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Free-living Heterotrophic Stramenopile Flagellates from Gippsland Basin, South-eastern Australia

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Free-living heterotrophic stramenopile flagellates, which lack chloroplasts, were encountered in deep-sea sediments of Gippsland Basin (Australia) and classified into 10 species (8 genera, 5 families, 3 orders). Their descriptions were based on living specimens by light microscopy. Those species rarely found in this study were *Bicosoeca gracilipes*, *Caecitellus parvulus*, *Cafeteria minuta*, *Cafeteria roenbergensis*, *Pseudobodo tremulans*, *Spumella* sp., *Paraphysomonas* sp., *Actinomonas mirabilis*, *Ciliophrys infusionum* and *Developayella elegans*. Their morphological characters and geographic distribution are presented.

Key Words: Bicosoecida, Chrysophyceae, heterokont, Protista, Silicoflagellata, stramenopiles

INTRODUCTION

Stramenopiles was introduced as a rankless informal name (Patterson 1989), but usually included among the Protista. Some workers have sought to apply a rank (Kingdom Chromista or Kingdom Stramenopila, Beakes 1998). This group is one of the main groups of eukaryotes, comprising a photosynthetic group with chloroplast and a heterotrophic group. Most forms have flagellar in a unique arrangement, called heterokont. Heterokont forms are characterised by having two unequal flagella, which incerted subapically or laterally. The anterior flagellum extends forward and is covered by mastigonemes which have a unique tripartite structure (e.g., Patterson 1999). When the flagellum moves, these make a backwards current, pulling motile cells forwards and allow particles which impringe on the body surface to be ingested (Patterson and Larsen 1991). The posterior flagellum is smooth and usually shoter than the anterior one. But some species (e.g. *Caecitellus parvulus*) do not have the typical heterokont organization in flagellate cells, but their relationship with other stramenopiles is supported by structural and molecular studies (e.g. O'Kelly and Nerad 1998).

The following references are useful guides to general informations of stramenopiles: Lee *et al.* (2000), Patterson (1989) and Preisig *et al.* (1991). In this study, among the stamenopiles, 10 species of heterotrophic stramenopile flagellates are reported from deep-sea sediments of Gippsland Basin, south-eastern Australia.

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MATERIALS AND METHODS

Gippsland Basin is located in south-eastern Australia (37° 59′S - 38° 49′S; 147° 21′E - 148° 42′E). A large wedge of sediments has been accumulated in the last 30 million years in the Basin (Wilson and Poore 1987). This study was conducted from 18 Sep. 1998 to 5 Oct. 1998 in Gippsland Basin as a part of the *R/V Franklin* Cruise (Fr 11/98) by CSIRO. Samples were collected from bottom sediments with a Smith-McIntyre grab sampler and sampling depths vary from 25 m to 471 m. After collecting, the samples were kept cool (~ 4°C) and then were transported to the University of Sydney for analysis. The samples were processed as described by Lee and Patterson (2000). The samples were placed in plastic trays in 1 cm deep layers. The sediments were covered with lens tissue and No. 1 22 x 22 mm coverslips were placed on the lens tissue. After 12-24 hours the coverslips were removed and flagellates were observed using a Zeiss Axiophot microscope equipped with photographic facilities. The flagellates were also recorded on U-MATIC video tapes and records were also made with video prints. Specimens were also drawn. The samples were maintained at room temperature (~20°C) for 2 weeks.

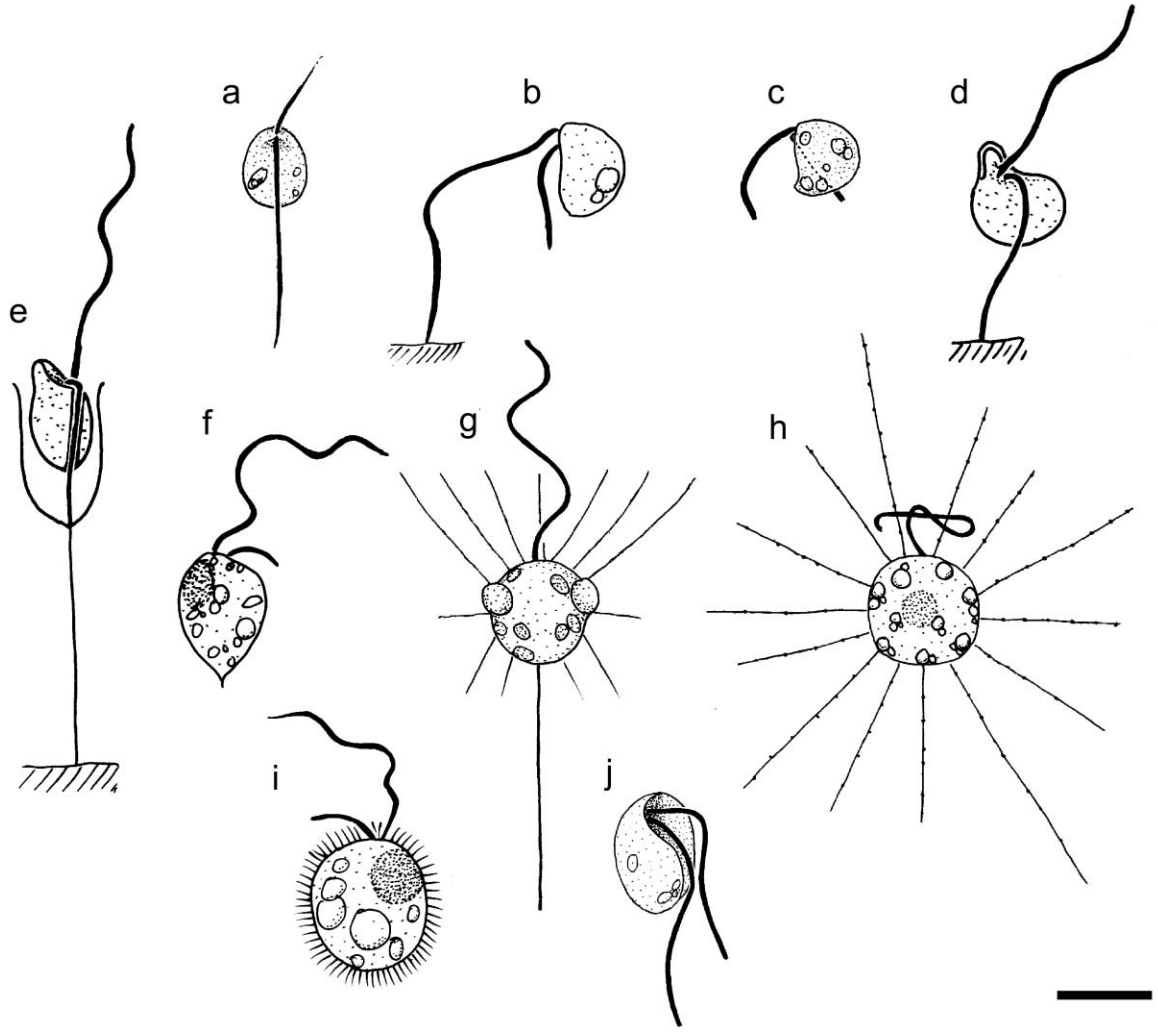

Fig. 1. (a) *Caecitellus parvulus* after Lee and Patterson (2000), (b) *Cafeteria minuta*, (c) *Cafeteria roenbergensis* after Lee and Patterson (2000), (d) *Biocosoeca gracilipes* after Lee and Patterson (2000), (e) *Pseudobodo tremulans*, (f) *Spumella* sp., (g) *Pteridomonas danica*, after Lee and Patterson (2000), (h) *Ciliophrys infusionum* after Lee and Patterson (2000), (i) *Paraphysomonas* sp., (j) *Developayella elegans* after Lee and Patterson (2000), Scale bar = 5 μm.

RESULTS AND DISCUSSION

The nomenclature of some of the groups represented in this study has been in compliance with the ICZN (International Code of Zoological Nomenclature 1999). The scheme of classification by Lee *et al.* (2000) was adopted.

Stramenopiles Patterson 1989
Order Bicosoecida Grassé 1926
Family Bicosoecaceae Moestrup 1995
Genus *Bicosoeca* James-Clark 1867

***Bicosoeca gracilipes* James-Clark 1867 (Fig. 1e)**

Description: Cells are oval and 3.5-5 μm long in a cylindrical lorica about 9 μm long. There is a fold or ridge at the anterior end of the cell. Two flagella insert near the base of the fold or ridge. The front flagellum is about 15 μm long and beats with a sine-wave, and the posterior flagellum is about 1.5 times the cell length, lies in a ventral groove and attaches to the lorica. The lorica attaches to the substratum using a stalk, which is about 3 times the cell length. Rarely observed and found in the depths of 62-88 m.

Remarks: This species has been reported from marine sites at Australia, England, Gulf of Elat and USA (Al-Qassab *et al.* 2002; James-Clark 1867; Kent 1880-1882; Lee *et al.* 2003; Thomsen 1978; Tong 1997b; Tong *et al.* 1998; Wailes 1929, 1939). The identities of species in *Bicosoeca* are not clear because nominal species are frequently distinguished by minor differences in cell or lorica size or shape (Tong 1997a). The aperture of the lorica is needed

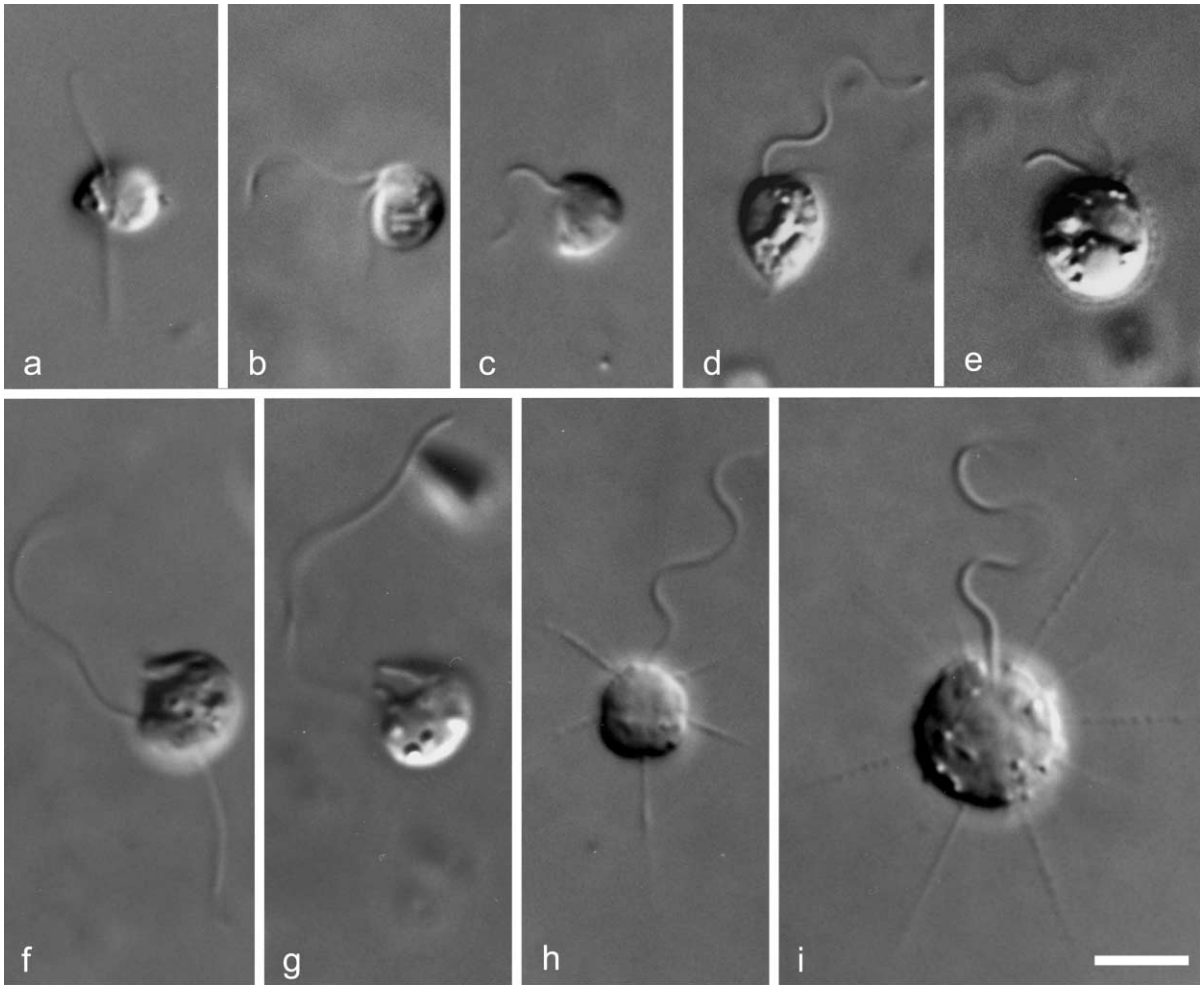

Fig. 2. (a) *Caecitellus parvulus*, (b) *Cafeteria minuta*, (c) *Cafeteria roenbergensis*, (d) *Spumella* sp., (e) *Paraphysomonas* sp., (f)-(g) *Pseudobodo tremulans*, (h) *Pteridomonas danica*, (i) *Ciliophrys infusionum*. All micrographs are DIC images. Scale bar = 5 μm.

to identify the species. Generally, the observations are in agreement with those of Tong (1997b) and Tong *et al.* (1998). *Bicosoeca gracilipes* is similar to *B. vacillans* Ŝtolc 1888 in having a cylindrical lorica, but can be distinguished by the smaller size - *B. vacillans* has a lorica that is 17-25 μm long. *Bicosoeca gracilipes* is distinguished from *B. conica* Lemmermann 1914 by its cylindrical lorica, and from *B. epiphytica* Hilliard 1971 by its smaller size of lorica and cell.

Family Cafeteriaceae Moestrup 1995

Genus *Caecitellus* Patterson *et al.* 1993

***Caecitellus parvulus* (Griessmann 1913) Patterson *et al.* 1993 (Figs 1a, 2a)**

Basionym: *Bodo parvulus* Griessmann 1913

Description: Cells are 4-4.5 μm long and somewhat triangular or rounded. There is a mouth protruding on the right ventral side of the cell. The cells have two flagella; the acronematic anterior flagellum beats slowly and stiffly with a small excursion, and inserts apically. It is about 1.5 times the cell length. The non-acronematic posterior flagellum is 2-2.5 times the cell length, emerges from the ventral face of the cell and trails under the body. The cells move slowly by gliding with the anterior flagellum in close contact with the substrate. Rarely found in the depths of 18-55 m.

Remarks: The size ranging 2 to 7 μm has been reported in previous studies. *Caecitellus parvulus* has been found in Australia, North Atlantic, Brazil, Danish Wadden Sea, England and equatorial Pacific (e.g., Al-Qassab *et al.* 2002; Lee 2006; Lee and Patterson 1998, 2000; Lee *et al.* 2003; Patterson *et al.* 1993). Generally, the observations of this organism are in agreement with those of Larsen and Patterson (1990) of the organisms reported under the name *Bodo parvulus*. *Caecitellus parvulus* is characterized by the protrusion on the ventral side of the cell, the beat pattern and the insertion of the flagella. This species is similar to *Glissandra innurende*

Patterson and Simpson 1996 in having a protrusion (mouth) on the ventral side (see Remarks to *Glissandra innurende*), but can be distinguished by the beating pattern of the anterior flagellum and the insertion of the flagella. Recent ultrastructural work suggests that *Caecitellus* is a stramenopile or is related to the stramenopiles (O'Kelly and Nerad 1998).

Genus *Cafeteria* Fenchel and Patterson 1988

***Cafeteria minuta* (Ruinen 1938) Larsen and Patterson 1990 (Figs 1b, 2b)**

Description: Cells are 4-6 μm long with a small ventral groove. Two flagella emerge from the anterior end of the groove. The long anterior flagellum is 2.5-4 times the cell length and beats with a sine-wave, and the posterior flagellum is 1-1.5 times the cell length. When the cells swim, the anterior flagellum is directed forward and the posterior one trails. The cells may attach to the substrate by the tip of the posterior flagellum. Commonly observed and found in the depths of 25-471 m.

Remarks: This species has been reported from marine sites in Australia, Belize, Brazil, India and Portugal (Larsen and Patterson 1990; Ruinen 1938; Tong *et al.* 1998; Vørs 1993). It is similar to *Cafeteria roenbergensis*, but is distinguished by the longer anterior flagellum relative to the cell and because the anterior flagellum of *C. roenbergensis* is curved over the body when attached. *Cafeteria minuta* can be distinguished from *Pseudobodo tremulans* by the lack of the anterior collar. This species is mostly similar to *Placidia cafeteriopsis* Moriya *et al.* 2002, but can be distinguished by the long anterior flagellum of *C. minuta* (Moriya *et al.* 2002). *Cafeteria* species attach to the substratum by only half of the posterior flagellum, but *P. cafetriopsis* attaches to it by the distal half of the posterior flagellum (Moriya *et al.* 2002). *Cafteria minuta* is similar to *Halocafeteria seosinensis* Park *et al.* 2006, but can be distinguished because *H. seosinensis* has a jumping motion (Park *et al.* 2006).

***Cafeteria roenbergensis* Fenchel and Patterson 1988 (Figs 1c, 2c)**

Description: Cells are D-shaped, 2-5 μm long, and laterally compressed. There is a shallow groove on the left side of the cell. Two flagella of similar length emerge subapically and are slightly longer than the cell. The anterior flagellum is directed perpendicular to the ventral face of the cell when attached. The posterior flagellum is reflexed, passing over one face of the cell and then attaching to the substrate by the tip. In swimming cells, the anterior flagellum is directed forwards and beats with a sine-wave, and the posterior flagellum is directed backwards and trails. Usually the cells move fast following a spiral path, but sometimes move slowly. Bacteria may be ingested near the anterior part or posterior part of the ventral groove. Found in the depths of 52-55 m.

Remarks: Generally, the observations are consistent with descriptions of Fenchel and Patterson (1988) and Larsen and Patterson (1990). Previous studies reported the size range to be 1.5-10 μm (e.g., Al-Qassab *et al.* 2002; Bernard *et al.* 2000; Fenchel and Patterson 1988; Lee 2002, 2006; Lee and Patterson 1998, 2000; Lee *et al.* 2003). This species has been found from marine sites in Antarctica, Australia, North Atlantic, Baltic, Denmark, England, Gulf of Finland, Greenland, Korea and equatorial Pacific. This species resembles *Cafeteria minuta* (Ruinen 1938) Larsen and Patterson 1990 in general appearance, but is distinguished because *C. minuta* has a longer anterior flagellum. *Cafeteria roenbergensis* resembles *C. marsupialis* Larsen and Patterson 1990 in general appearance and in having a short anterior flagellum, but *C. marsupialis* is larger and has a more strongly developed ventral groove with a posterior channel leading into the cell. It may not be clearly distinguished from *Acronema sippewissettensis* (Teal *et al.* 1998), which has acronematic flagella and is regarded as a synonym.

Genus *Pseudobodo* Griessmann 1913

***Pseudobodo tremulans* Griessmann 1913 (Figs 1d, 2f-g)**

Description: Cells are 4.5-6 μm long with an anterior collar around the anterior part of the cell in unstressed feeding cells. The insertion sites of the two flagella are separated by a protrusion at the anterior of the cell. The anterior flagellum has a sine-wave beating pattern and is about 3.5 times the length of the cell, and the posterior flagellum is about twice the length of the cell and may attach to the substrate by its tip. When the cells move, the anterior collar may be hard to see. The cells move by swimming with the anterior flagellum directed forwards. Found in the depths of 25-471 m.

Remarks: *Pseudobodo tremulans* was reported to be 2 to 8 μm long and has been found in marine sites in Antarctica, Australia, Brazil, Denmark, Hawaii and Korea (e.g., Griessmann 1913; Larsen and Patterson 1990; Lee 2002, 2006; Lee and Patterson 1998, 2000; Lee *et al.* 2003). This species mostly resembles *Monas neglecta* James-Clark 1867 in cell shape and cell length and in having an anterior collar. *Monas neglecta* is regarded as a senior synonym of *P. tremulans* (Lee 2002). *Pseudobodo*

tremulans may be confused with *Cafeteria minuta* (Ruinen 1938) Larsen and Patterson 1990 because both have a long anterior flagellum, but can be distinguished by a collar (mouth) around the anterior part of the cell in unstressed feeding cells.

Class Chrysophyceae Pascher 1914
Order Chromulinales Pascher 1910
Family Chromulinaceae Ehrenburg 1897
Genus *Spumella* Cienkowsky 1870

***Spumella* sp. (Figs 1f, 2d)**

Description: Cells are ovoid and 6-8 μm long. Two flagella emerge from a shallow subapical depression and are of unequal length. A long flagellum is directed anteriorly and is 2-3 times the cell length. A short flagellum is 0.3-0.6 times the cell length and directed laterally. A nucleus is located broadly anteriorly. The cells swim fast and occasionally attach to the substrate by the pointed posterior end of the cell. The cells contained small granules throughout the cell. No chloroplasts and body scales are seen. Observed commonly and found in the depths of 25-276 m.

Remarks: Generally, the observations are in accord with the identity of the genus by Preisig *et al.* (1991). The taxonomic history of the genus is very confused and *Monas* Müller 1773 is regarded as a senior synonym of *Spumella* Cienkowsky 1870 (Preisig *et al.* 1991). This genus has usually been found at freshwater sites, but there are some records from marine sites (e.g., Bernard *et al.* 2000; Daugbjerg *et al.* 1991; Vørs 1990).

Family Paraphysomonadaceae Preisig and Hibberd 1995
Genus *Paraphysomonas* De Saedeleer 1929

***Paraphysomonas* sp. (Figs 1i, 2e)**

Description: Cell is spherical and about 7.5 μm long with two flagella of unequal length. The cell appears to be covered with double layers of silica scales. The long flagellum is about 2.5 times the length of the cell, and the short flagellum is about 0.5 times the length of the cell and held laterally. A nucleus is located anteriorly. One cell was found in the depth of 37 m.

Remarks: The only species in *Paraphysomonas* with visible scales under light microscopy, which have been described to date, are *P. gladiata* Preisig and Hibberd 1982, *P. imperforata* Lucas 1967 and *P. vestita* (Stokes 1885) De Saedeleer 1929. The cell described here had visible scales and the outer layer of the scales may be formed by spines, but the cell could not be identified because species of *Paraphysomonas* have been identified on the basis of the ultrastructural features of the body scales (Preisig and Hibberd 1982a, b, 1983).

Class Silicoflagellata Lemmermann 1901
Order Pedinellids Zimmermann, Moestrup and Hällfors 1984
Family Actinomonadidae Kent 1880
Genus *Pteridomonas* Penard 1890

***Pteridomonas danica* Patterson and Fenchel 1985 (Figs 1g, 2h)**

Description: Cells are 5-6 μm long and have one flagellum emerging from a small depression in the anterior end of the cell. The cells have a ring of arms around the flagellum and below the equator of the cell; the arms around the flagellum are evenly spaced. The anterior part of the cell is slightly broader than the posterior part. The single thickened flagellum is 3-5 times the cell length and has an undulating beat. The cells usually swim rapidly, but occasionally attach to the substrate with a long posterior stalk trailing. Small particles are seen on the cell surface. Commonly observed and found in the depths of 39-467 m.

Remarks: *Pteridomonas danica* Patterson and Fenchel 1985 has been described from Australia, Brazil, Canada, Denmark, England, Fiji, Greenland, Hawaii, Japan, Korea and the equatorial Pacific, and has lengths ranging from 3.5 to 6.5 μm (e.g., Al-Qassab *et al.* 2002; Lee 2002, 2006; Lee and Patterson 1998, 2000; Lee *et al.* 2003; Patterson and Fenchel 1985; Sekiguchi *et al.* 2002). According to previous authors, swimming cells may withdraw tentacles or arms and the stalk may be variable in length. At the ultrastructural level, *Pteridomonas danica* can be distinguished from *Actinomonas mirabilis* because *P. danica* has flagellar transitional bands (Larsen 1985; Larsen and Patterson 1990; Patterson and Fenchel 1985). At the light microscopical level, *P. danica* and *A. mirabilis* are very similar and are difficult to distinguish with confidence. *Actinomonas mirabilis* more frequently has posterior or lateral arms and two anterior wreaths of arms; it typically has a more substantial flagellum.

Genus *Ciliophrys* Cienkowski 1876

***Ciliophrys infusionum* Cienkowski 1876 (Figs 1h, 2i)**

Description: In the heliozoan stage the cells are 4-9 μm across, and have a central nucleus and one flagellum held in a figure of eight (8). The cells are spherical with delicate pseudopodia extending radially from the body and bearing extrusomes. The cells may change from the

heliozoan stage with pseudopodia and a slow beating flagellum to a swimming flagellate without pseudopodia and with the flagellum beating rapidly. In swimming cells, the nucleus is located apically. When feeding, bacteria adhere to the pseudopodia and then are drawn to the body. Found in the depths of 39-242 m.

Remarks: *Ciliophrys infusionum* has been found at marine sites in south-eastern North America, Australia, Denmark, England, English Channel, Fiji, Gulf of Finland, Hawaii, Japan, Korea, Mediterranean, Norway and equatorial Pacific, and lengths of 3.5 to 20 μm have been reported (e.g., Al-Qassab *et al*. 2002; Lee 2002, 2006; Lee and Patterson 1998, 2000; Lee *et al*. 2003; Sekiguchi *et al*. 2002). Generally, the cell described here is in agreement with observations by Larsen and Patterson (1990). This species is similar to *Massisteria marina* Larsen and Patterson 1990, but can be distinguished by its regular symmetry and stiff pseudopodia, and by not being adpressed to the substrate and by having one flagellum. It resembles small heliozoa in having pseudopodia extending radially from the body, but is distinguished by having a flagellum. *Ciliophrys infusionum* is distinguished from the recently described *C. azurina* because the latter has peripheral nuclear material and tapering arms (Mikrjukov and Patterson 2001). *Ciliophrys marina* Caullery 1909 and *Dimorpha monomastix* Penard 1921 are synonyms of this species.

Stramenopiles *incertae sedis*

Genus *Developayella* Tong 1995

***Developayella elegans* Tong 1995 (Fig. 1j)**

Description: Cell outline is oval. Cells are 3.2-5 μm long and with two flagella emerging from a depression in the right anterior part of the ventral side of the cell. The anterior flagellum is about 1.3 times the length of the cell and the posterior flagellum is 1.5-1.7 times the length of the cell. The cells attach to the substrate by means of the posterior flagellum. In attached cells the anterior flagellum is held in a curve and beats slowly up and down, and the posterior flagellum beats rapidly with a shallow excursion. The cells move by swimming. Food ingestion takes place near the posterior end of the ventral groove. When feeding, the bacterium adheres to the body and then is drawn into the body. Rarely observed and found in the depths of 60-467 m.

Remarks: *Developayella elegans* has been described from subtropical Australia, England and Korea, and the cell length had been reported to range from 3.5 to 10 μm (e.g., Al-Qassab *et al*. 2002, Lee 2002, 2006; Lee and Patterson 1998, 2000; Tong 1995). Generally, the observations are in accord with the descriptions of Tong (1995). When *D. elegans* attaches to the substrate, it is recognised from other free-living flagellates, such as *Cafeteria*, *Colponema*, *Jakoba* and *Phyllomitus*, which have a large ventral depression and the different beating patterns of the two flagella - the anterior flagellum beats slowly up and down and the posterior flagellum beats rapidly with small excursion.

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