CHEMICAL COMPOSITION OF PEAT AND THE RÔLE OF MICROORGANISMS IN ITS FORMATION.*

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INTRODUCTORY.

It is commonly agreed that a study of the nature of peat involves problems which are distinctly different from those that one encounters in the study of the nature of rocks, on the one hand, and of soils on the other. First of all, peat is largely organic in nature and of plant origin; secondly, the processes involved in its formation are markedly different from those which led to the formation of either rocks or mineral soils; thirdly, microorganisms play a most important rôle in peat formation and peat decomposition, but they do not participate in the formation of rocks, while in the formation of ordinary mineral soils their part is only indirect in nature, except as they contribute, through the processes of decomposition of plant and animal residues and their own cell substance, to the organic fraction of the soil.

In a study of the chemistry of peat, certain pertinent questions immediately arise: What is the nature of the organic complexes that make up the peat material? What physical, chemical and biological processes led to its formation? What chemical and biological processes still go on in the peat bog? What happens to the various organic and inorganic constituents of the peat, when the latter is drained and exposed to the action of the oxygen of the air? What rôle do living organisms, especially the microbes, play in peat formation, in peat transformation, and, finally, in peat decomposition?

Some chemists tend to deny altogether the participation of microorganisms in peat formation. Some attempt to perform a chemical analysis of peat as they would in the case of a mineral, and then proceed to solve the problem of its chemical composition either on the basis of an elementary analysis or by determining the presence of certain hypothetical complexes, which may be similar to preparations produced in the laboratory on treatment of certain definite plant constituents with chemical reagents.

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Most of the botanists and geologists consider the process of peat formation as one of very simple transformation. It is usually assumed that all plant residues falling under water remain preserved from any action of microorganisms and may undergo only a weak hydrolysis. In some cases, the chemical constituents of the plant remains are believed to undergo in the bog a certain slow decomposition, being thereby gradually transformed into a dark brown mass, usually referred to as "humus" and believed to consist of "humic acids." The nature of this "humus" is still very little understood; all attempts to separate it into numerous fractions (so-called "humins," ulmins," "ulmic" and "humic acids") by means of alkali extraction failed completely to solve the problem of its origin and chemical composition.

It is sufficient to call attention to certain ideas current in recent literature, in regard to the origin of peat, without going into any detailed review of the very extensive literature on the subject. Potonié (22) described the process of peat formation as one of "self-decomposition" which was believed to represent the last phase of oxidation, decomposition and fermentation processes. Oden (19) spoke of the rôle of atmospheric agencies in peat formation. One of the earlier students of peat, Früh (10), considered peat formation as a result of a slow breakdown of plant constituents, at a low temperature and in the absence of oxygen, with an inner oxidation and the liberation of water. Soper and Osborn (27) explained the origin of peat from celluloses by a process of carbonization, whereby the carbohydrate loses hydrogen and oxygen in the form of water, and carbon and hydrogen in the form of methane. To sum up this attitude towards the nature of the processes involved in peat formation, it is sufficient to cite Bersch (4), who began his book "Handbuch der Moorkultur" with the statement to the effect that, in contradistinction to the processes of "decay" (Verwesung) of organic matter which take place under aerobic conditions and which are brought about by microorganisms, the processes of peat formation (Vertorfung) are purely chemical in nature.

Since celluloses form the largest single group of constituents in plant remains, it was frequently assumed that they give rise to peat, either by the removal of oxygen and water, or by their transformation first into oxycelluloses. The fact that the cellulose content tends to diminish in peat with age and may even disappear completely seemed to lend support to this hypothesis.

More recently, however, the work of Fischer and Schrader (8, 9) and others focussed attention upon the rôle of lignins in peat formation. According to this theory, the celluloses of the plant residues are decomposed by microorganisms under the anaerobic conditions prevailing in peat bogs, giving rise to gaseous products (CH_4, CO_2), water and organic acids. The lignins, on the other hand, are more resistant to decomposition by microorganisms and, therefore, accumulate. With the advance of decomposition, the methoxyl groups in the lignin complex are saponified and changed to hydroxyl groups, with the result that a phenol-like, alkali-soluble body, namely "humic acid," is formed; this complex may later be transformed into "humin," which is insoluble in alkalies. This theory has considerable evidence in its support, but, as shown later, it does not take into consideration certain important chemical constituents of peat which tend to modify this theory quite considerably.

According to Bergius (3), both celluloses and lignins are capable of giving rise to peat and to coal, under the proper conditions of temperature and pressure. Marcusson (16, 17) came to the conclusion that celluloses are changed by hydrolysis and oxidation to oxycellulose and pectin; the glucoronic acid compound of these substances is transformed, on heating, to "humic acid"; this mechanism is believed to be responsible for the formation of the peat and coal.

Most of these hypotheses are largely based upon speculation and have little experimental evidence to support them. Whenever a certain amount of evidence has been submitted, it was obtained not from a study of the transformation processes similar to those of decomposition of plant residues under natural conditions, but as a result of treatment of organic complexes with strong acids and alkalies, at high temperatures and pressures, conditions which are only seldom encountered in the natural process of peat formation.

One may then ask, whether there is available any experimental evidence, which would throw light upon the problem under consideration; also, to what extent do the microorganisms found in the peat bogs by numerous investigators contribute to the formation and the transformation of the peat. Wiegmann (42) was the first to attempt a solution of the problem of the origin of peat by chemical analysis of the peat-forming plants and of young and old peat. Most of these analyses, as well as those carried out by Websky (40) and others, who attempted to solve the problem of the chemistry of peat, did not go further than a study of the chemical composition of the ash. After a survey of the numerous contributions to this subject, Früh (10) came to the conclusion that all these analyses contributed very little to our understanding of the processes of peat formation. Unfortunately the efforts of Wiegmann (42) and Senft (26) to prepare peat under controlled conditions did not find the necessary response among the later investigators. Wiegmann placed peat-forming plants in a pit, covered them with water, and pressed them down with a heavy cover for a period of 6 to 12 months. Senft observed that, under such conditions, the plants (*Brassicae*) are transformed into brown, humus-like substances.

Früh's experiments date to 1882. A mixture of plants of *Sphagnum* with *Erioph. vaginatum* or with algae was placed in tall cylinders. The plants were covered with water, then with a 1.5 centimeter layer of oil and allowed to remain at 10°C; the cylinders were opened after 6 months. Früh noted the formation of so-called *ulmic acids* and *ulmins, humic acids* and *humins* as well as salts of these acids. A solution of 5 per cent KOH was used for the separation of these complexes. However, Achard (1) was the first who actually attempted to separate these "acids" from peat itself. Mulder (18) was the first to distinguish them sharply, while Sprengel (28) first used the term "ulmic acid" and probably had as clear a conception of these substances as any of the subsequent investigators.

Früh recorded the fact that cellulose "ulmifies" quite completely, and the more readily the younger the plant. Lignin containing substances decomposed with greater difficulty, while mosses were found to be quite resistant to decomposition; wax-like compounds were found to remain largely unchanged, especially in sphagnum bogs. As to the rôle of microorganisms in peat formation, Früh stated in 1879 that the tissues of peat-forming plants disappear "par une fermentation turbeuse, comme le preuve notre confrère M. van Tieghem.... de dissoudre la cellulose et de la faire fermenter avec dégagement des gas". However, in view of the fact that van Tieghem stated that this process does not apply to algae, mosses, Hepaticae, Lycopodia, and other plants which are important constituents of some peats, these generalizations could not be applied to all peats, especially to the highmoors. Früh himself could not demonstrate any bacteria which would be active in the "humification" process.

In view of the recent emphasis laid upon the rôle of lignins in peat formation, it is of interest to cite the ideas of Lesquerreux expressed in 1844 that "La tourbe est un compose ligneux dont la fermentation et par conséquence la décomposition sont retardées par la présence et la temperature de l'eau". Klason also stated in 1893 that "the process whereby dead plants change into the first stage of peat must consist in the fermentation of the carbohydrates; when this takes place under water, in the absence of air, the process must stop here, the active microorganisms being unable to ferment the other plant constituents. Peat actually consists of lignin-like substances of plants in a more or less unchanged condition."

Many years have passed since the time of Wiegmann, Lesquerreux and Früh, a whole science of microbiology originated and reached an advanced stage of development, and students of peat still doubt the rôle of microorganisms in peat formation; they even question their presence in peat and some go as far as to consider peat as having a decided disinfectant action upon microorganisms.

It is the purpose of this paper to call attention to the advances recently made in our understanding of the problems connected with the nature, origin and decomposition of peat, and the rôle of microorganisms in these processes. A detailed review of the various theories dealing with the nature and origin of soil organic matter or "humus" is given elsewhere (30); the occurrence of microorganisms in peat has also been reviewed elsewhere (36).

CHEMICAL COMPOSITION OF PEAT.

Von Feilitzen and Tollens (7) reported that the cellulose and pentosan content of peat diminishes with the advance of decomposition. Varying amounts of cellulose have since been demonstrated in different peats (20); in all cases, however, the amounts of cellulose and pentosan found were considerably less than in the plants from which the particular peat originated. In some peats a complete absence of cellulose has been recorded (24). Zailer and Wilk (42) recognized 4 chemical complexes in peat: 1. constituents of the original plant material; 2. transformation products, including the various so-called "humic acids"; 3. mineral constituents; 4. water. Keppeler (12) suggested that the chemical complexes of peat be divided into 2 groups on the basis of treatment with

72 per cent sulphuric acid; namely the soluble and insoluble portions. The reducing sugar produced by this treatment may be considered as a measure of the polysaccharide content of the peat and can thus serve as an index of the degree of decomposition of the plant material; the higher the carbohydrate content the less is the degree of decomposition, and *vice versa.*

To be able to bring out clearly the nature of the processes that have taken place in the formation of peat, it is important to compare its chemical composition with that of the plants from which the peat originated, using similar methods of analysis to determine its composition. Table I gives the proximate chemical composition of a series of plant materials which are commonly found in peat bogs and which are known to contribute to the formation of the various types of peat. Table II gives the chemical composition of several typical lowmoor and highmoor peats, which have been described in detail elsewhere (33-35). Tables III and IV give the composition of two typical peat profiles, one lowmoor and one highmoor.

TABLE I.

Proximate chemical composition of some plant materials which give origin to peat.
On per cent basis of dry material.

Plant constituent	*Carex,* stems and leaves	*Carex,* rhizomes and roots	*Cladium,* stems and leaves	*Cladium,* rhizomes and roots	*Sphagnum,* young growing portion	*Hypnum*	Mature oak leaves
Ether-soluble fraction..	2.54	1.66	1.14	0.90	1.47	4.58	4.01
Water-soluble fraction	12.56	3.18	6.87	5.21	3.86	8.41	15.32
Hemicelluloses	18.36	20.86	21.45*	20.75*	30.82	18.92	15.60
Celluloses	28.20	11.78	28.31	30.74	21.13	24.75	17.18
Lignins	21.08	41.74	29.09	30.90	6.97	21.13	29.66
Protein	7.08	14.62	7.19	3.81	5.88	4.16	3.47
Ash	3.30	4.56	3.89	3.57	3.18	4.33	4.68
Total	93.12	98.40	97.94	95.88	73.31	86.28	89.92

* Pentosans only.

The results brought out in these tables present a concise picture of the nature of the chemical changes that have taken place in the transformation of the plant residues into peat complexes; they also bring out markedly the differences in the chemical composition between different peat materials, due to the nature of the plants from which the particular peat originated, the conditions (reaction, presence of nutrients for microorganisms) under which the decomposition has taken place, and the microorganisms concerned in these processes. The methods used in the proximate analysis of the plant materials and of the peat have been described in detail elsewhere (32).

Fresh plant substances are characterized by a high content of water-soluble material, by a large amount of celluloses and hemicelluloses and by a rather low protein and ash content. As a result of decomposition of the various organic complexes in the plant remains, the water-soluble substances are appreciably reduced; the celluloses and hemicelluloses also undergo a process of rapid decomposition. From being the most abundant group of organic complexes in the various plant materials (except in the partially decomposed roots and rhizomes of the *Carex* and *Cladium*, and in the mature oak leaves), the celluloses are markedly reduced in the peats; they have disappeared almost completely in the lowmoor peats, are appreciably reduced in the forest peat, and have diminished to a considerable extent in the sphagnum peats. The hemicelluloses have also diminished in most of the peats, especially in the lowmoor formations. It is of importance to record the fact that while the pentosans form the most outstanding group of hemicelluloses in the fresh plant material (except in the *Sphagnum* plants), the hexosans are much more abundant among the hemicelluloses in the peat (32). This has been explained by the fact that the pentosans are much more rapidly decomposed

TABLE II.

Proximate chemical composition of some typical peats.
On per cent basis of dry material.

Peat constituent	Lowmoor Newton, N. J. upper 12 cm.	Saw-grass peat from Florida 7-20 cm. depth	Sedimentary peat, Florida 62-70 cm. depth	Lake peat, Florida 60-120 cm.	Forest peat, New York	Young Sphagnum peat, Germany	Old Sphagnum peat, Germany	Sphagnum peat, Orono, Maine 20-30 cm. depth
Ether-soluble portion	0.66	2.98	2.97	0.41	3.22	3.08	5.73	2.45
Water-soluble portion	3.08	1.73	1.07	0.71	....	....	....	....
Hemicelluloses ..	10.31	6.41	2.19	4.17	5.44	16.88	9.08	20.92
Celluloses	0	0.28	0	0	2.68	19.44	12.38	16.23
Lignins and lignin-like complexes..	38.35	46.12	19.33	35.19	60.73	34.04	52.50	25.43
Proteins	22.48	23.06	9.00	15.06	14.30	5.23	5.78	5.72
Ash	13.22	10.00	59.60	39.56	3.90	1.72	1.38	1.84
Total	88.10	90.56	94.16	95.10	89.67	80.39	86.85	72.59
pH	5.9	6.2	....	7.25	4.7	4.1	4.2	3.95

than the hexosans, while certain hexosans are also formed by microorganisms as a result of their synthesizing activities. The tendency towards an accumulation of hexosan-hemicelluloses and a diminution of pentosans is thus found to be characteristic of peats, especially of lowmoors; a similar phenomenon is observed in the study of the chemistry of the organic matter in mineral soils.

The lignins or lignin-like complexes have undergone a marked modification in the process of peat formation. The rhizomes and roots of the two plant materials show a considerable increase in the lignin content over the stems and leaves. This is due to the fact that the fungi- and the cellulose-decomposing bacteria have begun the decomposition of the carbohydrate complexes in the dying portions of the plant, but they have not attacked the lignins to any appreciable extent. Under aerobic conditions the lignins are not absolutely resistant to attack by microorganisms, but also undergo a certain degree of decomposition, to a much more limited extent, however, than the celluloses and hemicelluloses. Under anaerobic conditions, as in the case of the peat bogs, the lignins are practically preserved, while the celluloses and hemicelluloses are slowly but gradually decomposed. The great resistance of lignins to decomposition under anaerobic conditions led Fischer (8, 9) to base his theory of the origin of coal upon this phenomenon. However, this theory overlooks four very important facts, namely, 1. Lignins are not absolutely resistant to decomposition under aerobic conditions, as shown by the continuous disappearance of organic matter in cultivated soils; this process is carried out by certain bacteria, actinomyces, and probably

TABLE III.

Proximate chemical composition of a lowmoor peat profile (Newton, N. J.).
On per cent basis of dry material.

Depth of layer cm.	pH.	Ether-soluble fraction	Water-soluble fraction	Hemi-cellulose	Cellulose	Peat-lignin (ash and nitrogen free)	Crude protein	Ash
12	5.9	0.66	3.08	10.31	0	38.35	22.48	13.22
18	6.3	1.10	1.24	8.95	0	50.33	18.72	10.13
160-180	6.3	0.49	2.31	7.02	0	57.83	14.81	10.15
160	6.7	0.78	1.14	7.51	0	42.10	19.81	15.00
Lake peat	6.8	0.67	0.81	12.14	0	33.25	19.38	24.87
Gyttja layer	8.0	0.36	1.24	5.92	0	15.62	9.81	59.55

higher fungi; under certain conditions, various Basidiomycetes are capable of decomposing the lignins as rapidly as they do the celluloses and even more so, as in the destruction of wood by certain fungi, such as *Polyporus annosus* and *Tramytes pini* (6). 2. The high content of nitrogen in certain kinds of peat, especially in the lowmoor and sedimentary peats, where the celluloses and hemicelluloses have undergone marked decomposition and have practically disappeared; no consideration is given to the source and nature of these nitrogenous compounds, which may make up 25 to 30 per cent of the total organic complexes in the peat; no attempt is made to explain the rôle of this nitrogen in peat formation. 3. This theory does not consider the fact that certain types of peat, like the lowmoors, are practically free from celluloses, while others, like the highmoors or sphagnum peats, are rich in celluloses; it does not account either for the high hemicellulose content in nearly all types of peat. 4. Lignins form at most only 40-50 per cent of the peat material; at best, the theory proposed by Fischer only confirms and develops further the previous observations of other investigators that lignins are more resistant to decomposition than the other plant constituents and, therefore, accumulate in the process of degradation of plant materials by microorganisms. The further transformation of the peat into coal is probably largely physical and chemical in nature and need not concern us here.

TABLE IV.

Proximate chemical composition of a highmoor peat profile (Cherryfield, Maine).

On per cent basis of dry material.

Depth of layer cm.	pH.	Ether soluble	Alcohol soluble	Hemi-celluloses	Cellulose	Peat-lignins	Proteins	Ash
1-8	4.05	2.35	1.45	26.45	16.86	27.18	4.08	2.00
8-20	3.95	2.62	1.92	25.24	14.74	29.21	4.28	1.14
20-30	3.85	2.82	1.83	24.55	15.97	28.85	5.11	1.02
30-46	3.86	2.57	2.08	22.25	13.69	32.23	5.24	0.90
46-61	3.73	2.96	3.20	18.48	14.66	33.24	4.81	1.06
183-214	4.47	3.97	3.15	15.94	15.55	37.43	4.41	0.99
460-480	4.71	4.89	4.29	12.69	11.85	44.83	4.73	1.10
550-580	5.18	5.97	5.06	5.96	5.06	54.11	11.53	2.83

Special attention should be called to the changes which the nitrogen complexes undergo in the formation of peat from plant remains. In the case of the lowmoors, the proteins are considerably higher in the peat than in the plant substances from which the peat originated. In the case of the highmoors, however, the protein content is not much higher than in fresh sphagnum plants, but even tends to be lower. The following explanation has been suggested (32, 33) for these phenomena: In the decomposition of *Cladium* and *Carex* plants, as well as of other reeds and sedges, the celluloses and pentosans undergo rapid attack by fungi and aerobic bacteria at the surface of the bog and later by anaerobic bacteria when the plant remains are immersed in water. This is made especially easy due to the presence of mineral salts and available nitrogen as well as due to a favorable reaction, both phenomena being characteristic of lowmoor peats. The celluloses and pentosans gradually disappear, and the energy thus made available allows the microorganisms to synthesize considerable cell substance rich in nitrogenous organic complexes, referred here collectively as protein. This is not a mere hypothesis but is based upon actual experimental evidence, as has been shown elsewhere (31). As a result of these synthesizing activities of the microorganisms there is a gradual accumulation of proteins and other organic nitrogenous complexes, parallel to the decomposition of the celluloses and hemicelluloses (37).

In the case of the highmoor peats, the celluloses and hemicelluloses of the *Sphagnum* plants are much more resistant to decomposition than in the herbaceous plants, while the high acidity of the bogs and the lack of sufficient mineral nutrients make conditions unfavorable for the growth of many groups of microorganisms, especially under anaerobic conditions. On the other hand, the amides and certain other nitrogenous compounds of these plants decompose readily, even under the high acid conditions, liberating the nitrogen in the form of ammonia. This may either remain in an adsorbed state (the acid conditions preventing the activities of the nitrifying bacteria) or it is immediately utilized by the growing part of the plant which is thus able to obtain its nitrogen from the dead parts which undergo partial decomposition. This phenomenon accounts for the high ammonia content of sphagnum peat (15) and for its comparatively low protein content, or abundance of organic nitrogenous complexes.

The marked difference in the chemical composition of the several types of peat (lowmoor, highmoor, sedimentary, Gyttja or lake peat, and forest peat) is thus explained by the nature of the chemical complexes in the original plant materials, the nature of the decomposition processes carried out by microorganisms, and the conditions under which decomposition is taking place. An examination of the chemical composition of the two peat profiles tends to throw further light upon this subject.

The lowmoor peat profile shows an increase in alkalinity and in ash content with an increase in depth. The lignins form the most extensive and most important group of complexes throughout the whole profile. Next come the nitrogenous substances, followed by the hemicelluloses. Just as the cellulose-pentosan-lignin complex characterizes the cell membrane of higher plants, so does the lignin-protein-hemicellulose complex characterize the peat of the lowmoor profile. The ether-soluble portion is small throughout the profile; the same is true of the water-soluble materials. However, the mineral part of the complex is quite characteristic; the ash content is fairly high throughout the profile, but it increases markedly in the lake peat layer and becomes predominant in the Gyttja layer overlying the clay bottom of the bog. The lake peat layer of the profile is very similar in chemical composition to the lake peat from Florida (Table II), while the Gyttja layer resembles the sedimentary layer of the Florida Everglade peat.

The sphagnum profile from Maine (35) taken to a depth of 20 feet brings out some characteristic chemical properties of the highmoor type of peat, as distinct from other peats. The reaction is very acid (pH 3.73-4.71) throughout, until the sedge peat layer is reached (at 550 cm. depth). The ether and alcohol soluble fractions as well as the lignins gradually increase with depth, while the celluloses and hemicelluloses decrease. The protein content is low throughout the profile of the sphagnum peat. When the sedge peat layer is reached, there is a rapid drop in the cellulose and hemicellulose content and a considerable increase in the protein and ash content.

It is interesting to compare the chemical composition of the various layers of the Maine profile with the younger and older sphagnum peats of the German profile (Table II). The older sphagnum peat of the German profile contains more of the ether-soluble fraction, less cellulose and hemicellulose, more lignin and lignin-like complexes, and about the same protein and ash content. Similar results are obtained when we compare the upper 2-3 layers of the Maine sphagnum peat profile with the lowest layer (460-480 cm.) above the sedge peat formation.

These results bring out quite conclusively that a quantitative chemical analysis of different peats, even if only proximate in nature, can well serve to characterize a certain peat type. This information is important, not only for the chemical characterization of the peat, for gaining information concerning the biological and chemical processes that have taken place in its formation, but especially for the practical utilization of peat for agricultural and industrial purposes.

In considering the manner in which various types of peat should be characterized chemically, the following properties may be taken into consideration, on the basis of the studies summarized here and reported in detail elsewhere (32-36).

A lowmoor peat, originating from vegetation largely herbaceous in nature, in a bog fed by ground waters rich in mineral salts, especially calcium carbonate, will be characterized as follows: A very low cellulose content to almost complete freedom from true celluloses; a low hemicellulose content, ranging about 5 to 12 per cent of the total dry peat; a high content of lignins and lignin-like complexes, amounting to 30-60 per cent of the total dry weight of the peat; a fairly high ash content (4 to 15 per cent); a very high protein content (15 to 25 per cent), with very little water soluble material; the reaction is only slightly acid, usually pH 5.5 to 6.5.

On the other hand, the highmoor peat is distinctly different in its chemical composition. This type of peat is formed in waters poor in nutrients and containing little calcium; these waters originate usually from atmospheric precipitation or from mineral poor soil. This type of peat is usually formed either upon a lowmoor peat or directly upon rock, clay or sand, in regions of cold and moderate climate with high rainfall. Its chemical composition can be summarized as follows: A high concentration of celluloses and hemicelluloses; a low protein content and a high content of fats and waxes, or ether soluble fraction; a low ash content; a lower lignin content than in the case of the lowmoor peats; a high acidity, usually ranging from pH 3.5 to 4.5, although higher and lower acidities have also been reported (13).

Forest peats are formed from various trees with an admixture of ericaceous plants and various species of *Sphagnum*; they are usually fed partly by ground waters rich in mineral salts and partly by precipitation. This type of peat is frequently referred to as transition peat. It has a higher cellulose and lignin content than the typical lowmoor peat; it has less protein and ash and is usually more acid in reaction than the lowmoor peats. Chemically it stands midway between the typical lowmoor and highmoor peats.

In addition to these three types of peat, there is a fourth one which is also common, namely the sedimentary or mud peat (Lebermoor, Gyttja), which is formed largely by algae and other aquatic plants and animals, with a considerable admixture of spores, pollen and particles of clay and sand. It is frequently found superimposed by lowmoor and other types of peat. It is characterized by a very high ash content (35-60 per cent of the total dry material), a high content of nitrogenous and lignin-like complexes, a low content of material soluble in ether, freedom from celluloses and a low hemicellulose content.

What are the agents responsible for the formation of peat out of the plant residues? Without denying the rôle that chemical agencies play in the different processes involved in the transformation of the various plant residues which give rise to peat, it may safely be concluded that the most important chemical agents are the microbes inhabiting the peat. This will be elucidated in the following pages.

MICROBIOLOGICAL PROCESSES INVOLVED IN PEAT FORMATION AND PEAT TRANSFORMATION.

Früh (10) stated quite emphatically that bacteria have nothing to do with the formation of peat. Numerous reports appeared since the work of Früh, demonstrating the presence of bacteria in peat bogs, at different depths, the numbers diminishing with increasing depth; below 20 to 50 cm. the bog was considered to be practically sterile. It has even been found recently (2), that, although the plate method may show very few bacteria, a direct microscopic examination of the peat reveals a great abundance of microorganisms, numbering as many as 323 to 715 million cells per gram of moist material; the predominating organisms were found to be small rod-shaped and coccus-shaped bacteria. The use of the ordinary plate method for the study of numbers of bacteria in peat was found to have two distinct disadvantages: 1. It does not allow for the development of the obligate anaerobic bacteria, which may be abundant if not predominant representatives of the microorganisms in such an anaerobic system as a peat bog represents. 2. The common plate method proved to offer unfavorable conditions for the development of many specific organisms.

A detailed study of the occurrence of microorganisms in peat is reported elsewhere (36). A certain idea of the nature and relative abundance of the soil population is given in Tables V and VI, using the same two profiles, the chemical composition of which was reported in Tables III and IV respectively.

TABLE V.

Occurrence of microorganisms at different depths of a lowmoor peat profile (Newton, N. J.).
On the basis of fresh peat material.

Depth of sample cm.	Moisture content per cent	Bacteria (aerobic and facultative aerobic) and actinomyces	Per cent of actinomyces	Fungi	Aerobic* cellulose decomposing bacteria	Nitrifying* bacteria	Anaerobic* bacteria
Surface	61.1	6,000,000	90	105,000	++	+++	+
30	72.5	350,000	40	250	+	++	++
45	82.3	450,000	25	175	0	++	++
60	87.5	40,000	20	150	0	+	++
75	87.1	35,000	25	33	0	+	++
90	80.8	20,000	15	0	0	0	++
120	83.6	100,000	2	0	0	0	+++
150	84.5	500,000	0	0	0	0	++++
165	64.8	200,000	0	0	0	0	++++
Clay bottom							

*+ designates a few; ++ a fair number; +++ abundance of organisms; ++++ numerous (about 25,000 or more colonies formed by one gram of material).

TABLE VI.

Occurrence of microorganisms at different depths of a highmoor peat profile (Cherryfield, Maine).
On basis of fresh material.

Depth of sample cm.	Moisture content per cent	Aerobic and facultative aerobic bacteria per gram	Acid-resisting anaerobic bacteria
Surface layer	....	250,000	0
7.5-20	92.7	100,000	......
20-30	92.6	220,000	15,000
30-45	92.6	1,600,000	......
45-60	92.9	3,500,000	550,000
60-75	93.6	1,500,000	......
120-150	93.6	2,000,000	350,000
175-210	93.4	750,000	......
450-480	92.4	800,000	......
540-570	92.2	2,000,000	......

The results show that peat contains an abundant flora of microorganisms, consisting of aerobic forms in the upper layers and of anaerobic bacteria in the lower layers of the profiles. Fungi are limited largely to the surface layers. Actinomyces are found abundantly in lowmoor peats but they diminish rapidly with depth of the peat profile. Nitrifying and aerobic cellulose-decomposing bacteria are found abundantly in the upper layers of lowmoor peats. While the numbers of aerobic microorganisms diminish with an increase in the depth of the peat bog, the numbers of anaerobic bacteria increase with depth.

TABLE VII.

Influence of depth of a lowmoor peat upon its decompositions at a constant moisture and air supply.

100 gm. portions of moist peat incubated at 25-28° C. for 50 days.

Depth of sample cm.	Moisture content per cent	Total CO_2 liberated as carbon mgm.	Ammonia formed mgm. of N.	Nitrate formed mgm. of N.	Total nitrogen liberated mgm. of N.
Surface	61.1	98.7	0.40	8.10	8.50
60	87.5	118.2	3.78	0.60	4.38
120	83.6	36.4	1.98	0.30	2.28
165	64.8	63.2	1.60	0	1.60

To demonstrate whether these microorganisms are active in the peat and bring about the decomposition of the organic complexes, definite portions (100 gm.) of fresh peat were placed in flasks and a current of air passed over them for a period of 50 days; the CO_2 liberated was determined by an appropriate procedure. At the end of the incubation period, the ammonia and nitrate nitrogen present in the peat and produced by its decomposition were also determined (Table VII). The results show quite definitely that peat undergoes gradual but constant decomposition, as indicated by the evolution of CO_2 and the liberation of nitrogen in the form of ammonia and nitrate. When untreated sphagnum peat is subjected to decomposition, the nitrogen liberated accumulates as ammonia and does not change to nitrate, unless the peat is limed. Due to the high acidity of the sphagnum peat and the anaerobic condition, the growth of nitrate-forming bacteria is eliminated.

DISCUSSION.

Various systems of classification of peat have been proposed and used at various times. These classifications have been based either upon: 1. the nature of plant associations on the surface of the peat; 2. upon the formation of the peat either below or above the water level; 3. upon the higher or lower content of plant nutrients in the peat, lowmoor peats deriving their water supply by draining from surrounding hills or upper lands, which are, therefore, rich in nutrients, while the highmoor peats derive their water supply only by precipitation and are, therefore, poor in nutrients; 4. upon the physical and mechanical properties of the peat (fibrous, sedimentary, colloidal, etc.); 5. on the basis of the nature of the peat itself, by combining mechanical and physical properties with the botanical origin (25); 6. recently the tendency has been to classify peat on the basis of the plants which gave origin to it (21).

Shreiber (25) called attention to the fact that the chemical analyses as commonly employed do not yield sufficient information for the characterization of peat. Neither can the water level at which the peat has been formed give sufficient basis for differentiation, since various gradations are found. The separation of peat on the basis of plant associations upon its surface is possible only in the case of virgin bogs, since, on drainage and cultivation, the surface vegetation may be completely changed.

It has been shown here that by introducing a system of proximate quantitative chemical analysis, the nature of peat as characterized by its botanical composition can be further defined and its practical utilization better understood. This system of analysis also helps to visualize the processes that have taken place in peat formation. It helps one to understand the rôle of microorganisms in these processes. It eliminates speculation, by placing in the hand of the investigator a tool whereby he can express in definite chemical terms, in a quantitative manner, the nature of the material that he is dealing with.

A study of the chemical composition of peat and of the microorganisms present in the various layers of the natural bogs, as well as those active in the transformation of the organic matter when the bog is drained, brings out forcefully several important conclusions: The peat bog is not a sterile mass of material, where chemical processes take place slowly as a result of the action of atmospheric agencies. It is a medium teeming with life, largely bacteria, which are constantly at work breaking down the various constituents of the plant residues, liberating certain nutrients and building up microbial cell substance. The nature of the organisms, the rapidity and nature of the processes of disintegration are influenced to a large extent by the nature and composition of the plant materials as well as by the environmental conditions under which decomposition is taking place, especially concentration of mineral salts and reaction.

No better summary of the historical development of our conception of peat can be given than by citing several definitions of peat presented at various times.

Weber (39), one of the most outstanding students of peat, suggested, in the early part of this century, the following definition: "peat is an organic mineral formed out of dead cellulose-rich plants, by a special process of ulmification or peat formation; it becomes colored brown to black when exposed to air; it is soft in its natural moist condition and is very rich in water; its specific color depends on its content of ulmin. Peat consists largely of the elements carbon, hydrogen and oxygen, and contains, in addition, varying amounts of nitrogen, sulphur and ash. Various animal residues are admixed in varying amounts in peat, in the form of excreta and chitin. On drying, peat shrinks quite considerably, giving fragments hanging loosely together, or producing hard clumps breaking apart with the formation of sharp edges, or often forming fibrous or felt-like masses. The air dry substance swells, depending on the nature of the constituent plant residues, on the degree of peat formation and on the pressure to which it was subjected during the continuous contact with water; it never gives, however, even when completely softened, a crumbly soil-like mass. According to the degree of ulmification and the manner in which peat has been formed, the plant residues from which the peat has been formed can either still be recognized by the naked eye or by use of magnification or they break apart easily. From the geological point of view, peat formation is limited to the quaternary system."

No attention is paid at all, in this definition, to the chemical processes involved in the formation of peat from the different plants and the rôle of the various plant constituents concerned in the process. Even the nature of the plants which gave origin to the peat received none or only very scant consideration. The insufficient understanding of the chemical processes is covered by such vague generalizations as "ulmification" or "humin formation," which were just labels for certain preparations and not for definite chemical substances; they were found to be very useful, however, when exact knowledge of the processes was unavailable, so as to give an impression of a certain amount of definite information. The fact that only the elementary composition of peat, namely the carbon, hydrogen, oxygen, nitrogen and sulphur, was considered, pointed to an almost complete lack of appreciation of the organic complexes that go to make up the peat. The physical nature of the peat was overemphasized and used for purposes of characterization.

Frequently ultimate chemical analyses of peat and peat-forming plants led to a hasty conclusion that there is no chemical difference between the two.

Between this conception of peat and that prevalent in the middle of last century, very little progress has been made. This is brought out from the definition of peat presented by one of the early American chemists, Johnson (11), namely that "the production of peat from fallen and decaying plants, depends upon the presence of so much water as to cover or saturate the vegetable matters, and thereby hinder the full access of air. Saturation with water also has the effect to maintain the decaying matters at a low temperature, and by these two causes in combination, the process of decay is made to proceed with great slowness, and the solid products of such slow decay are compounds that themselves resist decay and hence they accumulate."[1]

The progress made during the six decades of investigation of peat consisted in a considerably better understanding of the geological formations, the botanical composition of the various peat profiles, and the physical nature of peat. Our knowledge of the chemical nature of peat was limited largely to the recognition of the presence of various organic complexes in varying concentrations, depending upon the nature of the plant that gave origin to the peat and to the conditions under which the decomposition processes have taken place. The knowledge available in regard to the rôle of microorganisms in peat formation has been limited largely to a study of the occurrence of bacteria capable of bringing about certain processes recognized to be of importance in normal cultivated soils.

During the last 25 years, considerable advance has been made

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[1] The fact must be recognized, however, that most of the students of peat did not have then a very clear conception of its nature and formation, defining peat "as a mass of dead organic matter," or "a formation originating from plants or living beings," or "material originating in swamps."

in our understanding of the botanical phase of the subject. Many bogs were carefully investigated and the plant residues tabulated in detail. One is able to correlate now a certain type of peat with a definite association of plants which have given rise to it. More definite information is also available concerning the chemical processes involved in the peat formation, although no attempt has as yet been made to bring the fragmentary information into a system. Even the century old "humic acids" were also beginning to be somewhat better defined in terms of definite chemical complexes.

This is well recognized from a more recent definition of the nature of peat given by Strache and Lant (29): "Peat is an organic material, formed primarily by the accumulation and decomposition of plant residues, colored brown to black, soft in a natural moist condition, rich in water and colloidal in nature, containing less than 40 per cent inorganic matter on a dry basis and containing considerable quantities of alkali-soluble humic acids." This definition emphasizes primarily the physical nature of the peat, gives no consideration to the microbiological processes involved in peat formation, and pays only scant attention to the chemical nature of the peat. A more appropriate and concise definition is given by Puchner (23): "Peat is a mass of dead plant residues, the decomposition of which took place very slowly due to a lack of sufficient oxygen, and which has not been completed yet. The physics and chemistry of peat is partly the physics and chemistry of the plants from which peat originated and which may still be present in it in a slightly changed form."

Even this definition can be improved upon, when the chemical and microbiological processes involved in peat formation are better understood. A definition is suggested here which tends to cover the present information concerning the nature and origin of peat:

Peat is a layer of the earth's crust consisting largely of organic matter, which has originated as a result of incomplete and partial disintegration of the various constituents of the natural plant materials due to the anaerobic processes under which plant decomposition has taken place; the nature of the peat depends upon the plant association which has given rise to it and the latter is controlled by the amount of mineral nutrients and reaction of the waters in which the plants were growing; chemically the composition of peat is influenced by *the nature of the plant associations from which it has originated, the moisture relations during and following the periods of its formation and accumulation, and the microorganisms active in the decomposition processes.*

The fundamental factors which influence the origin and nature of peat are predominantly functions of climate, and of soil and water relations. They influence the formation of a typical vegetation as well as the mechanism of its decomposition. These factors also modify the processes of peat formation as well as the nature of the particular type of peat produced under a given set of conditions (5). Peat will be formed on land which is poorly drained and where water may collect and stand permanently. Peat-forming plants will find these conditions favorable for their development, especially when the high humidity of the air prevents evaporation and the temperature is low. Under these conditions, the decomposition processes will be very slow and the partly decomposed plant residues will give rise to peat.

SUMMARY.

1. The progress made in the understanding of the nature and origin of peat has been from a geological to a botanical point of view, then to a physico-chemical and chemical, and finally to a microbiological.
2. A knowledge of the nature of peat involves an understanding of the nature and chemical composition of the plant materials which gave origin to peat, of the processes of decomposition of the various plant constituents by microorganisms, and the conditions under which this decomposition is taking place.
3. Peats formed from different plant residues and under different conditions vary markedly in their chemical composition.
4. In certain processes of peat formation, the plants undergo first an aerobic decomposition by fungi and bacteria, followed by anaerobic decomposition by bacteria.
5. In the process of lowmoor and forest peat formation, the celluloses and hemicelluloses are gradually decomposed and the lignins accumulate; this is accompanied by the synthesis of nitrogenous complexes and of certain hemicelluloses by microorganisms. The resulting peat is poor in celluloses as well as in ether- and water-soluble substances; it is rich in peat-lignins (and lignin-like complexes), peat-proteins (nitrogenous com-

plexes) and ash, and it contains hemicelluloses somewhat different in nature from those present in the plant materials.

6. In the process of highmoor peat formation, there is only a very slow decomposition of the celluloses and hemicelluloses, an accumulation of the lignin-like complexes (peat-lignins), a lack of accumulation and frequently even a decrease of nitrogenous complexes, and an increase in the ether-soluble substances.

7. A knowledge of the microbiological population of peats and of the activities of the various organisms is of considerable importance for an understanding of the processes that have taken place in the formation of different peats.

8. Instead of defining peat by color or physical appearance, at best empirical procedures which vary considerably in the hands of different workers, a knowledge of the proximate chemical composition of peat permits the expression, in a definite quantitative manner, of the nature of the peat and the processes involved in its formation.

9. The botanical characterization of peat combined with its proximate chemical composition tend to define the type of peat in the most exact terms. This knowledge is important not only for the characterization and description of peat, but also for its practical utilization for agricultural and industrial purposes.

10. Peat should be considered as a definite organic body, formed under definite conditions and as a result of definite processes. It is teeming with life, its microscopic population playing the most important rôle in its formation and transformation.

11. When a peat bog is drained and aerated, peat undergoes further decomposition, the nature of which is distinctly different from that which is taking place in peat formation. Numerous microorganisms, different in nature, are active in these processes as well.

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