Arcellaceans (thecamoebians): new tools for monitoring long- and short-term changes in lake bottom acidity

A. Kumar · R.T. Patterson

Abstract James Lake, northeastern Ontario, Canada, has been impacted by the dumping of waste rock from a pyrite mine. High levels of Fe, Al and SO_4, and low pH (2.0–5.5) are recorded in the lake. Lake configuration and current direction result in contaminated areas being restricted to the southwestern portion of the lake. Near neutral pH and low metal levels are recorded elsewhere. Analysis of arcellacean faunas from the lake indicate that one species, *Arcella vulgaris*, is able to thrive in even the most hostile areas of the lake. The absence of other arcellaceans indicative of contaminated substrates in higher pH lakes, such as centropyxids and *Difflugia protaeiformis* strains, suggests that pH is the dominant control on the distribution of this assemblage. Analysis of arcellaceans from a core at the site indicates that contamination and acidification (pH values <5.5) problems in James Lake have existed for at least 1300 years, clearly predating mining activity. Prior to that time high proportions of centropyxid species indicate less acid conditions (pH$>$5.5) prevailed, but a stressed environment existed for several thousand years. The recognition that Arcellacean faunas can now be used to characterize industrially, and naturally contaminated environments of both low and high pH, provides an important new paleolimnological tool.

Key words Arcellaceans · James Lake · Acidity · Pyrite mine

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Introduction

Arcellaceans "Thecamoebians" are testate rhizopods, characterized by the presence of lobose pseudopods, an amoeboid sarcodine cell, and a very simple sac-like shell, or test. These organisms occur abundantly in Quaternary to Recent lacustrine sediments (Loeblich and Tappan 1964). Most arcellaceans build their tests by agglutinating foreign particles (xenosomes) in an autogenous cement, usually mucopolysaccharide, forming xenogenous tests. The nature of the xenosomes is entirely controlled by the composition of the substrate, and may consist of sand grains and/or diatom frustules (Medioli and others 1990). In a series of pilot studies, arcellaceans have been successfully used to reconstruct late Quaternary-Holocene lacustrine environments (Scott and Medioli 1983; Patterson and others 1985; Medioli and Scott 1988; Ellison 1995; McCarthy and others 1995) and have proven to be excellent indicators of various, chemically polluted and rehabilitated sub-environments within lakes affected by industrial and mining pollution (Asioli and others 1996; Patterson and others 1996; Kumar and Patterson 1997; Reinhardt and others 1998). These studies have shown that there are few benthic environmental indicators in lacustrine environments with the potential for such broad limnological utility as arcellaceans. Their small size (60–300 μm) and generally high abundance mean that statistically significant populations are present even in very small samples. Research has documented within-species "morphing" of the asexually reproducing organisms in response to environmental stresses (Reinhardt and others 1998). Since they reproduce rapidly (generation times of only a few days), they are excellent ongoing indicators of an ecosystem's health. Conventional biological and chemical environmental proxies can only monitor present conditions in a lacustrine environment. For example, commonly used benthic bioindicators such as ostracodes and molluscs tend to dissolve in the lower pH environments typical of freshwater deposits. Other more resistant bioindicators such as diatoms, pollen, spores, and chrysophytes do not generally reflect conditions at the sediment–water interface (Medioli and Scott 1988). The agglutinated test and organic cement of the arcellaceans are very resistant to dissolution. They are therefore excellent indicators of both short- and long-term trends (Patterson and others 1985).

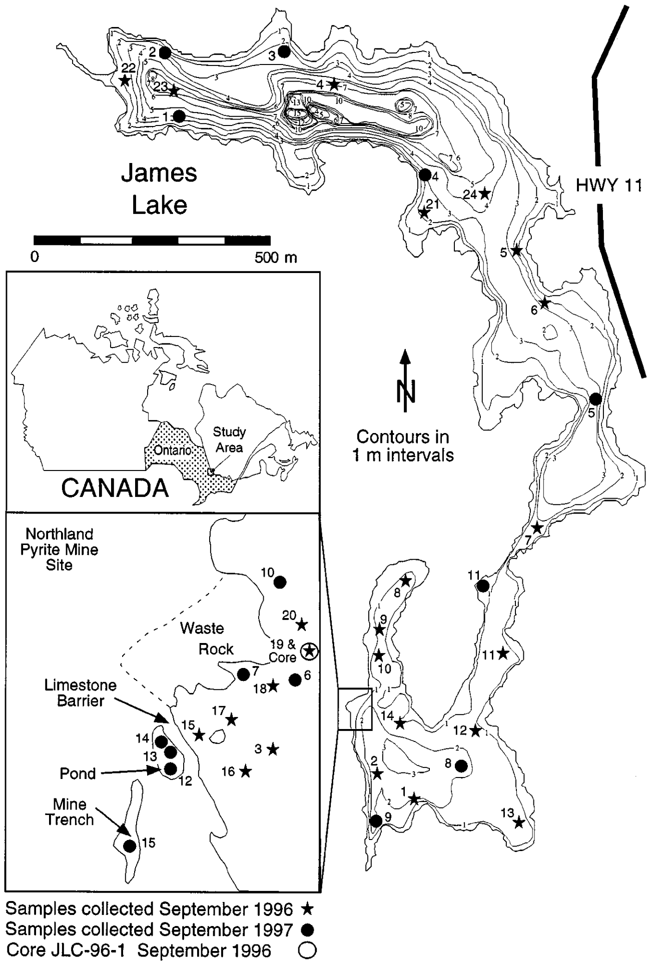

Fig. 1
Location Map showing position of James Lake in northeastern Ontario. Bathymetric map of lake shows relative position of sample and core stations as well as general layout of abandoned Northland Pyrite Mine Co. site

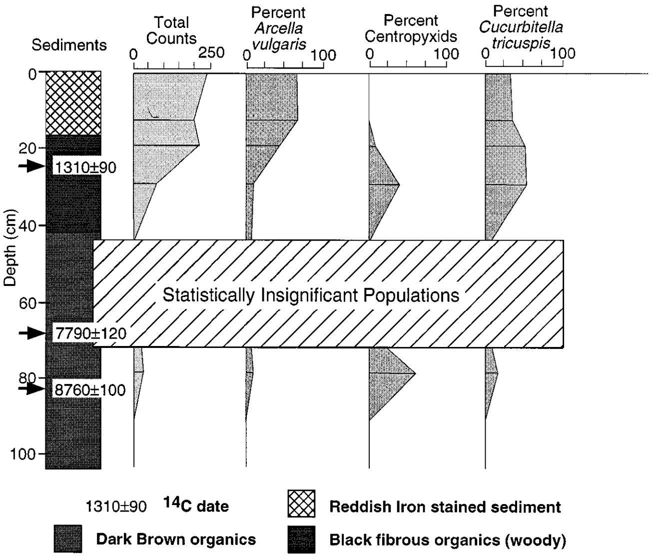

Fig. 2
Sedimentology, biostratigraphy and ^{14}C dates from a core collected in James Lake adjacent to the waste-rock pile. The ^{14}C date was obained from a nearby core collected for geochemical analysis (Mason 1998)

This paper demonstrates a new role for arcellaceans in paleolimnological research; as they can be a cost-effective tool for deciphering short- and long-term lake-bottom acidity levels. The research was carried out in James Lake, located in the environmentally sensitive Temagami region of northern Ontario, and polluted earlier this century by the dumping of sulfide-rich waste rocks from a pyrite mine (Fig. 1). As a baseline, the pH controlled distribution of arcellacean fauna throughout the lake was determined to establish arcellacean limnological proxies. To assess long-term changes to the lake, this proxy data was used to interpret paleolimnological conditions as recorded in a short core (Fig. 2).

Materials and methods

A major advantage of working with arcellaceans is the simple and inexpensive methodology required for processing, whereby several samples can be processed in less than an hour without use of chemicals or expensive equipment (Medioli and others 1990, Medioli and Scott 1988; McCarthy and others 1995; Patterson and others 1996; Reinhardt and others 1998).

Fifty-five samples collected over two field seasons were used in this study. Of the 40 samples collected in September 1996, 24 were lake bottom samples, 6 were from a mine-contaminated pond, and 1 from a mine trench (Fig. 1). The remaining 9 samples were from a short core (1.05 m) collected in the lake adjacent to the waste rock pile. An additional 15 samples were collected in September 1997, of which 11 were from the lake, 3 from the pond and 1 from the mine trench. Sediment–water interface samples were collected using an Eckman box corer. Water depth, sedimentology, pH, water temperature, and other physical characteristics were recorded for each location (Table 1). The exact geographic location of each sample was determined using a Trimble Scout Global Positioning System unit.

A commercial sonar device equipped with bottom hardness indicator was used for sample site selection. Samples were collected from muddy substrates. Winnowed sandy substrates generally have small allochthonous arcellacean communities and rocky substrates are normally barren. The upper 2–3 mm of sediment from each Eckman grab was removed for micropaleontological analysis (arcellaceans are epifaunal) to isolate arcellacean fauna of the sediment–water interface. The populations found in these samples are representative of conditions at the site for several seasons. In general, bioindicators provide a better overall indication of local conditions than the snapshot provided by geochemical methods as these results often

Table 1
Parameters measured at each sample station; water depth, oxygen concentration, pH, sediment color, and sediment texture. Sample station location shown in Fig. 1

Sample station	Water depth (m)	Sediment/ Water interface pH	Surface water pH	Sediment/ Water interface O_2 (mg/l)	Surface water O_2 (mg/l)	Surface water temp. (C)	Sediment/ Water interface temp. (C)	Sediment texture	Sediment color
JL-96-1	1.8	6.7	7.4	8.2	8.2	23.3	20.7	Clay	Greenish Brown
JL-96-2	2.6	3.9	6.7	5.6	8	22.4	20.4	Clay	Grayish Brown
JL-96-3	0.9	3.9	7.6	6.9	7.6	23.3	21	Clay	Rusty Brown
JL-96-4	9.8	7.1	7.8	1.4	8.3	24.4	6.7	Silt/Clay	Dk. Olive Green
JL-96-5	4.2	6.9	7.2	7.5	8.2	23.8	20.3	Clay	Dk. Olive Green
JL-96-6	2.4	7.3	7.4	7.4	7.6	23.8	20.8	Clay	Dk. Olive Green
JL-96-7	1	6.5	7.6	7.1	8	24.8	20.8	Silt/Clay	Dk. Olive Green
JL-96-8	1.8	6.9	7.1	6	7.1	21.7	21.3	Clay	Dk. Brown
JL-96-9	1.4	6.5	6.5	7.3	7.4	21.8	21.4	Silt/Clay	Grayish Brown
JL-96-10	0.6	2.5	5.7	7.4	8.4	21.7	21.5	Sand/Clay	Light Brown
JL-96-11	1.4	6.5	6.5	7.2	7.3	22.5	21.5	Silt/Clay	Greenish Black
JL-96-12	0.9	6.6	6.8	7.4	7.5	22.5	22.3	Sand/Clay	Dk. Brown
JL-96-13	1.1	6.7	6.8	7.4	7.7	22.3	21.5	Sand/Clay	Greenish Black
JL-96-14	1.1	6.7	6.9	7.4	7.5	22.8	22.5	Clay	Brownish Black
JL-96-15	1.3	2.6	6.9	6.9	7.3	24.6	22.9	Silt/Clay	Lt. Brown
JL-96-16	0.8	2.1	5.5	6.1	7.1	25.4	23.4	Sand/Clay	Brown
JL-96-17	1	4.1	5.7	7.4	8.1	23.4	23.4	Clay	Yellowish Brown
JL-96-18	0.8	5.3	5.9	6.9	6.9	24.7	23.7	Sand/Clay	Dk. Brown
JL-96-19	01.3	5.5	5.9	5.9	7.2	24.3	23.9	Clay	Greenish Black
JL-96-20	0.7	2.2	3.7	5.2	6.8	26.7	25	Clay	Greenish Black
JL-96-21	1	6.4	6.7	6.8	7.7	23.6	22.7	Clay	Greenish Black
JL-96-22	3	6.7	7.1	7.3	7.8	23.6	20.7	Clay	Black
JL-96-23	14.1	6.7	7.1	5.2	7.5	24	8.9	Clay	Black
JL-96-24	5.5	6.7	7.1	7.2	7.3	23.8	19	Clay	Black
JL 97-1	7.8	6.7	7.9	2.4	9	17	13	Clay	Dk. Brown
JL 97-2	3	7	7.3	NA	NA	17.5	17.5	Clay	Dk. Brown
JL 97-3	3.9	7.3	7.3	8.1	8.2	17.8	17.1	Silt/Clay	Greenish Brown
JL 97-4	3.1	7.3	7.3	8.1	8.2	18.2	17.7	Fine Clay	Greenish BrownGrayish Brown
JL 97-5	3.5	6.6	7.3	8.6	8.3	18.1	17.1	Fine Clay	Grayish Brown
JL 97-6	1.4	5.7	5.9	8.8	8.8	16.8	16.8	Clay	RustyBrown
JL 97-7	0.7	4.3	5.9	8.4	8.7	17.3	17.1	Clay	Greenish Brown
JL 97-8	1.4	6.6	6.5	8.1	8.2	17.2	17	Clay	Dk. Green
JL 97-9	1.6	6.1	6.5	8.2	8.1	17.3	NA	Clay	GrayishBlack
JL 97-10	1.1	4.4	6	7.9	8	17.9	NA	Clay/Pebbles	Grayish Brown
JL 97-11	1.5	6.4	6.7	8	8.1	18.8	18	Silt/Clay	Brownish Black
JL 97-12	0.3	2.9	2.9	NA	NA	17	17	Silt/Clay	RustyBrown
JL 97-13	0.3	2.8	2.9	NA	NA	17	17	Silt/Clay	RustyBrown
JL 97-14	0.3	2.8	2.9	NA	NA	17	17	Silt/Clay	RustyBrown
JL 97-15	16.7	4	3	2.4	6.7	15.5	NA	Silt/Clay	Rusty Brown

vary markedly with the season, recent precipitation levels, etc. A 1-cm-deep sediment sample was used for geochemical analysis of pore water. We did not analyze bulk sediment samples because the chemical makeup of compounds and elements found in pore water are in forms that can be directly ingested and absorbed by most organisms (Luoma 1983; Campbell 1995). Samples for micropaleontological analysis were first screened with 1000-μm sieve to remove coarse organics, then with a 55-μm screen to retain arcellaceans and to remove silts and clays. To avoid decay, all samples were treated with isopropyl alcohol and refrigerated after collection. All micropaleontological samples were then subdivided into aliquots for quantitative analysis using a wet splitter (Scott and Hermelin 1993). Wet aliquots were examined under a binocular microscope and, whenever possible, a statistically significant number of arcellaceans were counted (Patterson and Fishbein 1989). All samples collected from the open lake contained large arcellacean populations with the exception of those from “Green Holes”. The green holes are shallow (15–25 cm deep), almost circular depressions of about 1.0-m diameter at the lake bottom inhabited solely by colonies of green and blue-green algae, because the low pH makes these areas toxic to grazers and other organisms and are found in very shallow waters (1.0–1.5 m water depth) close to the waste rock dump. All samples from the pond and mine trench contained only rare specimens of *Arcella vulgaris*, and are considered barren. Although the total arcellacean counts from the core samples were lower than generally obtained at the surface, counts were sufficiently high to permit direct comparison with surface samples.

James Lake and the nature of the problem

James Lake is a mesotrophic, "C"-shaped lake located along Highway 11, 10 km north of Temagami in northeastern Ontario (Fig. 1). The narrow lake covers an area of 45.3 ha, and is elongated in a north-south direction. An inlet stream at the north end feeds the lake, with an outlet at the south end. A constriction divides the lake into north (80%) and south (20%) basins. The southern basin is shallow and reaches a maximum depth of only 4.0 m. The northern basin is deeper with a maximum depth of 15.0 m (Fig. 1). The northern basin is stratified, with both oxygen levels and temperature dropping significantly beneath 5.0 m depth. During our sampling in early September 1996 and 1997 the upper epilimnion temperature reached as high as 26.7 °C and oxygen levels as high as 9.0 mg/l were recorded. These values dropped to 8.9 °C and 2.4 mg/l respectively in the lower hypolimnion (Table 1).

The main rock types surrounding the lake are felsic and mafic volcanic rocks, pillow lavas, granites, granodiorites and gabbros of Keewatin age (3.4–2.3 b.y.). The volcanic rocks are rich in pyrite. Pyrite was discovered in lenses within greenschist in 1903. The Northland Pyrite Mine Co. mined pyrite on the southwest shore of the lake from February 1906 to March 1911, shipping more than 38000 tons of pyrite to Cobalt, a nearby silver mining town. Sulfuric acid made from the pyrite was used in the extraction of silver. Most waste rock from this mine was dumped on the southwest lake shore, and in the lake itself (Fig. 1). The waste-rock pile (3500 m^3) contains large amounts of pyrite (about 25%) with lesser amounts of pyrrhotite and traces of chalcopyrite and gold.

In 1979 local residents expressed concern that seepage from the waste-rock pile and mine trench was having a detrimental effect on Granite Lake, immediately (about 1.0 km) downstream from James Lake. An Ontario Ministry of the Environment (MOE) report indicated that iron staining was visible on all rocks cropping out along the shore throughout the entire southern basin (Gale 1990), as we also observed in both 1996 and 1997. The MOE study, began only two days after ice had melted in the lake on 10 May 1989, and continued throughout that summer, reported little evidence of insect benthos near the mine site. Three key water quality parameters (iron, aluminum and sulfate) were found to exceed provincial guidelines. Because the substrate in the southern basin contains large amounts of iron oxides, the clays and fine sands found there are of a rusty brown color. The bottom sediments in the northern basin of the lake are gray colored organic rich muddy sediment or "gyttja".

The pH of water and bottom sediments of the north basin is neutral (pH 6.8–7.0) and is not generally affected by conditions in the south basin because of the north-south water flow in the lake. The pH in the southern basin varies from <2.0 near the waste-rock pile to 5.5 in the surrounding region. Low pH values near the waste-rock pile ($pH<5.5$) were generated by percolating flow of rain water that oxidizes sulfide from pyrite and pyrrhotite in the waste rocks and bedrock (Gale 1990). There is a gradual increase in pH values to almost neutral (pH 6.8) in more distal areas of the south basin (Table 1).

Sulfide ions from the mineralized waste rocks and hydrogen ions from water react to produce sulfuric acid (H_2SO_4). In areas of the lake very near the waste-rock pile, sediment sulfate concentrations are very high, up to 17238 mg/l, at station 97-7 (Table 2). However, most pore water sulfate values measured from lake sediments adjacent to the waste rock pile were much less (396 mg/l and 682 mg/l at stations 97-15 and 97-10 respectively). Sediment pore water sulfate values drop to acceptable levels (9.9–25.2 mg/l) within 100 m of the waste-rock pile, although an anomalously high value of 668 mg/l was recorded in the eastern portion of the south basin at station 97-12.

Sulfate is almost always found in drinking water, and often in relatively high concentrations (Moore 1991). Drinking water guidelines are 250 mg/l in the US and 500 mg/l in Canada. The development of guidelines was based on aesthetic factors, particularly bad taste, as human health problems are not associated with these levels. However, high sulfate concentrations cause acidification of surface waters which does have a serious impact on fish and other aquatic species (e.g. fish cannot survive at $pH<5.5$; Baker and Christensen 1991).

Table 2
Pore-water pH and geochemistry values for Fe, Al and sulfate at selected stations

Sample	pH	Al (mg/l)	Fe (mg/l)	Sulfate (mg/l)
JL 97-2	6.73	0.46	2.44	7.5
JL 97-3	6.51	0.38	2.84	7.5
JL 97-4	6.55	0.37	2.36	9.2
JL 97-5	6.33	0.19	1.52	12.4
JL 97-6	2.49	64	1240	2884
JL 97-7	2.12	415	11800	17238
JL 97-8	6.24	1.11	59.7	9.9
JL 97-9	5.56	0.94	64.9	25.2
JL 97-10	2.69	146	6200	682
JL 97-11	6.31	0.43	14.3	18.8
JL 97-12	2.07	155.5	4190	668
JL 97-15	3.46	1.13	32.4	396

Extensive deposits of $Fe(OH)_3$ and Fe_2O_3, up to 5-cm thick were found covering the bottom of the southern basin. These layers precipitate out when there is a rapid increase in pH of lakewater, which occurs in James Lake during spring freshet (Gale 1990), and can suffocate benthic organisms (Moore 1991). Sediment pore-water Fe level varied from 1.52 mg/l in the northern basin to 11800 mg/l near the waste-rock pile (station 97-7; Table 2). Iron concentration in lake water varied from 0.09 mg/l in the northern basin to 2.4 mg/l near the waste rock pile (Gale 1990). All pore water and lake water samples were found to be well in excess of the provincial drinking water guideline of 0.3 mg/l for iron. The low drinking-water guideline/standard is based more on aesthetics than a health concern, as the taste of iron can readily be detected at 1.8 mg/l. Very high Fe concentrations can also lead to staining of laundry and plumbing and massive growth of bacteria in water systems (Moore 1991). The recommended daily intake for men is 10 mg and 18 mg for women. At 0.3 mg/l the daily intake of iron from drinking water would be only 0.6 mg.

Iron is so plentiful in the environment and as an essential trace element that high levels often accumulate in invertebrates with little ill effect (Tessier and others 1984; Vymazal 1984). However, extremely high concentrations of iron, as found in substrate pore water near the waste-rock pile can have toxicological significance (Moore 1991). Many species of insects are affected by Fe concentrations in excess of 16 mg/l. The high Fe pore water concentrations, the $Fe(OH)_3$ and Fe_2O_3 deposits coating substrate throughout the western southern basin, and elevated levels of Fe in the lake water itself may explain the observed low number of insects found there (Gale 1990). Although iron concentration guidelines for the protection for higher aquatic life range from 0.3 mg/l to 1.0 mg/l their tolerance is much greater ($>$10 mg/l; Moore 1991). During our study and as reported by the MOE (Gale 1990), a large number of vertebrates (fish and amphibians) were observed in the southern basin, although mostly in the eastern part.

Sediment pore-water aluminum concentrations varied from 0.19 mg/l to 415 mg/l at station 97-7 (Table 2). Aluminum values in the lake water itself varied from 0.05 in the northern basin to 0.24 mg/l near the waste-rock pile (Gale 1990). Aluminum is not essential for survival but it is found in virtually all plant and animal species. In higher pH regimes aluminum quickly forms relatively stable complexes (Plankey and Patterson 1987, 1988). However, in lower pH environments ($pH < 5.5$) such as found in the south basin of James Lake it mobilizes in biologically useable forms (Burrows 1977). Water quality guidelines for aluminum are highly variable and reflect differing opinions on the hazard posed by aluminum in drinking water but 0.2 mg/l seems to be the maximum allowable concentration agreed to by most agencies (Moore 1991). The aluminum concentration guidelines for the protection of aquatic life in Canada and several European nations are 0.005 mg/l at $pH < 6.5$ and 0.1 mg/l at $pH > 6.5$.

Results and discussion

James Lake is an ideal laboratory for assessing the sensitivity of arcellaceans in monitoring industrial pollutants (Kumar and Patterson 1997). The flow of lake water is from north to south, exiting near the source of pollution at the Northland Pyrite Mine Co. site. This circulation pattern has created habitats that range from unimpacted in the northern basin, and in some portions of the southern basin, to extremely contaminated near the mine site itself. This is a useful characteristic, as utilization of any flora or fauna as a bioindicator is comparative. The distribution of organisms in an uncontaminated environment found "upstream" is compared with that of that recorded in the contaminated area. These data can then be used to assess environmental damage "downstream", or in similarly polluted areas.

There is a mature literature concerning the constraints on arcellacean faunas in lake environments of eastern North America. For that reason, and since the thrust of this research is the characterization of arcellacean faunas as bioindicators of contaminated areas, the various faunas from the relatively uncontaminated near neutral pH environments elsewhere in James Lake are not described in detail here. Suffice it to say that these faunal assemblages are controlled by numerous factors including water temperature and level of oxygenation in areas beneath the hypnocline, substrate, and vegetation. The Shannon Diversity Index values for these faunas also tends to be much greater, ranging up to near 2.5 in the northern basin compared to <1 in areas of the southern basin.

Within assemblages certain species are particularly useful as environmental indicators. For example, in James Lake *Arcella vulgaris* varies inversely to most other arcellacean taxa (Fig. 3). High abundance of *Arcella vulgaris* seems to be closely linked to the environments of James Lake with

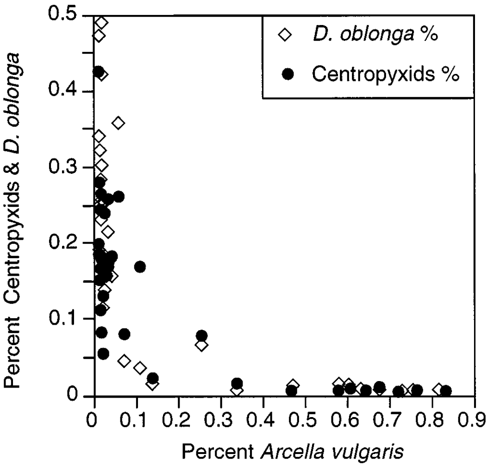

Fig. 3
Scatter plot of relative distribution of *Arcella vulgaris* Centropyxids and Difflugia oblonga in James Lake samples. The almost exclusive distribution of these species demonstrates the clear affinity that various taxa have for distinctive habitats

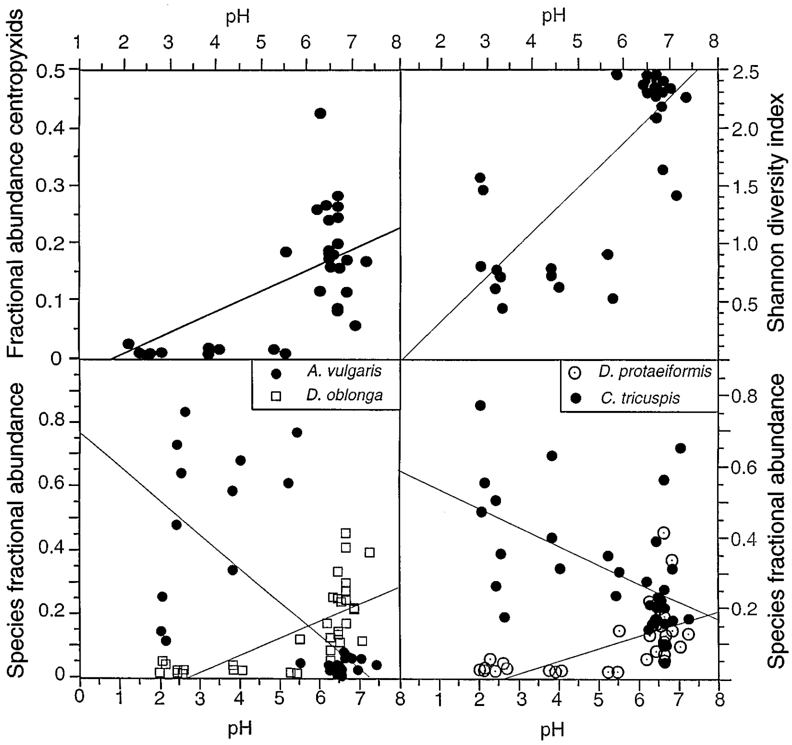

Fig. 4
Relative proportion of various taxa, and Shannon Diversity Index in relation to pH in James Lake. The linear least squares method was used to determine the best fit for the linear curve fits using Deltagraph 4.0 (Deltapoint 1996)

elevated metal concentrations and low pH. *Arcella vulgaris* is the dominant species in the most contaminated areas (pH < 5.5), but forms < 5% of the total assemblage (or even totally absent) in normal pH regions (6.5–7.5; Fig. 4). *Arcella vulgaris* is an important component of arcellacean faunas in boggy ponds in the Arctic and further south (Collins and others 1990). The low pH typical of these ponds has preadapted this species to dominate similar low pH environments. The most acidic sites in the lake with pH < 2.0 were in green holes near the waste-rock pile. Few specimens of *Arcella vulgaris* were even found in this environment.

Other opportunistic taxa notably missing from the low pH environments (pH < 5.5) of James Lake include the centropyxids. Many lakes in the vicinity of the nearby town of Cobalt are heavily contaminated by heavy metals and other mining related contaminants, but were deposited under alkaline conditions. In higher pH environments in the Cobalt area centropyxid species such as *Centropyxis aculeata* often dominate heavy metal contaminated substrates (Patterson and others 1996; Reinhardt and others 1998). Also notably missing from the lower pH environments of this lake are any strains of *Difflugia protaeiformis*. This species is commonly abundant in portions of James Lake with pH of 6.5–7.5, and also in higher pH and highly contaminated areas of Peterson and Crosswise lakes (Reinhardt and others 1998).

In Lake Orta of northern Italy the 'rapa' strain of *Difflugia protaeiformis* was reported as being very abundant in an industrially-polluted low pH (3.9–4.5) setting (Asioli and others 1996). It is apparent that *Difflugia protaeiformis* occurs in environments ranging from low pH to polluted high pH (6–7.5). The association of *Difflugia protaeiformis* with low-pH environments requires further study. The absence of other opportunistic, contaminated substrate indicator species leads us to conclude that pH may be a greater limiting factor than either high Fe or Al in controlling the presence or absence of the *Arcella vulgaris* dominated fauna in James Lake. The recognition that Arcellacean faunas can be used to distinguish both low and high pH, heavy metal contaminated environments, is significant as this means that deployment of the group as a paleolimnological indicator in most lacustrine settings is now possible.

Paleolimnological analysis

A major impetus for research in the James Lake area was concern by local area residents, mainly cottagers and wilderness outfitters, that ongoing contamination from the site was having an adverse effect. Although it is obvious that mining activity has had an impact on the lake, there are several requirements that must be met before an effective ecosystem management for James Lake, or any other body of water under study, can be achieved. These requirements include knowledge of baseline conditions and natural variability, identification of the time when conditions in the lake first began to change, and a description of possible outcomes of such changes (Ford 1988). These requirements include a temporal component and thus require long-term data so that realistic targets for remediation efforts can be set, anthropogenic activity discerned and measured, and future scenarios evaluated (Likens 1988; Elliot 1990; Smol 1992). Aquatic ecosystem

Table 3
Radiocarbon dates obtained from wood extracted from cores JLC-97-2, JLC-97-3, and JLC-97-4

Sample	Laboratory number	Wat number	Dated material	^{13}C	Percent modern	^{14}C Date
JLC-97-2; 155–157 cm	86860	4045	Wood	-29.37	41.59 ± 0.7	7050 ± 140
JLC-97-3; 24–25 cm	86861	4028	Wood	-24.42	84.97 ± 1.0	1310 ± 90
JLC-97-3; 66–67 cm	86862	4029	Wood	-27.46	37.95 ± 0.5	7790 ± 120
JLC-97-3; 80–81 cm	86863	4030	Wood	-29.39	33.62 ± 0.4	8760 ± 100
JLC-97-4; 46–48 cm	86866	4031	Wood	-24.29	77.09 ± 1.0	2029 ± 100

managers generally choose from four main sources of data to address these objectives. These data include direct historical measurements, space-for-time substitution (i.e. comparing chemistry and biota in similar but unaffected lakes), computer models based on empirical or dynamic data, and paleolimnological constructions (Smol 1992). The unusual configuration of the lake and position of the pollution source near the outlet permitted a comparative approach within the lake itself, a scenario not usually possible in most small lakes. The geochemical data (Mason 1998) and the observed arcellacean fauna indicated a highly contaminated area adjacent to the old mine site suggesting that mining activity has seriously impacted the lake. However, according to the requirements for effective aquatic management, a determination of baseline conditions in the southern basin of the lake must be made prior to attempting any remedial action.

As in most lakes, direct historical measurements are not available for the time-frame of interest in James Lake. Thus paleolimnological methods are the best approach for determining these baseline conditions. Unfortunately, except where the sediment sink is large and stable, geochemical methods do not always provide an accurate depiction of the historical record (Horowitz 1991; Bethke 1996) due to mobilization and redistribution of metals and other constituents in the substrate. On the other hand skeletonized microfossils, except in areas of excessive bioturbation, do not migrate and archive data on the scale of millennia to seasons, providing very valuable information to ecosystem managers. Benthic micropaleontological bioindicators such as arcellaceans, with their very high preservation potential, are thus amongst the best tools to make a temporal assessment of the history of pollution and/or remediation of the contaminated area.

The upper 30 cm of a piston core (JLC-96-1) collected in the lake adjacent to the waste rock pile is characterized by *Arcella vulgaris* dominated assemblages (Figs. 1, 2). As indicated by the distribution of this species in surface sediments the depositional environment through this interval was under low pH (<5.5) and possibly highly contaminated conditions. Lower intervals of the core with statistically significant populations are dominated by various centropyxid species and indicate environmentally stressed but higher pH conditions. This is caused by gradual and mild acidification in this part of the lake due to weathering of pyrite rich rocks much before pyrite mining began in the region. Centropyxid species are capable of withstanding a variety of hostile conditions better than most other arcellacean species, including cold temperature (Decloitre 1953), low salinity conditions (<5‰; Decloitre 1953; Scott and Medioli 1980; Patterson and others 1985; Honig and Scott 1987), low nutrient conditions, oligotrophic conditions (Schönborn 1984), and sites heavily contaminated by mercury and arsenic (Patterson and others 1996). The high abundances of the seasonally planktic arcellacean *Cucurbitella tricuspis* (Schönborn 1984) in most samples is the result of current transport unrelated to substrate conditions at the core site. Prior to obtaining ^{14}C dates from a nearby core collected in 1997 it was assumed that the rise of the *Arcella vulgaris* dominated fauna coincided with the initiation of mining activity and lake acidification. As the average sedimentation rates in lakes varies between 1 and 5 mm per year (Förster and Wittmann 1981), we assumed that the interval dominated by *Arcella vulgaris* had been deposited since mine activity began. However, five ^{14}C dates have been obtained from three newly obtained shallow cores in September 1997 very close to the core site JLC-96-1 (Table3). One of them, JLC-97-3, was collected only 1 m away from the one studied here. The dates require that sedimentation rate in the area of the lake adjacent to the mine site has been quite low for at least the past 8700 years (Table 3; Fig. 2). Apparently the *Arcella vulgaris* dominated fauna has characterized this site for over 1300 years indicating, once again, that lake acidification predated mining. Prior to that, centropyxids lived in a higher pH but still stressed environment for several thousand years. Although not always reliable, geochemical analysis of samples from core JLC-97-3 provide corroborative evidence that elevated levels of Fe, Al, and sulfate have also existed for thousands of years at this site (Mason 1998).

The lake in this area also seems to be directly acidified from migration of fluids along natural faults and fractures. A series of green holes, interconnected by narrow linear growths of bright green algae demarcate subsurface fractures. The extremely low measured pH values of 2.0 marked by the algal growths suggests that highly acidic springs are entering the lake here. Before obtaining ^{14}C dates we hypothesized that the acidic waters venting from the green holes was leachate from the waste pits that being focused by the natural fracture system. However, large veins of pyrite-rich ore were naturally exposed on the shore in the western part of the southern basin prior to the establishment of a pyrite mine (Gale 1990). The dates make it clear that natural acidification of the site, from sulfides leaching from these naturally exposed large pyrite veins, and from subsurface springs, began long before any anthropogenic contribution. This occurrence is not unusual as any area characterized by surficial metal-bearing formations will have elevated metal values (see Förstner and Wittmann 1981 for examples). In fact, detection of these elevated levels is a major exploration tool used by mineral exploration companies. Although mining activity at James Lake has at least locally exacerbated the contamination and acidification problem in the lake, it must also be recognized that the lake is naturally polluted. Similar results have been recorded in lakes of the Adirondack region of New York State. In this area recent acid precipitation has contributed to lake acidification but substantial declines in pH had occurred thousands of years previously (Whitehead and others 1989). Environmental managers have thus far concentrated their James Lake remediation efforts on increasing the pH of lake water in the western portion of the southern basin through construction of limestone barriers. These measures have proven ineffectual thus far. Remediation goals should therefore be revised, unless the goal of remediation here is to create an environment unrelated to natural conditions.

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References

Asioli A, Medioli FS, Patterson RT (1996) Thecamoebians as a tool for reconstruction of paleoenvironments in some Italian lakes in the foothills of the southern Alps (Orta, Varese and Candia). J Foraminiferal Res 26:248–263

Baker JP, Christensen SW (1991) Effects of acidification on biological communities in aquatic ecosystems. In: Charles DF (ed) Acidic deposition and aquatic ecosystems: regional case studies. Springer-Verlag, New York Heidelberg Berlin, pp 83–106

Bethke CM (1996) Geochemical reaction modelling. Oxford University Press, New York

Burrows WD (1977) Aquatic aluminum: chemistry, toxicology and environmental prevalence. Crit Rev Environ Control 7:167–216

Campbell PGC (1995) Interactions between trace metals and aquatic organisms: a critique of the free-ion activity model. In: Tessier A, Turner DR (eds) Metal speciation and bioavailability in aquatic systems. J Wiley, New York

Collins ES, McCarthy FM, Medioli FS, Scott DB, Honig CA (1990) Biogeographic distribution of modern thecamoebians in a transact along the eastern North American coast. In: Hemleben C, Kaminski MA, Kuhnt W, Scott DB (eds) Paleoecology, biostratigraphy, paleoceanography and taxonomy of agglutinated foraminifera. NATO Adv Study Inst Ser C 327:783–791

Decloitre L (1953) Recherches sur les Rhizopodes thecamoebiens d' A.O.F. (Suite). Faune du Lac Tamna (Senegal). Bull Inst Franc Afr Noire 31:1–249

Deltapoint (1996) Deltagraph user's guide. Monterey, CA

Elliot JM (1990) The need for long-term investigation in ecology and the contributions of the Freshwater Biological Association. Freshw Biol 23:1–5

Ellison RL (1995) Paleolimnological analysis of Ullswater using testate amoebae. J Paleolimnol 13:51–63

Ford J (1988) The effects of chemical stress on aquatic species composition and community structure. In: Lewin SA, Harwell MA, Kelly JR, Kimball KD (eds), Ecotoxicology: problems and approaches. Springer-Verlag, New York Heidelberg Berlin, pp 99–144

Förstner O, Wittmann GTW (1981) Heavy metals in industrial and domestic effluents. In: Metal pollution in the aquatic environment. Springer-Verlag, Heidelberg Berlin New York, pp 340–359

Gale P (1990) James Lake, Northland Pyrite Mine. Ont Dept Environ Techn Memo, Sudbury

Honig CA, Scott DB (1987) Post-glacial stratigraphy and sea-level change in southwestern New Brunswick. Can J Earth Sci 24:354–364

Horowitz AJ (1991) A primer on sediment-trace element chemistry, 2nd revised edn. Lewis Publishers, Chelsea, Michigan

Kukal Z (1971) Geology of recent sediments. Academic Press, London

Kumar A, Patterson RT (1997) Arcellaceans (Thecamoebians) as proxies of lake bottom acidity: an example from James Lake, northeastern Ontario. Geol Assoc Canada/ Mineral Assoc Canada Annu Meet, May 19–21 (Abstract), p. A-150

Likens GE, ed (1988) Long term studies in ecology: approaches and alternatives. Springer-Verlag, New York Heidelberg Berlin

Loeblich AR Jr, Tappan H (1964) Sarcodina, chiefly "Thecamoebians" and Foraminiferida. In: Moore RC (ed) Treatise on invertebrate paleontology, Part C. Protista II, 1, Geol Soc Am and Univ Kan Press, pp C16–C64

Luoma SN (1983) Bioavailability of trace metals to aquatic organisms – a review. Sci Total Environ 28:1–22

Mason G (1998) A study of the effects of past mining activities on James Lake sediment Chemistry. (B.S. (Hon.) Thesis) Carleton University College of Natural Sciences Environmental Science Institute

McCarthy FG, Collins ES, McAndrews JH, Kerr HA, Scott DB, Medioli FS (1995) A comparison of post glacial Arcellacean ("Thecamoebian") and pollen succession in Atlantic Canada, illustrating the potential of arcellaceans for paleoclimatic reconstruction. J Paleont 69:980–993

Medioli FS, Scott DB (1988) Lacustrine thecamoebians (mainly Arcellaceans) as potential tools for paleolimnological interpretations. Paloeogeogr Paloeoclimatol Paloeoecol 62:361–386

Medioli FS, Scott DB, Collins ES, McCarthy FMG (1990) Fossil thecamoebians: present status and prospects for the future. In: Hemleben C, Kaminski MA, Kuhnt W, Scott DB (eds) Paleoecology, biostratigraphy, paleoceanography and taxonomy of agglutinated foraminifera. NATO Adv Study Inst Ser C 327:813–840

Moore JW (1991) Inorganic contaminants of surface water: research and monitoring priorities. Springer-Verlag, New York Heidelberg Berlin

Patterson RT, Fishbein E (1989) Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. J Paleont 62:245–248

Patterson RT, MacKinnon KD, Scott DB, Medioli FS (1985) Arcellaceans (Thecamoebians) in small lakes of New Brunswick and Nova Scotia: modern distribution and Holocene stratigraphic changes. J Foraminiferal Res 15:14–137

Patterson RT, Barker T, Burbridge SM (1996) Arcellaceans (Thecamoebians)as proxies of arsenic and mercury contamination in northeastern Ontario lakes. J Foraminiferal Res 26:172–183

Plankey BJ, Patterson HH (1987) Kinetics of aluminum fulvic acid complexation in acidic waters. Env Sci Tech 21:595–601

Plankey BJ, Patterson HH (1988) Effect of fulvic acid on the kinetics of aluminum fluoride complexation in acidic waters. Env Sci Tech 22:1454–1459

Reinhardt ED, Dalby A, Kumar A, Patterson RT (1998) Utility of arcellacean morphotypic variants as pollution indicators in mine tailing contaminated lakes near Cobalt, Ontario, Canada. Micropaleontology 44:131–148

Schönborn WS (1984) Studies on remains of Testacea in cores of the Great Woryty Lake (NE-Poland). Limnologica 16:185–190

Scott DB, Hermelin JOR (1993) A device for precision splitting of micropaleontological samples in liquid suspension. J Paleont 67:151–154

Scott DB, Medioli FS (1983) Testate rhizopods in Lake Erie: modern distribution and stratigraphic implications. J Paleont 57:809–820

Scott DB, Medioli FS (1980) Post-glacial emergence curves in the maritimes determined from marine sediments in raised basins. Proceedings of coastlines 1980. National Science and Engineering Research Council, pp 428–449

Smol JP (1992) Paleolimnology: an important tool for effective ecosystem management. J Aquat Ecosyst Health 1:49–58

Tessier A, Campbell PGC, Auclair JC, Bisson M (1984) Relationships between the partitioning of trace metals in sediments and their accumulation in the tissues of the freshwater mollusc Elliptio complanata in a mining area. Can J Fish Aquat Sci 41:1463–1472

Vymazal J (1984) Short-term uptake of heavy metals by periphyton algae. Hydrobiologia 119:171–179

Whitehead DR, Charles DF, Jackson JP, Smol JP, Engstron DRJ (1989) The developmental history of Adirondack (N.Y.) lakes. Paleolimnolology 2:185–206