Heteropolar eunotioid diatoms (Bacillariophyceae) were common in the North American Arctic during the middle Eocene

PETER A. SIVER1*, JORDAN BISHOP1, ANNE LOT1 & ALEXANDER P. WOLFE2
1Department of Botany & Program in Environmental Studies, Connecticut College, New London, CT 06320, USA
2Department of Biological Sciences, University of Alberta, Edmonton, AB T6G 2E9, Canada
*Corresponding author (email: pasiv@conncoll.edu)

ABSTRACT – Eunotioid diatoms that express asymmetry in both the apical and transapical axes, forming heteropolar valves, are generally placed in the genus Actinella. The degree of heteropolarity varies between species, ranging from subtle differences between poles to highly differentiated head poles bearing an apical protuberance. Actinella species with less difference between the poles and lacking an apical protuberance are gradational with Eunotia. With over 100 known species reported globally, primarily in the tropics, only Actinella punctata Lewis, 1864 is currently known from North America. As part of a biotic survey and inventory project focused on the middle Eocene Giraffe crater locality near the Arctic Circle in northern Canada, we have uncovered a wealth of eunotioid diatoms including at least five heteropolar species attributed to Actinella, three of which are described formally herein as A. hickeyi sp. nov., A. goodwinii sp. nov. and A. kimberlitica sp. nov.. These diatoms all lack apical protuberances and bear resemblance to modern heteropolar counterparts within Eunotia. The objectives of this contribution are to report the findings from the Giraffe locality relative to modern and fossil eunotiophycid taxa, discuss the use of heteropolarity as a distinguishing character for the genus Actinella, and consider the palaeoclimatic and biogeographical implications of these observations.

KEYWORDS: Actinella, Eocene, Eunotia, Eunotiophycidae, non-marine diatoms

INTRODUCTION

The subclass Eunotiophycidae of the class Bacillariophyceae (diatoms) represents a relatively small assemblage of taxa that are unique in possessing short raphes (often referred to as rudimentary) but lacking central nodules, yet are the only rapho-bearing diatoms having rimoportulae (Patrick & Reimer, 1966; Round et al., 1990). The rimoportula is a primitive structure found on many centric and araphid diatoms, but is lacking on the vast majority of raphid diatoms with the exception of the Eunotiophycidae. Currently, there are eight genera recognized within the Eunotiophycidae: Actinella Lewis, Eunotia Ehrenberg, Desmogonium Ehrenberg (not recognized by some authors), Eunophora Wyverman, Sabbe & Mann, Peronia de Brébisson & Arnott ex Kitton, Semiorbis Patrick, Amphorotia Williams & Reid and Perinotia Metzeltin & Lange-Bertalot (Sabbe et al., 2001; Williams & Reid, 2006; Wetzel et al., 2012). These genera are distinguished on the basis of symmetry about the transapical axis, structure of the striae and position of the raphe either on the face of the valve (Peronia) or primarily on the valve mantle (all other genera). All of the genera, except for Peronia, are asymmetrical about the apical axis. Two of the genera, Actinella and Peronia, are also asymmetrical about the transapical axis, yielding heteropolar apices referred to as the head (larger or wider end) and foot poles (Sabbe et al., 2001; Melo et al., 2010). The heteropolar nature of the valve is the key feature separating Actinella from the other genera that also have the raphe situated largely on or close to the mantle (Sabbe et al., 2001; Ripple & Kociolek, 2013).

Two additional genera are noteworthy. Taylor et al. (2014) recently proposed the genus Actinellopsis Taylor, Karthick & Kociolek and separated it from Actinella based primarily on the position of the raphe being situated on the valve face along the margin. We question whether this character is sufficient to establish a new genus and, at this time, we are reluctant to consider Actinellopsis as more than a proposed taxon. We do agree with Taylor et al. (2014) that the structure of the raphe on Actinellopsis murphyi Taylor, Karthick & Kociolek bears resemblance to the raphe on Actinella giraffensis Siver, Wolfe & Edlund (Siver et al., 2010). Bicudoa Wetzel, Lange-Bertalot & Ector is a recently described genus lacking a raphe, helicoglossae and rimoportulae that may represent a highly derived eunotiophycid diatom (Wetzel et al., 2012).

Actinella punctata Lewis, the generitype, was first described by Lewis (1864) from Saco Pond, a small, shallow, waterbody situated in the mountains of New Hampshire, USA. Today, the pond is acidic, dilute, low in nutrients, and harbours most, if not all, of the intriguing diatoms originally illustrated by Lewis (1864, 1865) over 150 years ago (Siver & Camfield, 2007). There are now close to 100 described species of Actinella (Ripple & Kociolek, 2013), but interestingly A. punctata remains the only species that has been observed in modern collections from North American localities (Siver & Hamilton, 2011). This large and characteristic taxon is widespread along the east coast of North America, and has also been reported from midwestern and western localities on the continent, as well as other regions in the world (Kociolek et al., 1997; Ripple & Kociolek, 2013). A limited number of other heteropolar Eunotiophycidae species, currently classified under Eunotia, have also been reported from North American waterbodies. These include Eunotia rhomboidea Hustedt, Eunotia faba (Ehrenberg) Grunow in van Heurck, and
Table 1. Vertical depths of eleven studied samples from Giraffe Lake core and the presence of Actinella species in each sample.

<table>
<thead>
<tr>
<th>Number</th>
<th>Sample</th>
<th>Vertical depth (m)</th>
<th>Species present</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14-3-100</td>
<td>109.64</td>
<td>Actinella hickeyi</td>
</tr>
<tr>
<td>2</td>
<td>14-2-22</td>
<td>110.36</td>
<td>Actinella hickeyi</td>
</tr>
<tr>
<td>3</td>
<td>14-2-32</td>
<td>110.46</td>
<td>Actinella hickeyi</td>
</tr>
<tr>
<td>4</td>
<td>14-2-56</td>
<td>110.70</td>
<td>Actinella hickeyi, Actinella kimberlitica</td>
</tr>
<tr>
<td>5</td>
<td>14-2-107</td>
<td>111.21</td>
<td>Actinella kimberlitica</td>
</tr>
<tr>
<td>6</td>
<td>15-1-65</td>
<td>116.79</td>
<td>Actinella kimberlitica, Actinella goodwinii</td>
</tr>
<tr>
<td>7</td>
<td>15-1-100</td>
<td>117.14</td>
<td>Actinella kimberlitica, Actinella goodwinii</td>
</tr>
<tr>
<td>8</td>
<td>15-1-131</td>
<td>117.45</td>
<td>Actinella kimberlitica, Actinella goodwinii, Actinella sp. 2</td>
</tr>
<tr>
<td>9</td>
<td>16-3-23</td>
<td>117.87</td>
<td>Actinella hickeyi, Actinella goodwinii, Actinella sp. 1, Actinella sp. 2</td>
</tr>
<tr>
<td>10</td>
<td>16-3-42</td>
<td>118.06</td>
<td>Actinella goodwinii</td>
</tr>
<tr>
<td>11</td>
<td>16-3-81</td>
<td>118.45</td>
<td>Actinella goodwinii</td>
</tr>
</tbody>
</table>

*Eunotia papilioforma* Furey, Lowe & Johansen, each bearing slightly club-shaped and heteropolar valves. Sabbe et al. (2001) noted that valves of *E. rhomboidea* could be isopolar or heteropolar and noted that placement in *Eunotia* requires further study. Furey (2011) clearly stated that valve shape and position of the helictoglossae in *E. papilioforma* are asymmetrical to the transapical axis, but still placed the taxon in *Eunotia* despite also noting that *Actinella* species are distinguished from *Eunotia* by heteropolar valve shape. Placement of *E. papilioforma* under *Eunotia*, rather than *Actinella*, given their distinguishing criteria, is unclear and this taxon may more appropriately belong in *Actinella*. Regardless of the generic assignment of *E. rhomboidea* and *E. papilioforma*, it is clear based on the hundreds of diatom studies performed throughout North America over the last century that heteropolar Eunotiophycidae species are extremely rare. A similar case has been made globally (see Sabbe et al., 2001).

The Giraffe fossil locality (64°48′N, 110°04′W) is a kimberlite diatreme crater that formed following phreatomagmatic volcanism, subsequently infilled with a sequence of Eocene lacustrine and then paludal sediments, and was later entombed with Neogene glacial deposits (Wolfe et al., 2006; Siver & Wolfe, 2009). A 165 m long drilled core was retrieved from the crater by BHP Billiton Inc. during diamond exploration and later archived at the Canadian Geological Survey (Calgary). The core contains over 8.81 m of terrestrial sediment atop 65 m of lacustrine mudstone of middle Eocene age (Wolfe et al., 2006; Siver & Wolfe, 2009). Both the terrestrial (Doria et al., 2011) and lacustrine (Siver & Wolfe, 2005; Wolfe et al., 2006) deposits contain abundant fossil remains with extraordinary preservation, including numerous freshwater diatoms among other siliceous microfossils (Wolfe & Siver, 2009; Siver et al., 2010). As part of a biotic survey and inventory project focused on the lacustrine mudstones we have uncovered a wealth of Eunotiophycidae diatoms, mostly contained within a 16 m section of the core, and representing species of *Eunotia* and *Actinella*. Of special interest is the presence in this single fossil locality of five or more species each exhibiting a heteropolar condition and that are most appropriately classified as *Actinella*. The purpose of this contribution is to report our findings to date and formally describe three of the species.

**MATERIALS AND METHODS**

Mudstone chips (50–100 mg) from eleven sections of the Giraffe core spanning 8.81 m (Table 1) were oxidized using 30% H₂O₂ 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 many siliceous microfossils from the mudstone matrix. In addition, small fragments of mudstone, each containing many embedded microfossils, remain within each preparation. Aliquots of each slurry were air dried on to pieces of heavy duty aluminum foil and directly on to circular glass coverslips. The aluminum foil samples were trimmed, attached to aluminum stubs with Apiezon® wax, and coated with a mixture of gold and palladium for 2 min with a Polaron Model E sputter coater. Samples were examined with a Leo 982 field emission or an FEI Nova scanning electron microscope (SEM). The coverslips were mounted on to glass slides with Naphrax and examined with a Leica DMR or an Olympus BX51 light microscope (LM). A minimum of 20 specimens for each species were used for morphometric analysis.

Each sample from the Giraffe core is identified with a three-part number (Table 1). The first number represents the core box. Deeper sections of the core correspond to larger box numbers. Each box contains three 1.5 m core lengths, identified as channels 1, 2 and 3. The second number represents the channel. The third number indicates the length in centimetres measured down from the top of a core length. For example, sample 14-3-100 represents a sample taken from 100 cm down along the core length in channel 3 from box 14.

**RESULTS**

Eunotiophycidae specimens from the Giraffe locality represent at least five, and probably six, different species with heteropolar valves (Pls 1–6). One of these species, *Actinella giraffensis*, has been previously described (Siver et al., 2010), and we now have examined a sufficient range of specimens to describe three additional species formally. Remains of two more species have also been uncovered, but since we have examined a limited number of specimens to date, only preliminary observations are given herein.

**SYSTEMATIC PALAEOONTOLOGY**

*Actinella hickeyi* Siver, Bishop, Wolfe & Lott sp. nov.  
(Pl. 1, figs A–H; Pl. 3, figs A–F; Pl. 4, figs A–D)

**Derivation of name.** The epithet is in honour of the late Professor Leo Hickey, Yale University, an extraordinary
Heteropolar eunotioid diatoms in the North American Arctic

Explanation of Plate 1. figs A–H. Light micrographs of Actinella hickeyi sp. nov.; figs I–O. A. kimberlitica sp. nov.; figs P–Q. A. sp. 2. Note the heteropolar nature of the valve for all three taxa, the widely spaced striae for A. hickeyi, and the incised nature of the helictoglossa for A. kimberlitica. Fig. B is the holotype specimen for Actinella hickeyi and fig. M the holotype specimen for A. kimberlitica. Scale bar 10 µm.

palaeobotanist and friend who was keenly interested in the Giraffe locality.

**Holotype.** Here designated as the specimen circled on the glass slide marked ‘Giraffe 16-3-23 C’ and deposited at the Canadian Museum of Nature, CANA 94961. The holotype is illustrated in Plate 1, fig. B.

**Type material.** Material from section 16-3-23 of the Giraffe core collected by A. P. Wolfe & P. A. Siver.
Description. Specimens of *Actinella hickeyi* have a slight dorsiventral design, are asymmetrical with respect to the transapical axis, and have rounded head and foot poles (Pl. 1, figs A–H; Pl. 3, figs A–C). Valves have a slight convex margin and a straight ventral margin; they range in size from 27–40 µm × 4–6 µm. The foot pole is often bent slightly towards the ventral side of the valve (Pl. 3, figs A–D). The striae are parallel with the transapical axis, widely and often unevenly spaced in the middle of the valve, have a range of 8–13 in 10 µm, and become more closely and evenly spaced at the poles (Pl. 1, figs A–H; Pl. 3, figs A–C). The striae on the valve face are aligned with the striae on the dorsal mantle, but not with those on the ventral mantle. There is a series of short and closely spaced striae between the raphe slits and the lower edge of the mantle (Pl. 3, fig. E). The areolae are small, circular, evenly spaced pores that lack coverings (Pl. 3, figs D and F). Internally, the areolae are often recessed within a linear depression (Pl. 3, fig. B; Pl. 4, fig. A).

The raphe slits range in length from 5–7 µm and are situated on the mantle (Pl. 3, fig. E). The distal raphe fissure usually terminates on the mantle (Pl. 3, fig. E), or a short distance up on to the valve face (Pl. 3, figs D and F). Both the distal and proximal raphe fissures end as large circular pores (Pl. 3, figs D–F), and internally the distal end of the raphe terminates as a well-formed helicoglossa (Pl. 4, figs B–D). There is one rimoportula per valve positioned on the ventral mantle between the helicoglossa and the apex (Pl. 3, fig. E; Pl. 4, figs C–D). The rimoportula can be found on either the foot (Pl. 4, fig. C) or head (Pl. 4, fig. D) pole, and typically on opposite ends of valves from the same frustule (Pl. 3, fig. C, arrows). On each apex, the lower margin of the mantle is thickened and extended inward forming a shallow pseudoseptum (Pl. 4, figs A–D). There are typically three open girdle bands per frustule, each with two to three rows of pores. The pole-end of the valvocopula is thickened and extends past the valve apex (Pl. 3, fig. E).

Remarks. *Actinella hickeyi* sp. nov. was found in four sections, spanning over 8 m of the core (Table 1). These sections were largely dominated with other eunotioid diatoms, chrysophyte cysts and numerous species of *Mallomonas*, especially a species resembling *M. lycenensis* Conrad and *M. porifera* Siver & Wolfe.

*Actinella goodwinii* Siver, Bishop, Wolfe & Lott sp. nov. (Pl. 2, figs A–I; Pl. 5, figs A–F)

Derivation of name. The epithet is in honour of Professor Richard Hale Goodwin from Connecticut College, a botanist and pioneer in land conservation, and his wife of over 70 years, Esther.

Holotype. Here designated as the specimen circled on the glass slide marked ‘Giraffe 16-3-23 D’ and deposited at the Canadian Museum of Nature, CANA 94962. The holotype is illustrated in Plate 2, fig. F.

Type material. Material from section 16-3-23 of the Giraffe core collected by A. P. Wolfe & P. A. Siver.

Description. Specimens of *Actinella goodwinii* are strongly dorsiventral with a slight concave ventral margin, a convex dorsal margin with two undulations, and protruding apices (Pl. 2, figs A–I; Pl. 5, figs A–E). One apex, the foot pole, is narrower, slightly subcapitate and extended further than the other apex, or head pole, yielding a heteropolar condition. The undulations, especially the one towards the foot pole, are less pronounced on smaller valves. Valves range in size from 16–36 µm × 4.4–6.5 µm. The mantle is wide and forms a right angle with the valve face (Pl. 5, figs A–D) except around the foot pole where it is slightly wider, angled outward and extended past the valve face (Pl. 5, fig. A, arrow). This difference in the width and angle of the mantle between each pole often yields a slight rhomboidal shape in girdle view, more pronounced on the foot pole end of the frustule (Pl. 5, fig. D).

The striae are evenly spaced, parallel over most of the valve, become slightly radiate around the apices, and range from 16 to 20 in 10 µm (Pls 2 and 5). The striae on the valve face align roughly with those on the mantle; however, there are often additional shorter striae on the mantle (Pl. 5, figs A and D). There is a series of short and more closely spaced striae between the raphe slits and the lower edge of the mantle (Pl. 5, figs C–D). The areolae are very small, circular, evenly spaced pores that lack coverings on both the external and internal surfaces (Pl. 5). The raphe slits are short, terminated on each end with small pores, and are positioned on the mantle (Pl. 5, figs B–D). The proximal end of the raphe is situated about one-third of the distance from the valve face, traverses up to the valve margin, and terminates a short distance on to the valve face (Pl. 5, figs B–D). Internally, the distal ends of the raphe slits terminate as small helicoglossae along the ventral margin (Pl. 5, figs E–F). The helicoglossa on the foot pole terminates further from the apex than the one on the head pole. There is one rimoportula per valve positioned on the foot pole apex slightly towards the dorsal margin (Pl. 5, figs E–F, arrows). The lower margin of the mantle is thickened around each apex, especially around the foot pole where it is extended inward forming a shallow pseudoseptum (Pl. 5, fig. F). There are three to four wide, open and wavy girdle bands per frustule, each with well-developed striae.

Remarks. *Actinella goodwinii* was found in six closely spaced sections spanning 1.6 m of the core (Table 1). These sections were largely dominated with scaled chrysophyte remains, including especially high numbers of a species resembling *Mallomonas lycenensis*, *M. porifera* and chrysophyte cysts, other eunotioid diatoms, the diatom *Oxyneis apporrecta* Siver, Wolfe & Edlund, and euglyphids.

*Actinella kimberlitica* Siver, Bishop, Wolfe & Lott sp. nov. (Pl. 1, figs I–O; Pl. 6, figs A–C)

Derivation of name. The epithet refers to the kimberlite intrusion giving rise to the Giraffe maar.

Holotype. Here designated as the specimen circled on the glass slide marked ‘GP 15-1-131 Siver E’ and deposited at the Canadian Museum of Nature, CANA 94963. The holotype is illustrated in Plate 1, fig. M.

Type material. Material from section 15-1-131 of the Giraffe core collected by A. P. Wolfe & P. A. Siver.
Explanation of Plate 2. Light micrographs of Actinella goodwinii sp. nov., depicting a size diminution series. Note the extended and narrower foot pole and even distribution of striae. Fig. F is the holotype specimen. Scale bar 10 µm.
Explanation of Plate 3. Scanning electron micrographs of *Actinella hickeyi* sp. nov.: figs A–B. External and internal views depicting the distribution of striae and heteropolar nature of the valve. Insert in B shows the arrangement of areolae within shallow linear depressions on the internal surface. 

**fig. C.** Whole frustule showing the positions of rimoportulae on opposite ends of each valve (arrows). **fig. D.** Close-up of the foot pole of the specimen in C showing details of the copulae. Note the terminal pore on the distal raphe fissure. **fig. E.** Raphe slit positioned completely on the mantle. Note the large pores on both the distal and proximal ends of the raphe, the series of small closely spaced striae below the raphe, the rimoportula, and the thickened and extended end of the valvocopula. **fig. F.** Close-up of a head pole depicting the distal raphe fissure terminating close to the apex near the valve margin. Scale bars 10 µm (A and C), 5 µm (B) and 2 µm (D–F).
6, figs A–C). The dorsal margin is slightly convex, the ventral margin is straight and the apices are rounded. The foot pole is narrower and extends further relative to the helictoglossa than the head pole (Pl. 1, figs I–O; Pl. 6, figs A–B, arrows). There is a narrow, but distinct, axial area aligned along the ventral valve margin that connects the distal raphe ends (Pl. 6, fig. A). The striae are closely and evenly spaced across the entire valve, parallel with the transapical axis, and range in density from 22–26 per 10 µm. The areolae are small, circular, evenly spaced pores that lack coverings (Pl. 6; figs A–C).

The raphe slits are situated on the mantle and gradually bend up on to and terminate on the valve face (Pl. 6, figs A–B). Externally, the distal and proximal raphe fissures terminate as small pores. Internally, the distal end of the raphe terminates as a well-formed helictoglossa bent slightly towards the dorsal margin, yielding an incision-like appearance when viewed with a light microscope (Pl. 1, figs I–O). There is one rimoportula per valve apically positioned on the foot pole (Pl. 6, fig. C, arrow).

Remarks. *Actinella kimberlitica* was found in five sections spanning almost 7 m of the core (Table 1). These sections were largely dominated with scaled chrysophyte remains, including a species resembling *Mallomonas lychenensis* and *M. porifera*, chrysophyte cysts, numerous other eunotioid diatoms, the diatom *Oxyneis apporrecta*, and euglyphids.
Additional Actinella taxa

Specimens of two additional heteropolar forms representing Actinella were recovered from the Giraffe locality, including a long slender diatom designated provisionally as Actinella sp. 1 (Pl. 6, figs D–F), and a small club-shaped form designated as Actinella sp. 2 (Pl. 1, figs P–Q). We note their presence in the core, but elect not to officially describe them at this time until additional specimens can be investigated to establish their full range of characters. However, the presence of these additional taxa provides an expanded perspective of the full diversity of eunotiophycid diatoms from the deposit.

Actinella sp. 1. Specimens of this taxon ranged between 50 and 55 µm in length, and have heteropolar valves that taper gradually from about 5 µm wide at the head pole to 3 µm wide at the foot pole (Pl. 6, fig. D). A slight bend in valve shape occurs along the dorsal margin closer to the foot pole, and both apices are rounded. The mantle forms a right angle with the valve face except around the foot pole where it is angled outward and extended past the valve face (compare Pl. 6, figs E and F). There is a distinct axial area aligned along the ventral valve margin that connects the distal raphe ends (Pl. 6, figs D and F, white arrows). Striae are closely and evenly spaced, parallel with the transapical axis and composed of tiny areolae that lack occlusions at least on the external surface. Striae are continuous on to the mantle, and become radially aligned around the apices (Pl. 6, figs E and F). The raphe is straight, runs diagonally along the mantle to the valve margin, and bends sharply up onto and terminates midway on the valve face. The raphe on the head pole is more sharply angled onto the valve face and the distal fissure terminates closer to the apex than on the foot pole (compare Pl. 6, figs E and F). Each distal fissure is surrounded by a well-developed hyaline region. Although we have not yet been able to examine internal structure, we believe this taxon has at least one rimoportula situated on the foot pole (Pl. 6, fig. F, black arrow). Based on limited observations, frustules are slightly clavate in girdle view (not shown). The overall valve morphology and the structure of the raphe appear to distinguish this taxon from all other described Actinella species.

Actinella sp. 2. Valves are small, range in length from 10–14 µm to 2.5–3.5 µm, and are distinctly club-shaped with a wide head pole and narrow foot pole (Pl. 1, figs P–Q). Apices are rounded, and the striae are closely spaced and parallel with the transapical axis. It is possible that these specimens represent very small valves of Actinella giraffensis (Siver et al., 2010); however, since we have not found similar-shaped valves of this size in material containing numerous specimens of the later taxon, it likely represents a new species.

DISCUSSION

The position and reduced nature of the raphe, presence of rimoportulae, and features of the striae, areolae and helicoglossae are similar for Actinella and Eunotia, and both genera are, without doubt, evolutionarily closely related (Round et al., 1990; Kociolek, 2000). The primary, and to date perhaps only valid, character separating Actinella from Eunotia is the heteropolar shape of the valve (Round et al., 1990; Sabbe et al., 2001; Melo et al., 2010; Ripple & Kociolek, 2013). By definition, valves of Eunotia are symmetrical to the transapical axis (Eunotia rhomboidea and a few related taxa being the exceptions, as stated previously), while those of Actinella are not, yielding the heteropolar condition. As noted by Sabbe et al. (2001), heteropolarity is the obligatory character for inclusion in Actinella, and this is the primary criterion on which we ascribe the new species from the Giraffe pipe as belonging to Actinella. In our opinion, given the current definitions of both genera, the new species are best classified as Actinella.

Although all Actinella species are heteropolar in valve view, polarity in girdle view remains an open question. Many Actinella species are also heteropolar in girdle view forming clavate or wedge-shaped frustules (Sabbe et al., 2001; Siver et al., 2010). However, a few species have been noted to be rectangular or linear in girdle view, and sometimes narrower in the middle of the frustule (Lewis, 1864; Patrick & Reimer, 1966; Metzeltin & Lange-Bertalot, 1998). Also, as noted by Sabbe et al. (2001), polarity in girdle view is not always given in original descriptions and this character needs to be determined for many Actinella species before a thorough study can be made for the genus. Although we believe frustules of Actinella hickeyi are indeed slightly clavate in girdle view based on observations of a few specimens with light microscopy, whole frustules have proven difficult to find and we have not been able to examine this character thoroughly with SEM despite observing hundreds of isolated valves.

Based on our current observations, Actinella goodwinii is also heteropolar in girdle view (i.e. clavate), with a somewhat wider and rectangular-shaped head pole, and a slightly rhomboidal-shaped and narrower foot pole. This morphology is consistent with the different shapes found at each valve pole, and the rhomboidal-shape of the foot pole is reminiscent of that observed on some Eunotia taxa, particularly Eunotia rhomboidea Hustedt. Valves of Eunotia rhomboidea can be isopolar or heteropolar in valve view and, as noted by Sabbe et al. (2001, p. 337), ‘heteropolarity in Eunotia cells is the exception rather than the rule’. Since valves of A. goodwinii are always heteropolar in valve view, this taxon is best described as Actinella.

The degree of heteropolarity found in Actinella species ranges from very slight to extreme. Many species of Actinella, such as A. punctata Lewis and A. guianensis Grunow, produce valves with uniquely shaped and highly inflated head poles relative to the foot pole. This difference is taken to extremes in taxa such as A. maylaertii Sabbe & Vyverman and A. comperei Sabbe, Vanhoutte & Vyverman, where the foot pole is more or less reduced to a narrow point with a width of less than 2 µm (Sabbe et al., 2000; 2001). However, there are a fair number of Actinella species that bear only a slight heteropolarity and at first glance could be mistaken for Eunotia. For example, Actinella indistincta Vyverman & Bergey, A. pararobusta Metzeltin & Lange-Bertalot, A. parva Vanhoutte & Sabbe and A. pareunotoideos Metzeltin & Lange-Bertalot display limited heteropolarity in valve view, possess valves that lack inflated poles, and are ‘Eunotia-like’. In fact, some species were initially described as Eunotia, only later being transferred to Actinella based on the heteropolar nature of the valve (Metzeltin & Lange-Bertalot, 2007). Other species, such as A. gessneri Hustedt and A. sioli Hustedt, have very inflated head and foot poles and display only slight heteropolarity in the transapical axis. Still, other species were initially described belonging to Asterionella Hassall, only later discovered to possess reduced raphe, and transferred to Actinella (Kociolek & Rhode, 1998). Metzeltin & Lange-Bertalot (2007) described A.
Explanation of Plate 5. Scanning electron micrographs of Actinella goodwinii. figs A–C. Valves depicting the valve face (A–B), dorsal mantle (A) and ventral mantle (C). Note the deep width of the mantle, the small raphe slits positioned on the upper part of the mantle, and the outward-angled foot pole (arrow on A). fig. D. Whole frustule depicting both the valve and ventral girdle view. Note the slight rhomboidal shape in girdle view at the foot pole (arrow). fig. E. Internal view of a valve. Note the apical position of the rimoportula (arrow). fig. F. Close-up of the foot pole showing the small helicoglossa, position of the rimoportula (arrow), and the thickened portion of the mantle forming the shallow pseudoseptum around the apex. Scale bars 10 µm (C–E) and 5 µm (A–B, F).
Explanation of Plate 6. figs A–C. Scanning electron micrographs of *Actinella kimberlitica* sp. nov.: A, external and B, internal views showing the arrangement of striae and position of the raphe slits. The foot poles are depicted with arrows; C, close-up of the foot pole of the specimen in B showing the raphe and terminal position of the rimoportula (arrow). figs D–F. Scanning electron micrographs of *A.* sp. 1: D, specimen depicting the long, slender and tapering nature of the valve. Note the bending of the valve on the foot pole (arrow); E–F, close-ups of the head (E) and foot (F) poles of the specimen in D. Note the bending of the distal raphe fissure up on to the valve face and the hyaline zone surrounding the distal end of the raphe. In F, black arrow indicates the rimoportula, while the white arrows denote the position of the axial area along the ventral margin. Scale bars 10 µm (D), 5 µm (A–B) and 2 µm (C, E–F).
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Metzeltin & Lange-Bertalot (2010) proposed the genus Actinella as being commonly intriguing from three points of view. First, there are species known from the Giraffe locality. This finding is Actinella genus in need of re-evaluation. If the hypothesis was proven correct, Actinella goodwinii and Actinella goodwinii species in this single Eocene locality than known taxa have morphologically similar Actinella explain why some Actinella such a hypothesis would of species now classified as Hustedt, condition evolved multiple times within Eunotia, yielding a suite of species now classified as Actinella peronioides Hustedt, A. robusta Hustedt, A. peronoioides Hustedt, and the Giraffe taxa described in this paper and earlier by Siver et al. (2010).

Heteropolarity is likely an adaption for attachment, either directly on to a substrate, through formation of a mucilaginous stalk (e.g. Actinella aoteaeroaia), or to each other to form a colony (Sabbe et al., 2001). In fact, in his original description of Actinella, Lewis (1864) recorded stellate colonies of A. punctata, with cells connected to each other by their foot poles. One of us (PAS) has observed such colonies of A. punctata in plankton samples from Lewis’ type locality, Saco Pond. If a heteropolar shape facilitates attachment, and if attachment would prove beneficial for survival, then one possible scenario is that the heteropolar condition evolved multiple times within Eunotia, yielding a suite of species now classified as Actinella. Such a hypothesis would explain why some Actinella taxa have morphologically similar counterparts in Eunotia. As discussed below, we certainly recognize this possibility with respect to the relationship between Actinella goodwinii and Eunotia bidentula W. Smith. If this scenario is proven correct, Actinella would represent a polyphyletic genus in need of re-evaluation.

Combining Actinella giraffensis (Siver et al., 2010) with the results of this study, there are now at least five, and probably six, Actinella species known from the Giraffe locality. This finding is especially intriguing from three points of view. First, there are more Actinella species in this single Eocene locality than known today from all of North America and Europe (Siver & Wolfe, 2009; Ripple & Kociolek, 2013). In addition, a review of the literature for Eunotia shows that heteropolar specimens are extremely rare (Sabbe et al., 2001), making the range of heteropolar eunotiophycid taxa in the Giraffe material even more impressive and unique. Second, the high-latitude geographical location of the Giraffe locality is far removed from the modern centres of biodiversity for Actinella in the Southern Hemisphere (Kociolek et al., 2001; Sabbe et al., 2001), which is especially pronounced in low pH brown-water (humic) ecosystems of the tropics (Melo et al., 2010). These observations support the hypothesis proposed by Siver & Wolfe (2009) that this genus was historically much more widespread than at present in the Northern Hemisphere. This hypothesis is further supported by the fact that the only other known fossil finds for Actinella are from the Northern Hemisphere, having being uncovered from eastern Russia (Actinella penzhicha; Lupikina & Dolmatova, 1984), France (Actinella pliocenica; Héribaud, 1902), and the northern Province of Jiling in China (Actinella miocenica; Li, 1988). Third, it is equally intriguing that these Eocene taxa lack highly heteropolar Actinella species and ones with apical protuberances, as well as more elaborately shaped Eunotia taxa similar to ones found today especially in South America (Metzeltin & Lange-Bertalot, 1998; 2007). It is tempting to suggest that the Eocene may represent a time period where Actinella was beginning to diverge from Eunotia by evolving a heteropolar condition more adapted for an attached life style, and prior to the time where both genera began to develop more elaborate valve morphologies. Future molecular phylogenetic studies will undoubtedly help elucidate the evolutionary histories of these two closely related genera and determine their generic validity.

The morphological structure of Actinella goodwinii is similar to Eunotia bidentula (Siver & Hamilton, 2011), and it is possible that the two taxa shared a common ancestor. The overall valve shape, structure of the raphe, striae pattern and wide girdle bands are very similar in both species (Siver & Hamilton, 2011). In addition, Siver & Hamilton (2011) illustrated a similar apical structure for E. bidentula as found on A. goodwinii, and the base of the mantle around the apices is thickened on both taxa. However, the consistent heteropolar nature of Actinella goodwinii specimens clearly distinguish it from the modern E. bidentula. In addition, valves of A. goodwinii have a slight, but clearly discernable, concave ventral surface and frustules with foot poles that are slightly rhomboid in girdle view. The ventral surface on E. bidentula specimens is straight and the frustules rectangular in girdle view. Eunotia bidentula specimens are also larger, have more pronounced capitulate apices, and have a longer raphe. Lastly, the distal raphe fissure terminates at the valve margin on E. bidentula (Siver & Hamilton, 2011), whereas on A. goodwinii specimens it bends up and extends on to the valve face. In our opinion, the slight modifications on A. goodwinii that yield its heteropolar nature and reduced raphe structure may be the result of adaption to an attached life style.

Actinella goodwinii also bears some resemblance to Eunotia camelus Ehrenberg, E. camelopsis Metzeltin & Lange-Bertalot, E. schneideri Metzeltin & Lange-Bertalot and E. didon Ehrenberg, but can be distinguished from each based on the heteropolar nature of the frustules, differences in valve morphology and raphe structure. Specimens of E. camelus and E. camelopsis have concave ventral margins and two undulations along the dorsal margin similar to A. goodwinii. However, on larger specimens of both E. camelus and E. camelopsis the number of dorsal undulations increases and becomes less distinct. In addition, the distal raphe end of E. camelus encircles the apex, and specimens of E. camelopsis possess widely spaced striae. Relative to
A. goodwinii, valves of E. schneideri have less-defined dorsal undulations and a straight ventral margin, whereas valves of E. diodon have wider apices and a different raphe structure.

The overall structure of A. hickeyi is unique among Actinella species, especially in regards to the spacing of the striae. There are Eunotia species, for example E. odebrehitiana Metzeltin & Lange-Bertalot and E. parasiliensis Metzeltin & Lange-Bertalot, with similar wide-spaced striae, but these species are easily distinguished from A. hickeyi based on valve morphology. Actinella kimberlitica is very similar in overall structure and dimensions to E. rhomboidea and E. papilloforma Furey, Lowe & Johansen. All three taxa are small, possess heteropolar valves with rounded apices, and have a slightly wider head pole. The foot pole on A. kimberlitica is more extended and the striae density greater than on either of the Eunotia species. In addition, the rimoportula on E. papiloforma specimens is restricted to the head pole, whereas on A. kimberlitica it is on the foot pole. Nevertheless, based on morphological structure, these three taxa are closely related and, as already discussed, given the heteropolar nature of the valve, E. rhomboidea and E. papiloforma may more appropriately belong in Actinella.

On some species of Actinella the base of the mantle around the apex is thickened and extended inward forming a pseudoseptum (Metzeltin & Lange-Bertalot, 1998; Kociolek et al., 2001). The extent of the pseudoseptum, and on which pole it is found, varies among taxa. On most species, as is the case for Actinella goodwinii, the pseudoseptum is shallow and found on the foot pole. On other taxa the pseudoseptum is extensive (e.g. A. falceifera), or located on the head pole (e.g. A. eunotioides and A. peroniioides). The presence of pseudosepta on both poles, as observed for Actinella hickeyi, has not been documented previously. The role of the pseudoseptum is not known, but it likely strengthens the valve and may be associated with attachment.

Based on modern analogies, the sections of the Giraffe core harbouring large concentrations of Eunotiophyceae specimens, including the heteropolar forms, likely represent relatively shallow, acidic, humic habitats (Sabbe et al., 2001; Melo et al., 2010; Siver & Hamilton, 2011). As a genus, Actinella taxa are commonly reported in highly acidic habitats with high concentrations of dissolved humic substances (Melo et al., 2010), and either low (Melo et al., 2010) or high (Sabbe et al., 2001) dissolved salt content. In addition, morphologically similar taxa, such as Eunotia bidentula and E. rhomboidea, are consistently reported with average weighted mean pH values close to or below 5 (Camburn & Charles, 2000; Gaiser & Johansen, 2000; Siver et al., 2005; Siver & Hamilton, 2011). The ecological inferences based on the eunotioid specimens are further supported by the remains of other acidophilous and acidobiontic diatoms (Siver et al., 2010), as well as euglyphid rhizarians (Barber et al., 2013) and scaled chrysophytes (Siver & Lott, 2012) typical of low-pH environments.

In summary, the large number of heteropolar Actinella taxa uncovered from the Giraffe core significantly extends the geological record of the genus, and more than doubles the number of species known from the fossil record. Most of the species have isopolar counterparts in the closely related genus Eunotia, implying that they are recently diverged forms. The presence of Actinella in the Giraffe core further demonstrates how greenhouse conditions of the middle Eocene exerted profound biogeographical reorganizations; these and other taxa with temperate to tropical affinities are of particular utility in reconstructing the ontogeny of the Giraffe maar lake.

ACKNOWLEDGEMENTS AND FUNDING
This work was funded with support to PAS from the US National Science Foundation (DEB-0716606 and DEB-1144098), and to APW from the Natural Sciences and Engineering Research Council of Canada.

Manuscript received 4 July 2014
Manuscript accepted 15 October 2014
Scientific editing by Alan Lord.

REFERENCES
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