 23·9   | 171                                     | ·890    | Below 20     |
| Black Boghead, -            | 110                         | 29·6   | 156                                     | ·895    | 30           |
| Wolgan, -                   | 130                         | 25·6   | 175                                     | ·883    | Below 20     |
| Lillie's, -                 | 74                          | 41·3   | 126                                     | ·910    | 29           |
| Kiltongue, -                | 35                          | 32·4   | 52                                      | ·890    | 33           |
| Levenseat (Normal), -       | 44·7                        | 58·15  | 107                                     | ·895    | 30           |
| Levenseat (Lingula), -      | 31·7                        | 71·04  | 109                                     | ·892    | 31           |
| Wheatrigg, -                | 51                          | 16·50  | 61                                      | ·944    | 31           |
| Chapel, -                   | 28                          | 32·0   | 41                                      | ·946    | 27           |
| Brora, -                    | 32                          | 31·2   | 46                                      | ·924    | 27           |
| Craigen Glen, -             | 43                          | 59·27  | 105                                     | ·880    | 33           |
| Thorntonhall (Black), -     | 29                          | 62·66  | 78                                      | ·910    | 30           |
| Thorntonhall (Grey), -      | —                           | —      | —                                       | —       | —            |
| Edmondia, -                 | 9                           | 80·62  | 46                                      | ·949    | Below 18     |
| Darnley Parrot, -           | 30                          | 42·15  | 52                                      | ·986    | 31           |
| Cadder Cannel, -            | 55                          | 14·5   | 65                                      | ·982    | 33           |
| Skye, -                     | 17                          | 62·0   | 45                                      | 1·006   | Below 18     |
| Kimmeridge, -               | 58                          | 28·3   | 81                                      | ·996    | Below 16     |
| Isle of Wight Brown Coal, - | { 32                        | { 7·5  | { 34                                    | ·937    | 40           |
|                             | { Moisture 10%.             | {      | { 39                                    |         |              |

*Note.*—Unfortunately the determination of the percentage of ash was not done on the broken-up material distilled, but was an afterthought carried out on another portion of the same samples, except in the case of the Kiltongue, the ash in which had to be determined from a sample from another locality.

TABLE III.

*Visible Organic Constituents of Materials Tested.*

| Material.                     | Megascopic.   |         |         |                | Microscopic. |                 |     | Wood and Spore Fragments. |
|-------------------------------|---------------|---------|---------|----------------|--------------|-----------------|-----|---------------------------|
|                               | Fish Remains. | Shells. | Plants. | Yellow Bodies. | Ground-mass. | Animal Remains. |     |                           |
| Brown Boghead,                | - —           | —       | x       | xxxxx          | x            | —               | —   |                           |
| Black Boghead, -              | - —           | —       | x       | xxxx           | xx           | —               | x   |                           |
| Wolgan, - -                   | - —           | —       | —       | xxxxx          | xx           | —               | —   |                           |
| Lillie's, - -                 | - —           | —       | x       | xxxx           | xx           | —               | x   |                           |
| Kiltongue, - -                | - x           | x       | —       | xx             | xxx          | x               | xx  |                           |
| Levenseat (Normal),           | - x           | x       | x       | xxx            | x            | x               | x   |                           |
| Levenseat (Lingula),          | - x           | x       | x       | xx             | x            | xxxx            | x   |                           |
| Wheatrigg, - -                | - —           | —       | x       | xxx            | x            | —               | xxx |                           |
| Chapel, - -                   | - x           | x       | —       | x              | xx           | —               | xx  |                           |
| Brora, - -                    | - —           | —       | x       | x              | xx           | —               | xx  |                           |
| Craiglen Glen, - -            | - x           | x       | —       | xxx            | x            | xxxx            | x   |                           |
| Thorntonhall (Black),         | - x           | x       | x       | x              | xxx          | xx              | xxx |                           |
| Thorntonhall (Grey),          | - x           | x       | —       | —              | x            | xxxx            | x   |                           |
| Edmondia, - -                 | - —           | x       | —       | —              | xx           | xxx             | x   |                           |
| Darnley Parrot, - -           | - —           | —       | —       | x              | xx           | —               | xx  |                           |
| Cadder Cannel, - -            | - —           | —       | —       | x              | xx           | —               | xxx |                           |
| Skye, - -                     | - —           | x       | —       | —              | x            | x               | xx  |                           |
| Kimmeridge, - -               | - —           | x       | —       | xxx            | —            | xx              | —   |                           |
| Isle of Wight Brown Coal, - - | - —           | —       | x       | —              | —            | —               | —   |                           |

*Note.*—No attempt at putting a numerical value on the different constituents is possible megascopically, and this can be done only roughly microscopically. A single x merely indicates the presence of the particular material, but when it forms any considerable proportion of the whole its quantity is indicated by repetition of the sign.

Different methods have been tried for the purpose of assigning a definite proportion or percentage to the various constituents visible in thin section, but no useful result has yet been attained.

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EXPLANATION OF PLATES.

PLATE VIII.

- FIG. 1.—Levenseat Normal Shale, showing numerous yellow bodies and scarce animal remains in dark groundmass. x 24.
- FIG. 2.—Levenseat Lingula Shale, showing very numerous *Lingula* shells in addition to the materials present in the normal shale. The shells show markedly the effects of pressure which the yellow bodies have been able to resist. x 24.
- FIG. 3.—Torbanite, Boson, France, showing “Pila” structure in yellow bodies. x 66.
- FIG. 4.—Torbanite, Wolgan Valley, New South Wales, showing “Reinschia” structure in yellow bodies. x 66.

PLATE IX.

- FIG. 1.—Thorntonthall Grey Shale, with very abundant ostracod remains. x 66.
- FIG. 2.—Thorntonthall Black Shale, showing well-defined yellow bodies with shells bent around them. x 66.
- FIG. 3.—Spores of Tasmanite type in a Canadian shale. x 66.