UCRL-JRNL-205853

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

A prehistorical record of cultural eutrophication from Crawford Lake, Canada

Ekdahl, EJ., Teranes, J.,Guilderson, T., Turton, CL., McAndrews, JH., Wittkop, C.,and Stoermer, EF.

August 5, 2004

Submitted to the journal *Geology*

A prehistorical record of cultural eutrophication from Crawford Lake, Canada

Erik J. Ekdahl*, Department of Geological Sciences, University of Michigan, 2534 C.C. Little, Ann Arbor, Michigan 48109-1063, USA

Jane L. Teranes, Scripps Institution of Oceanography, University of California-San Diego, La Jolla, California 92093 USA

Thomas P. Guilderson, Lawrence Livermore National Laboratory, L-397, 7000 East Avenue, Livermore, California 94551, USA

Charles L. Turton, Royal Ontario Museum, 100 Queens Park, Toronto, Ontario M5S 2C6, Canada

John H. McAndrews, Departments of Botany and Geology, University of Toronto, Toronto, Ontario M5S 3B2, Canada

Chad A. Wittkop, Limnological Research Center, Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota 55455, USA

Eugene F. Stoermer, School of Natural Resources, University of Michigan, Ann Arbor, Michigan 48109, USA

---

[1]GSA Data Repository item 2004##, Table DR1, ^{14}C ages and calibrated dates from Crawford Lake sediment, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

ABSTRACT

Cultural eutrophication—the process by which human activities increase nutrient input rates to aquatic ecosystems and thereby cause undesirable changes in surface-water quality—is generally thought to have begun with the start of the industrial era. The prehistoric dimension of human impacts on aquatic ecosystems remains relatively undescribed, particularly in North America. Here we present fossil plankton data (diatoms and rotifers), organic and inorganic carbon accumulations, and carbon isotope ratios from a 1000-yr sediment core record from Crawford Lake, Ontario, Canada. The data documents increased nutrient input to Crawford Lake caused by Iroquoian horticultural activity from A.D. 1268 to 1486 and shows how this increased nutrient input elevated lake productivity, caused bottom-water anoxia, and irreversibly altered diatom community structure within just a few years. Iroquoian settlement in the region declined in the fifteenth century, yet diatom communities and lake circulation never recovered to the predisturbance state. A second phase of cultural eutrophication starting in A.D. 1867, initiated by Canadian agricultural disturbance, increased lake productivity but had comparatively less of an impact on diatom assemblages and carbon-storage pathways than the initial Iroquoian disturbance. This study deepens our understanding of the impact of cultural eutrophication on lake systems, highlights the lasting influence of initial

environmental perturbation, and contributes to the debate on the ecological impacts of density and agricultural practices of native North American inhabitants.

Keywords: diatoms, eutrophication, Iroquoian, carbon, ecological disturbance, Crawford Lake

INTRODUCTION

Human population growth and resource consumption have placed increasing demands on aquatic and terrestrial ecosystems and have profoundly affected global biogeochemical cycles of carbon, nitrogen, and phosphorous. Cultural eutrophication—a condition in which human activities increase nutrient input rates to aquatic ecosystems and thereby stimulate algal productivity—is recognized as a global water-quality problem (Smith, 1998). Despite evidence that pre-industrial societies modified watershed vegetation and water chemistry in lakes of Europe (Fritz, 1989; Digerfeldt and Håkansson, 1993; Renberg et al. 1993; Anderson et al. 1995) and tropical America (Deevey et al. 1979; Binford et al. 1987), the study of cultural eutrophication in North America has been largely limited to documenting the increase and abatement of nutrient inputs since the start of the industrial revolution. The only significant report of native modification to a lacustrine system in North America comes from the high Arctic, and is related to localized effects from Inuit whaling (Douglas et al. 2004). The paucity of data on pre-European modification to lacustrine systems in North America is due in part to limitations in the temporal resolution of paleoenvironmental archives and by the preconception that population density and agricultural practices of native inhabitants would not have been large enough to have a significant impact on local ecology.

Here we report fossil plankton abundances and geochemical paleoproductivity data from meromictic Crawford Lake (2.5 ha, 43°28.1′N, 79°56.9′W) that describe the impact of a native Iroquoian community upon the ecosystem of Crawford Lake. Pollen evidence of early forest disturbance caused by fourteenth- and fifteenth-century Iroquoian settlements is well-documented in Crawford Lake sediment (Byrne and McAndrews, 1975; McAndrews and Boyko-Diakonow, 1989). A new chronology, used with new pollen and paleoenvironmental data, describe the effects of (1) human activity on forest disturbance and (2) the impact of these activities upon the lake ecosystem with near-yearly resolution for the past 1000 years. Our analyses document significant and lasting change in the lake ecosystem in response to land clearance and Iroquoian village phases with maize cultivation around Crawford Lake from A.D. 1268 to 1486.

MATERIALS AND METHODS

Three freeze cores were recovered in June 2001, ranging from 70 to 85 cm in length, from the deepest point (22.5 m) of Crawford Lake by using an aluminum wedge filled with an ethanol and dry ice slush. All cores were preserved frozen and photographed. One core, sampled every varve for the upper 26 cm and at 0.2 cm intervals for the remainder of the core, was used for carbon isotopic analysis. A second core was sampled at 0.2 cm intervals for pollen, fossil diatom, and additional geochemical analyses.

Carbonate content was determined by the carbonate bomb method of Müller and Gastner (1971). Total organic carbon (TOC) and atomic C/N ratios were measured on carbonate-free sediment by a Carlo Erba CHNS-O analyzer (values expressed as whole-sediment percentages corrected for the missing carbonate fraction). We determined the carbon isotope ratios of the authigenic carbonate by reacting homogenized bulk-sediment samples in orthophosphoric acid at 90 °C on an autocarbonate preparation system. Isotopic ratios of the evolved CO_2 gas were measured on line by a Finnigan 251 isotope-ratio mass spectrometer. Carbon isotope composition is expressed in the δ notation as per mil deviation from the international Peedee belemnite (PDB) carbonate standard. The standard error on replicate samples is 0.1‰. Diatom sample preparation follows Battarbee (1973); species identification follows Patrick and Reimer (1966) and Krammer and Lange-Bertalot (1987-1997).

The sediment record is well suited for ^{14}C dating because of an abundance of preserved terrestrial macrofossils, such as leaves and twigs, which are typically deposited into the lake the year that they grew. These macroscopic remains were radiocarbon dated by accelerator mass spectrometry (AMS) at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Labs (see Table DR1[1]). All ^{14}C dates were converted to calendar dates (A.D.) through calibration with the IntCal98 calibration curve using CALIB 4.4 software (Stuiver and Reimer, 1993; Stuiver et al. 1998).

RESULTS AND DISCUSSION

Our age model is based on (1) varve counts from the top of the core (A.D. 2001) back to A.D. 1867 and (2) four equations fit to 23 AMS ^{14}C dates from A.D. 1867 to the bottom of the core (Fig. 1). Four calibrated AMS ^{14}C dates confirm the varve chronology to 1867. Our age model revises previous Crawford Lake chronologies that were based solely on varve counts (Byrne and McAndrews, 1975; Finlayson, 1998); our results indicate that the earlier studies missed 80–100 yr because of intervals of low sedimentation rates or sedimentation without varves.

The core displays four palynological zones—the pre-Iroquoian, Iroquoian, post-Iroquoian, and Canadian (Fig. 2). Varves are not well defined in the pre-Iroquoian zone, indicating bioturbation and oxic bottom waters. Appearance of maize (*Zea mays*) pollen at 62.2 cm (A.D. 1268) defines the start of the Iroquoian zone (Fig. 2). The first period of large-scale Iroquoian village occupation at Crawford Lake is identified from numerous pollen of *Zea* (maize), Poaceae (grasses), and *Portulaca* (purslane), spores of *Ustilago* (corn smut, a fungal disease of corn), and pollen and seeds of *Helianthus* (sunflower) from ca. A.D. 1325 to 1375 (Fig. 2). An intermittent period of low horticultural activity (an assumed abandonment of the Crawford Lake watershed) was followed by a second horticultural phase (resettlement) spanning A.D. 1410–1445 (Fig. 2). Iroquoian villages typically contained several dozen to several hundred people; given the size and number of reconstructed longhouses within the watershed, Iroquoian population is estimated at ~225 during the first settlement phase and ~375 during the second settlement phase (Finlayson, 1998).

Changes in lake productivity began at the start of the Iroquoian Zone. Increased algal production utilized aqueous CO_2, which raised pH and carbonate supersaturation and resulted in increased $CaCO_3$ accumulations. An increase in the flux of algal organic matter, which has lower organic C/N values than terrestrial plants (Meyers, 1994), explains the observed decrease in C/N values from 16 to near 13 and increased TOC accumulations. Elevated dissolved inorganic carbon (DIC) consumption related to increased photoautotrophic activity depleted the DIC reservoir in ^{12}C (which is preferred by most photosynthetic algae) relative to ^{13}C; subsequently, carbonate $\delta^{13}C$ values increased from –5.5‰ to –1.8‰ by A.D. 1354 (Fig. 3). Increased oxygen use during respiration and degradation of sinking organic matter produced anoxic bottom water, allowing for preservation of undisturbed, laminated sediments. Together, these changes reflect an increase in photosynthetic algal production and the onset of permanently anoxic bottom water, stimulated by increased nutrient input to the lake.

Diatom assemblages responded immediately to signs of human activity in the watershed (Fig. 4). Meso-oligotrophic *Cyclotella michiganiana* and *Cyclotella bodanica* were quickly replaced by species of the more eutrophic genus *Stephanodiscus* at the start of the Iroquoian horizon, likely from increased human sewage in the watershed. The abundance of fossil rotifers—microscopic aquatic animals that feed primarily on unicellular algae—increased in the Iroquoian zone (Fig. 4), reflecting higher algal populations due to elevated nutrient concentrations. These prominent paleoecological changes were a more rapid response to the modest nutrient input compared to the geochemical proxies related to overall productivity; the data illustrate the sensitivity of diatom assemblages and rotifer abundance to small variations in nutrient concentration.

Expansion of Iroquoian horticulture and village settlement produced higher runoff and elevated nutrient loading that further altered diatom communities. Subsequently, diatoms that thrive at higher nutrient concentrations quickly succeeded *Stephanodiscus*. *Synedra nana,* a poor competitor for Si yet a good competitor for P (Anderson et al. 1995), increased first. *Synedra nana* was succeeded by *Fragilaria crotonensis* and *Asterionella formosa*, indicating increased concentrations of P such that Si became the limiting nutrient for diatoms. A second rise in *Synedra* species, following the *A. formosa* peak, indicates a return to P as the limiting nutrient as Iroquoian agricultural activity in the region subsided.

We place the start of the post-Iroquoian zone at 48.4 cm (A.D. 1486) on the basis of the disappearance of cultigen pollen. As Iroquoian activity and nutrient inputs within the watershed waned, sedimentation rates, carbon accumulation, and $\delta^{13}C$ values returned to predisturbance values. However, bottom waters remained anoxic, as shown by continued varve preservation. C/N ratios remained lower, indicating elevated aqueous organic matter relative to terrestrial organic matter. A meso-eutrophic diatom assemblage persisted through the post-Iroquoian zone.

In the nineteenth century, a second forest-clearance phase, caused by Canadians with plow agriculture, triggered another period of elevated productivity and ecosystem disturbance. This phase began at A.D. 1867 (~26 cm, Fig. 2); the Canadian Zone sediments are marked by a change in color and an increase in sedimentation rates (Fig. 1). Increased charcoal (Clark and Royall, 1995), *Ambrosia* (ragweed) pollen, and *Poaceae* pollen accumulations are also found at the beginning of the Canadian zone. TOC and $CaCO_3$ accumulation rates increased (to ~10 and ~25 $mg \cdot cm^{-2} \cdot yr^{-1}$, respectively), and organic matter C/N values decreased further from 13 to 11.5 (Fig. 3), again indicating increased photosynthetic algal activity stimulated by increased nutrient input.

Diatom productivity, determined from frustule-accumulation rates, and total rotifer abundance peak at the beginning of the Canadian zone (Fig. 4). The eutrophic planktonic species *S. nana* and *F. crotonensis* account for most of the diatom productivity

(Fig. 4). Benthic species show a corresponding decrease in percentage at the beginning of the Canadian zone (Fig. 4). Though sediment focusing and core location may bias the diatom stratigraphy towards planktonic species (Anderson et al. 1994), benthic accumulation rates were at the lowest levels of the entire record at this time, presumably because elevated terrigenous input or planktonic production restricted littoral benthic habitat through light limitation (Stoermer and Smol, 1999; Vadeboncoeur et al. 2003). Unlike the Iroquoian zone, diatom response is mainly in terms of productivity without major changes in the diatom assemblage.

Carbonate $\delta^{13}C$ values show little response to elevated productivity in the Canadian zone. This suggests that the rate of productivity, and thus the rate at which DIC was metabolized and incorporated into organic material, was never high enough to significantly deplete the DIC reservoir in ^{12}C on a seasonal or long-term basis.

Reduced diatom productivity and a return of benthic species in the 1930s indicate increased light penetration and a recovery for the Crawford ecosystem, presumably owing to homesteading by the Crawford family, who allowed forest regrowth (Rybak and Dickman, 1988). As nutrient and P levels declined, *S. nana* again became the most common diatom species in the water column. *A. formosa* and *C. bodanica* reappeared in 1980. The presence of *A. formosa* suggests recent eutrophication from the construction of a replica Iroquoian village and visitor center associated with increased foot traffic around the lake. The return of *C. bodanica* in 1980 could be a result of favorable lake N/P ratios resulting from atmospheric deposition of N and/or use of nitrogen fertilizers.

IMPLICATIONS AND CONCLUSIONS

There is no consensus as to what extent early Native American agriculturists affected the eastern North American environment. Some investigators have argued, on the basis of archeological, palynological, and historical evidence, that precontact population densities in southern Ontario were too low and the duration of their impact on the environmental was too short to have had significant, lasting effects on the landscape (Campbell and Campbell, 1994). Other archeological evidence indicates that A.D. 1300–1475 was a period of dramatic population growth in southern Ontario and that oversized communities were a source of sociocultural and ecological impacts (Warrick, 2000). Our paleolimnological analyses of Crawford Lake support the latter interpretation. As such, our findings are similar to those from other continents that show long-lasting effects upon limnological systems due to prehistoric agriculture and forest clearance (Deevey et al. 1979; Fritz, 1989; Renberg et al. 1993). Nutrient input during the time of Iroquoian settlements (A.D. 1268–1486) fundamentally and permanently altered the Crawford Lake ecosystem from its natural baseline. Excessive nutrient enrichment induced bottom-water anoxia and permanently modified phytoplankton communities and carbon storage in the lake. These deleterious effects of prehistoric eutrophication were not abated with a reduction in nutrient supply. The eutrophic diatom assemblage emplaced at the start of the Iroquoian zone remains in place and is primed for further nutrient input, despite ~400 yr of minimum nutrient input between disturbances. Further nutrient input at the beginning of the Canadian zone resulted in greater diatom production, but did not result in a new diatom assemblage.

A broader question is whether the Crawford Lake record is an atypical localized example and, as such, not especially relevant to other areas of eastern North America. We would agree that the sediment record of Crawford Lake is exceptional, but only in the sense that the anoxic bottom waters preserve annual laminations that facilitated this ultra high-resolution study. It is likely that many native agrarian societies in North America influenced the ecology of nearby lakes and rivers. We believe that detailed study and careful dating of other lake records in the region will also carry examples of prehistoric ecological impact. Consequently, watershed management in North America, especially in regions where pre-European populations were high, should be aware of the pre-historical dimension of human impacts upon local ecology.

ACKNOWLEDGMENTS

We gratefully acknowledge the Halton Regional Conservancy Agency for lake access. We thank A. Zimmer, S. Mumma, and N. Andresen for field and laboratory assistance. This study received support from NSF (ATM-0102236 to J. Teranes) and the University of Michigan (Turner Award to E. Ekdahl). Funding for ^{14}C analyses from UCRP award through CAMS minigrant program at LLNL. Radiocarbon analyses were performed under the auspices of the U.S. Department of Energy by UC-LLNL (contract W-7405-Eng-48). We thank two anonymous readers for insight and thoughtful reviews of an earlier version of this manuscript.

REFERENCES CITED

Anderson, N.J., Korsman, T., and Renberg, I., 1994, Spatial heterogeneity of diatom stratigraphy in varved and non-varved sediments of a small, boreal-forest lake: Aquatic Sciences, v. 56, p. 40–58.

Anderson, N.J., Renberg, I., and Segerström, U., 1995, Diatom production responses to the development of early agriculture in a boreal forest lake-catchment (Kassjön, northern Sweden): Journal of Ecology, v. 83, p. 809–822.

Battarbee, R.W., 1973, A new method for the estimation of absolute microfossil numbers, with reference especially to diatoms: Limnology and Oceanography, v. 18, p. 647–653.

Binford, M.W., Brenner, M., Whitmore, T.J., Higuera-Gundy, A., Deevey, E.S., and Leyden, B., 1987, Ecosystems, paleoecology and human disturbance in subtropical and tropical America: Quaternary Science Reviews, v. 6, p. 115–128.

Byrne, R., and McAndrews, J.H., 1975, Pre-Columbian purslane *(Portulaca oleracea* L) in the New World: Nature, v. 253, p.726–727.

Campbell, I.D., and Campbell, C., 1994, The impact of Late Woodland land use of the forest landscape of southern Ontario: Great Lakes Geographer v. 1, p. 21–29.

Clark, J.S., and Royall, P.D., 1995, Transformation of a northern hardwood forest by aboriginal (Iroquois) fire: Charcoal evidence from Crawford Lake, Ontario, Canada: The Holocene, v. 5, p. 1–9.

Deevey, E.S., Rice, D.S., Rice, P.M., Vaughan, H.H., Brenner, M., and Flannery, M.S., 1979, Mayan urbanism: Impact on a tropical karst environment: Science, v. 206, p. 298–306.

Digerfeldt, G., and Håkansson, H., 1993, The Holocene paleolimnology of Lake Sämbosjön, Southwestern Sweden: Journal of Paleolimnology, v. 8, p. 189–210.

Douglas, M.S.V., Smol, J.P., Savelle, J.M., and Blais, J.M., 2004, Prehistoric Inuit whalers affected Arctic freshwater ecosystems. Proceedings of the National Academy of Sciences, v. 101, p. 1613-1617.

Edmondson, W.T., 1959, Rotifers, *in* Edmondson, W.T., ed., Freshwater biology: New York, Wiley, p. 420–494.

Finlayson, W.D., editor, 1998, Iroquoian peoples of the land of rocks and water, A.D., 1000–1650: A study in settlement archaeology: London, Ontario, London Museum of Archaeology Special Publication 1, 425 p.

Fritz, S.C., 1989, Lake Development and limnological response to prehistoric and historic land-use in Diss, Norfolk, U.K.: Journal of Ecology, v. 77, p. 182–202.

Krammer, K.H., and Lange-Bertalot, H., 1987-1997, Bacillariophyceae, *in* Ettl, H., Gerloff, J., Hynig, H., and Mollenhauer, D., eds., Süßwasserflora von Mitteleuropa: Stuttgart, Fisher, v. 1–4.

McAndrews, J.H., and Boyko-Diakonow, M., 1989, The laminated sediments of Crawford Lake, southern Ontario, Canada, *in* Fulton, R.J., ed., Quaternary geology of Canada and Greenland: Geological Survey of Canada, Geology of North America Series, v. K-1, n. 1, p. 528–530.

Meyers, P.A., 1994, Preservation of elemental and isotopic source identification of sedimentary organic matter. Chemical Geology, v. 114, p. 289–302.

Müller, G., and Gastner, M., 1971, The ‘Karbonat-Bombe,’ a simple device for the determination of the carbonate content in sediments, soils and other materials: Neues Jahrbuch für Mineralogie, v. 10, p. 466–469.

Patrick, R., and Reimer, C., 1966, Monograph series of the Academy of Natural Sciences of Philadelphia #13: Diatoms of the United States. Philadelphia, National Academy of Sciences, p. 688.

Renberg, I., Korsman, T., and Birks, H.J.B., 1993, Prehistoric increases in the pH of acid-sensitive Swedish lakes caused by land-use changes: Nature, v. 362, p. 824–827.

Rybak, M., and Dickman, M., 1988, Paleoecological reconstruction of changes in the productivity of a small, meromictic lake in southern Ontario, Canada: Hydrobiologia, v. 169, p. 293–306.

Smith, V.H., 1998, Cultural eutrophication of inland, estuarine and coastal waters, *in* Pace, M.L., Groffman, P.M., eds., Successes, limitations and frontiers in ecosystem science: New York, Springer, p. 7–49.

Stoermer, E.F., and Smol, J.P., editors, 1999, The diatoms: Applications for the environmental and earth sciences: Cambridge, UK, University Press, 469 p.

Stuiver, M., and Reimer, P.J., 1993, Extended ^{14}C data base and revised CALIB radiocarbon calibration program: Radiocarbon, v. 35, p. 215–230.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., v.d. Plicht, J., and Spurk, M., 1998, INTCAL98 radiocarbon age calibration 24,000-0 cal BP: Radiocarbon, v. 40, p. 1041–1083.

Vadeboncoeur, Y., Jeppesen, E., Zanden, M.J.V., Schierup, H.-H., Christoffersen, K., and Lodge, D.M., 2003, From Greenland to green lakes: Cultural eutrophication and the loss of benthic pathways in lakes: Limnology and Oceanography, v. 48, p. 1408–1418.

Wallace, R.L., and Snell, T.W., 1991, Phylum Rotifera, *in* Thorp, J.H., and Covich, A.P., eds., Ecology and classification of North American freshwater invertebrates. San Deigo, Academic Press, p. 187–248.

Warrick, G., 2000, The Precontact Iroquoian occupation of southern Ontario: Journal of World Prehistory, v. 14, p. 415–466.

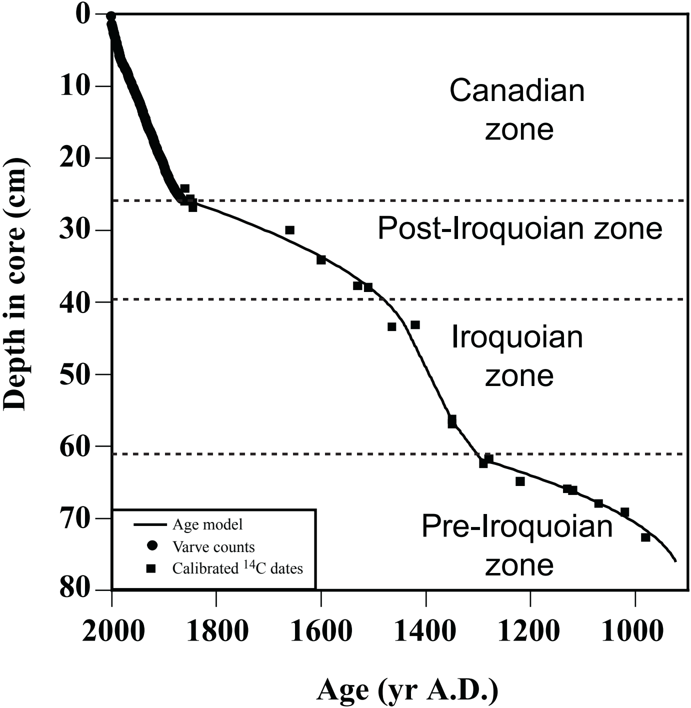
FIGURE CAPTIONS

Figure 1. Calibrated accelerator mass spectrometry (AMS) ^{14}C ages, age model, and varve counts plotted vs. depth. Age model consists of four equations fit to ^{14}C date trends. During pre-Iroquoian zone, $A = 1.3436d^2 - 211.35d + 9225.1$, where A is depositional age and d is depth in centimeters. During Iroquoian zone, age is based on linear sedimentation rates. Between 56 and 44 cm, sedimentation rates were 10.3 yr/cm, and between 44 and 37 cm, sedimentation rates were reduced to 6.8 yr/cm. For remaining Iroquoian zone and post-Iroquoian zone, $A = 0.9203d^2 - 87.562d + 3505.6$.

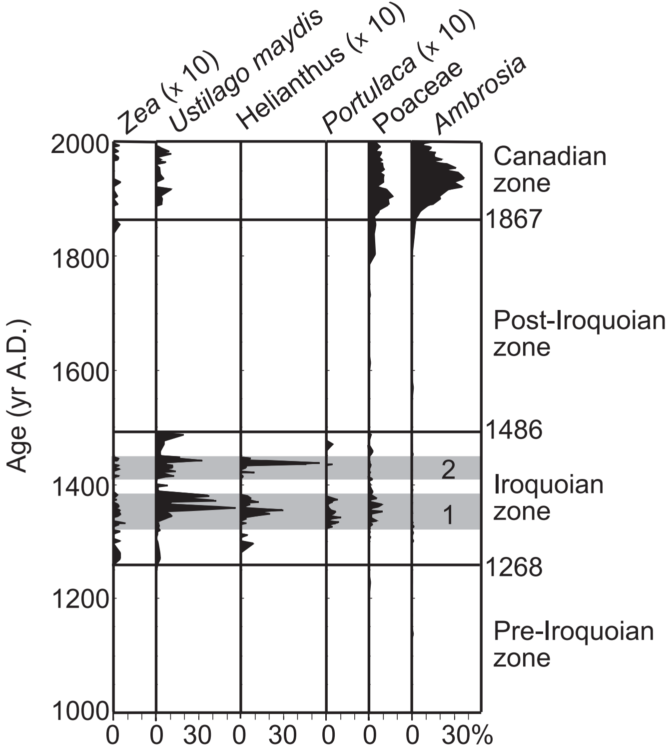
Figure 2. Crawford Lake pollen diagram showing cultigens *Zea* and *Helianthus*, fungal spores of *Ustilago*, and disturbance-related plants *Portulaca*, Poaceae, and *Ambrosia*. Shading illustrates the two Iroquoian village settlement periods nearest the lake, based on pollen evidence. Units in percent of total counted pollen grains.

Figure 3. Geochemistry of Crawford Lake sediments. A: $CaCO_3$ mass accumulation rates (MAR). B: Total organic carbon (TOC) MAR. C: C/N (atomic) ratio values. D: $\delta^{13}C$ values from authigenic carbonate precipitate. Dashed lines correlate to core depths and illustrate palynological zones described in text.

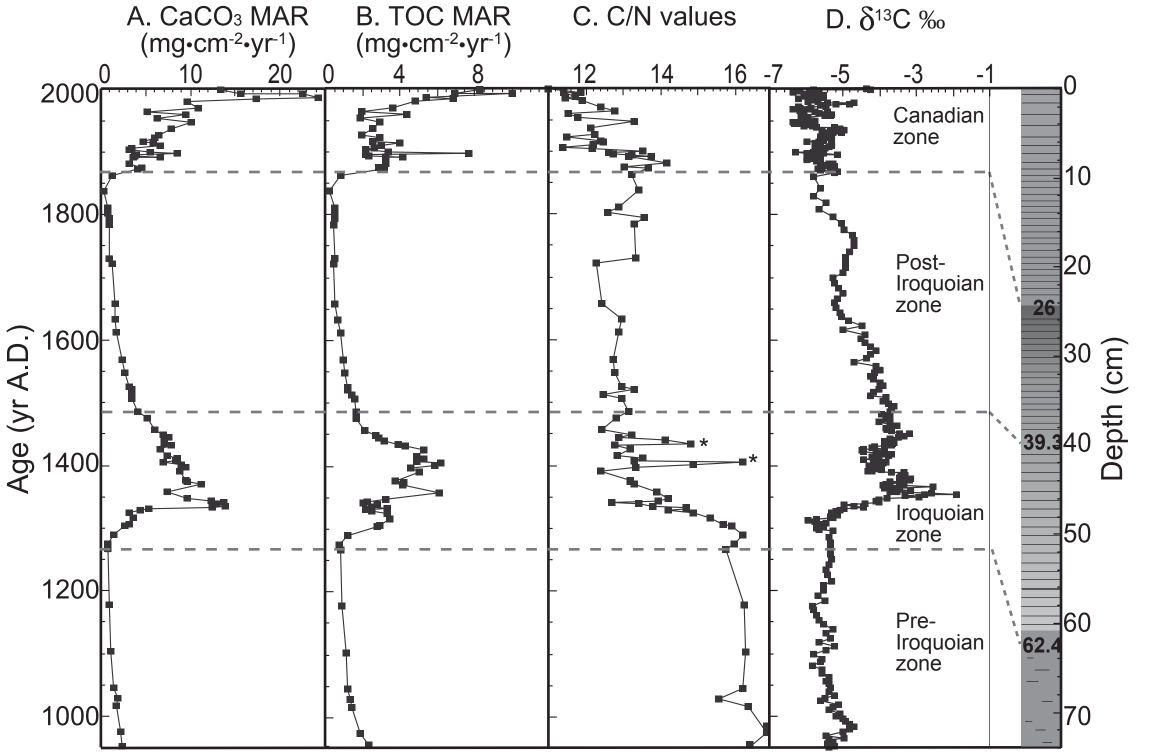
Figure 4. Diatoms, rotifers, and diatom accumulation rates (DARs). A: Planktonic diatom species expressed as percentages of total diatom valves (minimum 500 valves counted per sample). Diatom species from left to right are *Cyclotella bodanica* v. *lemanica, Stephanodiscus* spp. (the sum of at least four species, including *S. hantzschii, S. minutus,* and two unidentified or unknown species), *Synedra nana, Fragilaria crotonensis, Asterionella formosa,* and *Cyclotella michiganiana.* Fossil rotifers are *Kellicotia longispina, Keratella cochlearis, K. hiemali,* and *K. quadrata* (Edmondson, 1959; Wallace and Snell, 1991) expressed as percentages of pollen grains. B: Summed benthic species comprise all non-planktonic diatoms, mainly *Achnanthidium*, *Encyonopsis*, *Cymbella*, and *Cymbopleura* species. C: Diatom accumulation rates, in units of valves per cm^2 per year. Dashed lines are those described in Figure 3.



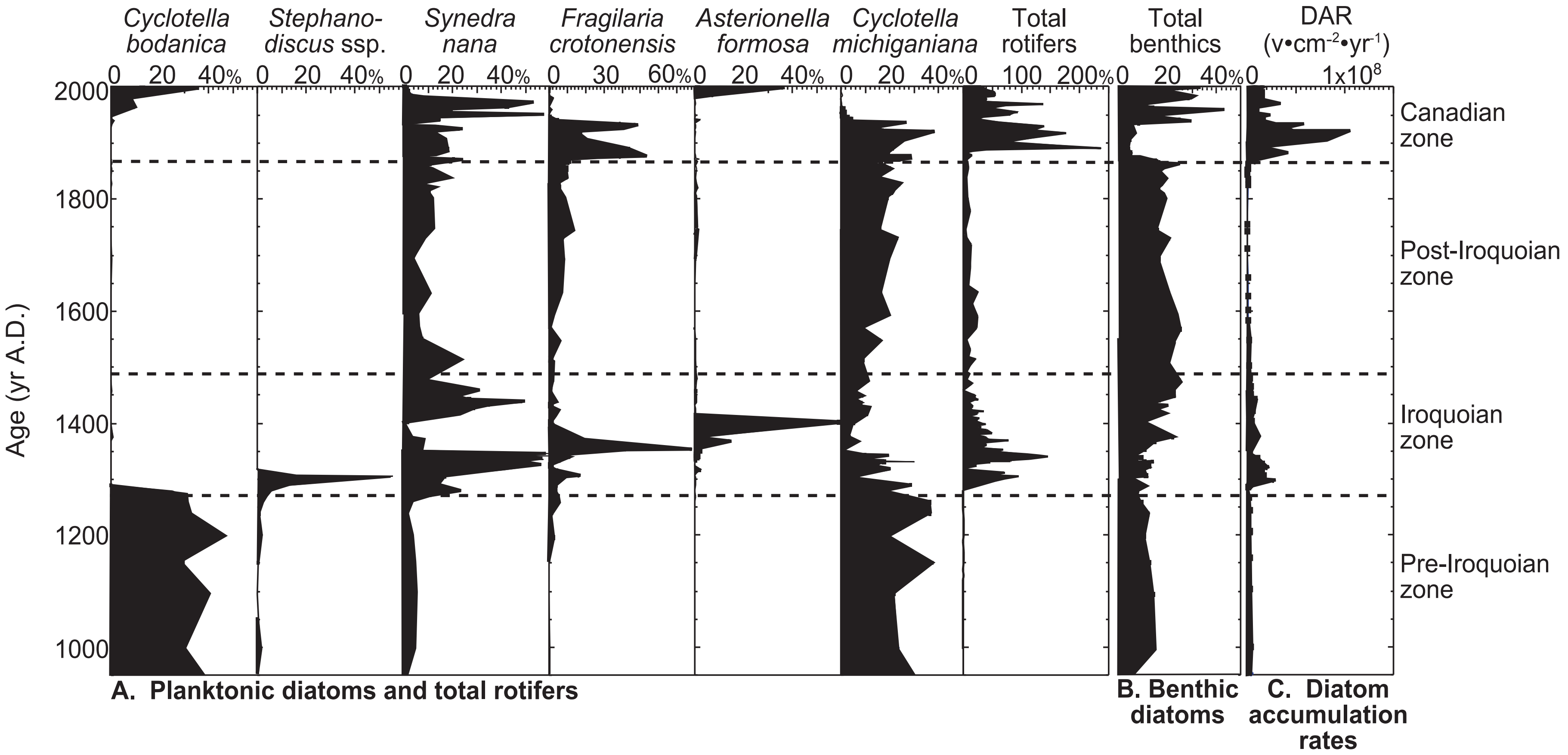
0
10
20
30
40
50
60
70
80
Depth in core (cm)
2000
1800
1600
1400
1200
1000
Age (yr A.D.)
Canadian zone
Post-Iroquoian zone
Iroquoian zone
Pre-Iroquoian zone
Age model
Varve counts
Calibrated 14C dates



Zea (x 10)
Ustilago maydis
Helianthus (x 10)
Portulaca (x 10)
Poaceae
Ambrosia
Age (yr A.D.)
2000
1800
1600
1400
1200
1000
Canadian zone
1867
Post-Iroquoian zone
1486
2
Iroquoian zone
1
1268
Pre-Iroquoian zone
0
0 30
0 30
0
0
0 30%



A. CaCO3 MAR (mg•cm-2•yr-1)
B. TOC MAR (mg•cm-2•yr-1)
C. C/N values
D. δ13C ‰
Age (yr A.D.)
Depth (cm)
Canadian zone
Post-Iroquoian zone
Iroquoian zone
Pre-Iroquoian zone
26
39.3
62.4



Cyclotella bodanica
Stephano-discus ssp.
Synedra nana
Fragilaria crotonensis
Asterionella formosa
Cyclotella michiganiana
Total rotifers
Total benthics
DAR (v•cm-2•yr-1)
0 20 40%
0 30 60%
0 100 200%
0 1x10^8
2000
1800
1600
1400
1200
1000
Age (yr A.D.)
Canadian zone
Post-Iroquoian zone
Iroquoian zone
Pre-Iroquoian zone
A. Planktonic diatoms and total rotifers
B. Benthic diatoms
C. Diatom accumulation rates