STRATIGRAPHY AND POLLEN ANALYSIS OF MALHAM TARN AND TARN MOSS

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Introduction

Perhaps the most outstanding feature of the Craven Pennines is the predominance of almost bare and intricately fretted limestone surfaces into which the heavy rainfall readily finds its way underground. Indeed, the occurrence of a lake almost surrounded by limestone is in itself remarkable. Malham Tarn owes its existence, however, to a series of springs, which emerge from the base of the limestone at its junction with an inlier of impervious Silurian slates, along the north edge of a broad but shallow depression which is lined with clayey glacial drift.

The main group of springs in the north-west corner of the depression gives rise to a short stream which meanders through the fen on the north side of Tarn Moss and enters the tarn itself scarcely half a mile from its source (Fig. 1). An even shorter stream originates from springs at the foot of Great Close Scar

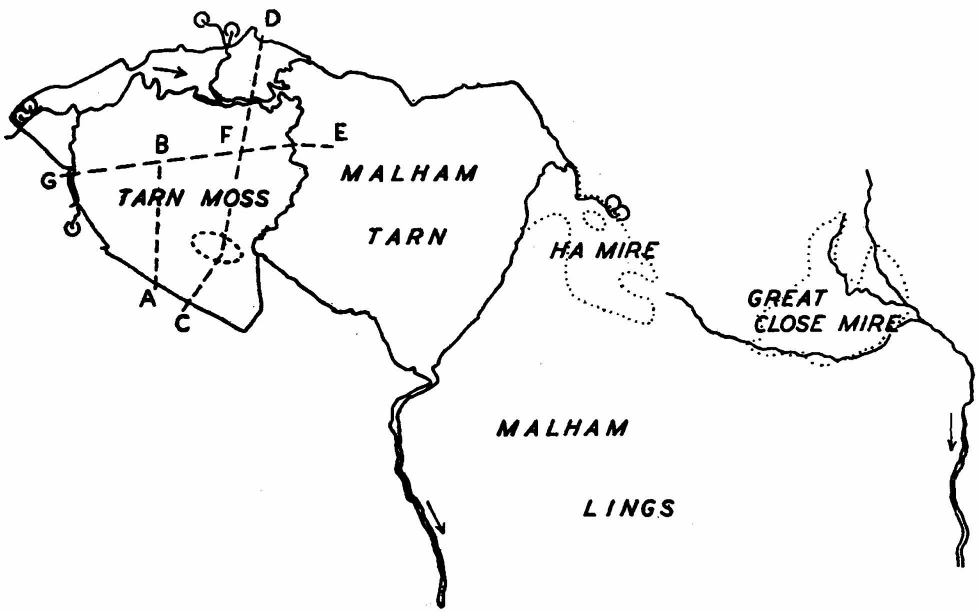


Fig. 1

Sketch-map of Malham Tarn and the adjacent basins. The broken lines and letters indicate the position of the three sections (Fig. 4). The main springs are marked by open circles.

and enters the tarn at its north-east corner. Water leaves the tarn over a slipway but below this the outflow stream follows a natural course and remains above ground only to the edge of the glacial drift where it disappears into one of several swallow-holes.

With the aid of borings it is readily established that the tarn was formerly not only very much deeper but also nearly twice its present area. Clays and calcareous muds, which by their nature must have been deposited in open water, extend under Tarn Moss and the fen to the north, while a thin layer of clay underlies a skin of black peaty soil on Ha Mire. These deposits represent the accumulation of sediment washed into the tarn; and it is apparent that the western and shallower end of the basin, which is closest to the source of water and sediment, became filled up sufficiently to allow the growth of a thick layer of peat.

In general, the stratigraphic order of the deposits represents a time sequence, as the deepest layers are the oldest and the superficial layers the most recent. A detailed study of the stratigraphy enables the history of the tarn to be reconstructed and, at the same time, it is possible to extract fragments of plants and animals, which are preserved as fossils, and thus learn something of the changes of vegetation throughout the period of deposition.

Stratigraphy

The stratigraphy of Tarn Moss was investigated by two lines of borings running from north to south across the basin, and one line running from east to west which was extended out into the tarn (Fig. 1). Several additional borings were made in Ha and Great Close Mires.

Most of the borings reached the bottom of the sediments and enough boulder-clay adhered to the auger-head to show that this is the underlying material. The basal surface is very uneven and, apart from Spiggot Hill, there are three other moraine hillocks under Tarn Moss, of which two are completely buried by peat and the third is partly exposed where the tarn is eroding the edge of the moss (Fig. 4). These three hillocks are separated from Spiggot Hill by a deep channel, but the central and largest hillock lies beneath the small stream which crosses from Spiggot Hill to the north fen and separates the two main domes of the moss. The inflow stream overlies the deepest part of the Tarn Moss basin and another deep hollow lies immediately to the west of Spiggot Hill (25 ft. (8 m.) and 18 ft. (6 m.) below present water level). Further moraine hillocks occur in the present tarn and scattered over Ha Mire and Malham Lings.

Over all the parts of the original basin which lie below 1,223 ft. O.D., a deposit of clay and silt rests either directly on the boulder-clay or separated from it by a thin intervening layer of sand. The clay in Ha Mire is at a higher level. These basal clays show a well-defined stratigraphical variation in colour and texture (Fig. 2). Immediately above the boulder-clay in the deepest parts of the basin, there is a layer of dark grey, silty clay which includes several seams of angular fragments of slate and limestone up to 1 cm. in diameter. Above this the clay is more compact, less silty and deep blue in colour except for a thin but conspicuous band of white sand. The top of the blue clay is marked by an abrupt change to coarser material which forms a layer usually about 20 cm.

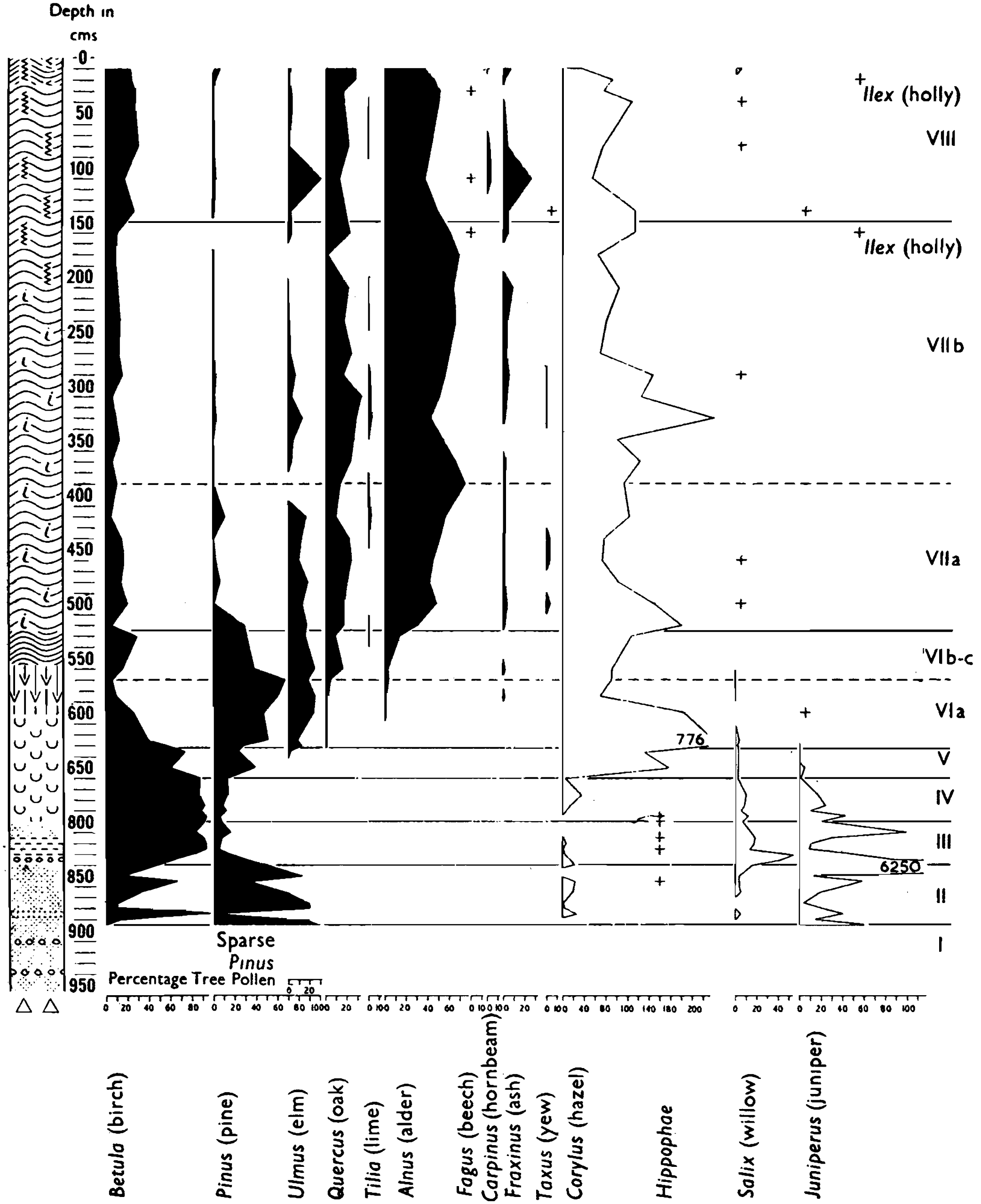
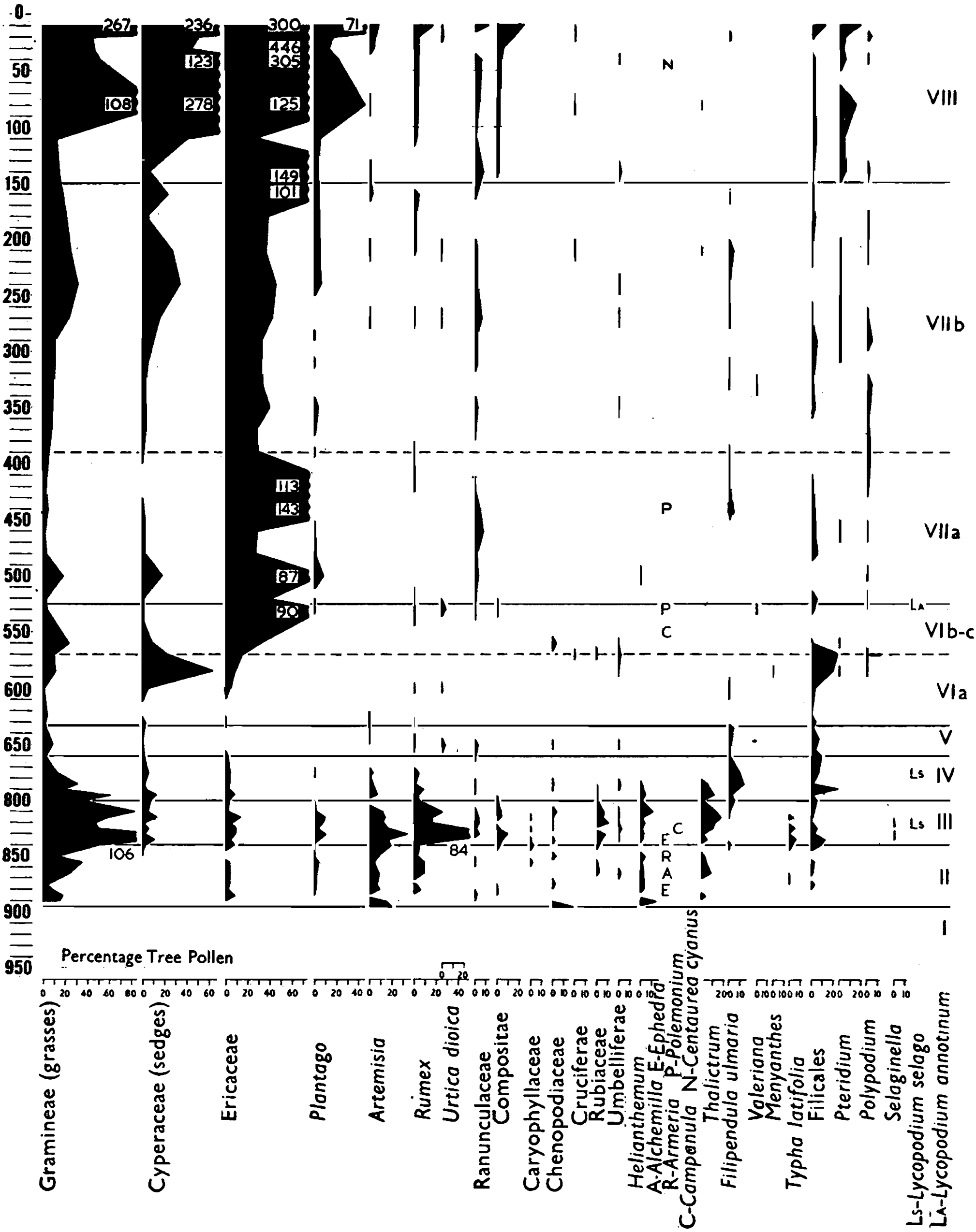


FIG. 2

Pollen diagram for Tarn Moss, Malham. The diagram is composite: the upper part is from a boring near position F on the long north to south transect and the basal part is from a deeper boring nearby. Stratigraphy symbols as in Figure 4.



Percentage Tree Pollen
Gramineae (grasses)
Cyperaceae (sedges)
Ericaceae
Plantago
Artemisia
Rumex
Urtica dioica
Ranunculaceae
Compositae
Caryophyllaceae
Chenopodiaceae
Cruciferae
Rubiaceae
Umbelliferae
Helianthemum
A-Alchemilla E-Ephedra
R-Armeria P-Polemonium
C-Campanula N-Centaurea cyanus
Thalictrum
Filipendula ulmaria
Valeriana
Menyanthes
Typha latifolia
Filicales
Pteridium
Polypodium
Selaginella
Ls-Lycopodium selago
LA-Lycopodium annotinum
VIII
VIIb
VIIa
VIb-c
VIa
V
IV
III
II
I

FIG. 2

thick and again includes stones but for the most part consists of thin seams of clay alternating with thin seams of silt and plant fragments.

There is a thin layer of blue clay above these laminated sediments but upwards the material becomes increasingly silty and calcareous and passes gradually into a creamy-white deposit of almost pure calcium carbonate (5-6 per cent. silt and clay). The granular texture and the inclusion of large numbers of oospores of *Chara* suggest that the lime was precipitated in shallow water. This marl also contains abundant shell fragments as well as undamaged shells of molluscs. Six species have been identified (Stratton 1956):

Valvata cristata	Planorbis contortus
Lymnaea peregra	Sphaerium corneum
Planorbis albus	Pisidium obtusale

The deposition of marl has continued up to the present day in the limited basin now occupied by the tarn but beneath the moss and fen there is a rapid transition through a pale brown, organic-enriched layer to a predominantly organic accumulation of peat.

The lowest peat over the whole of the Tarn Moss basin is composed largely of grass and sedge remains which are set in a strongly humified matrix with a substantial mineral content. Seeds and fruits of many fen plants and seams of mosses occur in the deeper channels below the inflow stream and near Spiggot Hill. Upwards the peat becomes almost amorphous and completely humified but includes a discontinuous and ill-defined layer of wood fragments which is thick close to the moraine hillocks and margins of the basin, where seams of hazel nuts may also be present, and thins out over the centre of the basin. This brushwood layer is exposed in the eroded edge of the Tarn Moss and most of the branches and occasional trunks can be identified as those of birch both by their bark and the microscopic structure of the wood.

Fen peat with brushwood and quite a high mineral content continues up to the present surface in the fens around the margin of the moss, but over the central part of the basin and in parts of the north fen, the proportion of *Sphagnum* in the peat increases and the mineral content decreases until an abrupt change to almost pure but less humified *Sphagnum* peat. The disappearance of mineral material marks the commencement of raised-bog growth and the peat assumes a layered structure, although, in fact, each layer thins out laterally and overlaps its immediate neighbours. These lens-shaped masses of fresh peat represent compressed hummocks and are composed almost entirely of *Sphagnum imbricatum* and *S.* section *acutifolium* (probably *S. rubellum*); they are separated from each other by intervening layers of strongly humified material containing twigs, leaves and flowers of heather (*Calluna vulgaria*). The raised-bog peat attains a thickness of 3-4 metres in the two main convex peat masses of the moss, but near the present surface fibrous tussock-bases of cotton-grass (*Eriophorum vaginatum*) become more numerous and eventually form the bulk of the peat immediately under the mat of living vegetation.

POLLEN ANALYSES

It is clear that the stratigraphical sequence in Tarn Moss represents the silting up of the west end of the original basin, which allowed first the spread of fen and subsequently the development of bog. In the present tarn, on the other hand, mineral sedimentation has been uninterrupted throughout the same period. By examination of the fossil pollen content of the successive layers, changes in the surrounding vegetation during the period of deposition can be reconstructed and, as these changes follow a well-recognized pattern, they can be used to co-ordinate events at Malham with those in the British Isles as a whole or even in north-west Europe.

The pollen of most forest trees and many shrubs and herbs is produced in great quantity and dispersed in the air, so that pollen grains become incorporated in sediments and peat. So long as the material remains water-logged and air is excluded, the outer pollen membrane resists decay sufficiently to allow it to be preserved more or less indefinitely and to be extracted in identifiable condition. For many species the pollen is quite characteristic but there are also groups of species, whole genera or families in which the pollen is distinctive but more or less uniform (Fig. 3).

The technique of pollen analysis requires the collection of clean samples of the deposits, which in this case were obtained from two borings in Tarn Moss and one deep and one shallow boring in the tarn itself. The pollen is extracted by digesting the peat chemically and dissolving the mineral matter in such a way that the fossil pollen remains undamaged and can be concentrated together, dispersed in a transparent medium and spread thinly on microscope slides. The slides are examined systematically with a microscope and the pollen encountered is identified; sufficient grains are counted to give a fair sample from which the proportion of each type can be calculated. In practice this involves counting all pollen types until 150 grains belonging to trees (other than ash, willow and hazel) have been recorded. The separate categories are then expressed as percentages of the tree pollen and are plotted graphically against the depth from which each sample was obtained to give a pollen diagram (Figs. 2 and 5).

Comparison of pollen diagrams from many sites scattered over the British Isles reveals a very great degree of similarity in the main pattern of change in frequency of the various pollen types and, to facilitate correlation, a scheme of zones has been devised for British diagrams and is now widely used (Godwin, 1940a, 1940b, 1956).

In the basal silts and clays of both Tarn and Tarn Moss basins there is a clear relation between the stratigraphy and pollen content. The lowest grey clay contains only traces of organic matter and very occasional damaged pollen grains of pine, as well as spores dissolved out of the Carboniferous rocks. Just below the thin white sand layer, the organic matter in the clay increases and is associated with the development of the deep blue colour; at the same level pollen of various herbs appears. Throughout the rest of the blue clay the frequency of pine pollen rises but, as birch is now present also, the proportion pine forms of the total tree pollen falls. Birch and pine together exceed the total quantity of herb pollen and juniper is plentiful but does not rise above 60 per cent. By contrast, the ratio of tree to herb pollen is reversed in the overlying laminated layer, in which grasses, *Artemisia*, *Rumex*, *Plantago* and *Helianthemum* are all well represented and juniper and willow become abundant.

The scarcity of tree pollen, the presence of stones in otherwise finely graded sediments and the laminations of silt and clay ("varves") are all evidence that the upper and lower clays were deposited during periods when climatic conditions were severe; whereas the intervening organically-enriched clay, in which the pollen frequency of trees exceeds that of herbs, represents a milder phase (Fig. 2). The influence of this climatic oscillation was first identified at Allerød in Denmark but has since been widely recognized over much of Europe in those sites where deposition continued through the greater part of the Late-glacial period while the ice-fronts of the last glaciation were shrinking away northwards. During the early cold phase (Zone I), the main ice-front in Britain probably lay across southern Scotland, but from about 10,000 to 8,800 B.C. a milder period (Zone II) allowed a more rapid retreat which was halted temporarily in the Scottish Highlands by a return of colder conditions for about 500 years (Zone III).

Above the laminated clay at Malham birch remains the only abundant tree-pollen, but hazel is now also present and juniper, willow and terrestrial herbs decline. Pollen of water plants becomes more frequent and the character of deposition changes to the precipitation of lime. This marks the opening of the Post-glacial or forest period (Zone IV) at about 8,300 B.C.

About half-way through the calcareous marl the proportion of hazel pollen suddenly rises rapidly and becomes over five times more abundant than birch which within a few centimetres begins to decline. Pine begins to increase again and first elm and then oak appear. Zone V, which extends from the rise of hazel to the appearance of elm, is thus scarcely represented and the upper marl in the Tarn Moss basin belongs to Zone VI.

Pine is the dominant tree-pollen throughout Zone VI and is associated with abundant hazel and frequent elm. The change to peat accumulation in Tarn Moss occurs at this level, so that the rise in grass and sedge pollen is to be expected and the rapid acidification of the surface, which is marked by the appearance of *Sphagnum* and heather, is accompanied by a rise in Ericaceous pollen. Small and temporary rises in the pollen frequency of Chenopodiaceae, Ranunculaceae, *Plantago lanceolata* and *Urtica dioica*, on the other hand, are unlikely to be associated with the spread of fen and, considered together with the occurrence of charcoal at this level, may more probably be regarded as the first signs of human influence.

The sudden rise of alder pollen frequency marks the opening of Zone VII, about 6,000 B.C., and corresponds exactly with the level where the growth of the raised-bog commences. At the same level pine declines, so that oak, elm and alder predominate, associated with small but constant quantities of ash pollen and occasional grains of lime (*Tilia cordata*) and yew.

Indeed, lime remains sparsely represented throughout Zone VII and the

FIG. 3

Some characteristic pollen grains and spores present in the Malham deposits. a, *Pinus* (pine); b, *Betula pubescens* or *B. verrucosa* (birch tree); c, *Betula nana*-type (dwarf birch); d, *Corylus* (hazel); e, *Taxus* (yew); f, *Juniperus* (juniper); g, *Ulmus* (elm); h, Gramineae (grasses); i, *Quercus* (oak); j, *Fraxinus* (ash); k, *Alnus* (alder); l, *Salix* (willow); m, Ericaceae (heather); n, Cyperaceae (cotton grass and sedges); o, *Plantago lanceolata* (ribwort plantain); p, *Tilia cordata* (lime); q, *Artemisia* (wormwood); r, Compositae, *Taraxacum*-type; s, *Potamogeton* (pondweeds); t, Umbelliferae, *Heracleum*-type (hogweed); u, *Helianthemum* (rockrose); v, *Sphagnum* spore; w, *Selaginella selaginoides* microspore.

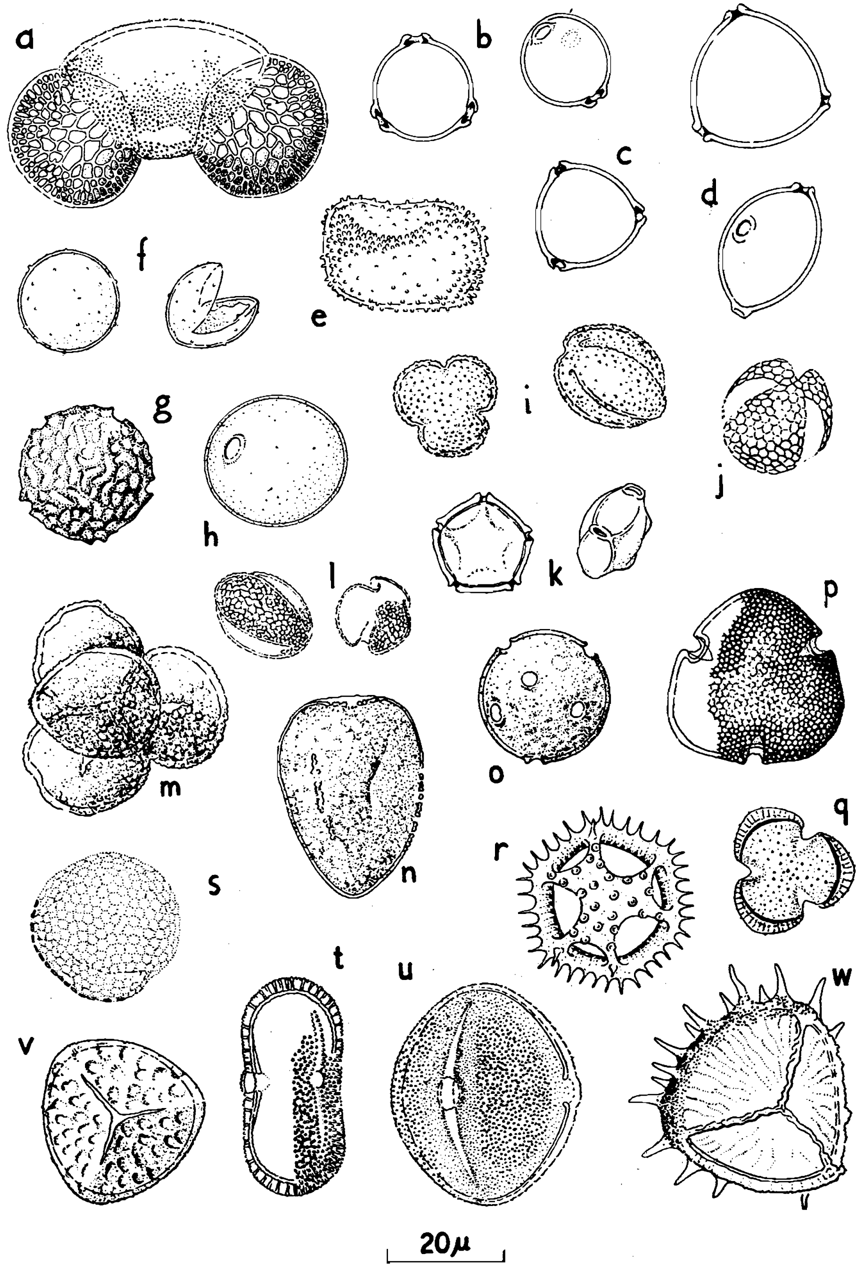
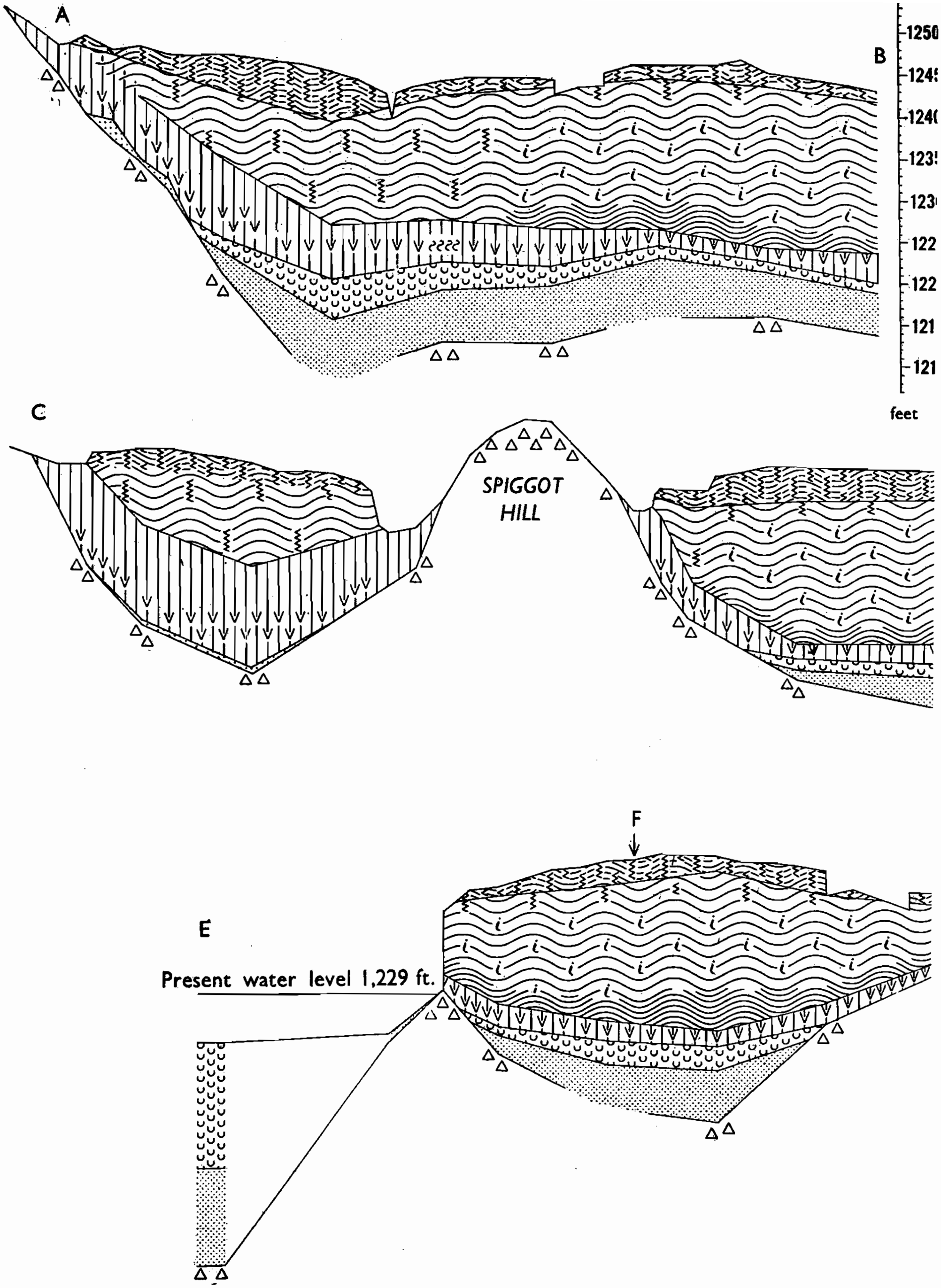


Fig. 3.



Stratigraphy of Tarn Moss, Malham. The relation of the three s
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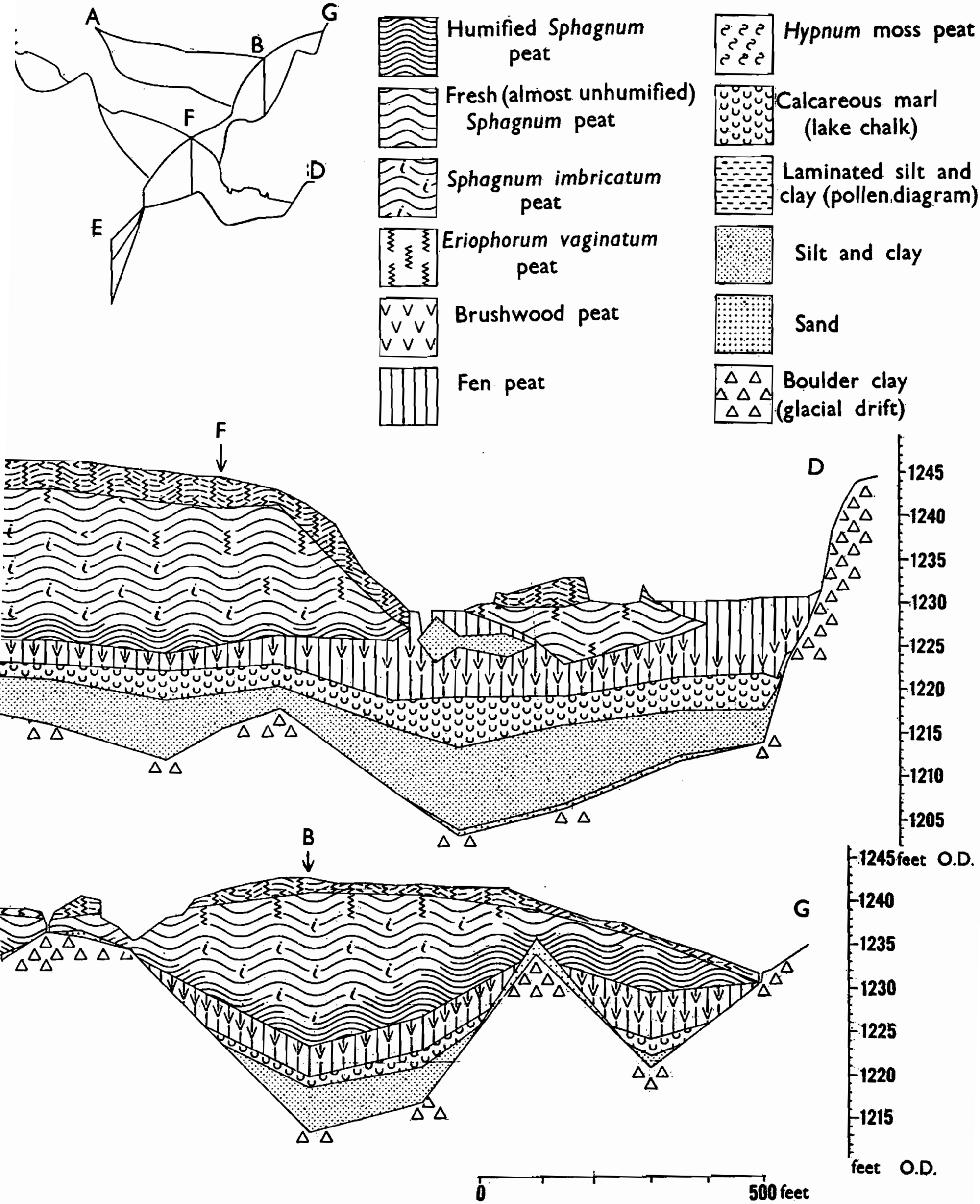

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ns to each other is shown on the map (Fig. 1) and is also illustrated
clays has been omitted. The vertical scale is given in feet above
the bench mark on Tarn House,

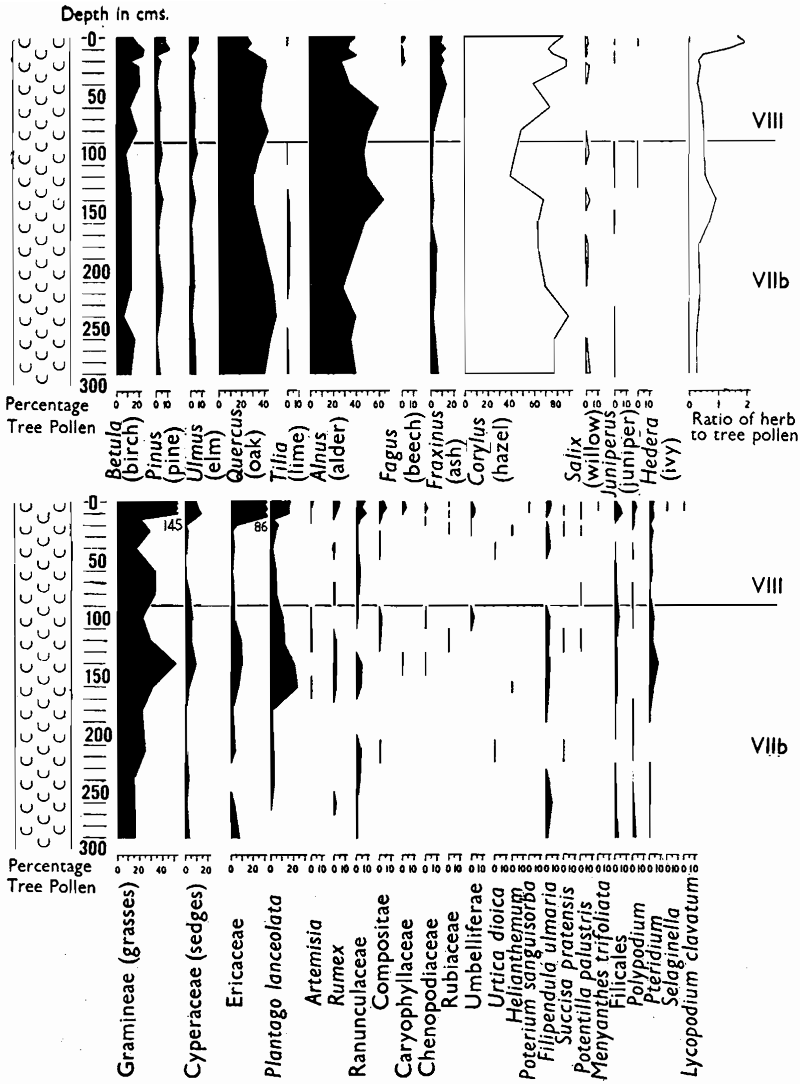

FIG. 5

Pollen diagram obtained from core-samples of the top three metres of sediment in Malham Tarn. The two main phases of forest destruction are clearly shown. Ericaceous pollen has been omitted in calculating the ratio of herb to tree pollen.

level at which elm shows a temporary lapse (Fig. 2) is probably the division of the zone into its two sub-zones VIIa and VIIb. A sudden and sustained rise of herb pollen occurs during Zone VIIb and is particularly well marked in the case of plantain (*Plantago lanceolata*) in the tarn diagram (Fig. 5).

In the upper part of the calcareous marl of the tarn and in the upper peat of the moss, there is one last distinct change in tree-pollen proportions when ash and birch begin to rise, alder declines and very occasional grains of beech and hornbeam appear. This is regarded as the boundary of Zone VIII, although elsewhere in Britain the close of Zone VII is marked by one or more abrupt stratigraphical changes from humified to fresh peat ("recurrence surfaces"). At Malham, however, the vigorous growth of *Sphagnum imbricatum*, which commenced at the start of Zone VII, has continued on the centre of the moss almost to the present day.

During Zone VIII there is an enormous rise in the frequency of many types of herb pollen. In the case of heather and sedge this must largely be attributed to the spread with grazing and burning of heather and cotton-grass (*Eriophorum vaginatum*) over the bog surface but high frequencies of plantain, *Artemisia*, *Rumex*, Chenopodiaceae and Ranunculaceae are clear evidence of widespread woodland destruction and the increase of grazing and cultivation.

Vegetational history

From the list of plants already mentioned, it will be clear that a deposit comes to include pollen not only from plants growing in the water or on the bog and fen but also from the vegetation of the surrounding region. Those species which produce abundant pollen and which are wind-pollinated will, of course, be particularly well represented. Interpretation of pollen diagrams is to a certain extent subjective and will depend on knowledge of the pollen-fall from present vegetation, as well as on inferences based on special features of the area concerned.

For instance, the pine pollen in northern English Late-glacial deposits is generally regarded as originating from pine forest lying much further to the south, because pine pollen is known to be widely dispersed and seeds, needles or fragments of pine wood are never encountered. Birch pollen, on the other hand, is often associated with fruits and even leaf fragments, although this is not the case in the Late-glacial layers at Malham.

The absence of organic matter in the clays of Zone I at Malham suggests that vegetation was sparse both in the tarn and on the surrounding uplands but in the milder Allerød period (Zone II), fruits of a pondweed (*Potamogeton praelongus*) are preserved in the clay and the proportional increase in birch pollen suggests that the tree may have been present locally, although quite a high proportion of the pollen grains are of the type characteristic of dwarf birch (*Betula nana*) (Fig. 3). The abundance of juniper pollen during Zones II and III suggests the occurrence of this shrub on the limestone pavements but presumably the vegetation was very "open" to judge by the high frequency of grasses, sedges, *Artemisia*, *Rumex* and *Helianthemum* and the occurrence of occasional grains of *Armeria maritima*, *Alchemilla*, *Campanula rotundifolia* and *Poterium sanguisorba*. Rare grains of *Hippophaë rhamnoides* and *Ephedra distachya* at this level are of particular interest. Both these plants, though occurring inland in central Europe and southern Asia, are restricted to the coast in western Europe at the present day. Moreover, the small shrub *Ephedra* (Gnetales, Gymnospermae) is no longer native further north than the south coast of Brittany. Whether either species was present in the late-glacial vegetation of the Craven limestone is not easily decided but the presence of *Ephedra* pollen in Late-glacial deposits on the limestone pavements of Öland in the Baltic (Iversen, 1954) suggests that this is plausible.

The change to a predominantly calcareous deposit at the opening of the Post-glacial period is accompanied by increasing numbers of *Potamogeton praelongus* fruits, high frequency of *Potamogeton* pollen and abundant remains of *Chara*. The pollen diagram suggests that tree-birches became locally plentiful but the decline and almost complete disappearance of juniper and herb pollen is delayed until the great rise of hazel in Zone V. There seems to be no reason why juniper should be suppressed unless a dense hazel scrub actually spread on to the limestone pavements. The well defined pine-hazel phase which follows, though characteristic of lowland England (Godwin, 1956), is unusual in the northern and western uplands. The same feature is shown in the diagram obtained by Raistrick and Blackburn (1938) from Linton Mires in the limestone district of Wharfedale. A possible explanation of this peculiarity is that pine (*Pinus silvestris*) became established on the shallow, limestone soils of the scars and pavements of Craven. Though often regarded as characteristic of heathland, pine grows well and regenerates freely on well-drained limestone soils.

During Zone VI the water must have become so shallow over the Tarn Moss basin that sedges were able to spread over the calcareous mud; the abundance of its fruits indicates that *Carex rostrata* was the pioneer species. Only the basal part of the fen peat is entirely free of the remains of birch and willow, so that the spread of carr was rapid. In the channel west of Spiggot Hill the fen peat includes a layer without wood and composed predominantly of mosses (Fig. 4). *Acrocladium sarmentosum*, *Aulacomnium palustre*, *Camptothecium nitens* and *Paludella squarrosa* occur together in this layer and indicate the development of a type of fen which is widespread in the mountains of northern Europe, particularly around the sites of springs. Beds of seeds and fruits, which probably accumulated in pools in the carr, provide evidence that the vegetation in the Tarn Moss basin during Zone VI was not unlike that found in parts of the fen today. The following species have been identified and all but three (*) still grow at Malham:

Betula sp.
Sorbus (probably S. aucuparia)

Carex rostrata
*C. vesicaria
Schoenoplectus lacustris
Potamogeton natans

Caltha palustris
Hippuris vulgaris
Menyanthes trifoliata (frequent)
*Nuphar lutea
*Lycopus europaeus
Potentilla palustris

A layer of rhizomes and leaves of reed (*Phragmites communis*) is exposed in the eroded edge of the moss at about this level. This grass is no longer present in the shallows of the tarn but a small patch occurs beside the inflow stream in the fen. Malham Tarn is close to the present altitudinal limit of *Phragmites* in the Pennines and well above the limit of *Lycopus europaeus*. The presence of both these species at this altitude during Zone VI is in accordance with the recognition of the so-called climatic optimum, when summer temperatures at least appear to have been a little warmer than at the present time.

The tendency for peat growth to become more or less free from the influence of calcareous ground-water is evident before the end of Zone VI and is marked by increasing quantities of *Sphagnum* and the remains of heather. The thin seams of charcoal and the small rise in weed pollen, even though they do not exactly coincide, are likely to be associated with activity of Mesolithic man. Plantain, nettle and members of the Chenopodiaceae are all plants generally associated with human settlement and disturbance, and the mound at the north end of the north to south transect (Fig. 4) is one of several sites around the tarn and Great Close Mire where microliths are numerous in the soil.

Alder probably became established in the wet hollows surrounding the tarn and in the fen at the opening of Zone VII, while hazel, elm (presumably *Ulmus glabra*) and even oak still occupied the limestone pavements to judge by the scarcity of herb-pollen. There is no evidence that ash played any important part in the vegetation and yew was probably on the cliffs where its descendants still survive. The spread of alder is usually regarded as a result of an important climatic shift towards increased oceanicity, which is associated also with the tendency for raised-bogs to develop in fenland and peat to begin to accumulate on gently sloping moorland soils ("blanket-bog"). Certainly both types of peat accumulation commenced about this time in the Craven Pennines. The change to peat composed largely of *Sphagnum imbricatum* on the Tarn Moss coincides exactly with the rise of alder pollen, while pollen analysis of the basal peats from the deep blanket-bog on Fountains Fell shows that bog growth began a little later but also in Zone VIIa.

Despite the evidence that woodland or at least scrub covered most of the limestone upland during Zone VIIa, the rare occurrence of pollen grains of *Helianthemum* shows that natural open habitats, even though limited in their extent, persisted in the vicinity of Malham Tarn. The presence of the characteristic pollen grains of *Polemonium caeruleum* is of particular interest, as this plant has been demonstrated to have been widespread in English Late-glacial vegetation (Godwin, 1956) and still occurs on cliffs and screes in the Craven Pennines. That the plant was present locally during the forest period bears out the belief that the present Craven localities are of long standing.

The abrupt rise in the proportion of herb pollen and particularly of *Plantago lanceolata* during Zone VIIb must be associated with late Neolithic forest clearance (possibly contemporary with early Bronze Age cultures in the south). To what extent this affected the upland limestone district is not easy to assess but polished hand-axes have been found quite close to Malham Tarn. Possibly the limestone scrub offered ground that was easily cleared.

This first increase of herb pollen is sustained and culminates during Zone VIII in a very much greater rise, which, in spite of the difficulty of precise dating, is likely to correspond with the Iron Age. This is well in accordance with archaeological evidence, as numerous hut circles and "corn-plots" are identifiable on Malham Moor and are attributed to this period (Raistrick, 1947).

A rise in the frequency of ash pollen is associated with each increase in herb pollen, so that the spread of ash seems to be related to forest clearance. This agrees well with the ecological behaviour of ash, which freely regenerates on cleared woodland soils when grazing is relaxed and other trees have been eliminated. It seems probable that the ash woods, which are today characteristic of the Craven limestone, are in most cases secondary woodland and not representative fragments of the original forest cover. It is likely then that the present treeless condition of the limestone pavements arose following clearance during the Iron Age and subsequently regeneration has been largely prevented by grazing and to a certain extent the absence of seed parents. The ratio of herb to tree pollen continues to rise rapidly throughout the historic period (Fig. 5). Malham Moor was an area which was settled and farmed by the Norse and subsequently, during the medieval period, was in the gift of two monasteries—Fountains Abbey and Bolton Priory—who maintained large flocks of sheep on the limestone uplands (Raistrick, 1947).

An indication of the extent to which soil erosion may have accompanied this destruction of woodland can be determined by examination of the sediments in the tarn where deposition in open water has been continuous and at least part of the water entering the tarn is derived from the surrounding limestone. By early Post-glacial time, mineral matter other than lime had almost ceased to be deposited in the basin as although the proportion of silt and clay in the calcareous marl is high in Zone IV it falls to about 5 per cent. in Zone VI. Even at the horizons in the Tarn deposits where pollen analysis indicates phases of forest clearance, however, the proportion does not rise above 6 per cent. (Fig. 5). Yet the scarcity of herb pollen during Zones VI and VIIa indicates a remarkably complete forest cover. To judge from fragments of woodland and scrub which survive on limestone pavements in Craven and in the Burren in western Ireland, a closed tree-canopy can be produced even if the trees are restricted to grykes. Under these conditions, shade and reduction of evaporation allows quite deep, but predominantly organic soils to develop on the clints, but these would waste away with little trace following deforestation.

The absence of evidence that extensive erosion of mineral soils has taken place during the Post-glacial period suggests that limestone pavement originated at an earlier time. Patches of mineral soil which do occur at the present day on the limestone surrounding Malham Tarn can be demonstrated to be derived from glacial drift and no traces of deep mineral soils of the type which cover most of the limestone plateau of north Derbyshire have been found in Craven. This difference must be attributed to the fact that Derbyshire is just outside the maximum extent of the last glaciation marked by the distribution of the Newer Drift, whereas Craven was invaded by ice. The soil cover was scraped away during glaciation and deep layers of boulder-clay were left only in the hollows. Probably thinner layers of drift were washed quite rapidly into grykes before vegetation cover was established. Examination of the mineral content of the Late-glacial sediments in Malham Tarn gives an indication of the extent to which this drift cover was eroded. In fact, only part of the silt which was brought into the tarn is certainly derived from drift, as small, unworn, perfect quartz crystals, which are characteristic of the insoluble residue of Carboniferous limestone, are frequent in the fine-sand and silt fractions.

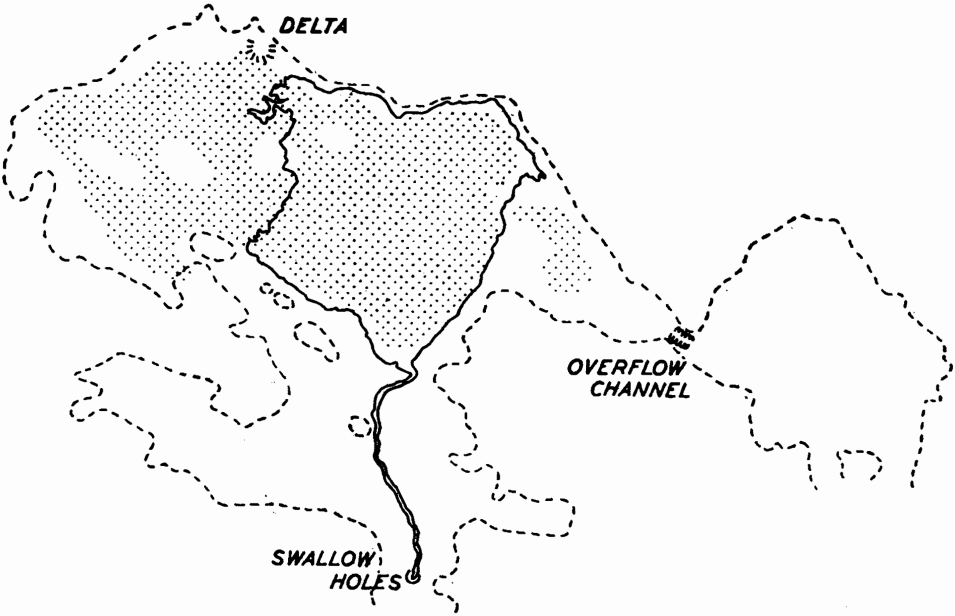

Fig. 6

Sketch-map of Malham Tarn and the adjacent basins. The broken line is the 1,250 ft. contour. The extent of silt and clay deposited during the Late-glacial period is indicated by stipple.

The evolution of the present drainage system

A feature of particular interest with regard to the history of Malham Tarn is the small limestone gorge below Great Close Plantation which at some time has clearly been the outflow channel from the tarn. The height of the upper end of this gorge would require the water level to have been at least at 1,240 ft. O.D. and the tarn would have extended across Ha Mire (Fig. 6).

It is possible that the line of small moraine hills which extend south-eastward from Spiggot Hill and form the present south-west shore of the tarn, previously formed a more complete ridge east of Lower Trenhouse and blocked the present outflow so that the water stood at a higher level. Similar moraine hills in the tarn basin have already been described and others occur scattered over Malham Lings. All are more or less oval with their long axes running from north-west to south-east and preliminary measurements show that the boulders in them are predominantly orientated on a similar axis. Thus these hillocks would seem to be small "drumlins" left behind by a north-west to south-east glacial passage. This explains the characteristic shape of the hills which seems unlikely to be the result of dissection of ridges. In this case, the present profiles of the hills either side of the outflow can be projected to give an indication of the depth of recent incision. This does not appear to support the existence of a barrier above 1,240 ft. O.D.

However, there is other evidence of a former high water-level. Two flat-topped mounds occur on the north shore of the Tarn Moss basin and excavation reveals bands of sand and gravel which dip steeply towards the moss. Similar outwash structures are exposed in some of the moraine hillocks near Trenhouse, but the flat-top and position of these mounds at the lower end of the valleys between High Folds and Chapel Fell suggests that they may be delta-fans. The top of the east mound is at 1,245 ft. O.D., so that if this represents the water-level at the time of formation, then it corresponds almost exactly with the head of the gorge below Great Close Plantation.

Excavation at the foot of the mound shows that it passes under the late-glacial clays which thin out against its slope. There is no sign of coarsening of the clay to suggest that sediment was washed into the basin from this point during the Late-glacial period, and, in fact, the clays become silty only near the present springs in the north-west corner of the Tarn Moss, so that even in Late-glacial time the water presumably entered at the same point. If then the mound is a delta it must have formed before at least the last part of Zone I but presumably after the glacial period when the moraine hills were formed.

The extent of the Late-glacial tarn can be determined from the distribution of the basal clays. These thin out marginally at 1,222-4 ft. O.D. and do not spread into the channel south of Spiggot Hill where the bottom is almost exactly at this level (Figs. 4 and 6). The Late-glacial shore is recognizable as a steep bank along the north side of the Tarn Moss fen. This again is evidence that the tarn did not overflow into the gorge below Great Close Plantation, but the existence in Ha Mire of a water-deposited clay, which contains only occasional pollen grains of pine, shows that at some time during Zone I either an extension of the tarn, or more probably because of the higher level (1,235 ft. O.D.), a separate pool was present here. Deposits of Zone II and later are not represented in Ha Mire so at the latest the tarn had assumed its present outflow by then. This absence of deposits from Ha Mire and the level at which mineral material ceases in the Tarn Moss peats both show that the water has not been above the present level during the end of the Late-glacial and the whole of the Post-glacial periods. As the present water-level is artificially maintained there has in fact been a slight fall since early Post-glacial time to the natural level before the sluice was built. This natural level is indicated not only by traces of the submerged shore in the tarn itself, but also by the broad bed of silt below the present inflow stream which corresponds with the depth to which recent sedge peat has accumulated in the east part of the Tarn Moss fen.

The adjacent basin of Great Close Mire has no open water deposits apart from a shallow layer of marl and peat in the pool which occupies the channel at the lower end of the gorge below Great Close Plantation. Over most of the basin only about 20-30 cm. of peat and occasional hummocks of tufa cover the boulder clay surface, so that it is clear that there has been no tarn in this eastern basin in either Late- or Post-glacial time.

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SUMMARY

Over 10 m. of peat, marl and clay underlie the central part of Tarn Moss and represent continuous accumulations since early Late-glacial time (before 10,000 B.C.). At least 6 m. of marl and clay occur beneath the Tarn. Pollen analysis indicates the existence of "open" vegetation with abundant juniper during the Late-glacial period. During the Post-glacial period, hazel spread on to the limestone pavement and may have been associated with pine and later with elm and possibly oak. The spread of ash is associated with late Neolithic and Iron Age forest-destruction, but the deposits show no evidence of Post-glacial erosion of mineral soils. The overflow channel into Goredale was apparently cut before the early part of the Late-glacial period.

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