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A LATE WISCONSIN BURIED PEAT AT NORTH BRANCH, MINNESOTA*

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ABSTRACT. At North Branch peat began to accumulate after the Grantsburg lobe (Mankato substage) started to retreat. The radiocarbon dates on the peat and its contained wood (12,700 and 12,030 B.P.) indicate that the Mankato substage preceded the Two Creeks interstadial rather than followed it. The peat was thus formed during the early part of the Two Creeks interstadial. The pollen and macrofossils from the peat suggest a landscape marked by sedge swamps and probably spruce-tamarack swamps on a broad river floodplain, bounded by oak and ash and prairielike communities on upland sites. The climate seems to have been only slightly colder than today and probably drier.

The peat is overlain by sand that contains involuted layers of silt or clay rich in organic matter. These organic layers are believed to have formed as normal fine-grained sediment in quiet water. The pollen analysis indicates a vegetation dominated by pine and oak, typical of the postglacial. A radiocarbon date of 2520 B.P. for the upper part of the series of organic layers confirms the postglacial correlation. The folding of the layers into involutions must therefore have been produced without the aid of a permafrost base and may have resulted from localized annual frost connected with tussock growth of plants.

INTRODUCTION

The stratigraphic and paleobotanical study of the Two Creeks forest bed at the type locality in northeastern Wisconsin (Thwaites, 1943; Wilson, 1932, 1936) focused attention on the nature of the vegetation during the late Wisconsin interstadial intervals, and the early application of the radiocarbon dating technique to this site has made it a central point in any discussion of late Wisconsin chronology and biogeography for the Great Lakes region. The early assumption that the forest bed represented the time of ice retreat between Cary and Mankato ice advances was refuted by Thwaites (1946, p. 82), who held the opinion that the red clayey till above the forest bed was not necessarily correlative with the Mankato, and who therefore introduced the name Valders for this stratigraphic unit. The history of the correlation problem has been reviewed elsewhere (Wright, in press), and it is now believed that the place of the Two Creeks interstadial is between Mankato and Valders rather than between Cary and Mankato (Wright and Rubin, 1956).

Especially critical in this major revision in the late Wisconsin chronology are the relations in Minnesota, whence the term Mankato. The relations of the Cary and Mankato drifts are best seen in the area of the Anoka sandplain north of Minneapolis. The Cary ice of the Superior lobe, after forming the massive St. Croix moraine at its terminus near Minneapolis, retreated far enough to the north into the Lake Superior drainage basin to allow the cutting and then the abandonment of a series of drainage channels across the newly exposed terrain in eastern Minnesota (Wright, 1956). During the Mankato interval the Des Moines lobe, which occupied the Red River and Minnesota River valleys in western Minnesota, including the type locality of the Mankato itself, projected the Grantsburg sublobe eastward across this area just recently

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bared by the retreat of the Cary Superior lobe. The Mississippi River was dammed by the Grantsburg ice to form Glacial Lake Grantsburg, which had its outlet via the St. Croix River (Cooper, 1935). Retreat of the Grantsburg ice back toward the southwest allowed the lake to drain, and during the retreat the Mississippi River, still diverted eastward to the St. Croix River, built the vast Anoka sandplain over a triangular area 75 miles broad in eastern Minnesota (fig. 1).

The buried peat site of North Branch is located on the Anoka sandplain and thus records events starting at the time of retreat of the Mankato Grantsburg sublobe. The site was discovered in 1955 by R. S. Farnham of the Soils Division, University of Minnesota. Initially, the site was considered important because of the opportunity of obtaining a radiocarbon date for the late Mankato for comparison with C^{14} dates of the Two Creeks forest bed in Wisconsin (11,400 B.P.). The dates obtained from the buried wood and peat (12,700 and 12,030 B.P., see below) suggested that the Mankato was older rather than younger than the Two Creeks interstadial, as had previously been

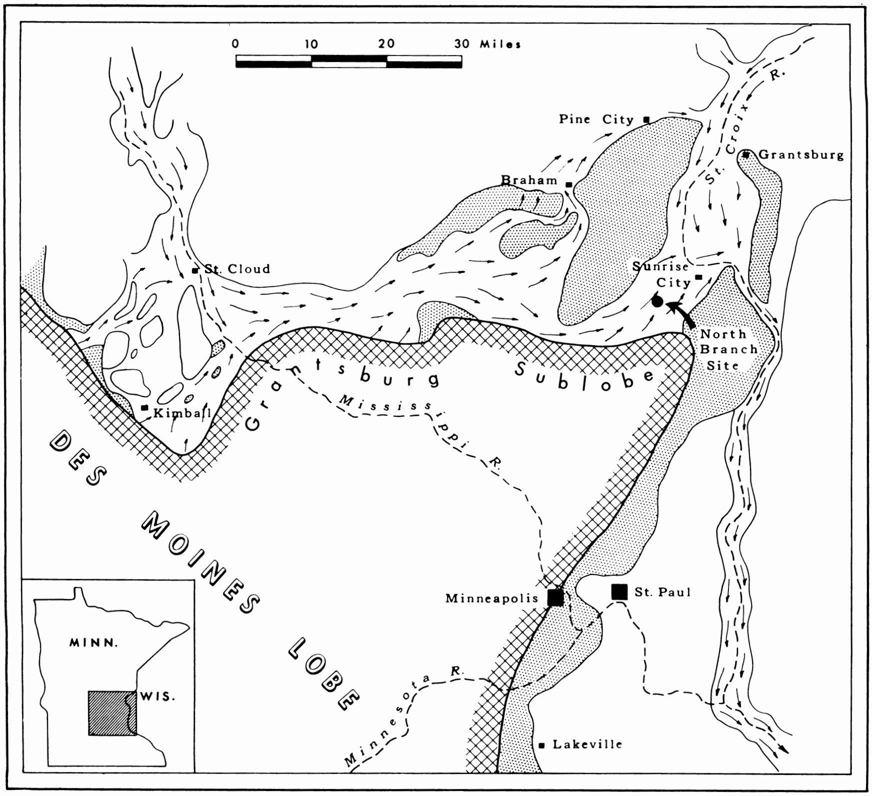


Fig. 1. Map showing location of North Branch site with reference to retreatal position of Grantsburg sublobe at time of formation of Anoka sandplain (small arrows from west to east). Stippled pattern indicates till deposited by Grantsburg sublobe at its maximum. (Redrawn by R. C. Bright from Cooper, 1935, fig. 24.)

assumed, and, along with other C^{14} dates associated with Mankato drift in eastern Minnesota, served as a principal impetus for the revision of the late Wisconsin chronology for the Great Lakes region (Wright and Rubin, 1956; Wright, in press).

A second feature of interest at the North Branch site is the strongly involuted layers of sand above the buried peat. Involutions of this type are generally considered to be indicative of permanently frozen ground, in this section possibly a record of a post-Mankato cold phase, i.e. the Valders in the revised chronology. Thereupon a pollen analysis of the complete profile was prepared to determine the nature of the late Wisconsin vegetation of the region, and an additional radiocarbon date was obtained to determine the age of the involutions.

In a recent article, Frye and Willman (1960) suggest dropping the term Mankato because it "introduces a complicating modification of both Mankato and Cary, [and] produces an unneeded substage". They have introduced the time-stratigraphic term "Woodfordian substage", to include all the time since the "Farmdalian substage" up to the "Two Creekan substage". This classification would do away with the terms Iowan, Tazewell, Cary, and Mankato. Despite the present lack of pedological and pollen-analytical evidence for climatic amelioration in the Cary-Mankato interval in the Great Lakes region, the geomorphic evidence in Minnesota (Wright, 1956) suggests significant ice retreat at this time, and the authors believe the terms Cary, Mankato, and Valders are still useful to refer to ice advances in Minnesota and adjacent regions, with the understanding that the Two Creeks interval separates the Mankato from the Valders rather than the Cary from the Mankato, as previously believed. Current mapping, pollen-analytical studies, and radiocarbon dating dedicated to this problem will certainly provide more precise data in the near future concerning the late Wisconsin history of this region.

The writers are obliged to Farnham for guidance to the site and for aid in the interpretation of some of the features, to numerous geological visitors who have offered candid opinions about the relations (among them F. M. Swain, Nicolas Prokopovich, Jean de Heinzelin, Friedrich Brandtner, Paul Woldstedt, Saskia Jelgersma), and to several students who have excavated and re-excavated the site in the course of field exercises (notably L. J. Maher, Jr., and John O'Brien). The pollen analyses were made by Fries in the Pollen laboratory of the Department of Geology, University of Minnesota, as a project supported by the Hill Family Foundation, St. Paul. The C^{14} analyses were made by Rubin at the U. S. Geological Survey, Washington, D. C.

LOCATION AND DESCRIPTION

The North Branch site is located 3.3 miles southeast of the village of North Branch, Chisago County, Minnesota, in the NE ¼ SW ¼ sec. 26, T.35N., R.21W., on the Forest Lake topographic quadrangle map of the U. S. Geological Survey (fig. 1). The section is exposed in a drainage ditch that carries water northward from a shallow depression for 600 feet to a small tributary of Hay Creek, which in turn flows to the St. Croix River (fig. 2). The site is 2 miles south of the terrace bluffs leading down to the St. Croix

River valley. The shallow depression is typical of the numerous small swamps and shallow lakes that dot the Anoka sandplain. Some are ice-block holes, some are blowouts, and some represent braids on the floodplain of the broad Mississippi River as it built the sandplain during its diversion eastward to the St. Croix River (Cooper, 1935). The intermittently wet part of the depression is about 5 acres in area at present. It is surrounded by a former swamp area of irregular branching shape that is somewhat drier and contains the buried peat site itself (fig. 2). The sandy "upland" on the north has an altitude of about 885 feet, or about 15 feet above the level of the center of the depression. This depression is now perennially dry because of the artificial drainage. The floor has only about a half-meter of sandy peat, so probably the depression has not often been wet.

The upland vegetation of today is characterized by scattered remnants of deciduous forest consisting of oak species (mostly *Quercus macrocarpa* and

Fig. 2. Air photograph showing location of North Branch site (arrow) in drainage ditch. Shallow branching depressions are probably braids on glacial river floodplain, but deeper depressions may represent buried ice blocks. Black east-west double bar is ¼ mile long. U. S. Dept. Agriculture photograph 1938.

ellipsoidalis) and other hardwoods in a landscape with large open tilled and grazed areas. Most of the swamps are covered by sedge mat. In the vicinity and towards the south and southwest there are scattered small treeless areas or "oak openings" which are believed to be outliers of the prairie (Farnham, 1956, p. 61; Marschner, about 1930). According to Upham's map of the pre-settlement forest cover (1884, pl. 1), the area is situated a few miles outside of the southwestern limits of pines (mostly *Pinus strobus*), black spruce (*Picea mariana*), and balsam fir (*Abies balsamea*) but within the range of southernmost outliers of tamarack (*Larix laricina*). Thus it lies in the tension zones between the boreal coniferous forest, the deciduous hardwood forest, and the prairie.

The buried peat is found on the west bank of the drainage ditch and has a maximum thickness of 15 cm (figs. 3, 4). It is underlain by white or gray sand and grit, and is overlain by about 90 cm of weakly stratified medium to fine sand containing layers and lenses of brown peaty sand, black clay rich in organic matter, and, near the top, sand blackened with organic matter. One organic layer consists of a black waxy material on which Farnham obtained the following data: pH 5.2, organic matter 25%, free Fe and Al oxides 6.6%. The section is capped uncomformably by about 25 cm of laminated peaty sand.

The buried peat layer has a lenticular saucerlike form and is traceable for 9 m horizontally along the ditch face. It slopes gently upward and passes into an organic silt layer, which can be traced an additional 3 m to the north and 3 m south.

Some of the organic clay layers above the peat may be traced northward along the ditch for about 40 m, but they also gradually pinch out as the terrain rises into the low swell that borders the depression on the north and is transected by the ditch.

The sand is partly oxidized to yellow or brown to a depth of 1.2 m; the oxidation zones are discontinuous and controlled in part by the textures of the sand layers.

Between depths of about 25 and 100 cm the silt and sand layers are strongly involuted into bell-shaped folds (fig. 3), some of which are cut off at the necks to reveal spherical or pearshaped forms in cross-section. Inasmuch as the organic layers form a saucerlike structure, they become involved in the involution layer as they rise laterally to the requisite level.

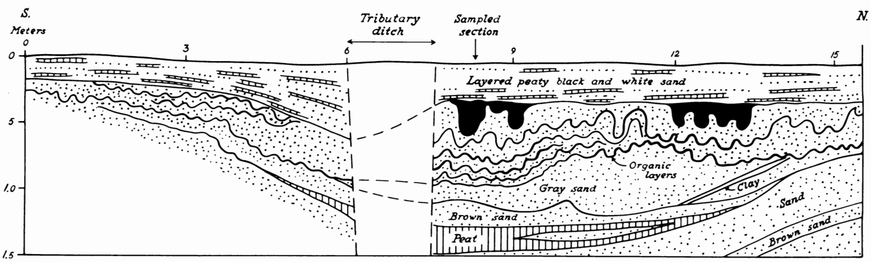


Fig. 3. Sketch of buried peat and involuted sand on west bank of drainage ditch at North Branch site.

Fig. 4. The sampled section with buried peat (at the bottom) and involuted sand. Positions of samples for radiocarbon dating are marked. Cf. fig. 3.

ORIGIN OF SEDIMENTS

The buried peat contains a few very thin laminae of sand, some of the laminae being only a few grains thick. The peat itself is weakly laminated. These laminations, as well as the thin layers of organic clay above the peat, suggest that the sediment was deposited in water. The site may represent initially a small depression on a braided river floodplain. When the floodplain was abandoned after complete retreat of the ice, the depression was filled by inwash of sand and finer sediment. There may not necessarily be any relation between the depression in which the peat was formed and the present swamp, for the latter may be the result of later collapse over a buried ice mass.

The organic material in the silt and clay layers that are interbedded with the sand may also have been deposited along with the fine clastic particles when pools of water stood in the depression. An alternative explanation involves transport of the organic matter (including pollen grains) downward through the sands at a later time during the process of incipient soil formation. In this explanation, the organic matter was illuviated as a kind of organic B horizon in the relatively impermeable fine-textured sedimentary layers. There is no additional evidence for soil formation during the accumulation of the organic layers, however, e.g. no podzolized horizons or illuvial iron-oxide horizons. The iron bands that do exist can be explained by fluctuations in the water table through sediments of differential permeability. The writers therefore favor the first view, that the black layers are of sedimentary origin and the organic material contained within them was not introduced later from above.

The "upland" just north of the swamp is exposed to a depth of about 4 m in the ditch. The material consists of a medium- to coarse-grained sand, locally cross-bedded and containing lenses of grit and some scattered pebbles. A few clay laminae may be traced into the upland area from the peat site. The sediment is interpreted as dominantly glacio-fluvial, with perhaps some eolian sand in the upper part. The involution layer so conspicuous near the peat site is traceable up the flank of the "upland" but is shallower and thinner. It is absent completely on the upland itself, as is also the capping peaty turf. Both of these features are thus confined to the lower regions of greater soil moisture.

PALEOBOTANICAL EVIDENCES OF VEGETATION, CLIMATE, AND AGE

RADIOCARBON DATES

In order to get an idea of the type of vegetation and climate during the transition from the Mankato to the Two Creeks interval, the buried peat and the overlying sand layers were subjected to macrofossil and microfossil (mainly pollen) analyses. In addition, the black involution layers were examined for their pollen content.

Macrofossils.—A collection of macrofossils from the buried peat was examined in 1957 by J. W. Moore, Dept. of Botany, University of Minnesota, who found the following plant species: *Picea glauca* (seed), *Sparganium minimum, Potamogeton foliosus, P. robinsii, P. zosteriformis, Najas flexilis, Carex cryptolepis, C. vesicaria, Hippuris vulgaris, Myriophyllum exalbescens,* and *Menyanthes trifoliata.*

For additional information on the macrofossil content of the peat and the sand just below and above, pieces 10 by 10 by 4 cm in size were cut out and treated with HNO_3 diluted to about 1:4, washed, and sieved through a fine gauze sieve of 0.4 mm^2 mesh size.

One large piece of wood was identified microscopically by the Forest Products Laboratory (U. S. Dept. Agriculture), Madison, Wisconsin, as *Larix laricina.* Probably there is also some wood of spruce, here likely black spruce (*Picea mariana*). This identification has not been verified by microscopic study, but the pollen spectra show a great amount of spruce pollen (see below).

The peat, 10 to 15 cm thick at the sampling site, consists mainly of mosses, especially in the upper half. Among the mosses *Calliergon Richardsoni* (Mitt.) Kindb. is the most common, followed by *Drepanocladus aduncus* (Hedw.) Warnst. (determined by O. Mårtensson, University of Uppsala, and H. Persson, Natural History Museum, Stockholm). They have on the whole a northern distribution (Grout, 1931, p. 96, 108). *D. aduncus* has been identified from the Two Creeks forest bed, Wisconsin by Cheney (1930, 1931) but not by Culberson (1955). Neither species was reported among the mosses at the Loring Park site, Minneapolis, Minnesota (Cooper and Foot, 1932), which is probably of Two Creeks age or slightly younger (Wright and Rubin, 1956).

The macroscopic plant remains in the peat, identified by Fries, are the following (in estimated frequencies):

Larix laricina, wood (one piece microscopically identified—see above), especially in the transition zone between the peat and the overlying sand, twigs with short spurs (rare), needles (common), cones (rare). Fig. 5a. Distribution map in Munns, 1938.

Cf. *Picea mariana*, seeds and seed wings (less common). Determination unsure; cross-sections of seeds show similarities to *Larix*. Fig. 5b. Map ibid.

Sparganium cf. *minimum*, fruits (rather common). Fig. 5f. Cf. fruits in Muenscher, 1944, p. 25; Gleason, 1952, p. 73; and Fassett, 1957, p. 52; map in Muenscher, 1944, p. 21.

Potamogeton cf. *alpinus* var. *tenuifolius* or var. *subellipticus*, fruits (common). Fig. 5c. Cf. fruits in Ogden, 1943, pl. 746; Gleason, 1952, p. 77; map in Ogden, 1943, p. 91.

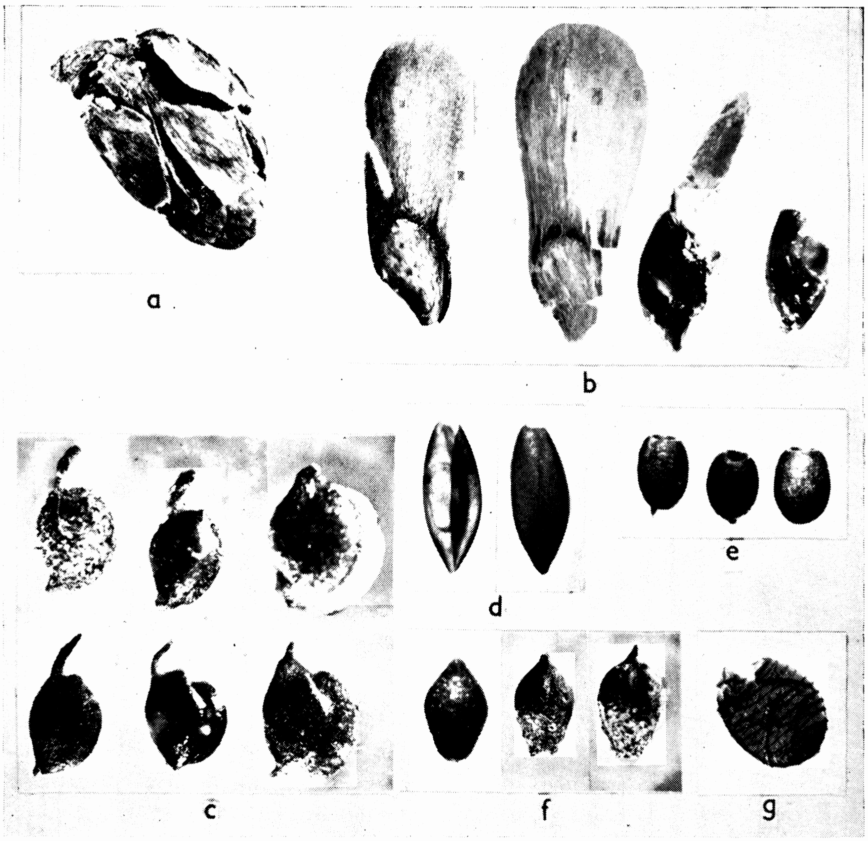


Fig. 5. Macrofossils identified from the buried peat in comparison with some modern forms. *a. Larix laricina*, cone. 2½X. *b.* Cf. *Picea mariana*, from left to right: modern seed with wing, fossil wing, two fossil seeds, one with partial wing. Determination unsure; cross sections of seeds show similarities to *Larix*. 6X. *c. Potamogeton* cf. *alpinus*, three fossil fruits (lower row) compared with three modern fruits of *P. alpinus* var. *tenuifolius* (upper row). The two fruits on the right with pericarp present. 6X. *d. Najas flexilis*, fossil seeds. 6X. *e. Hippuris vulgaris*, two fossil fruits (right) compared with one modern (left). 6X. *f. Sparganium* cf. *minimum*, two fossil fruits (right) compared with one modern (left). 6X. *g. Chara* sp., oosporangium. 30X.

Potamogeton cf. *zosteriformis*, fruits (rare). Cf. fruits in Fernald, 1932, pl. 28; Muenscher, 1944, p. 49; and Gleason, 1952, p. 79; maps in Fernald, 1932, p. 37; and Muenscher, 1944, p. 56.

Najas flexilis, seeds (common). Fig. 5d. Cf. fruits in Muenscher, 1944, p. 70; and Gleason, 1952, p. 85; maps in Muenscher, 1944, p. 66, Dansereau, 1957, p. 33; and Hultén, 1958, p. 194.

Carex spp., fruits (rather common).

Hippuris vulgaris, fruits (less common). Fig. 5e. Cf. map in Muenscher, 1944, p. 277.

Myriophyllum exalbescens, fruits (rare). Cf. map ibid., p. 283.

Menyanthes trifoliata, seeds (rather common). Cf. map ibid., p. 301.

Chara sp., oosporangia (common). Fig. 5g.

Mosses (see above).

Most of the fruits and seeds of the aquatic plants are more common in the lower half of the peat.

At present the species mentioned above show a distribution of more or less northern tendency. They all belong to the Boreal and the Great Lakes–St. Lawrence Forest regions north of the Deciduous Forest region (Rowe, 1959), even if some, as *Najas flexilis* (see above), are not confined to these regions.

Pollen.—The samples were prepared for pollen analysis with the use of hydrofluoric acid (in case of mineral material) and acetolysis solution according to the procedure summarized by Faegri and Iversen (1950, p. 58 ff.). The calculation of the percentages is based on the sum of arboreal pollen (Σ AP), cf. fig. 6.

The pollen spectra of the peat and the adjacent sand are characterized by high spruce-pollen values (fig. 6). The other tree-pollen types are of subordinate importance. Among these, however, oak and ash are rather prominent. The very low values of pine are worth observing. Also noted are some pollen grains of *Larix*, unexpectedly few in comparison with the macrofossils (cf. above), and some of *Thuja* or *Juniperus*. Of *Populus* very few pollen grains were observed.

Several nonarboreal pollen (NAP) types occur. Cyperaceae are strongly represented. Of special interest are the comparatively high values of *Artemisia* and of other Compositae pollen types (mostly *Ambrosia*). Also some pollen of Gramineae, Chenopodiaceae (or Amaranthaceae), Caryophyllaceae, and Cruciferae occur in small amounts. Only one pollen grain of Ericales type was observed. Eight pollen grains of *Elaeagnus commutata* were found in different layers of the peat.

Among pollen of water and swamp plants (except Cyperaceae) the following types occur in the peat, generally in low frequencies: *Typha latifolia*, *Sparganium* sp., *Potamogeton* sp., *Thalictrum* sp., *Myriophyllum* cf. *exalbescens*, and *Menyanthes trifoliata.* Among the green algae some specimens of *Pediastrum boryanum* (Smith, 1920) were noticed in the samples, all of which were acetolyzed.

The interpretation of these pollen spectra is tentatively the following:

In the shallow basins there were swamps of different types as well as open water. There were sedge swamps with open, moss-covered patches, and tree-

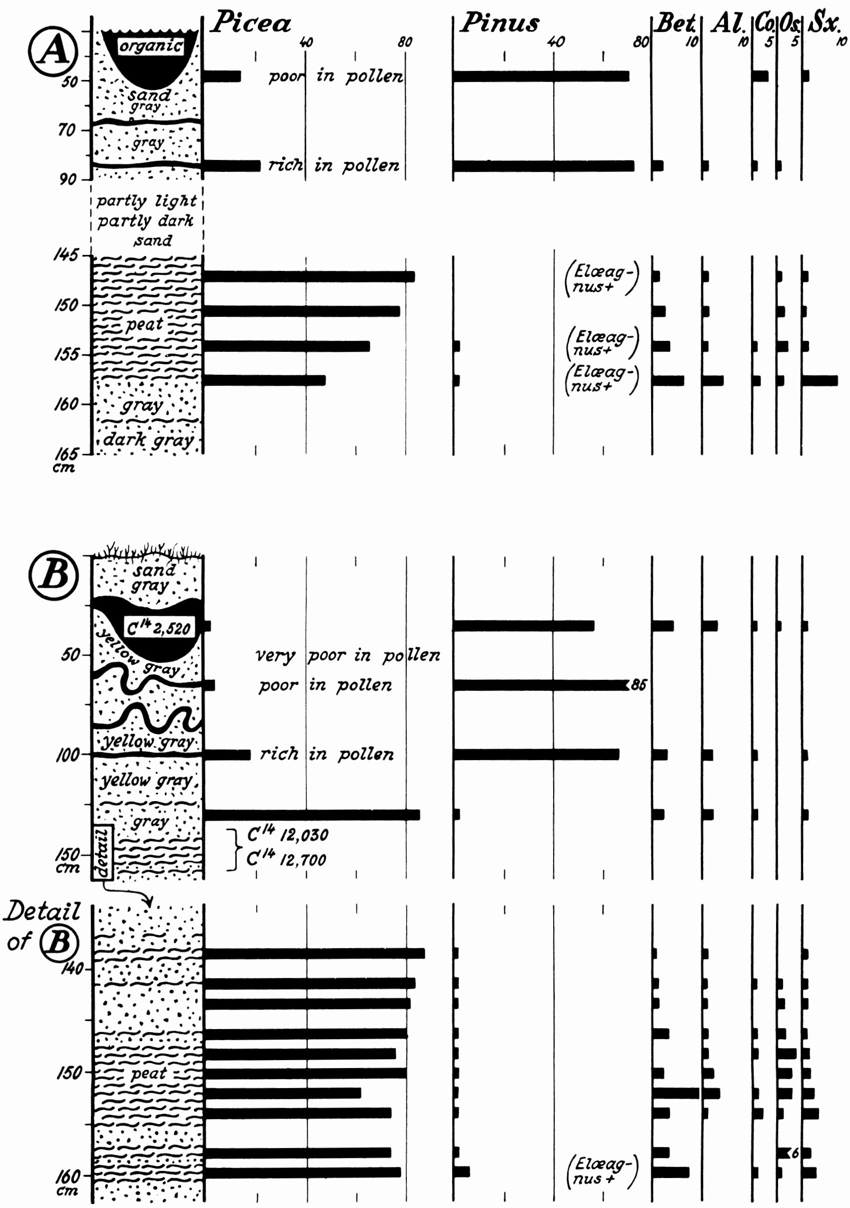
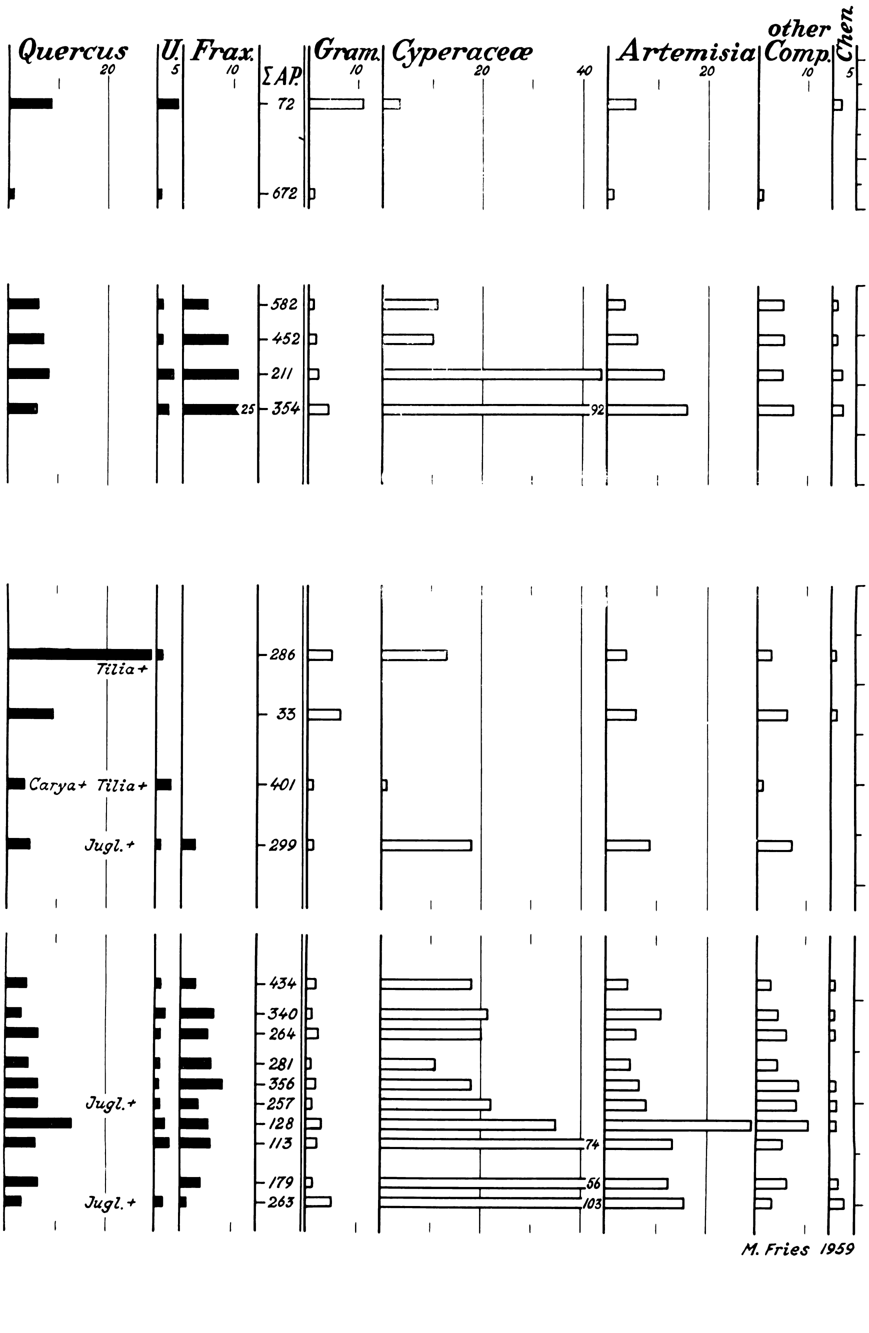


Fig. 6. Stratigraphic profiles and pollen spectra from North Branch site. Explanation: Bet. = *Betula*, Al. = *Alnus*, Co. = *Corylus*, Os. = *Ostrya* (or *Carpinus*), Sx. = *Salix*, U. = *Ulmus*, Frax. = *Fraxinus*, Gram. = Gramineae, other Comp. = Compositae except *Artemisia*, Chen. = Chenopodiaceae (or Amaranthaceae), ΣAP = sum of arboreal pollen.


Quercus
U.
Frax.
ΣAP.
Gram.
Cyperaceæ
Artemisia
other Comp.
Chen.
20
5
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211
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401
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M. Fries 1959

covered swamps with at least tamarack (*Larix laricina*) and most probably also with black spruce (*Picea mariana*). Equivalent types of swamp occur today in the surroundings and toward the north and northwest, e.g. Cedar Creek Bog about 15 miles WSW of the North Branch site, and others described by Conway (1945). It is not certain that the *Picea* pollen represents only the black spruce of the swamps or if it includes pollen of the white spruce (*Picea glauca*) of the upland. It seems more reasonable to assume that most of the spruce-pollen grains were derived from local *Picea mariana* stands.

The relatively great amount of NAP indicates that the upland with the low hills of outwash sand or locally of till was not totally covered by forest. In addition to limited places with ephemeral vegetation of pioneer character on sand bars in the river floodplain, there seem to have been at least patches of open ground or a sort of parklike landscape with scattered trees or groups of trees. Regarding the frequency of NAP together with relatively high amount of *Quercus* pollen there may have existed a type of oak forest, similar to those on dry hill slopes in the area today, or a savanna vegetation with oak openings, typical for the prairie border (Curtis, 1959, p. 132 ff., 325 ff.). Thus *Quercus* species such as *alba*, *borealis*, *ellipsoidalis*, and *macrocarpa* may be considered The NAP flora (*Artemisia*, *Ambrosia*, other composites, chenopod-amaranths) indicates rather xerophytic vegetation on the open areas. This is especially pointed out by the occurrence of *Elaeagnus commutata*, a prairie shrub in western Minnesota, the Dakotas, and areas to the west. Pollen of this xerophytic shrub was found in late-glacial sediments in Michigan by Andersen (1954, p. 144 ff., pl. VIII). These finds in eastern Minnesota and in Michigan seem to indicate that there were prairie conditions at least locally during some part of the late-glacial time over areas where later in postglacial time forest covered the landscape.

The amount of pollen of *Quercus* sp. and *Fraxinus* sp. may be considered surprisingly high for late-glacial deposits. The possibility of occurrence of redeposited (secondary) pollen must be taken into consideration. Although it might be possible that laminated moss peat was formed in situ (the mixed-in sand may have blown out over the swamp surface from time to time), an allochthonous peat formation in water may well have occurred in a floodplain landscape like this (cf. the preceding pages). In any case, the peat-forming material, including the embedded macrofossils, must be of late Mankato or early Two Creeks age, whether it is transported some distance or not. The radiocarbon dates confirm this. The more important question, whether or not there are secondary microfossils washed into the peat, may still be open. It seems more plausible to assume that the pollen contribution from the Anoka sand itself, extremely poor in microfossils, was so minute that it could not make itself conspicuous among the probably rich local pollen precipitation at that time. Furthermore, the list of macrofossils indicates a comparably favorable climate (cf. the maps referred to in the macrofossil list above). Even if the possibility of redeposited pollen grains in the peat cannot be totally excluded, it is more likely that the spectra show the real situation at the time of the peat formation.

The macroscopic plant remains and the pollen spectra from the peat and the dark sand just below and above indicate:

(1) The chronological position in late-glacial time because of dominating *Picea* and high amount of NAP.

(2) Temperature conditions favorable to certain northern hardwoods, especially oak and ash species, and some water plants (e.g. *Najas flexilis*), indicating a temperature perhaps only slightly colder than today.

(3) Probably drier conditions than nowadays shown by a vegetation of more or less xerophytic and heliophilous character.

The black organic layers with involutions in the sand overlying the buried peat show an opposite type of pollen spectrum, characteristic of postglacial pollen zones. The most important feature here is the dominance of *Pinus* pollen. Also *Quercus* is well represented, especially in the thick, uppermost involution layer. *Picea* has minor importance.

Radiocarbon dates.—A date of 12,700 ± 250 B.P. (W-389) was obtained from a sample of the buried peat, and a date of 12,030 ± 200 B.P. (W-354) for a piece of wood taken from near the base of the peat (Wright and Rubin, 1956; Rubin and Alexander, 1958). The discrepancy between the two dates is not explained but is not considered to be of great significance.

A sample for radiocarbon dating was cut out of the big involution layer about half a meter below the soil surface (cf. fig. 4). The date obtained, 2520 ± 200 B.P. (W-872) (Rubin and Alexander, 1960, p. 150), confirms the postglacial age of this layer of black organic soil.

ORIGIN OF THE INVOLUTIONS

Involutions of the type exposed at the North Branch site are generally attributed to the intense pressures developed during autumn near the base of the active layer of permafrost, as the water-saturated sediment is pressed between the downward-freezing crust of annual frost and the rigid base of permafrost (Steeger, 1944; Sharp, 1942). The features are also known as *Taschenboden*, *Würgeboden*, cryoturbations, and plications. They have also been termed *Brodelboden* with the implication that they are produced by convection of fine-grained sediment supersaturated with water during the time of temperature changes in the soil.

Involutions are common in the periglacial region of Europe and have been used to indicate the distribution of permafrost during the last glacial period (Poser, 1948). They are not ordinarily found in deposits of the last glaciation, and it is therefore inferred that permafrost did not follow the retreating ice.

If the North Branch involutions require the presence of permafrost, then their occurrence in sediments younger than the late Mankato–Two Creeks buried peat implies the recurrence of low temperatures in a younger climatic phase, i.e. the Valders, or at least the persistence of permafrost through the Two Creeks interval. The pollen analyses, however, show by their high percentages of pine relative to spruce that the involuted sediments were formed during the postglacial rather than late-glacial, and the radiocarbon date of 2520 B.P. confirms this postglacial age. The involutions therefore must have been formed in very recent time, when there is no possibility of permanently frozen ground. The mean annual temperature of the area at the present time is about 6°C, and a mean temperature certainly below 0°C is a requisite for permafrost formation. Either the involutions are related to annual frost or were formed in some entirely different way.

The mechanism of formation of the European periglacial involutions has not been fully explained because few features of this type have been observed in the process of formation in present permafrost regions. Hopkins and Sigafoos (1951, p. 98) describe soil distortions that have resulted from frost-heaving of tussocks in western Alaska, and suggest that some "fossil" involutions may have formed in this manner. In another study, Sigafoos and Hopkins (1951) describe similar tussocks in a swamp in Massachusetts, where the winter temperatures are even warmer than in Minnesota at present. Although no involutions were described in the Massachusetts occurrence, the authors indicate that tussock formation under the influence of annual frost action causes intensive soil disturbance.

Involutions similar to those at the North Branch site were described from the deposit of Glacial Lake Agassiz in eastern North Dakota by Horberg (1951), who adduced them to support his hypothesis that a peculiar pattern of intersecting grooves on the lake floor represents former ice-wedge polygons in permafrost. Nikiforoff (see Horberg, 1951) points out, however, that the involutions could not have formed until after Lake Agassiz had been drained, long after the ice retreated from the Valders terminus. All pollen-analytical evidence presently being assembled in Minnesota indicates that the climate by this time was too warm for the persistence of permafrost at shallow depth. It may therefore be concluded that involutions are not necessarily a valid criterion for past permafrost.

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