Thunder Lake: a lake sediment record of Holocene vegetation and climate history in North Cascades National Park Service Complex, Washington.

Prepared by:
Alecia M. Spooner, Linda B. Brubaker and Franklin F. Foit, Jr.
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Abstract

Pollen, charcoal and macrofossils from a lake sediment core are identified and analyzed to reconstruct past vegetation and climate change at Thunder Lake in North Cascades National Park Service Complex, Washington. Tephra chronology and radiocarbon dates indicate the sediment core spans approximately 14,000 years. The pollen record documents four zones of vegetation. Beginning ca. 14,000 cal BP, Zone I vegetation is likely dominated by herbs, with shrub *Alnus*, *Pinus* and *Picea* at lower elevation, indicating a cold, dry climate. At ca. 12,800 cal BP, Zone II begins with a shift to a fir-dominated forest with elements of *Tsuga mertensiana* and *Pinus*, suggesting somewhat warmer and moister conditions than previously. Two peaks in charcoal during Zone II support the presence of forests near the lake. Zone III (ca 9500-6000 cal BP) is characterized by the appearance of *Pseudotsuga menziesii,* indicating further climatic warming but a decrease in moisture. However, an increase in *Tsuga heterophylla* ca. 8000 cal BP suggests that moisture began to increase in the middle of the zone. At the end of this zone sediment characteristics indicate an erosional event such as a landslide. Zone IV (ca. 6000 cal BP-present) documents the establishment of the modern mixed forest of *P. menziesii*, *T. heterophylla*, *Thuja plicata* and *Abies* near the lake, confirming climate models that suggest cool and moist conditions in the region after ca. 6000 cal BP. The general trends in our data are consistent with climate and vegetation trends recorded at other lake sites throughout the Pacific Northwest.

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Introduction

Human populations have lived in and traveled through the North Cascade Mountains of western Washington for as long as 10,000 years (Mierendorf *et al.* 1998), but little is known about the region's vegetation and climate history over this period. Only a few studies (Prichard 2003, Cwynar 1987) have looked closely at the changes in plant communities and climate conditions during the Holocene (10,000 years to present) in the North Cascades. As a result, regional estimates of past vegetation and climate conditions must draw on records from as far away as coastal British Columbia, the Olympic Peninsula, Central Washington and the Puget Lowlands. Paleoenvironmental evidence from the North Cascade Mountains is needed to provide a context for understanding the archaeology of the region (Mierendorf *et al.* 1998). In addition, detailed records of pollen, macrofossils and charcoal will add new understanding of how regional plant communities have responded to the shifting climate conditions of the Holocene.

Thunder Lake is well suited for reconstructing paleoenvironmental history in the central North Cascade Mountains from pollen, plant macrofossils and charcoal. Given the transitional nature of the vegetation of the region (Franklin and Dyrness 1988), forests near the lake should be particularly sensitive to Holocene climate change. Second, Thunder Lake is a small basin surrounded by steep (but stable) slopes (Figure 1). As a result, the lake should receive identifiable leaves from nearby forests, providing an excellent opportunity to describe the species composition of forests near the lake. Lastly, the results of a Thunder Lake study can be compared to a recent vegetation and fire record from a montane lake, Panther Potholes in the Thunder Creek Valley (Prichard 2003), to provide the first regional perspective of North Cascade vegetation history.

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Study Area:
Thunder Lake is located near the center of North Cascades National Park, along State Road 20 (1380 ft asl, 48° 41.81' N, 121° 6.51'W; UTM 10 639187 E, 5395477 N). The lake is situated in a small canyon along the Thunder Lake Fault (Tabor and Haugerud, 1999). The vegetation in this area belongs to dry phases of the Western Hemlock Zone (Franklin and Dyrness 1988). Forests near the lake are dominated by *Pseudotsuga*

menziesii (Douglas-fir), with a minor component of *Tsuga heterophylla* (western hemlock), *Thuja plicata* (western redcedar) and *Abies* (fir). Due to the orographic effect of the Pickett Range to the west of Thunder Lake, the climate is transitional between the moist conditions to the west and dry conditions to the east of the Cascade crest. Annual precipitation at nearby Diablo Dam is 75 inches (Western Regional Climate Center, http://www.wrcc.dri.edu/).

The region was covered by the Cordilleran ice sheet during the Vashon Stade of the Fraser Glaciation (Waitt and Thorson 1983). As the Cordilleran ice sheet retreated about 14 000 cal BP, mountain glaciers remained in many valleys and today remain on mountain peaks. Glacial moraines in the Nooksack drainage, approximately 75 km west of Thunder Lake, show evidence of readvance of the Deming Glacier during the Younger Dryas (12 966-11 974 cal yrs BP (Kovanen and Slaymaker 2005), a well-recognized cold interval at the transition between glacial and post-glacial climate North Atlantic regions (Alley *et al.* 1993). More recent glacial advances have been recorded in the Canadian Cascades beginning ~3500cal yrs BP (summarized in Osborn *et al.* 2007). The glacial history of the area plays an important role in creating the complex soil patterns that influence vegetation (Franklin and Dyrness 1988).

Methods:

Core Collection and Sampling:

Two parallel sediment cores were extracted in 1-meter segments from 11 m of water in Thunder Lake, using a 7 cm diameter modified Livingston piston corer (Wright et al. 1984). The two cores were offset by 50-cm to provide a continuous record across breaks between each meter of core. Each core segment was wrapped in Saran wrap and aluminum foil in the field and stored in cold storage (4ºC) at the University of Washington. In the laboratory, magnetic susceptibility (a measure of inorganic sediment content, Thompson and Oldfield 1986) was measured on the intact cores with a Bartington Model MS2 magnetic susceptibility meter. Results are reported in standard units (SI). The core segments were then split longitudinally and photographed. The sediment stratigraphy was described based on visual and tactile characteristics. Using the visual stratigraphy, photographs and magnetic susceptibility data, the parallel cores were aligned to provide continuous sampling across breaks between core segments. The core segments were then sliced in 0.5 cm intervals and stored in Whirl-pak bags. All further subsampling was done from these bags.

Core Chronology:

The core chronology is based on age assignments for tephra layers and on four Accelerator Mass Spectrometry (AMS) radiocarbon dates. Dates were analyzed at the Lawerence Livermore Laboratory and calibrated using Calib 5.0 (available online, Stuiver and Reimer, 1986-2005).

Five tephra layers were visible in the cores and several hundred milligrams of each was deposited in glass rings mounted on a standard thin section. The tephra in each ring was mixed with epoxy, allowed to set, ground and polished to standard thin section thickness

(0.03 mm) and carbon coated. The glass component in each tephra was analyzed for 9 major and minor elements (Na, Ca, K, Fe, Ti, Mg, Si, Al, Cl) using the Cameca Camebax electron microprobe in the GeoAnalytical Laboratory, School of Earth and Environmental Sciences, at Washington State University, Pullman, Washington and the calibration procedure and standards given in Foit, Jr. *et al*. 2004. The Laboratory's database of 1700 (laboratory and literature data) western North American tephras was searched using eight elements (Na, Ca, K, Fe, Ti, Mg, Si, Al). The similarity coefficient of Borchardt *et al*. 1972 was used as a discriminator and the possible matches were selected based on its magnitude. With exception of Ti and Mg which were weighted at 0.25 because of their low concentrations (and high relative error of measurement), all other elements were given unit weights in the calculation of the similarity coefficients.

These tephra layers include: Glacier Peak (GP) (580 cm; 13 155 cal BP), Mazama Climactic (MC) (335 cm; 7674 cal BP), Glacier Peak Dusty Creek (GPDC) (244 cm; 5830 cal BP), and Mount Saint Helens Yn (165 cm; 3761 cal BP). The fifth and shallowest tephra (130 cm; ~2500 cal BP) is still being analyzed. The glass in this tephra has a Mt. St. Helens (MSH) compositional signature (relatively low K_2O and SiO_2 and relatively high Al_2O_3) and is compositionally very similar (similarity coefficient = 0.98) to MSH Wn (~490 cal BP). However, the CaO, MgO and TiO_2 contents differ significantly from those in the Wn standard and a radiocarbon date from sediments directly below the undisturbed tephra deposit (Table 1 CAMS # 120908) indicate it is much older (~2490 cal BP). Furthermore, this age has been independently confirmed by radiocarbon dating of a terrestrial deposit of this tephra elsewhere in the North Cascades National Park (Mierendorf, personal communication, 2006). The age of this tephra suggests it is possibly a MSH set B or MSH set P tephra. However, MSH set B tephras were not very voluminous and are found only proximally to Mount St. Helens. Set P tephras, on the other hand, are found distally (e.g. Foit, Jr. *et al*. 2004) and have an age range (2470-2760 cal BP, Foit Jr. *et al*. 2004; 2500-3000^{14}C years BP; Mullineaux 1996) which overlaps the apparent age of this tephra. Unfortunately, the composition of the glass in this unknown Thunder Lake tephra is only a weak match (similarity coefficients = 0.80 - 0.91) to several different MSH set P standards and published analyses and a similarity coefficient less than 0.88 is not meaningful(Bordchardt *et al*. 1972). It is clear from the data in the literature and that collected on standard samples both in this lab and elsewhere that set B and P tephras are perhaps the most poorly characterized of all the MSH tephras, with glass compositions reported for set P tephras varying widely even for the same tephra. Assuming the unknown Thunder Lake tephra TL1B 57 is a MSH set P tephra based on age, the best match (similarity coefficient = 0.91) is to what is thought to be a MSH set P tephra found in Cooley and Rockslide Lakes in southeastern British Columbia (Foit, Jr. *et al*. 2004). Although the weight of evidence supports this being a MSH set P tephra, we will be examining the composition of other mineral phases (i.e. Fe-Ti oxides) in an effort to verify this.

With the exception of the Glacier Peak sample (TL2F) and TL1B 57, all identifications were made based on similarity coefficients of .96 or better. The similarity coefficient for TL2F is 0.92 and this is due primarily to an anomalously low Fe_2O_3 content which may be the product of highly variable Fe content in the glass (one standard deviation of the analysis is almost half the Fe_2O_3 content) and the relatively few shards analyzed (this was a very fine-grained sample). An AMS radiocarbon date (582 cm; 13 636 cal BP; CAMS # 119176) on herbaceous leaf material from below this lowermost tephra provides confirming evidence that this tephra is Glacier Peak. Three additional radiocarbon dates were obtained on plant macrofossils at other core levels (Table 1). The estimated age assignments to individual samples are based on a linear regression fit to the age-depth relationships of the tephras and the AMS dates (Figure 2). Linear regression was chosen to provide an estimate of sedimentation rate that included all of the available age-depth data points without creating abrupt, and unconfirmed, changes in the sedimentation rate such as would occur with linear interpolation. Based on this equation, the sediment accumulation rate throughout the core is ~22.8 yr/cm. This value is used for calculations of pollen accumulation rates (PAR) and charcoal accumulation rates (CHAR).

Charcoal:
For every 0.5 cm sediment interval, a subsample of 5cc was extracted and processed for charcoal identification and counting. Sediment was soaked in a 10% solution of sodium metaphosphate for a minimum of two days and then rinsed gently through a 53 micron screen to wash away small particles. The samples were then soaked in hydrogen peroxide for 10-12 hours and sieved through nested screens with water to separate charcoal fragments into two size classes: >500 microns and 150-500 microns. These samples were stored in tap water. For each sample, both charcoal size classes were counted using a binocular stereomicroscope at 10-40x, and charcoal counts were converted to charcoal concentration (# of pieces/cm^3 of sediment). Charcoal concentrations were used to calculate charcoal accumulation rates (CHAR) by dividing these values by the estimated accumulation rate (22.8 yrs/cm) based on the age model.

Macrofossils:
Macrofossils (needle fragments of conifers) were identified to provide species-level identification of trees growing close to Thunder Lake (Dunwiddie 1987). Macrofossil analysis was done at ~250-year intervals throughout the core and at finer intervals for periods of vegetation transition (as identified in the pollen data). For each analysis, a 3 cc subsample of sediment was taken from two adjacent core samples, resulting in 6 cc sample/cm at the chosen intervals. The sediment was soaked in 10% sodium metaphosphate for 24 hours and then rinsed and examined under a binocular microscope at 10-40x. Identifications were made based on the morphological identification key in Dunwiddie (1985) and on a modern reference collection. Needle tips, bases and medial fragments were tallied separately. Needle tips and bases (medial fragments could rarely be identified to species) were combined into minimum number of individuals (MNI). For example, one tip and two bases equal two MNI. Although the total numbers of identified macrofossils are too low for statistical analysis, their presence/absence (Figure 4) is informative to vegetation interpretations.

Pollen:
One cubic centimeter of sediment was subsampled for pollen analysis at 5-20 cm intervals throughout the core (average = 10 cm.). Pollen samples were processed following Faegri and Iverson (1989). Tablets with known amounts of *Lycopodium* spores

(Stockmarr 1971) were added as tracers to allow calculation of pollen concentrations and accumulation rates (as described for charcoal). Pollen and spore residues were mounted in silicone oil and counted at 400-1000x magnification under a transmittance microscope. Total pollen sums for each sample range from 150 grains in inorganic samples to 326 in typical sediments, with an average of 280 grains. Percentages of all pollen and spore taxa were calculated based on the sum of terrestrial pollen grains. *Alnus* pollen was assigned to species (*A. sinuata* and *A. rubra*) based on pore morphology (Sugita 1990) and modern reference collections. An attempt was made to distinguish between haploxylon and diploxylon types of *Pinus* pollen, but such identification was not possible due to poor preservation of pollen (decayed or crumpled grains).

Results:

Core Stratigraphy

Basal sediments (700 to 600 cm; > ~ 14 000 cal yrs. BP) are dominated by gray clay. These sediments were most likely deposited when the Thunder Lake basin was part of a larger proglacial lake system. Silt becomes more common between 600 and 550 cm (~13 500 -12 500 cal yrs. BP) ,and gyttja dominates from 550 cm to the top of the core. The interval between 245-300 cm (~5500- 6800 cal yrs. BP) has higher sand content than the surrounding sediments and lacks any visible stratigraphy (such as discrete bands of inorganic sediment) commonly seen elsewhere in the core. The trends in magnetic susceptibility generally reflect these major stratigraphic units, with highest values (50-100) corresponding to clay-rich sediment and lowest (0-5) to gyttja. In addition, magnetic susceptibility is high (20-750) at the level of each of the tephras and for 245-300cm.

Charcoal

The charcoal record for Thunder Lake is characterized by low CHAR and indistinct peaks (1-20 pieces/cm^2/yr). CHAR is somewhat higher prior to 9000 cal BP than after. The major features of the record are two peaks (114, 139 pieces/cm^2/yr) between 9000-10 000 cal BP and four larger peaks (164, 139, 169, 252 pieces/cm^2/yr) between 6000-7200 cal BP. The 6000-7200 cal BP period corresponds to the 245-300 cm interval of high magnetic susceptibility and low pollen accumulation (Figure 3), suggesting that the charcoal peaks during this period result from one or more erosional events in the Thunder Lake catchment. Unfortunately, the relatively constant CHAR prevents interpretation of fire history at Thunder Lake. The rarity of distinct charcoal peaks is surprising, given the pronounced variations in charcoal content at nearby Panther Potholes (Prichard 2003).

Pollen and macrofossils

The pollen and macrofossil record (Figures 4-6) for Thunder Lake is divided into four zones identified visually for interpretation of past vegetation.

Zone I (~14,000-12,800 cal BP):

Zone I shows highest percentages of total nonarboreal pollen (NAP, 8-10%) for the entire record. The most common arboreal pollen (AP) taxa include *Alnus sinuata* (13-56%), *Picea* (6-11 %), *Pinus* (23-52 %) and *Abies* (3-8%). *Salix* pollen is also present (1-3%).

Pollen percentages of *Artemisia* (2-4 %), Asteraceae (Tubuliflorae) (<1 %), *Ambrosia*-type (~1 %) and other herbs are at their highest in this zone. No macrofossils were recovered. Total PAR are at their lowest in this zone (< 8000 grains/cm^2/yr).

Zone II (~12 800-9500 cal BP):
Like Zone I, Zone II is dominated by high percentages of *Alnus sinuata* (43-68%). However, *Abies* percentages (4-14 %) increase to their highest values in the record. With the exception of a brief period of near-zero percentages ~12 300-12 500 cal BP, *Picea* percentages (1-6 %) are half that of the previous zone. *Salix* pollen percentages (0.5-3%) remain relatively unchanged from Zone 1, but NAP percentages (0.5-3%) decrease to less than 5%. *Acer macrophyllum* pollen is present at very low percentages (<1%). Leaf fragments of *Abies lasiocarpa*, *A. procera* and *A. amabilis/grandis* as well as *Picea engelmannii*, *Tsuga mertensiana* and *Pinus* sp. are present in Zone II sediments. PAR values are at their highest in the record, with a distinct peak at ~12,500 cal BP for *Alnus, Pinus* and NAP. Another peak in PAR for most species occurs at ~10,900 cal BP.

Zone III (~9500-6000 cal BP):
Zone III is characterized by the first increase of *P. menziesii* pollen (0.5-25%), which reaches >20% between ~9000-8500 cal BP. *Alnus* pollen percentages remain high (30-50%), but shift from predominantly *A. sinuata* to a mixture of *A. sinuata* and *A. rubra* at ~9000 cal BP. *Picea* pollen disappears, but *T. heterophylla* pollen (0.5-8%) appears for the first time at the beginning of the zone and increases to 8 % ~7500 cal BP. *Abies* pollen (2.5-7 %) is still present, but at lower percentages than in the previous zone. *Salix* percentages (0.5-2%) remain constant in the lower half of the zone and then drop to zero by ~6000 cal BP. PAR in general decrease throughout the zone, although *P. menziesii* PAR reach peak values ~8500 cal BP. Total PAR are low between ~6000-7200 cal BP. Low PAR, in combination with high CHAR and high magnetic susceptibility (Figure 3), suggest that an erosional event(s) brought soil charcoal and inorganic material into the lake, diluting the input of aerial pollen. This is the only evidence of slope instability affecting lake sediments after forests established near Thunder Lake ca. 12 800 cal BP. *P. menziesii* and/or *T. heterophylla, A. amabilis/grandis, T. mertensiana* and *Pinus* sp. leaf fragments, which occur in this zone only between ~6000-7000 cal BP, were possibly washed into Thunder Lake during the erosional event(s).

Zone IV (~6000-0 cal BP):
Zone IV pollen assemblages are characterized by an increase in Cupressaceae (*c.f. T. plicata*, 5-23 %) and *T. heterophylla* (2-20 %) pollen. *P. menziesii* (6-13%) and *Abies* (3-6%) percentages show little change from Zone III. *Alnus* percentages (15-44%) gradually decline to 15 %, and continue to shift from a mixture of *A. sinuata* and *A. rubra* to almost entirely *A. rubra* (80% of *Alnus* pollen). *Betula* percentages (0.5-2%) increase to just above 1% at ~4000 cal BP. *T. mertensiana* pollen is occasionally present in trace percentages (<1%), and *Fraxinus* pollen (<1%) is present only in this zone. Macrofossils of *Abies* species and *T. plicata* indicate the presence of these trees around the lake at 5800 cal BP and continuing to present. PAR in general increase at ~5800 cal BP and then decrease throughout the zone. However, *T. heterophylla* PAR increase dramatically between ~4200-3000 cal BP.

Discussion of Past Vegetation and Climate:

Zone I (~14 000-12 800 cal BP):

The high percentages of nonarboreal pollen, coupled with the environmental affinities of indicator taxa (e.g. Chenopodiaceae, *Ambrosia*-type), low total PAR, and lack of macrofossils and charcoal, indicate a sparsely vegetated tundra/steppe or alpine parkland. In particular, the elevated percentages of *Artemisia* pollen suggest a dry vegetation often associated with steppe. Our interpretation of sparse vegetation cover is supported by the high magnetic susceptibility of these sediments, which implies the input of inorganic material from slope run off or glacial melt water. The pollen percentages of arboreal taxa such as *Pinus*, *Picea* and *Alnus* likely reflect long-distance pollen transport from tree populations at lower elevations, as these taxa are known to produce large amounts of well-dispersed pollen and their macrofossils are absent in these sediments. Zone I pollen assemblages are generally similar to postglacial assemblages at sites in the Puget Lowland and Olympic Peninsula (Barnosky 1981, Leopold *et al.* 1982, Barnosky 1985, Cwynar 1987, McLachlan and Brubaker 1995, Gavin *et al*. 2001), which have been interpreted to indicate a cold, dry late glacial climate.

An array of evidence from the Pacific Northwest indicates that this period was relatively dry and warmer than the previous full-glacial period. For example, alpine glaciers in the Cascade Mountains were retreating from their maximum full-glacial extent (Waitt and Thorson 1983) and long pollen records from the Olympic Peninsula indicate a warming from full-glacial time (summarized by Barnosky *et al.* 1987). In addition, simulations by global circulation models suggest much lower annual precipitation than at present during the late glaciation (Thompson *et al.* 1993).

Zone II (~12 800-9500 cal BP):

The decline in nonarboreal pollen, increase in arboreal pollen and total PAR, first appearance of conifer leaf fragments, and decline in magnetic susceptibility all suggest that forests became established near Thunder Lake during Zone II. This inference is further supported by the two distinct peaks in CHAR at the end of this zone, suggesting fire events near the lake. Leaf-fragment identifications indicate that *P. engelmannii* and a mix of *Abies* species including *A. amabilis/grandis, A. procera, A. lasiocarpa* dominated these forests, though *Pinus* and *T. mertensiana* were also present. This macrofossil assemblage shows that Thunder Lake, like numerous other sites in the Pacific Northwest, was surrounded by a rich mix of conifer species that do not occur together in modern forests. For example, *P. engelmannii* is common in the northeastern Cascade Mountains and in the Rocky Mountains, but *A. procera* occurs only in the southwestern Cascade Mountains (Franklin and Dyrness 1988) Although these unusual assemblages make environmental interpretations somewhat difficult, the Zone II assemblages generally suggest a period of continental climate that was colder and drier than present since many Zone II species grow at higher elevation and in drier climate than modern Thunder Lake. The shift in *Alnus* pollen from *A. sinuata* to a mix of *A. sinuata* and *A. rubra* may reflect a decline in snow, which had previously favored *A. sinuata* in avalanche paths, and an increase in riparian flooding that favored *A. rubra* in river flood plains.

The establishment of trees at the onset of Zone II is evidence of climatic warming near Thunder Lake. However, the beginning of Zone II also corresponds to the Younger Dryas cold period, when glacial moraines dated to this period in the Nooksack drainage have been interpreted as ice advances accompanying regional cooling. (Kovanen and Slaymaker 2005; Kovanen and Easterbrook 2001). The Nooksack glacial advances prompt questions about whether the Thunder Lake core contains evidence of the Younger Dryas cold event. Although the drop in *Picea* percentages (12 500-12 300 cal BP) might reflect a decline in *Picea* populations in response to a brief period of colder temperatures, no other data (e.g., changes in other pollen taxa, declines in PAR or increased magnetic susceptibility) for this period show evidence for cooling. For the zone as a whole, our inferences of generally cooler-and-drier climate than present agree with a recent assessment of temperature from fossil midge assemblages in lake sediments from southern British Columbia (Rosenberg *et al*. 2004), which indicates that this period was as much as 5 ºC cooler than present. The British Columbia record also indicates an abrupt warming toward the end of this zone (Rosenberg *et al*. 2004). At Thunder Lake, regional warming is indicated by the increase in *P. menziesii* (see below).

Zone III (~9500-6000 cal BP):

The sharp increase in *P. menziesii* and decline in *Picea* and *Abies* pollen at the beginning of this zone document a major change in forest composition near Thunder Lake. These shifts suggest a vegetation response to warmer and drier climatic conditions, as *P. menziesii* currently occupies warmer and drier climates than *Picea* and *Abies* in western North America (Thompson *et al.* 1999). *P. menziesii* dominated regional forests throughout this period, but *T. heterophylla* became an increasingly important component of forest stands by ~7500 cal BP. Macrofossil evidence also indicates the presence of *T. mertensiana*, *Pinus* sp. and *A. lasiocarpa* around the lake. As in Zone II, *Alnus* pollen likely originated from *A. rubra* at lower-elevation riparian sites with a minor component from *A. sinuata* in avalanche paths at higher elevation. We interpret the increase in magnetic susceptibility and charcoal, with a decrease in PAR between 6000-7200 cal BP as an erosional event. This could be an avalanche or mudslide from the steep slopes around the lake.

Pollen and macrofossil data from Panther Potholes (Prichard 2003) during this period (Early Holocene Zone) indicate a forest dominated by *P. contorta* with *P. menziesii*, *A. lasiocarpa* and *P. monticola* similar to modern xeric subalpine communities (Franklin and Dyrness 1988). This period at Panther Potholes is interpreted to indicate drier than present conditions, with warmer summers and colder winters (Prichard 2003). Thus, although pollen assemblages at the two lakes differed, climate interpretations from both records confirm a decrease in moisture during this period.

The climatic interpretations for this zone agree with previous inferences about early Holocene climate of the Pacific Northwest. In particular, a synthesis of pollen data, lake-level reconstructions and climatic simulations by Thompson *et al*. (1993) documents that this period was characterized by warmer and drier conditions than in previous periods and was warmer, drier than present. During this period, increased summer insolation resulted in a strengthening of the Pacific Subtropical High, which suppressed precipitation throughout the Pacific Northwest (Thompson *et al*. 1993).

Zone IV (~6000-0 cal BP):

The continued importance of *P. menziesii* pollen indicates that this species remained a dominant component of Thunder Lake forests. However, increased percentages of *T. heterophylla* and Cupressaceae (*c.f. T. plicata*) pollen at the beginning of this zone show the establishment of modern species composition in dense forests near the lake. Macrofossils confirm that *Abies* and *T. plicata* were present in forests surrounding the lake. *Tsuga mertensiana, Picea* and *Betula* (*c.f. B. papyrifera*) are present in the pollen data particularly after 4000 cal BP, indicating a diverse regional forest adapted to moister and cooler conditions than in previous periods.

During Zone IV at Thunder Lake, the forest at Panther Potholes (Mid-Holocene and Late Holocene Zones) shifts to a mixed conifer assemblage and *T.heterophylla* pollen appears (Prichard 2003). Around 5200 cal BP *T.plicata* and *T. heterophylla* percentages increase and by 2000 cal BP *T. mertensiana* and *Chamaecyparis nootkatensis* are present at Panther Potholes. These changes are interpreted as evidence of neoglacial cooling in the Panther Potholes record (Prichard 2003). Evidence for neoglacial cooling has also been described at sites in Canada. Pellat *et al.* (1998) document increased moisture at approximately 2600 cal yrs BP based on increases in *Abies* and Cyperaceae pollen percentages at Cabin Lake in the Canadian Cascades. Results from analysis of fossil chironomids suggest cooling around 3400 cal yrs BP (Pellatt *et al.* 1998). Records of glacial advances in the southern Coast Mountains and Canadian Rockies provide further evidence for neoglacial cooling at this time (Osborn *et al.*2007).

Pollen assemblages at Thunder Lake are similar to those of Panther Potholes around 5200 cal BP but do not show changes at 2000 cal BP consistent with neoglacial cooling in the region. However, the Thunder Lake record verifies findings throughout the Pacific Northwest, which also document the establishment of modern vegetation ca. 6000-5000 cal BP with little or no evidence of neoglacial cooling (Whitlock 1992). Regional records of pollen and lake levels indicate increasing effective moisture levels during this Zone due to reduced strength of the Pacific Subtropical High pressure system (Thompson *et al.* 1993).

Conclusion/Summary:

The general trends in pollen and macrofossil assemblages at Thunder Lake are consistent with previous inferences of regional vegetation change in the Pacific Northwest, based on pollen analysis of sites in the Washington Cascades, Puget Lowland, British Columbia and Olympic Peninsula. At ~14,000 cal BP, as the Cordilleran Ice Sheet retreated and mountain glaciers remained (Waitt and Thorson, 1983), the region experienced cool, dry conditions. Pollen assemblages indicate steppe-like vegetation, with *Picea*, *Pinus*, *Abies*, and *Tsuga* species present in the region. These tree species were components of the first forests that established following the late-glacial period. By ~9,000 cal BP the Pacific Northwest experienced its driest conditions as a result of increased summer insolation which enhanced the Subtropical Pacific High and suppressed regional precipitation. Regional vegetation generally showed an increase in *P. menziesii* and *A. rubra* while *Picea* and *Abies* declined. By ~6,000 cal BP the Northwest experienced wetter conditions than previously, as summer insolation and the strength of the North Pacific High pressure system decreased (Thompson *et al*. 1993). At Thunder Lake, as at numerous other sites, modern forest communities of *P. menziesii, T. plicata* and *T. heterophylla* established ~6000 cal BP. Thunder Lake, unlike nearby Panther Potholes does not provide supporting evidence for neoglacial cooling by ~2000 cal yrs BP documented by glacier advance and lake records in Canada.

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Table 1: Tephra and radiocarbon dates

Tephra Depth (cm)	**Probable Correlation**	**Similarity Coefficient**	**Measured Date**	**Calibrated Date**	**Sample**
130	Unknown	-	-	-	TL1B 57
165	MSH Yn[1]	.96	3000-4000 BP	3761 BP	TL1B 130
244	GP Dusty Cr[2]	.98	5000-5080 BP	5830 BP	TL1C 10
335	Mazama Climactic[3]	.99+	6850 BP	7650 BP	TL1D 54
580	Glacier Peak[4]	.92	11,200 BP	13,155 BP	TL2F

[1] Sarna-Wojcicki et al., (1980) p. 667-681 in Lipman and Mullineau eds. "The 1980 Eruptions of MSH, WA" USGS PP 1250.

[2] Foit, Jr. F.F., Gavin, D.G., Hu, F.S., (2004) The tephra stratigraphy of two lakes in south-central British Columbia, Canada and its implications for mid-late Holocene volcanic activity at Glacier Peak and Mount St. Helens, Washington, USA., Can.J.Earth.Sci.41(12): 1401-1410.

[3] USGS Mazama Climactic Standard W-97, from Wasco OR, Andre Sarna

[4] Foit Jr, F.F., Mehringer, P.J. and Sheppard J.C. (1993) Age Distribution and Stratigraphy of Glacier Peak Tephra in eastern Washington and western Montana, US, Can.J Earth.Sci., 30: 535-552.

Sample depth	**Measured ^{14}C age**	**Calibrated age**	**Sample type**	**Lab Number**
582 cm	11,780 BP +/- 180	13, 636 BP	Sedge fragment	CAMS # 119176
440 cm	10,190 BP +/- 50	12077-11647 BP	*Abies sp*. needle	CAMS # 123701
320.5 cm	5860 BP +/- 130	6325-7002 BP	Conifer needle	CAMS # 120907
129.1 cm	2490 BP +/- 40	2435-2729 BP	*Thuja pl*. leaf cluster	CAMS # 120908

Figure 1: Location of Thunder Lake in North Cascades National Park Service Complex and USGS map showing topography surrounding the lake.

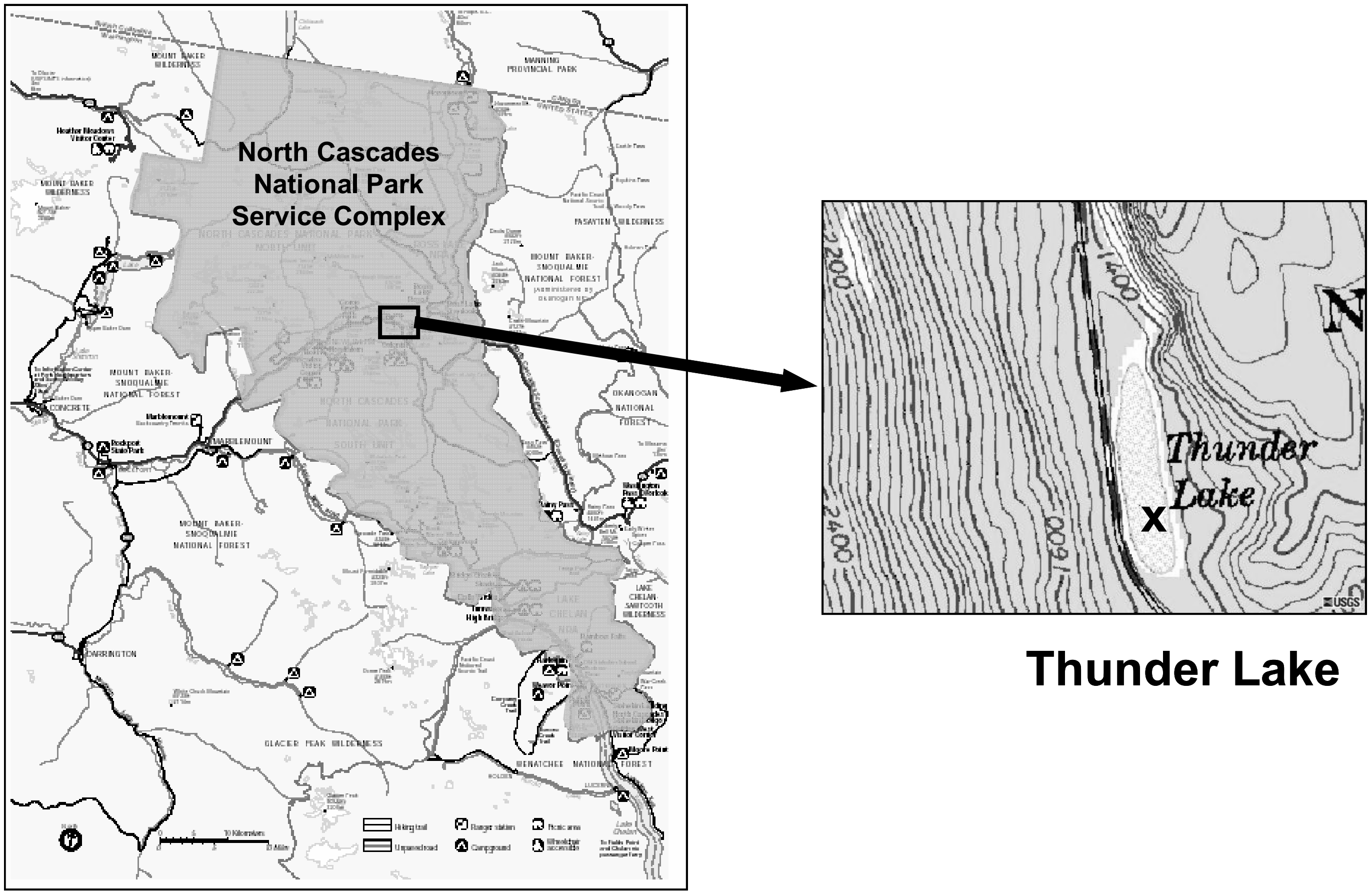
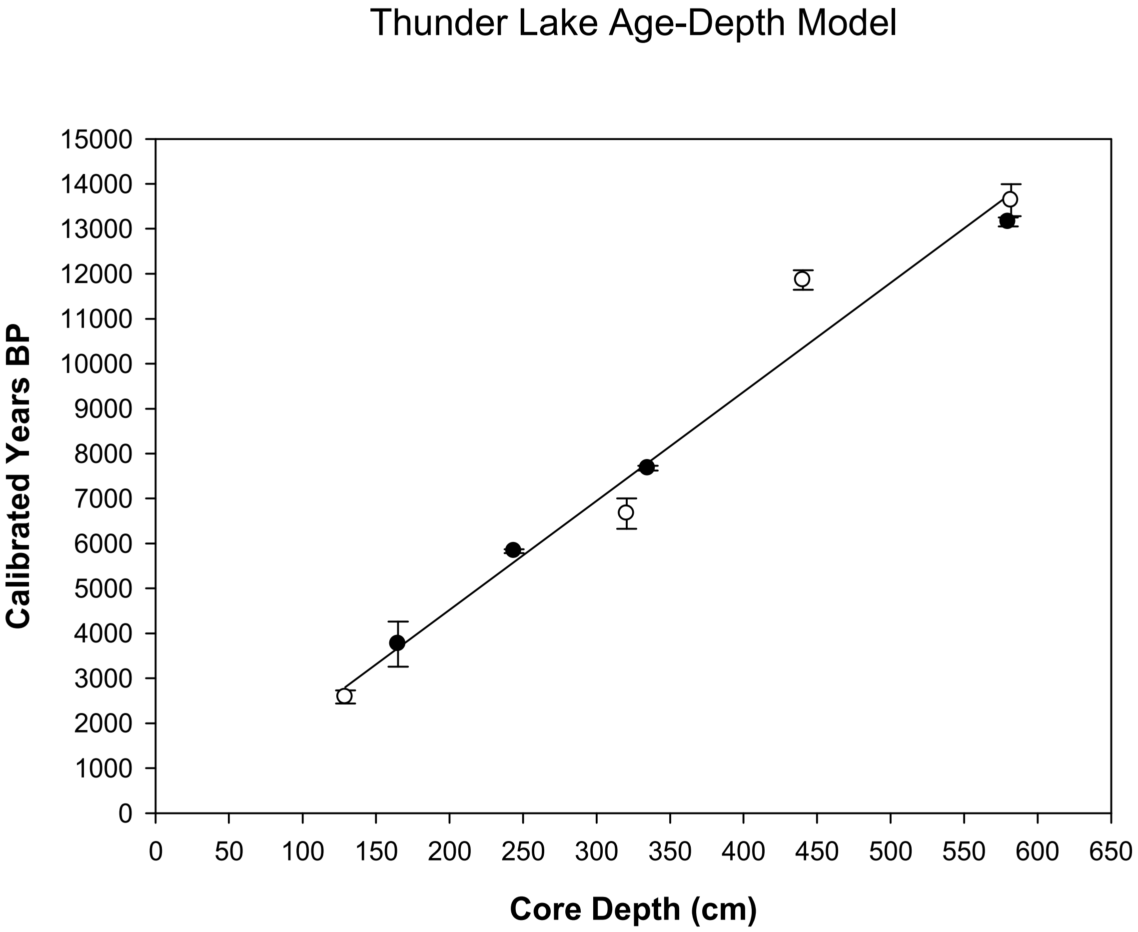


Figure 2: Age-Depth model for Thunder Lake sediment core. Regression line is calculated using all data points giving an estimated sedimentation rate of ~22.8 yrs/cm.



Black dot – Tephra
White dot – Macrofossil

Figure 3: Sediment stratigraphy, magnetic susceptibility, CHAR and PAR.

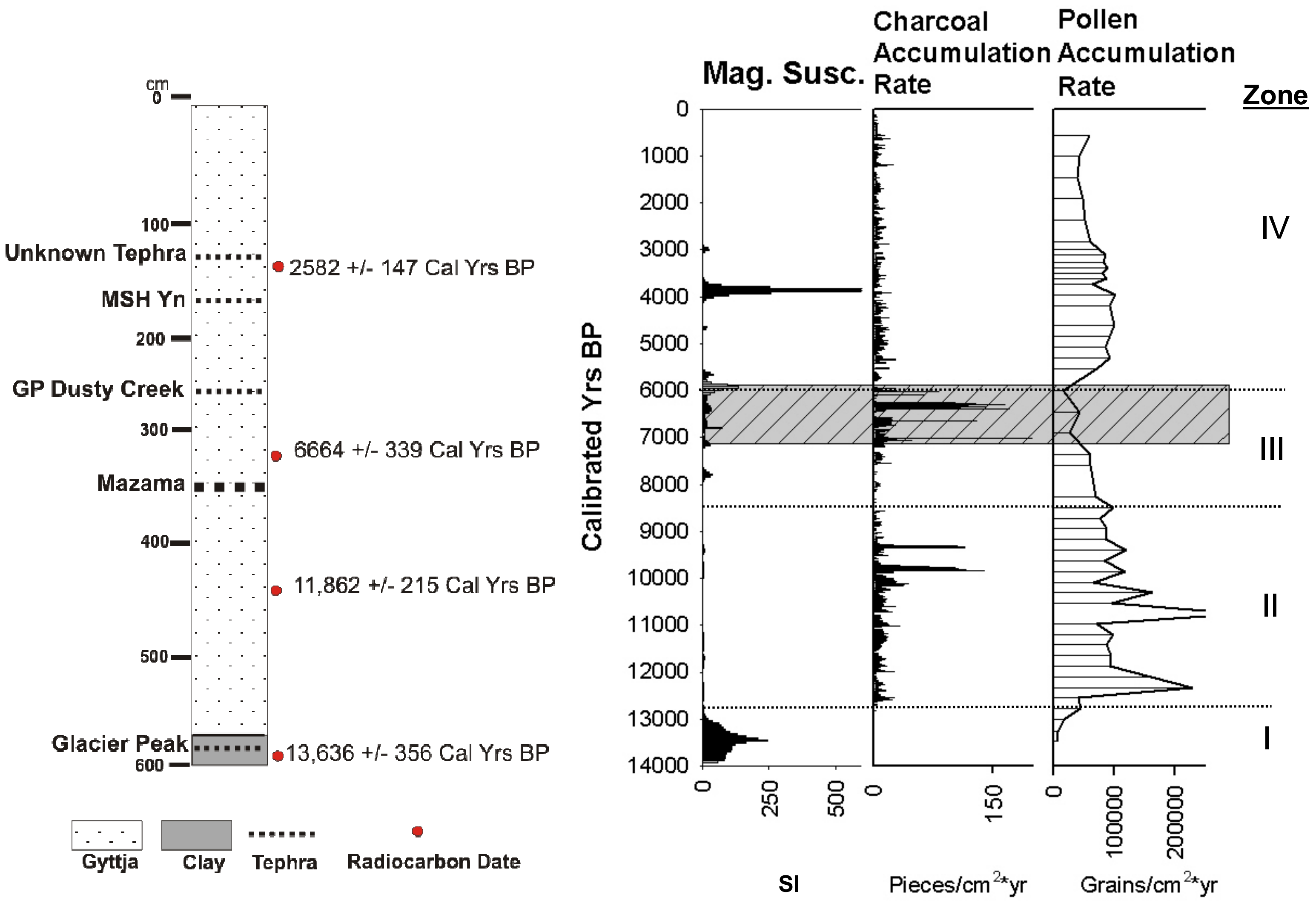


Figure 4: Percentage diagram showing major tree taxa, presence/absence of macrofossils, CHAR by calibrated years BP and Zone. PIEN- *Picea engelmannii*; ABAM/GR – *Abies amabilis/grandis*; ABPR – *Abies procera*; ABLA – *Abies lasiocarpa*

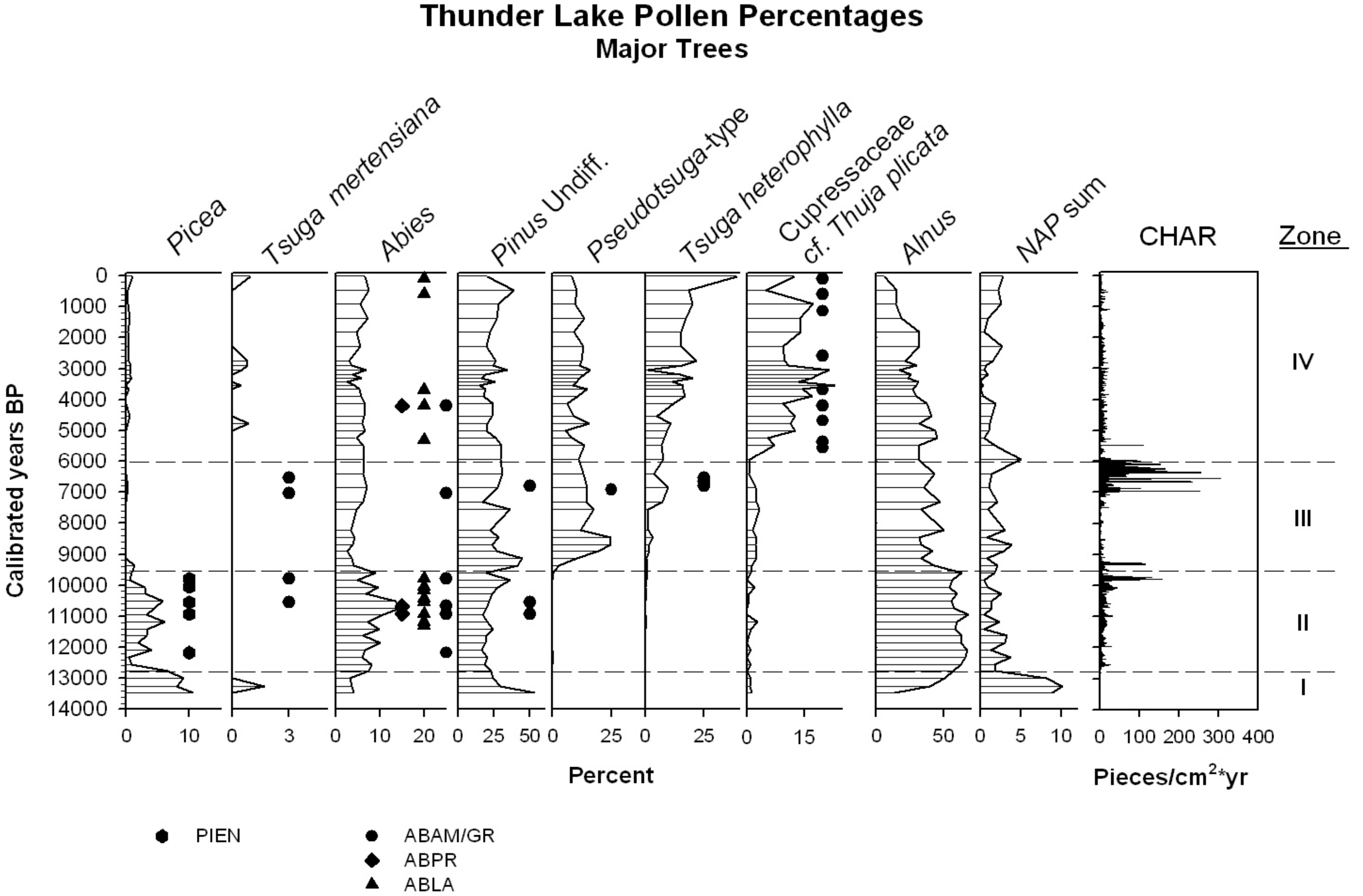


Figure 5: Pollen percentage diagram showing minor taxa.

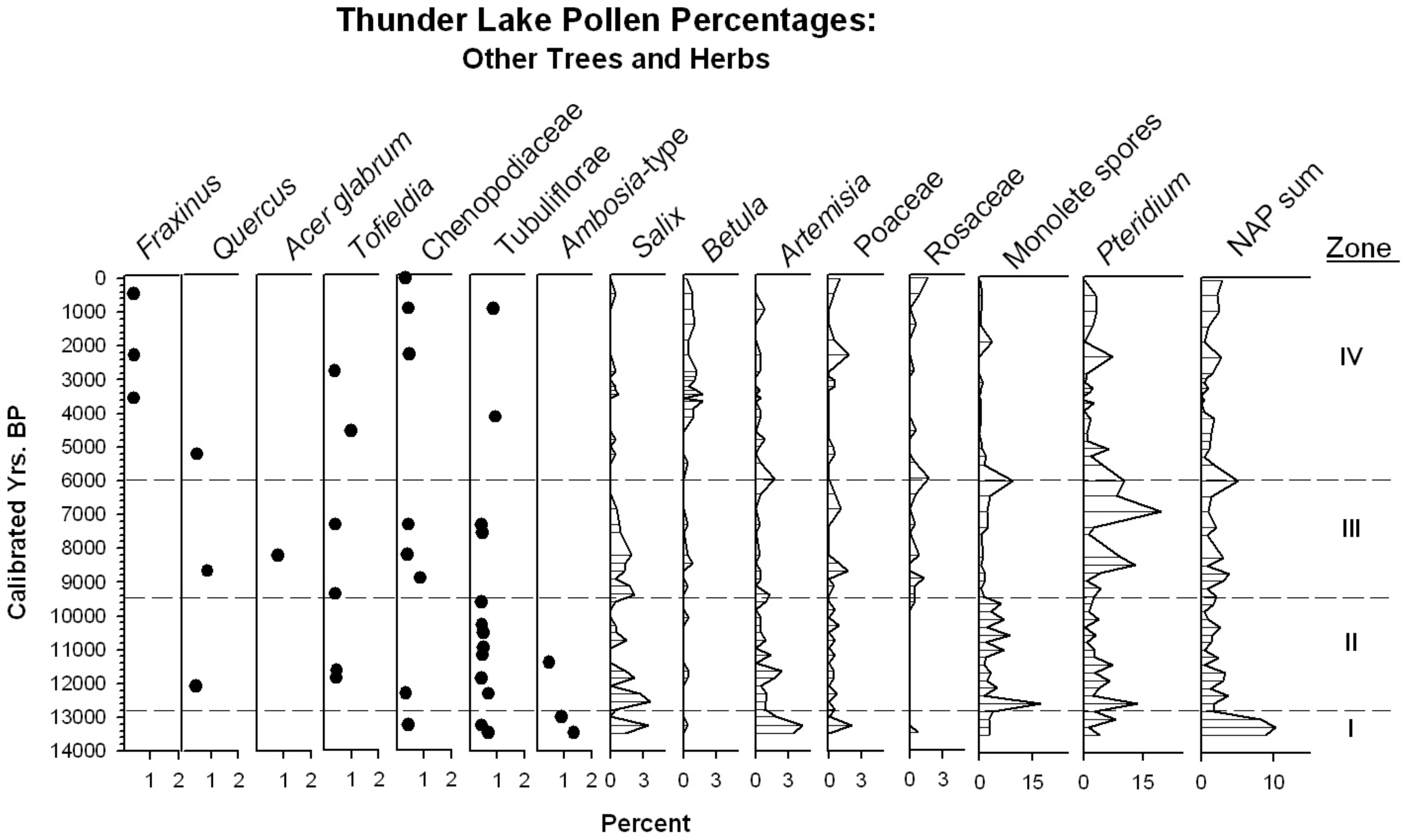


Figure 6: Pollen accumulation rate diagram (PAR)