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The effects of fire and tephra deposition on forest vegetation in the Central Cascades, Oregon

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ABSTRACT

High-resolution charcoal and pollen analyses were used to reconstruct a 12,000-yr-long fire and vegetation history of the Tumalo Lake watershed and to examine the short-term effects that tephra deposition have on forest composition and fire regime. The record suggests that, from 12,000 to 9200 cal yr BP, the watershed was dominated by an open *Pinus* forest with *Artemisia* as a common understory species. Fire episodes occurred on average every 115 yr. Beginning around 9200 cal yr BP, and continuing to the present, *Abies* became more common while *Artemisia* declined, suggesting the development of a closed forest structure and a decrease in the frequency of fire episodes, occurring on average every 160 yr. High-resolution pollen analyses before and after the emplacement of three distinct tephra deposits in the watershed suggest that nonarboreal species were most affected by tephra events and that recovery of the vegetation community to previous conditions took between 40 and 100 yr. Changes in forest composition were not associated with tephra depositional events or changes in fire-episode frequency, implying that the regional climate is the more important control on long-term forest composition and structure of the vegetation in the Cascade Range.

Introduction

Natural disturbances are an important component of ecosystem processes within forest environments. The interactive effects of multiple disturbance agents may increase their overall impact on forest composition and structure but may be difficult to interpret or predict (Turner et al., 2003). In the Cascade Range of the Pacific Northwest (PNW), two dominant disturbance agents are fire and volcanic eruptions. Fire regimes range from those with frequent low-severity surface burns in dry *Pinus contorta* (lodgepole pine) forests of the eastern slopes to those with infrequent high severity crown fires in wet *Tusga heterophylla* (western hemlock) forests on the western slopes (Franklin and Dyrness, 1988). A large portion, >50%, of Cascade Range forests fall between these two extremes, and can be characterized as having a mixed-severity fire regime such as that in the *Abies grandis* (grand fir) forests found the eastern Cascade Range and Sierra Nevada crest (Agee, 1993).

Volcanic activity is an episodic disturbance agent that may affect vegetation in several ways ranging from high severity plant-mortality impacts in the areas proximal to blast zones to inconsequential impacts of trace amounts of tephra falling on forest communities thousands of kilometers from an eruption source (Dale et al., 2005). Tephra deposition is the most common and widespread disturbance produced by volcanoes (del Moral and Grishin, 1999) and has been invoked as a catalyst for vegetation change (Haruki and Tsuyuzaki, 2001; Hotes et al., 2006; Millar et al., 2006). Tephra is used here to represent volcanic ash (0–2 mm diameter) and lapilli (2–64 mm in diameter) produced by pyroclastic ejecta (Mullineaux, 1996).

The AD 1980 eruption of Mt. St. Helens, located in the Cascade Range of the Pacific Northwest (PNW), provided one opportunity to examine vegetation response across a gradient of disturbance severity. Antos and Zobel (2005) examined vegetation response in tephra fall zones of varying depth at Mt. St. Helens using a network of permanent vegetation plots over the interval from AD 1980 to 2000. They concluded that although the spatial extent and impact of the tephra disturbance were heterogeneous, the initial impacts of ash fall on herb and shrub communities were significant and vegetation recovery to pre-eruption conditions required greater than 20 yr. Few studies have explored the longer-term ecological response of vegetation (as described by changes in pollen influx) to tephra deposition recorded by lake sediments, and currently, only Mehringer et al. (1977) have examined pollen changes at high resolution in proximity to PNW tephra deposits.

We present a millennial-scale record of fire and vegetation along with a series of decadal-scale records of fire and vegetation focused on periods of significant tephra deposition at a site in the central Cascade

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Range of Oregon. We used high-resolution pollen analysis to examine the nature of the vegetation response to tephra deposition and the timing of recovery to predisturbance conditions. This analysis provides a community-level perspective of vegetation recovery through multiple tephra fall episodes.

Holocene climate variability has been the ultimate control of vegetation change in the PNW (Hebda and Whitlock, 1997). Documenting the response of vegetation to an additional source of ecosystem disturbance, such as tephra fall, provides an opportunity to further understand the impact of disturbance on vegetation. Our model for vegetation response to tephra deposition is based on the amount of tephra deposited. Deposits of 70–100 cm have been shown to kill all vegetation (del Moral and Grishin 1999). Tephra amounts under 70 cm have had less impact on tree populations but tephra amounts of as little as 5 cm have diminished herb and shrub populations significantly (Antos and Zobel 2005). Based on the assumption that each tephra fall examined is less than 70 cm, we expect that herb and shrub populations would diminish significantly after each tephra fall regardless of the understory community present. We also presume that tree populations and species present would remain consistent. Tephra falls are not expected to induce fires by increasing fuels through tree mortality.

Charcoal accumulation was examined during each tephra fall episode as a proxy for watershed fires (Whitlock and Larsen, 2001) to identify synergistic relations between tephra fall, fire, and vegetation change. The goals for this study were to 1) examine the long-term relations between fire and vegetation, 2) examine the short-term response of vegetation to three individual tephra fall events, and 3) identify any synergistic relations, if present, between tephra fall, climate and fire over the last ca. 7600 yr at Tumalo Lake.

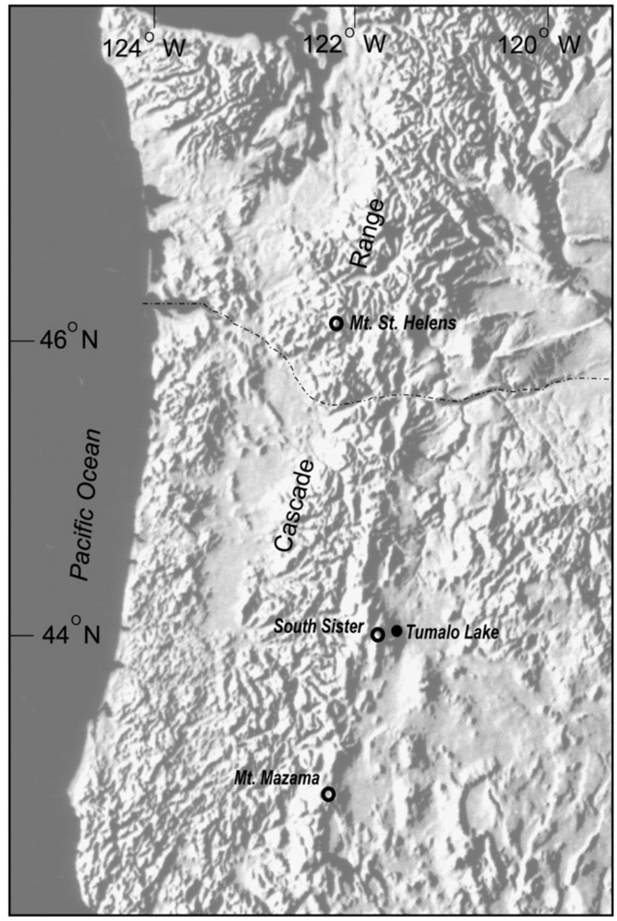

Figure 1. Location of Tumalo Lake, Mt. St. Helens, Mt. Mazama, and South Sister, location of the Rock Mesa and Devils Hill volcanic vents.

Study site

Tumalo Lake (44°02.27′N, 121°54.11′W, elev. 1536 m) is located on the eastern flank of the Cascade Range and is within 25 km of several volcanic peaks that have Holocene eruptive histories (Scott et al., 2001) (Fig. 1). The present-day climate of the area is characterized by cool wet winters and warm dry summers. Most of the annual precipitation comes from Pacific Ocean storms during the winter months. Winter precipitation falls mainly as snow. In summer, the eastern Pacific subtropical high strengthens, moves northward, and provides large-scale subsidence over the region suppressing precipitation and producing warm, dry summers (Mock, 1996). The fire season occurs from June to October as fuel moistures drop during the annual summer drought (Agee, 1993). January and July temperatures from Three Creeks Lake, located 10 km to the north, are −2.0 °C and 14.3 °C, respectively, and mean annual precipitation is 1050 mm (NRCS, 2006). The stream draining Tumalo Lake, which lies at the head of a small glacial trough (Hansen, 1942), was impounded in the AD 1920s, increasing the size of the lake from 2 ha to 7 ha. The watershed lies within the grand fir vegetation zone (Franklin and Dyrness, 1988). Dominant arboreal species include *A. grandis* (grand fir), *Abies amabilis* (Pacific silver fir), *Picea engelmannii* (Engelmann spruce) along with scattered *Tsuga mertesiana* (mountain hemlock) which occupy moist slopes and northern aspects, and *P. contorta* (lodgepole pine) and *Pinus ponderosa* (ponderosa pine) with a small component of *Pinus monticola* (western white pine) on dry slopes and southern aspects. Common nonarboreal species include *Ceanothus velutinus* (snowbrush), *Arctostaphylos nevadensis* (pinemat manzanita) with *Stipa occidentalis* (western needlegrass) and occasional *Epilobium angustifolium* (fireweed) on open slopes. Shrub and herb cover is minimal under closed pine and fir canopies. Riparian vegetation includes *Betula papyrifera* (paper birch), *Alnus sinuata* (sitka alder), and *Salix scouleriana* (Scoulers willow) along with scattered *Populus tremuloides* (quaking aspen) and *Acer circinatum* (vine maple). Several *Ranunculus* and *Lupinus* species act as ground cover in moist open areas.

Methods

Sediment cores were collected from the deepest portion of the lake using a 5-cm-diameter piston sampler (Wright et al., 1983). Samples for pollen analysis of 1 cm^3 were taken at every 10 cm over the length of the core, and at 1-cm intervals surrounding three tephra deposits at depths of 1.78, 1.87, and 4.84 m. Samples were processed using standard methods (Faegri et al., 1989). A known amount of *Lycopodium* pollen was added to each sample before processing to calculate pollen accumulation rates. The pollen samples were mounted in silicon oil and examined at magnifications of 400 to 1000×. Pollen was identified to the lowest taxonomic level and a minimum of 350 terrestrial grains were identified from each sample. *Pinus* grains were grouped into diploxylon-type (*P. contorta* or *P. ponderosa*) and haploxylon-type (*P. monticola*) based on examination of the distal membrane of the pollen grain. Undifferentiated *Pinus* pollen counts, considered to represent diploxyon- and haploxylon-types, were calculated as diploxylon or haploxylon-types based on the ratio of identified *Pinus* pollen grains from each sample. *Pseudotsuga*-type pollen was attributed to *P. menziesii* (Douglas-fir), and *Picea* pollen was assumed to represent *P. engelmannii. Abies* pollen was attributed to *A. grandis* (grand fir) and *A. amabilis* (Pacific silver fir). Cupressaceae pollen was attributed to *Juniperus occidentalis* (western juniper), a common present-day species east of the Cascades. Pollen grains that could not be identified were labeled “Unknown.” Terrestrial pollen percentages were calculated using the sum of

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terrestrial pollen and spores. Percentages of aquatic taxa were calculated based on total terrestrial and aquatic pollen and spores. Pollen accumulation rates (PAR) (grains/cm^2/yr) were determined by dividing pollen concentration by deposition time (yr/cm). The pollen percentage diagram was divided into zones based on constrained cluster analysis (CONISS, Grimm, 1987). Pollen types were grouped into arboreal which included *Pinus*, *Picea*, *Abies*, *Tsuga*, *Pseudostuga*, and Cupressaceae, and nonarboreal which included all remaining terrestrial pollen types. *Betula*, *Alnus*, and *Populus* were designated as nonarboreal pollen types because of their restriction to riparian areas at this site.

Variations in the abundance of macroscopic charcoal found in the lake sediments were used to reconstruct the fire history (Whitlock and Larsen, 2001). Sediment sampling for charcoal followed Long et al. (1998). Subsamples of 3 cm^3 were taken at contiguous 1-cm intervals and soaked in 5% solution of sodium hexametaphosphate for 24 hours. The samples were then gently washed through a series of nested screens with mesh sizes of 250 and 125 µm. The sieved samples were examined at 50× magnification, and all charcoal particles greater than 125 µm were tallied. Charcoal counts for each sample were first converted to concentration (particles cm^{-1}) and, using the sediment deposition rate, then converted to charcoal accumulation rates (CHAR, particles cm^{-1} yr^{-1}) at 15-yr time steps, the typical deposition time for each sample. This procedure minimizes any variations in the charcoal time series that might arise because of changes in the deposition rate. The CHAR record was then decomposed into background and peak components (Higuera et al., 2009; http://www.CharAnalysis.googlepages.com). Background charcoal is the slowly varying trend in CHAR as a primary result of changes in fuel composition (Marlon et al., 2006). Peaks, which are positive deviations from the background CHAR, represent input of charcoal as a result of a fire episode (one or more fires closely spaced in time; Long et al., 1998). The CHAR background component was determined using a lowess smoother with a 500-yr window width and one robustness iteration. The background values for each time interval were then subtracted from the total CHAR accumulation for each interval. The peaks in the charcoal record (i.e., intervals with CHAR values above background) were tested for significance using a Gaussian distribution where peak CHAR values that exceeded the 95th percentile were considered significant (i.e., not the result of natural signal noise or analytical error). This procedure was done on every 500-yr overlapping portion of the CHAR record producing a unique threshold for each sample. Once identified, all peaks were screened to eliminate those that resulted from statistically insignificant variations in CHAR (Gavin et al., 2006). If the maximum count in a CHAR peak had a >5% chance of coming from the same Poisson distribution population as the minimum charcoal count with the proceeding 75 yr, then the peak was rejected (Higuera et al., 2009).

The chronology for the sediment core was based on six accelerator mass-spectrometry (AMS) ^{14}C dates and the accepted calendar age of Mazama tephra (Zdanowicz et al., 1999) (Table 1). The AMS dates were converted to calendar ages (Stuiver et al., 1998; CALIB 5.0.1), and with the addition of the Mazama tephra date, a cubic spline was used to describe the age-vs-depth relations for the core (Fig. 2). We assumed that each tephra deposit in the sediment core occurred rapidly, thus they were excluded from the sediment column accumulation rate calculations.

Results

Lithology

We recovered a 13.01-m core which consisted of upper sediments of dark brown (10YR 3/3) fine-detritus gyttja, grading to very dark brown (10YR 2/2) medium-detritus gyttja and basal sediments of banded inorganic silty clay that alternated between light yellowish brown (2.5Y 6/4) and dark grayish brown (2.5Y 4/2). Three volcanic ash deposits 2 cm in depth or greater were noted: 2 cm from 1.78 to 1.80 depth, 3 cm from 1.87 to 1.90 m depth, and 50 cm from 4.84 to 5.34 m depth. Based on the age-vs-depth model and their proximity to each other in the core, we attributed the tephra deposits from 1.78 to 1.90 to two separate volcanic eruptions from South Sister vents (i.e., the Devils Hill and Rock Mesa eruptions, respectively; Scott et al., 2001). The 50-cm-thick tephra deposit was attributed to the eruption of Mt. Mazama (Simkin and Seibert, 1994). From the base of the core (13.01 m) to 7.48 m, the sedimentation rates were high, which was likely a consequence of landscape instability during deglaciation, therefore the pollen and charcoal analyses were limited to the top 7.48 m of sediment, corresponding to the last 12,000 cal yr BP (Fig. 2).

Table 1
Calibrated and uncalibrated ^{14}C ages and the age model for Tumalo Lake.

Depth (m)	Calibrated age (cal yr BP)[a] (cal yr BP ± 2 SD)	Uncalibrated ^{14}C age (± 2 SD)	Material	Lab number
0.0	−55		Mud/water interface	OS-663181
1.08	1790 (1715–1865)	1850 ± 30	Plant	UGAMS-03086
1.86	2150 (2000–2300)	2130 ± 30	Charcoal	Beta 202308
2.03	2730 (2690–2770)	2550 ± 40	Wood	
3.04	4630 (4560–4710)	4130 ± 40	Seed	Beta 202309
4.72	7630 ± 150		Tephra	Zdanowicz et al. (1999)
7.46	12,880 (12,800–12,940)	10290 ± 50	Sediment	Beta 194808
8.26	12,190 (11,981–12,400)	10350 ± 60	Plant	OS-66497
10.23	12,880 (12,800–12,940)	10777 ± 80	Wood	Beta 194808

[a] Based on CALIB 5.0.1 (Stuiver et al., 1998).

Long-term pollen record

The pollen record was divided into two zones (Fig. 3). Zone Tum 04-1 (12,000 to 9200 cal yr BP) pollen stratigraphy shows abundant *Pinus* pollen with significant percentages of *Picea* and *Tsuga mertensiana*, and nonarboreal taxa such as *Artemisia* and *Alnus*. Total PAR for Tum 04-1 averaged 3880 grains/cm^2/yr per sample which is typical of present-day subalpine forests (Brunelle and Whitlock 2003). Sub zone Tum 04-2a, from 9200 to 1650 cal yr BP, shows the continued dominance of *Pinus* in the pollen record and an increase in *Abies*, *Picea*, and *Betula* pollen, and *Dryopterius*-type spores. *T. mertensiana*, *Alnus*-type, and *Artemisia* pollen decreased during this period. PAR values were slightly higher than those of Tum 04-1 averaging 4350 grains/cm^2/yr. Sub zone Tum 04-2b, from 1650 cal yr

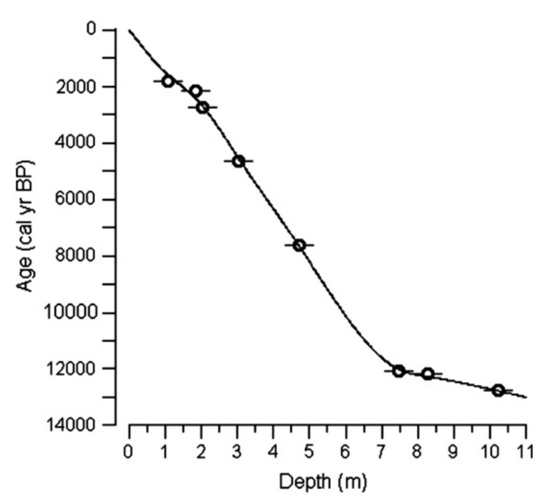

Figure 2. Calibrated age (cal yr BP) versus depth curve for Tumalo Lake. Symbols represent age data listed in Table 1.

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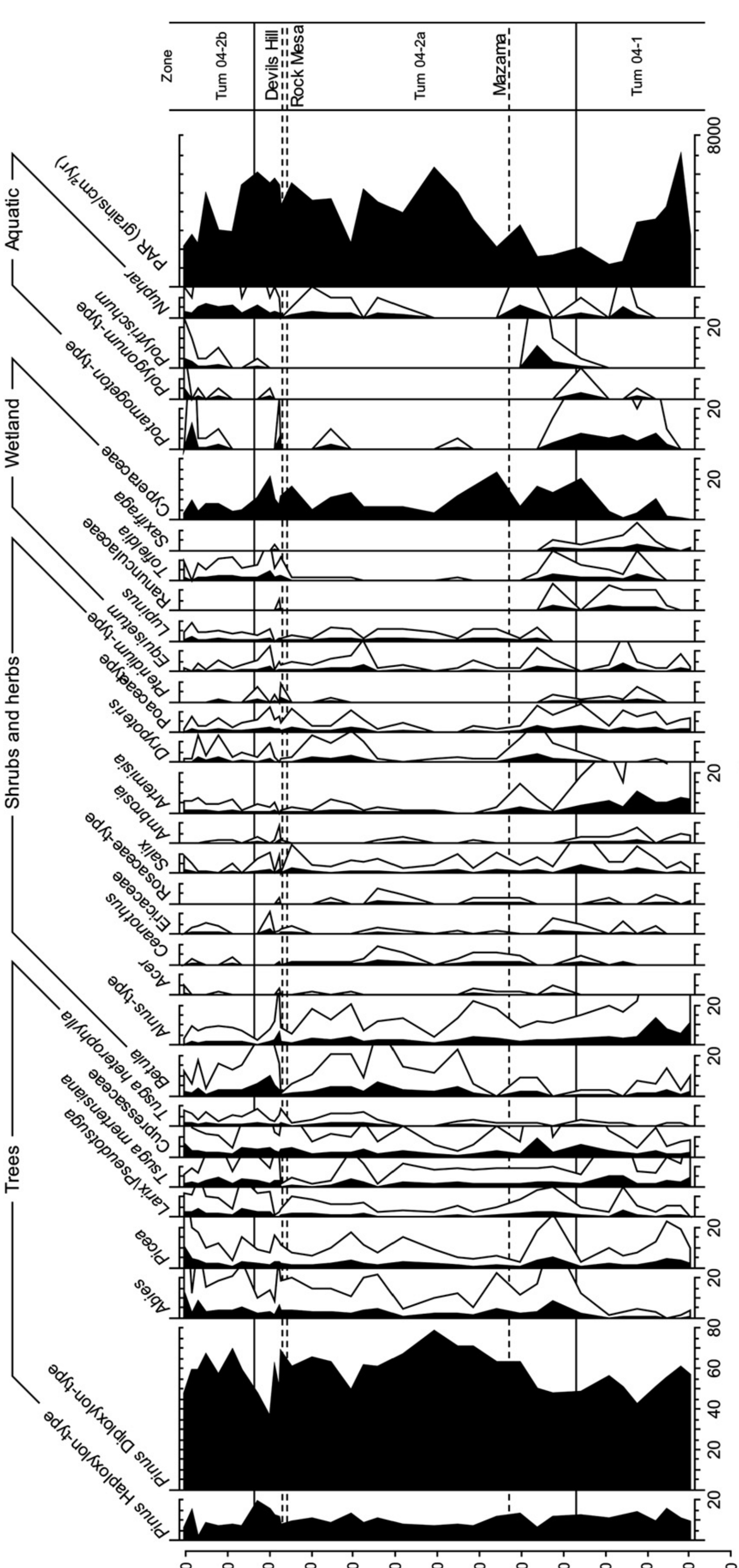

Figure 3. Pollen percentage rates for selected taxa from Tumalo Lake. The PAR curve represents the total pollen accumulation rate. Solid horizontal lines mark pollen-zone boundaries based on a constrained cluster analysis (CONISS; Grimm, 1987). Zone Tum 04-1 spans from 12,000 to 9200 cal yr BP, Sub zone Tum 04-2a spans from 9200 to 1650 cal yr BP, subzone Tum 04 2b spans from 1650 cal yr BP to the present. Open curves are 5× exaggerations of solid curves. Dashed lines represent stratigraphic locations of Mazama, Rock Mesa, and Devils Hill tephra deposits.

BP to present, shows a decline in haploxylon-type *Pinus* pollen an increase in *Abies* pollen over Tum 04-2a. The average PAR for this period is the lowest of the record at 3200 grains/cm^2/yr.

The pollen assemblage of Tum 04-1 points to a mixture of arboreal and nonarboreal communities by 12,000 cal yr BP following deglaciation. High *Pinus* and *Artemisia* percentages suggest an open forest. Higher-than-present percentages of Ranunculaceae and *Saxifraga* pollen also implies an open landscape with riparian habitat dominated by *Alnus*. *T. mertensiana* percentages greater than 3% in this zone suggest developed stands of subalpine forests upslope of the Tumalo Lake watershed (Minckley and Whitlock, 2000). Climate was likely drier than present during the time period represented by Tum 04-1.

In subzone Tum 04-2a, the decline in *Artemisia*, Ranunculaceae, *Saxifraga*, and *Alnus* pollen and the increase in *Abies* and *Betula* pollen indicate the development of an increasingly closed forest compared with that of zone Tum 04-1. This forest, still dominated by *P. contorta* and *P. ponderosa*, likely became more closed as *Abies* began to dominate mesic slopes. The pollen assemblage from zone Tum 04-2b suggests climate became wetter at Tumalo Lake. The continued increase in *Abies* and the decrease in haploxylon *Pinus* suggest a continued increase in effective moisture in the watershed. The similar PAR values between Tum 04-1 and Tum 04-2a and 2b imply a consistently forested landscape over the last 12,000 cal yr BP.

Long-term charcoal record

The CHAR record was divided into two zones, corresponding to the major pollen zones Tum 04-1 (12,000 to 9200 cal yr BP) and zone Tum 04-2a and 2b (from 9200 cal yr BP to present). The BCHAR values in zone Tum 04-1 show a general trend of increasing values (0.0002 to .007 particles cm^{-2} yr^{-1}) from 12,000 to 11,500 cal yr BP, followed by a more variable period from 11,500 to 9200 cal yr BP, in which BCHAR values ranged from 0.003 to .03 particles cm^{-2} yr^{-1}. Peak frequency during zone Tum 04-1 ranged from 2 to 11 fire episodes per 1000 yr, with highest fire-episode activity occurring between 10,000 and 9200 cal yr BP. Fire-episode intervals in zone Tum 04-1 averaged 160 yr (with 95% confidence intervals (CI) between 110 and 210 yr; $n=14$) (Fig. 4). In zones Tum 04-2a and 2b, BCHAR values increased from 0.004 particles cm^{-2} yr^{-1} at 9200 cal yr BP to 0.018 particles cm^{-2} yr^{-1} by ca. 7200 cal yr BP, and then subsequently averaged 0.016 particles cm^{-2} yr^{-1} (peaking at 0.320 particles cm^{-2} yr^{-1} at 1300 cal yr BP) before declining to present-day values of 0.005 particles cm^{-2} yr^{-1}. Peak frequency during zone Tum 04-2a and 2b declined from 10 to 5 fire episodes/1000 yr between 9200 and 8500 cal yr BP to between 4 and 6 fire episodes per 1000 yr from 8500 to 2000 cal yr BP. The highest rate of fire-episode frequency in zone Tum 04-2b, 8 fire episodes/1000 yr, occurred at 1400 cal yr BP, and then declined to present-day values of 3 fire episodes per 1000 yr. Fire-episodes intervals in zone Tum 04-2a and 2b averaged 210 yr (95% CI 180–240 yr; $n=45$) (Fig. 4).

Short-term vegetation and charcoal records

High-resolution pollen data surrounding the tephra deposits were summarized as percentages (Fig. 5) and pollen accumulation (PAR or pollen influx) rates for arboreal and nonarboreal taxa (Fig. 6). The first tephra deposit in zone Tum 04-2a, referred to as Mazama, was assigned a date of ca. 7670 cal yr BP (Zdanowicz et al., 1999) with contiguous 1-cm sampling intervals through the event and additional pollen samples spanning a 400-yr window before and after the event (i.e., from ca. 7780 to 7400 cal yr BP) with a sedimentation rate of 19 yr/cm. The second and third tephra deposits in this pollen zone, identified as the Rock Mesa and Devils Hill tephras, were assigned ages of 2440 and 2330 cal yr BP, respectively, also with contiguous 1-cm sampling through the events and additional pollen samples spanning approximately 450 yr, from 2550 to 2110 cal yr BP, with a sedimentation rate of 12 yr/cm.

The pollen percentage data associated with all three tephras reveal a decrease in nonarboreal vegetation immediately after tephra deposition (i.e., from 18% to 7% after Mazama, 18% to 16% after Rock Mesa, and 14% to 11% after Devils Hill (Fig 5)). Similarly, pollen accumulation rates show that nonarboreal pollen values declined by 29% after Mazama, 11% after Rock Mesa, and 9% after Devils Hill (Fig. 6). Post-Mazama nonarboreal pollen percentage and accumulation rate values did not return to pre-Mazama levels for approximately 80 yr after deposition of the tephras. Pollen percentage and

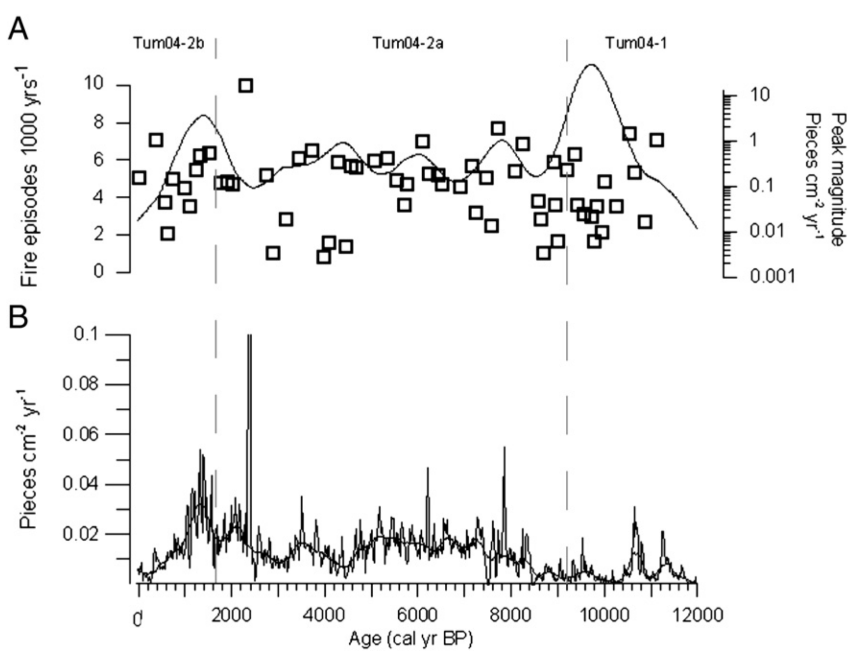

Figure 4. (A) Fire-episode frequency based on the number of peaks per 1000 yr. Boxes represent the total amount of charcoal associated with each peak. (B) Charcoal accumulation rates (CHAR) decomposed into 15-yr intervals with the background CHAR values determined using a lowess smoother with a 500-yr window width superimposed on the 15-yr CHAR values. Grey vertical lines represent the pollen zone boundaries Tum 04-1, Tum 04-2a, and Tum 04-2b.

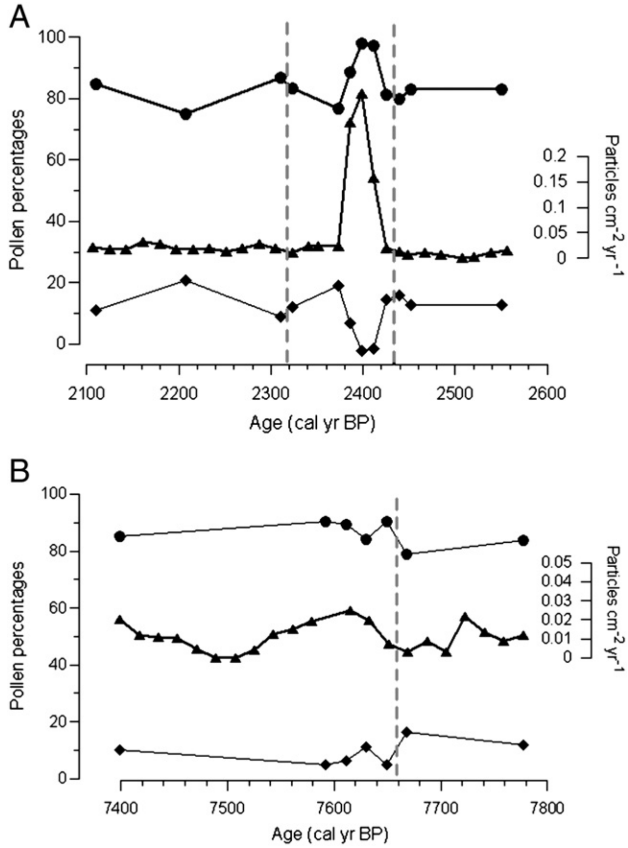

Figure 5. Arboreal (●) and nonarboreal (♦) pollen percentages and CHAR (▲) surrounding tephra deposits in the sediment core. Vertical dashed lines represent tephra deposits.

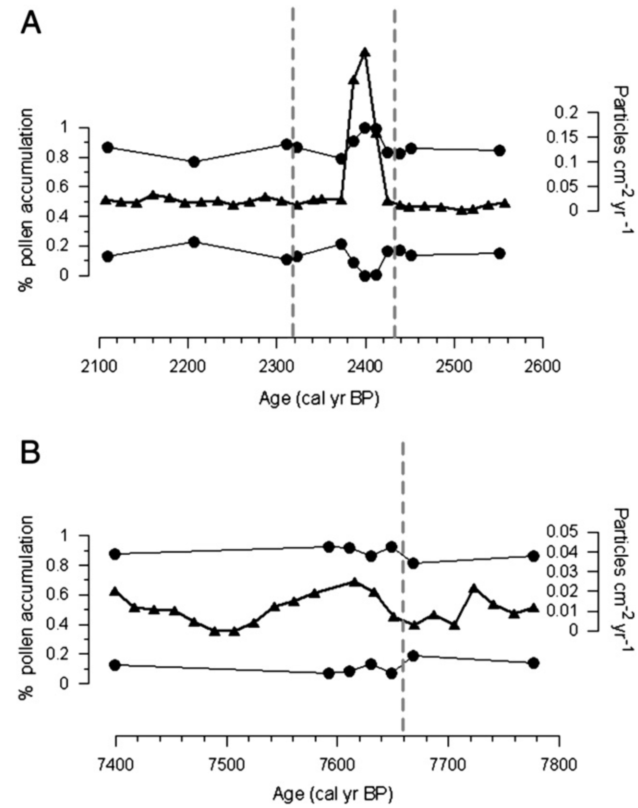

Figure 6. The percent of total pollen accumulation represented by arboreal (●) and nonarboreal (♦) pollen, and CHAR (▲) values surrounding tephra deposits in the sediment core. Vertical dashed lines represent tephra deposits.

accumulation rate values after the deposition of the Rock Mesa tephra suggest nonarboreal vegetation required around 70 yr to return to pre-Rock Mesa values. The pollen percentage and accumulate rates following Devils Hill tephra deposition indicate that nonarboreal values returned to pre-Devils Hill values between 20 and 100 yr after tephra deposition.

In comparing the charcoal record with the pollen data, the CHAR values surrounding Mazama varied between 0.004 and 0.025 particles/cm^2/yr, with a peak occurring at 7515 yr BP. CHAR values surrounding the Rock Mesa and Devils Hill tephras displayed similar patterns, ranging from 0.016 particles/cm^2/yr just before the deposition of the tephra, to 0.321 particles/cm^2/yr, and then declining to 0.018 particles/cm^2/yr (Fig. 5). CHAR values after the Rock Mesa tephra also identified a fire episode following the tephra deposition event.

Discussion

The 12,000-yr pollen and charcoal records from Tumalo Lake suggest a transition toward increasing arboreal vegetation and decreasing occurrence of fire in the watershed occurring at 9200 cal yr BP. This reorganization of the vegetation and fire regime was likely the result of large-scale changes in seasonal insolation patterns, driven by the occurrence of perihelion during the Northern Hemisphere summer at that time. Summer insolation was greater than present between 12,000 and 7000 cal yr BP, peaking around 9000 cal yr BP. General circulation model simulations suggest less effective moisture than present in the PNW during this period (Bartlein et al., 1998). The subsequent decline in seasonality since the early Holocene likely resulted in greater effective moisture in the PNW since 9000 cal yr BP (Thompson et al., 1993). From around 12,000 to 9200 cal yr BP, the forest around Tumalo Lake consisted of an open pine forest with *Artemisia* as a prominent understory species and *Alnus* occupying riparian areas. Fire episodes occurred more frequently than at present, on average every 160 yr, but did not produce abundant charcoal, which suggests smaller acreage burned or less available biomass to burn when compared with present. Tumalo Lake pollen data suggest a drier-than-present climate overall which matches well with evidence from other sites in the PNW that indicate lower-than-present effective moisture during the early Holocene (Whitlock and Bartlein, 1997; Whitlock et al., 2000).

Beginning at 9200 cal yr BP, the increase in *Abies* and a decrease in *Atremisia* in the watershed, along with the decline in fire-episode frequency suggests more mesic environmental conditions prevailed. The shift to longer fire episode intervals, averaging around 210 yr, during this period was significant, and implies that when fire episodes did occur there was likely higher fuel connectivity and/or more biomass available to burn, which resulted in generally high BCHAR values (Marlon et al., 2006). The relatively consistent nature of the pollen and CHAR records from 9200 cal yr BP to present suggest that the watershed has not experienced substantial oscillations in climate since 9200 cal yr BP. These findings are similar to those from Carp Lake, located on the eastern slopes of the Cascades ca. 120 km north of the Tumalo Lake watershed (Whitlock and Bartlein, 1997).

Low nonarboreal PAR values were observed following the Mazama deposition and can be linked to decreasing abundance of nonarboreal species. This response is similar to that seen within the tephra fall zone of the AD 1980 Mt. St. Helens eruption when arboreal and shrub communities expanded at the expense of herbaceous taxa (Antos and Zobel, 2005). The Mazama tephra was deposited during a period when forest understory composition was similar to present, which implies that processes of vegetation recovery to tephra deposition have been consistent for the last 7700 yr.

Mehringer et al. (1977), examining the effects of 7 cm of Mazama tephra in the Bitteroot Range of Idaho, found that there was no change

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in overall pollen abundance as a result of the tephra deposition. However, they did note short-lived annual-to-interannual changes in vegetation abundance but concluded that the tephra deposit was not a significant factor in changing vegetation composition. It is likely that the greater depth of tephra found at Tumalo Lake led to the decline in nonarboreal pollen. The peak in CHAR after the Mazama tephra was not of high magnitude and occurred during a period of relatively low CHAR in general (Fig. 4). The peak also occurred as nonarboreal vegetation was increasing and approximately 40–60 yr after the tephra deposition. Because of the delay after tephra fall, we suspect that this fire event was likely the result of characteristic fire-conducive weather conditions and not related to increased fuels as a result of vegetation mortality. Nonarboeral vegetation does decline after the peak in CHAR, suggesting that the post-Mazama fire may have slowed the recovery of herbs and shrubs to their pre-Mazama levels for several decades.

The response of vegetation to the deposition Rock Mesa tephra (2440 cal yr BP) is also complicated by the role of fire in altering vegetation composition and structure after the eruption event. The CHAR record associated with the Rock Mesa tephra suggests that a high-magnitude fire episode may have been triggered by increased fuel as a result of vegetation killed by the tephra deposition. The peak in CHAR occurred 20–30 yr after the tephra fall (i.e., after the deposition of 2 cm of sediment). A pulse of CHAR stratigraphically adjacent to the tephra would lend more weight to the assertion that the tephra deposition was a contributing factor to the fire (Walsh et al., 2008). The increase in arboreal taxa may reflect extra-local pollen deposition in the watershed. Forests around Tumalo Lake during this period were compositionally and structurally similar to those today and likely consisted of a mixture of closed and open forest stands. A fire episode, unrelated to the tephra deposition, could have by chance burned much of the local watershed while not affecting nearby forest stands and would have contributed to the higher arboreal counts and percentages during this time. However, the juxtaposition in time of the tephra deposition event and the large charcoal peak suggest a cause-and-effect relation.

Nonarboreal vegetation was least affected by the Devils Hill tephra. The response of vegetation may have been similar to that found by Mehringer et al. (1977) where recovery was relatively rapid. Nonarboeral pollen was at pre-tephra values within 100 yr and, with the absence of a fire during this time, likely approached pre-tephra values more quickly.

The pollen data surrounding the Mazama and Devils Hill tephra deposits suggest that the duration of forest vegetation recovery from tephra fall deposition ranged between 40 to 100 yr. Recovery from the Rock Mesa tephra fall and fire episode was closer to 100 yr and probably related to the severity of the fire episode within the watershed. Although fire severity is difficult to determine based on CHAR values alone, this particular fire episode had the highest CHAR value of the entire 12,000 yr CHAR record at Tumalo Lake, which suggests that a large amount of biomass was burned and deposited in a short time. The recovery of the vegetation over a time span of 80 to 100 yr is similar to the model of successional changes within grand fir forest communities after a high-severity fire (Agee, 1993). This pattern of response in the paleoenvironmental record of Tumalo Lake generates a hypothesis that may be testable using data from additional lake sediment records and future observations on the recovery of vegetation following the 1980 eruption of Mt. St. Helens.

Conclusions

The pollen and charcoal data from data from Tumalo Lake suggest that there was a fire-mediated transition from open *Pinus*- and *Atremisia*-dominated forests to *Pinus*/*Abies* forests around 9200 cal yr BP. Fire-episode frequency in these forests shifted from an average of one fire every 160 yr to an average of 210 yr after 9200 cal yr BP. The response of vegetation to tephra deposition over the last 7700 yr shows a recurrent pattern of change featuring an immediate decline in nonarboreal taxa after the tephra fall, followed by a recovery to the previous vegetation that lasts on the order of 40 to 100 yr. There is also evidence that fire episodes, possibly in conjunction with tephra fall events, provided a catalyst for short-term changes in the forest composition, but that recovery to predisturbance conditions occurred within 100 yr of the event. Our study indicates there were no permanent changes in forest composition as a result of tephra deposition and no consistent linkage between tephra deposition and fire episodes. This study also suggests that the trajectory of past vegetation recovery to tephra deposition at Tumalo Lake appears to be consistent with the ongoing response of vegetation to the AD 1980 Mt. St. Helens eruption (Antos and Zobel, 2005). However, the role of tephra fall events as a mechanism for vegetation change may be mediated by a rapidly changing climate and the relative availability of invasive seed sources following a disturbance. Despite the short-term impact that tephra deposition and fire episodes can have on forest composition, overall climate conditions likely have greater control on forest composition and structure.

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References

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, DC.
Antos, J.A., Zobel, D.B., 2005. Plant responses in forest of the tephra-fall zone. In: Franklin, J.F., Dale, V.H., Swanson, F.J., Crisafulli, C.M. (Eds.), Ecological Response to the 1980 Eruption of Mount St. Helens. Springer Science, New York, pp. 47–58.
Bartlein, P.J., Anderson, K.A., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb, R.S., Webb III, T., Whitlock, C., 1998. Paleoclimate simulations for North America over the past 21, 000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quaternary Science Reviews 17, 549–585.
Brunelle, A., Whitlock, C., 2003. Postglacial fire, vegetation, and climate history in the Clearwater Range, Northern Idaho, USA. Quaternary Research 60, 307–318.
Dale, V.H., Swanson, F.J., Crisafulli, C.M., 2005. Disturbance, survival, and succession: understanding ecological responses to the 1980 eruption of Mount St. Helens. In: Franklin, J.F., Dale, V.H., Swanson, F.J., Crisafulli, C.M. (Eds.), Ecological Response to the 1980 Eruption of Mount St. Helens. Springer Science, New York, pp. 3–11.
del Moral, R., Grishin, S.Y., 1999. Volcanic disturbances and ecosystem recovery. In: Walker, L.R. (Ed.), Ecosystems of Disturbed Ground. Ecosystems of the World 16. Elsevier, New York, pp. 137–160.
Faegri, K., Kaland, P.E., Krzywinski, K., 1989. Textbook of Pollen Analysis. Wiley, London.
Franklin, J.F., Dyrness, C.T., 1988. Natural Vegetation of Oregon and Washington. General Technical Report PNW-8. United States Department of Agriculture, Forest Service, Portland.
Gavin, D.G., Hu, F.S., Lertzman, K., Corbett, P., 2006. Weak climatic control of stand scale fire history during the late Holocene in southeastern British Columbia. Ecology 87, 1722–1732.
Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers and Geosciences 13, 13–35.
Hansen, H., 1942. The influence of volcanic eruptions upon post-Pleistocene forest succession in central Oregon. American Journal of Botany 29, 214–217.
Haruki, M., Tsuyuzaki, S., 2001. Woody plant establishment during the early stages of volcanic succession on Mount Usu, northern Japan. Ecological Research 16, 451–457.
Hebda, R.J., Whitlock, C., 1997. Environmental history. In: Schoonmaker, P.K., von Hagen, B., Wolf, E.C. (Eds.), The Rain Forests of Home: Profile of a North American Bioregion. Island Press, Washington, DC, pp. 227–256.
Higuera, P.E., Brubaker, L.B., Anderson, P.M., Hu, F.S., Brown, T.A., 2009. Vegetation mediated the impacts of postglacial climatic change on fire regimes in the south-central Brooks Range, Alaska. Ecological Monographs 79, 201–219.
Hotes, S., Poschlod, P., Takahashi, H., 2006. Effects of volcanic activity on mire development: case studies form Hokkaido, northern Japan. The Holocene 16, 561–573.

Long, C.J., Whitlock, C., Bartlein, P.J., Millspaugh, S.H., 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Canadian Journal of Forest Research 28, 774–787.
Marlon, J.R., Bartlein, P.J., Whitlock, C., 2006. Fire–fuel–climate linkages in the northwestern U.S. during the Holocene. The Holocene 16, 1059–1071.
Mehringer, P.J., Blinman, E., Petersen, K.L., 1977. Pollen influx and volcanic ash. Science 198, 257–261.
Millar, C.I., King, J.C., Westfall, R.D., Alden, H.A., Delany, D.L., 2006. Late Holocene forest dynamics, volcanism, and climate change at Whitewing Mountain and San Joaquin Ridge, Mono Count, Sierra Nevada, CA, USA. Quaternary Research 66, 273–287.
Minckley, T., Whitlock, C., 2000. Spatial variation of modern pollen in Oregon and southern Washington, USA. Review of Palaeobotany and Palynology 112, 97–123.
Mock, C.J., 1996. Climate controls and spatial variations of precipitation in the western United States. Journal of Climate 9, 1111–1115.
Mullineaux, D.R., 1996. Pre-1980 Tephra-Fall Deposits Erupted From Mount St. Helens, Washington: USGS Professional Paper 1563.
NRCS (National Resource Conservation Service) 2006. Instrumental weather data from SNOTEL stations in the western U.S. data archived at: http://www.wcc.nrcs.usda.gov.
Scott, W.E., Iverson, R.M., Schilling, S.P., Fisher, B.J., 2001. Volcano Hazards in the Three Sisters Region, Oregon. Open-file Report 99-437. U.S. Department of Interior, Vancouver.
Simkin, T., Seibert, L., 1994. Volcanoes of the World2nd Ed. Geosciences Press, Tucson.
Stuiver, M., Reimer, P.J., Braziunas, T.F., 1998. High-precision radiocarbon age calibration for terrestrial and marine samples. Radiocarbon 40, 1127–1151.
Thompson, R.S., Whitlock, C., Bartlein, P.J., Harrison, S.P., Spaulding, W.G., 1993. Climatic changes in the western United States since 18,000 yr BP. In: Wright Jr., H.E., Kutzbach, J.E., Ruddiman, W.F., Street-Perrott, F.A., Webb III, T., Bartlein, P.J. (Eds.), Global climates since the last glacial maximum. University of Minnesota Press, pp. 468–513.
Turner, M.G., Collins, S.L., Lugo, A.L., Magnuson, J.L., Rupp, T.S., Swanson, F.J., 2003. Disturbance dynamics and ecological response: the contribution of long-term ecological research. BioScience 53, 46–56.
Walsh, M.K., Whitlock, C., Bartlein, P.J., 2008. 14,300-year-long record of fire–vegetation–climate linkages at Battle Ground Lake, southwestern Washington. Quaternary Research 70, 251–264.
Whitlock, C., Bartlein, P.J., 1997. Vegetation and climate change in Northwest America during the past 125 kyr. Nature 388, 59–61.
Whitlock, C., Larsen, C., 2001. Charcoal as a fire proxy. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments: Vol. 3. Terrestrial, Algal, and Siliceous Indicators. Kluwer Academic Publishers, Dordrecht, pp. 75–98.
Whitlock, C., Sarna-Wojcicki, A.M., Bartlein, P.J., Nickmann, R.J., 2000. Environmental history and tephrostratigraphy at Carp Lake, southwestern Columbia Basin, Washington, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 155, 7–29.
Wright Jr., H.E., Mann, D.H., Glaser, P.H., 1983. Piston cores for peat and lake sediments. Ecology 65, 657–659.
Zdanowicz, C.M., Zuekubsju, G.A., Germani, M.A., 1999. Mount Mazama eruption: calendrical age verified and atmospheric impact assessed. Geology 27, 621–624.