

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

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July 7, 2008**

**Report submitted to: North Cascades National Park Service Complex,
Sedro Woolley, Washington, in partial fulfillment of Task Agreement
No. J9W88030002, Cooperative Ecosystem Studies Unit, National Park
Service**

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Abstract

A lake sediment record of pollen, charcoal and macrofossils is analyzed to reconstruct vegetation, fire and climate history surrounding Ridley Lake in the North Cascades, Washington. Ridley Lake is situated at 3140 feet between Desolation Peak and Hozomeen Mountain, along the east side of Ross Lake. The Ridley Lake sediments document 14,000 years of vegetation, fire and climate history, with excellent age control in upper portions of the record through volcanic tephra deposits and radiocarbon dates. General trends in climate interpreted from the pollen agree with other regional lake records. Following glaciation (~14,000-11,800 cal BP) the vegetation consisted of dry, cold adapted plants such as *Artemisia*, *Alnus sinuata* and *Picea*, often associated with steppe and treeline communities. Sediment characteristics between ~11 800-9800 cal BP suggest environmental changes associated with a Younger Dryas cooling. Under warmer conditions of the mid-Holocene (~9800-7000 cal BP), tree communities surrounding the lake show high diversity, including *Abies*, *Pseudotsuga menziesii*, *Tsuga heterophylla*, Cupressaceae (*cf. Thuja plicata*), *Alnus rubra* and *Betula*. Increasing charcoal accumulation rates from ~8500 cal BP support our interpretation of increased warmth and forest cover during this period. The mixed forest communities continue into the late Holocene (~7000 cal BP- present) with *T. heterophylla* and Cupressaceae dominating the assemblage, indicating a closed canopy forest adapted to cool, moist conditions. Charcoal input remains relatively steady, with peaks at ~3000 cal BP and ~500 cal BP. Very few macrofossils were recovered for analysis. The results of this study combined with other regional lake sediment records of pollen, charcoal and macrofossils provide a picture of the complexity of Holocene vegetation change in a complicated topography and confirm general regional trends of Pacific Northwest climate history.

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Introduction:

Previous studies in North Cascades National Park Service Complex have documented human history and illustrated the need for a paleoenvironmental study (Mierendorf *et al.* 1998). Reconstructing past environments in the North Cascades provides context for interpreting the archaeological record and understanding prehistoric settlement and subsistence patterns. This paleoecological history of Ridley Lake is the second part of a paleoenvironmental study to meet this need. Coupled with two recent sediment records from the North Cascades National Park Service Complex, Thunder Lake (Spooner *et al.* 2007) and Panther Potholes (Prichard 2003), a regional picture of vegetation change, fire history and climate change can be constructed.

Ridley Lake is an excellent site for paleoecological analysis. It is a small, closed basin that should be sensitive to changes in vegetation near the site (Sugita 1994). In addition, the transitional location of the lake in the rainshadow of the Pickett Range, should make vegetation near Ridley sensitive to climate change through the Holocene. Furthermore, the record from Ridley Lake fills a gap in the paleoecology and paleoclimate records of the Pacific Northwest, providing additional coverage of the diverse montane communities of the North Cascades. In particular, comparison of the Ridley Lake record with Panther Potholes and Thunder Lake records will provide an opportunity to examine how elevation may have affected trends in Holocene vegetation change. Similarly, comparison of these three records may lead to a better understanding of how vegetation and climate change is recorded in lake sediments in areas of topographic complexity. Of particular interest is whether the record at Ridley Lake records a neoglacial cooling documented at Panther Potholes, and/or cooling associated with the Younger Dryas documented by glacial advances in the region.

Funding for the following report is through Seattle City Light and the National Park Service through a Task Agreement with the University of Washington. Additional funding for radiocarbon dating and pollen processing was provided by the Quaternary Research Center, The Mazamas, and the Department of Earth and Space Sciences at the University of Washington.

Study Area:

Ridley Lake is located to the east of Ross Lake between Desolation Peak and Hozomeen Mountain in the North Cascades National Park Service Complex, (3140 ft asl, 48.949° N, 121.030° W; UTM 10 644259 E, 5423426 N) (Figure 1). The lake is situated in a

glacially scoured valley (Tabor and Haugerud 1999). Due to the influence of the Pickett Range to the west the area experiences a generally more continental climate than similar elevations of the west Cascade Mountains. Annual precipitation at nearby Ross Lake weather station is 57 inches, with 47 inches average snowfall (Western Regional Climate Center, <http://www.wrcc.dri.edu/>). The forests in this area contain some elements of forest zones located east of the Cascade crest suggesting a continental influence (Franklin and Dyrness 1988). The vegetation surrounding modern-day Ridley Lake is dominated by *Pseudotsuga menziesii* and *Tsuga heterophylla* with some *Pinus contorta*, *Abies amabilis*, *Abies grandis* and *Pinus monticola*.

The glacial history of this region of the Cascades plays an important role in creating the complex soil patterns that influence vegetation (Franklin and Dyrness 1988). During the Vashon Stade of the Fraser Glaciation the Cordilleran ice sheet covered this area. When the ice sheet retreated ~14 000 cal BP many valleys remained glaciated (Waitt and Thorson 1983). Alpine glaciers today remain on mountain peaks and in some high elevation valleys. There is evidence of at least two periods of glacial advance in the North Cascades since the beginning of the Holocene. Moraines in the Nooksack drainage of Mount Baker approximately 80 km west of Ridley 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 in North Atlantic regions (Alley *et al.* 1993). Similarly, recent glacial advances have been recorded in the Canadian Cascades beginning ~3500 cal yrs BP and interpreted as a response to neoglacial cooling (summarized in Osborn *et al.* 2007).

Methods:

Core Collection and Sampling:

Two parallel sediment cores were extracted in 1-meter segments from 9 m of water in Ridley 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 segment of core. Each core segment was wrapped in Saran wrap and aluminum foil in the field and stored in cold storage (4°C) 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 and Tephra Identification:

Age Determinations: The core chronology is based on age assignments for four tephra layers and four Accelerator Mass Spectrometry (AMS) radiocarbon dates (Table 1). Samples for radiocarbon dates were analyzed at Lawrence Livermore National Laboratory and calibrated using Calib 5.0 (available online, Stuiver and Reimer, 1986-2005).

Tephra Identification: Four tephra layers (Table 1) 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, following 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 tephtras 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, with possible matches 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. With the exception of tephra RY2A-1, all identifications were made based on unusually high similarity coefficients of 0.99 (Table 2).

Age-Depth Relationships: The age of each core sample was estimated based on a linear regression curve fit to the ages and depths of tephra and radiocarbon dates (Figure 2). Linear regression was chosen as the age-depth model because all of the points fell relatively close to the curve and because this choice makes fewest assumptions about age-depth relationships. Limited funding did not allow for additional dates in the 210-360 cm portion of the core. The estimated sediment accumulation rate throughout the core is ~41 yrs/cm and this value was used to calculate charcoal and pollen accumulation rates (CHAR and PAR).

Charcoal:

A subsample of 3 cubic centimeters of sediment was extracted from every 0.5 cm interval throughout the core for charcoal identification and counting. The sediment was deflocculated by soaking in 10% sodium metaphosphate for a minimum of 48 hours. Each sample was then sieved through a 53 micron screen and soaked in 10% hydrogen peroxide for 10-12 hours to oxidize any uncharred organic particles. Following this step the sediment was sieved through nested screens with water to separate charcoal fragments into two size classes: >500 microns and 150-500 microns. All samples were then 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/cm³ of sediment). Charcoal concentrations were used to calculate charcoal accumulation rates (CHAR) by dividing these values by the estimated accumulation rate (~41 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 Ridley Lake (Dunwiddie 1987). Macrofossil analysis was done every 5 cm throughout the core using 6cc of sediment. The sediment was soaked in 10% sodium metaphosphate for 24 hours and then rinsed and examined under a binocular microscope at 10-40x. Unfortunately, all macrofossils recovered from Ridley Lake are small needle fragments and not identifiable to species level. In addition, the number of macrofossils recovered from Ridley Lake is very low (n =15) and does not aid interpretation of past vegetation change.

Pollen:

One cubic centimeter of sediment was subsampled for pollen analysis at 20 cm intervals for the first meter of the core and 10 cm intervals for the remaining three meters, with additional samples taken between 185-215 cm (~4200-5400 cal BP) to clarify patterns in the pollen data for this period. Initially, 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.

The nature of the sediment resulted in much difficulty extracting sufficient pollen from the sediment for some samples. In many samples fine-grained clastic sediment could not be dissolved chemically or deflocculated to sieve effectively. This resulted in the pollen being clumped together and unidentifiable. After consulting experts in geochemistry and pollen extraction, samples were reprocessed multiple times using different methods (e.g. preliminary dehydration with ethyl alcohol, deflocculation with concentrated potassium hydroxide, oxidation with dilute bleach, multiple sieving steps combined with concentrated and/or heated pyrophosphate rinses). A few samples (260-280 cm; ~9800-11 800 cal BP) still did not provide sufficient pollen to be counted. Most samples were countable but still exhibited clumps of pollen and organic material.

A minimum of 300 arboreal pollen grains was counted for each sample resulting in total pollen sums between 300-350. In one sample with extremely low pollen concentration, the pollen sum was 270 (Sample 565, 313 cm.). 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 pollen reference collections. *Pinus* pollen grains were identified as haploxylon-type or diploxylon-type based on the presence or absence of distal verrucae (Kapp *et al.* 2000).

Results:

Core Stratigraphy (Figure 3):

Basal sediments (358-353 cm) are dominated by gray clay. Between 353-277 cm, sediments alternate between clay and brown gyttja, with a prominent band of gray clay at 293-277 cm. The upper 3 m of core (277-0 cm) are brown gyttja, with the topmost 90 cm very loosely compacted. Four tephra layers were visible at 100 cm, 129 cm, 166 cm, 206

cm. The trends in magnetic susceptibility generally reflect the major stratigraphic units. The lowermost clays show highest values near 200; clay-rich sediments between 350-280 cm are intermediate (50-100); and uppermost gytt records with lowest values (0-5). In addition, magnetic susceptibility is elevated (20-950) at the level of each of the tephras.

Tephra (Table 1 and Table 2):

The tephra layers include: RY2B-4, Mazama Climactic (MC) (206 cm; 7674 cal BP); RY2B-3, Glacier Peak Dusty Creek (GPDC) (166 cm; 5830 cal BP); and RY2A-2, Mount Saint Helens Yn (129 cm; 3761 cal BP). The fourth and shallowest tephra, RY2A-1 (100 cm; ~2500-3200 cal BP) is still being analyzed. This tephra (Table 2) is compositionally very similar to TL1B 57, the shallowest tephra in the Thunder Lake core (Spooner *et al.* 2007). With exception of Na₂O, the oxide weight percents are within one sigma of the analysis and the similarity coefficient between TL1B 57 and RY2A-1 is 0.97. Therefore, these are assumed to be samples of the same tephra.

Charcoal (Figure 3):

Charcoal concentrations in Ridley Lake range from 0-66 pieces/cm³, with an average of 8 pieces/cm³. CHARs are between 0-4 pieces/cm²/yr with an average of 0.62. CHARs are low from 14,000 – 8500 cal BP (CHAR = 0.03-0.2). After ~8500 cal BP CHARs increase slightly but remain low (CHAR = 0.1-1.0) until a distinct peak at 91 cm, ~3000 cal BP (CHAR = 2.5). The highest CHAR values are in the uppermost sediments with 3-4 fire events (CHARs = 1-3.5) before CHAR values dramatically increase at ~ 500 cal BP (CHARs = 7-15).

Pollen (Figure 4 and Figure 5):

The pollen record for Ridley Lake is divided into four zones identified visually for interpretation of past vegetation (Figures 4, 5). The core section between 11 800-9800 cal BP is given a zone designation (Zone II) due to its potential association with the Younger Dryas climatic period. The pollen in these sediments is sparse, clumped and crumpled, making counting extremely difficult and time consuming. These samples will be examined in the future to gain a first-order interpretation of vegetation during this period (e.g., relative abundance of tree, shrub and herb pollen). In this report Zone II will be interpreted on the basis of sediment data.

Zone I (358-309 cm):

Zone I shows highest percentages of Cyperaceae (20-70%), *Picea* (5-10%), *Alnus sinuata* (9-17%) and nonarboreal pollen (NAP) (3-7%) of the entire record. *Artemisia* (2-4%), *Salix* (2%), and *Abies* (1-5%) are present in relatively low percentages, and *A. rubra* (12-30%) in relatively moderate percentages. Haploxyton-type *Pinus* reaches its highest percentages (13%) at the end of this zone. Total PARs are highest (~20 000 grains/cm²/yr) in this zone.

Zone II (309-260 cm):

No identifiable pollen has been recovered from this zone.

Zone III (260-190 cm):

Zone III shows a shift in dominant arboreal species from *Picea* (<1%) and *Pinus* haploxyylon-type (1%) to *P. menziesii* (5%) and *A. rubra* (20-52%) while maintaining steady NAP (4-6%) values from the previous zone. *P. menziesii* reaches its highest values at the end of this zone (~15%). Herbs such as *Artemisia* (1.5-3%) and Rosaceae (~2%) remain relatively constant throughout this zone while Cyperaceae values (3-10%) drop dramatically. *Salix* (1-2%) and *A. sinuata* (2-8%) are still present and *T. heterophylla* appears at low percentages (2-6%). Total PARs drop to around 2000 grains/cm²/yr with a peak (~7000 grains/cm²/yr) at 8400 cal BP.

Zone IV (190-0 cm):

Zone IV pollen assemblages are characterized by the appearance of Cupressaceae (c.f. *T. plicata*, 5-22%) and increases in *T. heterophylla* (10-30%) and *Betula* (2-6%). *A. rubra* values are lower than in the previous zone (20-25%), and *A. sinuata* values are at their lowest in the entire core (0.2-5%). *Abies* and *P. menziesii* percentages remain relatively steady throughout this zone (4-10%). NAP values (0-3%) are at their lowest for the record, with *Artemisia* (<0.6%) and Rosaceae (<1%) present only in trace amounts. PARs vary between 1600-6000 grains/cm²/yr throughout this zone.

Discussion:

Tephra Identification:

The glass in both Ridley Lake RY2A-1 and Thunder Lake TL1B 57 has a Mt. St. Helens (MSH) compositional signature (relatively low K₂O and SiO₂ and relatively high Al₂O₃) and is compositionally very similar (similarity coefficients = 0.98) to MSH Wn (~490 cal BP). However, the CaO, MgO and TiO₂ contents differ significantly from those in the Wn standard and a radiocarbon date from pollen directly below the undisturbed tephra in Ridley Lake indicates that it is much older (~3200 cal BP, CAMS # 123699, Table 1). A radiocarbon date from beneath this tephra in Thunder Lake (~2490 cal BP) confirms that it is not MSH Wn (Spooner *et al.* 2007). Furthermore, these dates have been independently confirmed by radiocarbon dating of a terrestrial deposit of this tephra elsewhere in the North Cascades National Park Complex (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 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; 2500-3000¹⁴C years BP; Mullineaux 1996) that overlaps the apparent age of this tephra. Unfortunately, the composition of the glass in this unknown Thunder and Ridley Lake tephra is only a weak match (similarity coefficients = 0.80 - 0.91) to several MSH set P standards and published analyses and a similarity coefficient less than 0.88 is not statistically significant (Borchardt *et al.* 1972). The 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 that the unknown Thunder Lake TL1B 57 and Ridley Lake RY2A-1 tephras are MSH set P tephras based on age, the best matches (similarity coefficients = 0.91) are to a probable 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 RY2A-1 and TL1B 57 being MSH

set P tephras, we will be examining the composition of other mineral phases (i.e. Fe-Ti oxides) in an effort to verify this.

Paleoenvironmental Interpretation:

Zone I (~14 000-11 800 cal BP):

During Zone I, Ridley Lake was probably surrounded by an herbaceous vegetation, with trees in the general region. This is indicated by the high percentages and PARs of herbaceous pollen coupled with the occurrence of *Picea* and *Pinus* haploxylon-type, which likely represents the subalpine species *Picea engelmannii* and *Pinus albicaulis*, respectively. As both *P. albicaulis* and *P. engelmannii* are found in high elevation parklands today and requires cool summers, cold winters and deep snowpack (Franklin and Dyrness 1988), these pollen assemblages suggest an open, subalpine parkland of species adapted to a cold, dry climate. The moderate percentages of *A. sinuata*, probably indicate the presence of these shrubs on moist, concave slopes, which accumulate deep snow. The relatively low percentages of *A. rubra* likely represent trees present at lower elevation. Pollen accumulation rates in this zone are high, likely as a result of low organic input. This zone also illustrates relatively high magnetic susceptibility values, suggesting that lake sedimentation was largely inorganic material, possibly derived from glacial meltwater or aeolian sources on nearby recently un-glaciated slopes. Charcoal accumulation rates are low in this zone, supporting our inference of an open parkland.

Comparisons of the Ridley Lake record with Thunder Lake (Figure 1) at lower elevation permit the development of hypotheses about elevational trends in vegetation in the North Cascades. Zone I at Ridley Lake roughly coincides with Zone I at Thunder Lake (~14 000-12 800 cal BP), which shows similar taxa, but with lower representation of herbaceous species. The identification of *Alnus* and *Pinus* pollen in Ridley Lake sediments leads to the interpretation of a high-elevation parkland near Ridley Lake, whereas similar taxa at Thunder Lake were assumed to have originated at lower elevation (Spooner *et al.* 2007). The difference in this interpretation results from the more precise identification of *Pinus* pollen to haploxylon- or diploxylon-type in the Ridley Lake record. The predominance of haploxylon *Pinus*, interpreted to be *P. albicaulis*, at Ridley Lake is strong evidence for the existence of trees at high-elevations, perhaps on mountain slopes close to the lake. Determining the elevational distribution of trees is inherently difficult from pollen data because of the complex transport of pollen in mountain terrain (Markgraf 1980). To understand the late-glacial distribution of tree species in the North Cascades, future research should target lakes with macrofossil records during Zone I. Lastly, the 1000-yr earlier termination of Zone I at Thunder Lake than at Ridley suggests that regional forest composition changed earlier at lower elevation than higher elevation or that unexplained differences occur in core chronologies. Overall, existing pollen records suggest strong elevational gradients in late-glacial vegetation and physical environments in the North Cascades. Additional pollen and macrofossil records are required to describe these gradients in greater detail.

Zone I pollen assemblages at Ridley Lake are generally similar to other records of post-glacial vegetation in Puget Sound region and the Olympic Peninsula (Barnosky 1981, Leopold *et al.* 1982, Barnosky 1985, Cwynar 1987, McLaughlin and Brubaker 1995,

Gavin *et al.* 2001). This regional consistency suggests that a broad parkland-tundra extended across throughout Puget Sound during this period. Global circulation models for the late glacial period suggest much less precipitation than at present (Thompson *et al.* 1993). Other evidence suggests that alpine glaciers in the region were retreating at this time from their full glacial extent (Waitt and Thorson 1983). While warmer and drier than the previous full glacial environments, these post-glacial conditions were still cold and dry relative to today. This resulted in sparse vegetation cover, similar to modern alpine treeline ecotones.

Zone II (~11 800- 9800):

Geomorphological evidence (~12 900-11 900 cal BP) from the Nooksack drainage, approximately 80 km to the west of Ridley Lake, suggests a cooling associated with the Younger Dryas climate interval (Kovanen and Slaymaker 2005, Kovanen and Easterbrook 2001). Roughly during this interval, several aspects of the Ridley Lake sediment record suggest a return to severe environmental conditions. For example, the sediment changes dramatically to clays at the beginning of this interval. At the beginning of Zone II magnetic susceptibility values remain moderate (30-70 SI), similar to values for glacial clays in Zone I. At approximately 10 500 cal BP, these values drop to near zero, reflecting a shift toward low clastic input to the lake sediments. Charcoal is absent or rare in Zone II samples, suggesting little vegetation to burn on the nearby landscape. Lastly, the low abundance and degraded condition of pollen grains is evidence for sparse vegetation and harsh depositional environments. All of these changes are consistent with a response to Younger Dryas cooling, reducing vegetation on nearby slopes, resulting in higher clastic input relative to other zones, and possibly even a persistent snowcover on the lake itself.

No clear Younger Dryas response was interpreted from the Thunder Lake record or the nearby, slightly higher elevation Panther Potholes record (Figure 1). The variability among these records highlights the need for additional research to evaluate potential evidence of Younger Dryas at Ridley Lake. Firm chronological control is essential to any investigation of the Younger Dryas, and a proposal for two additional radiocarbon dates has been submitted to the Quaternary Research Center at the University of Washington. This research will require additional time and is beyond the scope of the original project. We anticipate completing Younger Dryas analyses during fall of 2008.

Zone III (~9800-7000 cal BP):

Zone III at Ridley Lake documents significant changes in the composition and structure of local vegetation. The pollen assemblages suggest a rather uniform conifer forest of *P. menziesii*, with a minor component of *Abies*. *A. rubra* was likely present in riparian sites. The relatively high percentages of nonarbooreal pollen suggest that the forest canopy was partially open, providing sufficient light to support herbs in the understory. The presence of low elevation species such as *P. menziesii* and *A. rubra*, with decline in high-elevation taxa such as *Picea*, *Pinus* haploxyton and *A. sinuata* suggests a warmer climate than in Zone I (and II). In addition, the continued presence of *Artemisia* suggests drier conditions than at present. CHAR values in this zone increase slightly at ~ 8500 cal BP

likely due to the increase in fuel biomass associated with more continuous vegetation as well as warmer, drier conditions.

Zone III at Ridley Lake coincides with Zone III at Thunder Lake (~9500-6000 cal BP) and illustrates generally similar changes in composition, such as *P. menziesii* increase and *Picea* decline, suggesting warmer and drier conditions than previously. However, NAP values are lower and *T. heterophylla* higher at Thunder Lake, indicating a closed forest canopy with an understory of shade-tolerant trees. In contrast, at Panther Potholes the forest resembled a xeric subalpine community with a parkland structure and important herbaceous component (Prichard 2003). The difference in forests among these sites may reflect environmental difference related to elevation. For example, a gradient of decreasing temperature and increasing snowpack from intermediate elevation (e.g., Thunder Lake) to high elevation (e.g., Panther Potholes) may have resulted in a decrease in tree canopy cover and an increase in herb component of forests in the North Cascades.

Other evidence from the Pacific Northwest supports the climatic interpretations of the North Cascade pollen records. Thompson *et al.* (1993) suggest that increased summer insolation during this period resulted in less precipitation than present throughout the Pacific Northwest. Other lake sediment records from Puget Sound Lowland and Olympic Peninsula support these conclusions (Whitlock 1992, McLachlan and Brubaker 1995, Gavin *et al.* 2001), and a synthesis of pollen and lake level records indicates this period was the driest during the Holocene for sites in the western United States (Thompson *et al.* 1993).

Zone IV (~7000 cal BP – present):

Increases in *T. heterophylla*, *Pinus* haploxyton-type and Cupressaceae (*c.f. Thuja plicata*) pollen, coupled with decreases in herbaceous pollen document major changes in the forest composition and structure near Ridley Lake. In this zone *Pinus* haploxyton-type likely represents *P. monticola*, which is commonly found in mixed conifer zones and in association with *T. plicata* and *T. heterophylla* in modern forests (Franklin and Dyrness 1988). These changes plus the relatively constant percentages of *P. menziesii* and *Abies* pollen indicate the establishment of modern mixed forests. During this zone, Ridley Lake was surrounded by a closed-canopy forest, with the development of a dense understory of shade-tolerant conifers. The increase in *T. heterophylla*, and *T. plicata* indicate a cooler, moister climate than in the previous zone. The increasing CHAR values in this zone suggest fire became more common in this region during the late Holocene. The large peak at ~3000 cal BP, suggests a fire event near the lake. In the last 500 years higher CHAR values may be the result of Native American fire-setting (Lepofsky *et al.* 2005) or reflect the fire-return intervals (50-130 years) documented for forests in this region over the last 200 years (Agee *et al.* 1990).

The Ridley Lake changes in forest composition resemble those at Thunder Lake in Zone IV (6000 cal BP-present), although *P. menziesii* and *Abies* were more common in Thunder Lake forests. Panther Potholes exhibits a transition to mixed forest species at ~7700 cal BP but does not show high percentages of *T. heterophylla* and Cupressaceae until ~5200 cal BP, when *Chaemacyparis nootkatensis* and Ericaceae also become

present. These changes at Panther Potholes have been interpreted as evidence of neoglacial cooling. No evidence for similar cooling is seen at Ridley Lake. It is possible that climate cooled only at high elevations in the North Cascades or that only high-elevation vegetation was sensitive to a general cooling within the region. The reason for the earlier dates for this zone with increasing elevation (6000 at TL, 7000 at RL, 7700 at PP) is unclear. Overall, our interpretation at Ridley Lake agrees with other paleovegetation records in the Pacific Northwest that document the establishment of modern vegetation at the beginning of this time (Whitlock 1992).

Conclusion:

The Ridley Lake pollen record verifies general trends documented at Thunder Lake and Panther Potholes in the North Cascades, as well as regional records from the Puget Lowlands, Olympic Peninsula and British Columbia. Close comparison of changes in the vegetation at the three North Cascade sites illustrates subtle differences in the timing of forest changes as well as forest composition attributable to the differences in elevation. Our record suggests at least three distinct periods of climate and vegetation change at Ridley Lake as well as possible environmental changes due to Younger Dryas cooling. As the Cordilleran Ice Sheet retreated, the landscape was sparsely vegetated by taxa adapted to the cool dry, post-glacial conditions. Around ~11 800 cal BP the pollen content of sediments drops dramatically as clastic input to the lake increases, suggesting a dramatic change in response to Younger Dryas cooling. Between ~9800 - 7000 cal BP the vegetation near Ridley Lake remained dominated by herbaceous species, with open forests of dry-adapted species. At ~7000 cal BP forest composition changed substantially, with the establishment of the modern mixed forest dominated by species adapted to moister and cooler conditions.

Acknowledgements:

The authors thank the National Park Service and Seattle City Light for the opportunity to pursue this research. The Mazamas organization provided a graduate student research grant that assisted in laboratory costs. Bob Mierendorf provided valuable encouragement and insight throughout the research. The North Cascades National Park Service Complex and Bob Mierendorf were instrumental in logistical support to core Ridley Lake. The Quaternary Research Center at the University of Washington contributed additional funds for radiocarbon dates and facilities for processing and analyzing pollen, charcoal, and macrofossil data. Phil Higuera assisted with lake coring. University of Washington undergraduates, Emily Spaulding and Kyle Linebarger, were invaluable lab assistants.

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Table 1. Tephra and Radiocarbon Dates

Tephra Depth (cm)	Probable Correlation	Similarity Coefficient	Measured Date	Calibrated Date	Sample
100	Unknown	-	-	-	RY2A-1
129	MSH Yn ¹	.96	3000-4000 BP	3761 BP	RY2A-2
166	GP Dusty Cr ²	.98	5000-5080 BP	5830 BP	RY2B-3
206	Mazama Climactic ³	.99+	6850 BP	7674 BP	RY2B-4

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

²Foit, 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.

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

Sample/ Depth	Measured ¹⁴C age	Calibrated Age	Sample Type	Lab Number
RY 31/30 cm	285 +/- 35	308 +/- 153	<i>Abies</i> sp. leaf	CAMS 123697
RY 70/60.5 cm	2385 +/- 50	2516 +/- 184	Pollen extract	CAMS 123698
RY 151/101 cm	3005 +/- 35	3204 +/- 127	Pollen extract	CAMS 123699
RY 650/361 cm	12020 +/- 80	13889 +/- 164	Pollen extract	CAMS 123700

Table 2: Glass Chemistry of Thunder Lake and Ridley Lake, North Cascades National Park, tephtras.

Oxide	Unknown Mt. St. Helen's		Mount St Helens Yn		Glacier Peak Dusty Creek		Mazama O		Glacier Peak	
	Ridley Lake	Thunder Lake	Ridley Lake	Thunder Lake	Ridley Lake	Thunder Lake	Ridley Lake	Thunder Lake	Ridley Lake	Thunder Lake
	RY2A-1	TIIB 57	RY2A-2	TLIB 130	RY2B-3	TLIC 10	RY2B-4	TLIC 44	TL2F	
	1.00m	1.30m	1.29m	1.65m	1.66m	2.44m	2.06m	3.35m	5.80m	
SiO ₂	74.85(0.29)	74.66(0.27)	75.63(0.31)	75.46(0.57)	78.35(0.17)	78.24(0.17)	73.50(0.22)	73.15(0.20)	77.90(0.32)	
Al ₂ O ₃	14.09(0.10)	13.96(0.18)	14.36(0.16)	14.40(0.32)	12.14(0.11)	12.08(0.10)	14.42(0.12)	14.43(0.14)	12.53(0.16)	
Fe ₂ O ₃	1.88(0.09)	1.88(0.07)	1.44(0.07)	1.33(0.16)	1.02(0.06)	0.99(0.05)	2.11(0.03)	2.08(0.08)	0.73(0.30)	
TiO ₂	0.33(0.04)	0.30(0.02)	0.18(0.03)	0.15(0.02)	0.21(0.02)	0.18(0.02)	0.45(0.03)	0.43(0.02)	0.20(0.02)	
Na ₂ O	4.03(0.15)	4.40(0.16)	4.00(0.12)	4.30(0.14)	3.35(0.10)	3.47(0.08)	4.59(0.15)	4.89(0.14)	3.55(0.15)	
K ₂ O	2.29(0.06)	2.26(0.11)	2.05(0.07)	1.99(0.07)	3.68(0.06)	3.82(0.09)	2.72(0.04)	2.76(0.10)	3.53(0.26)	
MgO	0.45(0.04)	0.42(0.03)	0.39(0.03)	0.38(0.07)	0.17(0.02)	0.16(0.02)	0.45(0.03)	0.46(0.04)	0.19(0.05)	
CaO	1.94(0.07)	2.01(0.16)	1.82(0.07)	1.89(0.19)	0.94(0.04)	0.94(0.05)	1.60(0.05)	1.62(0.04)	1.26(0.17)	
Cl	0.14(0.05)	0.11(0.02)	0.11(0.02)	0.11(0.02)	0.14(0.02)	0.12(0.02)	0.16(0.03)	0.17(0.02)	0.12(0.04)	
Total**	100	100	100	100	100	100	100	100	100	
Number of shards analyzed	17	16	15	18	18	18	15	14	14	
Similarity Coefficient***			0.99	0.96	0.99	0.98****	0.99	0.99	0.92	

* Standard deviations of the analyses given in parentheses

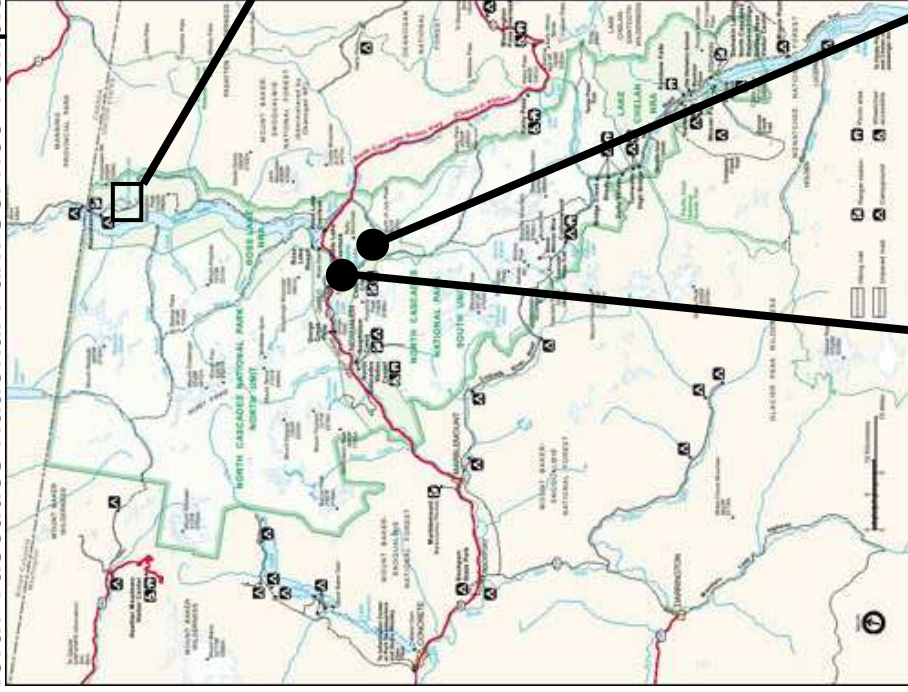
** Analyses normalized to 100 weight percent

*** Borchart et al. (1972) J. Sed. Petrol., 42, 301-306

**** compared to Dusty Creek std Hallett et al. 2001, QR, 55, 284-292

Figure 1. Location of Study Site: Location of study site and other sites mentioned in the text.

North Cascades National Park Service Complex



Ridley Lake



Thunder Lake

Panther Potholes

Figure 2: Age-Depth Model

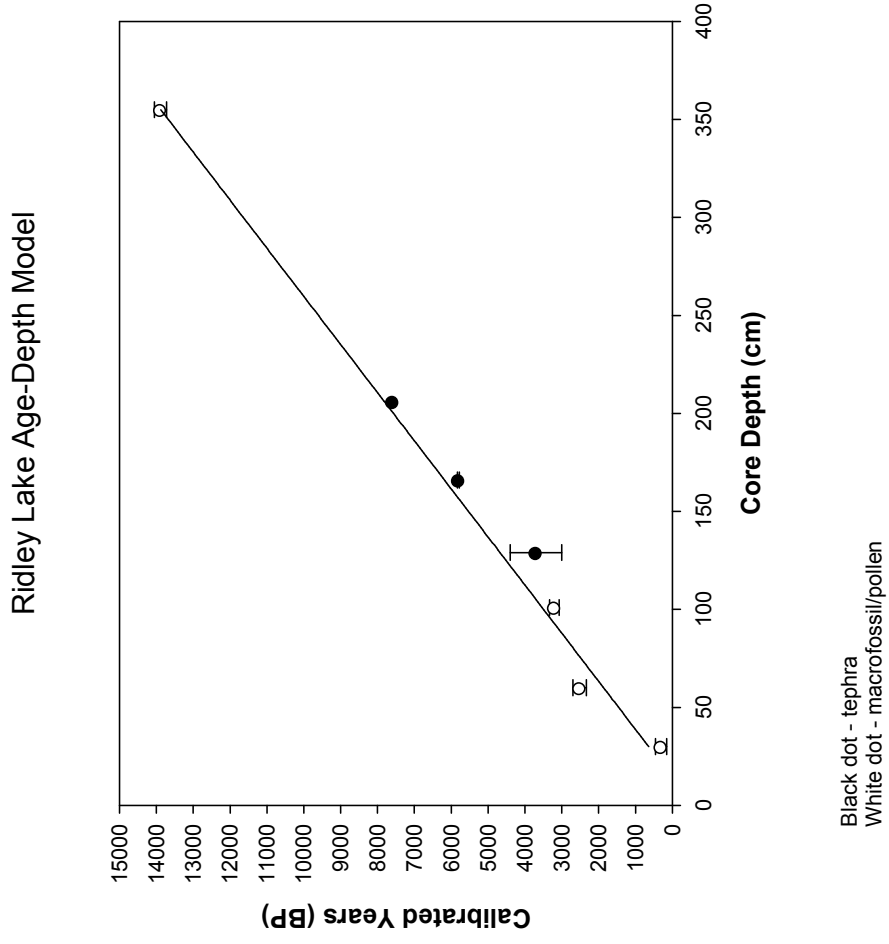


Figure 3: Core Stratigraphy and Sediment data.

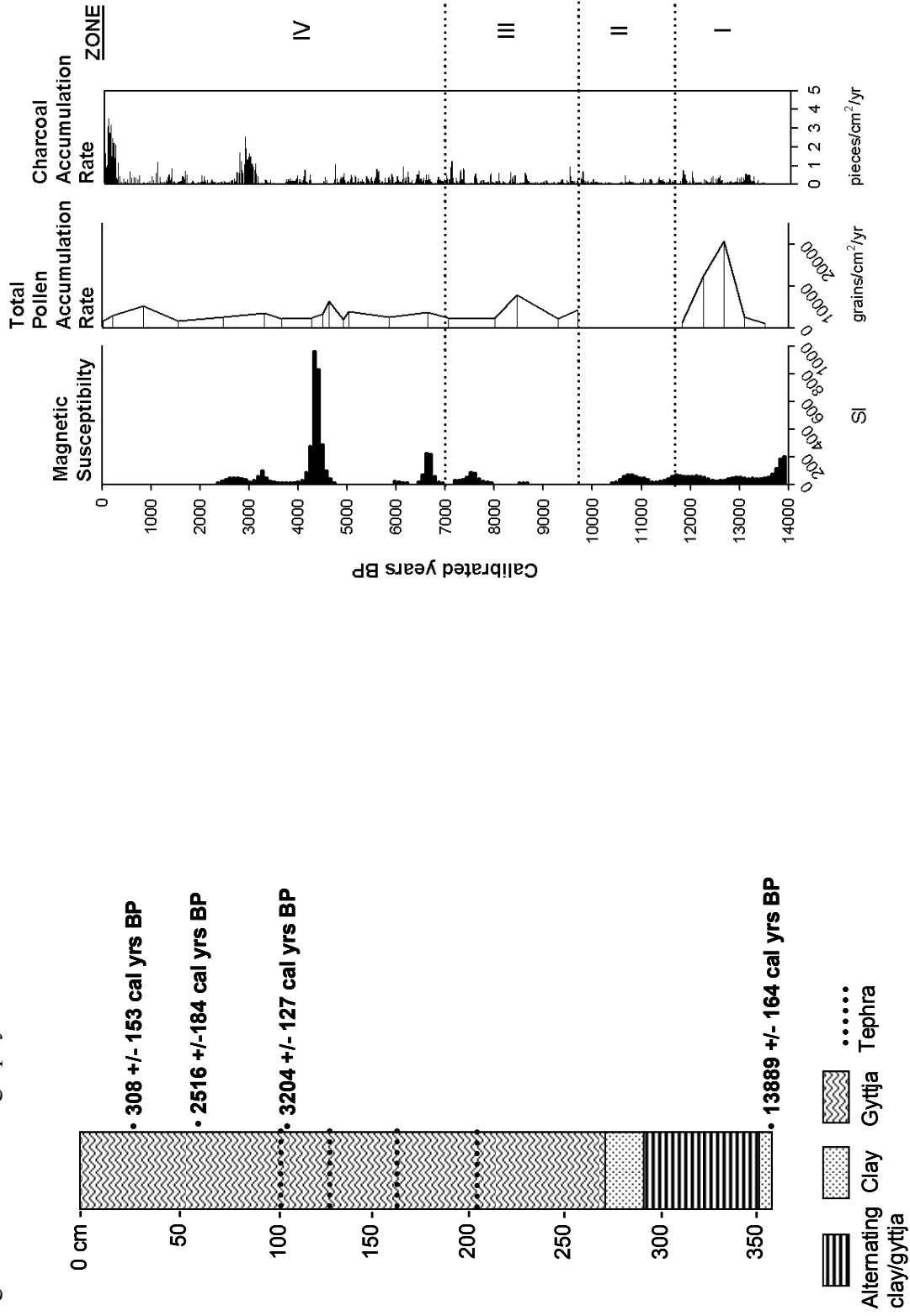


Figure 4: Ridley Lake pollen percentages of major taxa

Percentages of Major Taxa

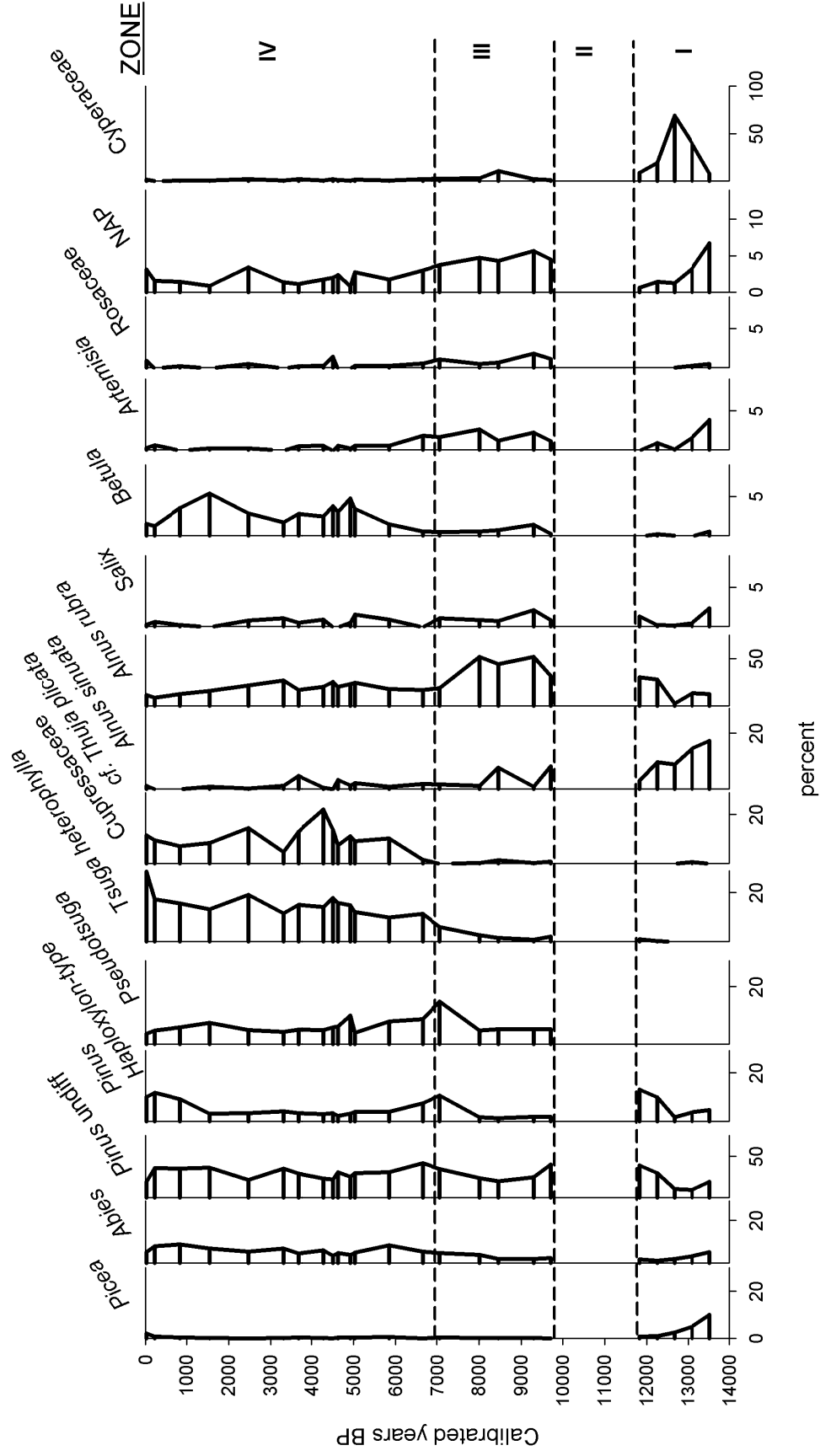


Figure 5: Ridley lake pollen accumulation rates for major taxa.

