

Rainwater-fed peat as a precursor of coal

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ABSTRACT: About 3% of the Earth's land surface is peat-covered at present. Most peat forms where there is waterlogging, because oxygen diffuses down through water more slowly than it is consumed by micro-organisms. The anaerobic micro-organisms in peat continue the decay process, but only slowly.

A great variety of rheotrophic (usually minerotrophic and eutrophic) peats form if the waterlogging is caused by groundwater. Of greater extent, but less varied, are the ombrotrophic peats which are dependent on precipitation. Most of these peatlands are in Russia, Canada, Fennoscandia and the British Isles. The main peat-forming plants in such places are bogmosses (*Sphagnum*), sedges and heaths, with pines (*Pinus*) and larch (*Larix*) in some places. These peats may be analogous to those which formed the Permian coals of Australia. In western Malesia are large areas of coastal ombrotrophic forest-bogs. These tropical forest peats may be analogous to those which formed the Carboniferous coals. The organic chemistry of newly dead plants differs considerably amongst all these plant groups, and they in turn may be very different from the majority of plants which formed the starting materials for the formation of coals in the past.

In spite of these differences the study of present-day moss and sedge bogs may be helpful and particularly in the study of Permian coals. There is usually a two-layered structure. In the 5–50 cm thick surface layer aerobic decay may remove as much as 90% of the original matter and do so selectively. Below is the much thicker waterlogged anaerobic layer in which microbial decay is of a different sort and is much slower. But there is evidence that it continues for thousands of years at least. The extent to which peat is a product of microbial activity operating on a slowly changing substrate is unknown. Equally unknown is the balance between microbially mediated and chemical changes. One consequence of bacterial decay is that there seems to be an inherent limit to the depth of such peat-forming systems. At least one (unusual) case is known which has resulted in the production of a lignitic peat, which breaks with a conchoidal fracture, and which is barely 12 000 years old. The limiting depth, assessed from growth during the last 10 000 years, seems to be too little to account for the observed thickness of coals.

Keywords: Peat, coal, ombrotrophic mire, lignite, Permian coals, *Sphagnum*

Coals are often assumed to have passed through a stage when they would have been called peat. But the botanical remains in the wide variety of present-day peats are very different from those in coals. This observation prompts the question: to what extent does the organic chemistry of coals depend on that of the plants from which they formed, and to what extent is it determined by the processes of peat formation, and independent of the original botanical composition?

The types and distribution of present-day peats

Most, but not all, peats form as a consequence of waterlogging (see Moore, *this volume*). Dead plant matter is attacked by microorganisms and, where oxygen is available, usually decays quickly. The rate of diffusion of oxygen in water is only 10^{-4} that in air, so where the dead plant matter is

waterlogged and microorganisms are active then oxygen is used up faster than it can be replaced by diffusion. The incipient peat thus becomes anoxic. This does not mean that there is no further decomposition by microorganisms, but it does mean that different species—those able to grow in anoxic conditions—survive. The rate at which they operate seems to be much slower than that of aerobic microorganisms, and they are probably less abundant, so peat accumulates even though decay and consequent changes do continue. In general, both fungi and bacteria contribute to aerobic decay, but anaerobic decay is predominantly due to bacteria (Table 1). General reviews of peat formation and properties are given in Moore & Bellamy (1974), Fuchsman (1980), Clymo (1983), Gore (1983), Hobbs (1986) and Moore (*this volume*).

There are numerous ways of classifying peats and peat-forming systems: see, for example, Kivinen *et al.* (1979). For the present purpose the

TABLE 1. Abundance of microorganisms in the surface layers of blanket peat in the Moor House National Nature Reserve (54° 65' N, 2° 45' W). The fungi were estimated by direct observation; the bacteria (of many different groups) by plating on nutrient agars of various sorts (from Collins et al. 1978).

Depth (cm)	Zone	Fungi: stained mycelium ($m\ g^{-1}$)	Bacteria ($10^5\ g^{-1}$) [range]	
			Aerobic	Anaerobic
0-5	Litter	2450	9-260	9-250
5-12	Dark brown	1030	6-150	32-200
12-20	Green brown	750	11-76	16-500
20-32	Red brown	200	0.7-42	28-260

most important distinction is between peats formed from plants influenced by groundwater and peats entirely dependent on precipitation.

Peats dependent for inorganic solutes on ground water are rheotrophic: their nutrition depends on flowing water even if the rate of flow is very slow. The concentration of inorganic solutes in such waters is usually, but not invariably, markedly greater than that in precipitation. Peats formed in these conditions are therefore sometimes called minerotrophic, and as the supply of solutes is relatively high the peat may also be called eutrophic: that is it formed under 'good' nutritional conditions. Most rheotrophic peats are also minerotrophic and eutrophic. Peats which depend entirely on precipitation for their supply of inorganic solutes are called ombrotrophic (Greek ombros=rainstorm). The term 'swamp' is usually reserved for perennially flooded areas where rheotrophic peat may be accumulating. 'Marsh' is best reserved for situations where there is a large proportion of solid inorganic matter in the substrate. The cavalier use of these terms not only destroys useful distinctions but obscures understanding of important features of peat (see Moore, *this volume*). The vegetation of minerotrophic peats is very varied, ranging from that of reedswamp and calcareous fen dominated by grasses, sedges, and other monocotyledonous plant species to freshwater swamps. These very varied minerotrophic peats may be found in small amounts in all those parts of the world, including the tropics, which provide an assured supply of groundwater.

Ombrotrophic or weakly minerotrophic, peats cover far larger areas today than do strongly minerotrophic peats: a single peatland in western Siberia is 1800×800 km (Walter 1977). Because they usually depend on precipitation exceeding evaporation for most of the year they are geographically more restricted than minerotrophic peats: most ombrotrophic peats are in, or close to the Boreal Zone. The dominant plants are bog-mosses (*Sphagnum*), cotton sedges (*Eri-*

phorum) and low shrubs of the heather family (*Ericaceae*). Such peats are usually acid with pH 4.0 or less—*Sphagnum* makes them so (Clymo & Hayward 1983)—and poor in inorganic nutrients. *Sphagnum* and the heathers, at least, are intolerant of solute-rich groundwater.

Minerotrophic peats frequently contain the remains of trees. Some ombrotrophic or weakly minerotrophic peatlands may support trees—pine (*Pinus sylvestris*) in Europe, tamarack and black spruce (*Larix laricina* and *Picea mariana*) in North America. Of special interest are the ombrotrophic tropical forest peats formed of the remains of trees, particularly *Shorea albida*, alongside estuaries in Sarawak, Brunei and Malaya (Anderson 1964).

Estimates of the area covered by peat have tended to increase. Taylor (1964) gave a world total of 121 Mha, with 10 Mha in Canada. Twenty years later (Taylor 1983) the total was 240 Mha, with 130 Mha in Canada. Kivinen & Parkarinen (1981) reached 480 Mha—about 3% of the Earth's land surface. These differences reflect genuine difficulties of definition and mapping. Even the 1:5 000 000 UNESCO/FAO Soil Map of the World is unsuitable for it shows no histosols (predominantly organic soils) in Newfoundland. All estimates agree on the joint premier position of the USSR and Canada, with Fennoscandia next, followed by the USA, British Isles, Germany, Poland and surprisingly large areas of coastal Malaysia and Indonesia. Remote sensing has been used to make an accurate map of peatlands in Ontario province (Pala 1984) and holds promise for the future.

In summary, there is a lot of peatland at present, but its botanical composition is very varied. Most ombrotrophic peats are Boreal and contain moss or herb remains, with a few shrubs and occasional trees. They may perhaps be analogous to the precursors of the Permian coals of Australia, which were geographically Boreal at the time they were deposited, and which show underlying 'stone-roll swarms' reminiscent of the

structures formed today beneath string mires and palsas in the northern Boreal zone (Conaghan 1984). It may be significant that fossils of *Protosphagnum*, having two types of cell in the leaf, are known from the Permian in Russia (Lacey 1969), whilst *Sphagnum* is one of the commonest sub-fossils in modern peats.

Analogues of tropical Carboniferous coals may perhaps be sought in the present-day coastal ombrotrophic forest-bogs of west Malesia. The peat in such bogs is mostly formed from wood (see also Collinson & Scott, *this volume*).

What then of the chemical composition of peat? As an illustration consider the bog-moss (*Sphagnum*) which is one of the most abundant plants in Boreal peatlands and which, because it decays relatively slowly, comes to be over-represented in peat (Clymo 1984).

The bog-mosses are an ancient and structurally distinct group of plants. About 20–30% of the cell wall is uronic acid residues in long polymers, possibly mixed (Clymo 1963, Theander 1954). Some of the uronic acids are unusual. For example, D-lyxo-5-hexosulopyranuronic acid has been found by Painter (1983). The 'lignins' of *Sphagnum* seem to be odd too (Bland *et al.* 1968), and the walls also contain two remarkable phenolic compounds: *Sphagnum* acid (p-hydroxy- β -carboxymethyl-cinnamic acid) and a number of sphagnorubins (based on a unique phenylphenanthropyran skeleton) which give several of the species their characteristic red colour (e.g. Rudolph & Johnk 1982). All of these substances form 0.5–5% of the plant dry mass, and are normal constituents. We thus know that one of the most important components of modern Boreal ombrotrophic peats is chemically very different from other modern components. The same distinctive chemical variety *may* have characterized the vegetation which formed coals, but it would only by chance have been the same compounds in similar amounts to those in modern peats.

The processes of formation of ombrotrophic peat

It is convenient to consider the surface of 5–50 cm thick aerobic layer—the acrotelm of Ingram (1978)—from the much thicker anoxic catotelm below. Suppose plant matter (measured as dry mass on a unit area basis) is added to this layer at a constant rate, p , and that the rate of decay, α , is proportional to the remaining mass. Then the mass, x , of plant matter accumulated on a unit area is given by $dx/dt = p - \alpha x$. The

solution of this is $x = \frac{p}{\alpha}(1 - e^{-\alpha t})$. The realism of these assumptions is discussed by Clymo (1984). For large values of t then $x \rightarrow p/\alpha$, and if α is large then a negligible amount of peat accumulates. But if α is small—say 0.10 a^{-1} , as it is for *Sphagnum*—and particularly if the decay process is cut off (t small) because the plant matter has been submerged by a rising water table, then the steady-state thickness of the acrotelm may not be negligible. Even more important is that a proportion of the plant matter survives its passage through the acrotelm and reaches the catotelm. A limited number of measurements on ombrotrophic peatlands indicate that about 10% of the original material passes into the catotelm (Clymo 1984). This steady 'rain' of organic matter from the acrotelm into the catotelm is exactly analogous to the constant addition of new plant matter at the surface. If one assumes that the rate of decay, which is known to be much smaller in the catotelm (Clymo 1965), is still at a rate proportional to what is left, then one gets exactly the same defining equation and solution. The variable p now represents the rate at which matter enters the catotelm (about 10% of the rate at which it enters the acrotelm), α is the decay rate constant for the catotelm, and t is time in the catotelm. The effects are shown in Fig. 1, which uses realistic parameter values derived in the way explained later. This hypothesis, for so it is, has two interesting consequences.

The first is that in such circumstances there is a limit to the thickness of peat which can accumulate. Formally it is p/α . At this asymptotic value the integrated loss at all depths exactly balances the injection of matter at the surface. Because the model concerns mass the effects of compaction and compression are irrelevant, though these processes certainly occur and are important (Clymo 1978, Hobbs 1986). Provided only that decay does continue—however slowly—then there must be a limit to the depth of peat.

The second consequence of this hypothesis, which can be used to test it, is to be seen at the right side of Fig. 1. Although the rate at which matter has been injected has remained constant (p) the age versus depth (as mass) relationship is clearly a hollow curve. The five cases of suitable data were examined (Clymo 1984) and found to show such a hollow curve. Since then three more sets of data which satisfy the criteria of being from ombrotrophic peat, with at least ten ^{14}C dates and a complete set of bulk density measurements, have appeared (Lewis Smith & Clymo 1984, Middeldorp 1984, Dupont 1985). One of them is shown in Fig. 2. A minimization technique (Clymo 1984) allows p and α to be

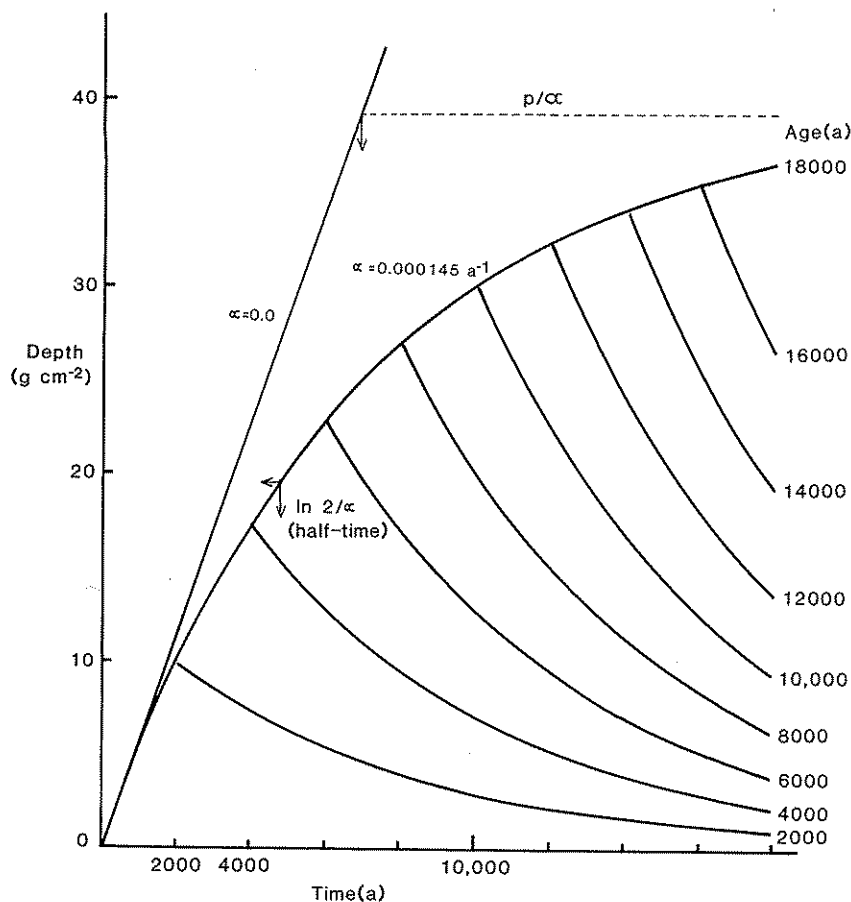


FIG. 1. Growth in depth of a peat mass, modelled by $dx/dt = p - \alpha x$, where x , is the organic dry mass, p is the rate of addition of dry mass, α is the proportional rate of decay and t is time. Both x and p are on a unit area basis. The parameter values, estimated from the data in Fig. 2, are: $p = 0.0057 \text{ g cm}^{-2} \text{ a}^{-1}$ $\alpha = 0.000145 \text{ a}^{-1}$. The depth scale is given as mass/area. If the bulk density were 0.05 g cm^{-3} then multiplying the values given by 20 would give the depth in cm linear measure (e.g. the limiting depth of $p/\alpha = 39.3 \text{ g cm}^{-2}/786 \text{ cm depth}$). The straight diagonal line shows what would happen if there were no decay. It intersects p/α at $1/\alpha$. The convex curve is for the surface. The concave curves show what would happen to peat which was at the surface at 2000 year intervals. The right margin shows that although both p and α are assumed constant the age versus depth profile is *not* linear (as is usually supposed).

estimated: in essence the general slope governs p and the curvature governs α . For the eight cases the value of α is in the range $0.1-1.0 \times 10^{-3} \text{ a}^{-1}$. This implies half-lives ($\ln 2/\alpha$) of 700-7000 years. Very few present-day peat deposits have had the luxury of 20000 years relatively undisturbed development, but some might hope for this. By that time there would be left between 2×10^{-9} and 0.13 of the mass which entered the catotelm. Even the larger of these values (corresponding to $\alpha = 0.0001$), when combined with a 10% survival into the catotelm, implies that barely 1% of the original plant matter survives.

Survival is certainly selective. The leaves of species such as *Rubus chamaemorus* and *Andromeda polifolia* are often abundant on the surface of northern ombrotrophic peatlands but rarely survive in recognizable form into peat, whereas *Sphagnum* and *Eriophorum* shoot bases survive unusually well. Indeed it was only Ockham's advice 'Nunquam ponenda est pluralitas sine necessitate' which persuaded me in the face of such selective survival to try the simple single component model which appears to be sufficient to account for results such as those in Fig. 2. Some of the consequences of applying the same

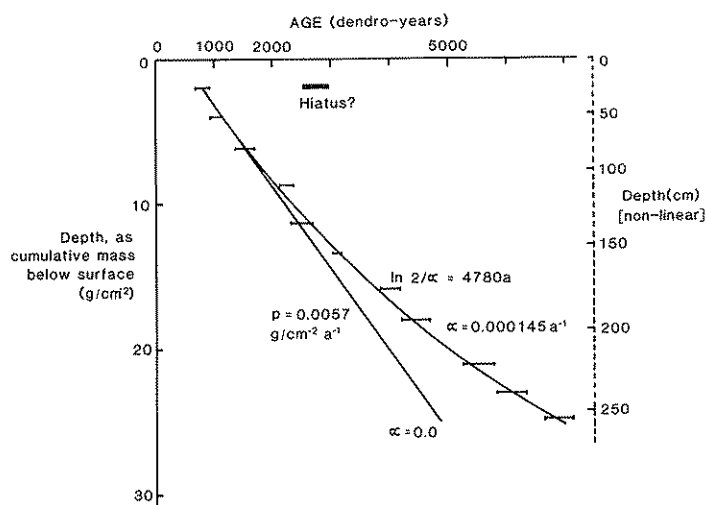


FIG. 2. Age versus depth (as cumulative mass below the surface) for K2 Hollow in the Meerstalblok of Bargerveen on the Dutch-German border ($52^{\circ}41'N$, $7^{\circ}02'E$). The data are those of Dupont (1985) supplemented by privately communicated bulk density values. I acknowledge, with thanks, Dr Dupont's help. The right vertical axis shows actual linear depths at 50 cm intervals. The ages are derived from ^{14}C dates after calibration to 'true' (dendro) age. Horizontal bars are 5% confidence limits. The curve was fitted to the model specified in the text and Fig. 1 by methods described in Clymo (1984): its parameters are $p = 0.0057 \text{ g cm}^{-2} \text{ a}^{-1}$, $\alpha = 0.000145 \text{ a}^{-1}$. The straight diagonal line shows what would have occurred if $\alpha = 0$. There may be a hiatus from 2500 to 3000 years ago. This would slightly increase the value of p and slightly decrease the value of α .

ideas to mixtures are considered in Clymo (1984).

These ideas apply to chemical structures as well as to macroscopic or microscopic visible structures. An illuminating example is that of the very unusual peat formed almost entirely of the remains of the tussock grass *Poa flabellata* (Lewis Smith & Clymo 1984). On Beauchêne Island, in the South Atlantic, the peat is at least 11 m deep. Near the surface plant structures are visible, but further down the peat becomes more humified and the basal 1.5 m, which are about 8000–12000 years old, have a hard cheesy texture. When exposed to the air this peat becomes black and hard, and breaks with a conchoidal fracture. It can only be described as lignitic, though it is barely 10000 years old and has not been subjected to geothermal heat. The age versus depth profile shows the same sort of concave curve as that in Fig. 2.

What are the sources of old, often structureless, peats? There seem to be three main possibilities (Fig. 3): (a) material, produced by the plants which grew on the surface, which has survived chemically unchanged; (b) products of the continued slow activity of microorganisms—probably mostly bacteria; (c) products of slow chemical reactions, not requiring the presence of microorganisms.

The idea that microorganisms may still be

living and causing changes at such depths is not yet generally accepted. It is known that the concentration of methane in the depths of the peat is near or above saturation (Svensson & Rosswall 1984, Clymo 1984, Claricoates *in lit*) and methane efflux, which is known to be large (Clymo & Reddaway 1971, Svensson 1980, Harriss *et al.* 1985), could easily account for the mass loss during decay. The existence of a methane concentration gradient from the base to the surface of a peat mass (Claricoates *in lit*) is explicable only if there is *continued* production. Is this a microbiological process—it seems likely—or could it be a consequence of slow chemical reactions? It should be simple enough to distinguish these possibilities, but what *proportion* of the peat at the base of a deposit is produced in these three ways? Where 99% of the original material has been disposed of the possibility—though not the probability—of a degree of Procrustean tailoring cannot be ignored.

Other important questions may be asked. What is the maximum depth to which ombrotrophic peat may accumulate? The analysis presented here gives the result as p/α , which is a *mass* per unit area. The linear depth will depend on the dry bulk density of the peat. Values between 7 and 15 m have been derived so far. Compaction during coal formation might reduce this to

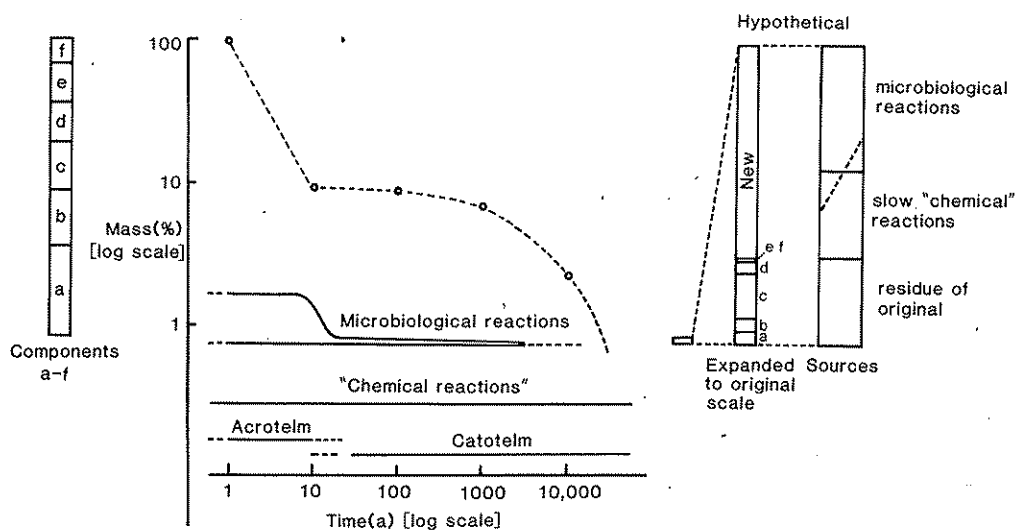


FIG. 3. Summary of known and hypothetical features of peat formation. The central graph shows the probable change in mass with time (both axes have been log transformed). The left column shows hypothetical components a-f. At the right of the graph is what is left after 10 000 years or so. This is expanded to show the selective change of components and the possibility of new materials produced by microbiological or chemical change, or by their interaction (diagonal dashed line).

perhaps 1/5 of these values. If the concentration of acid-insoluble ash at the top of the catotelm of an ombrotrophic peat is about 10 mg g^{-1} , then towards the base after a very long time it might approach 10% of the dry mass. Further compression (without loss of mass) would not affect the concentration. These calculations imply that the concentration of ash might increase downwards in a coal seam to as much as 10%, and that the maximum thickness of such a seam might be about 3 m. The Permian coals of the Sydney basin do not seem to have these characteristics: it may be necessary to postulate more complicated origins.

We have no idea whether these values, or even the same model, are applicable to the tropical ombrotrophic forest peat. Finding out is simple in principle, but may be difficult in practice. Even more difficult is to assess the probability that any of these peats may survive to become coal.

Whatever the answers to these questions it seems likely that much of the material which is eventually subject to coalification proper has already undergone extensive changes, both quantitative and qualitative.

Conclusions

(1) Ombrotrophic peats cover about 3% of the Earth's land surface today.

(2) There is a limit to the depth which such deposits may grow.

(3) As much as 99% of the original plant materials may have disappeared during peat formation, and losses are selective. It is this highly modified residue which may be the material in which coal formation proper begins.

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