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Article

Synura cronbergiae sp. nov., a new species described from two paleogene maar lakes in northern Canada

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With 2 figures and 1 table

Abstract: A new species representing the genus *Synura*, *S. cronbergiae*, is described from two Paleogene maar lakes situated near the Arctic Circle in northern Canada. The new taxon is characterized by long, slender, siliceous scales each bearing a small forward projecting spine, a base plate with evenly spaced pores and a secondary layer consisting of hexagonal chambers. Each chamber encloses a base plate pore, opens dorsally via a small pore, and collectively the chambers fuse to form a continuous secondary layer. Although *S. cronbergiae* is believed most closely related to species in the Sectio Synura due to the presence of a distal spine and lack of a median keel, scales superficially resemble those from a rare species in the Sectio Petersenianae, *Synura longisquama*. The potential evolutionary history, in the context of the genus, is discussed.

Key words: *Synura*, synurophytes, Paleogene, Eocene, new species.

Introduction

The genus *Synura*, first described by Ehrenberg in 1834, consists of 41 taxa in three sections based on descriptions made with a combination of light and electron microscopy (Škaloud et al., 2012). The three sections, Sectio Synura, Petersenianae and Lapponica, are distinguished largely based on whether the taxa form scales with forward-projecting spines, a median keel or a large central papillae, respectively. Of the 41 taxa, 24 belong to the Sectio Synura, 16 to Sectio Petersenianae, and a single species comprises the Sectio Lapponica.

Andersen (1987) established the Class Synurophyceae with one order, the Synurales, that included single-celled (family Mallomonadaceae Diesing) and colonial (family Synuraceae Lemmermann) chrysophyte flagellates with a cell covering of precisely arranged siliceous scales. The status of the Synurophyceae as a separate class based on molecular gene sequences is, however, in question. Cavalier-Smith & Chao (2006)

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concluded that the group did indeed form a distinct lineage, but at the ordinal level within the Class Chrysophyceae, and not as a separate class. Using four nuclear gene sequences, Grant et al. (2009) also found the synurophytes to form a clade within the Chrysophyceae. The vast majority of taxa in the Synurophyceae are within the genera *Mallomonas* and *Synura*. Jo et al. (2011) reported that relationships among *Mallomonas* species based on a combination of nuclear and chloroplast genes tracked nicely scale and bristle ultrastructure characters. A similar analysis has yet been completed for *Synura*, however, in a study using only the chloroplast gene *rbc*L the genera *Synura* and *Mallomonas* were not resolved (see supplemental material in Young et al., 2012). It remains to be seen if the two genera, as well as the sections within *Synura* based on scale morphology, will be resolved using multiple molecular sequences that also include nuclear genes.

The genus *Synura* has a global distribution and is an important component of phytoplankton communities in numerous freshwater localities (Siver, 2003). Species of *Synura* can be found over a broad spectrum of environmental conditions, with highest concentrations most often found under cooler and acidic conditions (Kristiansen, 1975; Siver, 1987; Siver, 2003). Many species of *Synura* are differentially distributed over environmental gradients, especially temperature, nutrient and pH gradients, making them excellent bioindicators (Siver, 2003). Coupled with the fact that the siliceous scales can remain in sediments for tens to millions of years, species can also be effectively used to reconstruct historical conditions (Siver, 2003; Stevenson & Smol, 2003).

Due to a poor fossil record, very little is known about the evolutionary history of *Synura*. Siver & Wolfe (2005a) described a fossil species of *Synura*, *S. recurvata*, from a middle Eocene maar lake known as Giraffe Pipe. In many respects, scales of *S. recurvata* resembled those of *Synura uvella*, the type species for the genus. More recently, Boo et al. (2010) reported additional *Synura* taxa from the same Eocene deposit, including another species within the Sectio Synura and one within the Sectio Petersenianae. The purpose of this paper is to formally describe the extinct taxon noted by Boo et al. (2010) from the Sectio Synura based on numerous additional observations from the Giraffe Pipe locality and ones from an older Paleocene deposit known as Wombat. The relationship of the fossil taxon relative to modern species is discussed.

Materials and methods

Mudstone or rock chips (0.1–0.5 g) from the Giraffe and Wombat cores were oxidized using 30% H_2O_2 under low heat for a minimum of an hour, rinsed with distilled water, and the resulting slurries stored in glass vials. This procedure results in separation of numerous siliceous microfossils from the mudstone or rock matrix as well as intact fragments each containing many embedded microfossils. Aliquots of each slurry were air dried onto pieces of heavy duty aluminum foil. The aluminum foil samples were trimmed, attached to aluminum stubs with Apiezon® wax, coated with a mixture of gold and palladium for 2 min with a Polaron Model E sputter coater, and examined with a Leo 982 field emission scanning electron microscope (SEM). The sizes of specimens were measured during examination with SEM.

Each sample from the Giraffe and Wombat cores is identified with a three-part number. The first number represents the core box. Deeper sections of the core correspond to larger box numbers. Each box contains three (Giraffe) or four (Wombat) 1.5 m core lengths, identified as channels 1, 2, 3 and 4. The second part of the number represents the channel. The third number represents the length in cm measured down from the top of a core length. Thus, sample 20-2-31 represents a sample taken from

31 cm down along the core length positioned in channel 2 from box 20. The lacustrine phase of the Giraffe Pipe maar lake is contained within boxes 26 (deepest) to 11 (youngest). The lacustrine phase in Wombat is considerably longer, approximately 23 boxes in length, but has not yet been completely determined. The current investigation is based on examination of 11 samples from boxes 13–15 of the Giraffe core and five samples from box 65 of the Wombat core. The estimated depth of each sample within the lake contained in the Giraffe core, measured downward from the point where the aquatic phase transitions to the overlying terrestrial phase, is given.

Site descriptions

GIRAFFE PIPE: The Giraffe Pipe locality (64°44'N, 109°45'W) is a kimberlite diatreme located in the Lac de Gras region of the Northwest Territories, Canada, that was emplaced into the Slave Craton approximately 47.8 million years ago during the Middle Eocene (Siver & Wolfe 2005b; Wolfe et al. 2006). The diatreme crater subsequently filled with water, becoming a maar lake and slowly infilled with a sequence of lacustrine, then paludal sediments, and was later capped by a thick layer of Neogene glacial deposits (Siver & Wolfe 2005b; Wolfe et al. 2006). The Giraffe Pipe is one of many kimberlites in the Lac de Gras field, most of which have Cretaceous or Paleogene emplacement ages (Heaman et al. 2004). A 163 m long drilled core was uncovered from the Giraffe locality in 1999 by BHP Billiton Inc. (Siver & Wolfe 2009). A total of 113.1 m of the core contained well preserved stratified organic sediment, including 68.3 m of lacustrine lake sediments, overlain with 44.8 m of peaty material. An air-fall tephra bed located near the transition between lake and terrestrial sediments was dated using fission tracking to be 40 Ma (Doria et al. 2011), indicating that all of the lake sediments are Eocene in nature. It is envisaged that, after phreatomagmatic kimberlite emplacement, a waterbody formed within the deep crater that persisted for about 7 to 8 million years before transition to a terrestrial environment.

WOMBAT PIPE: The Wombat Pipe represents another kimberlite deposit located in the Lac de Gras field with a crater that contained aquatic habitats. The age of emplacement of the Wombat kimberlite into the Slave Craton has not yet been determined, however, the lake sediments have been dated to the Paleocene based on extensive examination of pollen remains (Hu et al., 2011). An extensive drilled core, measuring 386.7 m in length, was uncovered from Wombat by BHP Billiton Inc in 1993. The section of the core from 227.6 m to 386.7 m, or 159.1 m, represents laminated aquatic sediments that are contained within core boxes 43 through 66. The majority of the laminated sediments down to approximately box 62 contain significant amounts of silt, while the portions in boxes 62–65 are lighter weight with a significant organic component. The sections of the Wombat core examined to date, primarily from boxes 62–66, contain numerous microfossils.

Results

Synura cronbergiae sp. nov. Siver

DESCRIPTION: Scales are slender, elongate, and possess a posterior rim, a short pointed spine and a well developed secondary layer (Figs 1–2). Scales range in size from 6.5–13 µm × 1.75–3.75 µm, with means of 10 × 3 µm and 11.5 × 3.25 µm for Giraffe and

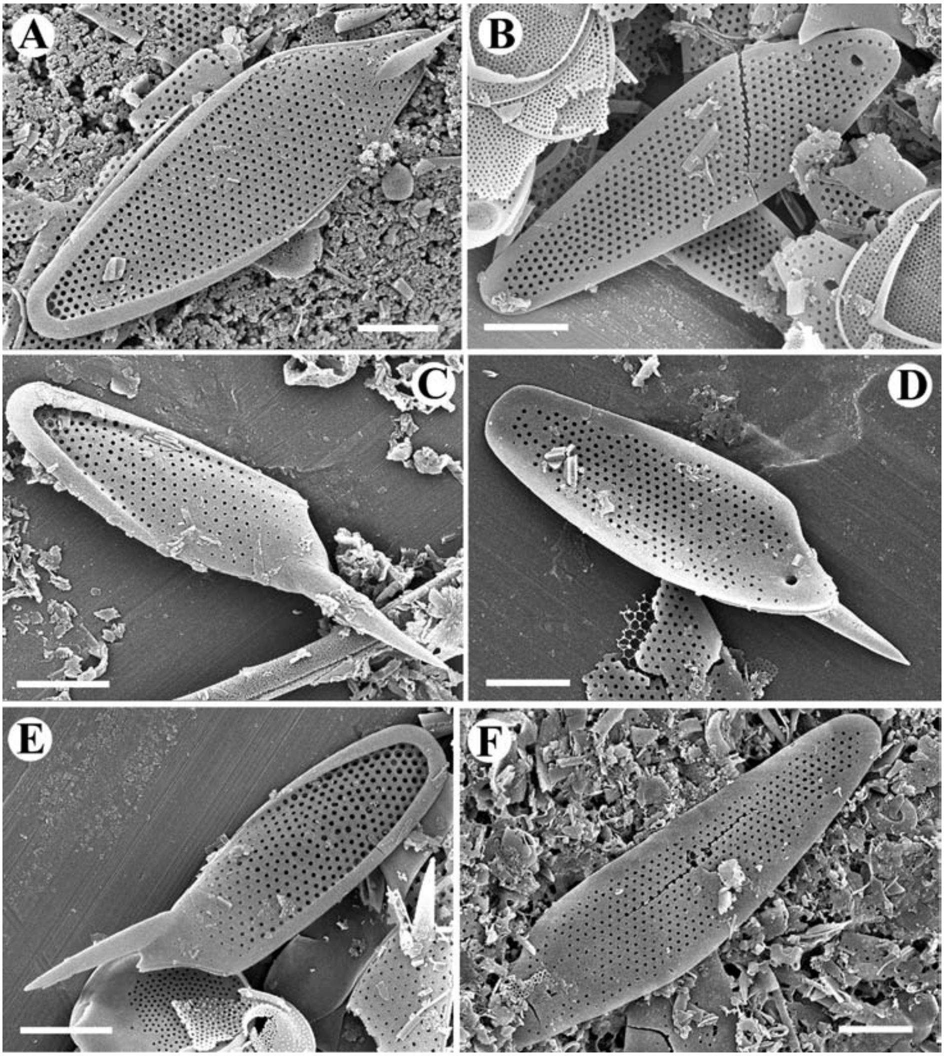

Fig. 1. Whole scales of *Synura cronbergiae* as viewed from the top (A, C, E) and bottom (B, D, F) surfaces. Note the distribution of base plate pores, posterior rim, the position and size of the apical spine and large foram. Scale bars = 2 µm.

Wombat, respectively. There is often a slight indentation of the scale margin just below the left-hand side of the spine (Figs 1C, E; 2 C–D), otherwise the outline is symmetrical along the longitudinal axis. The posterior rim is well-formed, but shallow, and encircles about 2/3 of the perimeter, often extending slightly further along the left-hand side of the scale (Figs 1A, C, E). The anterior spine is sharply pointed (Figs 1 C–D; 2 B–D), hollow, ranges in length from 1.75–3.5 µm, and originates approximately 2 µm from

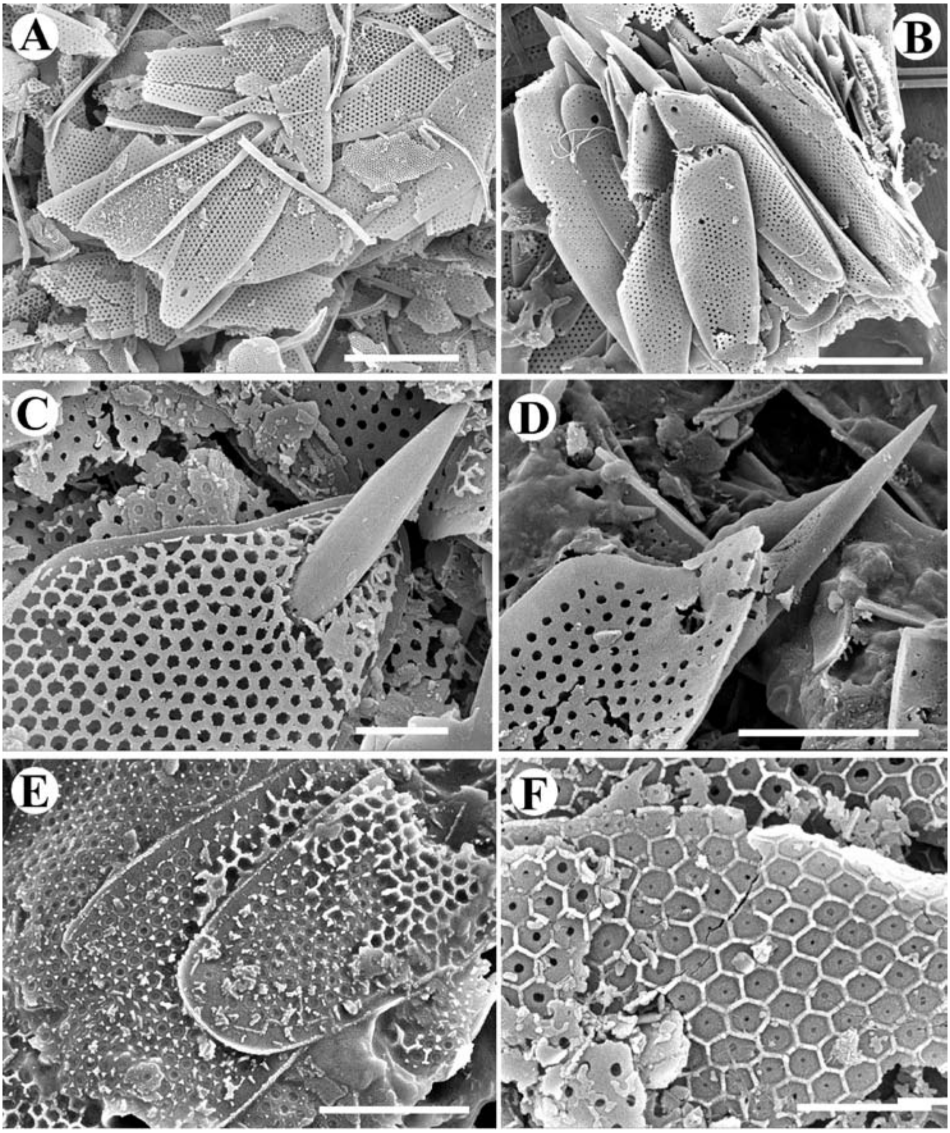

Fig. 2. Scales of *Synura cronbergiae*. A–B. Remains of whole cells within intact rock fragments. C–D. Close-up views of the top (C) and underside (D) of the spine. Note that the secondary layer on the surface of the scale surrounds the base of the spine, and the position of the spine relative to the large foram on the base plate. E–F. Close-up views of scales with partially formed and/or an eroded secondary layer denoting the ultrastructure of the hexagonal chambers. Note that each chamber surrounds a base plate pore (F) and originates from six nucleation sites at the edges of the hexagon structure (E).

the distal margin atop of a small-diameter foram on the base plate. Except for the margin of the scale and the area surrounding the foram, the base plate is perforated with evenly spaced pores (Figs 1B, D, F; 2A). The pores are of equal diameter with slightly thickened rims on the dorsal surface. Each base plate pore becomes enclosed within a hexagonal chamber, and the chambers collectively fuse to form a secondary layer that covers the scale surface and connects with the posterior rim (Figs 1A, C, E; 2E–F). There is a pore, or opening, on the upper surface of each hexagonal chamber which is more or less aligned with the corresponding base plate pore. Each pore on the base plate is surrounded by six adjacent pores (Fig. 2F), and initiation of silica deposition to form the secondary chambers begins at each corner of the chamber (Fig. 2E), yielding a precise and highly structured patterning on the scale.

Except for scales from Wombat being slightly larger, the ultrastructural details were virtually identical for specimens from both sites. In addition, scales lacking a spine were not uncovered, and in both localities large piles of scales often numbering over several hundred were found in-situ within the rock matrix.

HOLOTYPE: Here designated the collection of specimens on SEM stub deposited at the Canadian Museum of Nature, CANA 85821. Specimens are from section 13-1-15 of the Giraffe Pipe core collected by P.A.Siver. Fig. 1A is of the holotype.

TYPE MATERIAL: Material from section 13-1-15 of the Giraffe Pipe core deposited at the Canadian Museum of Nature, CANA 85821. Additional material from section 13-1-15 was also archived at the Smithsonian Museum, Washington, D.C., U.S.A.

ETOLOGY: This species is named in honor of the chrysophyte expert, Gertrud Cronberg.

WHERE FOUND: To date, large numbers of *S. cronbergiae* scales have been found in 16 samples, 11 from Giraffe Pipe and five from Wombat Pipe (Table 1). At both localities, the new species has been confined to specific sections of the long cores. In the Giraffe core, *Synura cronbergiae* was abundant in all samples examined to date from Boxes 13–15, representing lake depths between 8.5 and 15.5 m, and in the Wombat core from 6 m of sediment core from Box 65 (Table 1).

Discussion

There are no known extant species of *Synura* that match precisely the characteristics presented by *S. cronbergiae*. Based on the current concept of the genus, *S. cronbergiae* would be placed into the Sectio Synura since it forms scales with a distinct, forward-projecting spine (Kristiansen & Preisig, 2007). However, there is one rare species known only from a few sites in South Carolina, U.S.A., *Synura longisquama* Wujek & Elsner, that does share features with and bears resemblance to *S. cronbergiae* (Wujek & Elsner, 2000). Scales of *Synura cronbergiae* are similar in size and overall outline to those of *S. longisquama*, and both taxa have a similar highly patterned secondary layer formed by hexagonal chambers that covers all but the very posterior portion of the scale. The primary and significant difference is that scales of *S. longisquama* form a median keel and are clearly within the Sectio Petersenianae (Kristiansen & Preisig, 2007). Formation of projecting spines vs. a median keel is the primary basis for defining the Sectio Spinosa vs. Sectio Petersenianae, respectively.

Table 1. Sections of the Giraffe and Wombat cores containing remains of *Synura cronbergiae*. In each of these samples large groups of scales were observed within the rock matrix, presumeably representing whole cells or colonies. For the Giraffe core, approximate depth in the maar lake is given. These details have not yet been determined for the Wombat locality.

Core	Section	Depth in Waterbody (m)
Giraffe	13-2-120	8.56
	13-1-15	8.89
	13-1-33	9.02
	13-1-80	9.36
	13-1-144	9.83
	14-3-20	10.02
	14-2-32	11.2
	14-1-60	12.51
	15-3-75	13.71
	15-2-40	14.56
	15-1-15	15.47
Wombat	65-4-55	NA
	65-3-30	NA
	65-3-120	NA
	65-2-137	NA
	65-1-45	NA

Scales of synurophytes are formed within a specialized vesicle known as the silica deposition vesicle, or SDV, that is first molded into the shape of the scale and then serves as the site of silica deposition to produce the finished scale (Mignot & Brugerolle, 1982; Siver, 2003; Kristiansen, 2005). In species within the Sectio Petersenianae, the SDV invaginates near the distal margin and folds back onto the base plate forming the hollow, median keel. The distal portion of the keel may be pointed and is positioned above a large base plate pore, or foram, that represents the origin of the SDV invagination. In contrast, when scales within the Sectio Synura are formed, the SDV invaginates in the same fashion near the distal end, but projects forward past the scale margin to form a hollow spine. The base of the spine becomes fused with the base plate and surrounds the large distal pore. This difference in the orientation of the SDV invagination yields the primary difference between the Sectio Petersenianae and Sectio Synura.

The SDV invagination on *Synura cronbergiae* forms a distinct forward projecting spine, not a median keel, placing it within the Sectio Synura. Other species within the Sectio Synura, such as *Synura curtispina* and *S. mollispina*, also produce scales with secondary hexagonal chambers that each enclose a base plate pore (Wee, 1982; Siver, 1987; Kristiansen & Preisig, 2007), similar to those on *S. cronbergiae*. However, the secondary layer on *S. cronbergiae* scales is more highly structured than those found on other species within the Sectio Synura, and in this regard similar to scales of *S. longisquama*. Perhaps, *S. cronbergiae* and *S. longisquama* shared a common ancestor and that these lineages diverged depending on the pattern formed by the SDV invagination. If this is true, *S. cronbergiae* and *S. longisquama* may represent early attempts at forming a scale with a spine or median keel, respectively. It is also possible that *S. cronbergiae* is an early ancestor of *S. longisquama*.

Although we can not be certain, our assumption is that *S. cronbergiae* was colonial, based on the findings of large deposits of hundreds of scales, far more than typically found on an individual cell. Likewise, unlike many species within the Sectio Synura that form spineless caudal scales, *S. cronbergiae* does not produce scales lacking spines. It is most likely that the scales with very short spines surrounded the posterior portion of the cell. Since *S. cronbergiae* thrived in both Giraffe and Wombat its known geologic range is at least ca. 60 to 40 Ma. This encompasses much of the Cenozoic hot house, a very warm time period in the history of the Earth (Zachos et al., 2001; 2008). Whether *S. cronbergiae* survived into the Oligocene as global temperatures dropped (Zachos et al., 2001) is not known, but hopefully as other geologic sites are uncovered the evolutionary history of this interesting species can be fully realized.

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