



Preliminary Report on the Late Pleistocene and Holocene Diatoms of Swamp Lake, Yosemite National Park, California, USA

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Abstract

Swamp Lake, Yosemite National Park, is the only known lake in California containing long sequences of varved sediments and thus has the potential to provide a high-resolution record of climate variability. This preliminary analysis of the diatom assemblages from a 947-cm-long composite sediment core (freeze core FZ02–05; 0–67 cm, Livingstone core 02–05; 53–947 cm) shows that the lake has been freshwater, oligotrophic, and circumneutral to alkaline throughout its ~16,000-year-long history. The first sediments deposited in the lake show that the vegetation in the watershed was sparse, allowing organic matter-poor silt and clay to be deposited in the basin. The basin filled quickly to a depth of at least 5 m and remained at least that deep for most of the sediment record. Several short intervals provided evidence of large fluctuations in lake level during the Holocene. The upper 50 cm of the core contains evidence of the Medieval Climate Anomaly and Little Ice Age.

Key words: paleolimnology, lake ontogeny, climate record

Introduction

Diatom studies from Sierra Nevada lakes have, until recently, been somewhat limited in number (Holmes *et al.* 1989, Whiting *et al.* 1989, Bloom *et al.* 2003) and have generally been focused on relatively short-term environmental changes. Studies using diatom stratigraphies for longer Holocene reconstructions are rare. Diatoms have also been part of multi-proxy studies focused on longer time scales (MacDonald *et al.* 2008) as well as numerous pollen, chironomid, and charcoal studies (Davis *et al.* 1985, Davis & Moratto 1988, Anderson 1990, Koehler & Anderson 1994, Porinchu *et al.* 2002, 2003, Brunelle & Anderson 2003, Potito *et al.* 2006, Hallett & Anderson 2010). These studies have provided an increasingly coherent story of environmental change in the central Sierra Nevada over the last 15,000 years: 1) a relatively warm Bølling-Allerød (~14,600–2,900 cal yr B.P.); 2) a cooler (by 2–4°C) Younger Dryas (~12,900–11,500 cal yr B.P.); 3) a gradual warming through the early Holocene; 4) a middle Holocene that was warmer and drier than present; and 5) a slight cooling in the late Holocene leading to modern conditions. These studies utilized uniform, structureless silts and clays or organic-rich gyttjas, sediments which are not ideal for high-resolution (annual to decadal) analyses except over the last couple of centuries.

A composite 947-cm-long sediment core (freeze core FZ02–05; 0–67 cm, Livingstone core 02–05; 53–947 cm) collected from Swamp Lake, located in the northwest corner of Yosemite National Park, Tuolumne County, California (37.95°N; 119.83°W; 1554 m a.s.l.) is partially varved. This record of paleoenvironmental changes in the central Sierra Nevada covers the last *ca.* 16,000 years. This site is unusual in its antiquity because late Pleistocene glacial advances in the region have limited most lake records to the last 12,000 years. This preliminary analysis of the diatom assemblages in Swamp Lake is part of a larger study evaluating late Quaternary climate variability on the western slope of the Sierra Nevada.

TABLE 1: Diatom taxa in Swamp Lake sediments found at more than 1% abundance in any sample.

<i>Achnanthes childanos</i> Hohn & Hellerman	<i>E. naegelia</i> Migula
<i>A. didyma</i> Hustedt	<i>Fragilaria capucina</i> var. <i>gracilis</i> (Østrup) Hustedt
<i>A. helvetica</i> (Hustedt) Lange-Bertalot in Lange-Bertalot & Krammer	<i>F. fasciculata</i> (Agardh) D.R. Williams and Round
<i>A. laterostrata</i> Hustedt	<i>F. nanana</i> Lange-Bertalot
<i>A. levanderi</i> Hustedt	<i>F. parasitic</i> Grunow
<i>A. microscopica</i> (Cholnoky) Lange-Bertalot & Krammer	<i>F. tenera</i> (W. Smith) Lange-Bertalot
<i>A. minutissima</i> Kützing	<i>Frustulia rhomboides</i> (Ehrenberg) Dayton
<i>A. nodosa</i> Cleve	<i>Gomphonema angustum</i> C.A. Agardh
<i>A. pusilla</i> Grunow in Van Heurck	<i>G. demerarae</i> (Grunow) Frenguelli
<i>A. rossii</i> Hustedt	<i>G. parvulum</i> (Kützing) Kützing
<i>Anomoeoneis brachysira</i> (Brébisson ex Kützing) Cleve	<i>Hantzschia amphioxys</i> (Ehrenberg) Grunow in Cleve & Grunow
<i>Asterionella formosa</i> Hassall	<i>Luticola mutica</i> (Kützing) Mann in Round, Crawford & Mann
<i>Aulacoseira alpigena</i> (Grunow) Krammer	<i>Meridion circulare</i> var. <i>constrictum</i> (Ralfs) Van Heurck
<i>A. ambigua</i> (Grunow) Simonsen	<i>Navicula cryptocephala</i> Kützing
<i>A. distans</i> (Ehrenberg) Simonsen	<i>N. digitulus</i> Hustedt
<i>A. italica</i> (Ehrenberg) Simonsen	<i>N. disjuncta</i> Hustedt
<i>A. lirata</i> var. <i>biseriata</i> (Grunow) Haworth	<i>N. laevissima</i> Kützing
<i>A. perglabra</i> (Østrup) Haworth	<i>N. radiososa</i> Kützing
<i>A. subarctica</i> (O. Müller)	<i>N. saxophila</i> Bock in Hustedt
<i>A. valida</i> (Grunow in Van Heurck) Krammer	<i>Neidium ampliatus</i> (Ehrenberg) Krammer in Krammer & Lange-Bertalot
<i>Brachysira vitrea</i> (Grunow) Ross in Hartley	<i>Nitzschia fonticula</i> (Grunow) Grunow in Van Heurck
<i>Caloneis molaris</i> (Grunow) Krammer in Krammer & Lange-Bertalot	<i>N. frustulum</i> (Kützing) Grunow in Cleve & Grunow
<i>C. undulata</i> (Gregory) Krammer in Krammer & Lange-Bertalot	<i>Pinnularia divergens</i> W. Smith
<i>Cyclotella striata</i> (Kützing) Grunow in Cleve & Grunow	<i>P. interrupta</i> W. Smith
<i>Cymbella amphicephala</i> Nägeli	<i>P. microstauron</i> (Ehrenberg) Cleve
<i>C. cesatii</i> (Rabenhorst) Grunow in A. Schmidt	<i>P. nodosa</i> (Ehrenberg) W. Smith
<i>C. gracilis</i> (Ehrenberg) Kützing	<i>P. subcapitata</i> Gregory
<i>C. naviculiformis</i> (Auerswald) Cleve	<i>Pseudostaurosira brevistriata</i> (Grunow in Van Heurck) Williams & Round
<i>Discostella pseudostelligera</i> (Hustedt) Houk & Klee	<i>P. brevistriata</i> var. <i>inflata</i> (Pantocsek) Edlund
<i>D. stelligera</i> (Cleve and Grunow) Houk & Klee	<i>Sellaphora pupula</i> (Kützing) Mereschkowsky
<i>Encyonema minutum</i> (Hilse ex Rabenhorst) Mann in Round, Crawford & Mann	<i>Stauroneis anceps</i> Ehrenberg
<i>E. silesiacum</i> (Bleisch ex Rabenhorst) Mann in Round, Crawford & Mann	<i>Staurosira construens</i> var. <i>venter</i> (Ehrenberg) Hamilton <i>et al.</i>
<i>Eunotia arcus</i> Ehrenberg	<i>Staurosirella lapponica</i> (Grunow in Van Heurck) Williams & Round
<i>E. glacialis</i> Meister	<i>S. pinnata</i> (Ehrenberg) Williams & Round
<i>E. musicola</i> var. <i>tridentula</i> Nörpel & Lange-Bertalot in Lange-Bertalot	<i>Surirella bifrons</i> Ehrenberg
	<i>Synedra ulna</i> (Nitzsch) Ehrenberg
	<i>Tabellaria fenestrata</i> (Lyngbye) Kützing

Study Site

Swamp Lake is located at 1554 m a.s.l., has a surface area of approximately 8 ha and a maximum depth of more than 20 m (Fig. 1; Smith & Anderson 1992). The watershed covers about 130 ha. At present, there is no permanent inlet stream, although the bathymetry of the lake suggests that a stream may have flowed into the eastern end of the lake at some time during its history. There is a shallow shelf and marshy area at the western end (outflow) of the lake. The lake basin comprises the biotite granite and granodiorite of the Early Cretaceous El Capitan Granite. The southern and southwestern margin of the lake is bordered by Quaternary alluvium (Huber *et al.* 1989).

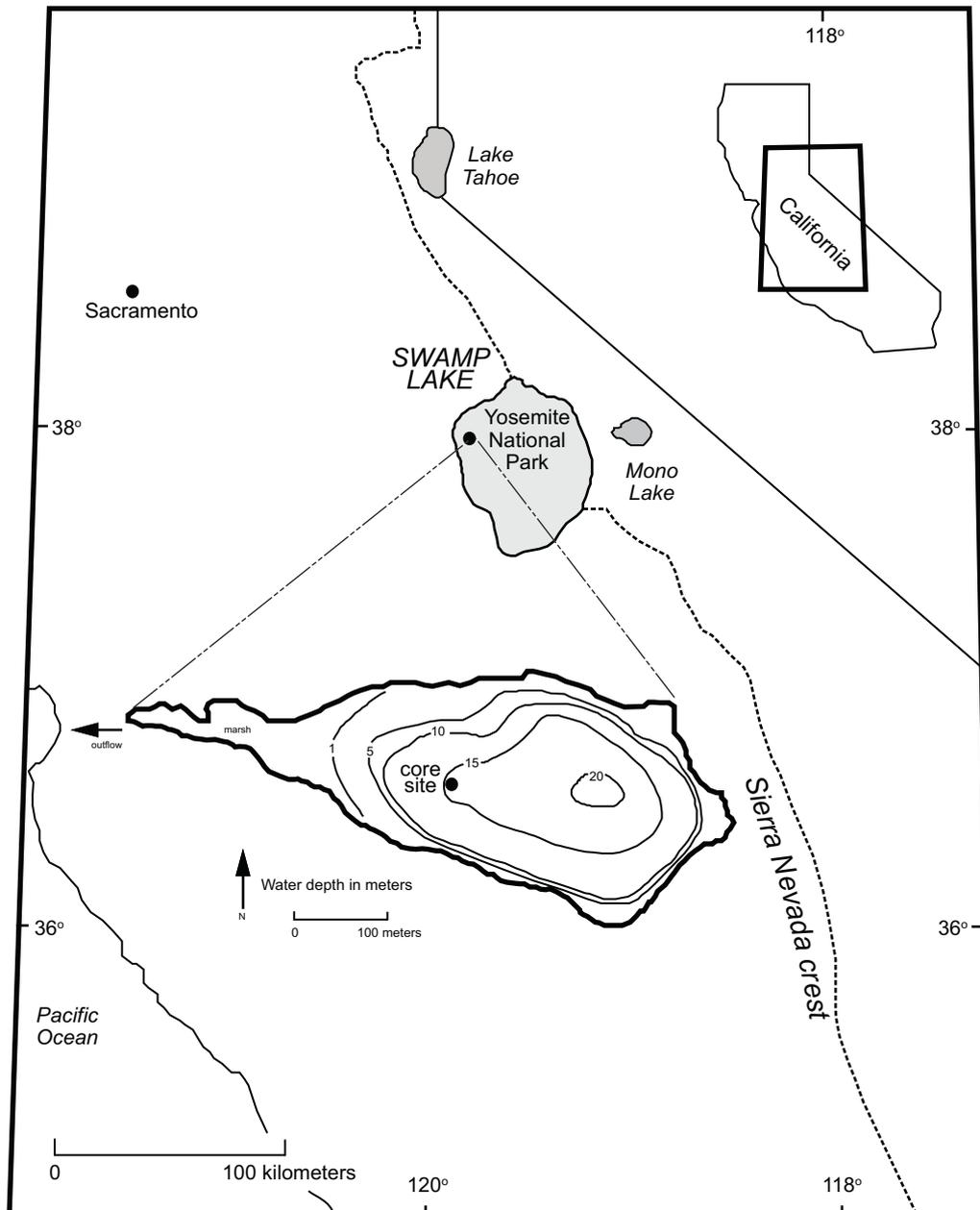


FIGURE 1: Location of Swamp Lake, Yosemite National Park, California. The lake is located on the western side of the Sierra Nevada crest.

Material and Methods

In August 2002, a sediment core (nine drives) was collected with a modified Livingstone piston corer (Wright, 1967) from the deep central basin (>20 m) of Swamp Lake. To assure the collection of a complete sediment record, a freeze-core was collected at the same site. The site was chosen for study because it is in approximately the same location previously studied by Smith & Anderson (1992).

Ten samples of plant material taken from Core 02–05 were dated by the U.S. Geological Survey ^{14}C Laboratory in Reston, Virginia. Dates were calibrated using CALIB 5.0.2 and the IntCal04 dataset (Reimer *et al.* 2004, Stuvier *et al.* 2005). In addition, eight tephra samples from discrete layers were analyzed using the JEOL electron microprobe at the U.S. Geological Survey (Menlo Park, California).

Seventy-four samples (60 from core 02–05; 14 from core FZ02–05) for diatom analysis were processed using hydrogen peroxide, hydrochloric acid, and nitric acid, (Battarbee 1986) to remove carbonate and organic matter, and sodium pyrophosphate to deflocculate the remaining clay. Approximately 50 µl of the resulting suspension were dried on a 22 X 30 mm coverslip and permanently mounted using Naphrax®. At least 500 frustules were enumerated following the method of Schrader & Gersonde (1978) using a Leica DM LB2 microscope with Nomarski optics at magnifications of 630X and 1000X. Diatom identifications and ecological interpretations were based on Lowe (1974), Gasse (1986), Krammer & Lange-Bertalot (1986, 1988, 1991a, 1991b), Lange-Bertalot & Krammer (1987, 1989), Cumming *et al.* (1995), Round & Bukhtiyarova (1996), Krammer (1997a, 1997b, 2000, 2002), and Lange-Bertalot (2001).

Results

Chronology

Preliminary AMS ¹⁴C dates and tephra correlations are plotted in Fig. 2. The eight tephtras were identified by comparing the chemistry of the tephtra samples to the more than 5,900 tephtra geochemical records in the U.S. Geological Survey Tephrochronology Project database. The Tsoyowata and Mazama ashes both originated from Mount Mazama (now Crater Lake) in southern Oregon. Six of the tephtras identified are from the Mono Craters, which lie on the east side of the Sierra Nevada. These tephtras are chemically similar and cannot be differentiated using current tephrochronological techniques, and are therefore shown as undated. The youngest Mono Craters tephtra was erupted about 665 cal yr B.P. We do not report an age model here pending additional ¹⁴C and tephtra analyses (D. Hallett, personal communication, 2009). Based on these dates, the average sedimentation rate above 700 cm is about 74 cm/1000 yr.

Sediments and stratigraphy

Core 02–05 is composed of nine 1-meter-long drives. Core FZ02–05 collected the top 67 cm of sediment. The two cores were correlated using a Mono Craters tephtra layer (665 cal yr B.P.). The composite core is 947-cm-long (Fig. 2). The sediments that make up the core include massive gray clay, layered silt and clay, peat, diatom-rich varved silt and clay, and massive gyttja. The preliminary description was reported in Starratt *et al.* (2006).

Below 700 cm, the sediments are dominated by glacially derived massive gray clay and layered silt and clay. The lowermost 40 cm of the core contains relatively few diatoms. Massive dark brown gyttja is present between 805 and 785 cm and 760 and 705 cm. The first varved diatom-rich silt occurs at the top of this sequence. The interval between 700 and 600 cm contains massive gyttja and short varved sections between gaps on the core. A 3-cm-thick layer of peat is present at the top of this section. The core is dominated by diatom-rich silt varves through the remainder of the core. A 12-cm-thick layer of peat occurs between the Tsoyowata and Mazama ashes.

Diatoms

A total of 228 species and varieties are present in the composite core 02–05, of which 76 compose more than 1% of the assemblage in one or more samples. Thirty-one species are present in the sample collected from the top of FZ02–05.

Discostella Houk & Klee (2004: 204–205) is the most abundant genus in the lake, composing as much as 75% of the assemblage (Figs 3 & 4). *Discostella* abundance is lowest during the initial development of the lake and during the two intervals of peat deposition. *Discostella stelligera* (Cleve and Grunow) Houk & Klee (2004: 208) is more abundant below 800 cm and quickly falls to below 20% abundance for the remainder of the record, whereas *D. pseudostelligera* (Hustedt) Houk & Klee (2004: 223) becomes the dominant species, reaching abundances of greater than 50% at several intervals. In FZ02–05 the abundance of *Discostella* is above 40% between 65 and 50 cm, and then drops to less than 20% from 45 to 10 cm, and returns to levels above 40% in the upper 5 cm of the core.

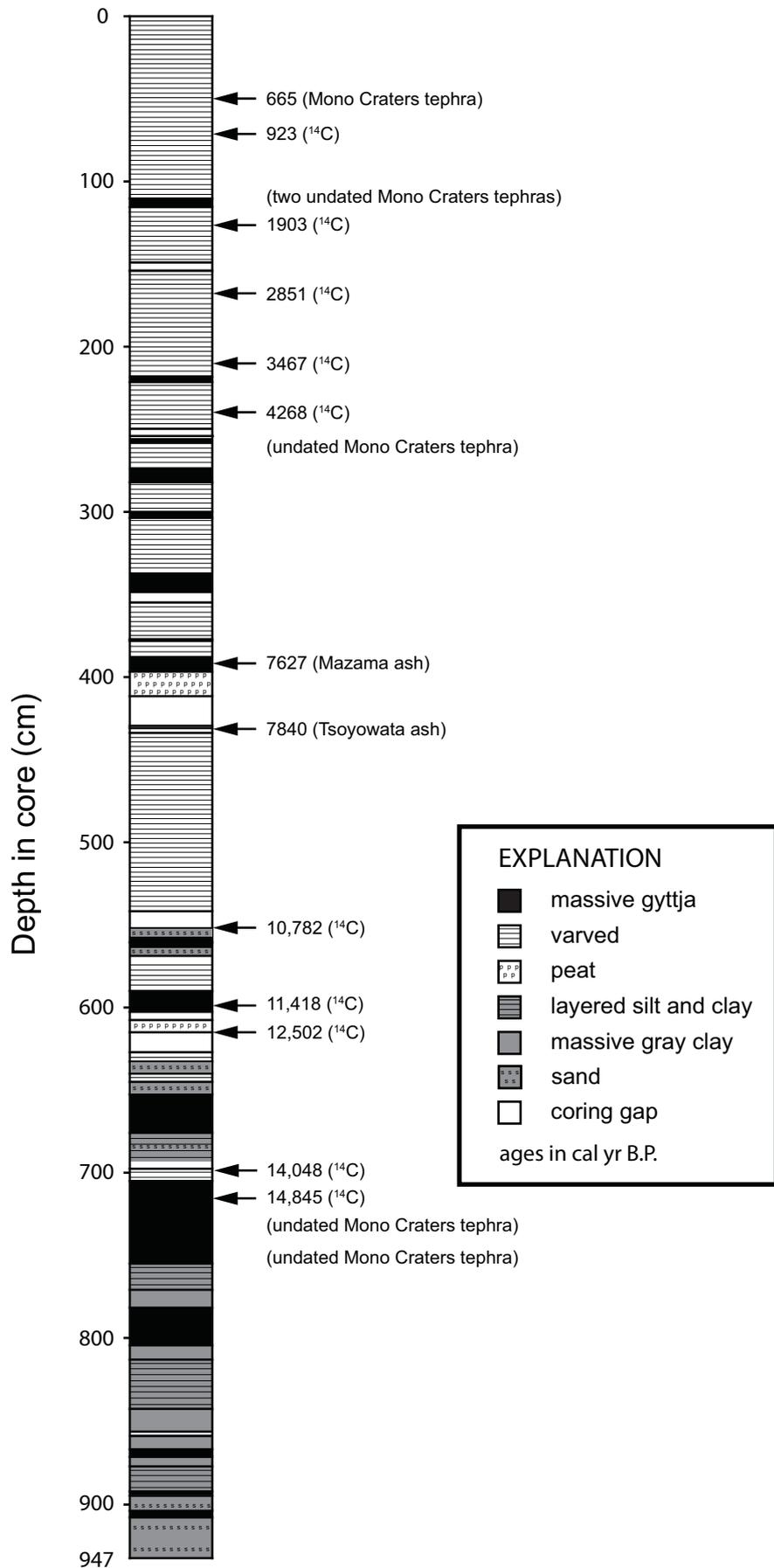


FIGURE 2: Generalized stratigraphic column and ages (¹⁴C and tephrochronology) for a composite of freeze core FZ02-05 and Livingstone core 02-05.

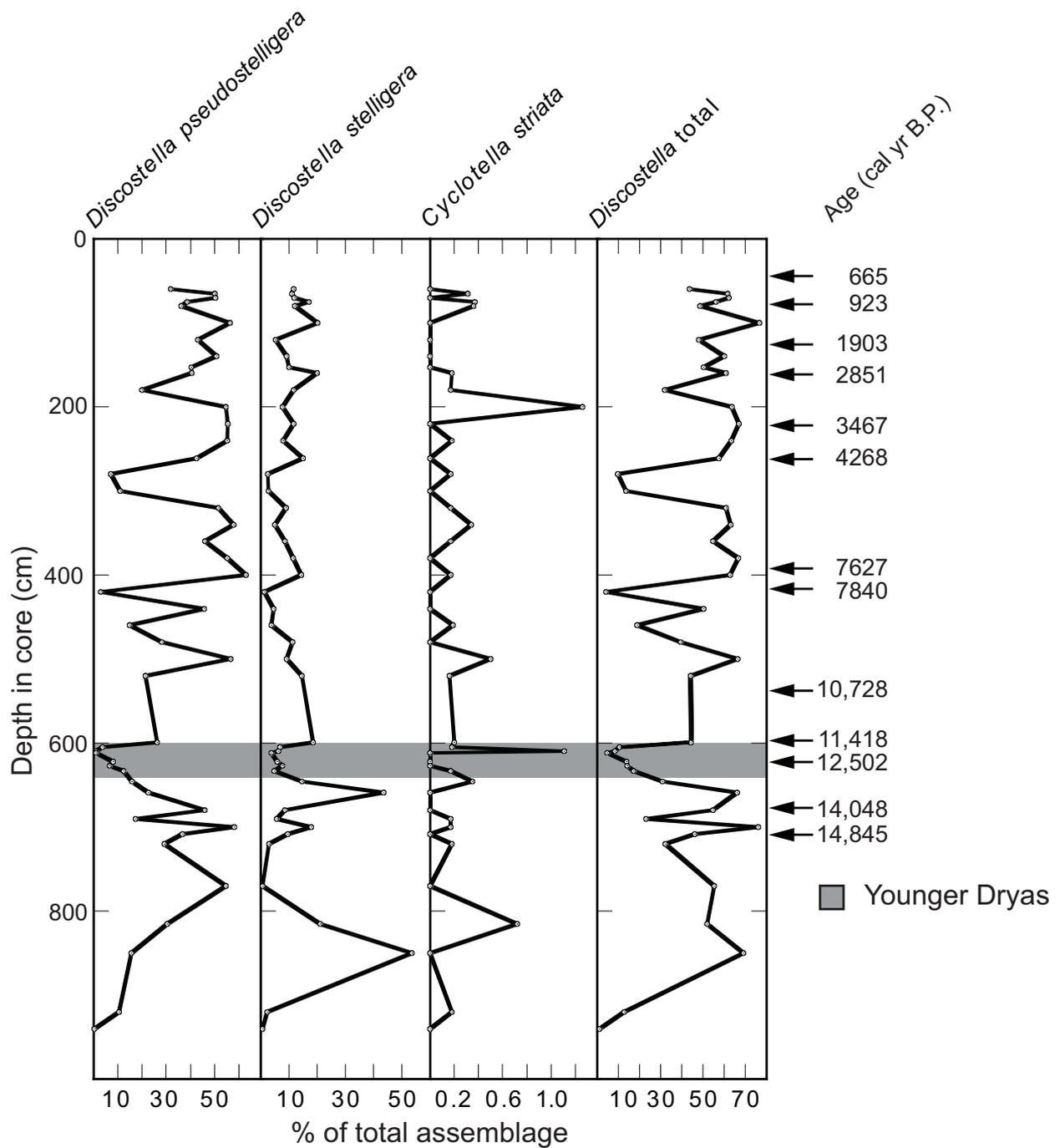


FIGURE 3: Relative abundances of species of *Discostella* and *Cyclotella* in Livingstone core 02–05 with abundances of greater than 1% of the assemblage in at least one sample.

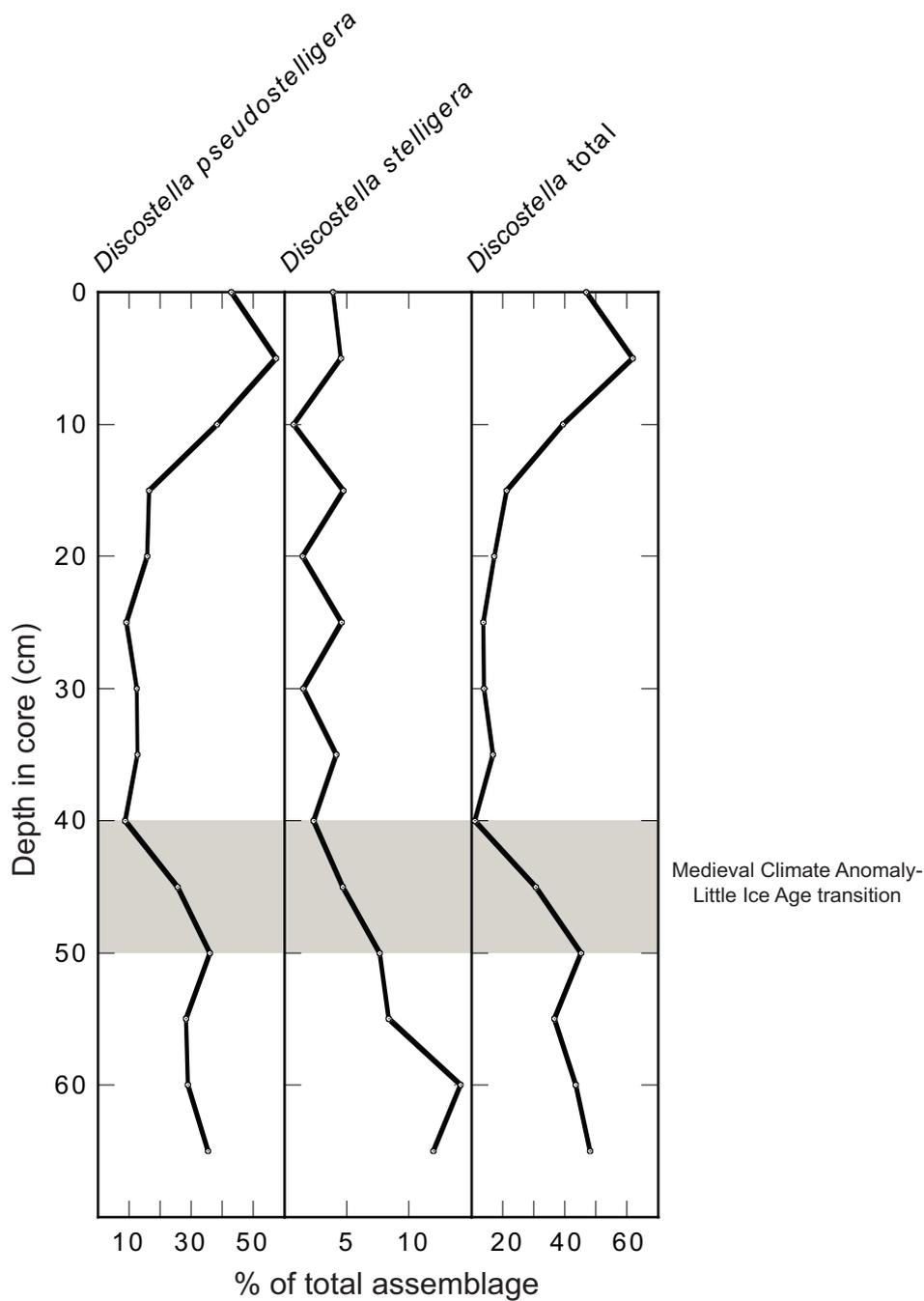


FIGURE 4: Relative abundances of species of *Discostella* in freeze core FZ02–05 with abundances of greater than 1% of the assemblage in at least one sample. The freeze core record represents the last 1000 years.

Ten species and varieties of *Aulacoseira* Thwaites (1848: 167) are present and the genus composes almost 40% of the assemblage (Figs 5 & 6). The diversity of those taxa making up more than 2% of the assemblage is greater in core 02–05 (six species and varieties) than in core FZ02–05 (five species and varieties). *Aulacoseira* is most abundant above 650 cm in the varved sequences where it reaches a maximum of 39% abundance; several subpeaks of 25–30% abundance also occur. The most common species are *A. distans* (Ehrenberg) Simonsen (1979: 57), *A. italica* (Ehrenberg) Simonsen (1979: 60), and *A. alpigena* (Grunow) Krammer (1991: 93).

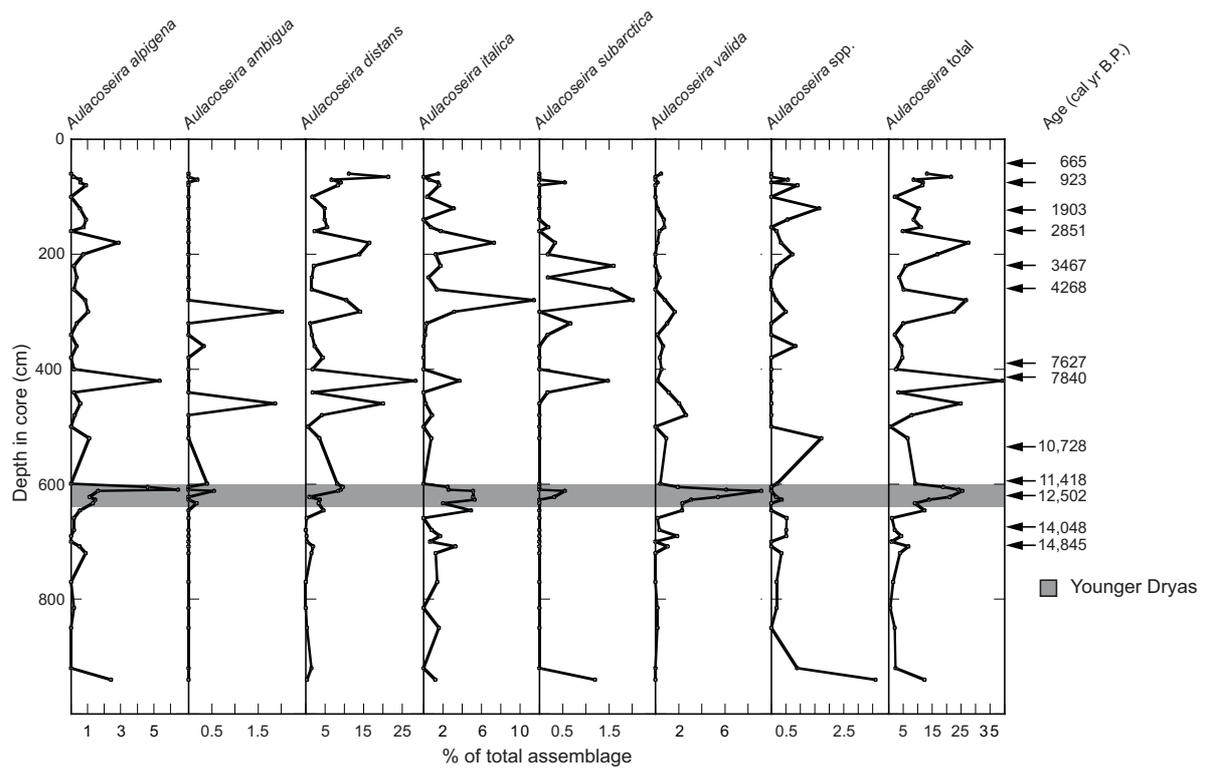


FIGURE 5: Relative abundances of species of *Aulacoseira* in Livingstone core 02–05 with abundances of greater than 1% of the assemblage in at least one sample.

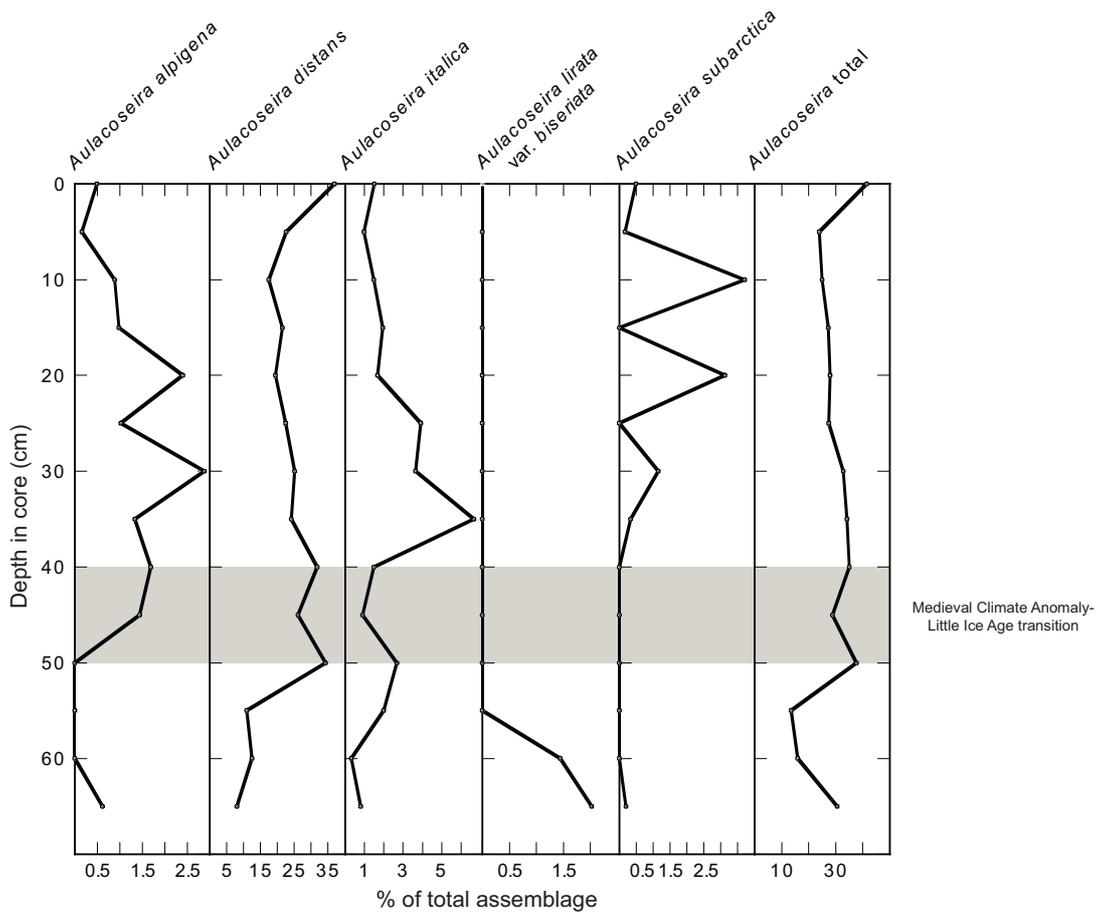


FIGURE 6: Relative abundances of species of *Aulacoseira* in freeze core FZ02–05 with abundances of greater than 1% of the assemblage in at least one sample. The freeze core record represents the last 1000 years.

The third dominant group is the *Fragilaria* “complex,” which includes *Fragilaria* Lyngbye (1819: 182), *Pseudostaurosira* Williams & Round (1988: 276), *Staurosira* Ehrenberg (1843: 45), and *Staurosirella* Williams & Round (198: 274). Together, these genera account for more than 40% of the assemblage in some samples (Figs 7–11). The overall pattern of abundance is similar to that of *Aulacoseira* and opposite that of *Discostella*. Many of the specimens can only be identified as part of this “complex” and are placed in the category “*Fragilaria* spp.” The majority of these are small *Fragilaria*, *Pseudostaurosira*, *Staurosira*, and *Staurosirella* spp. Of those specimens that can be identified to the species level, lanceolate species (*F. nanana* Lange-Bertalot in Krammer & Lange-Bertalot (1991: 130), *F. tenera* (W. Smith) Lange-Bertalot (1980: 746), and *F. capucina* var. *gracilis* (Østrup) Hustedt (1950: pl. 36, fig. 31) are relatively rare; the exception is *F. nanana* which reaches an abundance of 15%, but quickly returns to 3–4% of the assemblage (Fig. 7). *Staurosirella* is most abundant (7%) at 750 cm and then falls to levels below 3% through the upper part of the core. *Staurosira*, primarily *Staurosira construens* var. *venter* (Ehrenberg) Hamilton in Hamilton *et al.* (1992: 29), is most abundant at 300 cm and is almost absent below that depth. The abundance of *Pseudostaurosira*, primarily *Pseudostaurosira brevistriata* (Grunow in Van Heurck) Williams & Round (1987: 276) and *P. brevistriata* var. *inflata* (Pantocsek) Edlund (1994: 12), is generally greater in core FZ02–05 than *Staurosira* and *Staurosirella* spp., reaching a maximum of 10% at a depth of 45 cm. *Staurosira* (10%) and *Staurosirella* (7%) are both more abundant in core FZ02–05 than in the lower part of the record.

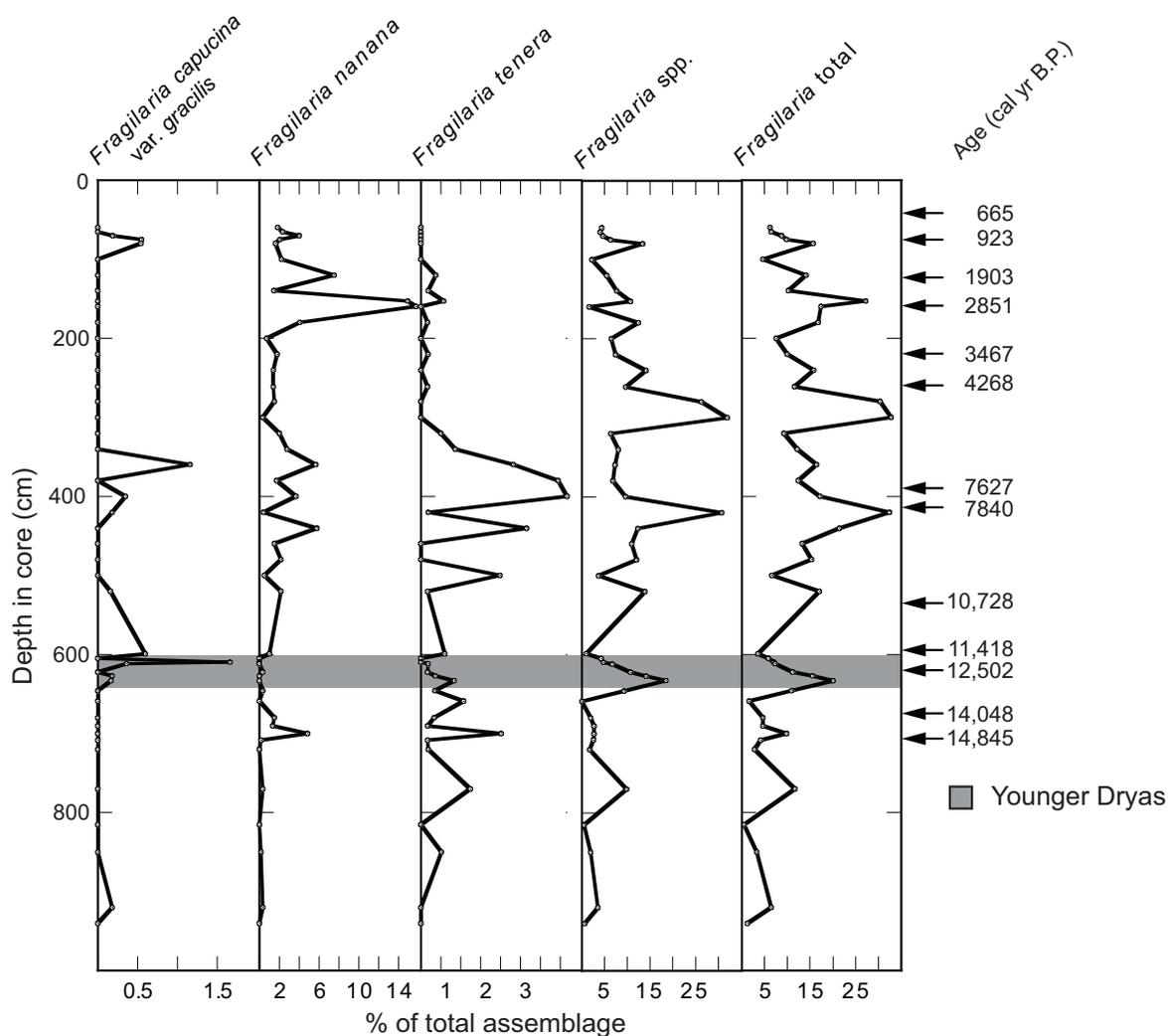


FIGURE 7: Relative abundances of species of *Fragilaria* in Livingstone core 02–05 with abundances of greater than 1% of the assemblage in at least one sample.

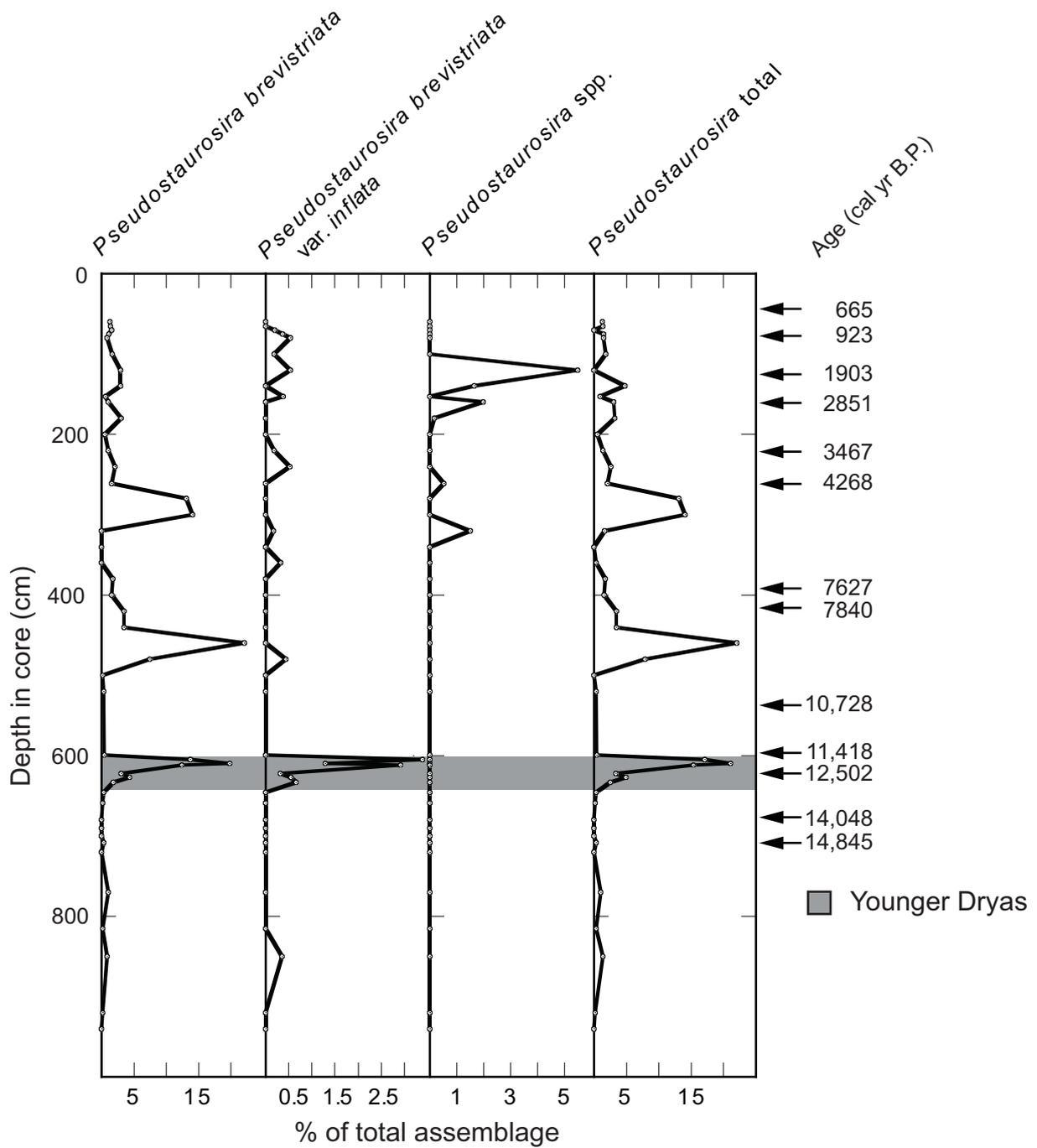


FIGURE 8: Relative abundances of species of *Pseudostaurosira* in Livingstone core 02-05 with abundances of greater than 1% of the assemblage in at least one sample.

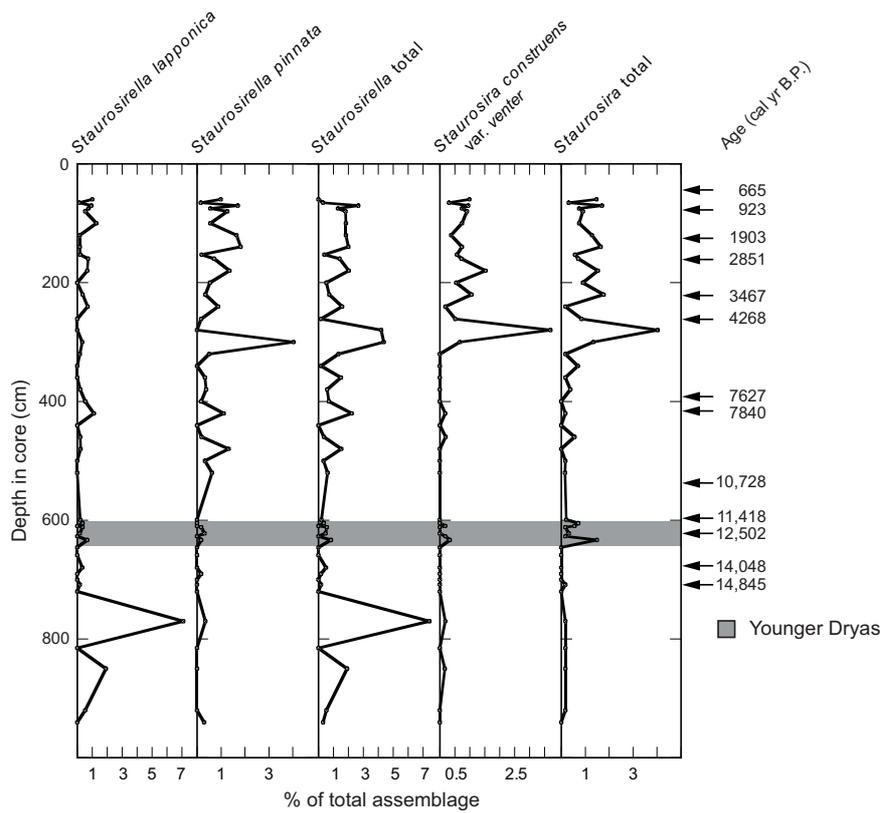


FIGURE 9: Relative abundances of species of *Staurosira* and *Staurosirella* in Livingstone core 02–05 with abundances of greater than 1% of the assemblage in at least one sample.

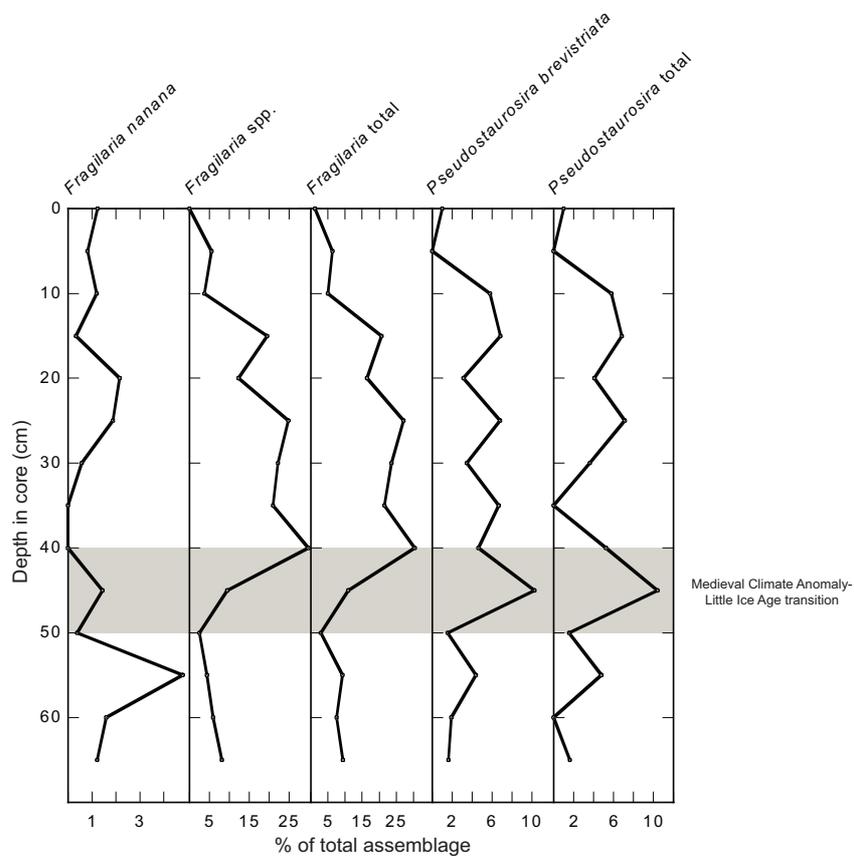


FIGURE 10: Relative abundances of species of *Fragilaria* and *Pseudostaurosira* in freeze core FZ02–05 with abundances of greater than 1% of the assemblage in at least one sample. The freeze core record represents the last 1000 years.

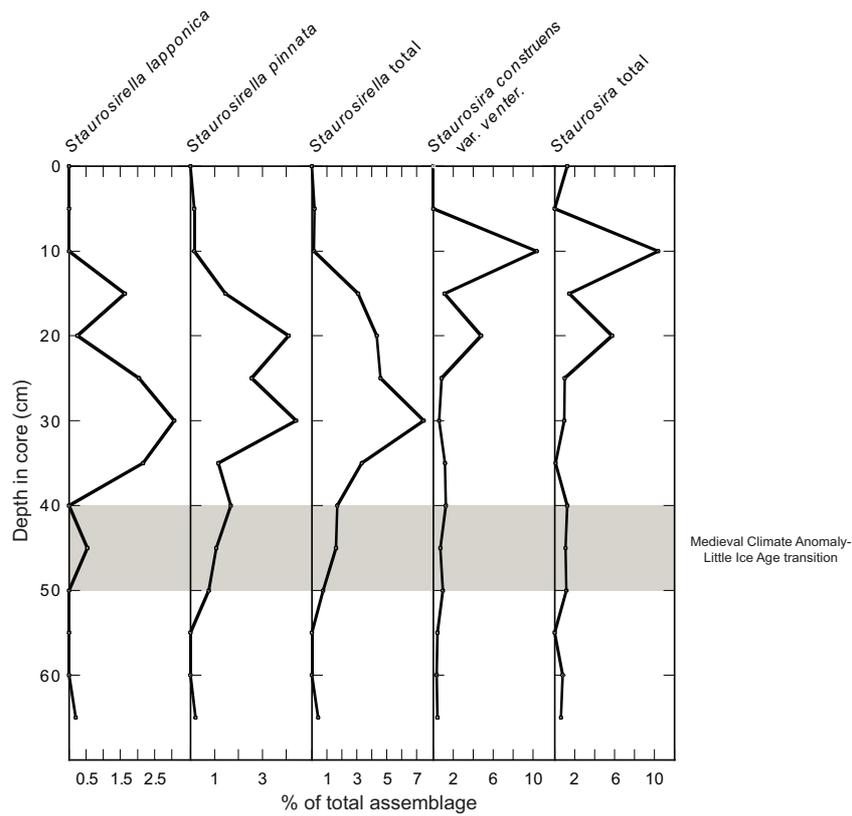


FIGURE 11: Relative abundances of species of *Staurosira* and *Staurosirella* in freeze core FZ02–05 with abundances of greater than 1% of the assemblage in at least one sample. The freeze core record represents the last 1000 years.+

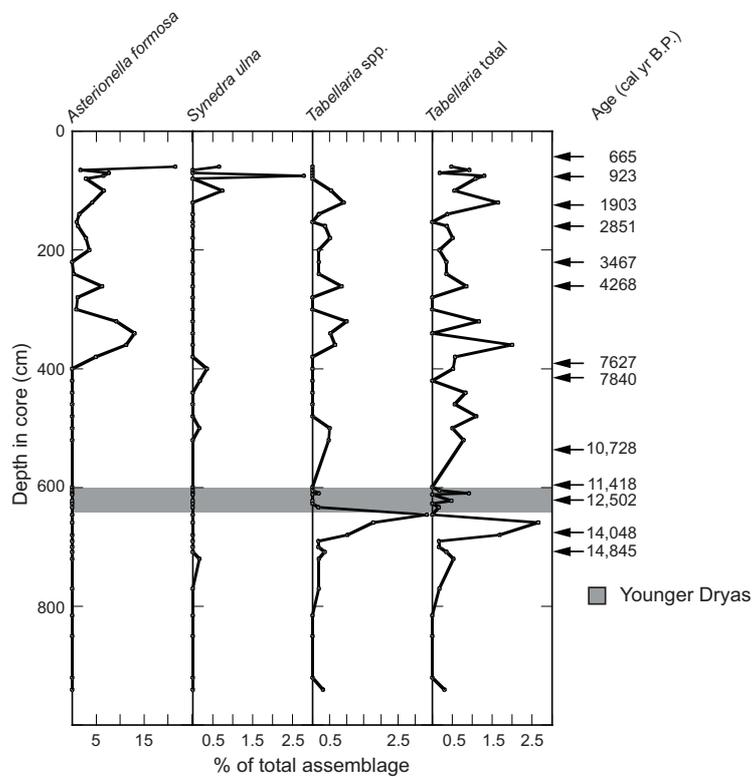


FIGURE 12: Relative abundances of species of *Asterionella*, *Synedra*, and *Tabellaria* in Livingstone core 02–05 with abundances of greater than 1% of the assemblage in at least one sample.

Asterionella formosa Hassall (1850: 10) is present only above the upper peat layer at 400 cm (Figs 12 & 13); its abundance exceeds 15% at 340 cm and then returns to less than 10%. The greatest abundance (23%) in core 02–05 occurs near the top at 57 cm. The trend in abundance continues in core FZ02–05 with the highest (24%) abundance at 65 cm. From 50 to 0 cm, the abundance is below 5%. *Synedra ulna* (Nitzsch) Ehrenberg (1832: 87) and *Tabellaria* Ehrenberg ex Kutzing (1844: 127) spp. (primarily *T. fenestrata* (Lyngbye) Kützing (1844: 127)) are present in abundances below 3%. Abundances of these taxa are lower in core FZ02–05.

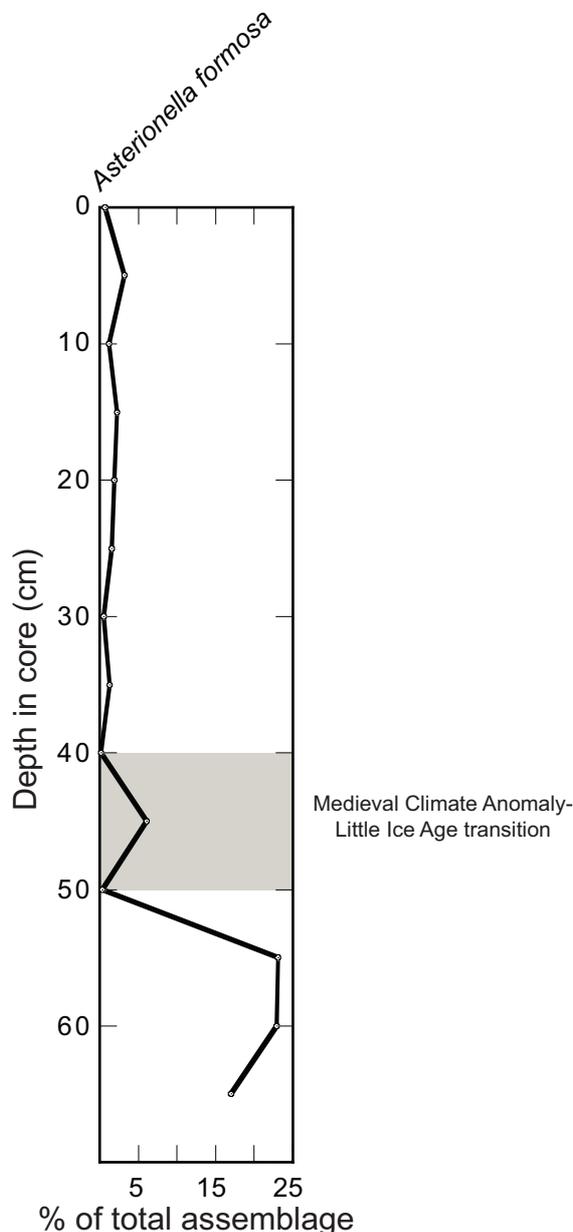


FIGURE 13: Relative abundances of *Asterionella formosa* in freeze core FZ02–05 with abundances of greater than 1% of the assemblage in at least one sample. The freeze core record represents the last 1000 years.

Achnanthes Bory de Saint-Vincent (1822: 79, 593) *sensu lato* is the most diverse genus recovered with 34 species and varieties enumerated (Fig. 14 & 15). *Achnanthes helvetica* (Hustedt) Lange-Bertalot in Lange-Bertalot & Krammer (1989: 63), *A. minutissima* Kützing (1833: 578), and *A. pusilla* Grunow in Van Heurck (1880: pl. 27, fig. 33, 34) are most abundant in core 02–05; *A. helvetica* and *A. microscopica* (Cholnoky) Lange-Bertalot & Krammer (1989: 99) are most abundant in core FZ02–05. The highest abundance (17%) of *Achnanthes* species occurs in the lowest part of core 02–05; above 760 cm, the abundance does not exceed 10%.

Other relatively abundant species in core 02–05 include *Encyonema* Kützing (183: 589) and *Cymbella* C.A. Agardh (1830: 1) (Fig. 16; 15% and 9.5%, respectively; 13 species combined). *Encyonema minutum* (Hilse ex Rabenhorst) Mann in Round, Crawford & Mann (1990: 667) (12%) and *Cymbella gracilis* (Ehrenberg) Kützing (1844: 79) (6.5%) are the most common. These two genera are most abundant below the lower peat layer. The highest abundance (7.5%) of *Eunotia* Ehrenberg (1837: 44) (16 species and varieties) and *Frustulia rhomboides* (Ehrenberg) Pfitzer (1871: 164) (3.7%) are in the massive gyttja below 600 cm (Fig. 17). *Gomphonema* Ehrenberg (1832: 87) (Fig. 18; 10 species; maximum abundance of 7%) is present throughout the core, but is most abundant in the varved and massive gyttja between 740 cm and 610 cm. *Hantzschia amphioxys* (Ehrenberg) Grunow in Cleve & Grunow 1880: 103) and *Luticola mutica* (Kützing) Mann in Round, Crawford & Mann (1990: 670) are present in abundances above 2% at 940 cm (Fig 18).

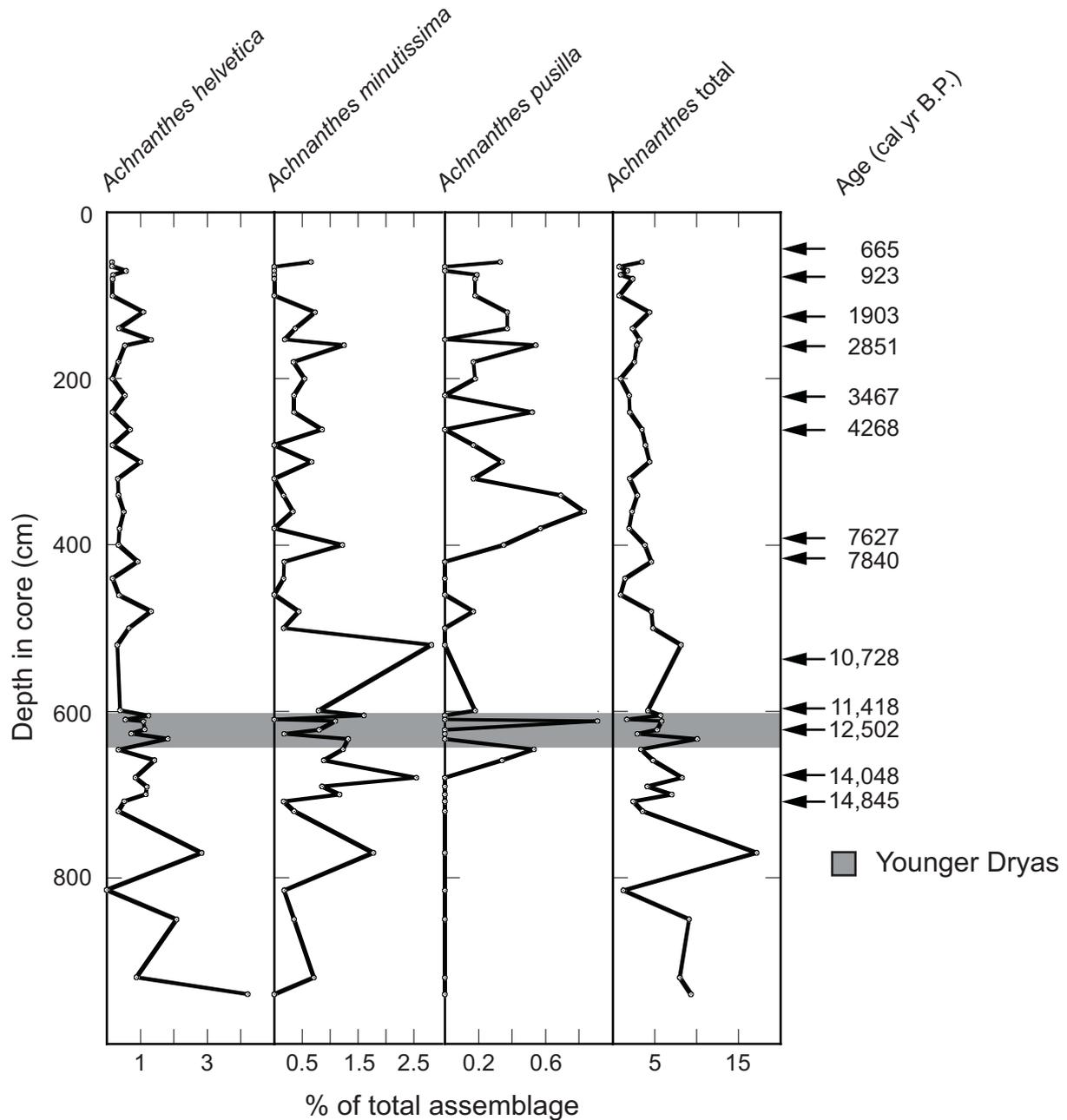


FIGURE 14: Relative abundances of species of *Achnanthes* in Livingstone core 02–05 with abundances of greater than 1% of the assemblage in at least one sample.

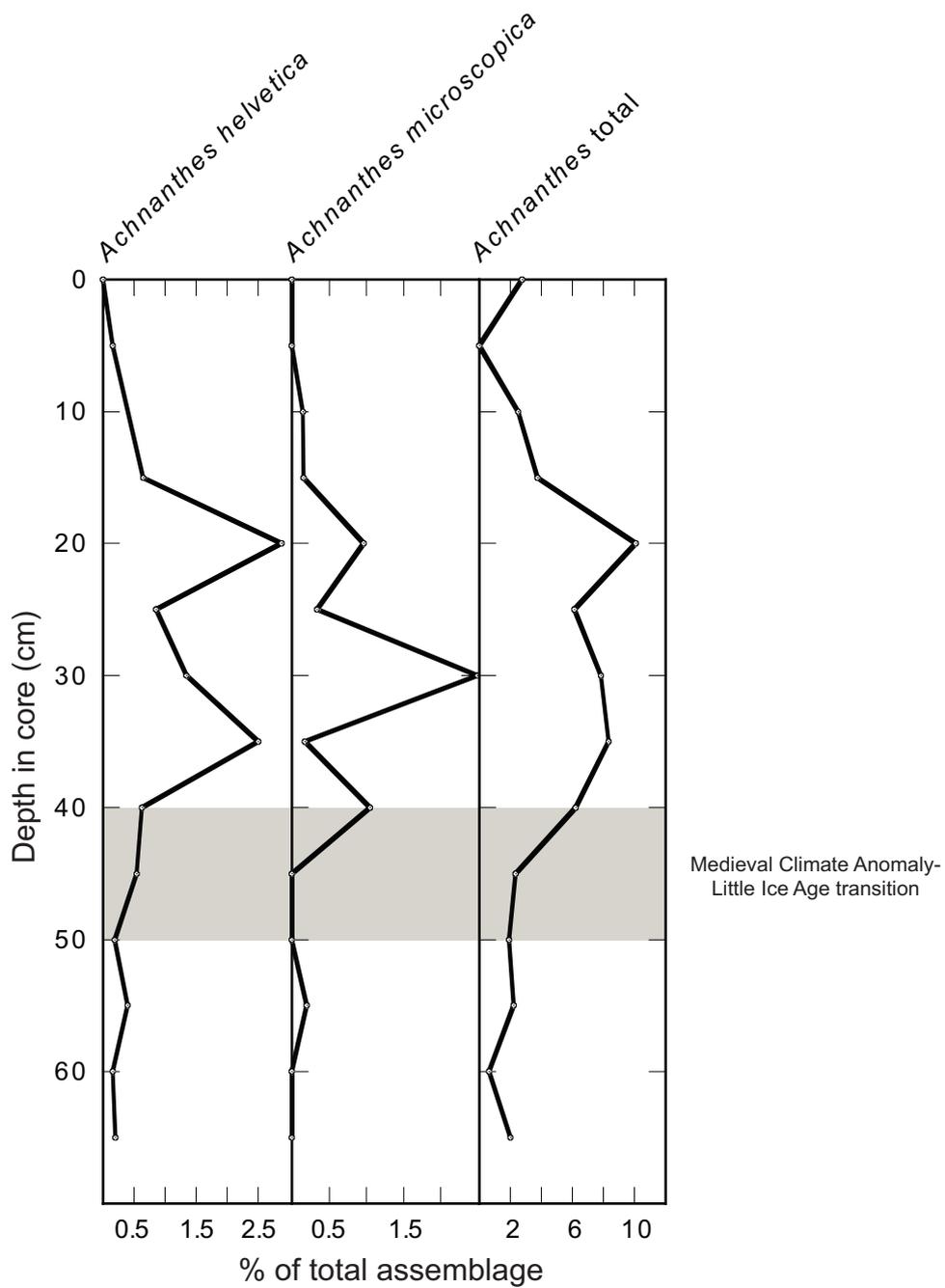


FIGURE 15: Relative abundances of species of *Achnanthes* in freeze core FZ02–05 with abundances of greater than 1% of the assemblage in at least one sample. The freeze core record represents the last 1000 years.

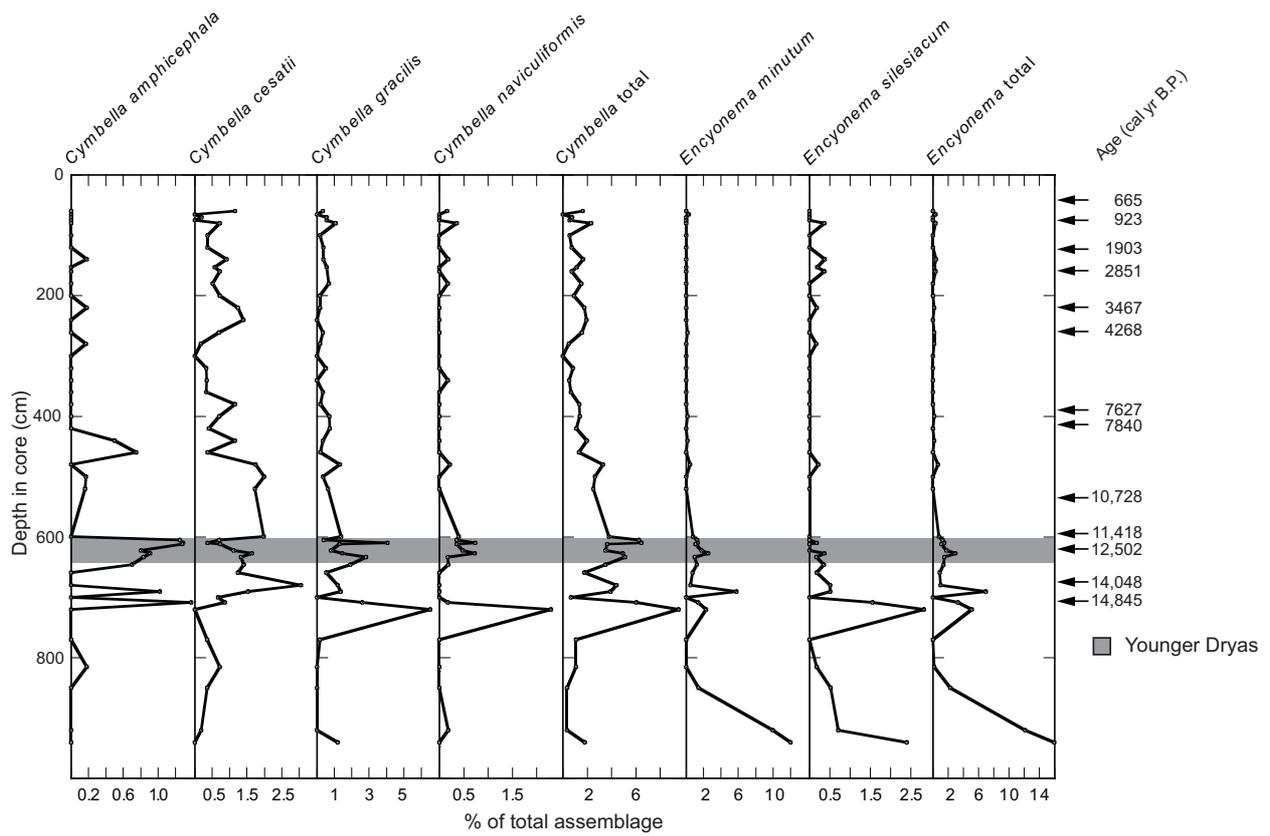


FIGURE 16: Relative abundances of species of *Cymbella* and *Encyonema* in Livingstone core 02–05 with abundances of greater than 1% of the assemblage in at least one sample

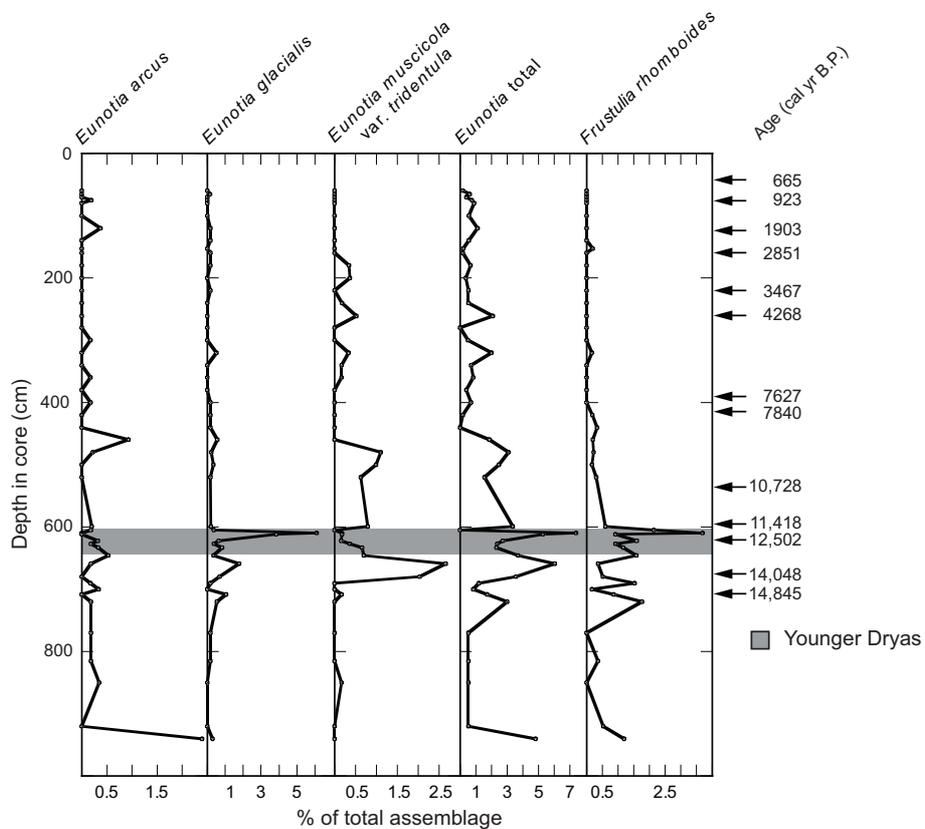


FIGURE 17: Relative abundances of species of *Eunotia* and *Frustulia* in Livingstone core 02–05 with abundances of greater than 1% of the assemblage in at least one sample.

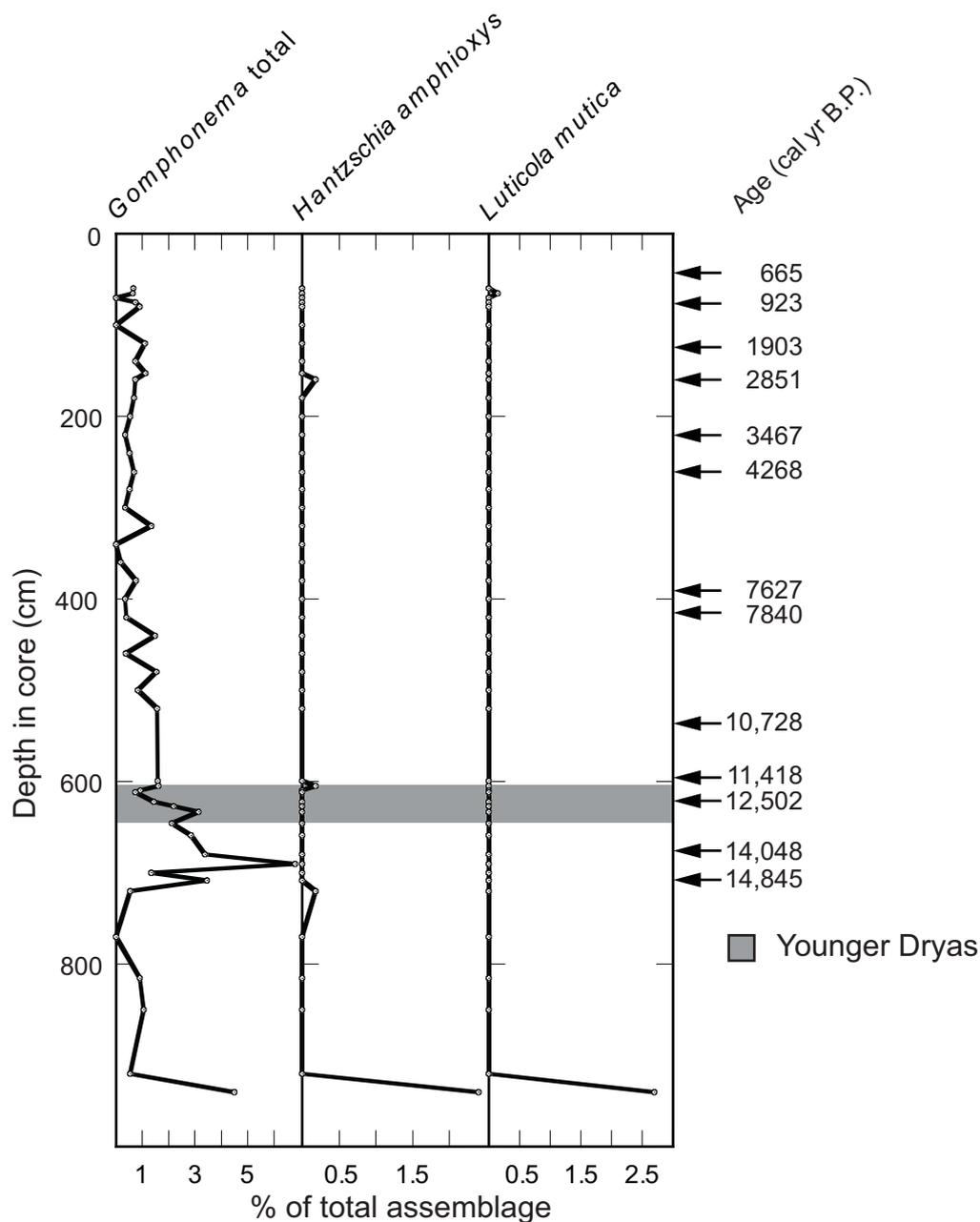


FIGURE 18: Relative abundances of species of *Gomphonema*, *Hantzschia*, and *Luticola* in Livingstone core 02–05 with abundances of greater than 1% of the assemblage in at least one sample.

Discussion and Conclusion

Smith & Anderson (1992) and Anderson (2011) presented a 16,000-year-long paleoecological record from Swamp Lake that provided an important middle elevation view of late Pleistocene and Holocene climate through vegetation change on the western slope of the Sierra Nevada. They showed that the environment at the time of the Pleistocene-Holocene transition was distinctly different from the modern, with a mix of high elevation conifers and lower elevation montane trees that suggest that vegetation lagged the climate change experienced elsewhere in the Sierra Nevada. The early Holocene was marked by increased temperatures and drier conditions, followed by a late middle Holocene cooling trend which continued into the late Holocene as modern oceanographic conditions became established along the northern California coast (Barron *et al.* 2003, Barron & Bukry 2007).

The record from composite core 02–05 contains an approximately 16,000-year-long record of climate-driven changes within the Swamp Lake watershed similar to those reported by Smith & Anderson (1992) and Anderson (2011). The lowest 250 cm (Late Glacial period) show a gradual change from fine-grained clastic sediments (primarily silt and clay) to more massive organic-rich gyttja. This suggests that during this time the glaciers of the Tioga Stage retreated from the area, leaving behind a minimally vegetated surface. As the surface became vegetated, the amount of clastic sediment that washed into the lake decreased. Above 700 cm (Younger Dryas and younger), relatively little clastic sediment was being washed directly into the lake. Street *et al.* (2012) show a general increase in organic matter in the lake and vegetation (relatively high C/N) in the surrounding watershed

The only significant numbers of diatoms associated with subaerial environments (*Hantzschia amphioxys*, *Luticola mutica*) appear at a depth of 930 cm (late glacial period), followed by epipelagic and epiphytic taxa (*Gomphonema*, *Cymbella*, and *Encyonema*) and small *Achnanthes*, which may also indicate active, well-oxygenated water. Bloom *et al.* (2003) have shown that many of the species common at this time are found in water of relatively low temperatures. The epiphytic genus *Cocconeis* Ehrenberg (1837: 173) occurs, but is very rare in these sediments, suggesting that aquatic macrophytes were not abundant.

The lake appears to have filled rapidly. The increase in the abundance of *Discostella* indicates that a water depth greater than 5 m was reached by a depth of 840 cm (last glacial period) in the core, where the abundance of *Discostella* reaches 70%. Rühland *et al.* (2003) and Rühland & Smol (2005) have shown that small cyclotelloid species such as *D. pseudostelligera* and *D. stelligera* occur in great abundance in arctic lakes greater than 5 m in depth. Tycoplanktonic taxa (*Aulacoseira*, *Fragilaria* “complex”) are present in this interval, but generally don’t exceed 15% of the total assemblage. Throughout most of its past, the dominance of the diatom assemblage by *Discostella* indicates that Swamp Lake was a freshwater, slightly alkaline, oligotrophic lake. The presence of *Aulacoseira* and members of the *Fragilaria* “complex” suggests that the shallower areas may have had higher nutrient levels.

With the exception of the two peat layers, the remainder of the core (above 600 cm) is dominated by varved sediments. The lower peat interval contains the greatest abundance of acidophilic species (*Eunotia*; 7.1%, *Frustulia* Rabenhorst (1853: 50); 3.7%). The abundance of tycoplanktonic taxa also increases. The lower peat interval may correspond to the Younger Dryas as recognized at Starkweather Lake (2424 m a.s.l.) in the central Sierra Nevada, just west of the crest of the range, by MacDonald *et al.* (2008), with a relatively high abundance of planktonic diatoms in the early part of the interval followed by a substantial decrease (~50%) in the later part of the Younger Dryas. MacDonald *et al.* (2008) report decreased diatom-inferred salinity and lake depth at Barrett Lake (2816 m a.s.l.) in the central Sierra Nevada, just east of the crest of the range, during the early part of the Younger Dryas followed by a slight decrease in depth and increase in salinity. This corresponds to a slight increase of *Cyclotella striata* (Kützing) Grunow in Cleve & Grunow (1880: 119) at the end of the Younger Dryas in Swamp Lake. The upper peat interval also has a substantial decrease in *Discostella* and increase in some tycoplanktonic and benthic taxa, and may represent a dry interval in the middle Holocene.

The upper 600 cm (Holocene) varved section is dominated by *Discostella*, and to lesser extent, *Aulacoseira* and the *Fragilaria* “complex” with high *Discostella* abundances corresponding to low numbers of *Aulacoseira* and *Fragilaria* “complex” taxa. Most of the *Aulacoseira* species present have a high number of pores per 10µm which Kilham (1990) suggests is an indication of shallow water. *Aulacoseira distans* has a relatively high light:phosphorous ratio which may reflect better mixing of nutrient-poor waters (Kilham 1990). The abundance of *Asterionella formosa*, which appears at 400 cm (middle Holocene), may reflect an increase in the abundance of Si in the system. Starratt *et al.* (2006) and Street *et al.* (2007) have shown that biogenic silica increases in that interval, and that the fluctuations in the abundance of *A. formosa* and biogenic silica are similar. Kilham (1971) and Kilham (1975) have shown that the abundance of *A. formosa* is related to Si availability.

Variations in the abundance of *Discostella* indicate the lake level fluctuated in response to the Medieval Climate Anomaly and Little Ice Age. Between 65 and 45 cm *Discostella* composes about 40% of the flora,

between 40 and 15 cm it composes between 15 and 20%, and above 15 cm its abundance reaches between 50 and 60%. The interval of low abundance may represent an interval during which ice covered the lake for a greater portion of the year. This is supported by the low abundance of *Asterionella formosa* above 50 cm. Agbeti & Smol (1995) have shown that the abundance of planktonic species such as *A. formosa* is lower during periods of extended ice cover.

The Swamp Lake sediment sequence is rare among the limited lacustrine records of climate change in the Sierra Nevada. It is the only sediment history that contains significant varved sections with the potential for establishing an ultra-high resolution climate record for much of the Holocene. The sediments also record the transition from sediment-dominated diatom-poor varves in the late Pleistocene to diatom-dominated varves over much of the last 10,000 years. Swamp Lake also has one of the few records that includes the last glacial maximum and the entire Holocene.

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