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CLIMATE VERSUS FIRE AND SOIL AS FACTORS IN POSTGLACIAL FOREST SUCCESSION IN THE PUGET LOWLAND OF WASHINGTON.[1]

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ABSTRACT. There is considerable evidence for well defined postglacial climatic trends in northern Europe and North America from pollen analysis and various other sources. In the Pacific Northwest pollen profiles from many well distributed sedimentary columns reveal several postglacial regional climatic stages. In the Puget Lowland of western Washington, however, climate apparently has not been the major control of forest succession. Normal forest succession influenced regionally by fire and locally by soil conditions, and to a limited extent by climate, is portrayed by the pollen profiles. The postglacial pioneer invaders of deglaciated terrain were lodgepole and western white pine, which were rapidly replaced by Douglas fir and western hemlock. Hemlock expanded slower than Douglas fir because of unfavorable soil conditions, the development of a warm, dry climate reaching a maximum between 8,000 and 4,000 years ago, and periodic fire. After a return to a moister and cooler climate about 4,000 years ago, hemlock expanded more rapidly to supersede Douglas fir in some areas and to become coabundant in others. In certain areas, however, unfavorable soil conditions have prevented hemlock from becoming as abundant as Douglas fir. For the region as a whole, the pyric influence has prevented hemlock from assuming complete predominance as it normally would in the absence of fire.

INTRODUCTION.

SPHAGNUM bogs and other types of postglacial organic sediments are more abundant in the Puget Sound region than in other parts of the Pacific Northwest. The abundance of sites favorable for hydrarch succession is due to glaciation which resulted in the formation of many undrained depressions. Adequate precipitation has maintained sufficient water in these depressions and other climatic conditions have favored the accumulation of thick peat beds. Pollen analysis

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of peat sections from 13 well-distributed bogs in the Puget Lowland reveals evidence for a generally consistent pattern of postglacial forest succession, which expresses a regional climatic trend. Although the postglacial forest succession in this region was primarily normal succession modified to some extent by climatic fluctuations, periodic fire and local soil conditions have played an important part in many areas.

This study is concerned with the interpretation of the pollen profiles of six peat sections from widely scattered bogs in the Puget Lowland. The forest succession, climate, and chronology is supported by and correlated with pollen profiles of seven other bogs in the same region that have been described in previous papers (Hansen, 1938, 1940, 1941, 1943). These interpretations are well supported by the pollen analytical data from many other sedimentary columns located in the several diverse phytogeographic and climatic provinces of the Pacific Northwest.

LOCATION AND CHARACTERISTICS OF THE BOGS.

All of the bogs of this study rest directly upon glacial drift and are necessarily postglacial in age. The northernmost bog is located in a small tributary of the Middle Fork of the Nooksack River about 17 miles east of Bellingham (Fig. 1). The pond in which the sediments have accumulated is one of a series that was dammed in the tributary by aggrading of the main stream valley with glaciofluviatile deposits. The bog is about 13 meters deep in the area of sampling, and is one of the deepest bogs sampled in the Pacific Northwest. A stratum of volcanic ash occurs at 8 meters which is undoubtedly synchronous with and of the same source as that in most other postglacial organic sedimentary columns from Washington bogs. A second peat section was obtained from a sphagnum bog near the north edge of the town of Granite Falls about 12 miles northeast of Everett (Fig. 1). The bog has developed in an elongated swale between ground moraines. A peat column 8 meters thick was obtained, with the volcanic ash layer present at 5.3 meters. A third sedimentary column was obtained from a sphagnum bog on the eastern part of the Olympic Peninsula near the town of Poulsbo, located between Puget Sound and Hood Canal (Fig. 1). The

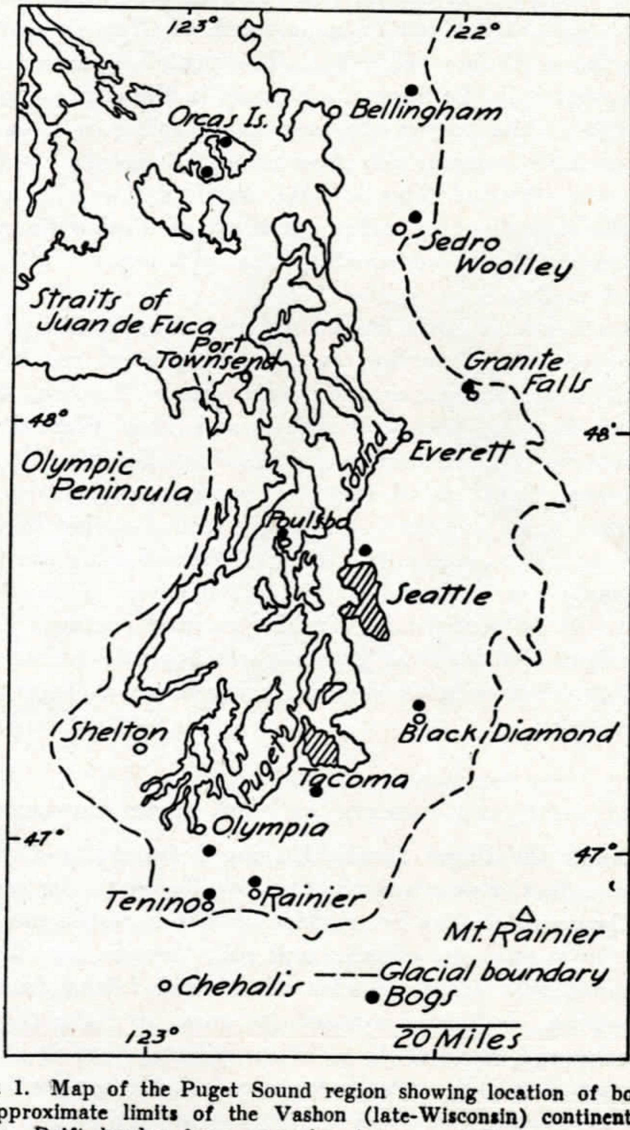

Fig. 1. Map of the Puget Sound region showing location of bogs and the approximate limits of the Vashon (late-Wisconsin) continental glaciation. Drift border from maps by Antevs and Bretz.

thickness of the sediments in the area of sampling is 8.75 meters with the volcanic glass at 5.5 meters. The peat has accumulated in a kettle pond. A fourth section was obtained from a bog a few miles south of Olympia at the southern end of Puget Sound (Fig. 1). The section is 5.4 meters thick with the ash layer at 3.2 meters. A fifth section was taken from a bog located about 12 miles south of Olympia and one mile north of Tenino (Fig. 1). The peat has accumulated in a deep kettle in the floor of a channel in the outwash plain. The depth of the bog in the area of sampling is about 13 meters with the volcanic ash stratum at 9.6 meters. A sixth column was obtained from a small kettle a few miles north of Rainier and about ten miles northeast of Tenino (Fig. 1). The thickest section obtainable is only 3 meters with the ash at 1 meter.

Seven other bogs in the Puget Lowland whose pollen profiles have contributed supporting data to the general results and conclusions of this paper are located near Tacoma, Black Diamond, Seattle, Sedro Woolley, and New Westminster, B. C., and on Orcas Island of the San Juan Islands (Fig. 1). The average thickness of 16 pollen-bearing sedimentary columns from as many bogs in the Puget Sound region is about 7.8 meters. The average thickness of the sediments overlying the volcanic ash stratum is about 4.7 meters. The average thickness of 30 sections in Washington and northern Idaho resting upon glacial drift or its chronological equivalent is about 7.2 meters with the ash occurring at an average depth of 4.4 meters.

VEGETATION AND CLIMATE OF THE PUGET LOWLAND.

Although the Puget Lowland, lying between the Olympic Mountains to the west and the Cascade Range to the east, is generally considered as being more or less homogeneous with respect to vegetation, climate, and soil, there is considerable local variation. Moisture-laden air flowing inland from the Pacific Ocean is forced upward to pass over the Olympic Mountains and much of its moisture is lost before it reaches the Puget Lowland. The mountains on Vancouver Island also cause a rain shadow in the northern part of the Puget Lowland, while to the south of the Olympic Mountains the lower range and the Chehalis River valley permit greater precipitation on the outwash plains south of Puget Sound. At Bellingham which lies in the rain shadow of the Vancouver Island mountains the mean annual precipitation is about 31 inches. Granite Falls, which is located well inland but in line with the Straits of Juan de Fuca, has a mean annual rainfall of about 60 inches because of the break in the mountain barrier. At Bremerton, the nearest station to the Poulsbo bog, the annual rainfall is about 38 inches, while at Seattle across the sound it is about 33 inches. Olympia has an annual rainfall of over 50 inches, while the area to the south, the

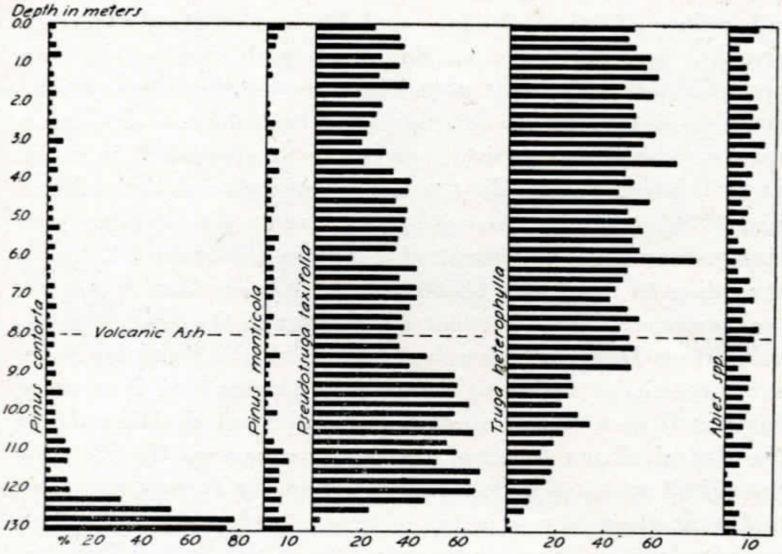

Fig. 2. Pollen diagram of Bellingham bog.

vegetation of which is recorded in the Olympia, Tenino, and Rainier bogs, has a rainfall of more than 40 inches. In the San Juan Islands, the rainfall is about 30 inches, some areas having more some less, depending upon the altitude and whether on the windward or leeward slopes of the hills. At Sequim in the northeastern part of the Olympic Peninsula and just west of Puget Sound, the annual precipitation is only 17 inches which is the lowest in the Puget Sound region. These variations are reflected in the present vegetation, while similar differences during postglacial time are indicated by the pollen profiles. The average of the mean annual precipitation for 13 stations in the Puget Lowland between the Canadian boundary and the Columbia River is slightly more than 41 inches, with between 25 and 30 per cent occurring from May to October inclusive (Climatic Summary, 1930).

Most of the Puget Lowland is designated as having a "humid, microthermal climate with adequate precipitation at all seasons" (Thornthwaite, 1931). A small area south of Puget Sound is classified as having inadequate summer precipitation.

All of the Puget Sound region lies within the cedar-hemlock association of the Coast Forest (Weaver and Clements, 1938). In this forest western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), and lowland white fir (*Abies grandis*) are the principal dominants with hemlock by far preponderant. The most abundant tree over the entire region, however, is Douglas fir (*Pseudotsuga taxifolia*), a subclimax species, which has persisted generally predominant in most areas because of periodic fire during postglacial time (Munger, 1940). In the absence of fire, five to six centuries are required for the development of a mature climax forest, which according to the pollen profiles would indicate that fires have been widespread and frequent down through the ages. In the drier areas Douglas fir has been more abundant and its present successional status in these areas denotes that it may be considered as a climax species. The greatest deviation from the typical climax forest of the region occurs on the Tacoma "prairies" south of Puget Sound. Here the forests are open and park-like with vast areas of grasses and other herbaceous prairie plants. The most common tree of this area is Douglas fir which seems to be invading the open prairies. Hemlock is not common but occurs sparingly within groves of older Douglas fir. The low availability of moisture during the growing season is reflected by groves of oak (*Quercus garryana*), the frequent occurrence of lodgepole pine (*Pinus contorta*), and the occasional presence of western yellow pine (*P. ponderosa*). The oak and yellow pine, both xerophytic species, may be relicts of the warm, dry period between 8,000 and 4,000 years ago which is so strongly evidenced by pollen profiles of bogs scattered throughout the Pacific Northwest. These drouth-loving species have been able to persist in one of the wettest parts of the Puget Lowland because of the dry summers and the gravelly soil which together bring about a dearth of available moisture during the growing season. Lodgepole pine has persisted from its early postglacial predominance because of the absence of competition by species of greater longevity and tolerance of shade. The prevalence of prairie vegetation in this region during all or most of the Postglacial is indicated by prairie soil profiles in some areas (Nikiforoff, 1937). These soils are dark or black in color and in many places a foot or more thick and are a typical result of a grassland environment. Nikiforoff ascribes these prairie soil profiles to the dry shadow cast by the Olym-

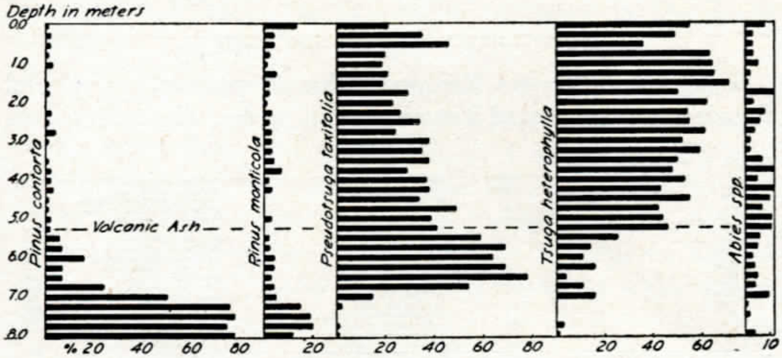

Fig. 3. Pollen diagram of Granite Falls bog.

pic Mountains. They are probably more a result of the original soil and the dry summers, because this area receives from 10 to 15 inches more of rain than other parts of the Puget Lowland where dense forests of hemlock and Douglas fir exist. Periodic fire may have also favored the persistence of the open prairies.

A few miles west of Puget Sound, in the vicinity of Shelton, there are vast, pure stands of lodgepole pine which may have persisted from early postglacial time. Here also, the gravelly soil and the low summer precipitation have permitted lodgepole to compete successfully with hemlock and Douglas fir in spite of their greater longevity and shade tolerance. Periodic fire has probably been another factor that has favored lodgepole over the other species. Lodgepole is also abundant on the glacier-scoured terrain at higher elevations in the San Juan Islands. Oak also thrives on the south exposures of these islands, while the presence of prickly pear (*Opuntia fragilis*) on some of these islands, on the southern part of Vancouver Island, and near Port Townsend on the northeast corner of the Olympic Peninsula attests to the localized occurrence of dry areas in the Puget Lowland. Two other species of forest trees that have persisted from greater abundance during early postglacial time are western white pine (*Pinus monticola*) and Sitka spruce (*Picea sitchensis*). The former occurs sparingly in open forest and occasionally on mature peat bogs, and the latter persists in swamps and bogs and on flood plains.

POSTGLACIAL FOREST SUCCESSION.

Lodgepole pine was the predominant, pioneer, postglacial invader of deglaciated terrain in all areas adjacent to the

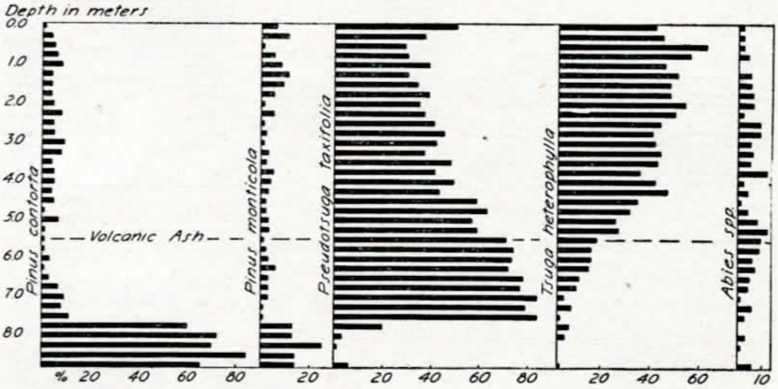

Fig. 4. Pollen diagram of Poulsbo bog.

sites of the sediments (Figs. 2, 3, 4, 5, 6, 7). Its pollen profile in all sections exhibits a similar trend. In the lower levels it is recorded to proportions ranging from 60 to 80 per cent and then sharply declines upward in each section to only a few per cent long before the volcanic activity responsible for the ash stratum. It maintains these low proportions to the top. In only the Rainier column does lodgepole maintain appreciable proportions up to the ash horizon. In most lodgepole pine pollen profiles in the Puget Sound region there is an abrupt increase from the bottom level for one or two levels upward, before the sustained decline to its lowest proportions. This consistently recorded trend may reflect a slight readvance of the ice with the attendant physiographic and edaphic instability which tended to favor a temporary expansion of lodgepole. The average profile from

10 sedimentary columns in the Puget Lowland reveals the consistent regional trend of lodgepole pine postglacial succession (Fig. 8). On Mount Constitution on Orcas Island the postglacial record of lodgepole deviates from this general pattern and shows this species as having been predominant during all of postglacial time to the present (Hansen, 1943). This is due undoubtedly to the rocky terrain which is unfavorable for Douglas fir, its normal successor in the Puget Lowland.

The recorded postglacial trend of western white pine is similar to that of lodgepole, but it is represented less abundantly in the lower levels (Figs. 2, 3, 4, 5, 6, 7). Its proportions near the bottom range from 12 per cent in the Bellingham section to 25 per cent in the Poulsbo column. It then declines upward in the profiles and is recorded to only a few per cent in the middle third, and then shows a slight general increase in the upper third.

Douglas fir invaded deglaciated terrain soon after lodgepole pine and then rapidly expanded to supersede the latter perhaps from three to four thousands years after sedimentation began, or about 15,000 years ago (Fig. 8). In the bottom levels it is recorded to only a few per cent and then rapidly increases to maxima ranging from 67 per cent in the Olympia profile to 84 per cent at Poulsbo, its highest representation in Pacific Northwest sedimentary columns. In practically all Puget Lowland pollen profiles Douglas fir attains its maximum proportions below the volcanic ash stratum and then slowly declines to almost the top. In a few profiles it deviates from this trend. In the Tenino and Olympia sections it remains generally constant after it attains its maximum below the ash horizon (Figs. 5, 6). In the Rainier profile it does not reach its peak until after the volcanic activity, owing to the persistence of lodgepole in adjacent areas (Fig. 7). On Mount Constitution on Orcas Island it did not reach its maximum until after the volcanic activity, but it was never able to supersede lodgepole pine.

Although western hemlock invaded deglaciated terrain adjacent to the sites of the sediments as soon as Douglas fir, it was apparently less abundant and its expansion much slower. Instead of such an abrupt increase in the lower levels it is recorded as having made a more gradual rise, remaining generally static until almost the time of the recorded volcanic activity (Figs. 2, 3, 4, 5, 6, 7). Hemlock superseded lodgepole pine about 4,000 years after Douglas fir, or perhaps about 10,000 years ago (Fig. 8). Its supersession of lodgepole, however, was largely relative, because the latter was replaced by Douglas fir while hemlock was expanding at an extremely slow pace (Fig. 8). Below the ash horizon the highest proportions of hemlock range from 6 per cent in the Olympic profile to 52 per cent in the Bellingham profile. The maximum of hemlock above the ash level ranges from only 26

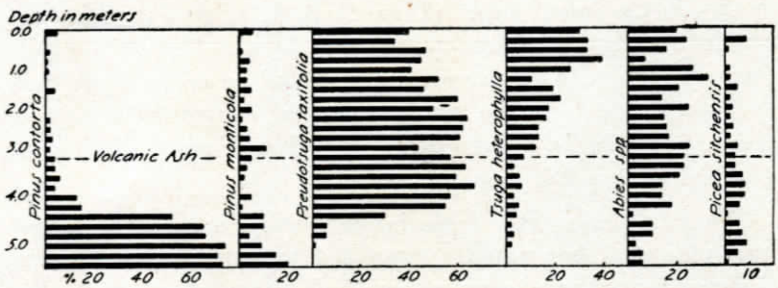

Fig. 5. Pollen diagram of Olympia bog.

per cent in the Rainier section to 77 per cent in the Bellingham profile. The lowest proportions throughout are recorded in the three sections on the outwash plains while the highest are found in the three northernmost columns. In most of the sedimentary columns in the Puget Sound region, hemlock superseded Douglas fir at various levels above the ash horizon, with the exception of those on the Tacoma "prairies" and the rocky terrain of Orcas Island, where Douglas fir has remained predominant throughout postglacial time. Hemlock was first able to surpass Douglas fir about 4,000 years ago, and since then the two species have alternated with respect to abundance.

Other forest trees recorded in the several sections include lowland white fir, silver fir (*Abies amabilis*), western yellow pine, oak, Sitka spruce, Engelmann spruce (*Picea engel manni*), and mountain hemlock (*Tsuga mertensiana*). Oak and yellow pine are recorded in only the Tenino and Rainier sections. A few pollen grains of grass and composites were noted in the prairie columns, but insufficient to be considered significant.

POSTGLACIAL CLIMATE AND CHRONOLOGY.

All of the sedimentary columns of this study have three common time markers. These are the glacial drift upon which they lie, the volcanic ash stratum, and the top. Of these the underlying glacial drift is the least reliable chrono-

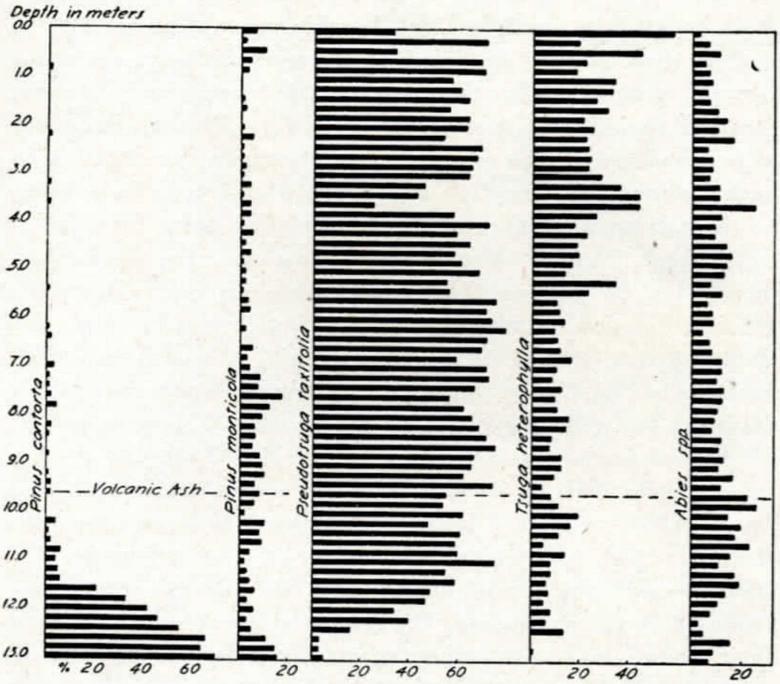

Fig. 6. Pollen diagram of Tenino bog.

logical indicator because of local differences in ice positions, rate and mode of glacial retreat, persistence of dead ice, inundation, erosion, drainage changes, and yet other fluctuating conditions controlling the initial and sustained sedimentation and invasion of forests upon deglaciated terrain. The Puget Lowland was subjected to at least two glaciations during the Pleistocene (Bretz, 1913). The first is known as the Admiralty and the last is called the Vashon and is probably equivalent to the late-Wisconsin. The maximum of the last glaciation is dated at about 25,000 years ago (Antevs, 1945), but it is doubtful if any of the pollen-bearing sediments are that old, and they may vary several thousand years in age. The thickness of the peat sections is not a criterion for their relative ages because the rate of deposition has varied so greatly. This is well shown by the varying thickness of sedimentary columns overlying the volcanic ash stratum which has been found in 30 or more peat sections in Washington and northern Idaho. The source of the ash seems to be Glacier Peak located in north central Washington (Waters, 1939), and as there is only one layer it is undoubtedly synchronous for all sections. The thickness of the peat above the ash stratum varies from 9 meters to 1 meter, although it occurs approximately at the same relative stratigraphic position in each section. The location and depth of the bogs in relation to the maximum advance of the ice are of no value for relative chronology, because some of them lying near the glacial terminus are no deeper than those situated well within the glaciated region. Furthermore, the Puget glacier was relatively narrow, and where the ice was thin, it may have melted across the Puget Lowland, leaving alternate areas covered by stagnant ice and free of ice to the south. The average age of 30 sedimentary columns in the Pacific Northwest resting upon glacial drift or its chronological equivalent is estimated from 18,000 to 20,000 years. This figure is based upon the thickness and typological succession of the sediments, the stratigraphic position of pumice and volcanic ash strata, the recorded forest succession, the indicated climatic trends, and their correlation with other chronologic data from several sources. Pollen profiles of 70 sedimentary columns from widely scattered sites in the Pacific Northwest provide strong evidence for definite postglacial climatic trends. Although these pollen-bearing sediments are located within several different climatic and physiographic provinces the pollen record reveals a consistent climatic sequence for almost the entire region (Hansen, 1947a). This record is especially significant because the pollen was contributed by many different species and groups of species with diverse ecological requirements. Pollen profiles of species common to several climatic provinces and with different phytosociological status in each tend to increase the reliability of the record for a regional climatic trend, although of varying degree in the several areas. The first period was one of slow warming and drying as the influence of the retreating ice waned. This early stage began with the time of initial sedimentation and persisted until about 15,000 years ago (Fig. 8). Some of the sections may represent 5,000 years or more of this initial period, while others may hardly have had their inception by its end. The second

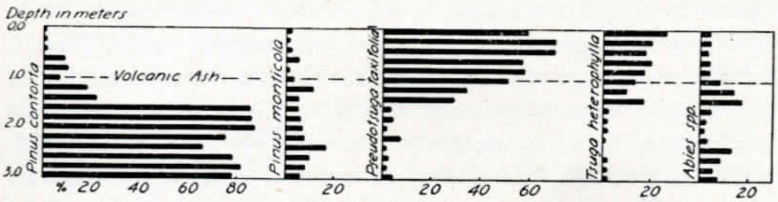

Fig. 7. Pollen diagram of Rainier bog.

period was one of accelerated warming and desiccation and endured from 15,000 to 8,000 years ago. The third climatic interval was one of maximum warmth and dryness and occurred between 8,000 and 4,000 years ago. It is best reflected in pollen profiles of sediments in eastern Washington, south central Oregon, and the Willamette Valley (Hansen, 1939, 1941a, 1942, 1943a, 1944, 1947). The final stage marked a return to a cooler and moister climate about 4,000 years ago which in general has held to the present. The occurrence of a climatic maximum during the Postglacial is supported by evidence from several sources, including pollen analysis and peat stratigraphy in northern Europe, England, and eastern North America, fluctuating lake levels in the Great Basin, salinity of lakes in south central Oregon and California, and movement of western mountain glaciers during the past 4,000 years (Hansen, 1946, 1947a). These data correlated with the chronological evidence offered by the pollen record and the several strata of volcanic ash and pumice provide a fairly detailed Recent chronology. The Pacific Northwest postglacial chronology as applied here begins indirectly with the application of De Geer's varved clay chronology in Sweden (De Geer, 1910, 1940) to the Blytt-Sernander climatic sequence for the Postglacial of Scandinavia (Blytt, 1881; Sernander, 1908, 1910). The Blytt-Sernander scheme was formulated upon the basis of peat stratigraphy in Norway and then applied to other parts of northern Europe. De Geer's chronology correlated with this climatic sequence has provided an approximate absolute time scale in Europe, dividing the last 15,000 years into six stages. They are a cold Arctic, 15,000 to 11,000 years ago; a cool sub-Arctic, 11,000 to 9,100 years ago; a cool to warm, dry Boreal, 9,100 to 7,500 years ago; a warm, moist Atlantic, 7,500 to 4,500 years ago; a warm, dry sub-Boreal, 4,500 to 2,600 years ago; and a cooler and moister sub-Atlantic, 2,600 years ago to the present. Further evidence for a postglacial warm, dry stage in Europe is based upon pollen analysis of bogs in northern Europe by von Post (1930, 1933), who has divided the Postglacial into three climatic stages. The first was one of increasing warmth, followed by an interval of maximum warmth, which in turn was succeeded by a final stage of diminishing warmth. Von Post states that during and just after glacial retreat the temperature gradually rose and reached its maximum between 7,000 and 6,000 years ago. He includes the Boreal, Atlantic, and sub-Boreal stages in his "Age of Warmth." Granlund (1936) upon the basis of peat stratigraphy in Sweden also defines a period of mild winters and warm summers between about 7,500 and 2,500 years ago, while Godwin (1940) interprets the pollen profiles of England and Wales upon the basis of the von Post scheme. In eastern North America, Sears (1942) and Deevey (1943) have applied both the climatic and chronologic sequences to pollen profiles, and the former speaks of the equivalent of the sub-Boreal as the xerothermic period.

Antevs (1931, 1933) dates the postglacial age of distinctly higher temperatures in Sweden and Denmark between 8,000 and 4,000 years ago, and uses these dates as a starting point in trans-Atlantic climatic and chronologic correlations. The fluctuating levels of Great Basin lakes are attributed to the Pleistocene glacial and interglacial stages, and their highest levels reflect the Iowan (early Wisconsin) and the late Wisconsin glaciations (Antevs, 1945; Allison, 1945). The present salinity of Owens Lake in California and Abert and Summer lakes in south central Oregon need not have required more than 4,000 years to have been attained (Van Winkle, 1914; Gale, 1915), indicating that they are not direct descendants of the Pleistocene lakes that occupied their basins. The earlier lakes apparently dried up during the Postglacial xerothermic interval and their saline sediments were either buried or removed by deflation. Antevs (1945) dates this dry stage between 8,000 and 4,000 years ago. About 4,000 years ago there was an increase in moisture and a rebirth of these lakes, at which time they attained higher levels than at present. Further support for the above dates is provided by the correlation of Spitaler's warm and cool summer hypothesis, as based upon astronomic calculations, with glacial and postglacial chronology (Spitaler, 1932). According to Spitaler's data there was a period of warm summers between 15,000 and 4,500 years ago, and since then cooler summers have prevailed. Antevs (1931) upon the basis of these cycles and the Swedish chronology believes that about 10,000 years ago, the temperature had risen to a degree similar to that of today. Yet further evidence for a post-Wisconsin xerothermic period is indicated by the occurrence of wind-polished rocks in the mountains of Trans-Pecos Texas which are attributed to the Neville-Calamity period between 7,500 and 5,000 years ago (Bryan and Albritton, 1942).

Pollen profiles from south central Oregon provide a link between the Great Basin and the Pacific Northwest with respect to climate and chronology. In two sedimentary columns grasses, chenopods, and composites are recorded to a significant maximum in levels immediately above a stratum of pumice from the eruption of Mount Mazama which formed the caldera holding Crater Lake (Hansen, 1947). The eruption occurred after the maximum of the last Wisconsin glaciation (Williams, 1942), but before the warm, dry period, and it is dated at about 10,000 years ago. Pollen analysis of bogs in the Oregon Cascades resting upon Mount Mazama pumice also reveal that postglacial warming and drying had reached a significant degree by the time of the eruption (Hansen, 1946, 1947a). In Eastern Washington a similar influx of grasses, chenopods, and composites as recorded in peat sections further emphasizes the regional occurrence of the xerothermic interval (Hansen, 1939, 1941a, 1943a, 1944). It was during this climatic maximum that the volcanic ash common to the Washington bogs was deposited and it is dated at about 6,000 years (Fig. 8).

Although pollen analysis reveals well-defined regional postglacial climatic trends in the Pacific Northwest, in certain areas, however, climate apparently has not been the only or major factor in controlling postglacial forest succession. This is especially true in the coastal strip of Oregon and Washington, which today is characterized by a typical marine climate. That such an equable climate was prevalent during much of postglacial time is denoted by the pollen profiles of 10 peat sections from bogs along the coast (Hansen, 1941b,

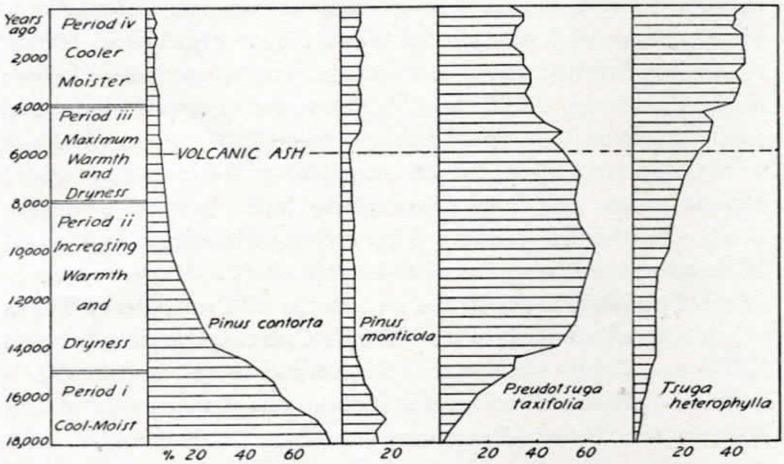

Fig. 8. Average pollen profiles of 4 principal forest trees from ten Puget Lowland sedimentary columns, including all but the Rainier profiles of this study and profiles from bogs located near Tacoma, Black Diamond, Seattle, and Sedro Woolley, and New Westminster in southern British Columbia. The volcanic ash level is considered to be of common age and serves as a starting point for averaging both upward and downward and also for adjustment of the different depths.

1943b, 1944a). The coastal strip was not glaciated so that the postglacial forests were those that had persisted through the Pleistocene. Forest succession and retrogression during the Pleistocene and Recent have probably resulted largely from edaphic disturbances brought about by sand movement. That succession was interrupted and climax forests destroyed from time to time is evidenced by the burying of forests at present and the exhumation of those buried in the past. These periods of accelerated sand movement may have been indirectly the result of climatic changes that are more strongly reflected by pollen profiles from bogs located farther inland. Although pollen profiles of coast bogs do portray various trends of forest succession, there seems to be no consistent regional evidence for climatic fluctuations. Most of the successional trends are local and can be explained upon the basis of sand movement and arboreal invasion of mature bogs.

In the Puget Lowland postglacial climatic trends are somewhat better defined than on the immediate coast, but not so well as to the east of the Cascade Range. Although climate was perhaps the major regional control of postglacial forest succession, fire and edaphic conditions were more important in local areas. It seems probable that normal forest succession was more nearly realized in the Puget Lowland than in the rest of the Pacific Northwest.

Lodgepole pine was the pioneer postglacial invader probably because it persisted closer to the ice front than Douglas fir and western hemlock. It was better able to do this because of its habit of producing an enormous amount of seed at an early age, which permitted it to migrate more readily under the unstable physiographic and edaphic conditions that must have existed before the ice front. If the forests were destroyed by readvancing ice, inundated, buried, or otherwise destroyed, lodgepole produced seed at a much earlier age than other arboreal species and reinvaded as soon as conditions were favorable. Its ability to thrive under a variety of soil conditions is shown by its invasion of sand dunes on the Pacific Coast, its predominance on the vast pumice-covered areas of the southern Oregon Cascades, its invasion of mature peat bogs on the coast, and its persistence on rocky, glacier-scoured soil of the San Juan Islands. Its invasion of burns in pure stands on the east slope of the Cascades, the Blue Mountains, and in northern Idaho is also indicative of its aggressiveness which is derived from its prolific, early seed-bearing habit. Lodgepole failed to persist in its early postglacial predominance, however, because of its short life span and its intolerance of shade. Its local abundance in the Puget Lowland is largely owing to soil conditions which have permitted it to compete successfully with the longer-lived and more shade tolerant Douglas fir. Too little moisture was evidently not a contributing factor because the annual precipitation where it occurs today is as great or greater than in other parts of the Puget Sound region where Douglas fir and hemlock are the preponderant species. Although a cooler and moister climate was prevalent in early postglacial time, it was only one of several causes of lodgepole predominance. Its present distribution and successional trends in the Pacific Northwest suggest that it is not a good climatic indicator.

The present distribution and characteristics of western white pine denotes that it prefers a cool, moist climate such as in northern Idaho where it attains its greatest present development. Its strongest record in the lower levels of all sections reflects the cool and moist early postglacial climate, while its decline in the middle third of the columns denotes its response to a warmer and drier climate as well as competition by Douglas fir and hemlock. A slight expansion of white pine in the upper third of many Puget Lowland profiles suggests its response to a cooler and moister climate during the past 4,000 years (Fig. 8).

The replacement of lodgepole and white pine by Douglas fir was seemingly rapid, but the lower sediments are finer and represent a longer time per unit of thickness than the fibrous peat in the higher levels. Using the same sampling interval throughout the section probably has caused the pollen profiles to portray a more rapid replacement of pine by Douglas fir than actually occurred. Douglas fir apparently superseded lodgepole pine between 8,000 and 10,000 years after the glacial maximum or about 15,000 years ago (Fig. 8). Although the climate undoubtedly became warmer and drier as the influence of glaciation lessened, this probably was not the major or only reason for the expansion of Douglas fir. With its greater age before producing seed it was slower to invade deglaciated terrain, but its greater longevity and tolerance for shade and its larger stature enabled it to practically eliminate lodgepole about 10,000 years ago. In most profiles Douglas fir attains its maximum well below the volcanic ash stratum and reveals a general decline to the top. This contraction probably was not directly in response to a warming and drying climate, but more to the competition of the more shade-tolerant hemlock. The persistence of Douglas fir as one of the predominant arboreal species in the cedar-hemlock association, of which it is not a climax species, may have been the result of a periodic fire.

The pollen record of hemlock reveals that it encroached upon deglaciated terrain as early as Douglas fir. It expanded at a much slower pace, however, and remained more or less static while the latter was making its most rapid expansion (Fig. 8). This successional trend is to be expected, because hemlock requires better soil conditions than Douglas fir. It must have required thousands of years for the sterile glacial soil to develop sufficient humus for the growth of hemlock seedlings, while in some areas the soil apparently never became favorable for their development. Although Douglas fir attained its maximum degree of expansion and abundance about 10,000 years ago and then suffered a slow gradual decline to the present, hemlock continued to expand at a slow pace, first retarded by sterile soil and perhaps fire, and later by the warm, dry climate between 8,000 and 4,000 years ago. It made its most rapid increase about 4,000 years ago with the advent of a cooler and moister climate, and was able to supersede Douglas fir locally. Regionally these two species have been generally coabundant.

On gravelly, well drained and rocky terrain, however, hemlock was never able to supersede Douglas fir. This is particularly true on the outwash plains south of Olympia and Tacoma and the glacier-scoured San Juan Islands (Fig. 9). While hemlock thrives with more moisture than Douglas fir, it attains its greatest proportions in the Bellingham sedimentary column where the annual rainfall is less than that in areas adjacent to the other bogs of this study (Fig. 2). On the other hand, it reaches its lowest maximum in the Olympia section where the precipitation is greater than that near any of the other sites with the exception of Granite Falls. In the Willamette Valley between the Cascade and Coast Mountain ranges in western Oregon, hemlock likewise has been scarce during postglacial time, probably because of the dry summers (Hansen, 1942). The mean annual precipitation here is about 42 inches.

Pollen profiles of a bog a few miles south of Tacoma support the slight evidence of this study and others for a postglacial period warmer and drier than the present (Hansen, 1938). In this section oak is recorded to 14 per cent, grass to 19 per cent, and composites to 13 per cent in horizons below the volcanic ash stratum, which is perhaps stronger evidence than offered in the columns of this study in the same region. Apparently the moisture available during the summer was more nearly at a critical minimum than in the rest of the Puget Lowland, and during the xerothermic period it dropped sufficiently to cause an expansion of these drouth-loving plants.

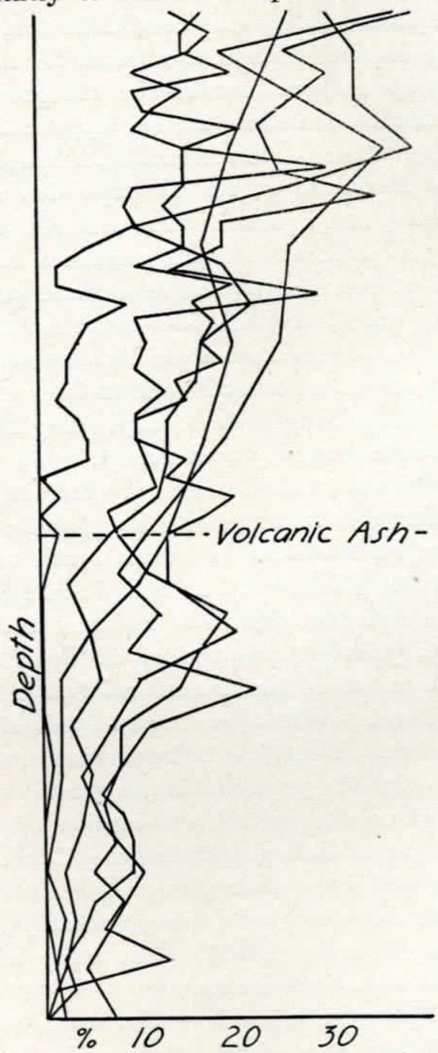

Fig. 9. Pollen profiles of western hemlock from six sedimentary columns in the Puget Lowland, revealing the influence of the gravelly and/or dry soil of the Tacoma "prairies" and the rocky soil and dry summers of Orcas Island. Bogs represented include those from near Tenino, Olympia, and Rainier of this study, and one near Tacoma and two on Orcas Island. Adjustments for variation in depth begin at the ash level. In the Tenino profiles, each two successive levels above the ash were averaged to fit the other profiles. With the exception of the top and ash levels, it is not presumed that the horizons are synchronous.

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