

ARCELLACEANS (THECAMOEBIANS) AS PROXIES OF ARSENIC AND MERCURY CONTAMINATION IN NORTHEASTERN ONTARIO LAKES

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ABSTRACT

Q-mode cluster analysis of arcellacean populations in three small lakes (two heavily polluted by mine tailings) near the town of Cobalt in northeastern Ontario permitted five distinct faunal assemblages to be recognized and related to ecologic tolerance. Mine waste and mill tailings were dumped into Crosswise Lake until 1970, and a leaking tailings dam continues to pollute Peterson Lake. Natural sedimentation is slowly burying the tailings in these lakes but areas of highly toxic sediments remain exposed in several areas. Levels of arsenic and mercury contamination in the substrate are as high as 7,110 ppm and 2.54 ppm, respectively, in Crosswise Lake; and 8,330 ppm and 0.77 ppm, respectively, in Peterson Lake (maximum acceptable concentrations for aquatic life are 50 ppm and 0.100 ppm, respectively). A Contaminated Substrate Assemblage (1), dominated by *Centropyxis aculeata* (\bar{x} = 27.5%), *Centropyxis constricta* (\bar{x} = 13.5%), and *Arcella vulgaris* (\bar{x} = 9.7%), characterizes the most heavily polluted parts of the lakes. Centropyxids, known to be opportunistic and capable of withstanding hostile conditions, become less dominant in biofacies found in substrates characterized by progressively less mine tailing contamination (Mine Tailings Assemblage [2], Muddy Substrate Assemblage [3], and Diatom Mud Assemblage [4]).

Unpolluted Gillies Lake was not comparable with Crosswise or Peterson lakes as a pronounced thermocline results in significantly different limnological conditions (i.e., very low bottom temperatures and oxygen concentrations) in that lake. The presence of a *Cucurbitella tricuspidis* (\bar{x} = 90.3%) dominated fauna (Transported Fauna Assemblage [5]) in most Gillies Lake samples is enigmatic as no significant populations of *Spirogyra* spp., the algae with which the partially planktic *Cucurbitella tricuspidis* has a symbiotic relationship, have been observed. We suspect that Assemblage 5 is allochthonous.

The results of this pilot study indicate that arcellaceans are useful not only to monitor environmental pollutants but to assess rates of lake remediation.

INTRODUCTION

Silver was discovered in the summer of 1903 at Mile 103 (as measured from North Bay) of the Northern Ontario Railroad. Eleven silver mines were in operation by 1905, and by 1911 annual silver production at Cobalt Camp, as the town which sprung up at Mile 103 was now called, exceeded 30,000,000 oz. (850,000,000 g)/yr. (Fig. 1). Cobalt Camp became the largest silver producing region in the world. Production tailed off in the 1930's, picking up again in the 1950's only to drop off again. By 1993 there were no active

silver mines in the area (Murphy, 1977; Barnes, 1986; Dumaresq, 1993). An unfortunate legacy of the Cobalt mining boom is severe environmental contamination, caused by dumping of millions of tons of mine waste and mill tailings into local lakes and streams. In addition to being unsightly, these tailings pose a considerable health risk to the people of Cobalt and surrounding towns (approximately 10,000 inhabitants). In Cobalt Camp area ores, silver was associated with As minerals. Little of this As was ever recovered, so it ended up in the tailings and waste and today contaminates much of the surface and ground water supplies in the area. In addition, huge quantities of Hg and cyanide, used in the ore milling process, are also present in mine wastes, presenting additional environmental hazards (Dumaresq, 1993).

Arcellacean distributional studies have been carried out in lakes from all over North America and a few from Europe. These studies have been mostly of a reconnaissance nature, primarily concerned with determining the ranges of the various species (see Medioli and Scott, 1988 for a summary). However, some of these studies have attempted to correlate species with various parameters such as rate of clastic input, level of organics, bedrock type, or seasonal water temperature (Medioli and Scott, 1983, 1988; Scott and Medioli, 1983; Medioli and others, 1985, 1987, 1990; Patterson and others, 1985; Honig and Scott, 1987; Collins and others, 1990). Only one study to date has linked lake sediment chemical pollutants and arcellacean distribution (Asioli and others, in press). Results of these previous studies have made it apparent that arcellaceans are valuable paleolimnological tools, but a paucity of research linking species and assemblages to quantified environmental data limits their utility at this time.

The primary purpose of this study is to test the applicability of arcellaceans as bioindicators in areas polluted by mining activity. This area provides an ideal setting for such research as there are many heavily polluted lakes (e.g., Peterson and Crosswise lakes) in close association with other lakes (e.g., Gillies Lake) that have never been affected by tailings (Fig. 1). A secondary goal is to determine the recovery status of the polluted lakes. Since no tailings have been introduced to Crosswise and Peterson lakes (although a leaking tailings dam still contributes some tailings to Peterson Lake) in at least twenty-five years, we have determined the degree to which tailings buried beneath lake bottoms can still influence benthic populations, using arcellaceans as proxies.

TOXICITY OF MAJOR CONTAMINANTS IN COBALT AREA

Although lakes in the Cobalt area have been contaminated by numerous agents including Ni, Co, and cyanide, it is As and Hg that are the most significant pollutants (Dumaresq, 1993). In the following section we outline the general en-

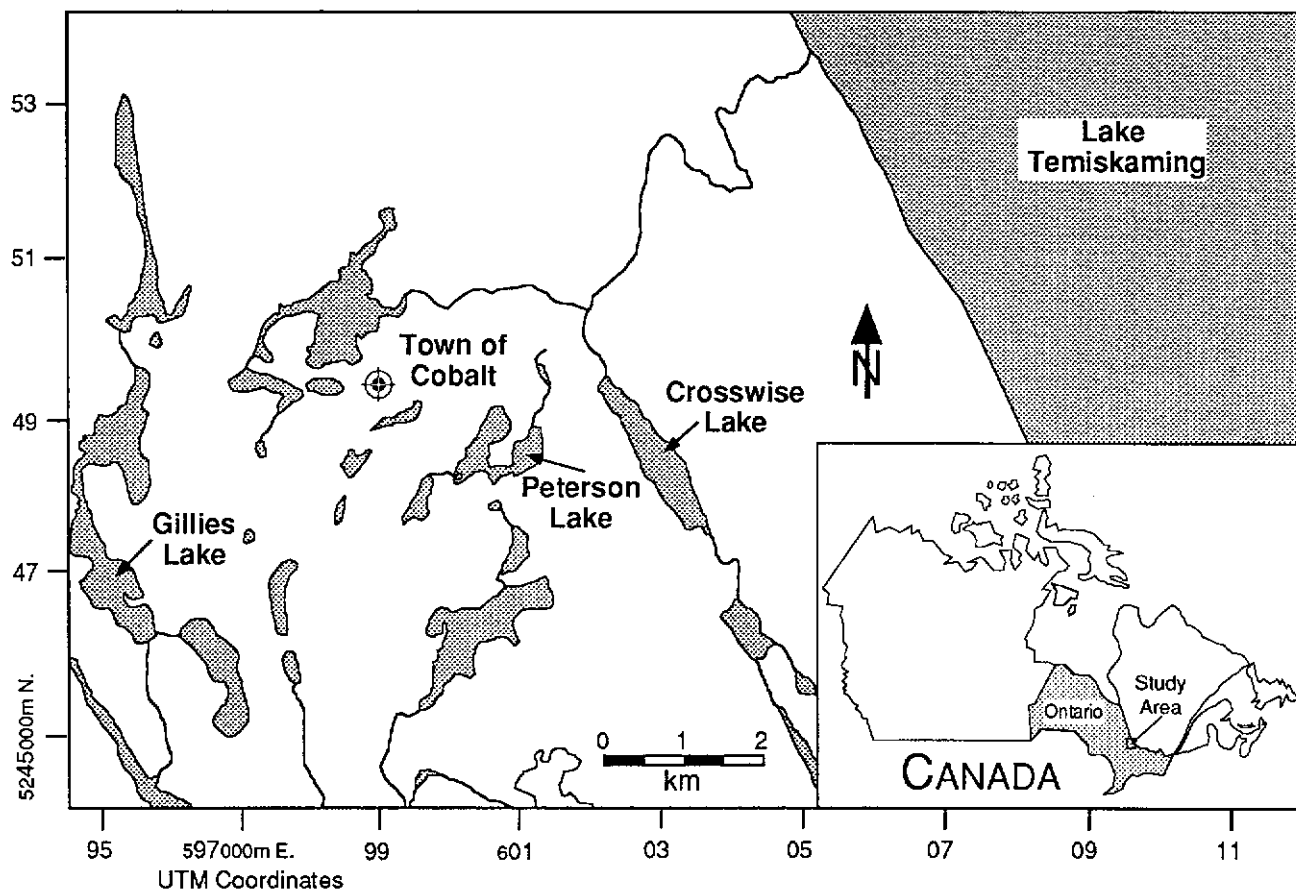


FIGURE 1. Location map of lakes examined for this study (UTM coordinate system).

vironmental chemistry and toxicity of these contaminants. The concentrations of various contaminants found in the lakes studied is provided in the subsequent section on lake characteristics.

ARSENIC

Arsenic is a metalloid element, chemically behaving like both metals and nonmetals. In Cobalt area ores, As is commonly found in sulfide, sulfarsenide, and arsenide minerals [e.g., realgar (AsS), orpiment (As_2S_3), arsenopyrite (FeAsS), cobaltite (CoAsS), and the skutterudite series ($(\text{Co}, \text{Ni})\text{As}_2\text{S}_3$) (Berry and others, 1983)]. In aerobic waters, arsenate (AsO_4^{3-}) is the most common As-bearing solute, whereas under anaerobic conditions arsenite (AsO_3^{3-}) is most common. In lake sediments, As may remain dissolved in pore waters and it can be adsorbed onto or coprecipitated with Fe and Mn oxyhydroxides (Cullen and Reimer, 1989).

In tissue, As exists in dissolved form as any number of organoarsenicals such as arsenosugars, arsenobetaine, and arsenocoline (Cullen and Reimer, 1989). Due to its complex chemistry, As transformations are common, resulting from changes in pH, Eh, temperature, concentration, and biological activity.

Arsenic is taken up in water plants through absorption in roots and leaves. Arsenic intake by animals is by ingestion, inhalation or through permeation of the skin or mucous membranes. Although As is bioaccumulated by aquatic or-

ganisms, it is not bioconcentrated through the food chain. Lower forms of aquatic animal life tend to accumulate greater amounts than fish, and bottom feeding fish accumulate greater amounts than other fish (CPHA, 1977). Thus benthic protists such as arcellacea should be excellent indicators of As contamination.

Natural freshwater As concentrations are typically less than 2 ppm (Table 1). In the Canadian Great Lakes, As concentrations range from 0.1–2.5 ppm (Nriagu, 1983; Traversy and others, 1975). In areas surrounding mines and smelters, As concentrations may be much higher (e.g., 20 ppm in a lake adjacent to a copper smelter in Noranda, Quebec, 3,000 ppm in Kam Lake near Yellowknife, and 19,800 ppm in river water near Yellowknife; Azzaria and Frechette, 1987; CPHA, 1977). Under the Canadian Water Quality Guidelines, the maximum acceptable concentration of As in drinking water and for aquatic life is 50.0 ppm (Table 1).

MERCURY

Elemental Hg is a unique metal because it is liquid at room temperature. Although elemental Hg is rare in nature, it is common in solid solution with native gold and silver (Berry and others, 1983). The most common Hg mineral is Cinnabar (HgS) (Eckstrand, 1984). Mercury also occurs with several other sulfide minerals, particularly tetrahedrite ($\text{Cu}_{12}\text{Sb}_4\text{S}_{13}$) (NRCC, 1978). Since Hg was commonly used

TABLE 1. Relative pH, O₂, (As) and (Hg) levels in Gillies, Crosswise, and Peterson lakes. Canadian water quality guideline data, maximum As and Hg concentration for freshwater life, and background levels of As and Hg from CCREM (1987).

	pH	O ₂ (ppm Surface)	O ₂ (ppm Bottom)	As (ppm)	Hg (ppm)
Peterson Lake (E. Basin-Water)	7.4–8.5	11.0	8.5	0.406–4.050	0.100
Peterson Lake (E. Basin-Substrate)	—	—	—	8,330.000	0.770
Crosswise Lake (N.-Water)	7.6–8.4	11.0	8.0	0.800	0.100
Crosswise Lake (S.W.-Substrate)	—	—	—	5,120.000	2.540
Crosswise Lake (S.E.-Substrate)	—	—	—	7,110.000	2.370
Gillies Lake (Water)	8.1	12.0	2.0	0.056	0.030
Average Background Levels	—	—	—	2.000	0.050
Drinking water (Max. Accept. Conc.)	—	—	—	50.000	1.000
Aquatic Life (Max. Accept. Conc.)	—	—	—	50.000	0.100

as an amalgam in the recovery of gold and silver, it is very common in mine tailings.

Once released into the environment, the biogeochemical cycling of Hg is complex, with bacterially mediated methylation playing an important role. The rate of methylation is pH dependent, with rates in lake water at pH 4.5 being seven times faster than at pH 8.5 (D'Itri, 1991). Once formed, methylmercury (CH₃Hg⁺) is readily absorbed by organisms and its excretion is very slow (e.g., biological half-life of Hg in fish is two years; D'Itri, 1991; CCREM, 1987). In natural aerobic waters, elemental Hg is also oxidized and removed from the water column by sorption onto suspended solids and bottom sediments (CCREM, 1987).

Both Hg and methylmercury are available for organisms to take up and bioconcentration does occur. Bioconcentration factors as high as 81,670 have been measured in some fish (US EPA, 1984). Mercury has also been shown to be bioconcentrated in ecosystems, with higher trophic consum-

ers containing higher Hg concentrations than organisms lower in the food chain (Cuthbert, 1992). Therefore, arcellaceans may not be sensitive indicators of mercury contamination.

Background concentrations of Hg in Canadian freshwater sources are usually close to 0.05 ppm (Table 1). In the Great Lakes, mean Hg concentrations range from 0.13 to 0.18 ppm. Near Hg deposits, concentrations in streams and rivers can range up to 100 ppm (CCREM, 1987). The maximum acceptable concentration of Hg in drinking water is 1.0 ppm, while the maximum acceptable concentration of Hg for aquatic life is 0.1 ppm (Table 1).

LAKE CHARACTERISTICS

CROSSWISE LAKE

Crosswise Lake (also known as Cross Lake locally) forms a rough parallelogram and has an area of approximately 3.2 km² (Figs. 1 and 2). This lake has steep slopes along the western and eastern margins and appears to be formed from a down-faulted block associated with the nearby Temiskaming-Bonnechare Graben. Slopes are much shallower at the north and south ends of the lake. Two streams are associated with this lake; an unnamed stream flows into the lake at the south end and a second stream, Farr Creek, exits the lake at the north end.

Tailings from five different mills were deposited in the northern part of Crosswise Lake, starting in 1908 (Fig. 2). Tailings dumping ceased in 1970 when the Deerhorn Mine on the eastern margin of the lake closed. Deposition of tailings has substantially modified the shape and depth of the lake, which is 300 m shorter than it was prior to the dumping of tailings (Dumaresq, 1993). Subbottom sonar profiles indicate that the present lake depth of 6.0–6.9 m is less than half the pre-tailings water depth (Wallis, 1993). Sonar profiles also indicate that introduction of very fine tailings into the lake has given the lake a remarkably flat bottom, sloping at only 2° (Wallis, 1993).

Results of our 1993 analysis indicate that water column pH values in this lake range from neutral to slightly alkaline (7.6 to 8.4). Water temperatures in early September declined uniformly from 22°C at the surface to 16°C at the bottom (≈7.0 m), indicating no thermocline. Oxygen solubility was good through the water column, varying from 11.0 ppm at the surface to 8.0 ppm on bottom (Table 1).

The lake is heavily contaminated with both Hg and As. As a result, consumption of fish from this lake is severely

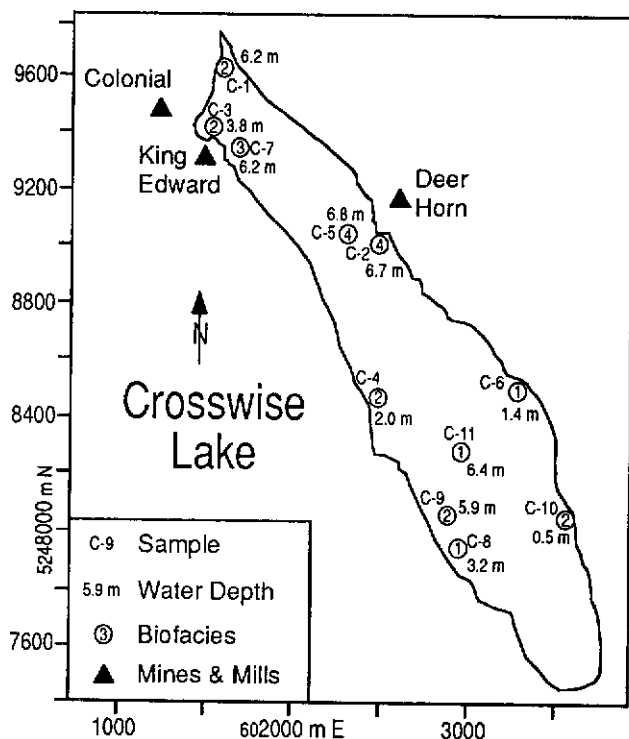


FIGURE 2. Positioning, water depth, and assemblage designation for samples collected from Crosswise Lake (UTM coordinate system). Sites of former mines and/or mills are also indicated.

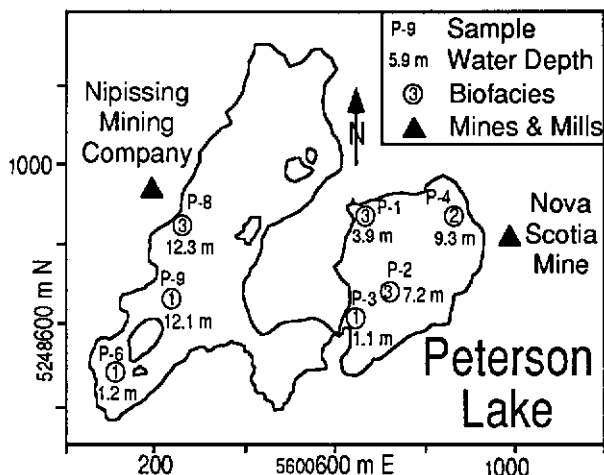


FIGURE 3. Positioning, water depth, and assemblage designation for samples collected from Peterson Lake (UTM coordinate system). Sites of former mines and/or mills are also indicated.

restricted (Dumaresq, 1993). In fact, women of child-bearing age and children under 15 are restricted entirely from consuming fish from this lake. Water measurements from Farr Creek, just down stream from Crosswise Lake, indicate a mean annual As concentration of discharge water from the lake of 0.663 ppm (Dumaresq, 1993). It has been estimated that Farr Creek discharges nearly 31,000 kg of (As) into Lake Temiskaming each year. As might be expected, concentrations of As in lake bottom sediments are extremely high, ranging from 5,120–7,110 ppm (Hawley, 1980; Table 1).

Mercury levels in water samples measured at the north end of the lake were <0.1 ppm (Dumaresq, 1993). Mercury levels measured in the substrate at the southern end of the lake range from 2.37–2.54 ppm (Hawley, 1980; Table 1). Evidence of higher concentrations of Hg in the substrate is indirectly provided by the distribution of benthic plants. Our high frequency sonar lake-bottom survey found that lake bottom weeds only grew abundantly in the southern part of the lake near the mouth of the inflowing stream. Studies have shown that freshwater plants are negatively impacted by concentrations of Hg as low as 5.0 ppm (Cuthbert, 1992).

PETERSON LAKE

Peterson Lake is actually a pair of lakes separated by a man-made dam (Figs. 1 and 3). The terrain surrounding Peterson Lake consists of bedrock knobs interspersed with patches of till. Relief ranges from steep cliffs to rolling terrain. This topography also characterizes the lake bottom. The western and larger basin (2.3 km²) has an irregular bottom but can be divided into three main regions; the very shallow and weed-filled southern end, a small shallow bay adjacent to the dam, and a deeper main basin. The western shore of this lake has been extensively modified by dumping of large piles of waste rock from a nearby mine site (Nipissing 407 shaft; Dumaresq, 1993; Wallis, 1993).

The smaller eastern basin (0.8 km²) has very steep sides but unlike the western basin is flat-bottomed. The flat bottom originates from the nearly 400,000 tons of tailings deposited in this basin from the nearby Nova Scotia Mill be-

tween 1910 and 1918 (Fig. 3). Additional quantities of fine tailings entered the lake when a tailings dam adjacent to the Nova Scotia Mill site broke. In 1965, the eastern lobe of the lake was drained and nearly 55,000 tons of tailings removed. In the near shore area, these tailings were dredged to a uniform depth of 8.8 to 9.0 m, but huge quantities were left behind (Wallis, 1993). Tailings continue to migrate into the eastern lobe of the lake from leaks in containment dams adjacent to the Nova Scotia mill site.

Our 1993 analysis indicated that pH values in this lake range from neutral to slightly alkaline (7.4 to 8.5). Water temperatures in early September declined uniformly from 23°C at the surface to 16°C at the bottom (≈12.0 m), indicating no thermocline. Oxygen solubility was good through the water column, varying from 11.0 ppm at the surface to 8.5 ppm on bottom (Table 1).

Arsenic levels are very high in this lake. Depending on the season, water column As levels ranging from 0.406 to 4.050 µg/L have been measured in the eastern basin (Dumaresq, 1993). Arsenic levels in the substrate of the eastern basin adjacent to the Nova Scotia Mine range up to 8,330 ppm. Mercury levels measured from the water column in the eastern basin lake ranged up to 4.050 ppm (Dumaresq, 1993; Table 1). As the western basin of the lake is 0.7 m lower than the eastern basin, there is considerable flow of water and suspended sediments into the western basin. These sediments, primarily fine grained tailings, have settled into the large central basin. The results of this study, presented below, suggest that As and Hg levels may be higher in the western basin than the eastern basin.

GILLIES LAKE

Gillies Lake is bisected by highway 11B, dividing the lake into northern and southern basins (Figs. 1 and 4). Samples were collected exclusively from the southern basin. The southern basin of Gillies Lake has a surface area of 0.8 km² and a mean depth of 16 m, much deeper than either Peterson or Crosswise lakes. Based on an internal 1987 MOE survey (G. Myslik, MOE, written personal communication, 1993), it was determined that the water quality of Gillies Lake is good, with all trace elements falling within provincial guidelines. Gillies Lake is slightly alkaline (with pH values of 8.1). The lake also has a strongly developed thermocline at about 10 m. Temperatures in the summer and early fall range from around 22°C at the surface to 6°C beneath the thermocline. The lake is well oxygenated (up to 12 ppm near the surface), although values drop quickly beneath the thermocline (to as low as 2.0 ppm in some deep basins at depths greater than 35 m; our measurements; Table 1). Levels of As and Hg contamination are low. Levels of As in the water column were 0.056 ppm and Hg levels were 0.03 ppm (unpublished 1987 MOE internal report, G. Myslik, MOE, written personal communication, 1993; Table 1).

METHODS AND MATERIALS

Twenty-nine sediment-water interface samples were collected from Crosswise, Gillies, and Peterson lakes using an Eckman box corer. Water depth and sediment type were recorded at each station (Table 2). The geographic position of each sample was determined using a Trimble Scout Global

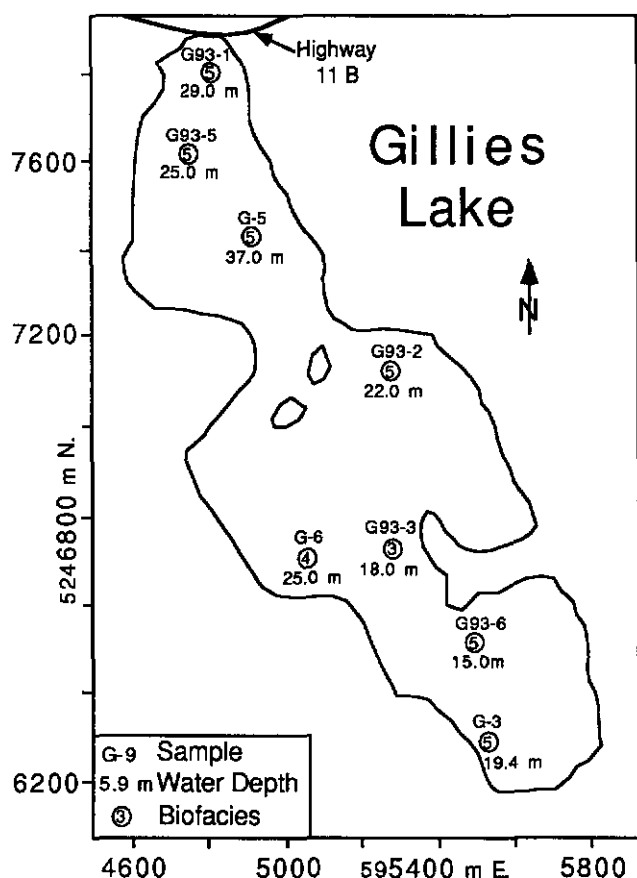


FIGURE 4. Positioning, water depth, and assemblage designation for samples collected from southern part of Gillies Lake (UTM coordinate system).

Positioning System (GPS; Table 2; Figs. 2, 3, and 4). Sample site selection was determined using a RATHEON PTR-106C-1 low frequency (7 kHz) sub-bottom seismic profiling system and a commercial "fish finder" sonar equipped with bottom hardness indicator. The bottom hardness indicator saved considerable sampling time as it readily distinguished rocky, sandy, and muddy substrate. Winnowed sandy substrates usually have only small allochthonous arcellacean populations whereas rocky substrates are invariably barren. A one-cm surface layer was removed from each sample to obtain 10 cc subsamples for analysis. These subsamples were screened with 1,000 μm sieves to remove coarse debris such as sticks and grass, and with 63 μm (no. 230 mesh) screens to retain arcellaceans and remove the clay fraction. To avoid decay of these organic-rich sediments, processed samples were immediately placed in formalin and refrigerated.

Subsamples were subdivided into manageable aliquots for quantitative analysis using the wet-splitter of Scott and Hermelin (1993). Aliquots were immersed in water and examined using a binocular microscope. Wet examination of organic-rich lacustrine sediments is necessary because in dried samples the vegetable debris usually mats together, making identification and quantitative analysis of arcellaceans nearly impossible.

Twenty-six of the 29 samples contained arcellacea. All 26 arcellacea-bearing samples contained populations large

TABLE 2. Coordinates, water depth, and sediment type of samples examined for this study. Coordinates not available for barren sample G-1.

Sample	Sediment	Water depth	Easting	Northing
G-1	coarse sand	14.9 m	unknown	unknown
G-2	coarse sand	5.4 m	595 442	524 6,220
G-3	gyttia	19.4 m	595 519	524 6,274
G-4	coarse sand	7.0 m	594 562	524 7,362
G-5	silt	37.0 m	594 947	524 7,425
G-6	silt	25.0 m	595 055	524 6,713
P-1	gyttia/mud	3.9 m	600 605	524 8,824
P-2	gyttia	7.2 m	600 714	524 8,679
P-3	tailings/mud	1.1 m	600 596	524 8,646
P-4	tailings/silt	9.3 m	600 850	524 8,779
P-6	tailings/mud	1.2 m	600 126	524 8,494
P-8	gyttia	12.3 m	600 123	524 8,863
P-9	tailings/mud	12.0 m	600 123	524 8,683
C-1	tailings/mud	6.2 m	601 751	524 9,746
C-2	diatom mud	6.7 m	602 070	524 9,047
C-3	tailings/silt	3.8 m	601 553	524 9,396
C-4	tailings/mud	2.0 m	602 428	524 8,443
C-5	diatom mud	6.8 m	602 312	524 8,921
C-6	tailings/mud	1.4 m	602 816	524 8,439
C-7	gyttia	6.2 m	601 684	524 9,357
C-8	tailings/mud	3.2 m	602 762	524 7,931
C-9	tailings/silt	5.9 m	602 708	524 8,046
C-10	tailings/mud	0.5 m	603 641	524 8,050
C-11	tailings/mud	6.4 m	602 825	524 8,240
G93-1	gyttia/mud	29.0 m	594 960	524 7,990
G93-2	gyttia/mud	22.0 m	595 306	524 7,176
G93-3	mud/silt	18.0 m	595 245	524 6,712
G93-5	gyttia/mud	25.0 m	594 750	524 7,620
G93-6	gyttia/mud	15.0 m	595 552	524 6,460

enough for statistical analysis (Patterson and Fishbein, 1989; Table 3). Eighteen species of arcellacea were identified. The percent error associated with each species tally was calculated using the standard error equation (s_{x_i}):

$$s_{x_i} = 1.96 \sqrt{\frac{X_i[1 - X_i]}{N}}$$

where N is the total number of counts, and X is the fractional abundance of a species (Patterson and Fishbein, 1989). The percent error calculated for all 18 species are included in Table 3.

Q-mode cluster analysis was carried out on the data using a technique that has been demonstrated to closely emulate the results of a statistically significant "error-weighted maximum likelihood" clustering method (Fishbein and Patterson, 1993). Q-mode cluster analysis determines similarity between samples, whereas R-mode cluster analysis determines relationships between species through all samples. This method requires that only species present in statistically significant populations be analyzed. *Diffugia bidens* Pénard, 1902, and *Heleopera sphagni* (Leidy, 1874) were not present in statistically significant numbers in any sample and were thus excluded from subsequent cluster analysis. Q-mode cluster analyses were carried out on the 16 statistically significant species using SYSTAT (v. 5.2; Wilkinson, 1989). Euclidean distance correlation coefficients were used to measure similarity between pairs of species, and the Ward's linkage method was utilized to arrange sample pairs and sample groups into a hierarchic dendrogram (Fig. 5).

Species/sample Water depth (m) Assemblage Total counts	P1 3.9	P2 7.2	P3 1.1	P4 9.3	P6 1.2	P8 3	P9 12.0	C1 6.2	C2 6.7	C3 3.8	C4 2.0	C5 6.8	C6 1.4	C7 6.2	C8 3.2	C9 5.9	C10 0.5	C11 6.4	G3 19.4	G5 37.0	G6 25.0	G93-1 29.0	G93-2 22.0	G93-3 18.0	G93-5 25.0	G93-6 15.0
<i>Arcella vulgaris</i>	0.000	0.012	0.205	0.109	0.184	0.000	0.009	0.000	0.000	0.022	0.000	0.000	0.065	0.005	0.038	0.007	0.000	0.079	0.004	0.000	0.000	0.001	0.000	0.005	0.002	0.008
Standard Error (±)	0.000	0.009	0.036	0.028	0.030	0.000	0.007	0.000	0.013	0.009	0.000	0.000	0.021	0.005	0.014	0.007	0.000	0.023	0.005	0.000	0.000	0.003	0.000	0.006	0.004	0.007
<i>Centropages aculeata</i>	0.184	0.047	0.266	0.053	0.094	0.115	0.300	0.075	0.066	0.205	0.230	0.046	0.421	0.075	0.341	0.092	0.133	0.230	0.060	0.009	0.162	0.022	0.029	0.070	0.020	0.013
Standard Error (±)	0.032	0.017	0.040	0.020	0.023	0.028	0.037	0.023	0.035	0.035	0.019	0.043	0.021	0.035	0.024	0.035	0.024	0.031	0.036	0.020	0.008	0.033	0.011	0.014	0.021	0.010
<i>Centropages constricta</i>	0.048	0.065	0.065	0.094	0.244	0.070	0.199	0.020	0.024	0.085	0.068	0.000	0.051	0.078	0.080	0.066	0.028	0.170	0.012	0.009	0.061	0.011	0.013	0.016	0.006	0.008
Standard Error (±)	0.017	0.020	0.022	0.026	0.034	0.022	0.032	0.012	0.013	0.024	0.020	0.000	0.019	0.021	0.020	0.021	0.015	0.032	0.009	0.008	0.021	0.008	0.009	0.01	0.007	0.007
<i>Curculiatella tricuspis</i>	0.022	0.000	0.021	0.311	0.065	0.013	0.021	0.192	0.413	0.256	0.223	0.526	0.068	0.041	0.104	0.189	0.124	0.057	0.813	0.937	0.627	0.937	0.942	0.059	0.905	0.883
Standard Error (±)	0.012	0.000	0.013	0.041	0.019	0.013	0.012	0.034	0.042	0.035	0.045	0.022	0.016	0.012	0.023	0.033	0.030	0.020	0.033	0.020	0.043	0.018	0.019	0.019	0.026	0.027
<i>Diffugia bacillifera</i>	0.000	0.000	0.000	0.162	0.006	0.000	0.022	0.000	0.026	0.006	0.006	0.006	0.006	0.052	0.004	0.004	0.000	0.019	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Standard Error (±)	0.000	0.000	0.003	0.006	0.003	0.000	0.012	0.000	0.014	0.006	0.007	0.007	0.007	0.017	0.005	0.005	0.000	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
<i>Diffugia bidens</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.002	0.003	0.000	0.000
Standard Error (±)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.004	0.004	0.000	0.000
<i>Diffugia corona</i>	0.014	0.017	0.000	0.000	0.300	0.023	0.151	0.099	0.079	0.022	0.031	0.037	0.055	0.006	0.040	0.037	0.04									

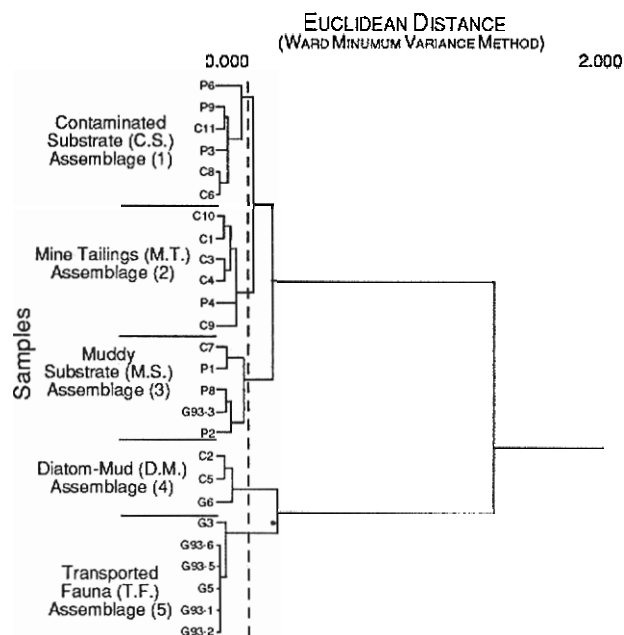


FIGURE 5. Q-Mode dendrogram showing the 26 most populous samples (listed vertically by sample number) from Crosswise, Gillies, and Peterson lakes, divided into distinct assemblages as indicated by the dashed line. Distinct clusters of samples with correlation coefficients greater than a selected level were considered biofacies.

Specimens of *Arcella vulgaris* and *Centropxyxis aculeata* were examined using a LINK exL L24 x-ray analyzer coupled to a JEOL 6400 scanning electron microscope. Due to the similarity of results only spectra for *Centropxyxis aculeata* are presented herein (Fig. 6). X-ray spectra were collected at 20 kv accelerating potential and measured both semi-quantitatively (molecular weight percent) and in counts (live counting time of 100 seconds).

All scanning electron micrographs were obtained using the JEOL 6400 scanning electron microscope in the Carleton University Research Facility for Electron Microscopy (CURFEM). The plate and Figure 6 were digitally produced using Photoshop® v. 3.0 on an Apple Macintosh computer platform and outputted using a Linotronic printer.

RESULTS AND DISCUSSION

Previous research indicates that relative arcellacean abundance is controlled by an assortment of limnological, climatic, and other environmental conditions, including oxygen levels, minimum average water temperature, and level of organics and clastics (Scott and Medioli, 1983; Patterson and others, 1985; Medioli and others, 1990; Collins and others, 1990). Species distribution and diversity found in three northeastern Ontario lakes is consistent with the results of similar quantitative studies carried out elsewhere in eastern North America and is primarily controlled by the substrate. Interpretation of a dendrogram generated by Q-mode cluster analysis resulted in recognition of five assemblages, each characterizing distinctive environments.

CONTAMINATED SUBSTRATE (C.S.) ASSEMBLAGE (1)

The C.S. Assemblage (1) dominates very contaminated mine tailings in the south-central part of Crosswise Lake

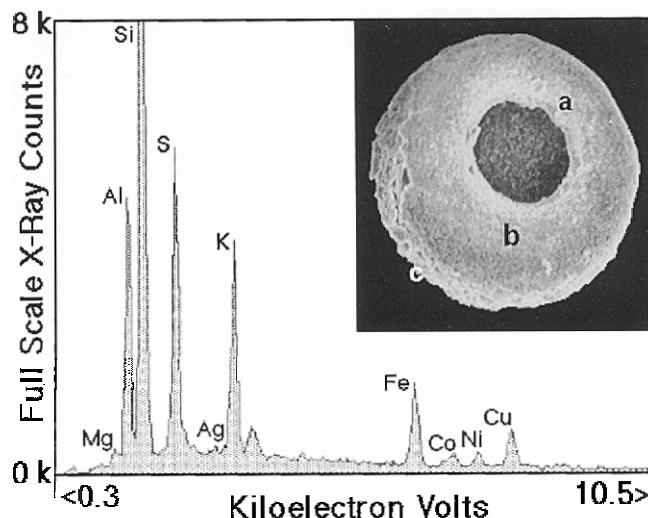


FIGURE 6. Energy dispersal x-ray (EDX) analysis showing the elemental composition, as measured in counts, at site (a) on apertural side of *Centropxyxis aculeata* (Ehrenberg) specimen from Peterson Lake. Beam width is $\approx 5 \mu\text{m}$. Results of semi-quantitative energy dispersal x-ray (EDX) analysis, measured in elemental weight, at sites a-c listed in Table 5.

and the western basin and dam area of Peterson Lake, separating the eastern and western basins of this lake (Figs. 2, and 3). These samples were vile smelling, silver particle-bearing muds, that permanently stained the collection bottles. Although not geochemically analyzed for this study we presume that these samples are highly contaminated.

In Peterson Lake, it is notable that these heavily contaminated sediments are concentrated in the western basin whereas most tailings dumping and seepage occurred in the eastern Basin. Although the eastern basin has been dredged, nothing was done to clean up downstream in the western basin. The concentration of heavily contaminated sediments in the south-central part of Crosswise Lake must be related to current movements as all tailings dumping occurred further north.

The arcellacean assemblage living on this substrate is dominated by *Centropxyxis aculeata* (Ehrenberg, 1832; $\bar{x} = 27.5\%$), *Centropxyxis constricta* (Ehrenberg, 1843; $\bar{x} = 13.5\%$) and *Arcella vulgaris* (Ehrenberg, 1830; $\bar{x} = 9.7\%$; Table 4). The centropxyxid species have long been characterized as opportunistic, capable of withstanding cold temperatures (Decloître, 1956), low salinity conditions ($<5\%$; Decloître, 1953; Scott and Medioli, 1980; Patterson and others, 1985; Honig and Scott, 1987), and low-nutrient, oligotrophic conditions (Schönborn, 1984). Based on our results, centropxyxids also opportunistically colonize sites heavily contaminated by Hg, and particularly As. Centropxyxids are apparently not good indicators of all industrial contamination however. In Lake Orta, northern Italy, Asioli and others (1996) found very few centropxyxids in substrates contaminated by copper sulfates and ammonium sulfites. They found that various phenotypes of *Diffugia protaeiformis* Lamarck, 1816, were much better indicators of polluted and acidified sediments (pH = 3.9–4.5) in this setting. These results indicate to us that 1) substrate characterized by the C.S. Assemblage may be too contaminated by As

TABLE 4. Mean fractional abundances and associated standard deviations of species best characterizing each assemblage. As sample G-6 was misclustered with the Diatom Mud Assemblage (4), it was not considered in the summary.

	Mean %	St. dev.
Contaminated Substrate (C.S.) Assemblage (1)		
<i>Centropyxis aculeata</i>	0.275	0.111
<i>Centropyxis constricta</i>	0.135	0.08
<i>Arcella vulgaris</i>	0.097	0.08
Mine Tailings (M.T.) Assemblage (2)		
<i>Cucurbitella tricuspidis</i>	0.216	0.064
<i>Diffflugia oblonga</i>	0.182	0.068
<i>Centropyxis aculeata</i>	0.131	0.072
<i>Diffflugia protaeiformis</i>	0.113	0.063
Muddy Substrate (M.S.) Assemblage (3)		
<i>Diffflugia oblonga</i>	0.409	0.081
<i>D. urceolata</i> "elongata"	0.183	0.172
<i>Centropyxis aculeata</i>		
Diatom Mud (D.M.) Assemblage (4)		
<i>Cucurbitella tricuspidis</i>	0.469	0.080
<i>Diffflugia oblonga</i>	0.141	0.008
<i>Diffflugia protaeiformis</i>	0.131	0.005
Transported Fauna (T.F.) Assemblage (5)		
<i>Cucurbitella tricuspidis</i>	0.903	0.050

and Hg for *Diffflugia protaeiformis* or; 2) this species may be more tolerant of low pH conditions than centropxyids, as Peterson and Crosswise lakes were characterized by much higher pH levels (up to pH 8.5) than Lake Orta.

The abundance of *Arcella vulgaris* in this assemblage is surprising. Collins and others (1990) observed that this species is characteristic of boggy ponds from the Arctic southward. As Peterson and Crosswise lakes are in no way bog-like, it seems that certain heavily polluted substrates also provide suitable environments for *Arcella vulgaris* as well. Further research may indicate that this species is a much better indicator of contamination than the centropxyids, as *Arcella vulgaris* is not normally tolerant of low salinity and oligotrophic conditions. *Arcella vulgaris* also seems to have an affinity for silver, and various other metals, as the tests of many specimens were constructed of this material. Many of the centropxyid species had test rims completely composed of metallic particles as well. This selectivity for metal displayed by both *Arcella vulgaris* and the centropxyids is probably related to availability of particles in required size ranges at different stages of test construction (Fig. 6; Table 5).

MINE TAILINGS (M.T.) ASSEMBLAGE (2)

The M.T. Assemblage clusters very closely with the C.S. Assemblage and is also restricted to Crosswise and Peterson lakes (Figs. 2 and 3). These samples consist of white, muddy to silty mine tailings. It was from sedimentologically similar samples that the very high levels of As and Hg were measured in these lakes (Dumaresq, 1993; Hawley, 1980). We presume that the mine tailing samples hosting the M.T. Assemblage are similarly contaminated.

The arcellacean fauna is diverse with several species dominating; *Cucurbitella tricuspidis* (Carter, 1856; \bar{x} = 21.6%), *Diffflugia oblonga* (Ehrenberg, 1832; \bar{x} = 18.2%),

TABLE 5. Results of semi-quantitative energy dispersal x-ray (EDX) analysis, measured in percent elemental weight, at three sites on apertural side of *Centropyxis aculeata* (Ehrenberg) specimen from Peterson Lake. Totals do not add up to 100% because oxygen (bound up in many compounds, e.g., SiO₂) is not listed. Sites analyzed illustrated in Figure 6.

Element/Site	Site a	Site b	Site c
Total Wt. %	60.86	60.43	57.4
Mn	0	0	0
Fe	5.38	5.36	4.52
Co	0.72	0.49	0.19
Ni	1.98	1.34	0.72
Cu	6.74	5.82	6.35
Zn	0	0	0
Ag	0	0.47	0.3
S	10.88	9.04	7.76
As	2.17	1.71	0.96
Ba	0.55	0.6	0.53
Na	3.36	5.67	2.86
Mg	0	0	0
Al	7.12	6.86	4.59
Si	19.42	21.18	22.8
K	0.82	0.79	4.52
Ca	1.72	0.95	1.09
Cl	0	0.15	0.21

Centropyxis aculeata (\bar{x} = 13.1%), and *Diffflugia protaeiformis* (\bar{x} = 11.3%; Table 4). The abundance of *Centropyxis aculeata* in this assemblage indicates continued environmental stress, although not as severe as in substrates dominated by the C.S. Assemblage. The presence of *Diffflugia oblonga* and *Diffflugia protaeiformis* is indicative of the relatively high organic content in these samples. Collins and others (1990) report that *Diffflugia oblonga* thrives from tropical to Arctic conditions in virtually any lake environment so long as the sediments are sufficiently organic. Until recently, abundant populations of *Diffflugia protaeiformis* were thought to indicate warm eutrophic conditions because significant numbers of specimens in present day lakes had only been found as far north as Virginia (Collins and others, 1990). McCarthy and others (1995) have reported large populations of this species in lake cores from Nova Scotia, but only in intervals deposited during the warm Holocene Hypsithermal. In the northern lakes of our study the abundance of *Diffflugia protaeiformis* in the M.T. Assemblage may be linked to the contaminated substrate. As described above, Asioli and others (1996) have found this species to be opportunistic in polluted lakes of northern Italy. In our study area, less contaminated substrates characterized by the M.T. Assemblage (as compared to substrates dominated by the C.S. Assemblage) may provide suitable conditions for this species. This suggests that levels of As and Hg contamination rather than pH are controlling the distribution of *Diffflugia protaeiformis*. The implications of the occurrence of *Cucurbitella tricuspidis*, associated with warm, shallow eutrophic conditions and sometimes coexisting with *Spirogyra* algae, is described in a later section.

MUDDY SUBSTRATE (M.S.) ASSEMBLAGE (3)

The M.S. Assemblage (3) characterizes organic-rich substrates in all three lakes. Samples containing this assemblage were all composed of mud and/or gyttia, and were found at

water depths from 3.9–18.0 m (Figs. 2, 3, and 4). The assemblage is dominated by *Diffugia oblonga* (\bar{x} = 40.9%), *Diffugia urceolata* phenotype "elongata" (\bar{x} = 18.3%), and *Centropyxis aculeata* (\bar{x} = 9.8%; Table 4). The presence of this fauna indicates a return to near normal conditions. Following cessation of tailings dumping in Peterson and Crosswise lakes, natural sedimentation has resumed. Providing that there are no major disturbances, the tailings in these lakes will eventually be completely buried. The dominance of *Diffugia oblonga* in all samples reflects the high organic content of this substrate (Collins and others, 1990). Significant numbers of the opportunistic species *Centropyxis aculeata* in all samples and *Diffugia urceolata* Carter, 1864, phenotype "elongata" in some samples may be indicative of an arrested succession. Based on studies of Pleistocene sediments from eastern Canada, Collins and others (1990) and McCarthy and others (1995) concluded that *Diffugia urceolata* phenotype "elongata" is an opportunistic early colonizer. The high proportion of *Diffugia urceolata* phenotype "elongata" may indicate a reduced but continued influence of As and Hg contamination on the benthic community at some sites in Crosswise and Peterson lakes. The presence of this partially opportunistic fauna at a single site in Gillies Lake—G93-3 from beneath the thermocline at 18.0 m—may be related to reduced temperatures and oxygen levels at this depth (6.5°C and 3.5 ppm, respectively).

DIATOM MUD ASSEMBLAGE (4)

The Diatom Mud Assemblage (4) is dominated by *Cucurbitella tricusps* (\bar{x} = 46.9%), *Diffugia protaeiformis* (\bar{x} = 13.1%), *Diffugia oblonga* (\bar{x} = 14.1%) and *Centropyxis aculeata* (\bar{x} = 5.6%; Table 4). The fauna is restricted to diatomaceous mud (6.7–6.8 m) associated with lake weeds along the margins of Crosswise Lake (Fig. 2). There is no physical evidence of tailings at these sites.

The seasonally planktic *Cucurbitella tricusps* sometimes occurs in high abundances in water bodies characterized in summer by conspicuous, floating, bright green algal mats comprised of *Spirogyra* spp. (Schonburn, 1984; Patterson, 1985; Medioli and others, 1987; Collins and others, 1990). In laboratory culture Medioli and others (1987) determined that *Cucurbitella tricusps* has a parasitic relationship with *Spirogyra* spp., upon which it preferentially feeds. Following germination in the spring, *Spirogyra* spp. comes to the surface of freshwater bodies. Attached specimens of feeding *Cucurbitella tricusps* float up with the algae, eventually becoming buoyant themselves from ingested fat droplets and capable of an independent planktic existence. High proportions of *Cucurbitella tricusps* in the absence of *Spirogyra* spp. have also been associated with highly eutrophic conditions in Lake Erie and certain small lakes in New Brunswick and Nova Scotia (Patterson and others, 1985; Scott and Medioli, 1983). The weeds and diatom-rich mud found in association with this biofacies indicate that similar eutrophic conditions exist along the margin of Crosswise Lake. As observed for the M.T. Assemblage, high proportions of *Diffugia protaeiformis* and lesser numbers of *Centropyxis aculeata* may indicate residual high levels of As and Hg even in these post-tailings deposits.

The grouping of a deep water sample G-6 (25 m) from

Gillies Lake with this assemblage is probably due to the low proportion of *Cucurbitella tricusps* (62.7%) in this sample, compared to most other samples from Gillies Lake. That sample, deposited beneath the thermocline under low oxygen and temperature conditions, is probably more appropriately grouped with the rest of the deep water Gillies Lake Transported Assemblage samples described below.

TRANSPORTED FAUNA (T.F) ASSEMBLAGE (5)

The T.F. Assemblage (5) characterizes almost every sample from Gillies Lake (Fig. 4). The sediments bearing this assemblage vary in composition from silt to mud to gyttia and are typically found in deep water (15–37 m), well beneath the thermocline and with minimal oxygen levels. These samples are overwhelmingly dominated by *Cucurbitella tricusps* (\bar{x} = 90.3%; Table 4). Considering the low year-round lake bottom oxygen levels and temperatures (as low as 2.0 ppm and 6°C in June and September, unpublished MOE data and this study), the dominance of a planktic species such as *Cucurbitella tricusps* in these sediments is not unexpected. However, at this time the source of *Cucurbitella tricusps* is not known. During numerous late summer visits to the lake, when conditions are warmest and most suitable for algal growth, we have never seen any significant populations of *Spirogyra* spp. or any other algae, and the lake is not particularly eutrophic. It is, therefore, likely that these populations are transported, probably from the very shallow part of Gillies lake north of the Highway 11B causeway, the major inlet to the southern part of Gillies Lake.

CONCLUSIONS

The distinct faunas found in the Contaminated Substrate, Mine Tailings, Muddy Substrate and Diatom Mud assemblages, each associated with substrates that are highly, moderately, and slightly contaminated by As and Hg, indicate that substrate contamination exerts an important control over arcellacean distribution. However, as shown in Gillies Lake, certain characteristics of the water column such as currents, oxygen level, and minimum annual temperature also have a profound effect on arcellacean distribution. The follow-up to this pilot study will entail a higher resolution quantitative geochemical and arcellacean analysis of both surficial and cored samples from Peterson and Crosswise lakes to obtain a more precise determination of arcellacean sensitivity to As and Hg contamination and rates of substrate remediation.

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APPENDIX 1. Faunal list

Due to space considerations, and as this is not a taxonomic paper, arcellacean species observed are listed in alphabetical order with only the author and year of description indicated. In cases where the present generic designation differs from the original, the original genus name is provided in capital letters.

- Arcella vulgaris* Ehrenberg, 1830
Centropyxis aculeata (Ehrenberg, 1832) ARCELLA
Centropyxis constricta (Ehrenberg, 1843) ARCELLA
Cucurbitella corona (Wallich, 1864) DIFFLUGIA
Cucurbitella tricuspis (Carter, 1856) DIFFLUGIA
Diffflugia bacillifera Perty, 1849
Diffflugia bidens Pénard, 1902
Diffflugia fragosa Hempel, 1898
Diffflugia globulus (Ehrenberg, 1848)
Diffflugia oblonga (Ehrenberg, 1832)
Diffflugia protaeiformis Lamarck, 1816
Diffflugia urceolata Carter, 1864
Diffflugia urceolata Carter, 1864 phenotype "elongata" (in sense of Pénard, 1902)
Diffflugia urens Patterson, MacKinnon, Scott, and Medioli, 1985
Heleopera sphagni (Leidy, 1874) DIFFLUGIA
Lagenodiffflugia vas (Leidy, 1874) DIFFLUGIA
Lesquereusia spiralis (Ehrenberg, 1840) DIFFLUGIA
Pontigulasia compressa (Carter, 1864) DIFFLUGIA

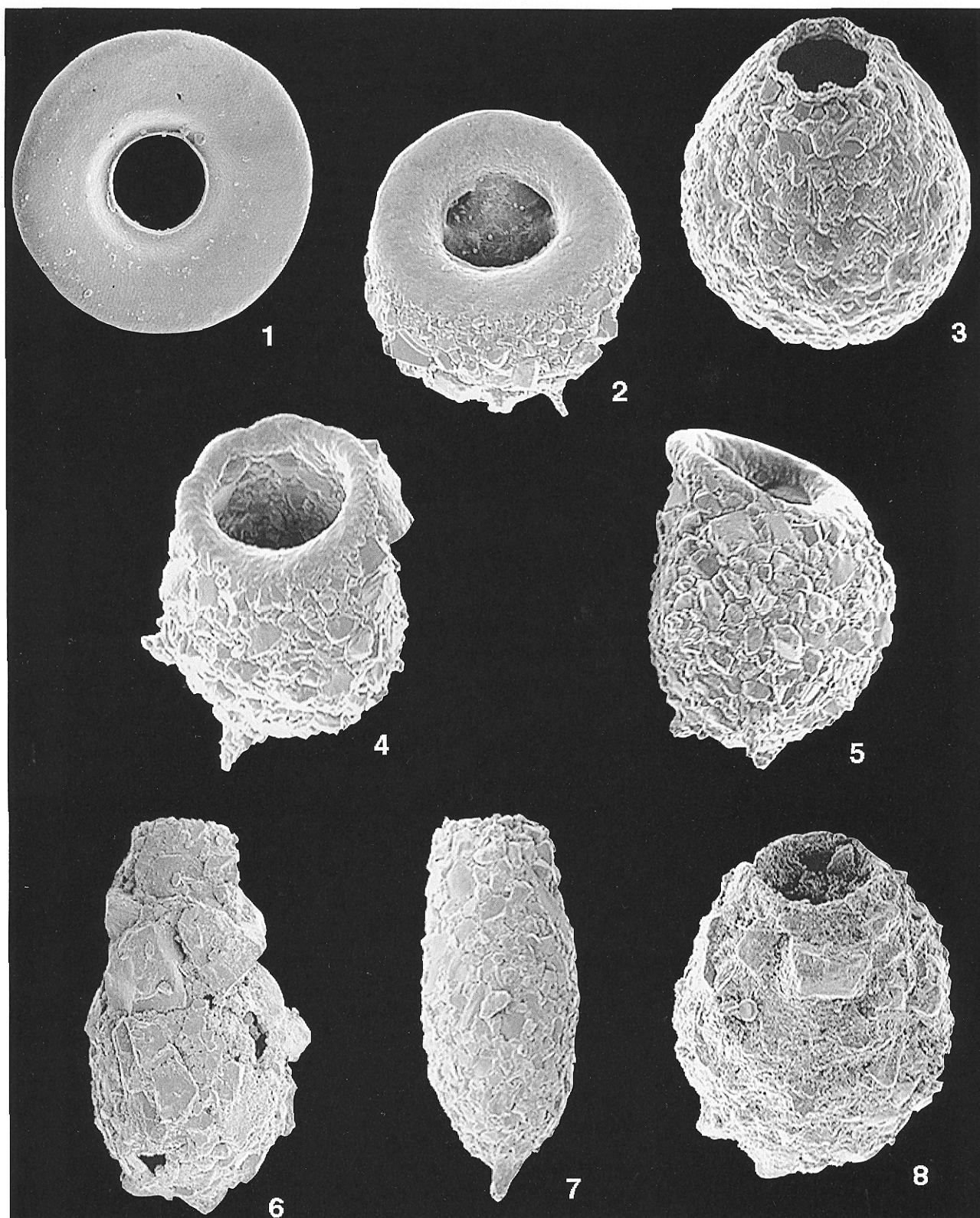


PLATE 1

1 *Arcella vulgaris* Ehrenberg, Apertural view, $\times 600$, Peterson Lake. 2 *Centropyxis aculeata* (Ehrenberg), Apertural view, $\times 500$, Gillies Lake (G93-2). 3 *Cucurbitella tricusps* (Carter), Oblique side view, $\times 750$, Gillies Lake (G93-6). 4-5 *Centropyxis constricta* (Ehrenberg). 4 Apertural view, $\times 650$, Gillies Lake (G93-3). 5 Side view, $\times 700$, Gillies Lake (G93-3). 6 *Diffugia oblonga* (Ehrenberg), Side view, $\times 250$, Gillies Lake (G93-3). 7 *Diffugia protaeiformis* Lamarck, Side view, $\times 350$, Peterson Lake. 8 *Diffugia urceolata* Carter phenotype 'elongata,' Oblique side view, $\times 200$, Gillies Lake (G93-3).