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STUDIES ON CONNECTICUT LAKE SEDIMENTS.

I. A POSTGLACIAL CLIMATIC CHRONOLOGY FOR SOUTHERN NEW ENGLAND.

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ABSTRACT. Pollen-analytical investigation of five lakes and bogs in southern Connecticut reveals a vegetational sequence which can be attributed to postglacial changes in climate similar to those described elsewhere in North America, and which therefore constitutes a climatic chronology. This sequence is tabulated in Table 1.

The evidence that local oscillations of the ice-border may be accompanied by climatic deterioration consists in part in a demonstration of comparable relations in Indiana, Wisconsin, and Illinois.

Because of the chronologic uncertainties created by the irregular deglaciation of Connecticut, the sequence cannot be directly related to varved-clay chronologies; this conclusion implies the probable incompleteness of all North American pollen profiles.

Certain other pollen-diagrams from eastern North America are discussed, and particularly close resemblances to the Connecticut sequence are found in eastern Canada and Ohio.

The hickory-maximum during the mixed-deciduous forest period is tentatively correlated with the world-wide climatic optimum. The latter is attributed to extra-terrestrial causes, and deductive analysis suggests that it may be regarded as contemporaneous in the absolute sense in all parts of the world. In this respect it is shown to differ from the earlier segment of the climatic chronology, in which events are determined by the proximity of a retreating glacier-terminus, and which is consequently considered as relative.

INTRODUCTION.

IN 1936, at the suggestion of Mr. G. E. Hutchinson, the writer undertook an investigation of the typology of Connecticut lakes. This study has consisted in a stratigraphic inquiry into the nature of typological succession, as well as in a

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[1] This paper represents a revision of a portion of a thesis presented to the faculty of the Graduate School of Yale University in candidacy for the degree of Doctor of Philosophy. The revision has been accomplished during the author's tenure of a Sterling Fellowship in Biology.

more orthodox limnological reconnaissance. As the profiles of lake sediments secured rest without distinct unconformity upon coarse sands of undoubted late-glacial date, and as postglacial deposits in Connecticut and elsewhere vary considerably in thickness, the necessity for a chronologic division not based directly upon accumulation was immediately apparent. The widely used technique of pollen-analysis seemed to offer the most satisfactory time-scale available, in default of annual or other obvious lamination within the sediments. The application of this method to the deposits of two lakes in the New Haven region permitted chronologic correlation between those lakes; but although the inferred sequence of vegetational changes bore indubitable resemblances to similar sequences in other parts of North America, and even to the much more securely established succession of Europe, the differences were such as to demand a larger number of profiles from southern New England before the chronology could adequately be harmonized with events elsewhere.

In the present paper the results of pollen-analysis of eight profiles from five lakes and bogs within thirty miles of New Haven are presented. No pretense at finality of interpretation can be made on the basis of such a small number of analyses, and indeed considerable revisions of opinion have been necessary with the completion of nearly every section. Yet the eight pollen-diagrams are at last seen to be almost, although not entirely, consistent among themselves, and the resulting chronology is offered with some confidence as a working hypothesis, necessarily to be modified as the number of available profiles increases. Moreover, certain problems, primarily geologic in nature, have arisen during the investigation which require the collaboration of specialists in geology and botany, as well as in animal ecology, for their solution, and it is the author's purpose to discuss some of these questions and to indicate, if possible, methods for obtaining their answers.

It is with great pleasure that the author's indebtedness to Mr. G. E. Hutchinson is acknowledged; without his stimulating guidance this investigation would have been impossible. Particular gratitude is also expressed to Dr. R. F. Flint, Dr. Esa Hyyppä, and Dr. H. J. Lutz, all of whom have read the manuscript. Dr. G. E. Nichols also gave invaluable advice.

PHYSIOGRAPHY, CLIMATE, AND VEGETATION.

The physiography and glacial geology of Connecticut have been described by Flint (1930), and in less detail by many other geologists. The lakes and bogs investigated all lie within the limits of the Central or Connecticut Valley Lowland, an area developed upon the weak sandstones and arkoses of the Triassic Newark series, and divided into northerly-southerly strike valleys by outcrops of the interbedded Triassic dolerites and basalts, which stand up as prominent "trap ridges." The Lowland, throughout Connecticut and Massachusetts, is drained by the Connecticut River, which, however, leaves the province at Middletown, just west of the northernmost bog investigated, to pursue its famed anomalous course through the crystalline rocks of the Eastern Highland.

All of Connecticut lies within the limits of the Wisconsin glaciation, the outermost deposits of which are found on Long Island. The Wisconsin ice, by comparison with its erosive effects in other regions, accomplished surprisingly little remodelling of the preglacial topography; the till mantle attributable to active ice probably averages five to ten feet in thickness (Flint 1930, p. 72). Despite this relative feebleness, which undoubtedly was due in part to the resistant lithology and uneven surface of the preglacial crystalline upland, evidence of plural glaciation is excessively scanty, and in no case does it consist of sections of more than one till sheet.

Opinions differ as to the details of the last deglaciation of Connecticut. Although Antevs (1922, 1928), in his attempt to chronicle the retreat of the ice through New England and eastern Canada by telecorrelations of varved-clay sections, assumed a "normal retreat," Flint has shown (1929, 1930, 1932) that recessional moraines do not exist in Connecticut. The evidence accumulated by Flint demonstrates in convincing fashion the stagnation and downwasting of the terminal zone of the ice in Connecticut, a process of decay which is recorded by a profusion of kame terraces, eskers, crevasse fillings, and kettled outwash plains. Although his early work led Flint to reject in its entirety the concept of south-to-north retreat of the ice-front, re-examination of the evidence in the Connecticut Valley (1932, 1933) led to a modification of this extreme position, and to the adoption of a theory of general south-to-north removal of an ice-sheet having a thin and eventually stagnant distal zone. In a recent critical re-evaluation of the glacial geology of New Hampshire, Goldthwait (1938) has adopted a similar view. The late-glacial history of southern Connecticut will be discussed in greater detail after the presentation of the pollen chronology.

The climate of Connecticut presents both continental and oceanic features, having wide annual range of temperature and evenly distributed rainfall. The mean annual temperature varies from 45 to 50 degrees Fahrenheit, being distinctly higher along the coast, and the annual rainfall varies from 45 to 50 inches. The winds along the seashore show a pronounced monsoon effect, being southerly for five months at New Haven, but the monsoon influence is not apparent in the distribution of rainfall, owing to the frequency of cyclonic storms. The proximity of the ocean is evident in the proportion of winter precipitation falling as snow, for both Hartford and Middletown have more snow than New Haven during every winter month.

Connecticut is situated in a transition region between the coniferous forest of the north and the deciduous forest of the south, and this region has been considered an ecological unit by Nichols (1935). Over most of the region the climatic climax (in the use of this term the writer follows Nichols (1923)) is composed of sugar maple (*Acer saccharum*), beech (*Fagus grandifolia*), and hemlock (*Tsuga canadensis*), in varying proportions, and geographically its limits are nearly congruent with the ranges of hemlock and white pine (*Pinus strobus*). Species of subordinate importance within the climax association-type are yellow birch (*Betula lutea*), white pine, basswood (*Tilia glabra*), American elm (*Ulmus americana*), white ash (*Fraxinus americana*), red oak (*Quercus borealis*), black cherry (*Prunus serotina*), red spruce (*Picea rubra*), red maple (*Acer rubrum*), Norway pine (*Pinus resinosa*), balsam fir (*Abies balsamea*), and white spruce (*Picea glauca*); the last two are not found as climax trees in Connecticut. Among the important physiographic climax associations in Connecticut may be mentioned the bog climax, usually dominated by black spruce (*Picea mariana*) in the west and by coast white cedar (*Chamaecyparis thyoides*) in the east; salt-marshes; and pitch pine stands (*Pinus rigida*), for example those on the North Haven sand plains (Olmsted 1937). For a comprehensive treatment of the vegetation of Connecticut the reader is referred to the papers of Nichols: 1913 a and b, 1914, 1915, 1916, 1920 a and b.

METHODS.

Borings have been made by means of the Davis peat-sampler or its U.S.G.S. modification. Sections from lakes have been secured from the ice-cover. In general samples were taken at every foot-level, and the major portion of each core was transferred to a shell vial and kept without preservative.

Various methods have been employed in preparing samples for analysis of fossil pollen. The method found most generally useful, and the one commonly adopted for such studies, consists in boiling a minute amount of sediment in dilute KOH, to loosen the pollen-grains from their colloidal matrix, and mounting in glycerine or glycerine jelly. But in many instances, including a few samples from every profile investigated, preparations made in this manner are too poor in pollen for satisfactory analysis, either because of inorganic sediments or because of an excessive amount of undecomposed plant detritus. In the first case the mineral material has been largely removed by hydrofluoric acid, by the method of Assarsson and Granlund (1924). In the second case the excess cellulose has been dissolved by the method of Erdtmann (1934). In some cases both types of treatment were necessary. No sample has been rejected as "too poor in pollen to count" until the appropriate method of concentration has failed to provide satisfactory preparations. Mounts have usually been made in glycerine jelly previously stained with methyl green (Wodehouse 1935a), but the stain is of no advantage and is removed by a KOH-treated sample.

As aids in the identification of pollen-grains reference slides were prepared from herbarium specimens of many critical species; the published figures of Sears (1930a), Wodehouse (1935a) and Meinke (1927) were also extremely useful.

In general at least 150 grains of forest trees were counted. Occasionally, when only three or four species were present, counts were terminated between 100 and 150 grains. The following counts of less than 100 forest tree grains may be regarded as suspect on statistical grounds: (N = total number, Ft. = forest trees)

Series LH-3, Sample 1 foot, N = 141, Ft. = 66
QN-1, 23 feet, N = 15
JPK-3, 38 feet, N = 35

Barkley (1934) has treated the reliability of pollen-counts by means of Pearson correlation coefficients between half-counts, and shown that while counts of 100 to 200 grains give reliability coefficients of approximately 0.90, the number neces-

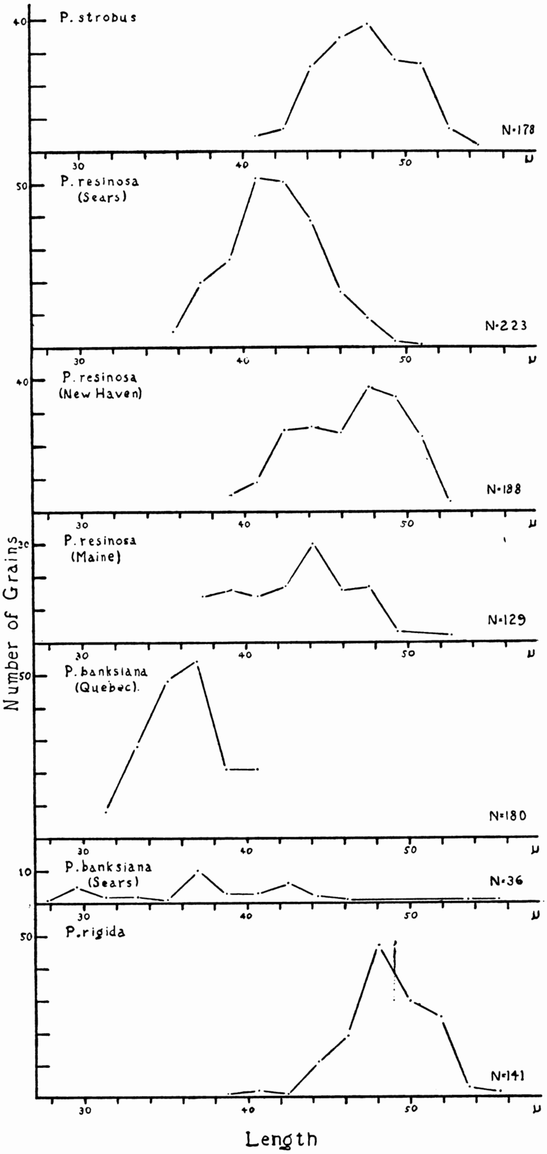

Fig. 1. Frequency-distribution of size among pollen-grains of various species of Pinus.

sary to increase this value to 0.95 is so large as to be impracticable; moreover, a statistical consideration of equatable samples from adjacent borings in the same bog frequently shows such low values of the coefficient that no advantage can accrue from increasing the significance of any sample beyond 0.90. Barkley's analysis demonstrates the need for a large number of profiles, rather than for a large number of grains in a single sample.

Several investigators have expressed the opinion that pollen-grains of different species of *Pinus* can be distinguished (Wilson and Galloway 1937; Hansen 1938; McCulloch 1939). No published evidence for this view exists except the well-known size-histograms for European species presented by Stark (1927) and Hörmann (1929). This evidence is by no means as conclusive as those authors believed, as has been pointed out by Jaeschke (1935) and von Sarntheim (1936), who showed that the size of the pine pollen-grain varies with the treatment to which it has been subjected. A series of histograms has been prepared by the author (Fig. 1), in part from species represented in the Yale Herbarium, and in part from slides prepared by Dr. Paul B. Sears and loaned the author by Mr. A. L. Washburn. Although the number of measurements is small, the figures show clearly that size variability among grains of different trees of the same species can be as great as that found among different species. Accordingly, and in consideration of the results of the later European workers, the attempt to distinguish species was abandoned. There is some evidence that exceedingly small grains may be derived from *P. banksiana*, but unless this conclusion is fortified by adequate statistical demonstration of significance, it cannot successfully be applied to unknown grains.

DESCRIPTION OF LOCALITIES.

(See map, Fig. 2.)

Linsley Pond is a strongly eutrophic lake, about 25 acres (10 hectares) in area and 48 feet (14.8 meters) deep, situated at an elevation of about 65 feet in the headwaters of the Branford River in North Branford. It occupies a kettle in a mass of stratified drift at 85 feet, mapped by Flint (1930). The deepest boring, L-10, penetrated to 43 feet below the present bottom in 42 feet (13 meters) of water; this boring failed to reach glacial sand, but chemical analyses of the sediment (Hutchinson and Wollack, unpublished) indicate a practically pure inorganic silt at 43 feet, so that not more than two or three feet of such silt probably lie below. The original depth of the kettle must therefore have been at least 87 or 88 feet, and if the vertical distance from lake surface to terrace-scarp be added, the thickness of the ice-block must have been at least 108 feet.

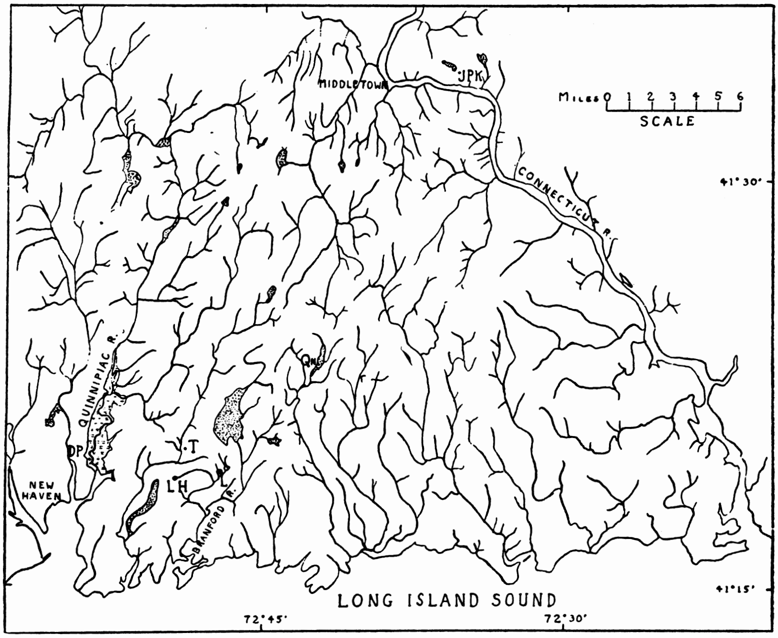

Fig. 2. Map of south-central Connecticut, showing location of pollen profiles. L—Linsley Pond; LH—Lyd Hyt Pond; T—Totoket Bog; QN—Lake Quonnipaug; JPK—Job's Pond Kettle.

Four profiles have been secured from this lake. L-1A, on the margin of the lake, is 15 feet long. L-2, just offshore from L-1A and from the major inlet, in 13 feet (4 meters) of water, is 26 feet long. L-9, in 19 feet (6 meters) of water, is 31 feet long, and L-10, just described, is 43 feet long. (For a bathymetric map of Linsley Pond, see Riley 1939.)

Lyd Hyt Pond. The same mass of stratified drift can be traced down the Linsley Pond outlet in Branford for about a mile, and up the outlet of Lyd Hyt Pond for about the same distance. The pond itself lies at about 120 feet, occupying what appears to be a kettle in a deposit of sandy glacial material not mapped by Flint. No detailed geomorphic studies have been made by the author, but it seems likely that the drift at 120 feet represents an earlier generation of deposits, perhaps approximately contemporaneous with stratified drift at corresponding elevations in the valley of the Farm River, referred to below.

The present lake is a senescent body of water about seven acres in area, carpeted by submerged and emergent aquatic vegetation, and nowhere deeper than three feet (1 meter). Boring LH-3, approximately in the center of the lake, is 33 feet long.

Totoket Bog fills the bottom of a kettle in a terrace of stratified drift along the Farm River near Totoket in North Branford. Although of approximately the same area as Lyd Hyt Pond, it is not shown on topographic maps. There is no outlet, and the surface of the bog is carpeted by shrubs and sedges. The boring, T-1, is 15 feet long, and was made near the center.

Continuous deposits at the 120-foot level indicate that the glacial lake which received them was not confined to the valley of the Farm River, but was ponded over the divides into the adjacent Quinnipiac and Branford River drainages. The spillway controlling the entire series lies north of Linsley Pond (Flint, op. cit., p. 183).

Lake Quonnipaug, in Guilford, is a eutrophic lake of compound kettle origin, occupying a long, narrow depression in a mass of glaciolacustrine material at 160 feet in the headwaters of the West River. Before the level was artificially raised by about five feet there were two lakes separated by a crevasse filling, as the bathymetry clearly shows (Riley, op. cit.). The present area is 118 acres (47 hectares), and the maximum depth in the northern basin is 48 feet (14.8 meters). The boring QN-1 was taken in ten feet (3 meters) of water in the southern basin, and is 23 feet long.

Job's Pond Kettle. In the southernmost reach of the Connecticut River within its lowland, between Rocky Hill and Middletown, lies an extensive body of glacial outwash, locally deeply pitted by kettles, which appears formerly to have filled the valley from side to side. This deposit has been described by Flint (1933) and shown by him to constitute the obstruction behind which was ponded the large glacial lake which received the Hartford varved clay. The largest depression is now occupied by Job's Pond in Portland; southeast of this lake, immediately below State Highway 14, is the partially bog-filled depression called by the author Job's Pond Kettle. The area of the bog is about two acres, and the boring JPK-3, made approximately in the center, is 40 feet long. The surface vegetation is ericaceous, and the shelf of firm ground which surrounds the bog and in part floors the kettle supports a stand of red cedar (*Juniperus virginiana*).

NOMENCLATURE OF DEPOSITS.

Stratigraphic sections based on microscopic examination accompany the pollen-diagrams in Figs. 3 to 10 (for key to symbols see Fig. 10). The usual geologic criteria have been employed to distinguish the mineral sediments, although mechanical analyses have not been attempted. The inclusion of both bogs and lakes, however, together with the more detailed examination of typological succession reserved for future publication, necessitates more precise differentiation of lake sediments than has usually been practiced by pollen investigators.

The characteristic organic sediment of a harmonic oligotrophic or eutrophic lake is a gelatinous, palpably greasy material, dark brown or black when fresh, gray, green, black, or brown in section, and gray or black when dry, typically containing 30 per cent to 60 per cent of organic matter, and composed of organic contributions from several sources in varying proportions: autochthonous components are derived from littoral higher vegetation, pelagic plankton organisms, and the bodies and excreta of benthic animals; the major allochthonous component consists of fragments of leaves of terrestrial plants. The amount of the organic fraction varies roughly with the productivity of the lake.

The accepted limnological term for this material is "gyttja." The term is used by Lundqvist (1927) and others in contradistinction to "dy," the organic deposit of a dystrophic lake, chiefly of allochthonous origin, and characterized by its flocculent colloidal structure, high proportion of carbonaceous material, and reddish color when dry. The introduction of these Swedish terms is due to Hampus von Post (1861). Acceptable English translations have never been proposed, although many authors have employed such non-specific and confusing terms as "mud," "muck," and "slime" without express reference to their European equivalent. The use of "silt" in the sense of an organic sediment cannot be tolerated.

The most satisfactory translation of "gyttja" appears to the author to be "ooze," a term already in use in similar connotation by oceanographers. "Sludge," used by Twenhofel and Broughton (1939), carries the unfortunate implication of sewage pollution. A recent report to the Sub-committee on Terminology of the Committee on Sedimentation of the National Research Council (Twenhofel 1937) is principally concerned with the fine-grained mechanical sediments, and though it sanctions the use of "ooze," omits adequate discussion of the nomenclature of limnetic organic sediments, and refers briefly to "sapropel" without mention of the dual connotation which precludes that term (for discussion see Wasmund 1930).

The author further proposes to follow Lundqvist in distinguishing "coarse-detritus ooze" from "fine-detritus ooze" on the basis of the proportion of material exhibiting cellular structure, and to qualify "ooze" when necessary by compounding with "silt-," "clay-," "diatomaceous," and "marl-" or "calcareous." "Dy" is then translated, as is usually done, by "peat" or "lake peat." It must be confessed that the present state of our ignorance of the chemistry, bacteriology, and diagenesis of lake sediments makes a final classification impossible, but unless substantial agreement with respect to provisional nomenclature can be reached by workers in various fields, the difficulty of dispelling this ignorance can only be enhanced.

DESCRIPTION OF PROFILES.

The pollen profiles, in terms of the percentage of total forest tree pollen, are presented in Figs. 3 to 10. Non-tree pollen, on the same percentage basis, includes only spermatophyte species. For the sake of convenience a generalized description will first be presented, followed by more detailed references to the individual borings. No single boring shows all the features regarded as important in equal detail, and it is suggested that the reader inspect QN-1 (Fig. 3) for the coniferous periods and L-10 (Fig. 4) for the deciduous.

The sequences observed can be divided into the following periods (shown at the right of each profile).

A-1. A coniferous period, characterized by pine, spruce, and fir, with some deciduous species present. Allowing for the well-known over-representation of pine (Wodehouse 1935b), this may be designated a spruce-fir period. Sudden rises in birch are seen locally.

A-2. Spruce and fir, particularly the former, attain their maximum and decline. Birch maxima are distinct in several profiles.

B-1. Pine reaches a more or less clearly defined maximum, locally as high as 95 per cent.

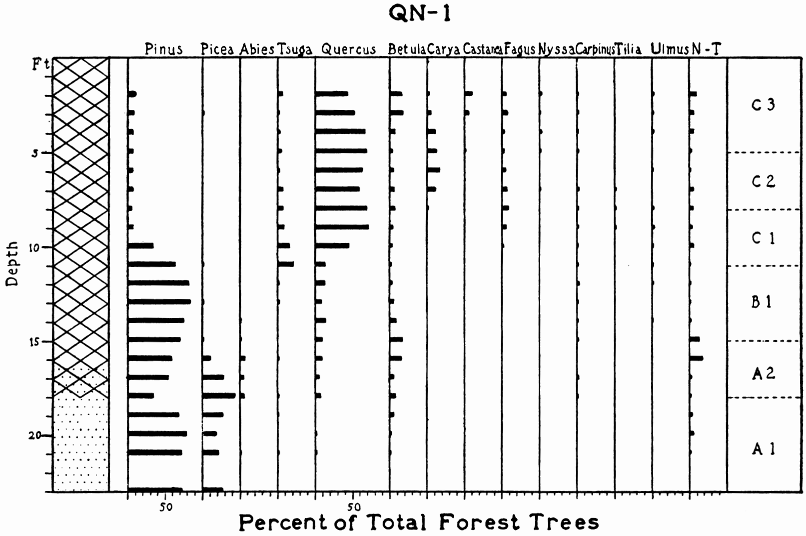

Fig. 3. Pollen profile for Lake Quonnipaug.*

C-1. Oak rises to a maximum, closely associated with and frequently preceded by a maximum of hemlock.

C-2. Hemlock and oak decline, while hickory rises, usually reaching its maximum.

C-3. Oak remains approximately constant, hickory declines, and chestnut and hemlock rise. An increase in spruce takes place in one profile (JPK-3), but is insignificant or absent in others.

The figures may now be examined individually, in order to see with what fidelity they reproduce the details of the generalized succession.

QN-1. (Fig. 3.) Despite the inclusion of an unreliable count for 23 feet, this profile reflects the changes within the coniferous periods with remarkable clarity. Indeed the entire section is diagrammatically faithful to the regional sequence, but the deciduous periods are singularly compressed in length.

*** For key to stratigraphy, see Fig. 10.**

The pine period (B-1) is best shown here, although it was first recognized elsewhere.

L-10. (Fig. 4.) A-1 is very short, A-2 likewise, although clearly present, and B-1 is absent. Of the Linsley Pond sections, L-10 is situated farthest from the source of inorganic sediment, and in this case the borer failed to reach the underlying sand. Comparison of chemical analyses and microscopic stratigraphy in L-10 and L-2 indicates, however, that the mineral sediment in L-10 is compressed rather than truncated, so that approximately the same time interval is spanned by this

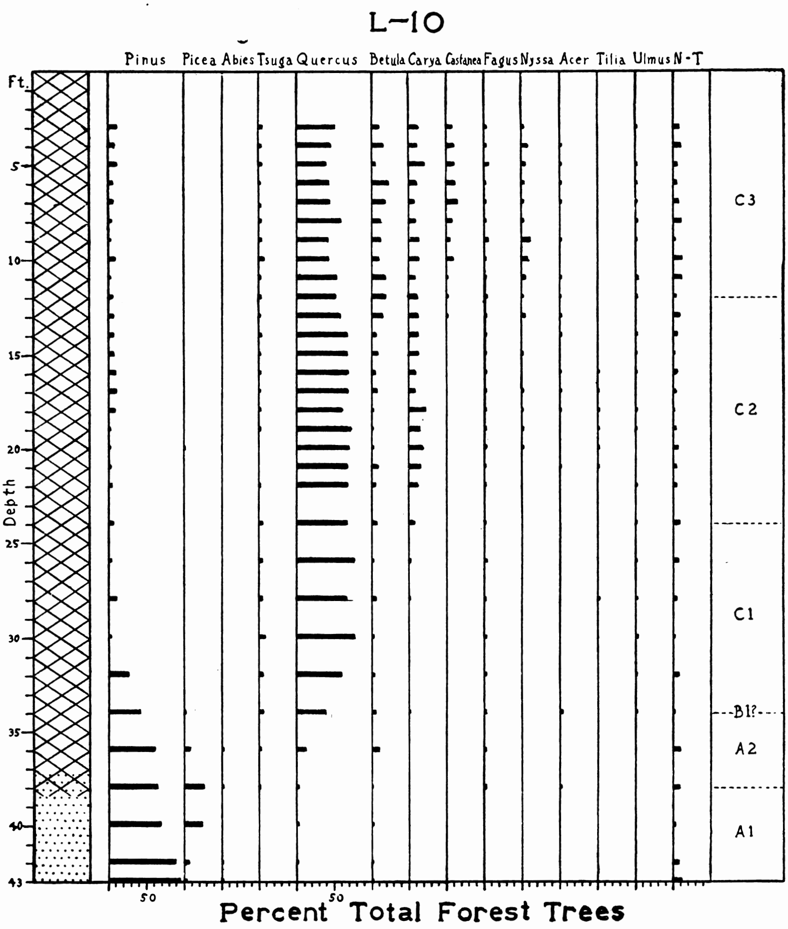

Fig. 4. Pollen profile for Linsley Pond, boring L-10.

material in both sections. The absence of B-1 may be explained by a sampling interval (two feet) too great to permit detection of rapid changes. The subsequent history is reflected in correspondingly elaborate detail, and affords a convincing demonstration of the generalized sequence from C-1 to C-3.

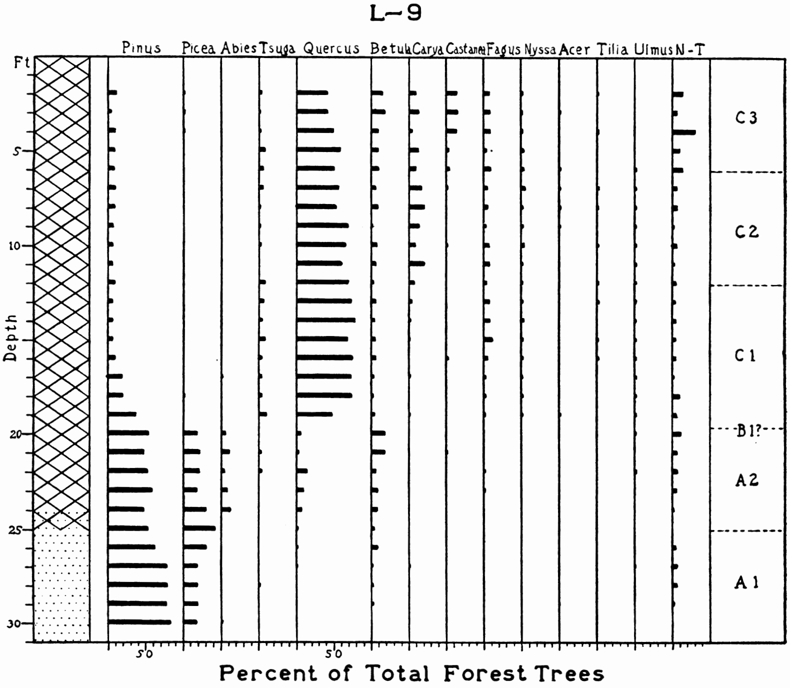

Fig. 5. Pollen profile for Linsley Pond, boring L-9.

L-9. (Fig. 5.) This profile confirms the validity of A-1 and A-2, and can be matched with L-10 from C-1 to C-3 with confidence; but B-1 is absent here as well as in L-10.

L-2. (Fig. 6.) The three coniferous periods here present no difficulties of interpretation; but events within the deciduous portion are obscure, and with the possible exception of LH-3, cannot successfully be correlated with any other profile. The principal anomalies lie in the behavior of the hickory curve and the absence of chestnut pollen. The possibility of completion of deposition before the beginning of C-3 cannot be entertained in view of the under-water location of the boring and the proximity of slope-binding littoral vegetation. If unconformities are represented, their least likely horizon is at the top of such a profile.

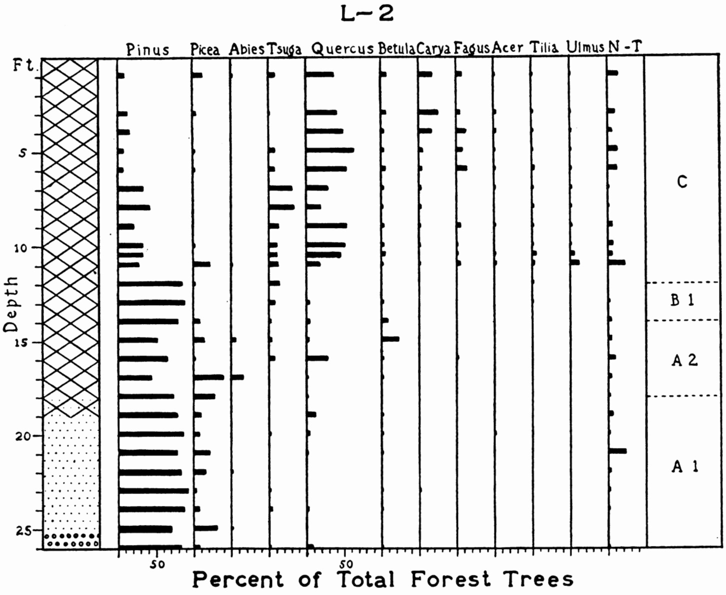

Fig. 6. Pollen profile for Linsley Pond, boring L-2.

L-1A. (Fig. 7.) This marginal boring clearly lacks A-1, suggesting erosion during this period at the lake shore. That deposition ceased before C-3 is indicated by the hickory-maximum at the top, and seems probable from the sedge-swamp conditions now obtaining at the site of the section. This ex-

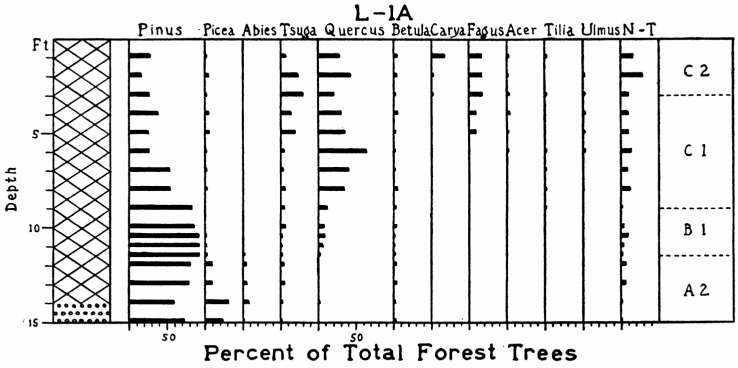

Fig. 7. Pollen profile for Linsley Pond, boring L-1A.

planation, however, ignores the anomalous position of the hickory-maximum of L-2. B-1 is particularly well-marked, and C-1 is somewhat less so, since hemlock rises relatively late.

T-1. (Fig. 8.) This bog also presents difficulties. The

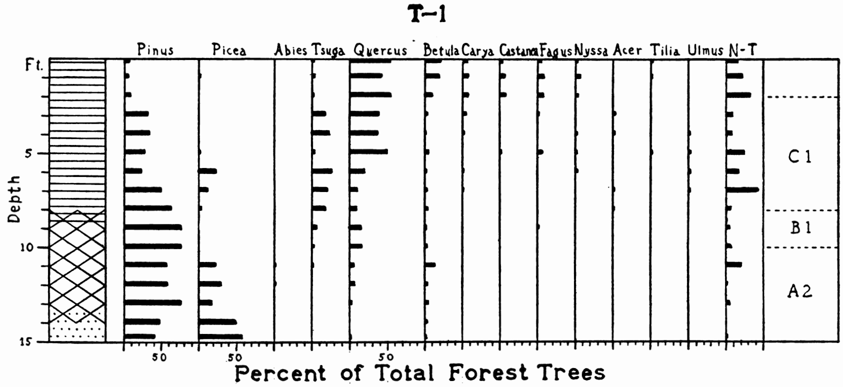

Fig. 8. Pollen profile for Totoket Bog.

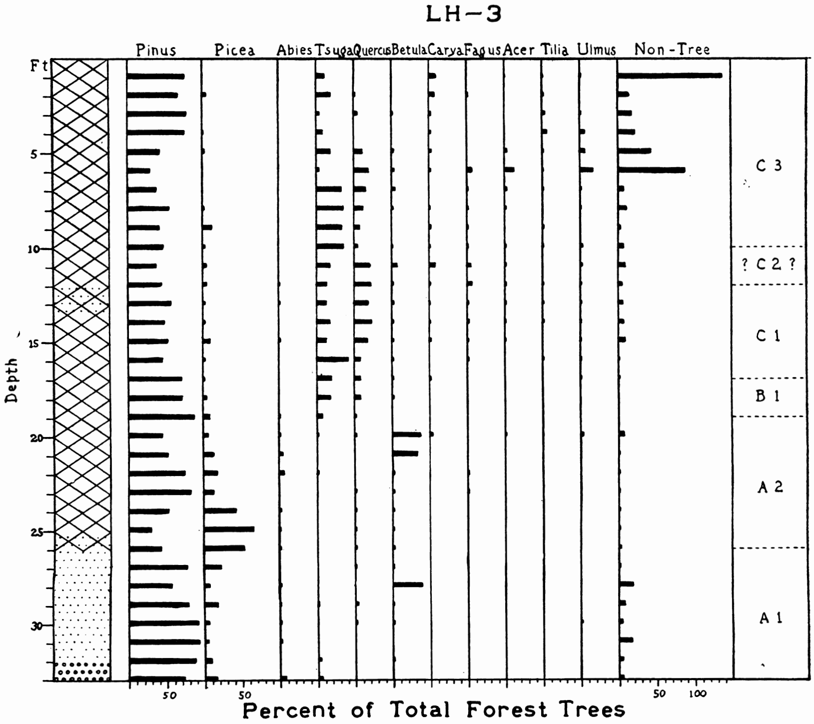

Fig. 9. Pollen profile for Lyd Hyt Pond.

spruce-maximum at six feet is probably a purely local variation, but nevertheless somewhat weakens the interpretation adopted, namely that A-1 is absent, and that the record begins in A-2. Although the borer was stopped by impenetrable sand at 15 feet, this sand proved to be black and organic; a considerable history may be recorded elsewhere in the bog, within more plastic sediments. B-1 is certainly present, as is C-1, but

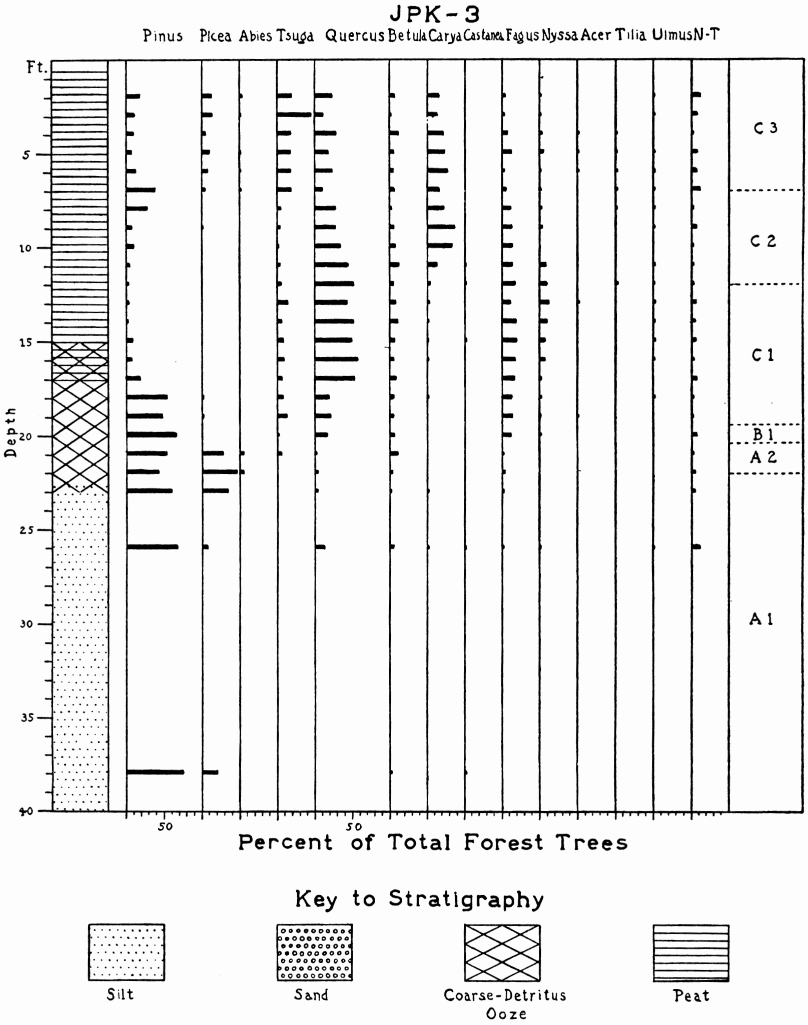

Fig. 10. Pollen profile for Job's Pond Kettle.

the uppermost analyses suggest early termination of bog-formation, either in C-2 or C-3.

LH-3. (Fig. 9.) A-1 and A-2 are most convincingly attested by this diagram; B-1 is brief; C-1 is nearly as well-defined as elsewhere; but conditions throughout the deciduous phase are complicated by an obviously local over-representation of pine. Chestnut is absent, and hickory is represented by two insignificant maxima, so that C-2 and C-3 cannot be demarcated with confidence.

JPK-3. (Fig. 10.) The silt of the lower part of the section is unfortunately poor in pollen; 35 grains, however, were found at the 38-foot level. A reliability coefficient of 0.987± .011 was calculated from half-counts of 16 and 19 grains on separate slides. This high agreement indicates that the percentages of the dominant grains (74 per cent pine, 20 per cent spruce) are reliable. These values are by no means unusual, and the sample and its immediate successors can safely be referred to period A-1. Period A-2 is clear, B-1 is very brief, and C-1 and C-2 are normal. The most striking feature of this boring, the increase in spruce during period C-3, will be discussed below.

INTERPRETATION.

The many factors which contribute to uncontrolled variation in single pollen spectra, such as sampling error, local variation in flora, peculiarities in composition of sediment, preservation of pollen, and over-representation of certain species, have been frequently discussed, particularly by Voss (1934), Erdtmann (1931a and b, 1935), and Wodehouse (1935b), and need not be elaborated here. Most investigators, however, have confined their attention to the retention of pollen by peat, and although Groschopf (1936) has considered flotation and lacustrine sedimentation of pollen, differences in permeability to water and sinking speed among various types of pollen have not been adequately studied. It is obvious that conditions in the epilimnia and hypolimnia of lakes are not equally favorable for the preservation of pollen, and it is quite conceivable that the chestnut pollen owes its fossilization in the hypolimnion of Linsley Pond to the low redox potential prevailing in that region (Hutchinson, Deevey, and Wollack 1939). Chestnut pollen is found only sporadically in profiles in Connecticut and elsewhere, and is said to be unusually susceptible to destruction by oxidation (McCulloch 1939). Wodehouse (1935b) has also pointed out that in Kashmir only stratified lakes afford the necessary conditions for the intact maintenance of pollen.

The over-representation of pine in pollen-spectra, due to excessive production or transportation from afar or both, creates a difficulty which is comparatively easy to circumvent when recognized. Although it has hitherto proved impossible to obtain a quantitative estimate of this disparity, its order of magnitude is indicated by some figures given by Wodehouse (1935b) who found that a forest containing 0.2 per cent pine was represented in modern lake sediments by a pine pollen percentage of 25 per cent.

But in spite of all the factors which prevent complete reliance on pollen-spectra as accurate indices of the composition of the surrounding forest, the major postglacial changes in vegetation can be inferred, provided that a sufficiently large number of profiles is available for a region. Since not all changes in vegetation are due to climatic variation, the chronologist must distinguish those events of climatic importance, which may be expected to occur over wide areas, from those of local or edaphic significance. Complete fulfillment of this task is impossible in the present state of North American pollen-analytical research.

The first spruce-fir period, A-1, must have approximated in climatic rigor the coniferous forest region of eastern Canada (Nichols 1918, 1935). The moisture of the period cannot be inferred from the available facts, since the species of spruce is not known.

Although the striking spruce-maximum of period A-2 appears at first sight devoid of parallel in any other region, its obvious importance in Connecticut justifies a search for comparable phenomena in published profiles. No reasonable edaphic cause can be assigned for an increase in spruce, which seems rather to require climatic deterioration.[2]

Such a cause was supposed by Hansen (1937) to be responsible for a less well-marked secondary spruce maximum in the Baraboo Bog, Wisconsin. The location of this bog on ground

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[2] The words "deterioration," "amelioration," and "optimum," as employed in this paper, conform to a common, but unfortunate usage, and require the debatable assumption that a warm-temperate, relatively moist climate not only favors the development of deciduous forest but is optimal for human welfare.

moraine of the third Wisconsin (Cary) substage suggested that re-advance of the ice in the fourth or fifth (Mankato) substage had produced the inferred cooling. Similar spruce-maxima have been observed by other authors, although only Hansen has ventured an explanation. Among the bogs investigated by Voss in 1937 are four situated immediately outside the Bloomington moraine (second or Tazewell substage) in Illinois, while two lie upon this moraine; the first four are characterized by a spruce-oscillation, while the last two are not. Several bogs studied by the same author in 1934 are located on drift of the Cary substage; those in Illinois are farthest removed from Mankato moraines, and of seven of these, six exhibit no spruce-oscillation. Such an oscillation is also absent from three of the four bogs in Wisconsin and Minnesota, while the fourth was closely approached by the Mankato glaciers. Of three bogs on Early Mankato drift, the two most nearly reached by Late Mankato ice are characterized by a secondary spruce-maximum. This distribution suggests a strong, though not inflexible relation, between a return of spruce and an advancing ice-sheet.

The majority of the bogs investigated in Indiana are shown by maps (Leverett and Taylor 1915; Thornbury 1937) to lie between the Bloomington and Mississinawa morainic systems. Secondary spruce-maxima are comparatively well developed in Marion and Hamilton Counties (Otto 1938; Prettyman 1937), and feebly or not at all developed in Madison, Howard, Cass, and Warren Counties (Barnett 1937; Howell 1938; Smith 1937; Richards 1938). A profile from Steuben County (Houdek 1932), within the Mississinawa moraines, shows no evidence of such an oscillation. The proposed correlation is less convincing in Indiana than farther west, since the most satisfactory spruce-maxima occur in bogs located farthest from the younger drift border, and the rather fragmentary evidence indicates the need for investigation of many more deposits within the several Wisconsin substages.

In many of the profiles referred to, the earliest spruce-maximum occurs immediately after a maximum of fir. Edaphic causes seem competent to explain this succession without recourse to climatic interpretation, and the secondary spruce-maxima discussed by the author succeed the decline of the combined spruce-fir percentages. This confusing feature is not shown by the Connecticut diagrams.

Evidence of a re-advance of the ice in the New Haven region during the last deglaciation is confined to a single exposure of till overlying stratified drift of an earlier ice-contact generation in the Quinnipiac Valley (Flint 1934, pp. 84-85; Krynine 1937). This generation in turn overlies varved clay in several localities (Krynine, op. cit.). That deposits of ice-contact character antedate the last advance of ice over the region is shown, however, by more generally distributed exposures in the vicinity of Middletown and Berlin (Loughlin 1905; Antevs 1928; Flint 1933). The available evidence suggests that the Connecticut re-advance was not comparable in intensity to the Wisconsin substages of the middle West, since the latest drift is thin and of very limited occurrence, and terminal moraines are absent; but topographic differences between the two regions are such as to minimize this apparent lack of resemblance. The spruce-maximum of period A-2 is therefore regarded as the result of climatic deterioration associated with an advancing ice-margin. The uncertainty of the temporal relation, emphasized below, between initial sedimentation in the kettles and deposition in the major valleys of Connecticut requires that this correlation be provisional; its likelihood, however, is increased by the demonstration of analogous relationships in other regions.

The sudden development of birch-maxima toward the close of period A-2 can most plausibly be attributed to forest fires. Temporary stands of birch (*Betula papyrifera*) are usually initiated after fire within the northern coniferous forest. Widespread destruction by insects, fungi, or wind, however, cannot be eliminated as causes for the catastrophe. Such an event evidently occurred during A-1 in the vicinity of Lyd Hyt Pond.

The pine association of period B-1 must be regarded as relatively xerophytic, since pines are normally succeeded by mesophytic hardwoods in Connecticut, and even the mesophytic *Pinus strobus* is relegated to a minor rôle in the climax forest (Nichols 1935). Climax associations of xerophytic species (*P. banksiana* and *P. resinosa*) occupy large areas of sandy soil in the Lake States, and considerable stands of pitch pine (*P. rigida*) are frequent on the sandy glacial outwash and kame terraces of New England; a typical pitch pine plain in the Quinnipiac Valley has been carefully studied by Olmsted (1937). Period B-1 conceivably represents a successional stage analogous to such physiographic climaxes, but that climatic agencies were effective seems probable from its long duration and from Olmsted's demonstration that the North Haven pine association is not a climax, but owes its preservation to attempted cultivation. The climatic explanation of B-1 is supported by the appearance of a well-marked pine period at the corresponding stage of many other North American sequences (Sears 1931, 1935a; Voss 1934, 1937; Auer 1930, 1933; Smith 1937). The period is therefore regarded as warmer and drier than the foregoing.

C-1 witnesses the advance of warm-stenothermal deciduous trees into the region (accompanied and frequently preceded by hemlocks) and their development into a forest essentially like that of the present.[3] Particular reliance may be placed on the hemlock, since it is not only a sensitive indicator of mesophytic conditions, but is coextensive in range with the "transition" or "hemlock-white pine-northern hardwood" region in which Connecticut is situated. The oaks are more equivocal, for both mesophytic and xerophytic species are found in the region, and at least one species (*Quercus palustris*) is occasionally a hydrophyte. As the pollen-spectra may be assumed to record a mean oak-assemblage, a figurative average of the species supposedly involved lies somewhat on the xerophytic side of mesophytism.

During period C-2 conditions in southern Connecticut became slightly more xerophytic, as is illustrated by the rise in hickory and the somewhat less striking decline in hemlock. These events are not shown by all the profiles in equal detail, and as has been pointed out, L-2 cannot be reconciled with the other sequences. Nevertheless, especially in profiles L-10, JPK-3, and QN-1, the alteration is of sufficient importance to justify the climatic interpretation offered.

Vegetational changes during period C-3 were of two distinct types. In the southern profiles the decline in hickory and rise in chestnut (L-10, L-9, QN-1) indicate a return to the mesophytic conditions of C-1, although the hemlock fails to show its expected recurrence, and the behavior of beech is disappoint-

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[3] The relative positions of oak and hemlock in the pollen-spectra do not agree well with our knowledge of their relations of competition, and in default of exact information it can be argued that oak pollen is greatly over-represented, at least with respect to hemlock, since an oak pollen-grain has approximately 1/27 of the volume of a hemlock grain, and is presumably much more buoyant.

ingly deficient in intelligible variations. At the northern station, JPK-3, however, not only does the resurgence of hemlock take place, but in addition a clearly defined re-invasion of spruce attests cooler climatic conditions. Inspection of L-2 and LH-3 also demonstrates the existence of spruces in the vicinity, but in insufficient quantity to suggest comparable climatic severity along the coast.

That climatic differences of such magnitude existed between regions less than 30 miles apart may seem surprising; but that similar differences exist today can easily be determined, and Church (1935, 1936) has emphasized the steep thermal gradient across New England. Since profile JPK-3 permits no analysis of the present-day vegetation of the region, and since only one such profile is available, no conclusions as to the permanence of the climatic severity are possible. Spruces are not important components of the modern Connecticut forest except at the considerably greater elevations of the Western Highland province; but this profile merely suggests a recent increase, rather than even local dominance, and reconstruction of the immediately pre-colonial vegetation of northern Connecticut must presumably await evidence not based upon pollen profiles.

CORRELATION.

Late-glacial Conditions in Connecticut.

Before the similarity of the Connecticut vegetational sequence to events elsewhere is considered, the relation between initial pollen-deposition and deglaciation may be discussed, in order to determine the degree of completeness of the record. The investigations of Flint and Goldthwait have supplanted the assumption of "normal retreat" with a concept of ice-shrinkage involving a distal zone of thinning, a process which leads to the production of discontinuous ice-remnants and differential rates of melting. Since the pollen profiles have been secured from depressions formerly occupied by such ice-masses, the detailed chronologic relation between deposition in kettles and removal of the glacier is highly uncertain. As the melting of bodies of buried ice and subsequent slumping to form kettles cannot be expected to occur simultaneously, synchronous origin of the earliest pollen-bearing sediments in any two kettles cannot be assumed; it has been shown that within the deposits of a single drainage system sections from kettles in a higher, slightly earlier terrace (Lyd Hyt Pond, Totoket Bog) can begin at about the same time as, or even later than those from kettles in a lower terrace (Linsley Pond). Moreover, profiles secured from a single kettle can differ in time of initial deposition, depending on the limnological history of the basin (see profiles L-1A and L-2, L-9, or L-10).

Since all North American pollen profiles that extend back to glacial deposits begin in a spruce-fir forest period, and since most, if not all, of these have been obtained from kettles, it follows that no known pollen-sequence certainly records an entire post-glacial history, as Sears (1935b) has realized. Agreement with this statement requires no particular mode of deglaciation in a region, as kettled ground moraine is often associated with an actively retreating ice-margin.

From this consideration it is possible to conclude that a segment of late-glacial time of unknown and probably variable length can be inserted between the deglaciation of any locality and initial deposition in lakes and swamps; the tundra flora and fauna (Hay 1912; Baker 1920; Antevs 1928) can be assigned to this period without controverting the evidence of the pollen chronology. Proof of a late-glacial tundra in New England has been presented by Emerson (1898, p. 718) and by Hollick (1931). The late glacial tundra, however, can scarcely have been either widespread or of long duration, in view of the paucity of satisfactory examples and in the light of inferred forest conditions in close proximity to the glacial border during Wisconsin substages (Cooper and Foot 1932; Voss 1933; Wilson 1932, 1936). Its existence in certain localities, therefore, is not regarded as a serious objection to the suggestion previously advanced, that the spruce-maximum of A-2 represents a climatic deterioration accompanying a local readvance of the ice, and that spruce-fir forests antedate this advance.

The fossil oak, maple, and hemlock flora reported by Brown (1930) from the sand overlying the varved New Haven clay at the Stiles Clay Pit must clearly be referred to some part of the mixed-deciduous period (C-1 or C-2). Despite published statements this sand is neither of ice-contact character (Flint 1930) nor a member of the "pink" generation (Krynine 1937), but represents a relatively quiet-water member of the "buff" series of postglacial stream deposits (Krynine, unpublished). The flora therefore postdates the last re-advance of ice in the Quinnipiac Valley, and antedates the postglacial marine transgression; more precise chronologic determination is impossible at present.

Other North American Sequences.

No detailed review of pollen-analytical work in North America need be attempted here, as the valuable papers of Sears (1935 a and b, 1938) have covered the field. Certain circumstances, however, require additional emphasis if the Connecticut chronology is to be satisfactorily related to events elsewhere. The general similarity of these profiles to those from neighboring regions is obvious upon superficial inspection. The diagram of Caribou Bog, a typical example from Nova Scotia (Auer 1930, 1933; Sears 1935a) illustrates the replacement of spruce-fir by deciduous forest, and is of particular interest in three respects:

1. A brief but well-defined maximum of pine precedes the development of deciduous forest. This period was invested with climatic significance by Sears (1932), who regarded it as warmer and drier than the foregoing. The incidence of a pine period in other North American profiles has already been pointed out.

2. The advent of mixed-deciduous forest species is heralded by a pronounced hemlock-maximum, indicating an increase in moisture. A similar phenomenon can be demonstrated in most of the Connecticut profiles, in which, however, a slightly delayed maximum of oak accompanies and overshadows the hemlock peak.

3. The oak-maximum, feebly developed at this northern station, bears witness not only to somewhat drier conditions, but to a postglacial, thermal culmination for the region; the ensuing deterioration is expressed in terms of a re-advance of spruce.

Parallel climatic changes are shown for Ohio by Sears (1930b, 1931, 1932). Hemlock is practically absent from the region, but is replaced as a moisture indicator by beech, so that a threefold division of the deciduous forest period is implicit in the succession: oak-beech, oak-hickory, oak-beech. The post-optimum refrigeration of eastern Canada does not extend to Ohio, but corresponds to an increase in moisture.

A recently published profile for the geographically intermediate region of central New York (McCulloch 1939) is of interest in that the postglacial oak-maximum is complemented by a pronounced dichotomy in the hemlock curve.

The recent spruce-advance which succeeds the oak-maximum in eastern Canada is not a universal phenomenon, and within the United States it is confined to profiles situated near the Canadian boundary, in Wisconsin and Minnesota. This circumstance has given rise to some controversy, for Voss, ignoring the recent increase in spruce shown by his own diagrams for those states, has maintained (1934) with support from Fuller (1935) that postglacial climates have remained static since the decline of coniferous trees, while Sears (1935a and b, 1938) has recognized a climatic deterioration, restricted in thermal character to more northern stations, but represented in Ohio by increasing moisture. "Northern" and "southern" types of pollen profile are well illustrated, respectively, by Bay Lake Bog, Minnesota (Voss 1934), near the 46th parallel, and Center Lake, Indiana (Houdek 1932), near the 42nd, and as has been shown, both types are encountered in Connecticut, where maritime influences produce an abnormally steep temperature gradient from north to south.

The correlations proposed may be summarized in the form of a table (Table 1), necessarily provisional in nature. In most respects this table constitutes a reinforcement, rather than a serious revision, of the correlation suggested by Sears (1932, Table 1). It should be noted that in this table horizontal equivalence does not imply absolute contemporaneity, as is emphasized below (p. 721).

History of the Connecticut Vegetation.

In its broad outlines the vegetational history of the New Haven region has already been treated, and the more precise details may be referred to students of plant ecology for elaboration. The need for more exact knowledge of the botanical corollaries of a decaying ice-sheet has been indicated; the relative extent and duration of the late-glacial tundra must be discovered, as well as the center of refuge and speed of migration of the coniferous trees which were the first certainly known invaders of southern Connecticut. With the acquisition of this information ecologists will be in a position to answer the interesting question raised by Flint (1930)—whether forests did not grow upon thin stagnant ice near the margin of the waning

TABLE 1.

Proposed Correlation of Climatic and Vegetational Changes in Eastern North America.[1]

Climate	*Eastern Canada* (Auer)	*Connecticut* (Deevey)		*New York* (McCulloch)	*Ohio* (Sears)	*Wisconsin* (Voss)
		Coastal	*Inland*			
Moister and/or Cooler	Spruce	Oak-Chestnut	Spruce-Hemlock	Oak-Hemlock	Oak-Beech	Spruce
Warm, Dry	Oak-maximum	Oak-Hickory		Oak-maximum	Oak-Hickory	Oak-mixed deciduous
Warm, Moist	Hemlock-Oak	Oak-Hemlock		Oak-Hemlock	Oak-Beech	
Warmer, Dry	Pine	Pine		?	Pine	Pine
		Spruce-maximum (last glacial advance?)				
Cool	Spruce-Fir			Spruce-Fir	Spruce-Fir	Spruce-Fir
Deglaciation		Spruce-Fir ←————Tundra Flora?————→				

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[1] These correlations imply contemporaneity only in the relative sense, as discussed on p. 692.

glacier, as they do today on the Malaspina glacier in Alaska (Tarr 1908), thus prolonging the period of melting.

Since deglaciation Connecticut has passed through a vegetational stage climatically equivalent to eastern Canada (northern coniferous forest), and through a stage edaphically, if not climatically similar to certain areas in the Lake States (pine climax). Evidence of both periods exists today in relict areas, the most notable examples being spruce-bogs and sandy pine plains or "edaphic deserts." With the onset of favorable climatic conditions the forest gradually acquired its characteristic mesophytism. The subsequent fluctuations in moisture régime, though perceptible in the pollen profiles and evidently general throughout eastern North America, have been of subordinate importance, and quite probably have found floristic expression only in critical localities, where physiography has permitted.

The sequence observed in southern Connecticut, unimpressive though it may be in comparison to the temperature changes attendant upon deglaciation, gains considerable interest from the discussion of the composition of the "original forest type." Bromley (1935) and Raup (1937) have presented evidence that the New England forest in colonial days was somewhat less mesophytic than studies of virgin forest remnants (Nichols 1913b) suggest. Bromley concluded from a search of the historic records that the pre-colonial type in southern New England was an open oak-hickory forest, and attributed the maintenance of this condition to the frequent fires set by the Indians. Raup, while criticizing Bromley's sources on the basis of unfamiliarity with the interior, and questioning the importance of the aboriginal pyromania, reached the same conclusion after study of the accounts of more adventurous and presumably more reliable observers. He therefore supposed the "xerothermic period of about 3000 years ago" (Gleason 1922; Transeau 1935) to have been responsible for the inferred xerophytism, and considered that the persistence of the forest until such recent times was due to an inherent stubbornness in the face of a moister climate. Proceeding to a stimulating review of the evidence for a postglacial climatic optimum accompanied by widespread dry conditions, Raup was able to find reasonable arguments for assigning to this period such diverse phenomena as the "Virginian element" in the New England-Acadian marine fauna and the diffusion of Old Algonquian cultures into New York and New England from the mound-builder area.

The concept of widespread and long-continued persistence of forests not adjusted to the prevailing climate logically leads to a negation of ecological theory, and Raup's hypothesis must be construed to include only local areas of relict vegetation. The possibility that such areas were encountered by early American travellers cannot be questioned, whether or not the delay in succession be attributed to fire. That climatic elements propitious for the development of oak-hickory forest obtained in southern Connecticut at the time of the climatic optimum can be determined by reference to the pollen-diagrams.

General Considerations.

In the foregoing discussion certain correlations have been proposed and certain events have been regarded as contemporaneous; regional differences between climatic sequences have also been demonstrated, notably in respect to evidences of recent climatic deterioration, which are convincingly shown only by northern profiles. It is now necessary to examine the relation between correlation and contemporaneity.

Given an ice-sheet uncovering a terrain from south to north, and given a center of refuge and subsequent dispersal for plants situated beyond the glaciated area, a simple deduction indicates that a chronology based upon the succession of floras must be a relative one, bearing no relation to astronomic time except a trend in the same direction. The development of geochronologic methods in Europe has provided the proof for this deduction; for example, Hyyppä (1936) has shown that the tundra reached the northern part of Finland later than the southern. But if we conceive of climatic time as relative and astronomic time as absolute, it is pertinent to inquire whether at some gnomonic level during deglaciation the relative time has not overtaken the absolute and ceased to have a separate existence.

This matter can be treated with the aid of an intuitive diagram (Fig. 11), on which climàtic favorability is plotted against astronomic time as a smooth curve. This curve is conceived as the resultant of climatic changes produced in part independently and in part concomitantly by deglaciation and by variable solar radiation. It is assumed that a régime of "glacial climates" in the sense of Brooks (1928) prevails, and that at the time of maximum favorability continental ice-sheets are absent from the region under consideration. The vertical lines, representing chronologic sequences at different latitudes, intersect the climatic curve at points A and A1, which indicate, let us say, the beginning of mixed oak forests at these two latitudes. This event takes place earlier (A) at the southern station (α) than at (A1) the northern station (β), and will not take place at all at a station (γ) too far north for oaks ever to occur; it is in this sense that the climatic chronology is a relative one. As the climatic favorability reaches its maximum and declines, a time C1 is reached at which mixed oak forests can no longer maintain themselves at station (β), but at station (α) this time has not yet arrived. The climatic optimum (B, B1), indicated by the regionally appropriate maximum of thermophilous trees (in Connecticut by oak-hickory forest) is inevitably contemporaneous at all stations, however, even though the succeeding deterioration may not be obvious too far north (γ) or too far south (α). This contemporaneity follows from the consideration that the phenomenon is so widespread as to preclude independent local causes; some external cause, such as an increase in solar radiation, must be responsible.

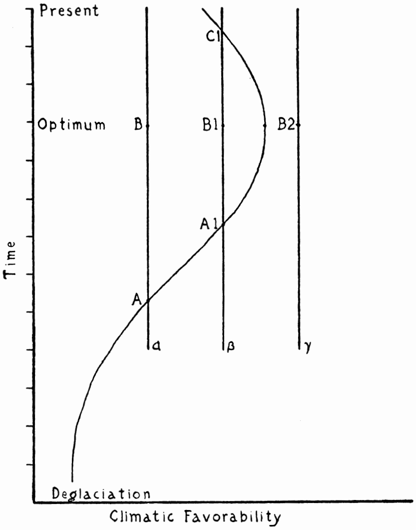

Fig. 11. Schematic diagram of the relation between astronomic and climatic time.

Should the assumption that the North American continent was free of ice at the time of the climatic optimum prove to be invalid, a retardation in the appearance of the optimum may be expected to occur at some undetermined, but undoubtedly high latitude.

It is immediately obvious that in the light of this discussion the correlations proposed in Table 1 do not inevitably imply absolute synchrony, and indeed simultaneous inception of spruce-fir forests in Connecticut and Nova Scotia is clearly impossible under the circumstances. In the author's opinion only period C-2 and its correlatives can be regarded as contemporaneous in the astronomic sense.

This theoretical analysis admittedly transcends the available evidence, and can only be confirmed by detailed comparison of Europe and North America in respect both to absolute and relative postglacial chronology. Although it has recently been possible to relate the pollen-analytical sequence to the Swedish geochronology (Fromm 1938), any attempt at transatlantic comparison would be premature. The complex physical history of the Baltic region constitutes the greatest barrier to such comparison. Nevertheless the existence of a postglacial climatic optimum is exceedingly well-attested by many diverse indications, and if, as deductive analysis suggests, this phenomenon can be regarded as absolutely as well as relatively contemporaneous over the northern hemisphere, many obstructions in the path of progress will vanish.

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