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Environmental history and tephrostratigraphy at Carp Lake, southwestern Columbia Basin, Washington, USA

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Abstract

Sediment cores from Carp Lake provide a pollen record of the last ca. 125,000 years that helps disclose vegetational and climatic conditions from the present day to the previous interglaciation (120–133 ka). The core also contained 15 tephra layers, which were characterised by electron-microprobe analysis of volcanic glass shards. Identified tephra include Mount St. Helens Ye, 3.69 ka; Mazama ash bed, 7.54 ka; Mount St. Helens layer C, 35–50 ka; an unnamed Mount St. Helens tephra, 75–150 ka; the tephra equivalent of layer E at Pringle Falls, Oregon, <218 ka; and an andesitic tephra layer similar to that at Tulelake, California, 174 ka. Ten calibrated radiocarbon ages and the ages of Mount St. Helens Ye, Mazama ash, and the unnamed Mount St. Helens tephra were used to develop an age–depth model. This model was refined by also incorporating the age of marine oxygen isotope stage (IS) boundary 4/5 (73.9 ka) and the age of IS-5e (125 ka). The justification for this age-model is based on an analysis of the pollen record and lithologic data. The pollen record is divided into 11 assemblage zones that describe alternations between periods of montane conifer forest, pine forest, and steppe. The previous interglacial period (IS-5e) supported temperate xerothermic forests of pine and oak and a northward and westward expansion of steppe and juniper woodland, compared to their present occurrence. The period from 83 to 117 ka contains intervals of pine forest and parkland alternating with pine–spruce forest, suggesting shifts from cold humid to cool temperate conditions. Between 73 and 83 ka, a forest of oak, hemlock, Douglas-fir, and fir was present that has no modern analogue. It suggests warm wet summers and cool wet winters. Cool humid conditions during the mid-Wisconsin interval supported mixed conifer forest with Douglas-fir and spruce. The glacial interval featured cold dry steppe, with an expansion of spruce in the late-glacial. Xerothermic communities prevailed in the early Holocene, when temperate steppe was widespread and the lake dried intermittently. The middle Holocene was characterised by ponderosa pine forest, and the modern vegetation was established in the last 3900 yr, when ponderosa pine, Douglas-fir, fir, and oak were part of the local vegetation.

Keywords: Quaternary palaeoclimates; last interglacial; Pacific Northwest; Quaternary vegetation history

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1. Introduction

Palaeoclimatic research in the western U.S. has largely focused on the last 21,000 yr, from the last glacial maximum (LGM) to the present day. As a result, the climate histories of the Pacific Northwest (PNW), the American Southwest, and the Rocky Mountains are reasonably well known for this time period (Thompson et al., 1993). Taken as a whole, the network of sites with palaeoclimatic data displays coherent broad-scale patterns of climate change that can be explained in light of large-scale changes in the climate system. Important among these large-scale controls have been orbital-scale variations in the seasonal cycle of insolation, the size of the ice sheet, sea-surface temperatures, and atmospheric CO_2. These components have affected regional climates directly through changes in temperature and effective moisture and indirectly by shifting the position of storm tracks, the intensity of onshore flow, and strength of the subtropical high-pressure system.

In contrast, our understanding of the regional response to large-scale changes in climate prior to the LGM is known from relatively few records. A pollen record from Carp Lake (Lat. 45°55′N, Long. 120°53′W, altitude 714 m) in the southwestern Columbia Basin of Washington (Fig. 1) provides a rare opportunity to examine late Quaternary environments back to the previous interglaciation. A 33,000-year long record was described by Barnosky (1985a). A longer record spanning the last 125 ka showed that the pollen variations at Carp Lake compared closely with those in the marine oxygen isotope record (Whitlock and Bartlein, 1997). In this paper, (1) we describe the pollen record and vegetational history that was the basis for Whitlock and Bartlein (1997), (2) characterise the tephra layers in the core based on microprobe analyses and discuss how these identifications affect the chronology, and

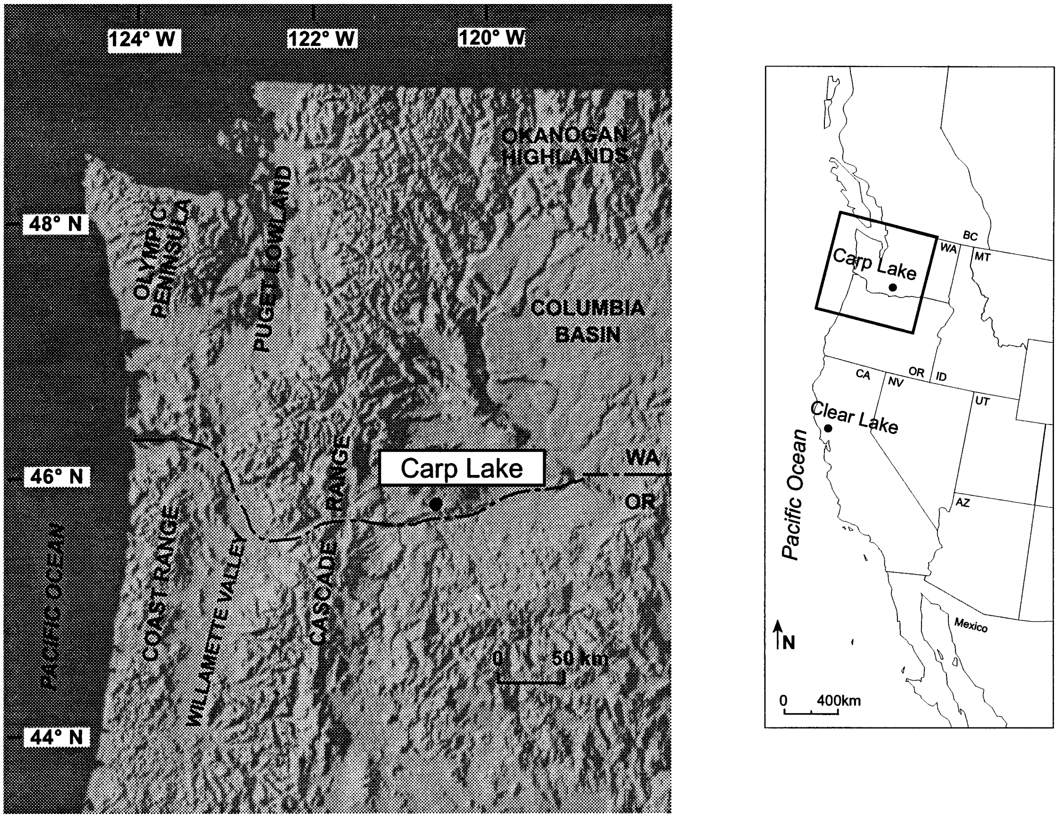

Fig. 1. Location of Carp Lake and Clear Lake.

(3) present a regional environmental history based on Carp Lake and other Pacific Northwest records.

Carp Lake lies 15 km north of Goldendale within a volcanic crater in the Simcoe volcanic field of Early Pleistocene age (Hammond, 1980). The lake covers 11 ha and a drainage area of less than 50 ha. The crater is isolated from the rest of the Columbia Basin by the Horse Heaven Hills, which reach an altitude of 1000 m to the north, and the Columbia River Gorge, a canyon 460 m deep to the south.

Carp Lake lies within the *Pinus ponderosa* Zone (600–1200 m) of Franklin and Dyrness (1988). *P. ponderosa* (ponderosa pine), *Pseudotsuga menziesii* (Douglas-fir), and a few *Pinus contorta* (lodgepole pine), *Juniperus communis* (common juniper), and *Abies grandis* (grand fir) grow within the crater. Deciduous shrubs near the lake include *Alnus rhombifolia* (white alder) and *A. sinuata* (Sitka alder) in the wettest areas; *Acer glabrum* (Rocky Mountain maple), *Corylus cornuta* (western hazel), *Ceanothus prostratus* (squaw carpet), *C. velutinus* (varnishleaf ceanothus), and *C. sanguineus* (redstem ceanothus). *Populus trichocarpa* (black cottonwood), *Salix* spp. (willow), *Holodiscus discolor* (creambush oceanspray), *Spiraea betulifolia* (shinyleaf spirea), *Amelanchier alnifolia* (Saskatoon serviceberry), *Berberis repens* (western barberry), and *Arctostaphylos uva-ursi* (kinnikinnick) grow on moist soils. *Purshia tridentata* (bitterbrush) and *Artemisia tridentata* (bigleaf sagebrush) are present in forest openings on dry substrate. The lake is bordered by *Typha latifolia* (broad leaved cat-tail), *Carex* spp. (sedge), *Juncus* spp. (rush), *Mentha arvensis* (field mint), and the moss *Drepanocladus sendtneri*. A continuous mat of *Brasenia schreberi* (water-shield) covers the water surface. (Botanical nomenclature follows Hitchcock and Cronquist, 1973.)

Montane forests typical of the *Pseudotsuga menziesii* and *Abies grandis* Zones are found between 1200 and 1500 m elevation in the eastern Cascade Range of southern Washington (Franklin and Dyrness, 1988). Included in these forests are *Pseudotsuga menziesii*, *Abies grandis*, *Pinus ponderosa*, *Pinus monticola* (western white pine), and *Larix occidentalis* (western larch). More humid regions support *Tsuga heterophylla* (western hemlock) and *Thuja plicata* (western red cedar). Subalpine forest and parkland of *Abies lasiocarpa* (subalpine fir), *Picea engelmannii* (Engelmann spruce), *Tsuga mertensiana* (mountain hemlock), and *Pinus albicaulis* (whitebark pine) occur between 1500 and 2000 m elevation and are succeeded by alpine tundra on the highest peaks. To the east, steppe vegetation dominated by *Artemisia tridentata* and bunch grass extends across most of the Columbia Basin. A well-defined ecotone between forest and steppe lies about 5 km south and east of Carp Lake and is clearly delineated by a band of *Quercus garryana* (Oregon white oak).

The climate in the Carp Lake area is generally cool and wet in winter and warm and dry in summer. Mean annual precipitation is about 510 mm, whereas the adjacent steppe receives less than 250 mm/yr. Meteorologic data collected from 1910 to 1970 indicate that average January temperatures are slightly below freezing; mean July temperatures range between 18° and 21°C. The growing season averages 260 days (Brown, 1979).

The southwestern Columbia Basin lies beyond the limit reached by either alpine or continental glaciers during the Late Pleistocene Fraser Glaciation (25,000–10,000 ^{14}C yr B.P.; Waitt and Thorson, 1983). The Columbia Basin was affected by glacial outburst floods that discharged from Glacial Lake Missoula in northwestern Montana, swept across the Channeled Scabland east of the study area, and drained southward and then westward down the Columbia River Gorge (Baker and Bunker, 1985). A large flooding episode occurred in latest Pleistocene time (Waitt, 1985; Atwater, 1986), although waters never reached the elevation of Carp Lake. McDonald and Busacca (1988) suggest that Scabland floods also occurred in pre-late Wisconsin time.

2. Methods

The last ca. 33,000 years at Carp Lake was described by Barnosky (1985a) from a 6.8-m-long pollen record (Core 85). The maximum water depth then was 2.0 m. A 20.19-m-long core was obtained in 1990 (Core 90) with a modified 5-cm-diameter Livingstone piston sampler (Wright et al., 1983) taken from an anchored platform in the centre of the lake in 1.3 m of water. A 23.13-m-long core (Core 93) was later collected with a truck-mounted drilling rig on a barge, when the water depth had dropped to 0.65 m. For Core 93, a Gus drilling rig was used to obtain the top 17.13 m of sediment, below that a California sampler was used to a depth of 23.15 m (Wing et al., 1995). Core 93 was used only to extend the record beyond that obtained in Core 90. The base of the sedimentary record at Carp Lake has yet to be reached.

Core sections were sliced longitudinally, photographed, and described in the laboratory. One cubic-centimetre samples were taken at regularly spaced core intervals to determine the percent organic content and percent carbonate content by weight (Dean, 1974). Samples of 1-cm^3 volume were taken every 10 cm for pollen analysis. 196 samples were prepared with standard palynological methods (Cwynar et al., 1979; Faegri et al., 1989). Pollen samples were mounted in silicon oil and examined at magnifications of 400 and 1000×.

At least 350 terrestrial pollen and spores were tallied for each stratigraphic level, except in two cases where pollen concentration was extremely low. *Pinus* pollen with intact distal membranes was separated into Diploxylon- and Haploxylon-types. Diploxylon-type was attributed to ponderosa pine or lodgepole pine based on present-day biogeography, and Haploxylon-type was assigned to either western white pine or whitebark pine. Pine grains that lacked a visible distal membrane were identified as *Pinus* undifferentiated, but they were assumed to represent Diploxylon-type and Haploxylon-type in the same proportion as the identifiable pine grains.

The pollen of *Pseudotsuga* and *Larix* (larch) are indistinguishable. Based on the predominance of Douglas-fir in the middle-elevation forests of the eastern Cascades, the *Pseudotsuga*/*Larix* pollen is generally attributed to Douglas-fir; although pollen may have also come from western larch or subalpine larch, especially during cold periods. *Alnus rhombifolia*-type includes pollen of white alder and red alder (*A. rubra*). White alder grows near the site today in riparian areas and would be expected whenever ponderosa pine forest was present in the past. Red alder is more typical of mesic environments and is found generally west of the Cascade crest. *Alnus sinuata*-type pollen is attributed to Sitka alder, which generally grows at higher elevations. Grains that were poorly preserved, hidden, or deteriorated beyond recognition were tallied as Indeterminate. Grains that were unfamiliar to the analysts were tallied as Unknown. Pre-Quaternary pollen types include *Carya*, *Juglans*, *Pterocarya*, *Liquidambar*, and *Ulmus*/*Zelkova*, which are believed to have gone extinct during the middle Tertiary (Leopold and Denton, 1987).

Percentages of trees, shrubs, herbs, and upland pteridophytes were calculated based on the sum of terrestrial pollen and spores. Percentages of aquatic taxa (excluding *Pediastrum* and *Isoetes*) were based on a denominator of terrestrial and aquatic taxa. *Pediastrum* and *Isoetes* were calculated based on the total terrestrial and aquatic palynomorphs, including *Pediastrum* and *Isoetes*. Pre-Quaternary pollen percentages were based on a sum that included all terrestrial and aquatic palynomorphs and pre-Quaternary taxa.

The pollen diagram was divided into eleven pollen assemblage zones using a constrained incremental sum of squares (CONISS) method (Grimm, 1988). These zones are site-specific and used to identify past vegetation types in the Carp Lake region. Zones CL-1 through CL-4 are generally equivalent to Zones C-1 through C-4 described in Barnosky (1985a). In the discussion that follows, scientific names are used for pollen taxa, while common names are reserved for the plants they represent.

Ratios of particular pollen types were helpful in reconstructing broad characteristics of the vegetation (Mehringer and Wigand, 1990; Whitlock and Bartlein, 1997). Ratios were plotted on a logarithmic (base 10) scale, as is appropriate for compositional data, such as pollen relative abundance data. Smooth (Lowess) curves (Cleveland, 1993) were added to plots of the ratios to emphasise the long-term variations. A ratio of the sum of the percentages of *Pseudotsuga*/*Larix*, *Quercus* and Cupressaceae to *Picea* (Pse + Que + Cup/Pic) provides a comparison of forest type, which is a proxy for relative elevation, temperature, and effective moisture. The pollen of *Pseudotsuga*, Cupressaceae and *Picea*, in particular, are not transported long distances (unlike that of *Pinus*) (Whitlock, 1993; Minckley, 1999). High values indicate warm xeric conditions, typical of present-day low elevations where Douglas-fir, Oregon white oak, and juniper are abundant. Low values are periods when Engelmann spruce is abundant and the climate is cool and mesic. A ratio of total arboreal to nonarboreal pollen (AP/NAP) provides an index of forest cover. High values indicate closed forest; low values imply periods of either tundra or steppe.

3. Lithology and chronology

Stratigraphic depths in Core 85 and Core 93 were adjusted to the 1990 water depth of 1.30 m, and this depth below water surface was used as datum (Table 1). Core 90 was the primary core used for the analyses to a depth of 19.90 m. Analysis of lowest part of the record (19.90–23.15 m depth) was based on Core 93.

From 1.30 m (mud–water interface) to 2.06 m depth was a *Brasenia* peat, similar to sediments deposited under the present water-lily mat. The organic content of this unit ranged from 27 to 41% and the carbonate content was <1.3%. From 2.06 to 3.82 m depth was a unit of interbedded peat and organic silt. The peat layers ranged from 1 to 30 cm thick, were composed of *Drepanocladus sendtneri*, and had an organic content of 48–56%. The silt layers were 1 to 25 cm thick and probably deposited in a lacustrine environment. Their organic content was between 4 and 37%. This unit suggests a period of fluctuating water level that allowed a wetland to occupy the basin some of the time and a lake at other times. From 3.82 to 5.82 m depth was a clayey silt with occasional root casts and basalt pebbles and <6.8% organics. The upper part of the unit correlated with Unit 4 of Barnosky (1985a). The lithology suggests a period of wetland or marsh sedimentation. From 5.82 to 16.93 m depth, the core consisted of a silty clay with fine sand. At intervals (13.85–14.18 m, 14.63–14.89 m, 15.55–15.89 m, and 16.67–16.93 m depth) the silty clay was crumbly and contained scattered basaltic pebbles. The organic content was 3 to 18.3%. The rest of the unit had low organic content (<6.8%). The interval from 16.93 to 19.62 m depth was characterised by high clay and a moderate organic content of 6–20% that implies lacustrine conditions. The stratigraphically lowest lithologic unit, from 19.62 to 23.42 m depth, was a silty clay with as much as 31% organics; the lithology suggests a deeper, more productive lake.

Radiocarbon years were converted to calendar years by use of the CALIB 3.0 program for the last 20,000 ^{14}C yr B.P. (Stuiver and Reimer, 1993), the U–Th calibration of Bard et al. (1990) for ages between 20,000 and 30,000 ^{14}C yr B.P., and the implications of the geomagnetic record described by Mazaud et al. (1991) for the period from 30,000 to 50,000 ^{14}C yr B.P. Hereafter, calibrated (or calendar) ages are presented as thousands of yr ago or ka. Conversion to calendar yr (ka) is necessary to compare the Carp Lake record with calendar year variations in insolation and the SPECMAP marine oxygen isotope record (where the most of the chronology is tuned to the insolation variations; Imbrie et al., 1984).

Sixteen radiocarbon ages were obtained from Carp Lake. The ages from Core 85 were combined with those from Core 90 by stratigraphic correlation, tephrochronology, and adjustments for water depth. One date, $28,110 \pm 990$ ^{14}C yr B.P. (Beta-57040) at 16.30–16.40 m depth, was out of sequence and considered anomalously young. Two dates, $32,760 \pm 420$ ^{14}C yr B.P. (Beta-57037) and $33,720 \pm 830$ ^{14}C yr B.P. (Beta-57038), from Core 90 overlap in age despite the fact that they came from core segments that are 2.35 m apart. Apparently, sedimentation during this interval was rapid, and neither date was used in favour of a radiocarbon date of $32,700 \pm 450$ ^{14}C yr B.P. (QL-1603) from Core 85. The lowest radiocarbon date, >44,000 ^{14}C yr B.P. (Beta-57041), lies beyond the age range of radiocarbon dating and was not used.

The identification of tephra layers in the cores was based on electron-microprobe analysis of glass shards (Table 2). Some relatively widespread tephra layers from Mount St. Helens (MSH) were not found at Carp Lake (e.g., layers T, We, and set S), and at least two tephra were from otherwise unknown eruptions. Carp Ash-1 (2.15–2.16 m depth) and Carp Ash-2 (2.29–2.31 m depth) were analysed chemically and identified as Mount St. Helens Ye. Carp Ash-3 (3.64–3.68 m depth) is the Mazama ash bed and assigned an age of ca. 6730 ^{14}C yr B.P. (Hallet et al., 1997). Carp Ash-4 (6.50–6.52 m depth) is a hitherto unknown tephra layer. Carp Ash-5 (9.51–9.85 m depth) is assigned to MSH layer C (either Cw or Cy) with an age range of 35 to 50 ka (Mullineaux, 1986; Berger, 1991). Carp Ash-6 (12.71–12.75 m depth) and Carp Ash-7 (17.17–17.19 m depth) lack vitrified glass and could not be identified.

Table 1
Radiocarbon ages and tephra information, Carp Lake

Core	Depth[a] (m)	Uncalibrated ^{14}C age (yr B.P.)	Calibrated ^{14}C[b] (ka)	Lab No./ Tephra	Comments
Core 85	3.10–3.20	5,820 ± 50	6.67	QL-1640	
	3.70–3.77	8,760 ± 40	9.75	WIS-1460	Base of Lithologic Unit 2
	3.82–3.92	9,470 ± 100	10.47	WIS-1468	Top of Lithologic Unit 3
	4.46–4.56	9,730 ± 400	10.96	QL-1641	Correlated by depth
	5.61–5.71	16,050 ± 400	18.93	QL-1642	Correlated by depth
	6.10–6.20	18,190 ± 100	21.73	QL-1603	Correlated by depth[c]
	6.76–6.86	21,100 ± 400	24.71	QL-1643	Correlated by depth
	7.30–7.40	21,040 ± 400	24.65	QL-1644	Correlated by depth[c]
	8.30–8.40	26,200 ± 200	29.59	QL-1646	Correlated by depth
	9.10–9.20	32,700 ± 450	35.00	QL-1603	Correlated by depth[c]
Core 90	2.15–2.16	3,450 ± 450	3.69	Carp Ash-1	Mt. St. Helens Ye (Mullineaux, 1986)
	2.29–2.31	3,450 ± 450	3.69	Carp Ash-2	Mt. St. Helens Ye (Mullineaux, 1986)
	3.64–3.68	6,730 ± 40	7.54	Carp Ash-3	Mazama ash bed (Hallet et al., 1997)
	6.15–6.25	19,790 ± 190	23.45	Beta-57036	
	6.50–6.52			Carp Ash-4	Unknown eruption
	9.25–9.35	32,760 ± 420	35.00	Beta-57037	
	9.51–9.85	35,000–50,000		Carp Ash-5	Mt. St. Helens layer C (Mullineaux, 1986; Berger, 1991)[c]
	11.50–11.60	33,720 ± 830	36.00	Beta-57038	
	12.71–12.75			Carp Ash-6	Unidentified, no glass
	13.95–14.05	40,290 ± 2,200	42.00	Beta-57039	Rejected as too young[c]
	16.20–16.40	28,110 ± 990		Beta-57941	Rejected as too young[c]
	17.17–17.19			Carp Ash-7	Unidentified; no glass
	18.57–18.64			Carp Ash-8	Mt. St. Helens, like layer C
	19.06–19.07			Carp Ash-9	Mt. St. Helens, like layer C
	19.11–19.50; 19.73–19.80	ca. 100,000		Carp Ash-10	= unnamed tephra layer in Palouse Fm, Washington (Busacca et al., 1992)
	19.99–20.22	>44,000		Beta 57041	
	20.18–20.185			Carp Ash-11	Unknown eruption
Core 93	19.91–19.915			Carp Ash-12	Unidentified, no glass
	20.065–20.07			Carp Ash-13	Similar to Carp Ash-11
	20.99–20.995		<218 ± 10	Carp Ash-14	= tephra layer E at Pringle Falls, Oregon (Herrero-Bervera et al., 1994)[c]
	22.18–22.20		174 ± 41; or <190	Carp Ash-15	= andesitic tephra layer at Tulelake, California (Herrero-Bervera et al., 1994); layer KK at Summer Lake, Oregon (Negrini et al., 1994)[c]

See Table 2 for electron microprobe data used to infer tephra layers.
[a] Depths in Core 85 and Core 93 have been adjusted to match correlative depths in Core 90; 0.65 cm was added to depths of Core 85 to provide equal depths in Core 90; Core 93 was correlated by the stratigraphic positions of Ash-10, -11, and -13.
[b] Calibration is based on Bard et al. (1990), Mazaud et al. (1991) and Stuiver and Reimer (1993).
[c] Not used in age models (see Fig. 2).

Carp Ash-8 (18.57–18.64 m depth) and Carp Ash-9 (19.06–19.07 m depth) are very similar to the MSH layer C layers and layers like these have apparently been misidentified as MSH C at other localities (unpublished data; Davis, 1985). Carp Ash-8 and -9 are obviously much older than MSH set C [= Carp Ash-5], and it may be noteworthy that they have less MgO than the type MSH set C and are more hydrated by 2–3%. These ashes (Carp Ash-5, -8, and -9) are present for the first time in superposition at Carp Lake, and because of the apparent uncertainty in age assignment they were not used in the age model.

The chemistry of Carp Ash-10 (19.11–19.50 and 19.73–19.80 m depth) matches that of an unnamed MSH tephra found in the Palouse Formation of Washington (Busacca et al., 1992) and Thatcher Basin of Idaho (Bouchard et al., 1998). In the Palouse section, two soil horizons occur between the unnamed ash layer and an overlying Early Mount St. Helens ash (dated at ca. 80 ka), the oldest of which has a thermoluminescence (TL) age of ca. 83 ± 8 ka (Berger and Busacca, 1995). Extrapolation from these dates suggests that the unnamed ash in the Palouse Formation and Carp Ash-10 were deposited between ca. 90 and 110 ka. Berger and Busacca (1995) recently inferred an age of 125 ka based on extrapolation of TL dates on MSH layer C. Bouchard et al. (1998) assume an age of 110 ka for the Carp Ash-10 equivalent. Carp Ash-11 (20.18–20.19 depth in Core 90) is from an unknown eruption.

Carp Ash-12 (19.91–19.915 m depth), Carp Ash-13 (20.065–20.07 m depth), Carp Ash-14 (20.99–20.995 m depth), and Carp Ash-15 (22.18–22.20 m depth) are present in Core 93. Carp Ash-12 is an unidentifiable tephra with altered glass. Carp Ash-13 is a crystal-vitric ash layer of unknown source, similar to Carp Ash-11 except for slight differences in MgO (Table 2). The stratigraphic position of Carp Ash-11 and -13 are the basis for correlating Cores 90 and 93. Carp Ash-14 and -15 match in composition a set of tephra layers referred to as the 'Orange' ash beds that have been identified at Pringle Falls, central Oregon (Herrero-Bervera et al., 1994), Summer Lake, central Oregon (Davis, 1985), Tulelake, northern California (Rieck et al., 1992), Walker Lake, central Nevada (Herrero-Bervera et al., 1994), and Mono Lake, central California (Herrero-Bervera et al., 1994). Age assignments based on magnetostratigraphy at Pringle Falls place the age of Carp Ash-14 as <218 ka (Herrero-Bervera et al., 1994). Carp Ash-15 matches an andesitic ash at Tulelake, which is dated at 171 ± 43 ka (Herrero-Bervera et al., 1994) and layer KK at Summer Lake, dated at <190 ka (Negrini et al., 1994).

A preliminary age-vs.-depth model was developed using a third-order polynomial regression on ten radiocarbon ages and the reported ages of St. Helens Ye and Mazama ash, and an estimated age of 100 ka for Carp Ash-10 (Model 1, Fig. 2). In this regression, we ignore the age assignments for Carp Ash-14 and -15, a decision we justify based on evaluation of the pollen stratigraphy, its palaeoenvironmental implications, and the lithologic information (see Section 5.3). Our preferred chronology suggests that the record extends back to the previous interglaciation, marine oxygen isotope stage (IS) 5. Extrapolation of the Model 1 regression placed the upper age of the lowest pollen zone at 125 ka, which fits its character as an interglacial assemblage. Moreover, the pollen zone boundaries at Carp Lake match well with the marine oxygen isotope stage boundaries. On the assumption that the bottom pollen assemblage was deposited during IS-5e, as implied by Model 1, the chronology was fine-tuned by including the age of the marine oxygen isotope stage (IS) 4/5 boundary (73.9 ka), and the age of the peak of IS-5e (125 ka) into the third-order polynomial regression (Model 2, Fig. 2). Model 2 was used to assign the ages of the pollen zones. We recognise, however, that if the identification of the two lowermost tephra layers is correct, the Carp Lake record is considerably older and more discontinuous than we propose here.

4. Results

The pollen stratigraphy is described in Table 3 and shown in Fig. 3. Because a longer sedimentary record may eventually be recovered from the site, zone numbering starts at the top of the core, following Barnosky (1985a). Vegetational interpretations for each zone are summarised below.

Zone CL-1 (0–9.1 ka; 1.30–3.71 m depth). This zone is dominated by Diploxylon-type *Pinus*, with lesser amounts of *Pseudotsuga*/*Larix*, *Tsuga hetero-*

Table 2
Electron microprobe analysis of volcanic glass shards from tephra layers in cores from Carp Lake and comparative data for shards of correlative or chemically similar tephra layers of the northwestern U.S.[a]

Ash *No. of shards*	Lab No.	SiO_2 ±sd[b]	Al_2O_3 ±sd	Fe_2O_3 ±sd	MgO ±sd	MnO ±sd	CaO ±sd	TiO_2 ±sd	Na_2O ±sd	K_2O ±sd	Total (O) ±sd	Total (R)
MSH layer Ye												
Carp Ash-1 (major)	T-279-1	75.73	14.12	1.36	0.34	0.04	1.61	0.23	4.32	2.24	100.49	99.99
$n = 13$		0.71	0.23	0.09	0.02	0.02	0.06	0.04	0.10	0.08	0.82	
MSH (Ye713721)[c]	T3,4	75.89	14.01	1.34	0.35	0.05	1.67	0.18	4.36	2.15	96.96	100.00
$n = 10–15$		na	na	na	na	na	na	na	na	na	na	
Carp Ash-1 (hi Fe, lo Ca)	T279-1	75.68	13.87	1.40	0.34	0.04	1.47	0.22	4.67	2.32	98.77	100.01
$n = 7$		0.83	0.24	0.07	0.04	0.04	0.12	0.04	0.08	0.05	0.85	
Carp Ash-2 (major)	T281-3	75.98	14.32	1.25	0.34	0.04	1.65	0.14	4.15	2.13	97.67	100.00
$n = 13$		0.79	0.46	0.08	0.04	0.02	0.09	0.04	0.15	0.09	1.13	
MSH Ye (10/70)[c]	T5-3	75.66	14.52	1.32	0.34	0.03	1.68	0.13	4.16	2.06	96.38	100.00
$n = 10–15$		na	na	na	na	na	na	na	na	na	na	
MSH Ye (8/93)	T5-3	76.12	14.40	1.25	0.34	0.05	1.72	0.16	3.85	2.11	97.54	100.00
$n = 6$		0.17	0.34	0.06	0.02	0.02	0.05	0.02	0.40	0.04	0.80	
Mazama ash bed												
Carp Ash-3	T279-2	72.76	14.60	2.04	0.46	0.06	1.49	0.43	5.48	2.68	97.87	100.00
$n = 12$		0.95	0.26	0.10	0.04	0.02	0.06	0.06	0.10	0.08	1.22	
Mazama Ash (avg. 94)		72.81	14.64	2.13	0.45	0.05	1.60	0.43	5.19	2.70	na	100.01
$n = \sim1400$		0.35	0.23	0.04	0.02	0.01	0.06	0.02	0.18	0.08		
No close matches												
Carp Ash-4	T279-3	77.74	12.89	0.88	0.13	0.03	0.97	0.10	4.22	3.04	96.20	100.00
$n = 15$		1.29	0.29	0.05	0.02	0.03	0.11	0.03	0.19	0.15	1.54	
MSH layer C												
Carp Ash-5 (bulk)	T279-4	76.54	13.83	0.97	0.26	0.03	1.58	0.10	4.34	2.41	95.13	99.99
$n = 15$		1.57	0.29	0.07	0.01	0.02	0.07	0.03	0.16	0.11	2.14	
MSH Cw (8/93)[d]	T5-11	76.81	14.03	0.91	0.27	0.03	1.66	0.12	3.92	2.24	96.10	99.99
$n = 6$		1.12	0.19	0.03	0.02	0.02	0.10	0.02	0.21	0.04	1.52	
MSH CwSH (10/70)[c]		76.89	13.66	0.94	0.26	0.03	1.69	0.10	4.12	2.30	94.11	100.01
$n = \sim10–15$		na	na	na	na	na	na	na	na	na	na	
MSH Cy[c]	T32-5	76.15	14.05	1.03	0.30	0.04	1.62	0.12	4.32	2.36	95.29	99.99
$n = \sim10–15$		na	na	na	na	na	na	na	na	na	na	
Like MSH layer C, but older												
Carp Ash-8	T281-3	76.49	14.17	1.00	0.23	0.04	1.52	0.10	3.96	2.49	91.88	100.00
$n = 13$		0.68	0.16	0.08	0.02	0.02	0.05	0.03	0.08	0.05	0.86	
Carp Ash-9	T281-5	77.07	13.73	0.93	0.18	0.03	1.58	0.11	3.85	2.53	93.37	100.01
$n = 13$		0.81	0.58	0.10	0.05	0.03	0.21	0.04	0.21	0.20	0.72	
Unnamed tephra layer in Palouse Fm, Washington												
Carp Ash-10	T279-5	75.43	14.38	1.20	0.38	0.04	1.81	0.12	4.39	2.24	93.20	99.99
$n = 6$		0.70	0.07	0.06	0.05	0.03	0.04	0.01	0.15	0.09	0.83	
CL-90A (1)[d] = Carp Ash-10	T255-3	75.52	14.51	1.21	0.24	0.05	1.82	0.11	4.14	2.29	92.65	100.00
$n = 10$		0.68	0.17	0.07	0.03	0.02	0.04	0.04	0.12	0.05	na	
CL-90A (2)[d] = Carp Ash-10	T255-3	75.38	14.51	1.29	0.35	0.06	1.84	0.13	4.19	2.25	92.85	100.00
$n = 16$		0.68	0.17	0.07	0.04	0.03	0.04	0.05	0.16	0.05	na	
Pelouse WA 5-19[d]	T127-3	76.05	13.61	1.25	0.36	0.06	1.90	0.12	4.26	2.20	93.67	100.00
$n = 5$		0.66	0.53	0.07	0.02	0.03	0.04	0.04	0.15	0.04	na	
No close matches (Ash-13 and Ash-11 match, except for MgO)												
Carp Ash-13	T343-1	74.74	13.50	1.88	0.39	0.03	1.42	0.38	3.81	3.84	96.63	99.99
$n = 18$		0.92	0.28	0.10	0.04	0.02	0.07	0.06	0.10	0.14	1.20	
Carp Ash-11	T281-6	74.49	13.78	1.93	0.32	0.03	1.39	0.37	3.99	3.70	94.53	100.00
$n = 13$		0.98	0.19	0.13	0.03	0.02	0.09	0.04	0.10	0.11	1.13	

Table 2 (continued)

Ash *No. of shards*	Lab No.	SiO_2 ±sd [b]	Al_2O_3 ±sd	Fe_2O_3 ±sd	MgO ±sd	MnO ±sd	CaO ±sd	TiO_2 ±sd	Na_2O ±sd	K_2O ±sd	Total (O) ±sd	Total (R)
Tephra layer E at Pringle Falls, Oregon												
Carp Ash-14	T352-1	73.43	14.34	2.11	0.41	0.04	2.04	0.25	4.30	3.08	94.64	100.00
$n = 7$		0.51	0.17	0.07	0.01	0.03	0.03	0.04	0.11	0.06	0.84	
Pringle Falls PF-88-E (1)	T173-6	73.65	14.46	2.13	0.42	0.04	2.00	0.26	4.03	3.02	95.64	100.01
$n = 8$		0.62	0.13	0.07	0.03	0.03	0.04	0.05	0.10	0.05	na	
Pringle Falls PF-88-E (2)	T169-2	73.41	14.61	2.14	0.43	0.04	2.06	0.26	3.95	3.10	95.70	100.00
$n = 15$		0.60	0.52	0.07	0.04	0.02	0.03	0.05	0.11	0.05	na	
Andesitic tephra layer at Tulelake, California, and tephra layer KK at Summer Lake, Oregon												
Carp Ash-15	T352-2	62.72	16.30	6.28	2.10	0.11	4.86	0.87	4.70	2.05	99.13	99.99
$n = 15$		0.43	0.20	0.25	0.15	0.03	0.22	0.06	0.23	0.11	0.52	
Tulelake 61284-14 ASW [d]	T81-8	62.93	16.22	6.10	2.10	0.11	4.82	0.95	4.63	2.13	95.17	100.00
$n = 8$		0.57	0.48	0.17	0.08	0.02	0.09	0.08	0.13	0.04	na	
Summer Lake KK [c]	DR-33	62.79	16.28	6.19	1.98	0.11	4.73	0.98	4.82	2.11	na	99.99
$n = 10–15$		na	na	na	na	na	na	na	na	na		

Samples were analysed using a 5-channel JEOL 8900 electron microprobe, except as noted. See Table 1 for stratigraphic information and age assignments for Carp Lake ashes. MSH = Mount St. Helens; Total (O) = original total on analysis; Total (R) = total recalculated to 100% fluid-free basis. The difference between Total (R) and Total (O) provides an approximation of the degree of hydration of the volcanic glass.

[a] Analyses were done between 1977 and 1997 by Charles Meyer, U.S. Geological Survey, Menlo Park, California.

[b] Standard deviations of compositions for shards analysed by the JEOL 8900 instrument are based on the actual concentrations obtained for the shard population; standard deviations for shards analysed by the SEQM instrument are based on counting statistics; standard deviations for shards analysed by the 3-channel ARL are not available (na).

[c] Samples were analysed with an ARL 3-channel instrument.

[d] Samples were analysed with a SEQM 9-channel instrument.

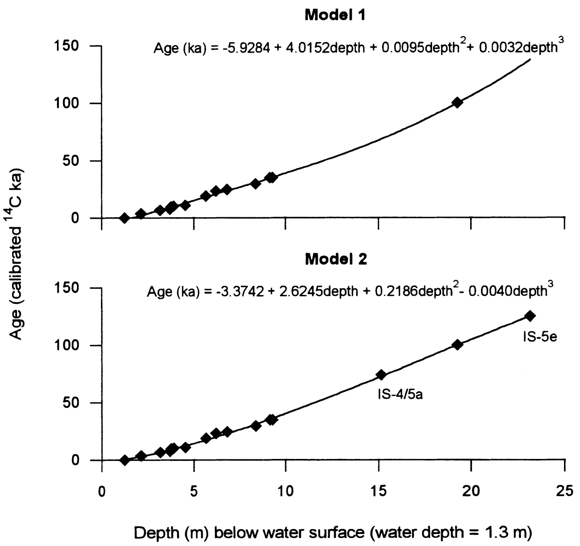

Fig. 2. Age-vs.-depth relations at Carp Lake based on Models 1 and 2 (see text for discussion). Dates are listed in Table 1.

phylla, Abies, Alnus, Corylus, Quercus, and Poaceae. We recognised two subzones. Subzone CL-1a (0–3.9 ka; 1.30–2.35 m depth) traces the development of the modern forest in the late Holocene. Ponderosa pine and Douglas-fir became the dominant trees in the vicinity of the crater, along with alder, hazel, and other shrubs. Higher elevations in the Cascade Range have been able to support grand fir, western white pine, and western hemlock. Oak woodland was established in dry sites just east and south of the site. Poaceae pollen indicates the establishment of mesophytic steppe vegetation at lower elevations and in forest openings. During Subzone CL-1b (3.3–9.1 ka; 2.15–3.71 m depth) time, the pollen data suggest that pine and oak forests were widespread and conditions were warmer and drier than at present. Fir, western hemlock, and Douglas-fir were not present. The climate fluctuated between wet and dry conditions, as evidenced by the lithologic changes between silt and peat.

Table 3
Pollen zone descriptions for Carp Lake

Zone	Depth (m below water surface)	Age (ka)	Description
CL-1	1.30–3.70		
CL-1a	1.30–2.15	0–3.3	Diversity of conifer types is initially low but increases towards the top of the zone. *Pinus* percentages (<42%) dominate the record, and the high representation of Diploxylon-type *Pinus* suggests that the source is ponderosa pine. Haploxylon-type *Pinus* is attributed to western white pine. Also registered are modest percentages of *Abies* pollen (<5%), *Pseudotsuga*/*Larix* pollen (<5%), *Tsuga heterophylla* (<5%), *Quercus* (<7%), *Corylus* (<2%), and *Alnus rhombifolia*-type (<2%). Poaceae accounts for <5%. Aquatic flora is equally diverse and dominated by Cyperaceae, *Typha latifolia*-type, and *Brasenia schreberi*.
CL-1b	2.15–3.71	3.3–9.1	Undifferentiated *Pinus* and Diploxylon-type account for most of the tree pollen (<85%). *Alnus rhombifolia*-type is <5% and *Quercus* is <4%. Aquatic taxa fluctuate between high percentages of *Hydrocotyle*-type, *Isoetes* microspores, and *Pediastrum boryanum*.
CL-2	3.71–4.62	9.1–13.0	Zone is characterised by poorly preserved pollen and low pollen concentrations. Mostly broken and degraded grains comprise the high *Pinus* percentages (<48%). *Alnus rhombifolia*-type is well represented (<10%) and attributed to white or red alder. Poaceae percentages are high at the top of the zone (up to 30%) and *Chenopodium*-type are abundant in some levels (<16%). *Typha latifolia*, *Sparganium*-type, and *Polygonum amphibium*-type are the dominant aquatic taxa. Indeterminate pollen accounts for up to 8%. The sediments are crumbly silty clay.
CL-3	4.62–8.25	13.0–31.0	High percentages of *Artemisia* (<56%), Poaceae (35%), and Compositae Tubuliflorae (11%) characterise this zone. *Artemisia*/Poaceae ratios are higher than in the overlying zones, but generally low. *Pinus* values are low (<32%), and *Picea* accounts for 3–6%, except between 14.6 and 16.8 ka when it reaches 10%. Nonarboreal pollen includes Caryophyllaceae, *Polygonum bistortoides*-type, *P. californicum*-type, *Eriogonum*, *Valerianella*-type, and *Phlox*-type. *Pediastrum boryanum* is abundant.
CL-4	8.25–10.40	31.0–43.2	Diploxylon-type *Pinus* is the dominant taxon, and *Picea* and *Pseudotsuga*/*Larix* pollen are present in low values. Poaceae, *Artemisia*, and other herbs are present in modest values as well. Cyperaceae, *Sparganium*-type, *Potamogeton*, *Myriophyllum*, and *Nuphar* are present in the aquatic assemblage. *Pediastrum*, a freshwater alga, is abundant in some levels.
CL-5	10.40–12.85	43.2–58.3	*Pinus* percentages (mostly Diploxylon-type) fluctuate (14–50%) and *Picea* and *Abies* pollen are consistently present. Percentages of Poaceae (<31%), *Artemisia* (<40%), and other Compositae Tubuliflorae (<8%) are moderate. *Phlox*-type pollen (<2%) is present in this interval. Cyperaceae and *Myriophyllum* percentages are high, and *Pediastrum boryanum* is abundant.
CL-6	12.85–15.15	58.3–73.0	Zone features high percentages of *Pinus* (<76%), mostly Diploxylon-type, and *Artemisia* (<25%). *Abies* (<5%), Poaceae (<6%), *Chenopodium*-type (<5%) are present in small amounts. *Myriophyllum* and Cyperaceae are the major aquatic pollen types.
CL-7	15.15–16.65	73.0–82.8	Percentages of *Pinus* and *Artemisia* are low, <24% and <10% respectively. *Abies* (<5%), Cupressaceae (<6%), *Tsuga heterophylla* (<6%), *Quercus* (<15%), Poaceae (<18%), *Chenopodium*-type (<6%), Ranunculaceae (<3%), and *Eriogonum* (<13%) are well-represented. Indeterminate (<29%) and pre-Quaternary pollen are abundant. The aquatics consist of Cyperaceae and *Hydrocotyle*-type (Umbelliferae).

Table 3 (continued)

Zone	Depth (m below water surface)	Age (ka)	Description
CL-8	16.65–18.46	82.8–94.6	Percentages of *Pinus* pollen (<88%) are variable in this zone, and most of the grains are broken and undifferentiated. *Picea*, *Artemisia*, and Poaceae reach values of <14%, <62%, and <17%. *Alnus sinuata*-type is also present consistently (<2%). *Selaginella densa*-type spores are present in trace amounts (<1%). The dominant aquatic taxa are *Myriophyllum* and *Pediastrum boryanum*.
CL-9	18.46–21.02	94.6–111.0	High percentages of *Pinus* (<70%) come from Haploxylon-type and Diploxylon-types. *Picea* and *Abies* percentages are present in values of 6% and 4%. *Pseudotsuga*/*Larix* reach high percentages (3.8%) at the bottom of the zone, and a peak of Cupressaceae pollen (4%) occurs in the middle of the zone. *Alnus sinuata*-type is well-represented (<4%). The nonarboreal component is dominated by *Artemisia* (<32%), Poaceae (<16%), and Other Compositae Tubuliflorae (<7%). Indeterminate pollen increases to 14% at the top of the zone. *Isoetes* percentages are high, and Cyperaceae, *Myriophyllum*, and *Pediastrum boryanum* are present.
CL-10	21.02–22.22	111.0–118.4	Zone is characterised by moderate percentages (<20%, with a peak at 80%) of *Pinus* (mostly undifferentiated), Poaceae (13.1%), and *Artemisia* (28.4%). *Picea* (8.5%), *Abies* (1.2%), *Pseudotsuga*/*Larix* (3.8%), and Other Tubuliflorae (3.7%) are present in low values.
CL-11	22.22–23.42	118.4–125.6	The assemblage is dominated by *Pinus* (mostly Diploxylon-type) (<65%) pollen, but percentages of *Pseudotsuga*/*Larix* (<7%), Cupressaceae (<14%), *Tsuga heterophylla* (<2%), and *Quercus* (4%) are noteworthy. Poaceae (29%) and Artemisia (43%) are relatively low, and *Chenopodium*-type (<10%), *Eriogonum* (<9%), and *Pteridium* (<8%) are high. Indeterminate pollen is also abundant in some levels reaching values of 6%. Among the aquatics, *Myriophyllum* (<24%), *Sagittaria* (<3%), and *Brasenia* (<4%) are well represented.

Zone CL-2 (9.1–13.2 ka; 3.70–4.65 m depth) records a period of steppe and lake drying in the early Holocene and latest Pleistocene. A hiatus occurs in the record at ca. 9.5 ka when the basin dried completely (Barnosky, 1985a). Abundant deteriorated *Pinus* grains suggest that pollen was deposited on exposed shorelines before washing into the lake. Alder pollen indicates wet areas, and its contribution to the pollen record may have been amplified by the sparseness of the upland vegetation. The abundance of *Chenopodium*-type (saltbushes) pollen suggests saline soils. Sagebrush was not present at the site, judging from the relatively low percentages of *Artemisia* pollen.

Zone CL-3 (13.2–30.9 ka; 4.65–8.25 m depth) suggests nonforested vegetation dominated by *Artemisia*, grass, and herb taxa during the full-glacial period. The absence of temperate aquatic taxa (e.g., *Nuphar*, *Sparganium*-type, *Myriophyllum*, *Polygonum amphibium*-type, and *Typha*) indicates colder-than-present conditions and a nutrient-poor lake. *Polygonum bistortoides*-type pollen implies subalpine or alpine conditions (Whitlock, 1993); other herb pollen types could be from steppe or alpine taxa. *Artemisia* pollen is attributed largely to sagebrush (e.g., *A. tridentata* or *A. cana*), based on modern phytogeography; however, alpine species may have been present as well (e.g., *A. norvegica*, *A. trifurcata*). In either case, the abundance of *Artemisia* indicates drier conditions than today. *Picea* pollen in moderate percentages suggests that Engelmann spruce may have grown near the site. Increased *Picea* percentages at the top of the zone signal the development of late-glacial spruce parkland and warmer and wetter conditions than before.

Zone CL-4 (30.9–43.1 ka; 8.25–10.40 m depth) records a forest with taxa from present-day low- and high-elevations in the eastern Cascades. Spruce and fir may have grown at high elevations, at a time when local forests supported lodgepole or ponderosa pine,

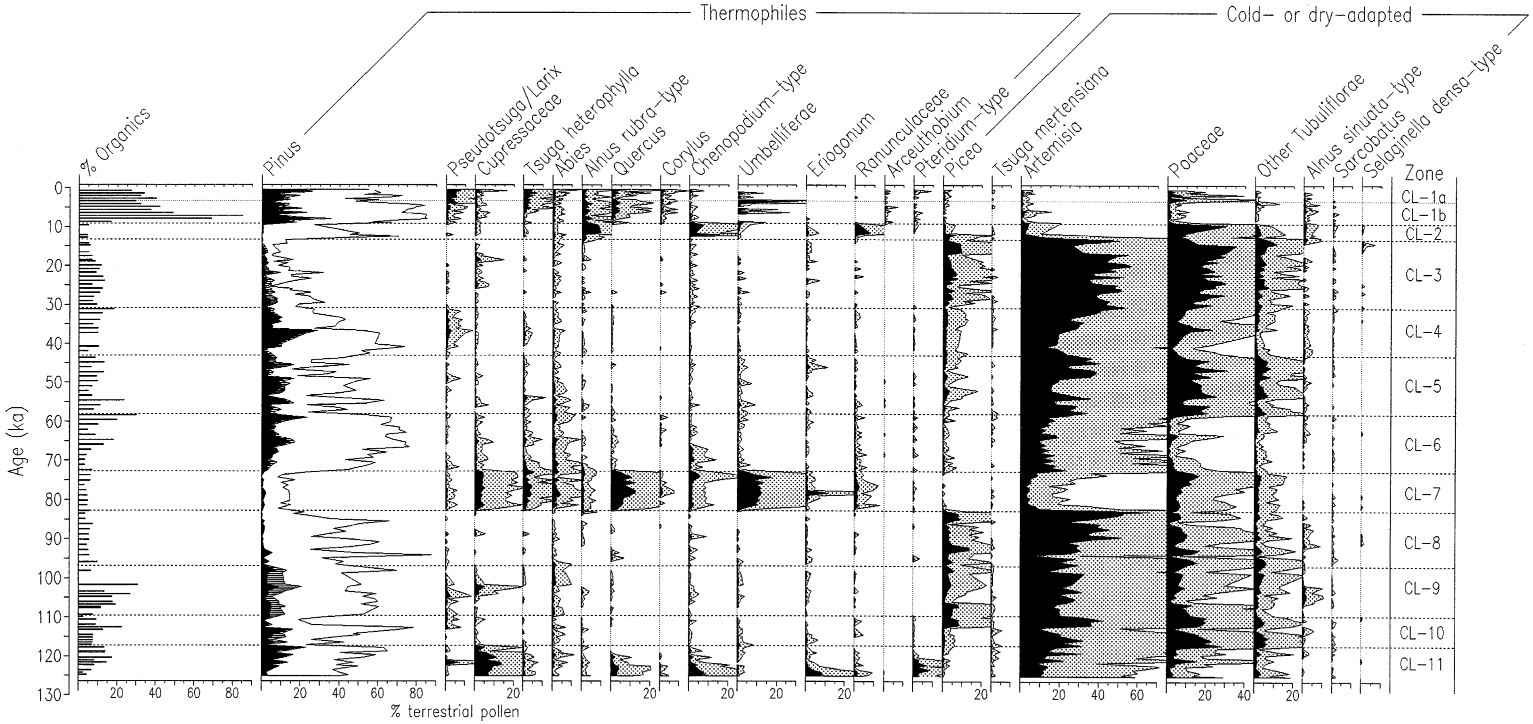

Fig. 3. Pollen percentage diagram of selected taxa from Carp Lake Cores 90 and 93. *Pinus* includes Diploxylon-type pollen (black curve) from *P. contorta* or *P. ponderosa*, and Haploxylon-type pollen (striped curve) from *P. monticola* or *P. albicaulis*. Shaded pattern shows 5× exaggeration.

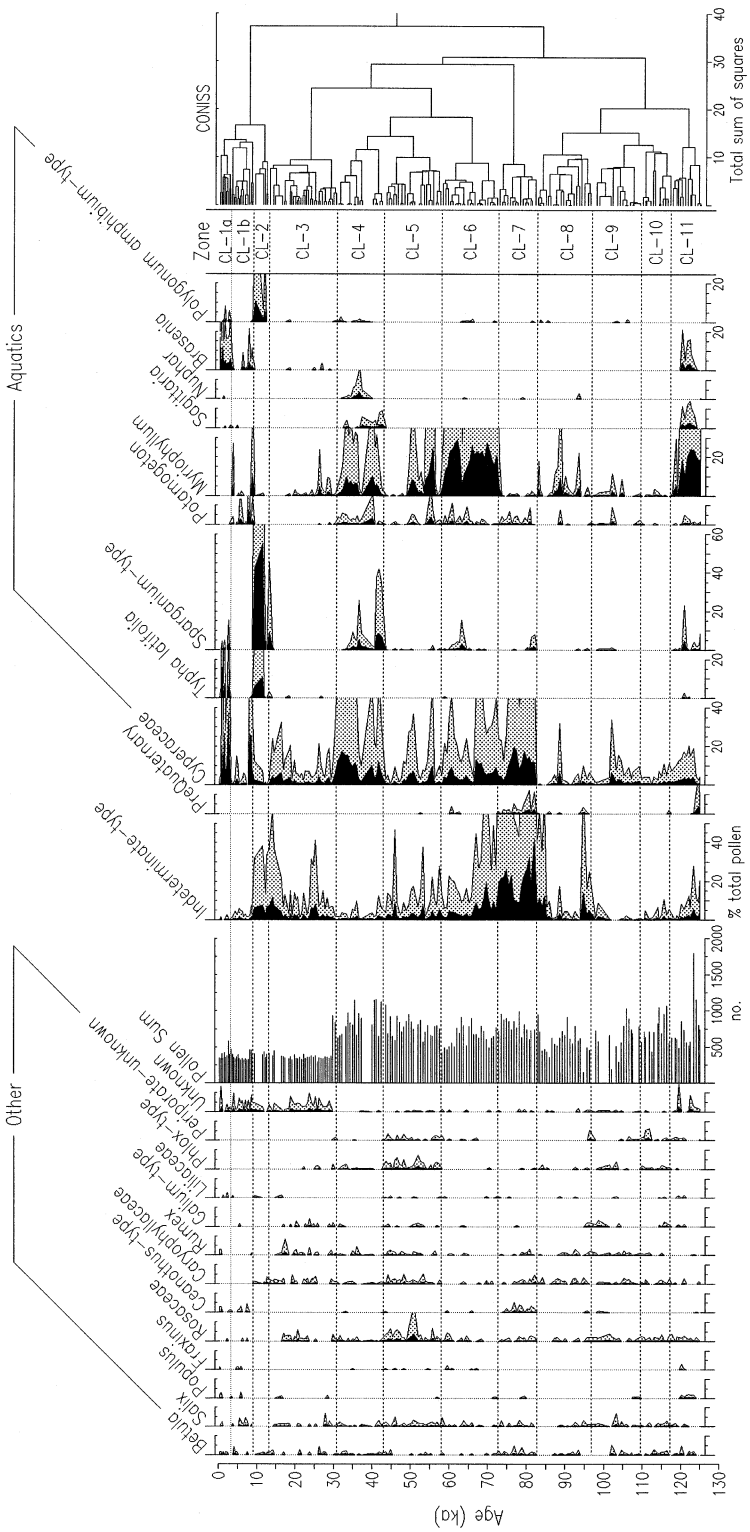

Fig. 3 (continued).

Douglas-fir or larch, and grand fir. Alternatively, the taxa may have comprised a mixed conifer forest near Carp Lake. *Picea* and *Artemisia* pollen are abundant at the bottom of the zone and replaced by *Pseudotsuga*/*Larix* and Poaceae pollen at the top of the zone. The aquatic taxa suggest that the lake was shallow with a well-developed macrophyte zone. The climate was cooler and drier than today, and conditions were warmer and drier at the beginning of the zone than at the end.

In Zone CL-5 (43.1–58.0 ka; 10.40–12.85 m depth) ponderosa pine and/or lodgepole pine were the dominant conifer species. *Amelanchier*-type pollen indicates an open shrub understorey that included serviceberry. Pollen of spruce and fir may have blown from higher elevations, or these conifers may have been minor elements in local mesic settings. In either case, their presence indicates cooler-than-present conditions. Poaceae and *Artemisia* are well represented suggesting grass and sagebrush in forest openings or nearby steppe. The lake was shallow with a vegetated littoral zone.

Zone CL-6 (58.0–72.7 ka; 12.85–15.15 m depth) is difficult to characterise, except to say that the forest was dominated by ponderosa pine and/or lodgepole pine. *Picea* and *Abies* percentages are like those of the present day, but in general the vegetation was less diverse than the modern forest. High values of *Artemisia* indicate dry conditions and the expansion of sagebrush over grass. Modest percentages of *Chenopodium*-type pollen at the beginning of the zone imply saline or very dry substrates. Conditions were apparently drier than present and cool.

In Zone CL-7 (72.7–82.8 ka; 15.15–16.70 m depth), the major pollen taxa, *Abies*, *Pseudotsuga*/*Larix*, *Quercus*, *Tsuga heterophylla*, and Cupressaceae, are typical of modern spectra from low elevations in the western Cascades of Oregon, where pine, spruce, and sagebrush are uncommon. In these forests, oak occupies the dry, frequently burned areas of the Willamette Valley and lower Cascade Range. Douglas-fir grows in somewhat wetter habitats and areas of intermediate fire frequency, and western hemlock, western red cedar, and fir occur in areas of greater precipitation and low fire frequency (Agee, 1993). A similar gradient may have occurred in the eastern Cascades during Zone CL-7 time. Middle elevations would have supported forests of western hemlock, fir, and Douglas-fir. Cupressaceae pollen may have come from western red cedar or Alaska cedar, in which case they probably shared similar habitats with western hemlock. If the Cupressaceae pollen came from western juniper (*Juniperus occidentalis*), the data imply a northward or elevational expansion of juniper, relative to its present distribution, and warm summers, consistent with elevated percentages of chenopods at this time. The abundance of *Quercus* pollen suggests that oak formed the lower forest border. In dry settings, grass, bracken fern, and *Eriogonum* (buckwheat) prevailed.

The juxtaposition of mesophytic conifers, with grass, steppe herbs, oak, and possibly juniper indicates a steeper-than-present moisture gradient and probably greater effective moisture than today. The high amounts of Indeterminate and pre-Quaternary pollen may have been introduced to the basin during a windy period. Loess deposits in eastern Washington pre-date the late Wisconsinan Scabland floods (McDonald and Busacca, 1988; A.J. Busacca, unpubl. data), and suggest early periods of intense winds. Alternatively, the poorly preserved pollen may have been introduced to the lake as slopewash following subaerial exposure.

Zone CL-8 (82.8–96.8 ka; 16.70–18.83 m depth) represents an open parkland of Engelmann spruce, lodgepole pine, and possibly ponderosa pine. Sitka alder may have grown in areas of seepage. High *Artemisia* percentages imply that sagebrush was present in nearby steppe or forest openings and generally dry conditions. *Myriophyllum* pollen suggests the existence of a shallow lake with some riparian vegetation. Percentages of *Picea* indicate cool conditions. The high percentages of Indeterminate taxa suggest that pollen grains were subaerially exposed prior to deposition, as a result of low lake levels or high eolian activity.

Zone CL-9 (96.8–109.5 ka; 18.83–20.75 m depth) registers a closed forest of pine, Douglas-fir or larch, fir, and spruce. This combination of taxa now occurs at middle-to-high elevations in the eastern Cascades and the Blue Mountains of northeastern Oregon (Franklin and Dyrness, 1988). *Pinus* pollen may have come from lodgepole pine, ponderosa pine, western white pine, and whitebark pine. Engelmann spruce either grew near the site or was present at higher elevations. *Abies* pollen is presumably from grand fir, Pacific silver fir, or subalpine fir. Sitka alder and birch (presumably *B. glandulosa*) suggest areas of wetland and seepage.

The fluctuations in *Pinus* percentages are consistent with frequent disturbances, such as fires and windthrow. *Artemisia* pollen indicates widespread forest openings or expanded sagebrush steppe in the Columbia Basin. High percentages of *Isoetes* indicate oligotrophic conditions. This zone registers a cool period, when the lake was less productive than today. Summers were apparently warm and dry, and winters were cool with abundant snow cover.

Zone CL-10 (109.5–117.3 ka; 20.75–21.95 m depth) probably records a period of pine forest, with grass and sagebrush in openings. Spruce and fir grew in cold mesic settings or at higher elevations. High percentages of grass relative to sagebrush imply reduced summer drought.

Zone CL-11 (117.3–124.9 ka; 21.95–23.15 m depth) features taxa found in the eastern Cascade Range of northeastern Oregon today and suggests that the site lay close to the forest–steppe border. *Pinus* pollen is attributed to lodgepole pine and/or ponderosa pine. High values of *Quercus* are equalled only in Zones CL-1 and CL-7 and suggest a dry woodland zone below pine forest. Cupressaceae may be ascribed to western red cedar or Alaska-cedar, but juniper is also a possibility. *Chenopodium*-type, *Eriogonum*, *Artemisia*, and Poaceae percentages reinforce the image of semiarid open vegetation. Oak and *Pteridium* suggest frequent fires. *Brasenia schreberi*, *Myriophyllum*, and *Sagittaria* indicate a shallow temperate lake, similar to the present one. *Brasenia* is present in this interval and the late Holocene, which attests to the temperate nature of this period.

5. Discussion

5.1. Environmental history since the last glacial maximum (LGM)

Palaeoclimatic simulations produced by GCMs suggest that three large-scale controls have been especially important in the PNW since the last glacial maximum (IS-2) (Fig. 4; COHMAP Members, 1988; Broccoli and Manabe, 1987a,b; Bartlein et al., 1998). The first was the Laurentide ice sheet and its influence on both temperature and atmospheric circulation. Attendant changes in SSTs in the north Pacific amplified the ice-sheet influence. The second control was the direct and indirect effects of variations in the seasonal distribution of insolation as a result of the Earth's orbital variations (Whitlock and Bartlein, 1993). These variations affected temperature, effective precipitation, and atmospheric circulation. The third control was changes in the atmospheric concentration of CO_2 and other greenhouse gasses (Sowers and Bender, 1995). Table 4 summarises the effects of these large-scale controls on the northern middle latitudes in general and the PNW in specific.

Model simulations of the LGM suggest that the Laurentide ice sheet caused general cooling throughout the northern mid-latitudes (Kutzbach and Guetter, 1986; Hall et al., 1996). The ice sheet was large enough to shift the North American jet stream south of its present position, diverting winter storms to the American Southwest. Glacial-anticyclonic circulation led to weaker-than-present westerlies along the southern ice margin, which enhanced the cold and dry conditions in the PNW. As the ice sheet shrank the influence of the anticyclone in the region diminished.

Estimates of temperature depression in the PNW based on palaeoenvironmental data are between 5º and 10ºC (Thompson et al., 1993). Carp Lake (Zone CL-3) was covered by periglacial steppe and spruce during the LGM, while pine and other conifers were restricted either to unglaciated regions in the Cascades or areas farther south. Elsewhere in the PNW, xerophytic subalpine parkland and forest grew west of the Cascades and in the Coast Range (Barnosky, 1985b; Whitlock, 1992; Worona and Whitlock, 1995). Evidence of weakened westerlies comes from the presence of freshwater Tertiary diatoms at Battle Ground Lake (southern Puget Trough) and in cores from the northeastern Pacific Ocean. These diatoms have their provenance in eastern Washington and are believed to have been transported by easterly winds (Barnosky, 1985b; Sancetta et al., 1992).

During the late-glacial period, from 16 to 10 ka, the shrinking of the Laurentide ice sheet shifted the core of the jet stream north of its LGM position. In GCM simulations for 14 ka (= 12,000 ^{14}C yr B.P in Thompson et al., 1993), a loss of the influence of the

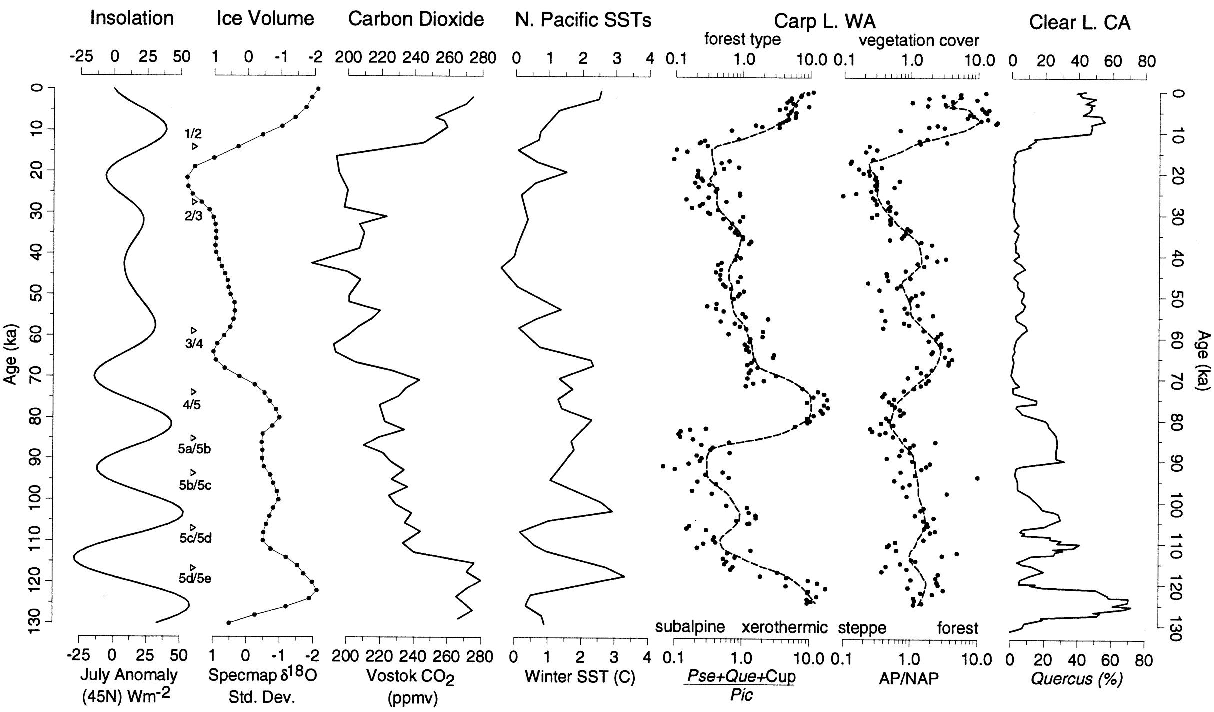

Fig. 4. Large-scale controls on climate in the Pacific Northwest and vegetational response at Carp Lake, Oregon (this paper), and Clear Lake, California (Adam, 1988). Insolation values were calculated using the routines of Berger (1978). Oxygen isotope data are the 'stacked and smoothed SPECMAP data (Imbrie et al., 1984). CO_2 concentrations are those measured in the Vostok ice core (Barnola et al., 1987). Sea-surface temperatures are winter temperatures inferred from fossil data by Morley et al. (1987) from a core from the northern Pacific Ocean. The ratios of the sum of *Pseudotsuga/Larix*, *Quercus*, and Cupressaceae pollen percentages to *Picea* pollen percentages (Pse + Que + Cup/Pic) and of total arboreal to total nonarboreal pollen (AP/NAP) provide an indication of vegetation type and openness at Carp Lake. *Quercus* percentages at Clear Lake are an indication of thermophilic vegetation (Adam, 1988).

glacial anticyclone in the region and a more northerly position of the jet stream account for warmer and wetter conditions than before (although still cooler than at present). Warming was amplified by higher levels of CO_2 and higher sea-surface temperatures (SSTs) than in the LGM.

Data from the PNW provide evidence of late-glacial warming trends (Grigg and Whitlock, 1998). From ca. 16.0 to 13.0 ka, Carp Lake registers an expansion of spruce forest into areas of cold steppe. Temperate taxa (e.g., Douglas-fir, red alder, and western hemlock) appear in the Oregon Coast Range by 16.1 ka, and in the unglaciated southern Puget Lowland by 13.1 ka (Barnosky, 1985b). Concurrently, lodgepole pine colonised deglaciated regions in the northern Puget Lowland and Olympic Peninsula and became the forest dominant for several centuries. In the rainshadow region of the Puget Lowland, dry open communities of herbs and shrubs grew on deglaciated substrates (Peterson et al., 1983). The Okanogan Highlands and Channeled Scablands supported a parkland of spruce, whitebark pine, and fir, following a tundra period (Mack et al., 1978; Whitlock, 1992).

The early Holocene is characterised by an amplification of the seasonal cycle of insolation as a result of perihelion occurring in summer then (as opposed to in winter today) in the Northern Hemisphere (Fig. 4). Summer insolation was greatest between 14 and 7 ka, and conversely winter insolation was less than present at that time. GCM simulations for 10 ka (= 9000 ^{14}C yr B.P. in Thompson et al., 1993) suggest increased temperatures and decreased effective moisture in the PNW. Indirectly, high summer insolation also strengthened the eastern Pacific subtropical high-pressure system, which intensified

Table 4
Effects of large-scale controls on palaeoclimates as simulated by general circulation model experiments [a]

Controlling factor and effects	Northern Hemisphere mid-to-high latitude response	Specific response in the Pacific Northwest
Ice-sheet temperature effects ($\delta^{18}O > 12$ ka level)	colder than present ($\Delta T_{Ann} \sim -4$ to -10ºC)	colder than present ($\Delta T_{Ann} \sim -7$ºC)
Ice-sheet circulation effects ($\delta^{18}O > 14$ ka level)	split jet/glacial anticyclone over North America	prevailing easterlies; drier than present
Direct insolation effects ($K_{Jul} > 6$ ka levels)	increased land–sea temperature contrast and seasonality; warmer continental interiors; ($\Delta T_{Jul} \sim +2$º to $+4$ºC)	warmer than present; ($\Delta T_{Jul} \sim +2$ºC); reduced P–E and soil moisture
Indirect insolation effects ($K_{Jul} > 6$ ka levels)	strengthened oceanic high-pressure systems and continental thermal lows; enhanced monsoonal circulation	strengthened East Pacific subtropical high-pressure system; greater subsidence and drought in summer
Additive insolation effects ($K_{Jul} > 126$ ka levels)	continental interiors 2ºC warmer than at 6 ka; greater seasonality and stronger monsoons	warmer and drier than the early Holocene; ($\Delta T_{Jul} \sim +2$º to $+4$ºC)
(Reduced) CO_2 temperature effects (CO_2 conc. ≤ 200 ppm)	cooler than otherwise; ($\Delta T_{Ann} \sim -1$ºC)	cooler than otherwise; ($\Delta T_{Ann} \sim -1$ºC)
(Lower) sea-surface temperature effects	cooler land-surface temperatures downwind of oceans; ($\Delta T_{Ann} \sim -2$ºC)	cooler than otherwise; ($\Delta T_{Ann} \sim -0.5$ºC)
Sea-ice, vegetation, and snow-cover feedback effects, 9 and 6 ka	reduced Arctic sea ice and snow cover; warmer autumns and winters than otherwise	warmer autumns and winters than otherwise

[a] Adapted from Bartlein et al. (1991).

drought. GCM simulations of 7 ka (= 6000 ^{14}C yr B.P. in Thompson et al., 1993) incorporate summer insolation values that are less than those at 10 ka, and conditions become cooler and wetter than those of the early Holocene in the PNW (Thompson et al., 1993).

Vegetation records throughout the region provide evidence of summer drought in the early Holocene, consistent with the amplification of the seasonal cycle of insolation. The Carp Lake area supported temperate steppe vegetation, and the lake dried out briefly. Sites in the Okanogan region record a northward shift in the present-day forest–steppe ecotone by much as 100 km (Mack et al., 1978). In the middle Holocene wetter conditions led to an expansion of mesophytic communities. Pine forest and oak woodland were replaced by closed pine, Douglas-fir, and Abies forest after 3.9 ka. In north-central Washington, pine parkland was present between 9.1 and 6.8 ka, and mixed mesophytic forest was present after 6.8 ka (Mack et al., 1978).

5.2. The period from 31 to 125 ka

Glaciers during the middle Wisconsin (IS-3) were smaller than during the LGM, both regionally and globally. The SPECMAP record suggests that IS-3 ice volume was similar to that between 12 and 16 ka. SSTs and CO_2 concentrations were less than present but greater than LGM levels. Summer insolation maxima occurred at 30 and 55 ka (Fig. 4).

Pse + Que + Cup/Pic ratios in Zones CL-4 (31–43 ka) and CL-5 (43–58 ka) imply that conditions at Carp Lake were cooler and effectively wetter than present and warmer than the LGM. AP/NAP ratios indicate that the early-middle Wisconsin (Zone CL-5) featured a more open forest than later (Zone CL-4). Higher Pse + Que + Cup/Pic ratios in Zone CL-4 suggest that the last half of the middle Wisconsin was temperate (although still cooler than today).

In the PNW, IS-3 is sometimes referred to as the Olympia Nonglacial Period (Clague, 1978). On the Queen Charlotte Islands, British Columbia, subalpine vegetation between 45.7 and 27.5 ka suggests a treeline depression of 400 m as a result of cool wet conditions (Warner et al., 1984). In the Puget Lowland and Olympic Peninsula, the climate varied between cool and temperate conditions (Heusser, 1977; Stuiver et al., 1978; Heusser and Heusser, 1981). A mixed conifer forest in the Coast Range of Oregon resembled present-day vegetation in the northern Rocky Mountains and suggests cool conditions (Worona and Whitlock, 1995), as does a fir-dominated assemblage in the western Cascades (Gottesfeld et al., 1981). Elsewhere, low temperatures are inferred from the expansion of pine forest in northern California (Adam, 1988), and woodland elements in the central Great Basin indicate cool conditions but warmer than at the LGM (Thompson, 1990).

Early Wisconsin (IS-4) ice volumes were generally less than 14-ka levels (Fig. 4), atmospheric CO_2 was at 12–16 ka levels, and SSTs ranged between present-day and 14-ka levels. Summer insolation during IS-4 was lower than at the LGM, but winter insolation was higher. These large-scale controls created cool humid conditions in the PNW. Moderate Pse + Que + Cup/Pic ratios in Zone CL-6 indicate cooler conditions, and high AP/NAP ratios suggest closed forest.

IS-5a through -5d is characterised by rapid changes in the large-scale controls, although no period reached the extreme conditions of the early Holocene or the LGM. Summer insolation exceeded 6-ka levels at 80 (IS-5a) and 105 ka (IS-5c), and summer insolation minima occurred at 90 (IS-5b) and 115 ka (IS-5d). Global ice volume and CO_2 levels were like 9–10-ka levels for most of this period. SSTs were less than today, except at 105 ka. Sea-level stands were near present during IS-5a, which has been attributed to high summer insolation (Ludwig et al., 1996).

Insolation during IS-5a was 106% of present in summer and between 92 and 96% of present in winter. The Pse + Que + Cup/Pic ratios for Zone CL-7 indicate conditions as warm as the early Holocene, but the mixture of conifers, including fir, western hemlock, Douglas-fir or larch, and possibly western red cedar, and the near-absence of pine and sagebrush were anomalous. A weakened subtropical high may explain the absence of pine and sagebrush, despite the overall temperate aspect of the vegetation. For example, such a weakening would have led to greater effective moisture in summer, which along with mild wet winters may have allowed mesophytic taxa to extend to lower elevations than at present east of the Cascade Range. Oak and possibly juniper would have been favoured at the forest–steppe border in the absence of pine, or at the least their relative pollen contribution to the lake would increase. Wetter-than-present summers would also explain the expansion of grass over sagebrush (Mehringer and Wigand, 1990). High percentages of Indeterminate and pre-Quaternary pollen are consistent with pre-late Wisconsin periods of eolian activity described by McDonald and Busacca (1988).

IS-5b features low summer insolation, ice volume, and SSTs. Pse + Que + Cup/Pic ratios in Zone CL-8 indicate cool conditions, and AP/NAP ratios are evidence of forest openness. The inferred vegetation is consistent with cool humid winters and relatively dry summers. IS-5c is characterised by summer insolation and SSTs above those at 6 ka. Zone CL-9 suggests a diverse conifer forest similar to that at middle elevations in the Blue Mountains. Pse + Que + Cup/Pic ratios suggest warmer, effectively drier conditions than in Zone CL-8, but not as extreme as during IS-5a. Zone CL-10 (109.5–117.3 ka) falls during IS-5d, an insolation minimum. Ratios of Pse + Que + Cup/Pic suggest cool, effectively wet conditions, especially in the upper part of the zone, and AP/NAP ratios indicate open forest.

Clear Lake (Lat. 39ºN, Long. 122º45′W; Fig. 1) in northern California has a record of comparable resolution for the early Wisconsin. Adam (1988) identifies multiple warm periods with high *Quercus* pollen that are generally correlated with summer insolation maxima and cool periods with low *Quercus* percentages during insolation minima (Fig. 4). The oscillations are similar to those registered by the Pse + Que + Cup/Pic and AP/NAP ratios at Carp Lake. At Carp Lake, however, IS-5a stands out as a period of warm wet summers, and IS-5c is not much different from the bracketing stadials.

The previous interglaciation, IS-5e, is characterised by summer insolation greater than 6 ka levels (124% of present), ice volume that was less than present, and CO_2 levels and SSTs that were higher than present (Fig. 4). Zone CL-11 shares strong similarities with Holocene assemblages and suggests a forest predominantly of pine, with some Douglas-fir or larch, and oak. Cupressaceae, *Chenopodium*-type and *Eriogonum* suggest a steppe–woodland with affinities to the northern Great Basin. Pse + Que + Cup/Pic ratios suggest warm effectively dry conditions and AP/NAP ratios indicate closed forest. The aquatic assemblage is similar to the middle and late Holocene with the *Brasenia*, *Myriophyllum*, and *Sagittaria*. Greater forest cover in Zone CL-11 than in the early Holocene may indicate that the warmest part of IS-5e was not recovered. It may be that differences in large-scale controls, particularly in levels of atmospheric CO_2, also contributed to the formation of steppe in the early Holocene and not in IS-5e.

Carp Lake and Clear Lake show little variation in vegetation during the previous interglaciation, in contrast to some records from northern Europe and Greenland that indicate rapid climatic fluctuations during IS-5e (e.g., GRIP Members, 1993; Thouveny et al., 1994). The complacency of interglacial records from western North America may arise from their location upwind and down-current from the North Atlantic (Broecker, 1997). The effects of subtle changes in North Atlantic circulation during interglacial periods may not have been strongly felt in the PNW. In contrast, millennial-scale variability is more evident during IS-2, -3, and -4, when changes in ocean and atmospheric circulation were more pronounced (e.g., Grigg and Whitlock, 1998; Heusser, 1998). Even so, most of the variability in the Carp Lake and Clear Lake records can be explained by the slowly varying controls of insolation, global ice volume, and atmospheric CO_2 concentration and their apparent influence on the climate system. Although millennial-scale events have been noted in high-resolution records from the region, the signal is relatively weak compared to the strong response to orbital variations (Whitlock and Grigg, 1999).

5.3. Reconsideration of the Carp Lake chronology

The interpretation of Zones CL-10 and -11 as belonging in IS-5 is necessarily incorrect if Carp Ash-14 and -15 are 'Orange' beds with assigned ages between 140 and 280 ka (see Section 3). These tephra layers imply that Zone CL-10 was deposited during the previous glaciation (IS-6), and Zone CL-11 represents an older interglaciation, possibly IS-7.

Three aspects of the Carp Lake record argue against this chronology. First, there is no indication of an unconformity between the base of Carp Ash-10 at 19.80 m depth, which is dated at ca. 100 ka, and the top of Carp Ash-14 at 20.99 m depth, which is assumed to be ca. 140 ka. Neither the lithology, loss-on-ignition data, palaeomagnetic stratigraphy (R. Reynolds and J. Rosenbaum, unpubl. data, 1995), nor the pollen record offers evidence of a hiatus between these two tephra. Second, if the sediments containing Carp Ash-14 were deposited during the previous glaciation, sediment accumulation must have been very slow or intermittent to account for the compressed record. In contrast, other glacial periods (IS-2 and -4) at Carp Lake feature well-preserved pollen and relatively fast sedimentation rates. Why would IS-6 be different? Third, the large-scale controls of climate for IS-6 indicate cold dry conditions in the PNW, like those of IS-2 (Table 5), and a period of cold steppe. Zone CL-10, which contains Carp Ash-14, is a forested assemblage and suggests cool humid conditions.

It is possible that Carp Ash-14 and -15 are spuriously correlated to the 'Orange' beds, and that another, yet unidentified couplet has similar chemistry but is several thousand years younger. It is also possible that the ages of the two tephra layers at Pringle Falls, Tulelake, and Summer Lake are in error and should be younger. In support of this idea is the fact that Carp Ash-14 is correlated to a tephra layer at Pringle Falls that itself is not dated but overlies a dated layer (Herrero-Bervera et al., 1994). The age of the Carp Ash-14 equivalent may be younger than previously thought. The match of Carp Ash-15 at Tulelake, California, and Summer Lake, Oregon, however, lies below the dated tephra (Herrero-Bervera et al., 1994).

In summary, the pollen and lithologic data at Carp Lake suggest a record back to IS-5, whereas the tephra identifications of the two lowermost tephra layers suggest an older record and the likely presence of unconformities. In the absence of independent information to resolve this discrepancy, we continue to favour the age model first described in Whitlock and Bartlein (1997).

Table 5
Correlation of Carp Lake record with marine oxygen isotope and geologic–climate units

Marine oxygen isotope[a]		Geologic climate unit	Carp Lake		
Stage	ka		Zone (CL-1)	Ka[b]	Inferred conditions
1		late Holocene	1a		temperate, humid; closed forest
				3.9	
		early Holocene	1b		warm, dry; closed forest
				9.2	
		late-glacial	2		cool humid; parkland
	14.1			13.2	
2		late Wisconsin Glaciation (Fraser Glaciation)	3		cold, dry; steppe
	27.6			30.9	
3		early-mid-Wisconsin Glaciation (Olympia nonglacial period)	4		cool-temperate, dry; closed forest
				42.9	
		late-mid-Wisconsin Glaciation	5		cool, humid; open forest
	58.9			57.7	
4		early Wisconsin Glaciation	6		cool, dry; closed forest
	73.9			72.2	
5a			7		warm, humid; open forest
	85.1			82.3	
5b			8		cold, dry; open forest
	93.6			96.3	
5c			9		cool, dry; closed forest
	107			109	
5d			10		cold, humid; open forest
	116.7			116.9	
5e		Last Interglaciation	11		warm, dry; open forest

[a] Ages for intrastage boundaries are interpolated from isotope event ages and definitions (Martinson et al., 1987).
[b] After Whitlock and Bartlein (1997).

6. Conclusions

Few records are available anywhere to examine the vegetation and climate during a glacial–interglacial cycle and to compare the previous interglaciation with the Holocene. The location of Carp Lake at the forest–steppe border contributes to its sensitivity to variations in temperature and precipitation, as evidenced by its history of alternating pine forest, mixed conifer forest, and steppe. The vegetation and climate record suggests a continuously changing environment over the last 125,000 years, and periods of stability were few and relatively short-lived. The synchroneity between the pollen zone boundaries and the timing of IS-1 through IS-5e suggests that the vegetation was responding to orbital-scale variations in global climate during the last 125,000 years (Table 5). The fluctuations between low-elevation taxa (Douglas-fir, juniper, and oak) and spruce, for example, record changes in temperature and effective moisture that track variations in summer insolation, ice volume and atmospheric CO_2 with remarkable fidelity.

The middle and early Wisconsin was characterised by forests and cool and humid conditions. These periods lacked glacial anticyclonic circulation and the jet stream was probably near or just south of its present position. The early-middle Wisconsin (31–43 ka) was the warmest period in IS-3 and -4, coinciding with summer insolation close to 6-ka levels. IS-5a featured extreme interstadial conditions. High summer insolation led to warmer-than-present temperatures, although cool SSTs may have limited the strength of the eastern Pacific subtropical high. Carp Lake area supported mixed conifer forests, oak woodland and grassland. In contrast, IS-5c stands out as an anomaly, because the climate was cooler than present, despite >6-ka summer insolation and high SSTs. In IS-5e, summer insolation, CO_2, and SSTs were higher than at any time in the early Holocene.

The result was intense summer drought but continued winter precipitation. The last half of IS-5e (117–125 ka) supported pine forest with Douglas-fir, oak woodland, and possibly a northward expansion of juniper, chenopods, and steppe herbs. The intervening IS-5b and IS-5d were cool and maintained open forests of pine, spruce, *Artemisia*, and grass.

The early Holocene and the LGM at Carp Lake stand out as unique periods. The low representation of *Artemisia* and spruce in the Holocene is unprecedented, as is the relatively high percentage of arboreal pollen. The early Holocene is characterised by steppe, in contrast to the previous interglaciation, which registers a diverse open forest. The LGM featured abundant *Artemisia* and Poaceae, during cold dry conditions. These two periods represent extremes in global controls (Bartlein, 1996), and as such they provide useful reference points for reconstructing earlier periods in the Quaternary.

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