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Effects of the White River Ash Event on Aquatic Environments, Southwest Yukon, Canada

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ABSTRACT. Chironomid and sedimentary records from four lakes in the southwest Yukon reveal that the effects of the White River Ash event on aquatic environments varied with distance from the source vent, with sites closer to the source experiencing a greater impact. Upper Fly and Jenny Lakes, located ~200 km away from the volcano, had the thinnest ash layers. The Upper Fly site showed no response to the fallout of the ash, but at Jenny Lake the ash event affected the lake environment for almost 20 years. Donjek Kettle and Lake WP02, which were closer to the source (~100 km), had considerably thicker ash layers that substantially affected the aquatic ecosystems. Initial impacts of the tephra on the aquatic environments at these sites lasted about 60 years; however, the chronic effects of the tephra deposition on the chironomid community continued for up to 40 years longer. Chironomid community abundance declined in the lake environments affected by White River Ash fallout following the event. However, species composition remained the same after recovery of the aquatic ecosystem as in the pre-deposition chironomid community.

Key words: chironomid, volcanic ash, tephra, lake sediments, lake ecosystem, redundancy analysis, Mount Churchill, Holocene, Yukon

RÉSUMÉ. Les enregistrements sédimentaires et les enregistrements de chironomidés en provenance de quatre lacs du sud-ouest du Yukon révèlent que les effets de l'événement de dépôt de cendres de la rivière White sur les milieux aquatiques varient en fonction de la distance qui les sépare de la source de l'évent, les emplacements les plus près de la source ayant subi les conséquences les plus importantes. Les lacs Upper Fly et Jenny, situés à environ 200 km de distance du volcan, présentaient les couches de cendres les plus minces. L'emplacement d'Upper Fly n'affichait aucune réaction en réponse à la tombée des cendres, tandis que dans le cas du lac Jenny, la tombée des cendres a eu des incidences sur l'environnement du lac pendant près d'une vingtaine d'années. Les emplacements de Donjek Kettle et du lac WP02, qui se trouvaient plus près de la source (environ 100 km), présentaient des couches de cendres considérablement plus épaisses, ce qui a eu des effets considérables sur les écosystèmes aquatiques. Les incidences initiales du téphra sur les milieux aquatiques de ces emplacements ont duré une soixantaine d'années. Toutefois, les effets chroniques du dépôt de téphra sur les chironomidés se sont poursuivis pendant une quarantaine d'années de plus. Après le dépôt des cendres, l'abondance des chironomidés a diminué dans les milieux lacustres de la rivière White. Cela dit, les espèces de chironomidés sont demeurées les mêmes après le rétablissement de l'écosystème aquatique qu'avant le dépôt des cendres.

Mots clés : chironomidés, cendre volcanique, téphra, sédiments lacustres, écosystème lacustre, analyse par redondance, mont Churchill, holocène, Yukon

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INTRODUCTION

Explosive volcanic eruptions eject large quantities of tephra that settle on the landscape and have the potential to affect both terrestrial and aquatic ecosystems (Birks and Lotter, 1994; Hickman and Reasoner, 1994; Lotter et al., 1995). In freshwater lakes, certain processes triggered by the deposition of volcanic ash can alter lake-water chemistry. Chemical weathering of the ash increases inorganic nutrients in solution (Edmondson, 1984), and the ash layer can also form a physical boundary at the sediment-water interface that can inhibit phosphorus recycling from the sediments, thereby increasing the silica-phosphorus ratio (Si:P) within the lake (Barker et al., 2000; Telford et al., 2004). Both of these mechanisms have the potential to affect the aquatic community (e.g., Barsdate and Dugdale, 1972; Abella, 1988).

In this paper, we report on the impacts of ash events on aquatic ecosystems in the southwest Yukon, Canada,

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through the analysis of lake sediment cores. Benthic organisms that occupy the interstitial areas at the bottom of the lake may be affected by decreased access to food resources due to the ash deposition, but also by the physical effects of large ash volumes that can potentially smother taxa (Edmondson, 1984). Chironomids (Diptera: Chironomidae) are the larval stage of non-biting midges that inhabit the benthic zone of lakes and consume organic detritus. Following emergence of the adult midge from the pupa, the chitinous head capsule of the larval casing becomes preserved within the sediments and can be identified. Changes in chironomid community composition and abundance following tephra events have been noted (e.g., Tsukada, 1972; Heinrichs et al., 1999; Massaferro et al., 2005; Araneda et al., 2007).

In the southern Yukon, major ash deposition events blanketed the area at least twice in the past 2000 years (Lerbekmo and Campbell, 1969; Lerbekmo, 2008) as the result of two late-Holocene volcanic eruptions that occurred about 4 BC and AD 803 (Lowdon and Blake, 1968; Clague et al., 1995). The earlier eruption was responsible for an ash plume that straddles the Yukon-Alaska border, whereas tephra from the second, more explosive eruption, the White River Ash event (WRA), covered most of the southern Yukon, extending as far east as Great Slave Lake in the Northwest Territories (Fig. 1; Robinson, 2001; Lerbekmo, 2008). Prevailing winds at the time of the eruptions were responsible for the deposition of the ash in different directions; today, upper atmosphere winds in the Yukon-Alaska region typically blow eastward in winter and northward in summer, suggesting summer deposition for the northern lobe and winter deposition for the eastern lobe (Workman, 1979; West and Donaldson, 2002). Although the location of the source of the WRA is not entirely clear—whether Mount Churchill, Alaska, or a vent under the Klutlan Glacier ~10 km to the east (Richter et al., 1995; Lerbekmo, 2008)—the source is not so important in this study. The ash deposition was presumably a one-point-in-time event across the southwest Yukon, and regardless of its source, the event left a record of the extent of the ash impact through the measure of the ash thickness in lake sediment cores. Therefore, study of the lake sediments of this area provides a unique opportunity to determine the impact of this abrupt event on aquatic environments.

Although studies have addressed the effects of the WRA on human and some wildlife populations (Workman, 1979; Hare et al., 2004), the impact of this catastrophic event on aquatic ecosystems has not been fully investigated. In this paper, we will examine the effects of the ash deposition event ca. AD 803 on four lakes in the southwest Yukon. Using sediment records from each site, we infer conditions that existed before and after the WRA; we combine measures of ash deposition, paleoproduction, and chironomid community abundance with an independent paleotemperature record to develop an integrated picture of the impacts of the ash deposition event on past aquatic ecosystems.

STUDY SITES

Sediment cores were collected from four lakes in the interior southwest Yukon within the eastern plume of the WRA (Fig. 1a). Two lakes are ~200 km from the source region of the WRA: Upper Fly Lake (61˚2.4′ N, 138˚5.4′ W, 1326 m a.s.l., 10.5 ha surface area) is located at the alpine tree line, whereas Jenny Lake (61˚2.4′ N, 138˚21.6′ W, 817 m a.s.l., 19.9 ha) is just to the east of Kluane Lake in an area of open boreal forest interspersed with small grasslands (Fig. 1b). Upper Fly Lake has no visible inputs, but has a stream flowing into the larger Fly Lake to the north, whereas Jenny Lake is a closed-basin kettle lake. The other two lakes, both of which are closed basins, lie within 100 km of the source region of the WRA: Donjek Kettle (unofficial name; 61˚41.4′ N, 139˚45.6′ W, 732 m a.s.l., 0.6 ha) is situated in the boreal forest, and Lake WP02 (unofficial name; 61˚28.8′ N, 139˚58.2′ W, 1463 m a.s.l., 0.65 ha) is in alpine tundra on the Wolverine Plateau. The records presented here also represent a replicated set of sedimentary and chironomid data because two of the four lakes are located in alpine tundra and two are from the boreal forest. One of the sites from each environment is located nearer to the source and as a consequence, has a deeper ash layer. Modern-day physical and chemical data from the lake environments are presented in Table 1.

METHODS

Field Methods

Sediment cores were retrieved from the lakes using a clear plastic tube fitted with a piston that was lowered on drive rods from a raft to the sediment. Rafts were stabilized with ropes attached to the shore. Cores of different lengths were collected from each site; however, only the portion of each core representing the years ~ AD 650 to AD 1150 was used for this study (Table 2). At Lake WP02, a thick ash layer was observed when the core was collected; however, the section of the core below the ash layer was disturbed in transit, and therefore only the portion above the ash was available for analysis (~ AD 800 to AD 1150).

Laboratory Methods

Core chronologies were determined using ^{210}Pb and accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dating methods, the known ages of tephra layers (4 BC from Lowdon and Blake, 1968, and AD 803 from Clague et al., 1995), and linear interpolation between dates (Tables 3 and 4). Lead-210 was measured at Flett Research Ltd. (Winnipeg, Manitoba) using alpha spectrometry on radiation emitted by ^{210}Po. A constant rate of supply (CRS) model was used with the ^{210}Pb analysis to date the sediments with measurable ^{210}Pb activity for Upper Fly Lake, Jenny Lake, and Donjek Kettle, and a constant initial concentration

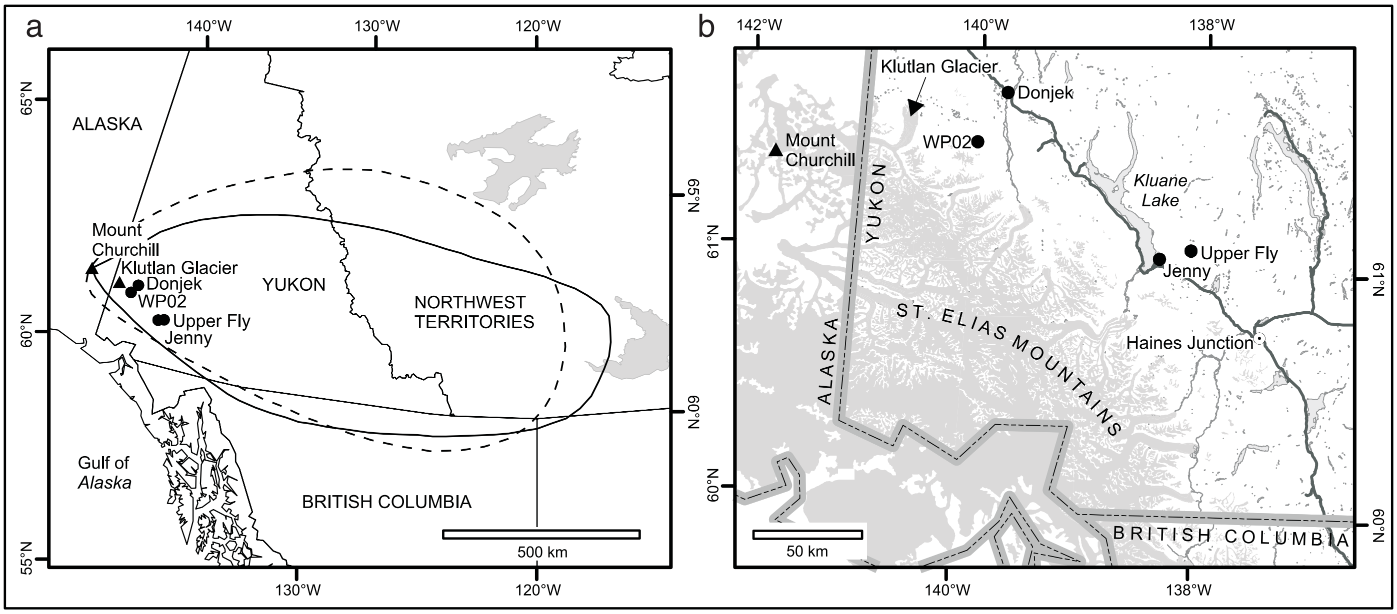

FIG. 1. Maps showing locations of Upper Fly Lake, Jenny Lake, Donjek Kettle, and Lake WP02 in the southwest Yukon. a) Study lakes in relation to the extent of the White River Ash after Lerbekmo (2008; dashed line) and Robinson (2001; solid line); b) Location of sites in relation to topography, Mount Churchill (Alaska), and the Klutlan Glacier.

(CIC) model was applied to unsupported ^{210}Pb activity versus cumulative dry weight values from Lake WP02. At this site, lack of sediment precluded reaching background (^{210}Pb activity below the "years before present" data); however, the reasonably constant sedimentation rate found there justified the use of the CIC model (Appleby, 2001). Terrestrial and aquatic macrofossils were extracted from the sediments and sent to Beta Analytic Ltd. (Miami, Florida) for ^{14}C dating. Dates were calibrated to calendar years using CALIB 6.0.1 calibration software and the IntCal calibration dataset (Reimer et al., 2009).

Magnetic susceptibility was measured on the sediment cores at 1 cm intervals using a Bartington MS2 meter (Thompson et al., 1975). Loss-on-ignition (LOI; Heiri et al., 2001) was used to determine the organic and carbonate content of the sediments, and the residual percentage was designated as the silicate content of the sediments. A wet-alkali digestion technique was used to extract biogenic silica (BSi) that was determined using a spectrophotometer (DeMaster, 1981; Parsons, 1984). Duplicate samples of known BSi content provided by an inter-laboratory study (Conley, 1998) were incorporated into each extraction batch to ensure laboratory experimental control.

Sediment was subsampled for chironomid head capsules at 0.25 cm intervals above and below the ash layer. Between 0.25 and 16.8 cm^3 of wet sediment was processed using standard methods, and head capsules were hand-picked with forceps from a Bogorov sorting tray, dried on a coverslip, and mounted using Entellan© (Walker, 2001). The number of capsules per sample varied from 1 to 320.5; although the numbers are in some cases very low, this result was due to the fine-resolution sampling interval. We indicate in our results the location of the low count sums. Chironomids were identified under 200× to 400× magnification primarily after Wiederholm (1983), with reference to Larocque and Rolland (2006), Brooks et al. (2007), and Barley (2004). The group "Other Tanytarsina" includes undifferentiated specimens that could not be assigned to other Tanytarsini groups.

Paleoclimate records are available elsewhere of the entire Holocene from Upper Fly Lake (Bunbury and Gajewski, 2009a) and of the past 2000 years from all sites (Bunbury and Gajewski, 2012). Those papers in some cases combined sediment intervals that are treated separately here, since for this study the sediments were sampled at higher temporal resolution. Details of the chronology, as well as the lower-resolution paleoenvironmental context for the present study, can be found in those previous papers.

Data Analysis

Chironomid taxa are presented as percentages of all head capsules counted. Only those taxa encountered in more than two samples, or which comprised two percent or greater abundance, or both, are presented in the stratigraphic diagrams prepared using the program C2 (Juggins, 2003) and the ordination analyses performed in CANOCO 4.5 (ter Braak and Šmilauer, 2002). Concentrations represent the total number of chironomid head capsules (hc) per cubic centimeter of sediment in a given level and represent the abundance of chironomids between ~ AD 650 and AD 1150. Detrended canonical correspondence analysis (DCCA) and redundancy analysis (RDA) were performed on square-root transformed percentage data matrices of 12 species and 49 samples from Upper Fly Lake, 14 species and 40 samples from Jenny Lake, 11 species and 28 samples from Donjek Kettle, and 15 species and 21 samples from Lake WP02. DCCAs constrained to age revealed short

TABLE 1. Physical and chemical data from the four lakes in the southwest Yukon.

Lake	Lake surface area (ha)	Sampling depth (m)	Conductivity (µS cm^{-1})	pH	Alkalinity (mg^{-L})	Total Kjeldahl nitrogen (µg^{-L})	Total phosphorus (µg^{-L})
Upper Fly	10.5	4.0	210	7.7	101	0.05	26.0
Jenny	19.9	4.2	640	8.7	197	1.56	11.0
Donjek	0.6	6	270	8.6	139	0.71	12.0
WP02	0.65	4.3	28	8.1	13	0.42	12.0

TABLE 2. Depth, length, and date range of core sections, as well as resolution obtained above and below the ash layer in the chronologies of the four sites in the southwest Yukon.

Site	Depth (length) of core section (cm)	Date of core section (AD years)	Resolution (years)	
			Above	Below
Upper Fly	38–60 (22)	630–1190	6–50	6–50
Jenny	58–96 (38)	644–1167	2–55	11–23
Donjek	23.5–35.25 (11.75)	553–1190	10–40	30
WP02	25.5–37.75 (12.25)	803–1204	8–60	na

gradient lengths in the chironomid data at all sites (Upper Fly Lake = 0.5 standard deviation (SD) units; Jenny Lake = 0.7 SD units; Donjek Kettle = 0.8 units; and Lake WP02 = 0.7 units); this result indicated that RDA (linear ordination methods) were appropriate (ter Braak and Prentice, 1988). Explanatory variables in the RDAs from each site included sediment organic content (Organics), sediment carbonate content (Carbonates), sediment silicate content (Silicates), biogenic silica content (BSi), and chironomid concentrations (Concentrations). An important consideration in the RDAs was to differentiate between the effects of the WRA and those of climate on the aquatic environment; therefore, we included a varve-inferred mean summer air temperature reconstruction (Temperature) from a lake in Alaska (Loso, 2009) in each of the analyses. Sedimentary and climate data were linearly interpolated to assign values to corresponding chironomid levels for each of the RDAs.

RESULTS

Sediments and Chronology

The WRA was easily identified in the magnetic susceptibility plots with sites closer to the source vent containing substantially greater amounts of tephra (Fig. 2); this pattern has been recognized at other lakes in the region (Bunbury and Gajewski, 2009b). The ash layer was 0.1 cm thick at Upper Fly Lake, 0.3 cm at Jenny Lake, and 44 cm at Donjek Kettle. The portion of the core from Lake WP02 below 33 cm was disturbed; therefore, we were unable to measure the total tephra thickness at this site accurately or to use the sediment below the WRA (Fig. 2d). Nevertheless, a thick layer of tephra was observed, and this core will be used to evaluate environmental response to the WRA at this site. A second, thinner tephra was identified in the Donjek Kettle core (Fig. 2c); however, aside from using this date in the chronology from that site, we will not discuss it further.

Lead-210 dating of the uppermost sediments, 10 radiocarbon determinations, and the dates of the tephra layers were used to estimate the sedimentation rates, with linear interpolation between dates at all four sites (Fig. 3; Tables 3 and 4). A correction was applied to the age-depth curve for Upper Fly Lake because the ^{14}C dates at this site were too old (Fig. 3a). The correction involved computing two regressions: one on the seven ^{14}C dates from the entire 298 cm lake sediment core (intercept a = 885 years; see Bunbury and Gajewski, 2009, for ages) and the second on the seven ^{210}Pb dates and the date of the WRA (~ AD 803; intercept b = 195 years) (Table 3). The difference resulted in a correction of 690 years (885 years minus 195 years), which we applied to the two ^{14}C dates included in this chronology, using an approach similar to that, for example, of Peros and Gajewski (2009). The final chronology was established with seven ^{210}Pb dates, two corrected ^{14}C dates, and the date of the WRA (Fig. 3a). No correction was applied to the dates from the other three sites. Ages were assigned to the Jenny Lake sediment core using five ^{210}Pb dates, two ^{14}C dates, and the date of the WRA. One of the ^{14}C dates was located stratigraphically above the WRA, but because it was older, it was not incorporated into the chronology (Fig. 3b). At Donjek Kettle, 11 ^{210}Pb dates, three ^{14}C dates, and the dates of two tephras (WRA, ~ AD 803; WRA2, ~ AD 4) were available; however, one of the dates at this site was rejected because it was older and located above the WRA (Fig. 2c, Tables 3 and 4). At Lake WP02, 11 ^{210}Pb dates, one ^{14}C date, and the date of the WRA were used, but a second ^{14}C date, located above the WRA but younger than its location indicated, was also rejected. Dates of samples on all graphs are presented as AD years (e.g., AD 650). The combination of the interpolated dates from our chronologies and the fine interval sampling performed around the WRA enables us to estimate dates above the ash at all sites within 10 years (Fig. 3, Table 2).

Chironomids

At Upper Fly Lake, *Sergentia*, *Cricotopus*/*Orthocladius*, Other Tanytarsina, *Chironomus anthracinus*-type, and *Paratanytarsus* were relatively abundant between AD 650 and

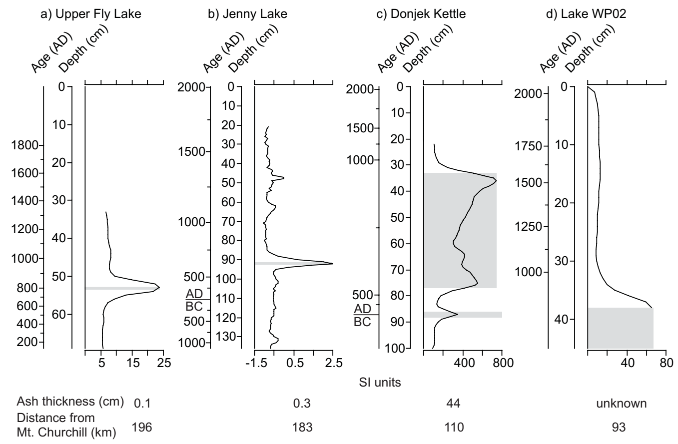

FIG. 2. Magnetic susceptibility depicting the timing and thickness of the White River Ash in lake sediment cores from the southwest Yukon (Lowdon and Blake, 1968; Clague et al., 1995). Shaded area illustrates the thickness of the ash at each coring location: a) Upper Fly Lake, b) Jenny Lake, c) Donjek Kettle, and d) Lake WP02. Distance from Mount Churchill, Alaska, is indicated for each site. Note varying scales on the x and y axes.

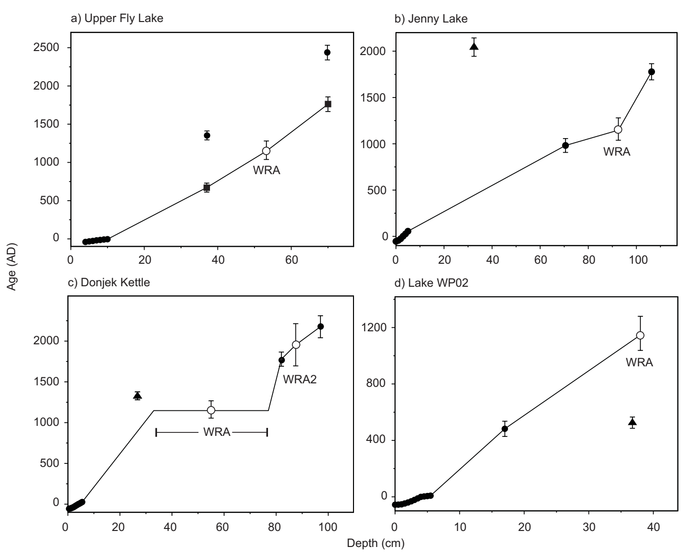

FIG. 3. Age-depth chronologies for a) Upper Fly Lake, b) Jenny Lake, c) Donjek Kettle, and d) Lake WP02, southwest Yukon. The solid circles in the uppermost 10 cm are ^{210}Pb determinations, and those with error bars are calibrated ^{14}C dates. Triangles are rejected ages, as they were older than the well-dated White River Ash. Open circles indicate the depths and ages of the White River Ash (AD 803 [2σ age range AD 694 to AD 936]) and at Donjek Kettle the WRA2 (4 BC [2σ age range 265 BC to AD 259]). In a), the solid squares are dates corrected by subtracting 690 years (the difference in the intercept of a regression through the radiocarbon dates and the ^{210}Pb and WRA ages) in order to align the radiocarbon chronology with the WRA. See Results section for details.

AD 1150; however, none of these taxa exhibited distinctive changes immediately after the ash event (Fig. 4a). At Jenny Lake, the most abundant taxa between AD 650 and AD 1150 were *C. anthracinus*-type, which clearly dominated the assemblage before the ash event, and Other Tanytarsina (Fig. 4b). Following the ash deposition, several taxa in the Tribe Chironomini appeared or increased in abundance at the expense of *C. anthracinus*-type, which decreased for about six years after ~ AD 810, increased briefly, and then decreased again between ~ AD 840 and AD 900. Tanytarsini and Orthocladiinae taxa were rare or absent between AD 750 and AD 800, then increased following the ash deposition, although in some cases the increase began just below the ash.

TABLE 3. Lead-210 dates from four lake sediment cores, southwest Yukon computed using constant rate of supply (CRS; Upper Fly Lake, Jenny Lake, Donjek Kettle) and constant initial concentration (CIC; Lake WP02) models. AT = alpine tundra site, BF = boreal forest site.

Depth (cm)	^{210}Pb total activity (Bq/g)	Years before present[1]
Southeast sites:		
Upper Fly (AT)		
3.0 – 4.0	15.54	6.8
4.0 – 5.0	12.80	13.7
5.0 – 6.0	10.48	20.3
6.0 – 7.0	8.93	27.6
7.0 – 8.0	6.77	32.9
8.0 – 9.0	5.53	38.4
9.0 – 10.0	4.16	42.8
10.0 – 11.0	3.35	
14.0 – 15.0	2.25	
19.0 – 20.0	1.80	
24.0 – 25.0	1.81	
Jenny (BF)		
0.0 – 1.0	9.62	10.0
1.0 – 2.0	7.42	28.2
2.0 – 3.0	4.59	55.4
3.0 – 4.0	1.50	81.0
4.0 – 5.0	0.57	109.2
5.0 – 6.0	0.25	
6.0 – 7.0	0.09	
7.0 – 8.0	0.01	
Northwest sites:		
Donjek (BF)		
0.0 – 0.5	9.61	1.0
0.5 – 1.0	13.61	4.7
1.0 – 1.5	10.08	10.4
1.5 – 2.0	7.94	16.9
2.0 – 2.5	7.94	25.7
2.5 – 3.0	6.62	36.6
3.0 – 3.5	4.42	45.8
3.5 – 4.0	4.14	55.7
4.0 – 4.5	3.3	64.0
4.5 – 5.0	2.77	73.4
5.0 – 5.5	2.36	82.0
5.5 – 6.0	1.75	
6.0 – 6.5	1.71	
7.0 – 7.5	1.72	
8.0 – 8.5	1.72	
10.5 – 11.0	1.89	
WP02 (AT)		
0.0 – 0.5	29.74	0.5
0.5 – 1.0	31.57	2.7
1.0 – 1.5	26.92	8.2
1.5 – 2.0	21.62	15.5
2.0 – 2.5	17.29	23.9
2.5 – 3.0	11.90	33.6
3.0 – 3.5	10.44	44.3
3.5 – 4.0	7.52	55.2
4.0 – 4.5	6.80	58.2
4.5 – 5.0	6.46	61.1
5.0 – 5.5	5.84	63.9

[1] Upper Fly Lake = AD 1997, Jenny Lake = AD 2003, Donjek Kettle and Lake WP02 = AD 2006.

TABLE 4. AMS radiocarbon ages from four lake sediment cores, southwest Yukon. AT = alpine tundra site, BF = boreal forest site.

Lake	Depth (cm)	Lab Code	Conventional radiocarbon age (yr BP)	2-sigma calibrated age range (cal yr BP)[1]	Median calibrated age (cal yr BP)	$\delta^{13}C/^{12}C$ (‰)	Material
Southeast sites:							
Upper Fly (AT)	34.0–36.0	Beta 229092	1490 ± 40	1302–1420	1360	-26.3	Macrofossils
	69.0–71.0	Beta 229093	2440 ± 40	2355–2547	2450	-22.2	Macrofossils
Jenny (BF)	31.5–34.5[2]	Beta 256717	2070 ± 40	1945–2144	2045	NA	Macrofossils
	69.5–71.5	Beta 255709	1040 ± 40	907–1057	980	-24.6	*Picea* twig
	105.0–107.0	Beta 255710	1820 ± 40	1691–1865	1780	NA	Twig, macrofossils
Northwest sites:							
Donjek (BF)	26.0–27.5[2]	Beta 255707	1350 ± 40	1227–1336	1280	-34.2	Moss fragments
	82.0–83.0	Beta 255708	1820 ± 40	1691–1865	1780	-33.8	Plant fragments
	96.0–98.5	Beta 256716	2160 ± 40	2041–2311	2175	NA	Macrofossils
WP02 (AT)	17.0–17.5	Beta 255711	430 ± 40	428–536	488	-29.4	Moss fragments
	36.5–38.0[2]	Beta 255712	480 ± 40	475–556	515	-29.5	Moss/plant fragments

[1] Calibration was based on IntCal04 (Reimer et al., 2009).
[2] These ages were not used in the respective chronologies.

At Donjek Kettle, Other Tanytarsina dominated the chironomid assemblage before the ash event (Fig. 4c); this dominance declined after AD 800, when a more diverse assemblage appeared. At Lake WP02, Other Tanytarsina, *Corynocera ambigua*, *Corynocera oliveri*-type, *Sergentia*, and *Zalutschia lingulata*-type were most abundant. The relative abundance of several taxa was greater immediately after deposition of the tephra and declined subsequently (i.e., *Hydrobaenus*/*Oliveridia*, *Heterotrissocladius maeaeri*-type, *Cricotopus*/*Orthocladius*, and *Stempellinella*/*Zavrelia*; Fig. 4d).

The concentrations of chironomids in the sediment changed little in the record at Upper Fly Lake (Fig. 5). At Jenny Lake, concentrations before the WRA were low (~2 hc•cm[3]), then increased (up to 9 hc•cm[3]) for ~5 years after the ash event, and subsequently decreased until ~ AD 815. The values then increased (5 to 9 hc•cm[3]) for about 20 years until AD 840. At Donjek Kettle, concentrations were ~10 hc•cm[3] before the deposition of the tephra, after which they decreased slightly to 3 or less hc•cm[3] until ~ AD 840. Following this, concentrations steadily increased, reaching 28 hc•cm[3], and after ~ AD 900 they declined to values similar to those that existed prior to the WRA. At Lake WP02, from tephra deposition until ~ AD 870, concentrations were lower (up to 47 hc•cm[3]) than during the subsequent period (AD 870 to AD 960), when they tended to be greater than 100 hc•cm[3].

Sediment Biogenic Silica, Organic and Carbonate Content

At Upper Fly Lake, BSi, Organics and Carbonates in the sediments showed that the post-eruption values were very similar to the pre-eruption values (Fig. 5). At Jenny Lake, BSi values were also comparable before and after the ash event, whereas organic content decreased following the ash deposition, remaining low until ~ AD 820. Organic content then abruptly increased and remained relatively high, although with several oscillations. Carbonate values decreased for about five years after the ash event, but otherwise showed little change.

At Donjek Kettle, BSi values were low (up to 3%) between ~ AD 650 and AD 803 and increased (up to 5% higher) immediately following the WRA until just after AD 880. Although this increase was not large, the average BSi values in the entire Donjek Kettle record were only ~2% (Bunbury and Gajewski, 2012), and thus the values immediately following the WRA are the highest in the sequence. At this site Organics and Carbonates appear to have decreased before the WRA, as the transition from ash to sediment in the core was not discrete, presumably because of some mixing of the sediments. However, by about AD 880, values of Organics and Carbonates had returned to levels similar to those measured at ~ AD 750. At Lake WP02, BSi, Organics, and Carbonates increased after the ash deposition, following a period of about 60 years when values were lower.

Redundancy Analysis

Redundancy analysis was used to determine where the pre- and post-eruption assemblages ordinated in relation to the explanatory variables. The amount of variance in the chironomid data explained by the explanatory variables on the first three RDA axes differed between sites. The amount of variance explained by RDA axis 1 was comparable at Upper Fly and Jenny Lakes. Both Donjek Kettle and Lake WP02 had higher values, and the latter value was statistically significant ($p \leq 0.05$; Table 6).

In the Upper Fly and Jenny Lake tri-plots, measures of biological production (BSi, Organics, and Concentrations) were correlated with temperature, although less strongly at Upper Fly Lake. At Donjek Kettle and Lake WP02, production indices were negatively correlated with temperature. In all sites, Silicates were associated with changes in the assemblages, although the effect is stronger at the southeastern sites (Upper Fly and Jenny Lakes). Samples immediately after the ash deposition differed from others at the

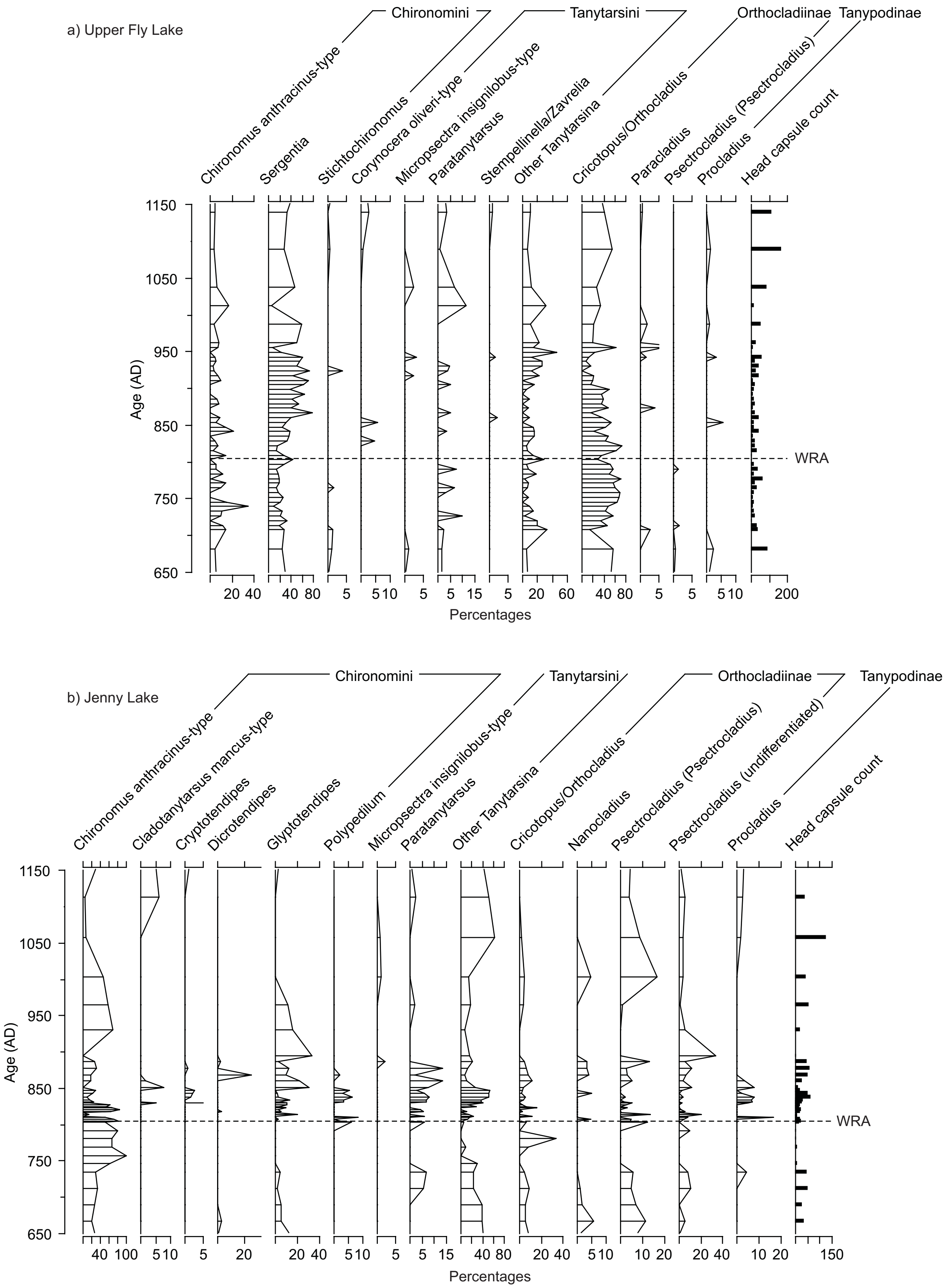

FIG. 4. Relative abundance of chironomid taxa from a) Upper Fly Lake, b) Jenny Lake, c) Donjek Kettle, and d) Lake WP02, southwest Yukon, organized by Tribe (Chironomini and Tanytarsini) and Subfamily (Orthocladiinae and Tanypodinae). The dashed horizontal lines represent the time of the White River Ash (AD 803). See Table 5 for taxon authorities. Note varying scales on the x and y axes.

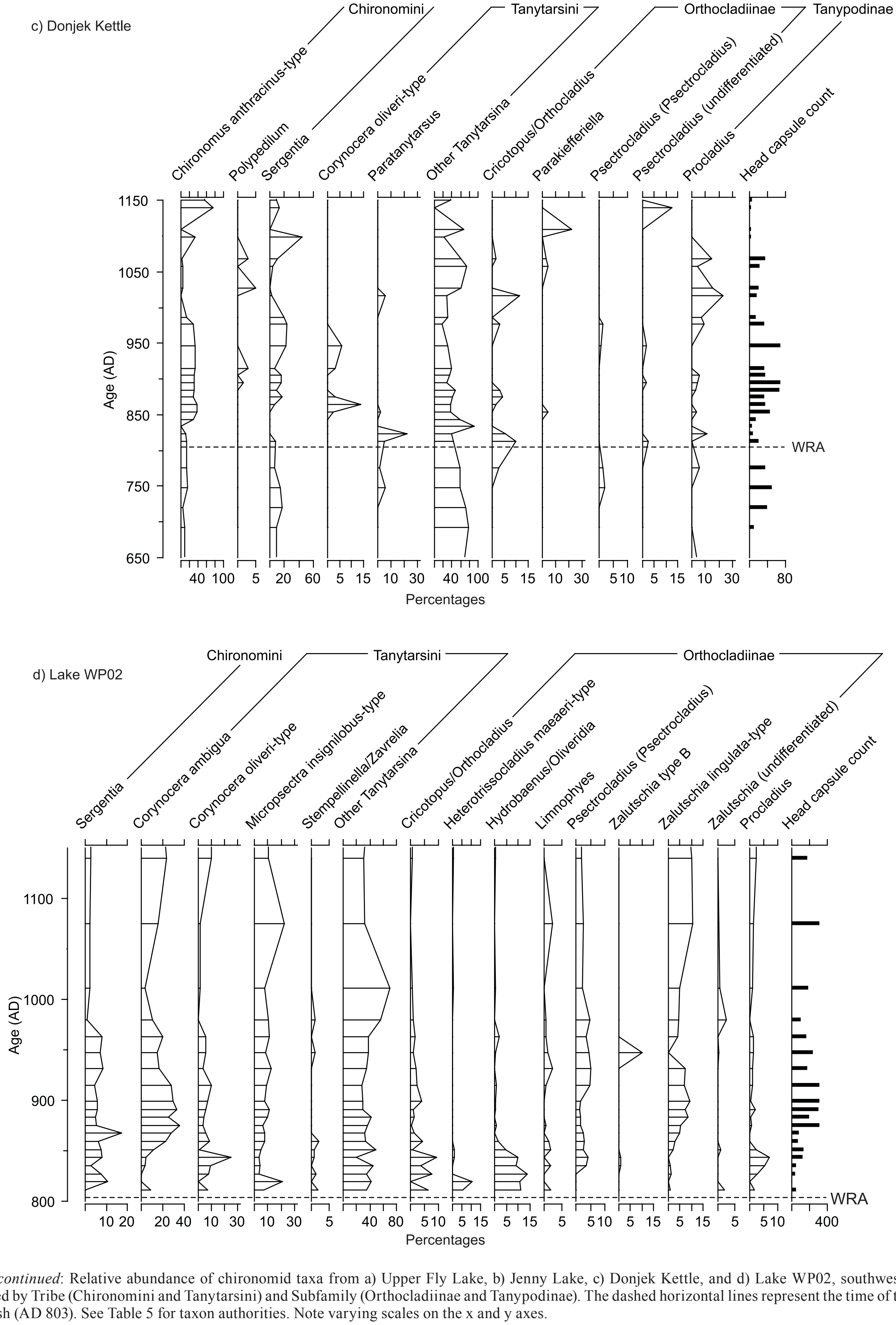

FIG. 4. *continued*: Relative abundance of chironomid taxa from a) Upper Fly Lake, b) Jenny Lake, c) Donjek Kettle, and d) Lake WP02, southwest Yukon, organized by Tribe (Chironomini and Tanytarsini) and Subfamily (Orthocladiinae and Tanypodinae). The dashed horizontal lines represent the time of the White River Ash (AD 803). See Table 5 for taxon authorities. Note varying scales on the x and y axes.

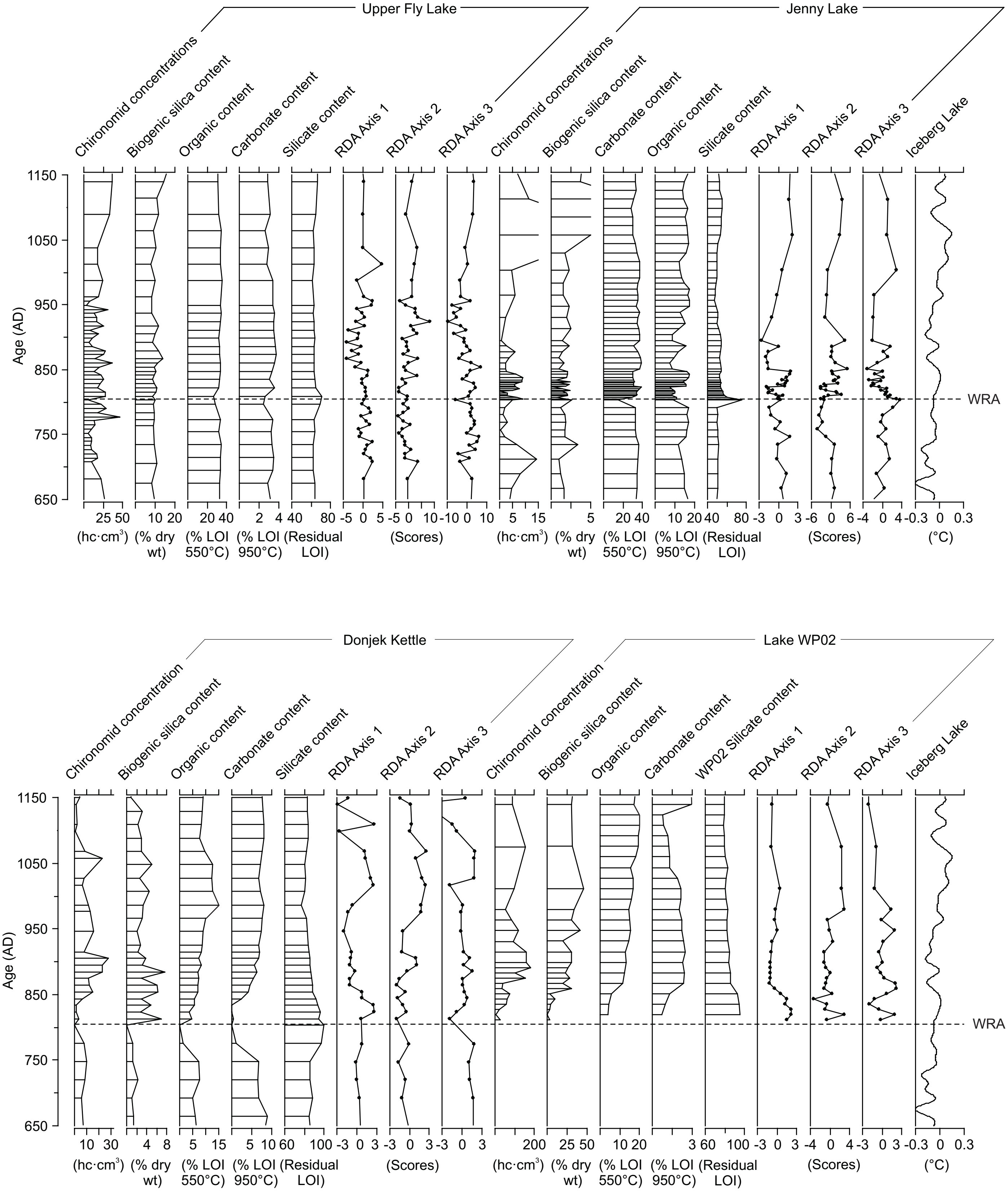

FIG. 5. Chironomid head capsule concentrations, biogenic silica, sediment organic, sediment carbonate, and sediment silicate content records between AD 650 and AD 1150 from Upper Fly Lake, Jenny Lake, and Donjek Kettle, and between AD 803 and AD 1150 from Lake WP02. A varve-inferred mean summer air temperature curve from Iceberg Lake in southeast Alaska (Loso, 2009) is provided for reference. The dashed horizontal lines represent the time of the WRA (AD 803). Note varying scales on x and y axes.

TABLE 5. Names and authorities of chironomid taxa presented in Figure 4, with the numbers used as labels in Figure 6.

No.	Taxon	Authority
1	*Chironomus anthracinus*-type	Zetterstedt, 1860
2	*Cladotanytarsus mancus*-type	(Walker)
3	*Cryptotendipes*	Lenz
4	*Dicrotendipes*	Kieffer
5	*Glyptotendipes*	Kieffer
6	*Polypedilum*	Kieffer
7	*Sergentia*	Kieffer
8	*Stictochironomus*	Kieffer
9	*Corynocera ambigua*	Zetterstedt, 1838
10	*Corynocera oliveri*-type	Lindeberg
11	*Micropsectra insignilobus*-type	Kieffer, 1924
12	*Paratanytarsus*	Bause
13	*Stempellinella/Zavrelia*	Brundin/Kieffer
14	Other Tanytarsina	
15	*Cricotopus/Orthocladius*	van der Wulp
16	*Heterotrissocladius maeaeri*-type	Brundin, 1949
17	*Hydrobaenus/Oliveridia*	Fries/Saether
18	*Limnophyes*	Eaton
19	*Nanocladius*	Kieffer
20	*Paracladius*	Hirvenoja
21	*Parakiefferiella*	Thienemann
22	*Psectrocladius* (*Psectrocladius*)	Kieffer (see Wiederholm, 1983)
23	*Psectrocladius* (undifferentiated)	Kieffer
24	*Zalutschia* type B	Lipina (Barley et al., 2006)
25	*Zalutschia lingulata*-type	Saether, 1976
26	*Zalutschia* (undifferentiated)	Lipina
27	*Procladius*	Skuse, 1889

three sites that have both pre- and post-eruption samples, although this group consisted of only 2–5 samples.

DISCUSSION

Studies investigating lakes affected by volcanic ashfall indicate that aquatic environments respond immediately to ash input (Kurenkov, 1966; Wissmar et al., 1982a, b, 1990; Lee, 1996), and paleoecological studies reveal that these environments return to conditions that existed prior to ash deposition events within 10 to 300 years (Barsdate and Dugdale, 1972; Abella, 1988; Lotter et al., 1995; Barker et al., 2000). The results presented here confirm these findings. The composition of the ash is dominated by silicates (67.4%; Lerbekmo and Campbell, 1969); therefore, we use the silicate content of the sediments (residual after ignition at 950˚C) as an index of the WRA impact in these lakes. In freshwater environments, biogenic silica (BSi; extracted using alkali digestion) derives from siliceous organisms, including diatoms, chrysophyte cysts, and to a lesser extent, sponge spicules, and higher values indicate greater primary production (Conley and Schelske, 2001). However, depending on the pH of the lake water (especially pH > 8.5), a change in the pH of lake sediments over time may result in the dissolution of amorphous silica and thereby alter the BSi record. Sediment organic content is composed of material washed into a lake from the watershed, as well as biota living within the lake (Kalff, 2001), and its value can be used to infer overall ecosystem production (e.g., Kaplan et al., 2002; Fortin and Gajewski, 2010). Increased carbonate content corresponds to higher lake-water pH in a spatial series of lakes (Fortin and Gajewski, 2009) and has been used as a proxy for pH in a sediment core (de Klerk et al., 2008). Although it is recognized that carbonate content may be affected by other factors, including water-level variations, there is no evidence of significant lake-level variations over the time period under study in these lakes. Chironomids are consumers that rely on primary production and organic matter as a food source; together, therefore, the various parameters measured in this study provide an integrated picture of the aquatic ecosystem and its response to the deposition of the tephra.

TABLE 6. Eigenvalues and percent of cumulative variance explained by the first three axes of a redundancy analysis (RDA) performed on the chironomid and environmental data from each of the four lakes, southwest Yukon.

Lake	RDA axis 1	2	3
Upper Fly			
Eigenvalues (λ)	0.088	0.031	0.010
Cumulative % variance explained	8.8	11.9	12.9
Jenny			
Eigenvalues (λ)	0.093	0.066	0.024
Cumulative % variance explained	9.3	15.9	18.3
Donjek			
Eigenvalues (λ)	0.141	0.051	0.024
Cumulative % variance explained	14.1	19.2	21.5
WP02			
Eigenvalues (λ)	0.358	0.078	0.034
Cumulative % variance explained	35.8	43.5	46.9

Few paleoclimatic records are available from the region that have a similar temporal resolution to this study, apart from a varve-inferred mean summer air temperature reconstruction in southeast Alaska (Loso, 2009). Therefore, we will use that climate record to help us differentiate between the effects of long-term temperature variations and those of the WRA on these sites.

At Upper Fly Lake, located in alpine tundra, neither the aquatic ecosystem (reflected by changes in the sedimentary variables) nor chironomid community abundance and composition appear to have been influenced by the ash input (Figs. 4 and 5). However, temperature does appear to have had an impact on chironomid production, as indicated by the association between chironomid concentrations and the Iceberg Lake temperature reconstruction (Fig. 6a, b). In contrast, at Jenny Lake, located just 10 km to the southwest in the boreal forest (Fig. 1b), the immediate impact of the WRA lasted several years, as shown by the decrease in organic content and chironomid concentrations and by changes in the chironomid assemblages (Figs. 5 and 6d). Although initially the chironomid concentrations increased following the ashfall, this increase may simply have been due to the resilience of *Chironomus anthracinus*-type, an opportunistic taxon that has been encountered elsewhere following significant environmental change (Fig. 4; Brooks, 1997). The coherency between the Iceberg Lake temperature reconstruction and RDA axis 1 indicates that a strong,

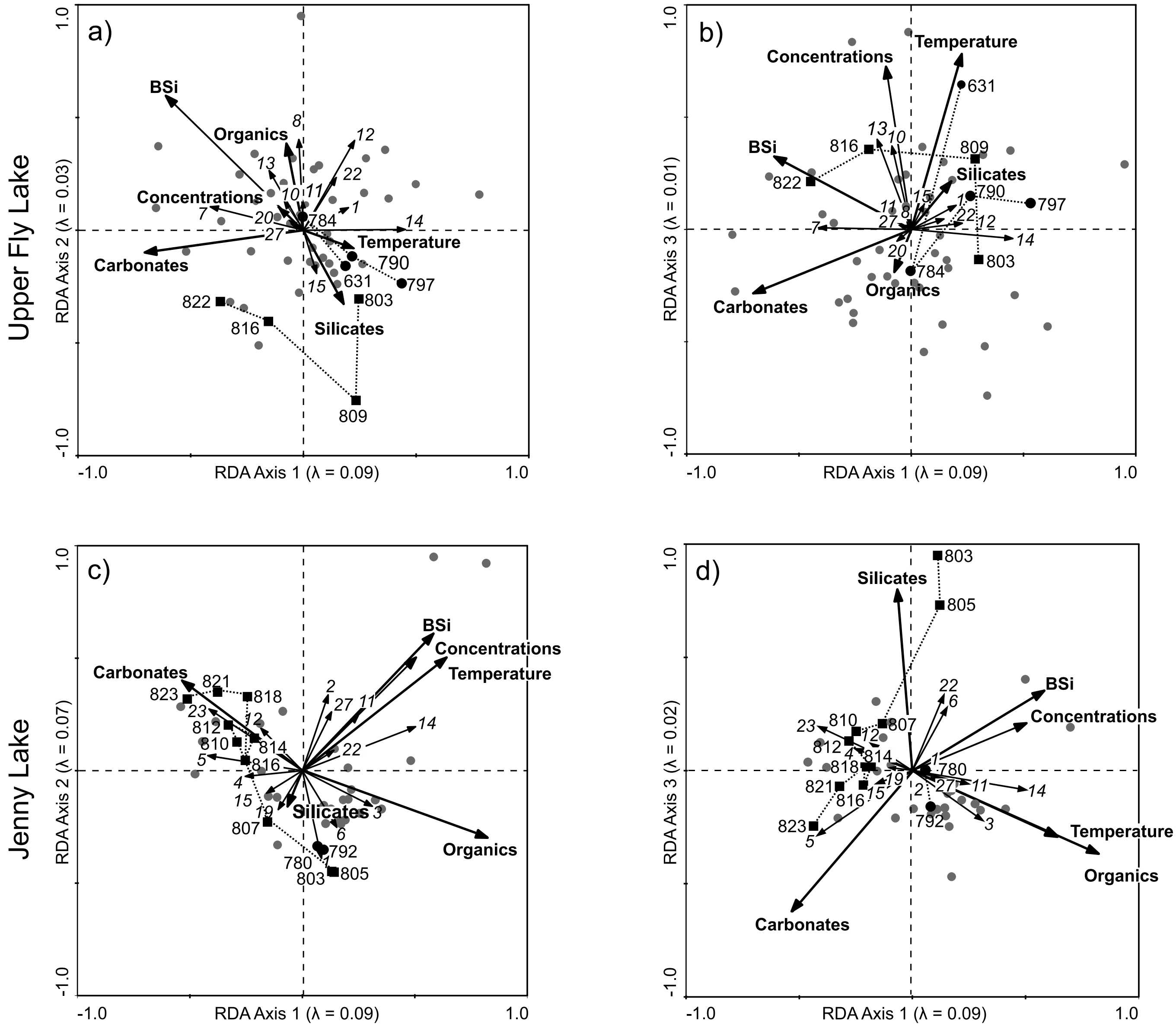

FIG. 6. Redundancy analysis (RDA) tri-plots for RDA axis 1 and 2, and RDA axis 1 and 3 from Upper Fly Lake, a) and b), Jenny Lake, c) and d), Donjek Kettle e) and f), and Lake WP02 g) and h), southwest Yukon. Labeled arrows are the environmental variable loadings, and numbered arrows are chironomid loadings. Solid black circles represent the scores of the samples just prior to the White River Ash (WRA; AD 803); solid black squares, scores immediately after the WRA; and grey circles, scores of all other samples. The dashed lines connect the scores and represent the trajectories, with a break at the time of the WRA.

long-term relation exists between the chironomid community and temperature (Figs. 5 and 6c, d). The very low biogenic silica content of the Jenny Lake record suggests that post-depositional dissolution may have occurred in these carbonate-rich sediments.

Sites located closer to the source vent had much thicker tephra layers and exhibited more obvious responses, with the immediate impact of the ash lasting ~50 years (Figs. 5 and 6e, g, h). With the exception of the biogenic silica content, the post-depositional changes in ecosystem-level parameters at these two sites resemble each other (Fig. 5). At Donjek Kettle, the ash induced an increase in primary production and a decrease in chironomid concentrations, whereas in Lake WP02, both trophic levels decreased. Large amounts of silicates throughout the sequence in the sediments in Donjek Kettle are partly due to loess input into the lake from the Donjek River valley. These values became elevated for about 50 years following the deposition of the WRA (Fig. 5). In addition to the decrease in chironomid production and organic matter content at Donjek Kettle, the lake water may have been more acidic, as suggested not only by the lower carbonate content of the sediments, but also by evidence in the chironomid community (Figs. 4c and 5). Taxa tolerant of lake water with lower pH were present immediately following the WRA and include *Chironomus anthracinus*-type, *Sergentia*, and Other Tanytarsina (Olander et al., 1999; Brooks et al., 2007). Except for Other Tanytarsina, the above taxa, *Paratanytarsus*,

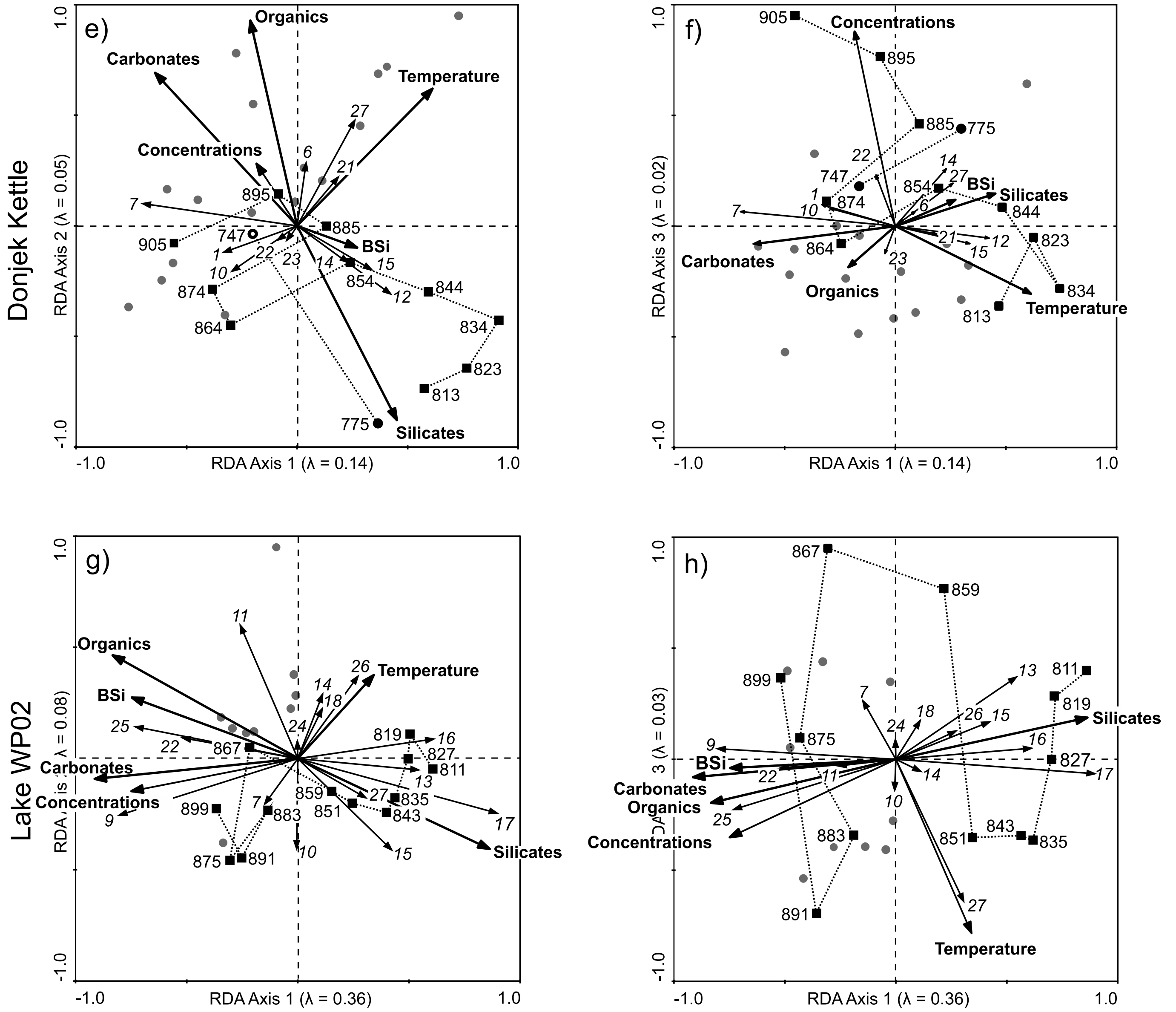

FIG. 6. *continued*: Redundancy analysis (RDA) tri-plots for RDA axis 1 and 2, and RDA axis 1 and 3 from Upper Fly Lake, a) and b), Jenny Lake, c) and d), Donjek Kettle e) and f), and Lake WP02 g) and h), southwest Yukon. Labeled arrows are the environmental variable loadings, and numbered arrows are chironomid loadings. Solid black circles represent the scores of the samples just prior to the White River Ash (WRA; AD 803); solid black squares, scores immediately after the WRA; and grey circles, scores of all other samples. The dashed lines connect the scores and represent the trajectories, with a break at the time of the WRA.

and *Cricotopus*/*Orthocladius* were encountered in minerogenic sediments in a modern chironomid study in this region (Wilson and Gajewski, 2004), suggesting they may be more resilient to the effects of the ash. Low chironomid concentrations indicate that the chironomid community was severely affected by the WRA for about 60 years (Figs. 5 and 6e). However, once the chironomids recovered from the initial effects of the ash, the community flourished until ~ AD 900.

Although pre-eruption conditions at Lake WP02 are not known, the synchronous nature of the chironomid concentration curve, RDA axis 1 scores, and the organic and carbonate content data with the same records from Donjek Kettle suggests a comparable impact (Fig. 5). Following the WRA, lower organic and carbonate content, reduced chironomid abundance, and altered chironomid community composition lasted until ~ AD 860. Other Tanytarsina were abundant at this lake following ash deposition, whereas *Hydrobaenus*/*Oliveridia* were most abundant immediately above the tephra layer (Fig. 4d). These taxa inhabit lakes with lower pH in the Canadian Arctic (Gajewski et al., 2005), suggesting more acidic conditions during that time. As the ecosystem recovered, taxa typically found in shallow, more productive lakes increased in abundance (e.g., *Corynocera* spp.).

At Donjek Kettle and at Lake WP02, chironomid concentrations exhibited similar tendencies until ~100 years after the deposition of the ash (Fig. 5). There may be evidence here of what Barker et al. (2000) refer to as an acute readjustment stage followed by a period of chronic ecosystem change. The acute effects on the community reduced chironomid production for about 60 years at these sites; a chronic phase lasted for another 40 years thereafter. This response was apparently independent of temperature changes occurring during this time, given the lack of correlation between the chironomid abundance and temperature data at these sites (Fig. 6e–h).

A key difference in the records from Donjek Kettle and Lake WP02 is their opposite tendencies in the BSi records following the WRA (Fig. 5). Increased diatom abundance has been attributed to the high ratio of silicon to phosphorus in the lake water (Abella, 1988; Lotter et al., 1995; Barker et al., 2000), caused by chemical weathering of the ash or by thick tephra layers that form a barrier between the sediments and the water column, reducing phosphorus recycling. This latter mechanism can be particularly influential at sites where one of these values is limited prior to ash input (Telford et al., 2004). Low BSi values below the ash suggest that this may have been the case at Donjek Kettle. The resulting increase in Si:P contributed to an increase in diatom concentrations following tephra deposition until just after ~ AD 880. This mechanism appears less important at Lake WP02, suggesting that BSi values may have been higher before the eruption, as they were after ~ AD 860.

Aquatic ecosystems with thin ash layers were either unaffected by the WRA or returned to pre-eruption conditions more quickly than did lakes with substantially thicker tephra layers. Ecosystem production appears to have been influenced by temperature during the period in question; nevertheless, evidence of a response to the WRA exists at three of the lakes. At Upper Fly Lake, the impact of the WRA was negligible, whereas ecosystems at the other sites exhibited a reaction to the tephra deposition. Recovery times varied from up to ~20 years at Jenny Lake to ~60 years at Donjek Kettle and Lake WP02, and at these latter two sites, the impact on the chironomid community lasted another ~40 years thereafter. Although the aquatic ecosystems were substantially affected at Donjek Kettle and Lake WP02, the impact did not alter the chironomid community composition.

Future studies of this nature should ensure that high-resolution analyses are performed for a long enough section of the core to capture the chronic environmental change. In addition, the known response of the aquatic environment to the WRA at Donjek Kettle and the presumed response at Lake WP02 suggest that this area would be particularly suitable for obtaining Holocene sequences and performing detailed, multiple proxy analyses to assess terrestrial and aquatic ecosystem response to both short-term and long-term environmental variability.

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