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Otodus-bitten sperm whale tooth from the Neogene of the Coastal Eastern United States

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A description and analysis is given of a single physeteroid tooth, from the Neogene of the Nutrien Aurora Phosphate Mine (formerly known as the Lee Creek Mine, Aurora, North Carolina, USA), that was bitten either by the extinct megatoothed shark *Otodus chubutensis* or *Otodus megalodon*. The tooth shows three gouges, one of which also preserves raking bite traces, made as the serrations on the *Otodus* sp. tooth struck and cut into its surface. We do not know if these bite traces came about as a result of scavenging or active predation. However, because the bite traces occur on part of the skull, this suggests a predatory interaction. This tooth preserves the first evidence in the fossil record of a predatory/antagonistic interaction between a sperm whale and a megatoothed shark.

An ever-increasing number of fossil cetacean bones are becoming known that exhibit shark bite traces (Deméré and Cerutti 1982; Cigala Fulgosi 1990; Purdy 1996; Bianucci et al. 2002, 2010; Renz 2002; Godfrey and Altman 2005; Aguilera et al. 2008; Ehret et al. 2009; Bianucci et al. 2010; Bianucci and Gingerich 2011; Kallal et al. 2012; Takakuwa 2014; Carrillo-Briceño et al. 2016; Collareta et al. 2017, 2019; Godfrey et al. 2018; Kent 2018; Collareta et al. 2019; Mierzwiak and Godfrey 2019). Only a small minority of these can be attributed to a specific shark, and fewer still to the feeding habits of the extinct megatoothed sharks, *Otodus chubutensis* or *Otodus megalodon* (Otodontidae) (Purdy 1996; Renz 2002; Godfrey and Altman 2005; Aguilera et al. 2008; Carrillo-Briceño et al. 2016; Collareta et al. 2017; Godfrey et al. 2018; Kent 2018; Mierzwiak and Godfrey 2019). Hitherto, all the known interactions between *Otodus* spp. and cetaceans have involved mysticetes or small odontocetes. Here, a single sperm whale tooth (Physeteroidea) is described that was bitten repeatedly by *O. chubutensis* or *O. megalodon*.

Institutional abbreviations.—CMM-V, Calvert Marine Museum fossil vertebrate collection, Solomons, USA; MNHN, Museum national d'Histoire naturelle, Paris, France.

Geological setting

The tooth described herein (CMM-V-8955) was surface collected by NLR from within the Nutrien Aurora Phosphate Mine (formerly known as the Lee Creek Mine) in Aurora, Beaufort County, North Carolina, USA. The Neogene geology and palaeontology of this site has been thoroughly described elsewhere (Ray 1983, 1987; Purdy et al. 2001; Ray and Bohaska 2001; Ray et al. 2008). Whitmore and Kaltenbach (2008) described the cetacean fauna from the Aurora Mine and noted that physeteroid teeth "…with enamel-coated crowns… are probably from the Pungo River Formation…" (Whitmore and Kaltenbach 2008: 236–237). In light of the fact that CMM-V-8955 has an enameled crown, it is possible that it derives from the middle Miocene Pungo River Formation. However, more recently, Fitzgerald (2011) described a physeteroid tooth with an enameled crown from the Pleistocene of Nauru, equatorial southwest Pacific. Therefore, the presence of an enameled crown in CMM-V-8955 is not sufficient evidence to confirm the stratigraphic origin. Consequently, it is possible that CMM-V-8955 originated from either the Miocene Pungo River Formation or the Pliocene Yorktown Formation.

Description

CMM-V-8955 (Fig. 1) is a shark-bitten physeteroid tooth. In its overall appearance, it approximates a gently curved spindle, 116.5 mm in its straight-line length and 28.5 mm in maximum diameter. The maximum height of the very lightly crenulated enamel crown is 19.5 mm. Most of the gibbous root of the tooth is marked by shallow longitudinal furrows. The short crown of CMM-V-8955 curves lingually. Because of occlusion with a functional tooth in the opposite jaw, the labial face of the crown and a portion of the root were worn to a smooth and very shiny surface (that side of the tooth is not shown in Fig. 1). The pulp cavity is approximately 26 mm deep and 13.5 mm in maximum diameter.

The two most prominent shark tooth marks (labelled as gouges 1 and 2 in Fig. 1) occupy approximately the midpoint in tooth length on the lingual face of the root. At 23.5 mm long, gouge number 2 is the longest. It is preserved as a ragged gouge mark that cuts approximately diagonally across the mid-length of the root of the tooth. Gouge number 1 is 11.5 mm in length. Its diagonal course parallels that of number 2. Adjacent to this bite trace, and associated with it, are finer traces that were made by the serrations on the cutting edge of the *Otodus* sp. tooth (Fig. 1A_3). There are 12 fine serration marks over a distance of 7.6 mm. Therefore, the center of each serration is separated

† Norman L. Riker passed away on 11th January 2021.

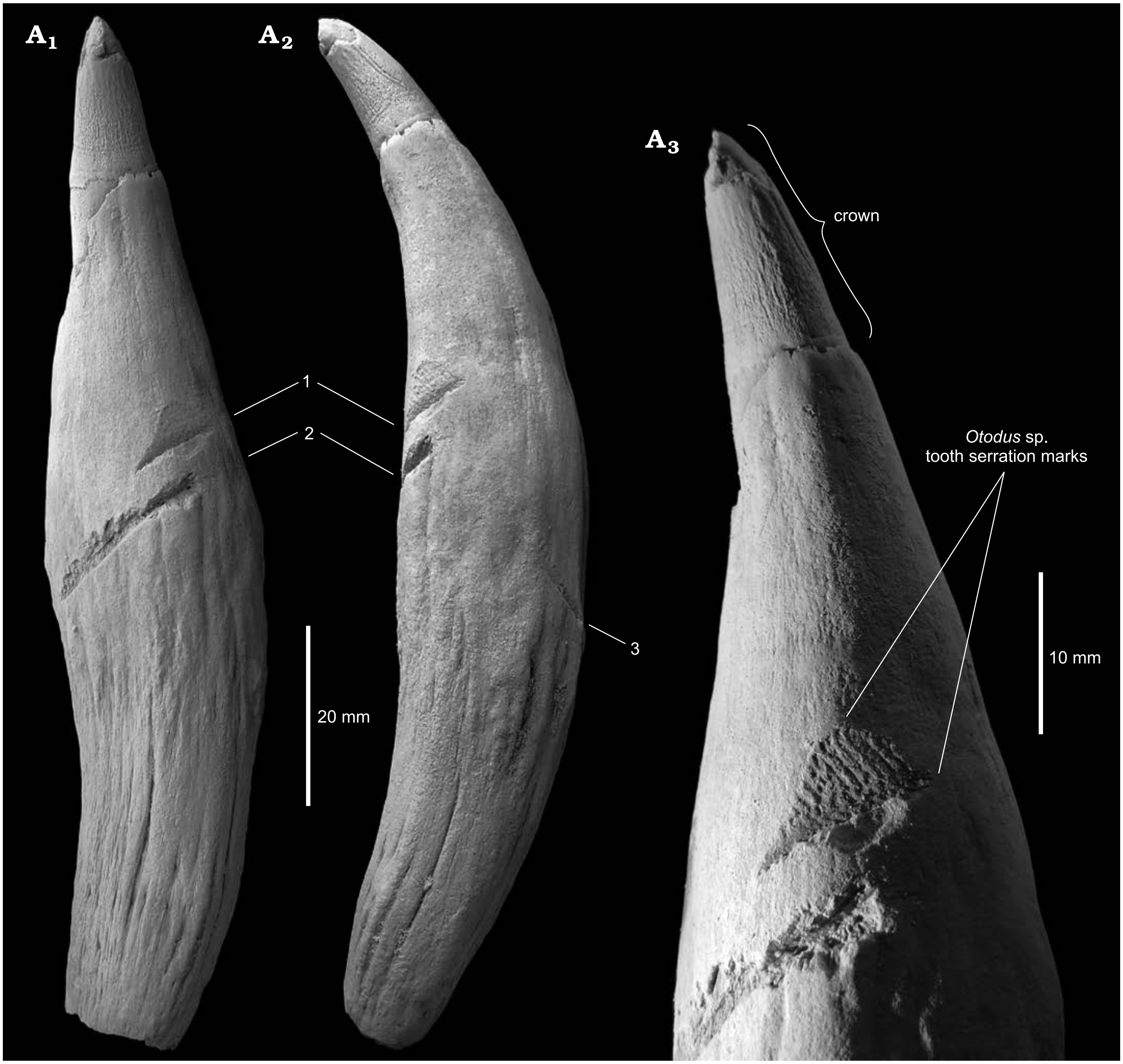

Fig. 1. *Otodus*-bitten sperm whale tooth (CMM-V-8955) from the Neogene of the Aurora Phosphate Mine, North Carolina, USA; in lingual (A_1) and anteromedial (A_2) views, showing all three bite traces, as indicated by the numbers 1–3; A_3, enlarged view of the two primary bite traces, one of which shows the serration marks left as the shark tooth cut into the sperm whale tooth. The specimen was whitened with sublimed ammonium chloride to enhance contrast.

from the center of its neighboring serration by about 0.63 mm. The third gouge, 11 mm long, is not as deep as the aforementioned bite traces. It occupies a position on the root more proximal than the others (number 3 in Fig. 1A_2). It also crosses the root of the sperm whale tooth diagonally and perpendicular to the direction of the other two gouges.

Concluding remarks

In addition to *Otodus chubutensis* and *Otodus megalodon*, there are other Neogene sharks known from the Nutrien Aurora Phosphate Mine that possess serrated crowns. They include *Notorynchus cepedianus*, *Hexanchus* sp., *Carcharodon carcharias*, *Hemipristis serra*, *Galeocerdo* sp., *Physogaleus contortus*, *Galeocerdo* cf. *G. cuvier*, and seven species within the genus *Carcharhinus* (Purdy et al. 2001). However, based on a combination of the size of the bite traces and the size and even spacing of the serration traces, we rule all of them out except for the *Otodus* spp. as possible contenders. We exclude *Carcharodon carcharias* because large teeth of this species have serrations that are too large and widely spaced to have made the gouge traces present on the sperm whale tooth

Fig. 2. A possible origin of the *Otodus* tooth bite traces on the root of the Neogene sperm whale tooth CMM-V-8955. An *Otodus* sp. (foreground) is biting the rostrum of a sperm whale (background). That the bite traces occur on the tooth of the sperm whale hints at a live antagonistic interaction between these two macropredators.

(Nyberg et al. 2006: fig. 8). The teeth of *Otodus* spp. exhibit fine and regular serrations whereas those of *C. carcharias* are coarse and irregular (Ehret et al. 2012: fig. 4).

Because of the parallel and close spacing of gouges 1 and 2, we think they represent cuts made by the same or a vicinal tooth during two separate bites. When the sperm whale tooth is held within a reconstructed jaw of *O. megalodon*, it would appear that gouge 3 was made when the sperm whale tooth was bitten by a separate *Otodus* tooth in the opposing mandible.

When the Nutrien Aurora Phosphate Mine was open to collectors, hundreds of physeteroid teeth were collected from spoil piles and placed within the collections of the National Museum of Natural History, the Smithsonian Institution (Whitmore and Kaltenbach 2008; Gilbert et al. 2018). A smaller collection of comparable teeth is housed in the Calvert Marine Museum. Unfortunately, most of these teeth do not exhibit diagnostic features allowing for precise taxonomic assignment below the familial level (Whitmore and Kaltenbach 2008; Gilbert et al. 2018). Of the three enamel-crowned sperm whale tooth morphotypes described by Whitmore and Kaltenbach (2008) from the Nutrien Aurora Phosphate Mine, CMM-V-8955 most closely resembles the smooth-enamel crown fusiform teeth attributed to morphotype 3. Unfortunately, this attribution does not confer a taxonomic assignment to the tooth. Therefore, the specific identity of CMM-V-8955 will remain a mystery until a closely similar tooth-bearing physeteroid skull is discovered and described. Furthermore, we do not know the position of the tooth within the dental arcade of the sperm whale.

CMM-V-8955 matches closely the length and girth of some of the larger teeth in a specimen of the Peruvian late Miocene physeteroid *Acrophyseter deinodon* (MNHN SAS 1626; Lambert et al. 2016). Based on equations from Lambert et al. (2010) using bizygomatic width and condylobasal length, they calculated a body length of 4.0–4.3 m for *A. deinodon*. Based solely on similarity in tooth size, we estimate that CMM-V-8955 came from a sperm whale that was also approximately 4 m in total body length. From the bite traces, we are not able to estimate the length of the megatoothed shark.

Although we do not know for sure if these bite traces came about as a result of scavenging or active predation, we think that a stronger case can be made for active predation (Fig. 2). It would seem unlikely that a large shark would target the jaws of a floating or seafloor carcass of a sperm whale. There would be little flesh in return for the effort. Rather, these bite traces suggest a live antagonistic interaction. They hint at an attack to the head with the goal of inflicting a mortal wound. Collareta et al. (2019) described a partial skull of a diminutive sperm whale (the holotype of the kogiid *Pliokogia apenninica*) from the lower Pliocene of Italy preserving shark bite traces (tentatively attributed to the extinct white shark, *Carcharodon hastalis*) at its rostrum base. These purported attacks to the skull contrast with the strategies used by modern large sharks to attack small, echolocating toothed whales. Modern large sharks are thought to concentrate their attacks on the posterior part of the body, whereby avoiding detection by both the lateral visual field and the anteriorly directed biosonar of their prey (Long 1991; Long and Jones 1996; Bianucci et al. 2010; Godfrey et al. 2018).

Apparently, in stark contrast to the aforementioned strategies on echolocating toothed whales, predation patterns of *Carcharodon carcharias* on non-echolocating marine mammals (i.e., pinnipeds) inferred from wounded carcasses differ in that bite marks are more evenly distributed all over the body. They have even been found with regularity on the head in the case of true seals, suggesting that great white sharks focus on the anterior part of the body when attacking these prey (Long and Jones 1996). Bite traces by megatoothed sharks have now been found in all regions of cetacean skeletons (Purdy 1996; Renz 2002; Godfrey and Altman 2005; Aguilera et al. 2008; Carrillo-Briceño et al. 2016; Collareta et al. 2017; Godfrey et al. 2018; Kent 2018; Mierzwiak and Godfrey 2019). However, we do not yet know if megatoothed sharks had preferred attack strategies for different prey types.

At a minimum, these bite traces demonstrate, for the first time, trophic interaction between a megatoothed shark and a medium-size sperm whale. What makes these bite traces more interesting is that they occur on part of the root that was originally embedded in the jaw (at least for gouge 3). In order for the shark teeth to have marked the sperm whale tooth, they would first have had to cut/break through the jaw bone. The bite most likely also damaged the surrounding bone. This implies the ability of a powerful bite on the part of the shark.

Based on their analysis of physeteroid teeth from the Nutrien Aurora Phosphate Mine, Gilbert et al. (2018) proposed that these odontocetes matured rapidly and had a relatively short life span (≤25 years) because of high predation pressures exerted by large predators, including *Otodus megalodon*. This bitten tooth lends support to their findings.

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