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The aquatic algae associated with mining areas in Peninsula Malaysia and Sarawak: their composition, diversity and distribution

by

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With 9 figures and 4 tables

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Abstract: The composition, diversity and distribution of algae in Malaysian mining areas contaminated with potentially toxic trace heavy metals are described. One site in Peninsula Malaysia (Sungai Luit) is an operational alluvial gold mine, Penjom is a mining area undergoing redevelopment, and Mengapur is a mineral prospecting area. Four abandoned mining areas studied in Sarawak (Jugan, Lucky Hill, Bidi, Tai Ton) had been mined for gold, antimony and mercury. Algal samples were collected at 31 sites ranging from small drainage areas on a sulphide outcrop to streams, ponds and soil-free rock surfaces. The pH was measured at most sites and water analysed for trace heavy metals (principally copper, iron, arsenic). One hundred and forty-two algal species (75 genera) were recorded and 272 taxa if included are those grouped into size categories ('morphotypes') and doubtful species. Diatoms and chlorophytes were the two most diverse algal groups, with 70 and 57 species recorded respectively. High flushing rates, substrate instability, intermittent flow regime, and differences in pH and potentially toxic metals are thought to be implicated in low algal diversity. Diversity was highest in ponds whose pH was above 5.7 and where a wide range of microhabitats were present. The algal assemblage at a Jugan stream site was similar to an assemblage described from Europe and North America that is known to be indicative of acid mine drainage; several of these algae are new records for Malaysia. The widely distributed filamentous green alga *Klebsormidium rivulare* was the most characteristic alga of acid drainage areas on the sulphide-ore outcrop at Jugan. One new chlorophyte species is described, the desmid *Closterium penjomium* D. Williamson sp. nov.

Key words: freshwater, algae, mining, Malaysia, Sarawak, heavy metals.

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Introduction

Our knowledge of the freshwater algae of Peninsula Malaysia extends back nearly 90 years with publication of Bernard's (1909) illustrated list that included material collected from Johore and Singapore. Twenty years later Biswas (1929) listed 58 species (32 desmid species) collected mainly from a thermal spring area near Kuala Lumpur. Over thirty years elapsed before Prowse published the first comprehensive accounts of the algae in a series of papers on diatoms (Prowse 1962a), desmids (Prowse 1957, 1969), euglenoids (Prowse 1958), and other flagellated groups (Prowse 1962b). In the 1970s several publications (e.g., Bishop 1973, Ratnasbapathy 1992, 1975, 1977, Prowse & Ratnasbapathy 1970) listed algae from specific areas or habitats, often accompanied by brief notes and descriptions. The first account of Malaysian freshwater red algae by Kumano (1978) and based upon material collected during the 'Joint Malaysia-Japan Project of Scientific Investigation into Freshwater Lakes of Malaysia'. A series of papers followed on red algal genera (see Kumano & Ratnasabapathy 1982; Ratnasabapathy & Kumano 1982a, b; Ratnasabapathy & Seto 1981). The most recent accounts of the algae of Peninsula Malaysia deal with the Uku Endau area of Johore, one a general list (Phang & Leong 1987) and the other on diatoms (Wah et al. 1987) in which 37 out of the 57 listed species were new records. No algal records have been traced for Sarawak, which along with Sabah became part of the Malaysian Federation in 1963.

Mining in Sarawak stretches back to the early part of the 19th century and pre-historic tin workings are known from Peninsula Malaysia. The mining of gold, tin, antimony, copper and mercury is still a major activity and of considerable importance for employment and infrastructure development. Of the mining areas visited in Sarawak, Jugan is the only one where the ore body was exposed to the atmosphere resulting in oxidation of the sulphides to produce very acidic drainage water. Drainage or adit water in mining areas contain elevated concentrations of potentially toxic metals due to oxidation of auriferous- and complex-metal sulphides. Where the mine drainage is highly acidic, the beds of streams, rivers and ponds are blanketed with orange hydrous oxide 'ochre' precipitated by a rise in pH and attendant Fe-saturation. Sufficient information now exists on algae to enable them to be used as sensitive indicators of acid mine drainage and water contaminated by toxic metals (see Whitton 1983). Until the present investigation there existed no published information on the algal assemblages associated with mine drainage water in Malaysia.

The aim of the study is to inventory the freshwater algae associated with disturbed and undisturbed sulphide deposits, and to determine whether any are useful indicators of acid-mine drainage. It forms part of a larger interdisciplinary team-based project to characterize mineral breakdown, model element mobility, and establish correlations between the distribution of freshwater organisms and acid-mine drainage containing potentially toxic trace elements. All the work came under a British Geological Survey/ Overseas Developmental Agency Technological Development and Research programme to address environmental aspects of gold and complex sulphide mining.

Materials and methods

Representative sites in mine drainage areas, streams and ponds were selected for sampling. Algae associated with rock surfaces, submerged tree trunks, and floating and submerged aquatic plants were removed by scraping. Epipelic and epipsammic algae were sampled by drawing a metre long tube across unconsolidated surfaces and allowing it to slowly fill with a mixture of water, sediment and algae. Planktonic algae were collected using a plankton net, water sampling bottles, and collecting the squeezings from finely divided aquatic plants and filamentous macroalgae. Plastic petri dishes were used as entrapment surfaces for delicate benthic algae that are frequently overlooked in aquatic surveys. These were positioned 20-30 cm below the water surface at sites in the Bau Area and sampled after five days.

Most of the samples were subdivided, one subsample was preserved in 4% formalin and the other in Lugol's Iodine solution. Larger algae (including stoneworts) and aquatic spermatophytes were washed in a jet of water to remove extraneous matter before mounting on herbarium sheets and air drying in a press. Diatoms were acid-cleaned and mounted in naphrax before identification. Some filamentous green algae were identified after growing them in laboratory culture. In several genera (e.g., *Oedogonium, Spirogyra*) species identification is impossible unless certain stages in sexual reproduction are present. Sexual reproduction was rare and therefore taxa attributed to such genera are grouped into 'morphotypes' based largely upon cellular dimensions. The majority of the cyanophytes are grouped into morphotypes unless very distinctive and corresponding closely to descriptions in the literature.

The majority of the biological sample sites had also been surveyed by the British Geological Survey (BGS) in April 1992 and September/October 1993. Temperature and pH were measured at each site using an Oakton Field meter. The BGS measured pH in the field and carried out laboratory analysis of trace elements in filtered, acidified water samples. They measured copper and iron using direct ICP-AES methods and arsenic by hydride-generation ICP-AES. The BGS results for arsenic, copper and iron are acknowledged (Breward & Williams 1994; Breward et al. 1994; Williams et al. 1993).

All the liquid-preserved specimens, permanent microscope slides, pressed plant specimens, and photographs of algae and sites are deposited in The Natural History Museum (NHM), London.

Sites investigated

Study sites were associated with a fully operational alluvial gold mine (Sungai Luit), a potential mine known as the Mengapur Prospect, or former mines (Bidi [Kusa], Jugan, Lucky Hill, Tai Ton, Penjom) (Fig. 1). For fuller details of the sites, see Douglas et al. (1994). The geology and mineralogy of the mining areas and prospects are described in reports of the British Geological Survey (see Breward & Williams 1994; Breward et al. 1994; Williams et al. 1993).

Peninsula Malaysia

All the mining areas are within Pahang State, with Mengapur and Sungai Luit lying about 50 km to the west of Kuantan, and Penjom about 7 km south-west of Kuala Lipis. The Mengapur area is drained by several rivers, with the Sungai Luit giving its name to the alluvial gold mine.

Mengapur Prospect: consists of a complex sulphide mineral deposit that might be mined for copper and associated gold if commercial and technical problems are overcome. All streams were in spate at the time of sampling due to heavy rainfall associated with rapid surface run-off.

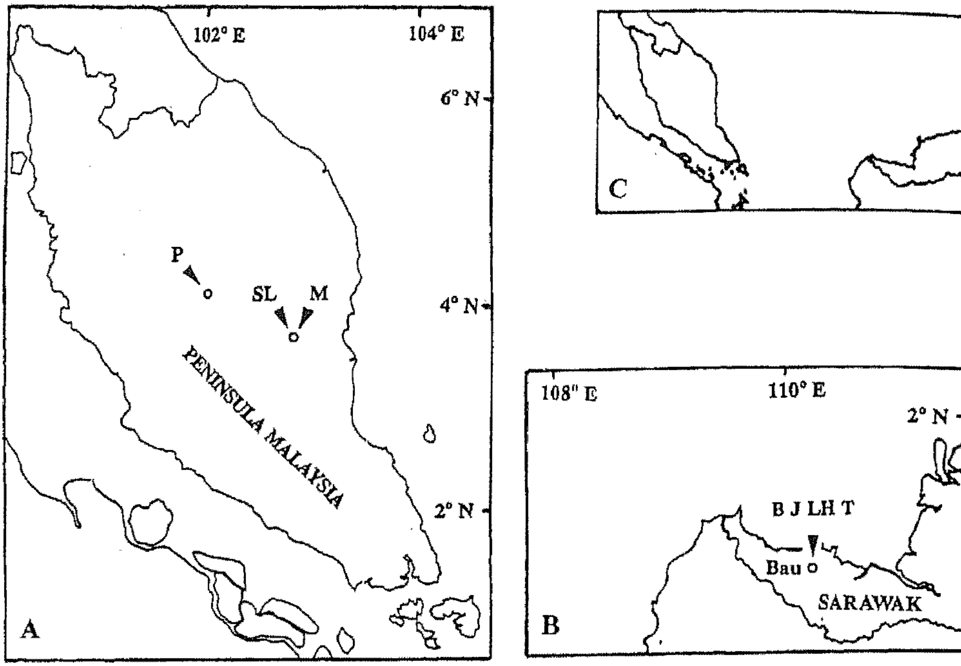


Fig. 1. Maps showing the position of mines and mine prospects in (A) Phang State, Peninsula Malaysia, (B) the Bau Area, Sarawak, and (C) the geographical relationship between Peninsula Malaysia and Sarawak. Key to sites: M = Mengapur (area of mining prospect), P = Penjom, SL = Sungai Luit (Peninsula Malaysia); B = Bidi, J = Jugan, LH = Lucky Hill, T = Tai Ton Mine (Sarawak).

M1. Stream about 2.5-3.0 m wide.

M2. About 1 km upstream of site M1, shaded by dense secondary forest.

M3. About 1 km upstream of site M2, sampled in vicinity of wooden platform supported on poles driven into the stream bed.

M4. Pool area of stream lying immediately downstream of a culvert and concrete sill.

M5. Artesian spring issuing through two circular orifices in an exposure of limestone rock and running directly into a pool shaded by dense, undisturbed forest.

Penjom Area: the history of mining for alluvial and bedrock gold in the area spans more than a century. Earlier mining activity has created a series of disused tailing ponds and dumps and present are small adits.

P3. Stream fed in part by an adit containing very alkaline water.

P5. Tailings pond of irregular shape, about 150 m long and 40 m in maximum width.

P6. Stream about 3 m wide, shaded by primary forest.

P7. Impoundment containing flooded trees, about 150 m long and 50 m in its widest part.

P8. Tailings pond, almost circular, about 100 m in diameter, flowing into a channel about 3 m in width.

P9. Pond about 12 m in diameter and destroyed by infilling immediately following sampling.

Sungai Luit Gold Mine: lies to the south-west of Mengapur in the floodplain of the Sungai Luit river. Once an area of extensive alluvial gold workings and still mined on a small-scale using the gravel-pump alluvial mining system. The scarring of the landscape with numerous shallow lakes and tailings dumps is evidence of its mining history.

SL1. River Burong, 2.0-2.5 m wide, sampled about 50 m upriver from where it flows into the Sungai Luit.

SL4. River Charis, sampled immediately downstream of a bridge where its channel was 2.5-3.0 m wide.

SL5. Tailings pond about 100 m in diameter, with stones embedded in its steep muddy banks.

Sarawak

All four mine sites lie within a 20 km radius of Bau, a town about 30 km south-west of the capital Kutching. The area is within the floodplain of the Sarawak River, its topography is that of an alluvial plain and steep-sided karstic limestone hills.

Bidi Mine (Kusa Mine): a small abandoned mine consisting of a series of flooded pits and some spoil heaps.

B1. Pond of irregular shape, about 25 m long and 15 m wide, probably a sink hole connected directly to the water table resulting in rapid fluctuations in water level following heavy rainfall.

B3. Pond lying about 100 m to the north-northeast of B1, about 15 m long and 5 m wide.

Jugan Mine: lies to the north-east of Bau and was operated for a short period in the early years of the century, now considered a prospective new mine site. It consists of a shale outcrop from which most of the vegetation and soil have been cleared to expose the sulphide ore.

J01. Temporary pools along margin of dump pond (J15).

J02. Number given to four seepage areas on the north side of the mine cut.

J1. Stream almost 2-3 m wide, sampled about 20 m downstream of a wooden bridge.

J3. Stream about 1.0-1.5 m wide, sampled 150 m downstream of bore hole drilling operation.

J8. Ditch about 1.0-1.5 m wide, sampled below a fish pond (J16); takes overflow water from pond but at time of sampling was fed by undergound seepage.

J12. Small drainage area with iron-oxide staining present and green filamentous algae evident.

J14. Stream about 1.0-1.5 m wide, sampled 500 m below lake, shaded by vegetation.

J15. Mine dump pond, about 50 m long and 20 m wide.

J16. Fish pond, almost square in outline, with each side about 50 m long; receives additional nutrients including those from a chicken coup positioned over it.

J17. Former tailings pond, about 200 m long and 180 m across.

Lucky Hill Mine: abandoned in 1982; consisting of flooded pits with adit and main pond draining into the Sungai Johara.

LH1. Main tailings pond, irregular in shape, about 150 m long and 80 m wide.

LH2. Stream about 2.0-2.4 m wide, sampled immediately upstream of a bridge, in spate on second visit.

LH3. Stream about 1.0-1.5 m wide, shaded by vegetation and probably fed by mine adit water.

Tai Ton Mine: former mine associated with a steep outcrop face of limestone and a large pond.

T1. Pond of almost circular outline, about 150 m in diameter, situated at the base of a steep limestone cliff.

T2. Temporary pools along track leading to pond (T1).

Results

Water chemistry

Sample sites were located in areas where there were ore-deposits or tailings that are known to contain high concentrations of complex heavy-metal sulphides. Mining of the ore or disturbance of the tailings has led to oxidation that in turn has released sulphuric acid and resulted in the mobilisation of potentially toxic metals. The buffering capacity of the nearby basic rocks (often limestone), and the undisturbed nature of the Mengapur mining prospect, probably accounts for the slight acid/alkaline nature of the streams (pH 5.5-7.8, see Table III) in the area. The most acidic water was measured at a shale ore outcrop at Jugan where small drainage and seepage areas had pHs below 3 and elevated levels of trace metals; the latter not precipitating out until the pH reaches about 3.3. The fish pond at Jugan (J16) was enriched by nutrients coming from chicken manure.

Floristic analysis

A total of 142 species (not including doubtful species) and 75 genera were identified, with chlorophytes (57 spp.) and diatoms (70 spp.) the two most diverse algal groups (Table I). Of the algae identified to species level all were new to Sarawak and 79 new to Peninsula Malaysia. Desmids were a diverse group and accounted for over

Table I. The number of taxa identified in the samples from Peninsula Malaysia and Sarawak.

	genera	spp.	doubtful spp./ 'morphospecies'
Chlorophyta	35	57	58
Euglenophyta	4	6	5
Cryptophyta	1	1	0
Dinophyta	1	1	0
Chrysophyta	1	2	1
Bacillariophyta	19	70	1
Rhodophyta	3	1	2
Cyanophyta	11	8	63
Totals	**75**	**142**	**130**

half of the chlorophyte species recorded. Of the 42 desmids identified to species almost two-thirds (28 spp.) were new records for Peninsula Malaysia and one was an undescribed species. The discovery of a new desmid species, *Closterium penjomium*, is hardly surprising in view of the phycological neglect of Malaysian aquatic habitats. A total of 130 morphotypes and doubtful species were recognized.

Table II. The total number of algal taxa present (species and 'morphotypes') at each site and pH where known (nd, no data). Peninsula Malaysia: Mengapur (M), Sungai Luit (SL), Penjom (P); Sarawak: Bidi (B), Jugan (J), Lucky Hill (LH), Tai Ton (T).

Peninsula Malayisa

	M1	M2	M3	M4	M5	P3	P5	P6	P7	P8	P9	SL1	SL4	SL5
no. of taxa	40	0	26	18	20	3	2	33	43	5	1	16	37	3
pH	7,7	7,0	6,9	7,8	7,6	7,2	8,5	5,7	8,7	nd	nd	6,9	7,6	7,2

Sarawak

	B1	B3	J01	J02	J1	J3	J8	J12	J14	J15	J16	J17	LH1	LH2	LH3	T1	T2
no.of taxa	26	11	22	6	0	0	15	2	0	0	11	50	21	18	12	10	0
pH	7,3	7,5	nd	2,5	5,7	2,3	2,5	nd	7,2	6,5	5,0	5,8	6,9	7,9	nd	8,1	nd

To simplify diversity comparisons, the data were pooled and expressed in terms of species and 'morphotypes' recorded in each of the 31 sample sites. There is considerable variation in algal diversity with no algae detected in samples from six sites (Table II). Four of these six sites are acid water drainage areas (J3), or streams (J1, J14, M2) in spate during or shortly before sampling. There were nine or more species/morphotypes present in over a third of the sample sites, with two ponds (J17, P7) containing a wide range of algal habitats and the most taxonomically diverse (>30 species, 19 genera) of the sample sites.

Systematic list

A listing is given of the algae recorded in the samples collected during February and March 1994. Sample/site codes are indicated. All doubtful species are included and new records are indicated by an asterisk.

Division Chlorophyta

Order Tetrasporales

Gloeocystis sp. J17, LH3

Order Chlorococcales

Ankistrodesmus sp. P7, J17

Cell needle-shaped, ca. 2 µm in diameter and 30 µm in length.

Characium ensiforme Herm. SL4

Coelastrum microporum Näg. J17

Coelastrum (aff. *C. pseudomicroporum* Korshikov) J17

Dictyosphaerium tetrachotomum Printz* var. *minutum* (W.R. Taylor) Komárek J17

Kirchneriella sp. J17

Pediastrum boryanum (Turp.) Menegh.* B3

Pediastrum tetras (Ehrenb.) Ralfs J8, J17

Scenedesmus aculeolatus Reinsch* J17

Scenedesmus (aff. *S. caribeanus* Komárek) J17

Each cell of colony with single short spine, double ridge present.

Scenedesmus obtusus Meyen J17

Scenedesmus quadricauda Chodat (var. *crassicaudatus* Hortob.) f. *granulatus* Hortob.* J16

Scenedesmus quadricauda Chodat B1, J17

Scenedesmus spp. B1, B3, J17, LH1

Three unidentified species or morphotypes: each cell bears a single short spine; each cell bears a single spine, with end cells curved; colony two-celled, short spine on corner of each cell.

Sporotetras? sp. SL4

Gelatinous colony, hemispherical, with cells ca. 8-10 µm in size, slightly depressed and grouped in fours.

Order Chaetophorales

Endoclonium? sp. M1

Filament 3-celled, with cells 9-10 µm in diameter and 36 µm in length, blunt tipped.

Chaetophora elegans (Roth) C. Agardh* SL1

Uronema confervicolum Lagerh.* LH2

Order Oedogoniales

Bulbochaete sp. LH1

Small fragment, developing on surface of petri dish placed for 5 days in water.

Oedogonium spp. M1, M5, P6, SL4, B1, J8, J16, J17, LH2, T1

Eleven morphotypes or size categories recognized: cells ranging from 3-24 µm in diameter and 2-12 times longer than broad.

Order Ulotrichales (= Codiolales)

Ulothrix tenerrima Kütz.* M1, J12

Ulothrix spp. SL5, J17

Two morphotypes: cells ca. 6 µm in diameter, 0.5-1.5 times longer than broad, parietal chloroplast almost filling cell; cells ca. 18 µm in diameter, 0.4-2.0 times longer than broad.

Order Microsporales

Microspora stagnorum (Kütz.) Lagerh.* M1

Order Trentepohliales

Trentepohlia annulata Brand* J02 (sporangia present)

Order Klebsormidiales

Klebsormidium rivulare (Kütz.) Morrison et Sheath* M4, J01, J12, LH2

Lokhorst (1996) considers this taxon to be a freshwater form of the brackishwater *Ulothrix implexa* based upon a morphological examinaton of the type of the latter. Until conclusively proven through experimental culture-based work and ultrastructural investigation, it has been decided not to follow Lokhorst but to regard them as separate taxa.

Order Zygnematales

Cylindrocystis sp. P7

Mougeotia spp. M1, M3, P3, SL4, B1, J02, LH1, LH2

Seven morphotypes recognized: cells range from 5-35 µm in diameter and 3-20 times longer than broad.

Netrium digitus (Bréb.) Itzigs. et Rothe P7

Netrium sp. P6

Each semi-cell narrowing towards pole, ca. 24 µm in breadth and ca. 105 µm in length.

Spirogyra spp. M1, M3, SL4, B1, J8, LH2

Ten morphotypes recognised, with cells ranging from 24-65 μm in diameter and 2-15 times longer than broad, 1-3 chloroplasts per cell and spiralled from 2-20 times.

Zygnema sp. M5

Cells ca. 12 μm in diameter and 0.8-1.5 times longer than broad.

Order Desmidiales

Actinotaenium cucurbitinum (Biss.) Teiling P6, J02

Actinotaenium curtum (Bréb.) Teiling ex Růžička et Pouzar* M1, M4

Actinotaenium turgidum (Bréb.) Teiling ex Růžička et Pouzar* P7

Closterium cornu Ehrenb. ex Ralfs* P6, P7

Closterium dianae Ehrenb. ex Ralfs P7

Closterium jenneri Ralfs SL4

Closterium moniliferum (Bory) Ehrenb. ex Ralfs J17

Closterium navicula (Bréb.) Lütkem. P7

Closterium penjomium D. Williamson sp. nov.* P7 (Fig. 2a, b)

Cellulae modice recurvatae (88°-100° arcus), semicellulis versus extrema attenuatis. Margines interiores nunquam tumidi. Apices truncato-subtruncati, poro extremo prominenti. Uterque semicellulae 3-5 pyrenoides axiales, et 2 chloroplasta visibiles lamellas instructae. Membrana levis atque aut sine colore aut pallide flavo-brunnea. Cingulum taeniae absens. Cellulae 87-100 μm longae et 9.2-10.0 μm latae, 8.7-10.8-plo longiores quam latae, extremis 3.0-3.8 μm latis.

Cells moderately curved (88°-100° arc), with semicells attenuate towards the ends. Inner margin never tumid. Apices subtruncate to truncate with prominent end pore. Each semicell has 3-5 pyrenoids arranged axially, and with two chloroplast lamellae visible. Cell wall smooth and either colourless or of a pale yellow-brown colour. Girdle bands not present. Cells 87-100 μm long and 9.2-10.0 μm wide, 8.7-10.8 times longer than broad, ends 3.0-3.8 μm broad.

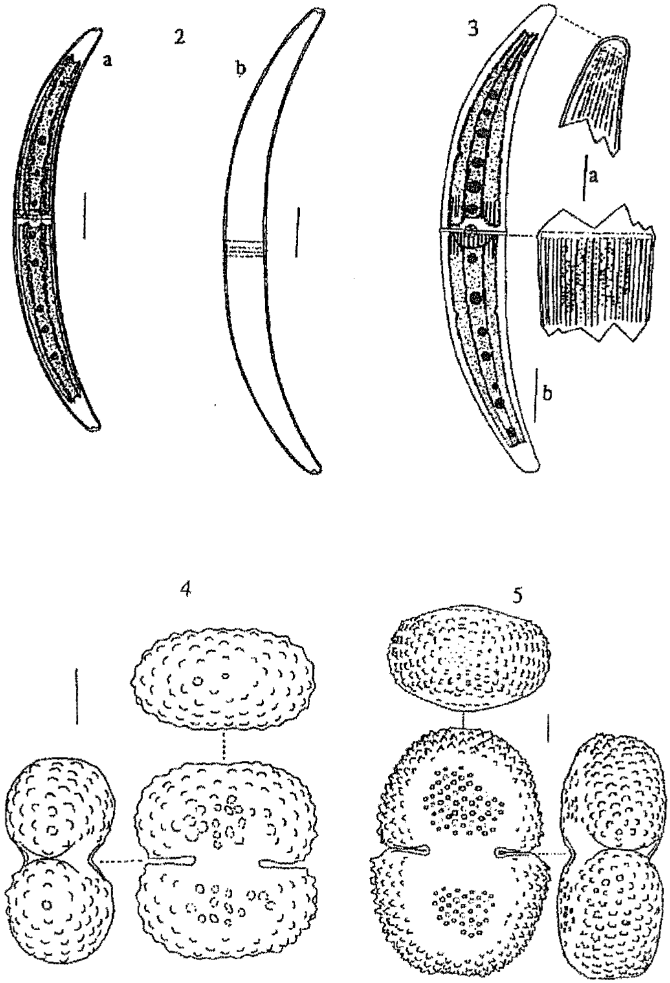
Holotypus: Fig. 2A. Sample from an impoundment lake at Penjom Mine, Pahang State, Peninsula Malaysia, 6 February 1994; collector D.M. John (sample no. 206/N, deposited at BM).

The new species of *Closterium* was moderately common in squeezings of *Chara fibrosa* collected within a small impoundment lake at Penjom Mine (site P7). Two species were considered for its preliminary assignment, *Closterium pulchellum* W. et G.S. West (originally found in the Singapore area, see West & West 1897) and *Closterium abruptum* W. West. In the former, the dimensions closely correspond to it but quite different is the shape of the cells and particularly the apices which are narrowly rounded. *Closterium abruptum* is larger, especially the breadth of the cell and its apices, never possesses an end pore, and usually is more robust and sturdier than the Penjom material. In view of these clear differences it is proposed to consider the Malaysian material as a new and undescribed species.

Closterium ralfsii Bréb. ex Bréb.* var. *hybridum* Rabenh. P7

Closterium striolatum Ehrenb. ex Ralfs P6, P7, J17 (Fig. 3)

Sample J17 contained a very curved form resembling Krieger's var. *borgei* which



Figs 2-5. Fig. 2a, b. *Closterium penjomium* D. Williamson sp. nov.: iconotype (a), scale bar 10 µm; Fig. 3. *Closterium striolatum*. scale bars a = 20 µm, b = 10 µm; Fig. 4. *Cosmarium creperum*, scale bar 10 µm; Fig. 5. *Cosmarium magnificum* forma, scale bar 10 µm.

Růžička (1977, p. 216) refers to *Closterium costatum* Corda ex Ralfs var. *borgei* (W. Krieg.) Růžička because of the absence of girdle bands.

Closterium tumidum Johnson SL4

Closterium venus Kütz. ex Ralfs LH1

Closterium spp. M3, M5, P6, J17, LH2

Five morphotypes not identified to species: cell range from 30-180 μm in length and 9-35 μm in breadth.

Cosmarium binum Nordst.* P7, J17

Cosmarium blytii Wille* M1, P7

Cosmarium contractum Kirchn. var. *pachydermum* Scott et Prescott P7

Cosmarium creperum W. et G.S. West* J17 (Fig. 4)

Cosmarium difficile Lütkem. P7

Cosmarium difficile Lütkem. var. *dilatatum* Borge P7

Cosmarium granatum Bréb. ex Ralfs* P7, J17

Cosmarium hammeri Reinsch* var. *africanum* F.E. Fritsch P7

Cosmarium hammeri Reinsch var. *protuberans* W. et G.S. West M4, M5

Cosmarium magnificum Nordst.* forma SL4 (see Fig. 5)

It was not possible to assign the material to any of the varieties including the type variety.

Cosmarium pseudoexiguum Racib.* P7

Cosmarium quadrum Lund. var. *sublatum* (Nordst.) W. et G.S. West J17

Cosmarium variolatum Lund.* var. *cataractarum* (Racib.) W. Krieg. et Gerloff LH3

Cosmarium spp. MI, P6, J17, T1

Five morphotypes recognized: cells range from 15-35 μm in breadth and 19.0-38.5 μm in length, each truncate or depressed-rounded, with walls smooth or granular.

Euastrum ansatum (Ehrenb.) Ralfs P7

Some cells in sample closely resemble var. *rhomboidale* Ducell.

Euastrum insulare (Wittr.) Roy* var. *lacustre* (Messik.) W. Krieg. P7, J17

Euastrum sinuosum Lenorm. ex W. Archer P7

Euastrum spinulosum Delp.* var. *lindae* Grönblad et Scott P7, SL4

Euastrum sp. (aff. *E. aboense* Elfving) J17

Breadth ca 33 μm, length ca. 60 μm.

Micrasterias radiosa Ralfs* J16

Micrasterias rotata (Grev.) Ralfs ex Ralfs* J16

Pleurotaenium baculoides (Roy et Biss.) Playfair P6

Pleurotaenium ehrenbergii (Bréb.) de Bary P7, LH2

Pleurotaenium ehrenbergii (Bréb.) de Bary var. *curtum* W. Krieg. P6

Pleurotaerium nodosum (Bail.) Lund. J17

*Staurastrum acanthocephalum** Skuja J17 (Fig. 6)

Unusual in that the central ornamentation on the semicells consists of granules/pores.

Staurastrum (aff. *S. avicula* Bréb. ex Ralfs) J17

Staurastrum javanicum (Nordst.) Turn.* var. *apiculiferum* (Turn.) W. Krieg. J17 (Fig. 8)

Staurastrum lapponicum (Schm.) Grönblad* P7, LH1
Staurastrum messikommeri Lund* P7, J17
Staurodesmus cuspidatus (Bréb. ex Ralfs) Teiling* P7
Staurodesmus obsoletus (Hantzsch) Teiling* var. *sitvensis* (Gutw.) Teiling J17 (Fig. 7)
Teilingia granulata (Roy et Biss.) Bourr.* P7
Triploceras gracile Bail.* P6 (Fig. 9)

Order Charales
Chara fibrosa C. Agardh P7, P8, B1

Division Euglenophyta

Order Euglenales
Euglena acus Ehrenb. P6
Euglena (aff. *E. clavata* Skuja) J16
Euglena (aff. *E. mutabilis* Schm.) J8, T1
Euglena spp. P6, B1, J8, J17

Three 'species' or morphotypes are recognized: apex blunt and pointed distally, ca. 12-15 µm in diameter and 20-24(-45) µm in length; apex slightly elongate and pointed distally, ca. 12 µm in diameter and ca. 30 µm in length; spindle-shaped, apex blunt and tapering to distal point, ca. 6 µm in diameter and ca. 22 µm in length.

Lepocinclis ovum (Ehrenb.) Lemmerm. P6
Phacus curvicauda Svirenko P6, J8, J17
Trachelomonas pulcherrima Roll* P6, J17
Trachelomonas superba Svirenko P6, B3
Trachelomonas volvocina Ehrenb. P6, J17

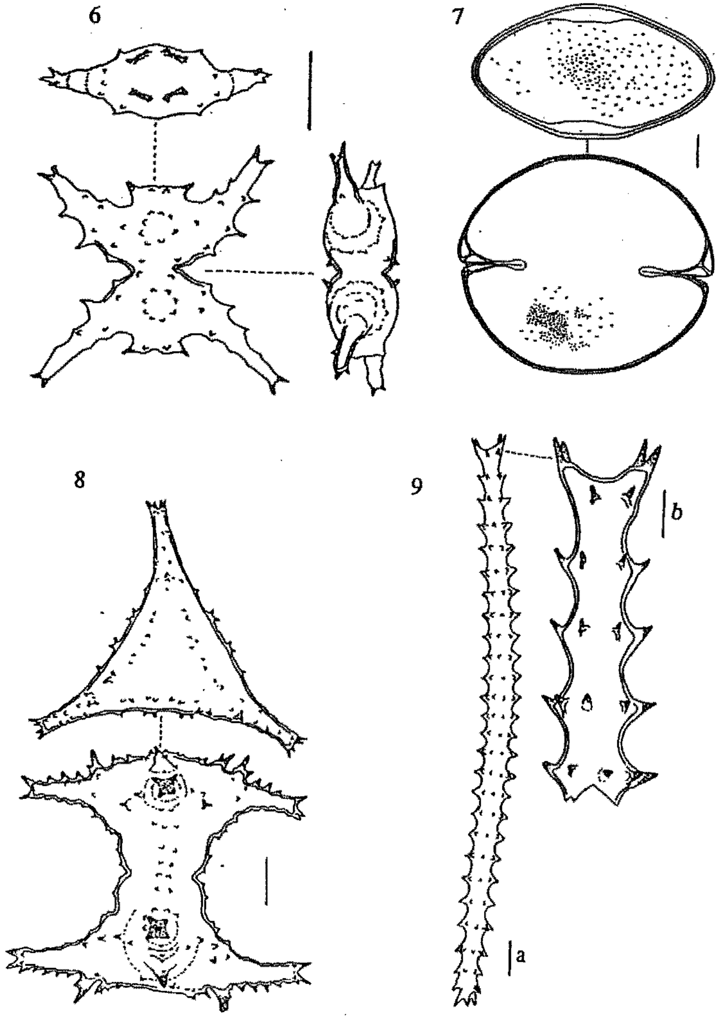
Division Cryptophyta

Order Cryptomonadales
Cryptomonas (aff. *C. ovata* Ehrenb.) P6, J8

Class Dinophyta

Order Peridiniales
Peridinium sp. B3

Distinctive apical notch, ca. 13 µm in diameter and 18 µm long, with armoured plates in two rows in apical region and a single row in distal region.



Figs 6-9. Fig. 6. *Staurastrum acanthocephalum*, scale bar 10 μm; Fig. 7. *Staurodesmus obsoletus* var. *sitvensis*, scale bar 10 μm; Fig. 8. *Staurastrum javanicum* var. *apiculiferum*, scale bar 10 μm; Fig. 9. *Triploceras gracile*, scale bars a = 20 μm, b = 10 μm.

Division Chrysophyta

Order Ochromonadales

Dinobryon bavaricum Imhof SL5

Dinobryon sertularia Ehrenb. P8, SL5

Division Bacillariophyta

Order Pennales

Achnanthes exigua Grunov LH2, LH3

Achnanthes inflata (Kütz) Grunov LH3

Achnanthes lanceolata (Bréb.) Grunov M1, M5, SL1

Achnanthes lanceolata (Bréb.) Grunov var. *rostrata* Hust. SL1

Achnanthes minutissima Kütz.* M1, M3, M4, M5, SL1, SL4, B1, B3, J17, LH1, LH2, LH3

Achnanthes minutissima Kütz. var. *affinis* (Grunov) Lange-Bert. M1, M3, M4, M5, SL1, SL4, B1, B3, J17, LH1, LH2, LH3

Achnanthes minutissima Kütz. var. *gracillima* (F. Meister) Lange-Bert. M1, M3, M4, M5 SL1, SL4, B1, B3, J17, LH1, LH2, LH3

Achnanthes oblongella Østrup* M1, SL1

Achnanthes pusilla (Grunov) De Toni* SL4

Amphora normanii Rabenh. M5

Brachysira serians (Bréb. ex Kütz.) Round et D.G. Mann* P7

Caloneis tenuis (Greg.) Krammer* M4, LH1

Cymbella gracilis (Ehrenb.) Kütz.* SL4

Cymbella minuta Hilse ex Rabenh.* M1, P6, SL4, B3, LH2, LH3

Cymbella silesiaca Bleisch* M1, P7

Cymbella tumidula (Bréb.) van Heurck M1

Cymbella turgidula Grunov* M1, M4, SL4, B3

Eunotia bilunaris (Ehrenb.) Mills* M1, P6, J8

Eunotia hexaglyphis Ehrenb. J8

Eunotia incisa Greg.* M3, SL4, J8, LH3

Eunotia naegelii Migula P6

Eunotia nymanniana Grunov* P6

Eunotia pectinalis (Dillw.) Rabenh. P6, J8

A very slender form found in J8 sample.

Eunotia sudetica O. Müll. J8

Eunotia tridentula Ehrenb.* LH3

Fragilaria tenera W.M. Sm.* SL4

Frustulia rhomboides (Ehrenb.) De Toni P6, SL4, J8

Frustulia rhomboides (Ehrenb.) De Toni var. *crassinervia* (Bréb.) R. Ross P6, P7, SL4, J8

Gomphonema affine Kütz. SL1

Gomphonema angustatum (Kütz.) Rabenh.* M1, M4, SL1, SL4

Cells in sample from M4 do not correspond to any known varieties.
Gomphonema augur Ehrenb. M1, SL1
Gomphonema augur Ehrenb. var. *sphaerophorum* (Ehrenb.) Grunov J17
Gomphonema gracile Ehrenb. Ml, M3, M5, SL4
Gomphonema parvulum Kütz. M1, M4, M5, SL1, SL4, B1, B3
Gomphonema rhombicum Fricke* M1
Gyrosigma spenceri (E.J. Quekett) J.W. Griff. et Henfr.* SL4
Navicula atomus (Kütz.) Grunov* M4
Navicula cryptotenella Lange-Bert.* P6
Navicula dahurica Skvortsov* SL4
Navicula egregia Hust.* P7
Navicula globulifera Hust.* Ml
Navicula heufieriana (Grunov) Cleve* LH3
Navicula hustedtii Krasske SL4
Navicula menisculus G.J. Schumacher* M1, M3, M5, P7, SL4
Navicula minuscule Grunov LH2
Navicula mutica Kütz.* SL1 , B1, J8
Navicula muticoides Hust.* M1, M3, M4, M5, P7, B1
Navicula subtilissima Cleve M1, M3, M4, P6, P7, SL4, LH3
Navicula tridentula Krasske M1, SL4
Navicula viridula (Kütz.) Ehrenb. SL4
Neidium alpinum Hust.* P7
Nitzschia acicularioides Hust.* J8
Nitzschia amphibia Grunov M5
Nitzschia commutata Grunov* M3, SL1
Nitzschia gracilis Hantzsch* M5
Nitzschia intermedia Hantzsch ex Cleve et Grunov* P6
Nitzschia linearis (C. Agardh) W.M. Sm.* SL1
Nitzschia palea (Kütz.) W.M. Sm. M1, M3, M4, M5, P6, P7, SL1, SL4, B1, B3, J17, LH1
Nitzschia sigma (Kütz.) W.M. Sm. SL4
Nitzschia sigmoidea (Ehrenb.) W.M. Sm.* M3
Pinnularia braunii (Grunov) Cleve* M3, SL1, SL4, J8
Pinnularia microstauron (Ehrenb.) Cleve J02
Pinnularia pulchra Østrup* SL1
Pinnularia stomatophora (Grunov) Cleve* M3
Pinnularia subcapitata Greg.* P7

Rhopalodia gibberula (Ehrenb.) O. Müll. M5
Surirella linearis W.M. Sm. M1
Surirella tenuis Mayer* M1
Surirella tenuissima Hust. J8
Synedra acus Kütz.* M1, SL4, J17, LH1
Synedra ulna (Nitzsch) Ehrenb. M1, M5, P6, SL4, B1, B3, LH3
Synedra ungeriana Grunov* M1
Synedra sp. J02

Order Centrales
Aulacoseira granulata (Ehrenb.) Simonsen J17
Cyclotella stelligera Cleve et Grunov* B1
Cyclotella striata (Kütz.) Grunov* B1

Division Rhodophyta
Chantransia-stage? SL1
Cells ca. 7-9 µm in diameter and 2-4 times longer than broad.
Sterile filaments attributable to the life history stage (*Chantransia*-stage) of red algal genus or to the genus *Audouinella* (Order Acrochaetiales).

Order Compsopogonales
Compsopogon caeruleus (Balb. ex C. Agardh) Mont. M1

Order Porphyridiales
Porphyridium sp. P7

Division Cyanophyta (=Cyanobacteria)

Order Chroococcales
Aphanocapsa pulchra (Kütz.) Rabenh.* P6, P7, J16
Chroococcus sp. P7
Merismopedia sp. P7
Gloeocapsa aeruginosa Kütz. P7, T1

Order Oscillatoriales
Lyngbya (aff. *L. allorgei* Frémy) J17
Lyngbya birgei G.M. Sm.* J17
Lyngbya spp. M1, M3, M4, P6, SL1, SL4, B1, B3, J17, LH3, T1
Twenty-six morphotypes or size categories: cells range from 1.5-27.0 µm in diameter and 0.2-6.0 times longer than broad.

Oscillatoria pseudogeminata G. Schmid M3

Oscillatoria princeps Vaucher ex Gomont* B3

Oscillatoria spp. M1, M3, M5, P3, P5, P6, P7, P8, SL4, B1, B3, J16, J17, LH1, LH2, LH3, T1

Twenty-five morphotypes or size categories: cells range from 2-21 μm in diameter and 0.2-3.0 times longer than broad.

Schizothrix (aff. *friesii* Gomont) B1

Several trichomes in each filament, with cells ca. 6 μm in diameter and 2-3 times longer than broad.

Spirulina sp. LH1

Order Nostocales

Calothrix sp. M4

Filament ca. 12 μm in diameter, with cells ca. 6 μm in diameter and 0.2-0.3 times longer than broad.

Hapalosiphon hibernicus W. et G.S. West M1, M5, J8, J16

Scytonema spp. M4, M5, B1, LH1, LH3, T1, T2

Seven morphotypes or size categories: filaments range from 5-20 μm in diameter and cells 0.2-4.0 times longer than broad.

Discussion

In the absence of longer term quantitative data, it is only possible to speculate on reasons for the low diversity or complete absence of algae in drainage areas and stream sites (see Table II). Likely factors are high discharge rates, intermittent flow regimes, absence of suitable microhabitats, low pH and the presence of toxic metal contaminants. The acidity of the water and intermittent flow regime might account for the absence or low algal diversity at drainage sites on the outcrop at Jugan. Undoubtedly scouring of surfaces following torrential rainfall, absence of stable algal attachment surfaces, and the presence of smothering brown flocks of ferric oxide significantly affect stream sites and algal diversity. It is likely that the failure to detect algae in a small dump pond at Jugan Mine (J15) is a consequence of low nutrient levels rather than high concentrations of heavy metals (see Table III). The absence of algae in the Jugan dump pond contrasts with the two biologically diverse ponds sampled at the same mine site (J16, J17).

The high algal diversity of ponds at Jugan (J17) and Penjom (P7) is not unexpected since both contain assemblages of aquatic macrophyte and a wide range of microhabitats. The high diversity at J17 (see Table II) is due to a single group of chlorophytes, the desmids. The pH of the water at the site was 5.8 and desmids are frequently most diverse and abundant in neutral to slightly acidic environments. In the nearby aquaculture pond at Jugan (J16), algal diversity is surprisingly low (9 taxa). High turbidity is just one of several factors accounting for the low diversity. Its nutrient

Table III. The range of pH and dissolved As, Cu and Fe (where measured) in small drainage channels, streams and ponds at each mine or mining prospect. Data in parenthesis are taken from British Geological Survey reports. Metals, mg l^{-1}, no data, nd.

	pH	As	Cu	Fe
Mengapur				
streams	6.9-7.8	nd		
	(5.5-7.1)	(<0.001-0.080)		
Penjom				
streams	7.2-12.2	nd		
	(2.5-5.0-7.1)	(<0.001-1.275)		
ponds	5.7-8.7	nd		
	(2.5-7.2)	(0.003-1.970)		
Sungai Luit				
streams	6.9-7.6	nd		
	(5.5-6.2)	(<0.00 1-0.009)		
Bidi (Kusa)				
ponds	7.3-7.5	0.060-0.120	<0.020	0.100-0.200
pond/stream	(6.1-6.4)	(0.941-1.129)	(<0.007)	(<0.001)
Jugan				
drainage areas	2.3-2.5	0.080-1.590	0.040-4.940	0.300->500
on outcrop	(2.2-2.8)	(0.101-0.939)	(0.506-1.026)	(0.422-0.675)
streams	3.8-7.2	<0.050	<0.020-0.650	<0.001-0.076
	(2.5-6.5)	(<0.001-0.016)	(0.007-0.176)	(<0.001-0.063)
ponds	5.0-6.5	nd	nd	nd
Lucky Hill				
pond	6.9	<0.050	<0.020	2.400
	(6.9)	(0.144)	(<0.007)	(<0.001)
stream	7.9	<0.050	<0.020	2.100
	(6.9)	(0.713)	(<0.007)	(<0.001)
Tai Ton				
pond	8.1	<0.050	<0.020	0.580
	(7.4-7.6)	(0.439-0.751)	(<0.007)	(0.0001-00004)

status is artificially enhanced compared to other sites and its biological productivity high to judge from the abundance of grazing copepods. The turbidity is accounted for by the high population density of bottom-feeding fish bringing bottom sediments into suspension as well as the abundance of planktonic organisms.

Devoid of algae was a sample from a drainage area (J3) on the Jugan outcrop where the seepage was very acidic (pH 2.3) and levels of arsenic and copper elevated (see Table III). Other drainage areas at Jugan Mine (J8, J12), with pHs from 2.5-6.8, were characterized by luxuriant growths of the green filamentous chlorophyte *Klebsormidium rivulare*. In studies of mine sites in North America and Europe, this *Klebsormidium* (often reported as *Hormidium*) is one of several algae characterizing acid drainage water sites (see Whitton & Diaz 1981). Its absence from site J3 cannot be accounted for by low pH and is more likely a consequence of an intermittent flow regime. Bleached mats of *Klebsormidium* are common on the outcrop and provide evidence of the presence of formerly flowing drainage areas. The ability of *Klebsormidium* to survive and reproduce in metal-contaminated water has been demonstrated experimentally to be the result of genetic adaptation (Say & Whitton 1977).

Table IV. List of taxa found in Peninsula Malaysia and Sarawak growing at pH 5 and below. The pH range of waters from which each taxon was collected is indicated.

Taxa	pH
Chlorophyta	
Pediastrum tetras	5.0-5.8
Oedogonium sp.	5.0-7.6
Ulothrix tenerrima?	2.5-7.7
Klebsormidium rivulare	2.5-7.9
Mougeotia sp.	2.5-7.7
Spirogyra sp.	5.0-7.7
Actinotaenium cucurbitinum	2.5-5.7
Euglenophyta	
Euglena (aff. *mutabilis*)	5.0-8.1
Phacus curvicauda	5.0-5.8
Cryptophyta	
Clyptomonas sp.	5.0-5.7
Bacillariophyta	
Eunotia bilunaris	5.0-7.7
E. hexaglyphis	5.0
E. incisa	5.0-7.6
E. pectinalis	5.0-5.7
E. pectinalis (slender form)	5.0
Frustulia rhomboides	5.0-7.6
F. rhomboides var. *crassinervia*	5.0-8.7
Navicula mutica	5.0-7.3
Nitzschia acicularioides	5.0
Pinnularia braunii	5.0-7.6
P. microstauron	2.5
Surirella tenuissima	2.6
Synedra sp.	5.0
Cyanophyta	
Oscillatoria sp.	5.0-8.7
Hapalosiphon hibernicus	5.0-7.7

An assemblage of algae frequently associated with acid-drainage in America and Europe was discovered at one site at Jugan (J8) where the pH was 2.5 (Table II). Outside Malaysia the assemblage is often reported from acid waters (see Whitton & Diaz 1981), often tolerating a pH below 3. Three of the diatoms (*Eunotia hexaglyphis, Nitzschia acicularioides, Surirella tenuissima*) found at J8 are new records for Malaysia. Of particular note is the presence of *Hapalosiphon hibernicus* and an unidentified *Oscillatoria* (cells ca. 3 µm in diam., (2.5-)3-6 times longer than broad) at J8 since cyanophytes are rarely reported in water with a pH below 5. Considerable doubt attaches to reports such as the one by Warner (1971) of an *Oscillatoria* growing in an Ohio, USA where the pH was less than 2.8. The site J8 is a ditch supplied by seepage water when sampled although at other times it receives nutrient-rich overflow water from a fish pond (J16). The same two cyanophytes were also discovered in the pond suggesting it to be the source of the material sampled in the ditch. It is impossible to determine whether the cyanophytes in the ditch were living or moribund when sampled.

The ability of certain algae to tolerate low pH and elevated levels of potentially toxic heavy metals makes them useful indicators of acid-mine drainage. It is therefore possible to relate the distribution patterns of such algae to pH and elevated levels of metals. Often causality needs to be established through meticulously planned programmes of laboratory experiments designed to test the tolerance limits of species and strains. There is often lacking information on intrinsic and extrinsic factors accounting for inter- and infraspecific differences in the sensitivity of algae to key environmental variables. The large majority of algae recorded from acid mine drainage sites in Malaysia are known to tolerate still lower pHs (<pH 4) in Europe and North America (e.g., *Neidium alpinum, Frustulia rhomboides, Gomphonema parvulum,* several *Eunotia* spp.). Whitton (1983) points out just how impossible it is to make generalizations concerning the pH and metal tolerances of algae because of the difficulty of separating acidity from multimetal toxicity effects.

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