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PRELIMINARY SURVEY OF ARCELLACEANS (THECAMOEBIANS) AS LIMNOLOGICAL INDICATORS IN TROPICAL LAKE SENTANI, IRIAN JAYA, INDONESIA

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ABSTRACT

Arcellacean (thecamoebian) assemblages recovered from Lake Sentani, a large tropical lake southwest of Jayapura, Irian Jaya, Indonesia, are characterized by low diversity and low abundances. Dominated by *Centropyxis aculeata* and *Arcella vulgaris,* this fauna is similar to those indicative of stressed environments (brackish conditions, high levels of industrial contaminants) in temperate regions. However, neither condition exists in Lake Sentani. Previous work has determined that the lake is oligomictic, characterized by weak circulation with turnover occurring only every few years. Prolonged isolation of the lake bottom produces progressively reduced oxygen levels and results in reduced productivity among benthic organisms. The feeble stratification that exists here creates reduced oxygen levels at depth providing a likely explanation of the stressed arcellacean fauna. The oligomictic conditions observed here and the resultant fauna are widespread and are characteristic of a large proportion of tropical lakes around the world. As the low bottom water oxygen conditions will have a serious impact on most benthic organisms in these lakes, other limnological signals including anthropogenic contamination will be masked. This is a disappointing result as the utility that has been developed for the group as a limnological indicator in temperate lakes does not appear to apply in a significant proportion of low latitude lakes.

INTRODUCTION

Arcellaceans (thecamoebians) are freshwater protozoans with agglutinated or autogenous tests that occur abundantly in most Quaternary lacustrine sediments (Medioli and Scott, 1983; Scott and Medioli, 1983). Distinct associations of arcellacean species and strains (infraspecific morphotypes) can be correlated with a variety of climatic and other environmental factors such as oxygen levels, minimum average water temperature, level of organics and substrate type, clastics, and pollution levels (Scott and Medioli, 1983; Patterson and others, 1985; Medioli and others, 1990; Collins and others, 1990; McCarthy and others, 1995; Patterson and others, 1996; Asioli and others, 1996). Recent studies carried out in lakes of northeastern Ontario, Canada and northern Italy have further identified a positive relationship between arcellacean infrasubspecific strains and heavy metal pollution (Asioli and others, 1996; Patterson and others, 1996; Reinhardt and others, 1998).

Previous studies have focused mainly on faunas found in higher latitude temperate zone lakes (Medioli and Scott, 1988). The minimal research that has been carried out in tropical regions has been primarily descriptive, with scant attention paid to limnological associations. Examples of this research include: faunas from lakes in Java and Sumatra, Indonesia (Hoogenraad and Groot, 1940, 1946; van Oye, 1949); lakes in Malaysia (Sudzuki, 1979); brackish and freshwater lakes and ponds on the islands of Bombay (Carter, 1856a, 1856b, 1864, 1865); the Sokoto River in Nigeria (Green, 1963) and the wetlands of central Brazil (Green, 1975).

The purpose of this study is to add to this database by documenting the arcellacean fauna found in tropical Lake Sentani, Irian Jaya, Indonesia, and variations in arcellacean assemblages to changes in measured limnological parameters.

LAKE PHYSIOGRAPHY

Lake Sentani occurs in the northeastern corner of the Province of Irian Jaya, Indonesia, southwest of Jayapura (Fig. 1). It is a large oligomictic lake (28 km east-west by 19 km north-south; area 10,400 ha), situated at an elevation of 73 m in a fault-controlled depression. The bedrock basement consists mainly of Mesozoic mafic and ultramafic rocks of the Cyclops Ophiolite Belt (Moore and others, 1995). The lake is fed by a catchment area of about 600 km^2 and has only one outlet via the Jafuri River to the nearby Pacific Ocean near the Papua New Guinea border. Average annual rainfall around the lake is high, averaging about 2 m. Due to seasonal variations in fluvial inflow, the lake level fluctuates about 0.4 m (Howard, 1987). The lake is oligomictic (infrequent turnover events) with oxygen stratification occurring in the western basin at 22 m depth (Canadian International Development Agency, 1985; Howard, 1987; Table 1; Fig. 1).

Measurements taken in this and previous studies indicate lake temperatures ranging from 29°C to 31°C. Surface water pH is near neutral with values measured between 6.2 and 7.2. Due to limited circulation, this oligomictic lake is quite turbid, particularly in the westernmost basin. Plankton levels are low at 1–2 mg/L, although periodic algal blooms often result in high levels of fish mortality (Canadian International Development Agency, 1985).

MATERIALS AND METHODS

Eighteen sediment-water interface samples were collected using an Eckman box grab sampler in September of 1994

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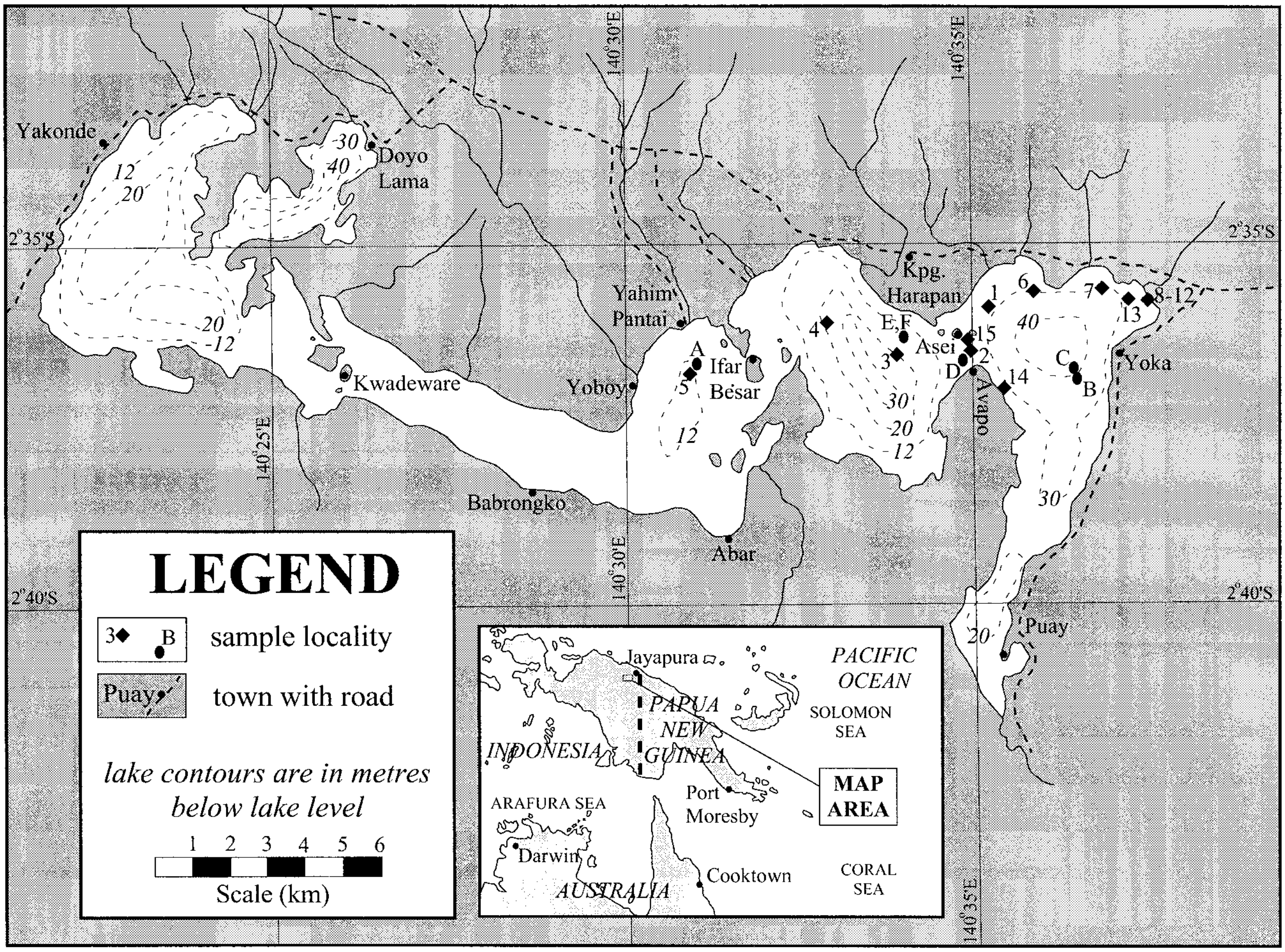

FIGURE 1. Lake Sentani Map showing sample localities. Numerical localities represent samples collected during 1994 and 1995, and alphabetical localities from 1997.

and May of 1995. Water depth, surface water temperature, water temperature at depth, and a relative measure of oxygen concentration at depth were recorded for each sample locality. Oxygen and temperature measurements were restricted to 15 m or less by limitations of the equipment. In August of 1997, pH and salinity readings were recorded from ten additional localities (Table 1; Fig. 1).

The geographical location of each sample site was determined using a Magellan Global Positioning System receiver. A commercial sonar device (fish finder) was used to determine the depth of each sample station. In 1997, lake bottom water samples were obtained using a WildCo 1510TT water sampler. Measurements of pH of water samples were calibrated against a pH 7.01 buffer standard. Salinity was measured with an automatic temperature compensating salinity refractometer calibrated with distilled water, and was below the detection limit in all samples.

Samples with significant populations of arcellaceans were found at muddy bottom sites with a large admixture of fine organic material. Sites characterized by winnowed sandy substrates generally yielded small allochthonous arcellacean assemblages. Some attempted sample stations were found to be floored by exposed rock, providing no samples for analysis.

Before shipment to Canada for processing, a 30% methyl alcohol solution was added to each sample to inhibit decay of organic material. Rose Bengal (acid red 94) protoplasmic stain was then added to indicate whether the specimens were alive at the time of collection. After standing for several hours, the samples were screened with a 1000 μm sieve to remove coarse particles, and a 43 μm screen to retain arcellaceans, and to remove silts and clays. Finally, all samples were treated with isopropyl alcohol and refrigerated. The samples had an average volume of 18 cm^3 and were entirely processed.

The samples were then subdivided into aliquots for analysis using a wet splitter (Scott and Hermelin, 1993). Although the low numbers of specimens found in this study did not really warrant splitting, low abundances could not be determined prior to counting, which was subsequently done using a binocular microscope.

Electronically stored scanning electron micrographs were obtained using a JEOL 6400 scanning electron microscope at the Carleton University Research Facility for Electron Microscopy (CURFEM). The plate was electronically produced on an Apple Macintosh computer using Adobe Photoshop and output to a Linatronic printer.

TABLE 1. A. Sample locations, physical characteristics of Lake Sentani, specimen counts and their percentages. Field data collected in September of 1994 and May of 1995 by J.M. Moore. B. Sample locations and pH measurements of water samples. Salinity was below detection limit in all samples and thus was not presented on this table. Field data collected in August of 1997 by J.M. Moore.

A

Sample Locality	**S1B**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8A**	**S9A**
Latitude (S)	02 35.87	02 36.48	02 36.53	02 36.08	02 36.79	02 35.66	02 35.93	02 36.11	02 36.14
Longitude (E)	140 35.24	140 34.98	140 33.91	140 32.92	140 30.92	140 35.90	140 36.88	140 37.55	140 37.56
Depth (m)	16.5	36	29	26	11	28	39	4.5	7.5
Surface Temp (C)	29	30	30	31	31	30	31	30	30
Surface Oxygen (mg/L)	7.7	7.7	7.6	7.6	7.5	7.6	7.5	6.8	6.8
Temp. at Depth (C)	29.5	30	30	30	30	30	30		30
Oxygen at Depth (mg/L)	-	5.2	4.5	4.6	6	2.3	4.9	-	7
Measurement Depth (m)	14.326	15.24	15.24	15.24	11.278	15.24	15.24	-	7.62
Arcellacean Counts									
Arcella vulgaris	2	6	12	10	3	30	73	46	19
Centropyxis aculeata " aculeata"	8	15	13	9		11	39	101	13
Centropyxis aculeata " discoides"	1	1							
Centropyxis constricta " spinosa"									
Centropyxis constricta " constricta"							2	3	
Centropyxis constricta " aerophila"		1		2					
Difflugia oblonga " glans"			2			2			
Difflugia oblonga "tenuis"	1								
Difflugia protaeiformis " claviformis"			10	3					
Incerta sp. A	4	7	4	13	2	22	20	25	2
Total	16	30	41	37	5	65	134	175	34
Percentages									
Arcella vulgaris	12.50%	20.00%	29.27%	27.03%	60.00%	46.15%	54.48%	26.29%	55.88%
Centropyxis aculeata "aculeata"	50.00%	50.00%	31.71%	24.32%		16.92%	29.10%	57.71%	38.24%
Centropyxis aculeata "psilata"	6.25%	3.33%							
Centropyxis constricta "bassa"									
Centropyxis constricta "constricta"							1.49%	1.71%	
Cucurbitella constricta		3.33%		5.41%					
Difflugia oblonga "glans"			4.88%			3.08%			
Difflugia oblonga "tenuis"	6.25%								
Difflugia protaeiformis "claviformis"			24.39%	8.11%					
Incerta	25.00%	23.33%	9.76%	35.14%	40.00%	33.85%	14.93%	14.29%	5.88%
Shannon Diversity Index	1.29965096	1.23477469	1.44233928	1.42639507	0.67301167	1.13127961	1.03676978	1.01614364	0.85944945

Sample Locality	**S10A**	**S10B**	**S11A**	**S11B**	**S12A**	**S13**	**S14A**	**S15A**	**S15B**
Latitude (S)	02 36.15	02 36.15	02 36.14	02 36.14	02 36.13	02 36.09	02 36.99	02 36.34	02 36.34
Longitude (E)	140 37.50	140 37.50	140 37.43	140 37.43	140 37.35	140 37.25	140 35.46	140 34.93	140
Depth (m)	11	11	15	15	18	21.5	12.5	24.5	24.5
Surface Temp (C)	30	30	30	30	-	-	-	-	-
Surface Oxygen (mg/L)	-	-	-	-	-	-	-	-	-
Temp. at Depth (C)									
Oxygen at Depth (mg/L)	-	-	-	-	-	-	-	-	-
Measurement Depth (m)									
Arcellacean Counts									
Arcella vulgaris	19	5	18	18		45		74	60
Centropyxis aculeata " aculeata"	10	9	21	35		39		93	91
Centropyxis aculeata " discoides"	1								
Centropyxis constricta " spinosa"						2			
Centropyxis constricta " constricta"	2		1	1		5		1	7
Centropyxis constricta " aerophila"				1		8			
Difflugia oblonga " glans"								1	
Difflugia oblonga "tenuis"									
Difflugia protaeiformis " claviformis"									
Incerta sp. A				5		12		18	28
Total	32	14	40	60	barren	111	barren	187	186
Percentages									
Arcella vulgaris	118.75%	16.67%	43.90%	48.65%		69.23%		42.29%	176.47%
Centropyxis aculeata "aculeata"	62.50%	30.00%	51.22%	94.59%		60.00%		53.14%	267.65%
Centropyxis aculeata "psilata"	6.25%								
Centropyxis constricta "bassa"						3.08%			
Centropyxis constricta "constricta"	12.50%		2.44%	2.70%		7.69%		0.57%	20.59%
Cucurbitella constricta				2.70%		12.31%			
Difflugia oblonga "glans"								0.57%	
Difflugia oblonga "tenuis"									
Difflugia protaeiformis "claviformis"									
Incerta				13.51%		18.46%		10.29%	82.35%
Shannon Diversity Index	0.95459572	0.65175656	0.78983788	1.01916017	0	1.37559676	0	0.99549759	1.12320911

B

Sample Locality	A1	A2	B1	B2	B3	C	D	E	F1	F2
Latitude (S)	2 36.72'	2 36.72'	2 36.84'	2 36.84'	2 36.84'	2 36.70'	2 36.50'	2 36.24'	2 36.10'	2 36.10'
Longitude (E)	140 30.99'	140 30.99'	140 33.53'	140 33.53'	140 33.53'	140 33.51'	140 34.92'	140 35.93'	140 35.93'	140 35.93'
Depth (m)	14	0.1	0.1	32	20	33	36	42	43	0.1
pH	7.12	7.17	7.16	7.11	7.11	7.12	7.12	7.12	7.11	7.16

RESULTS AND DISCUSSION

The arcellacean fauna of Lake Sentani is quite impoverished in terms of species numbers and Shannon Diversity Index scores (Table 1). Total counts of individual species and strains were very low as well, rendering more substantive multivariate cluster analyses unfeasable. Therefore, only a qualitative assessment of the data was carried out. All samples were dominated by two species, *Arcella vul-*

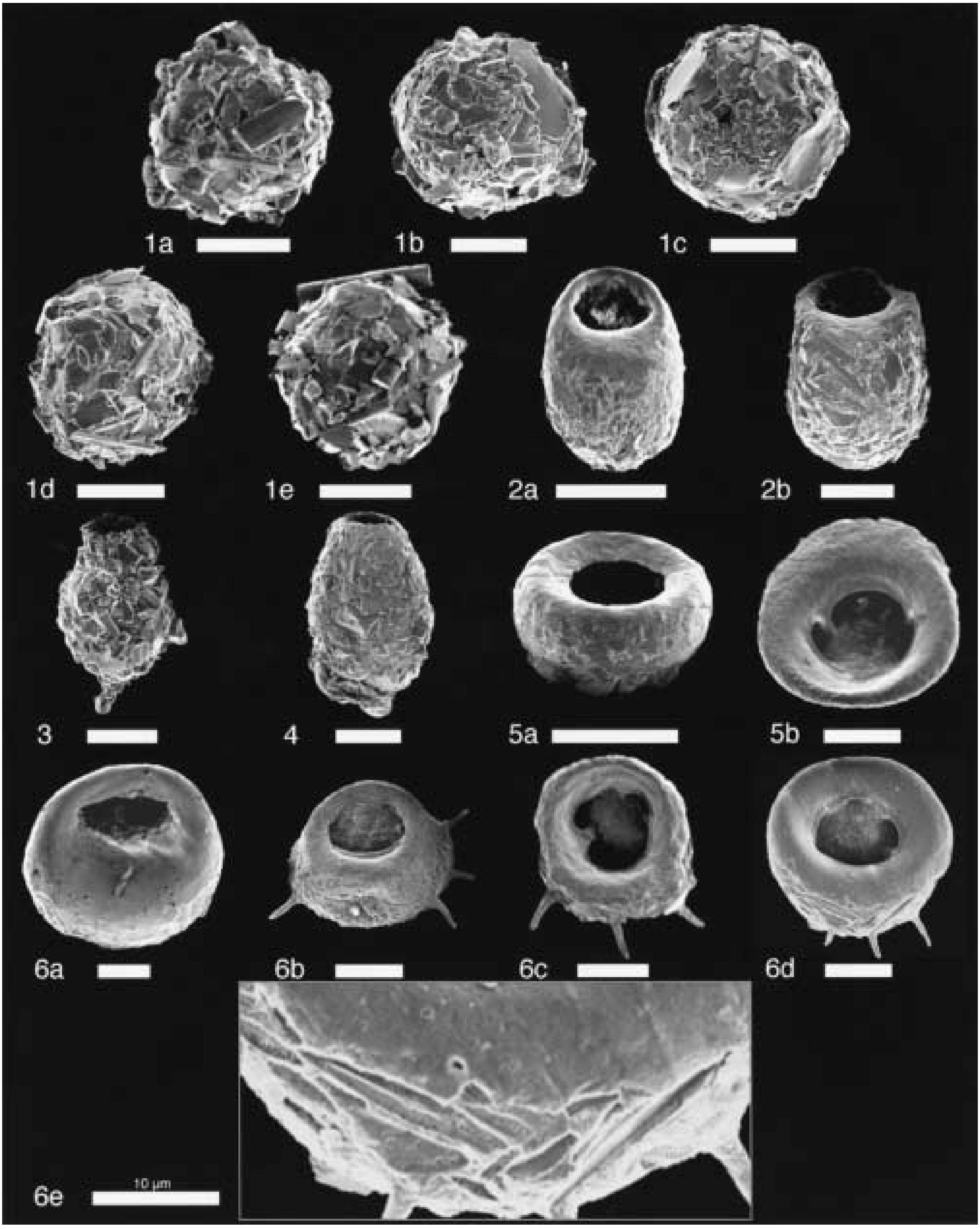

PLATE 1

Scanning electron micrographs of Lake Sentani arcellaceans. **1 a–e** Incerta sp. A. Agglutinated sphere of unknown affinity. **2 a–b** *Centropyxis constricta* ''aerophila''. Aperture forms an angle with the fundus. **3** *Difflugia protaeiformis* ''claviformis''. Test made from coarse grains and is *garis* Ehrenberg 1830 and *Centropyxis aculeata* Ehrenberg 1832. In a few samples various difflugids and a possible new species of arcellacean, identified as Incerta sp. A, also occur in appreciable numbers.

To evaluate the limnological significance of this arcellacean assemblage, it is important to understand their ecology and distribution. Impoverished faunas similar to those found in Lake Sentani have been described elsewhere, and could be attributed to one or more of the distinct environmental controls discussed below: brackish water conditions, low pH, anthropogenic contamination, substrate type, and environmental conditions peculiar to tropical lakes.

Moore and others (1995) proposed that Lake Sentani was an arm of the ocean well into the Holocene and that there still might be saline wedges present at depth. Centropyxids, primarily *Centropyxis aculeata*, are known to be opportunistic and capable of existing under hostile conditions (Patterson and others, 1996; Reinhardt and others, 1998) and have been reported from brackish environments in coastal areas with salinities as high as 5‰ (Decloitre, 1953; Todd and Bronnimann, 1957; Honig and Scott, 1987; Medioli and Scott, 1988; Hayward and others, 1996). Faunas similar to those in Lake Sentani are found in cores from lakes in uplifted coastal areas of New Brunswick, Canada, in intervals marking the transition from marine to freshwater conditions (Patterson and others, 1985). However, water testing indicated no trace of salinity in any Lake Sentani sample.

Arcella vulgaris is an important component of the arcellacean faunas of Lake Sentani, dominating many samples. This species is commonly reported from boggy ponds in the Arctic and further south to Florida (Collins and others, 1990), and is well adapted to the low pH typical of these ponds. In James Lake of northeastern Ontario, *A. vulgaris* almost exclusively dominates low pH (2.0–5.5) environments (Kumar and Patterson, 1997; Kumar and Patterson, 2000). However, in studies on lakes with varying pH in northeastern Ontario it was found that centropyxids, so dominant in Lake Sentani, cannot tolerate low pH ($<$5.5) environments (Patterson and others, 1996; Reinhardt and others, 1998; Patterson and Kumar, 2000). Thus the abundance of centropyxids in Lake Sentani samples indicates that pH is not a controlling factor here, and the measured pH values of 7.1 to 7.2 for lake water at several depths in different localities corroborate this conclusion.

Centropyxid species found in the Cobalt area, northeastern Ontario, such as *Centropyxis aculeata* often dominate substrates contaminated by heavy metals and other industrial contaminants (Patterson and others, 1996; Reinhardt and others, 1998). No geochemical analysis was carried out on samples in Lake Sentani so this influence cannot be categorically refuted. However, there is no major industry there, and human habitation consists of only small villages along the shores and on the islands of Lake Sentani (Fig. 1). Sewage from houses in the villages goes directly into this lake though, and the periodic fish-killing algal blooms suggest that some eutrophication, at least in surface waters, could be occurring. However, eutrophication is not indicated by the benthic arcellacean fauna because *Difflugia oblonga*, one of the major indicator taxa of high organic content (Collins and others, 1990), is almost entirely absent from the lake.

The dominance of the arcellids and centropyxids coupled with the dearth of difflugids may be a function of substrate type. With the exception of the barren samples (S12A, S14A) which contained a fair amount of mineral grains, all samples were rich in organic matter. Difflugids require mineral grains to construct their tests and in the absence of such will not be found in any appreciable numbers, if at all (Haman, 1990; Scott and others, 1991). Arcellids produce their tests autogenously, and centropyxids in Lake Sentani seen to be able to utilize diatom frustules to construct their tests (Plate 1, fig. 6e), so it is not surprising that they dominate the organic-rich samples.

Other factors that control the geographic distribution of modern arcellaceans include the vegetation in and around lakes and climatic conditions, which ultimately control water levels, chemistry, trophic levels, and the nature of a thermocline, if present (Collins and others, 1990). The low diversity and dominance in all samples by *Centropyxis aculeata* and *Arcella vulgaris* indicate a stressed environment unlike any recorded in northern hemisphere temperate lakes. A characteristic of tropical oligomictic lakes like Lake Sentani is very weak circulation with turnover occurring only every few years, thus resulting in diminished oxygen content (Wetzel, 1983).

Although our water temperature and oxygen data only extend to 15 m depth, other work has shown ''. . .that oxygen stratification occurs in the western basin at 22 m depth'' resulting in oligomictic conditions (Howard, 1987). Although most of our samples are from the eastern region of the lake, the feeble stratification recorded by Howard (1987) no doubt exists lakewide. This stratification ultimately results in the prolonged isolation of the lake bottom and progressively reduced oxygen levels. This would have in turn resulted in similarly reduced productivity among benthic organisms, as indicated by the stressed arcellacean fauna. Qualitative reports on similar arcellacean faunas have been reported from Nigeria (Green, 1963) and Brazil (Green, 1975) suggesting that this fauna is widespread and characteristic of tropical lakes.

Although our data are sparse, the impact of prolonged stratification on benthic organism productivity in these lakes is undoubtably strong enough to mask out most other limnological signals, such as anthropogenic eutrophication. This could also provide a possible explanation for the dearth of *Difflugia oblonga* in these samples, usually an excellent indicator of eutrophication, despite other kinds of evidence for lake eutrophication. Although it is dangerous to draw

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opaque. **4** *Difflugia oblonga* ''glans''. Test ovoid with rounded fundus. **5 a** *Centropyxis aculeata* ''discoides''. Same as ''*aculeata*'' but spines absent. **5 b** *Arcella vulgaris.* Test round, hyaline; aperture invaginate. **6 a–e** *Centropyxis aculeata* ''aculeata''. **6 a–d** This strain has a variable number of spines. **6 e** Enlargement of 6d showing imprints caused by diatoms, often used as xenogenous particles to construct arcellacean tests as in the case of Lake Sentani centropyxids. All scale bars are 50 μm.

sweeping conclusions based on results from a single lake we suggest that, because of the serious impact on productivity caused by stratification, benthic arcellacean faunas may be seriously affected throughout most oligomictic lakes. This probably means that the group, such an important limnological indicator in temperate lakes, is not useful in a significant proportion of low latitude oligomictic lakes.

SYSTEMATIC PALEONTOLOGY

Although infrasubspecific variants are not considered valid according to the International Code of Zoological Nomenclature (ICZN), their informal use is often useful in paleoecological studies. This is particularly true with regards to arcellaceans as the species concept within this clonal group is a highly subjective matter (see Deflandre, 1928; Medioli and Scott, 1983; Medioli and Scott, 1988 for discussion). For example, Reinhardt and others (1998) were able to separate and define numerous distinct and stable arcellacean strains that characterized various limnological conditions in northern Ontario lakes. In addition, Kumar and Dalby (1998) proposed a standardized key for lacustrine arcellacean species and strains, which is used here. As this paper is not of a taxonomic nature, only abbreviated systematic descriptions are included.

Subphylum SARCODINA Schmarda 1871
Class RHIZOPODEA von Siebold 1845
Subclass LOBOSA Carpenter 1861
Order ARCELLINIDA Kent 1880
Superfamily ARCELLACEA Ehrenberg 1830
Family ARCELLIDAE Ehrenberg 1830
Arcella Ehrenberg 1830
Arcella vulgaris Ehrenberg 1830
(Plate 1; Figure 5b)

Arcella vulgaris EHRENBERG 1830, p. 40, pl. 1, fig. 6

Diagnosis. Test depressed, hyaline, and autogenous, with an invaginated aperture.

Family CENTROPYXIDIDAE Deflandre 1953
Centropyxis Stein 1859
Centropyxis aculeata (Ehrenberg 1832)
strain: ''aculeata''
(Plate 1; Figure 6 a–e)

Arcella aculeata EHRENBERG 1832, p. 91

Diagnosis. Test depressed, circular with 1–8 spines on postero-lateral margin.

Centropyxis aculeata (Ehrenberg 1832)
strain: ''discoides''
(Plate 1; Figure 5a)

Arcella discoides EHRENBERG 1843, p. 139
Arcella discoides Ehrenberg, EHRENBERG 1872, p. 259, pl. 3, fig. 1
Arcella discoides Ehrenberg, LEIDY 1879, p. 173, pl. 28, figs. 14–38
Centropyxis aculeata var. *discoides* PENARD 1890, p. 150, pl. 5, figs. 38–41
Centropyxis discoides Penard [sic], OGDEN and HEDLEY 1980, p. 54, pl. 16, figs. a–e

Diagnosis. Test depressed, circular almost ''doughnut shaped'' without spines.

Centropyxis constricta (Ehrenberg 1843)
strain: ''aerophila''
(Plate 1; Figure 2 a–b)

Centropyxis aerophila DEFLANDRE 1929
Centropyxis aerophila Deflandre OGDEN and HEDLEY 1980, p. 48–49
Cucurbitella [sic.] *constricta* REINHARDT and others 1998, pl. 1, fig. 6

Diagnosis. Test shape varies from spherical, subspherical to elongated. It is characterized by a thick apertural lip.

Centropyxis constricta (Ehrenberg 1843)
strain: ''constricta''

Arcella constricta EHRENBERG 1843, p. 410, pl. 4, fig. 35, pl. 5, fig. 1

Diagnosis. Test less flattened than strain ''spinosa'' with 3 or less spines on the fundus.

Discussion. These specimens were fragile and became broken when mounted on the scanning electron microscope plug.

Centropyxis constricta (Ehrenberg 1843)
strain: ''spinosa''

Centropyxis spinosa CASH in CASH and HOPKINSON 1905, p. 135, text figs. 26 a–c, pl. 16, fig. 15
Centropyxis spinosa Cash, OGDEN and HEDLEY 1980, p. 62, pl. 20, figs. a–d

Diagnosis. Test more flattened than strain ''constricta'' with 3 or more spines on the fundus.

Discussion. Only two specimens were found and they became broken when mounted on the scanning electron microscope plug.

Family DIFFLUGIDAE Stein 1859
Difflugia Leclerc in Lamarck 1816
Difflugia oblonga Ehrenberg 1832
strain ''glans''
(Plate 1; Figure 4)

Difflugia glans PENARD 1902

Diagnosis. Test oval to ovoid, slightly elongated, fundus rounded, neck absent, aperture circular with smooth lip, test made of fine sand particles, small.

Difflugia oblonga Ehrenberg 1832
strain: ''tenuis''

Difflugia pyriformis var. *tenuis* PENARD 1890, p. 138, pl. 3, figs. 47–49

Diagnosis. Test elongated, ovoid almost bean shaped, fundus subrounded to subacute, neck indistinct or absent, aperture narrow and circular with crenulated lip, test made of generally medium to fine sand grains.

Discussion. Only one specimen was found and it became broken.

Difflugia protaeiformis Lamarck 1816
strain: ''claviformis''
(Plate 1; Figure 3)

Difflugia protaeiformis LAMARCK 1816, p. 95 (with reference to material in a manuscript by Leclerc)
Difflugia pyriformis var. *claviformis* PENARD 1899, p. 25, pl. 2, figs. 12–14
Difflugia claviformis OGDEN and HEDLEY 1980, p. 126, pl. 52, figs. a–d

Diagnosis. Test elongated almost cylindroconical, fundus acuminate, tapering to form a blunt spine, neck absent, aperture circular, narrow without lip, test made up of medium to coarse grained sand

INCERTA

Incerta sp. A
(Plate 1; Figure 1 a–e)

Diagnosis. Agglutinated sphere with no discernible aperture.

Discussion. This could be an encystment of an arcellacean or the aperture has been covered (F. Medioli, oral communication, 1997)

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