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Tooth marks of the Great White Shark from a Pliocene outcrop of the Northern Apennines (Castell'Arquato, Italy)

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Abstract: We describe and analyze a rib fragment of a small cetacean from the Castell'Arquato Plio-Pleistocene Basin (Northern Apennines, Italy) that displays various tooth marks featuring parallel striations similar to those left by the serrated tooth of the extant white shark, *Carcharodon carcharias*. The discovery locality, known as "Buca della Balena", was an inner-shelf marine setting where sharks may have scavenged on drifting cetacean carcasses in Piacenzian times. The high number of marks found on the small bone fragment suggests multiple bites by one or more shark individuals. The rib fragment studied is one of the few osteological specimens from the Pliocene of the Mediterranean Basin to preserve white shark tooth marks.

Keywords:

- Pliocene;
- Piacenzian;
- Cetacea;
- *Carcharodon carcharias*;
- great white shark;
- tooth marks;
- Castell'Arquato;
- Northern Apennines

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Résumé : ***Traces de morsures de grand requin blanc provenant d'un affleurement pliocène des Apennins du Nord (Castell'Arquato, Italie).***- Nous décrivons et analysons un fragment de côte d'un petit cétacé du bassin plio-pléistocène de Castell'Arquato (Apennins du Nord, Italie). Ce fragment présente diverses traces de morsures avec des stries parallèles similaires à celles laissées par la dent crénelée du grand requin blanc actuel, *Carcharodon carcharias*. Le site de la découverte, connu sous le nom de "Buca della Balena", est localisé dans la partie interne d'un plateau sous-marin où, au cours du Plaisancien, les requins pouvaient se nourrir de carcasses dérivantes de cétacés. Le grand nombre de marques relevées sur ce petit fragment d'os suggère de multiples morsures par un ou plusieurs individus. Le fragment de côte étudié est l'un des rares spécimens ostéologiques du Pliocène du bassin méditerranéen à conserver de telles marques de dents de grand requin blanc.

Mots-clefs :

- Pliocène ;
- Plaisancien ;
- cétacés ;
- *Carcharodon carcharias* ;
- grand requin blanc ;
- marques de dents ;
- Castell'Arquato ;
- Apennins du Nord

1. Introduction

Fossil evidence for the ancient trophic interactions between white sharks (*Carcharodon carcharias* Linnaeus, 1758) or other shark species (*e.g.*, *Cosmopolitodus hastalis*) and large marine mammals is mostly represented by tooth marks on bone. These ichnofossils result from the impact of the shark teeth on the skeletal elements of prey or scavenged items (Jacobsen & Bromley, 2009; Pirrone *et al.*, 2014; Collareta *et al.*, 2017; Freschi, 2017; Zonneveld *et al.*, 2022). In the case of the white shark, *Carcharodon carcharias* (Linnaeus, 1758), the tooth marks display a characteristic outline due to the marginally serrated tooth edges that produce parallel grooves on the bitten bones (Cigala-Fulgosi, 1990). To date, the fossil record of the Pliocene basins of the Mediterranean region has provided a few examples of trophic interaction between white sharks and cetaceans in which tooth marks are present (*e.g.*, Bianucci *et al.*, 2000; Bisconti, 2008).

This article describes some whiteshark tooth marks that were found on a single rib fragment of a small cetacean from the Pliocene of the North Apennines. This rib fragment has been mentioned by Cigala-Fulgosi (1990) and then figured by Collareta *et al.* (2023a: Fig. 5.C-D); however, it has only been described at some length in a conference paper in Italian (Freschi & Cau, 2020), hence our more complete characterization herein.

2. Material and methods

We describe the traces and assign a toothmark type based on the terminology proposed by Cigala-Fulgosi (1990) and subsequent studies (Bianucci *et al.*, 2010; Collareta *et al.*, 2017). The tooth marks are thus divided into five morphological-genetic types:

1. Type I: The tooth completely penetrates the bone, leaving a single, clean cut perpendicular to the bone;
2. Type II: The tooth penetrates the bone and then moves in a sawing fashion, producing a cut with light, jagged marks;
3. Type III: The tooth strikes the bone and then drags straight across the surface of the bone, producing shallow, parallel striae;
4. Type IV: The tooth strikes the bone and then drags in an undulating manner across the surface, producing shallow, wavy, parallel marks;
5. Type V: The tooth penetrates deep into the bone and carves out a prismatic or wedge-shaped indentation.

3. Geological background

The fossil specimen described herein was found at the 'Buca della Balena' locality (hereinafter, BDB), in the vicinity of the Osteria di Montezago (GPS coordinates: 44°50'00"N, 9°46'58"E) (Fig. 1). The BDB section is 55 meters thick and consists of inner-shelf deposits of the Castell'Arquato Plio-Pleistocene Basin (Roveri & Taviani, 2003). These deposits are part of the Upper Pliocene (Piacenzian) Montezago Superiore Unit (Freschi *et al.*, 2019, and references therein) (Fig. 1.B-C). The BDB section shows a rhythmic alternation of ten depositional cycles, each of which is 1–5 meters thick (Fig. 1.D). These cycles are formed by hemicycles of fine sandstone containing scarce macrobenthic fossils and poorly cemented biocalcarenite hemicycles of coarse sandstone that are rich in skeletal remains of macrobenthos. The bioclasts are unorganized and display abrasion and/or bioencrustation by bryozoans and cirripedes. The presence of *Discoaster tamalis* throughout the section indicates that the geological age of the BDB section is within the 3.40–3.10 Ma time interval (Cau *et al.*, 2019, 2020; Freschi *et al.*, 2019).

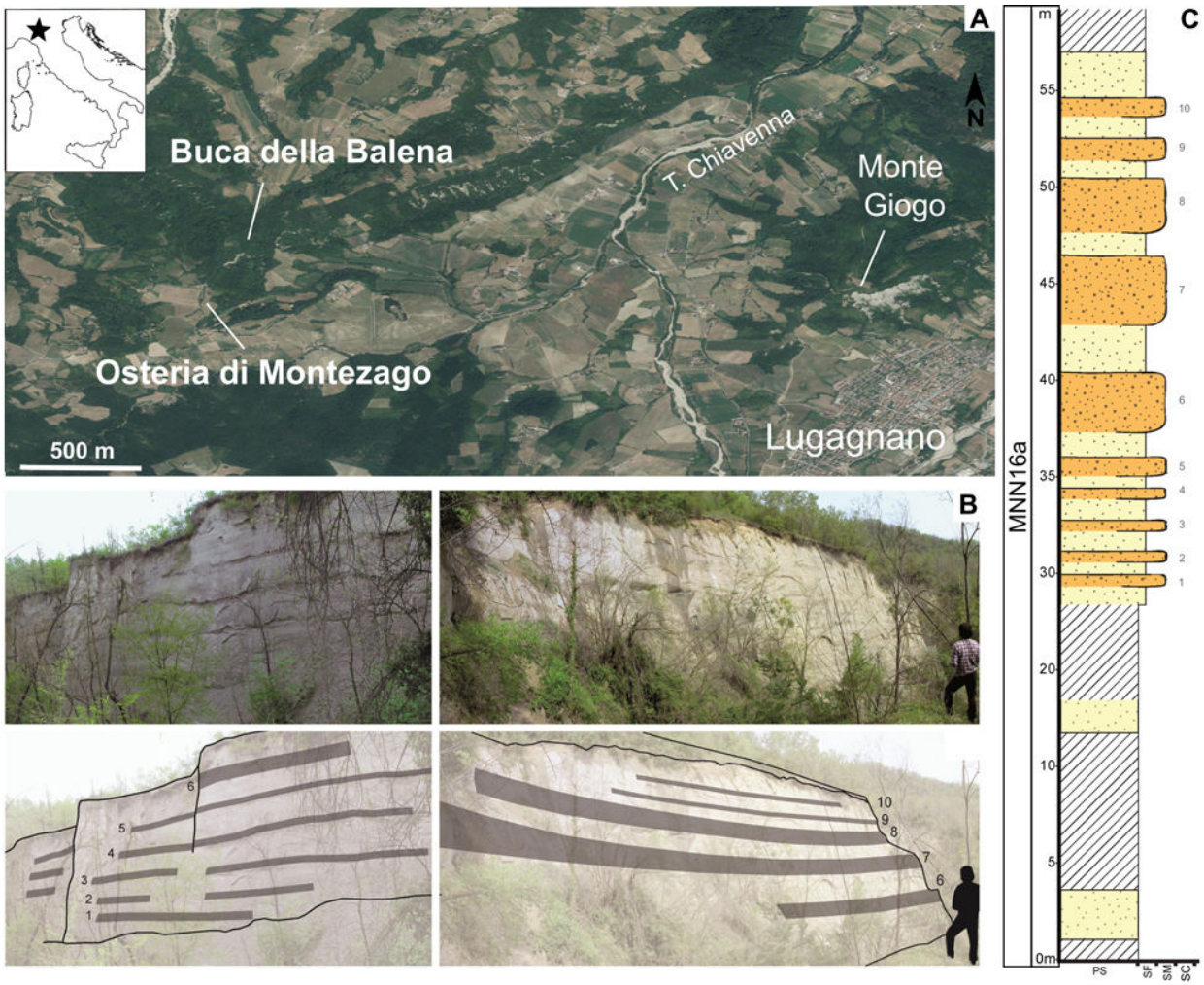

Figure 1: Geographical, stratigraphical, and lithological information of the Buca della Balena (BDB) outcrop. **A)** Geographical position of the BDB fossiliferous locality in Piacenza province (Italy); **B)** field photographs and corresponding line drawings of the upper part of the section, featuring ten distinct biocalcarenitic horizons; **C)** stratigraphic log of the BDB locality. Numbers in panels B and C identify the ten biocalcarenitic horizons. PS = sandy pelites; SF = fine sands; SM = medium sands.

4. Systematic vertebrate paleontology

Order: CETACEA Brisson, 1762

Cetacea indet.

(Fig. 2)

Referred material: VT0173, a rib fragment found at the 'Buca della Balena' locality, in the vicinity of the Osteria di Montezago. VT0173 is currently stored in the "G. Cortesi" Geological Museum in Castell'Arquato (Piacenza Province, Italy).

Description: The specimen is a medial rib fragment. It is 72 mm long and about 15 mm in maximum diameter, with an elliptical cross-section. The external surface of the bone is well preserved. The outer, compact bone is relatively thick, but the rib is neither osteosclerotic nor pachyostotic. Although a taxonomic assignment to any specific marine mammal taxon is difficult, we can exclude the sirenians based on their bone characteristics, and the pinnipeds based on the shape and overall size of the fragment. Owing to these observations, VT0173 is classified herein as belonging to a small, indeterminate cetacean.

Descriptive ichnology: Marks of various shapes and lengths are visible on the rib fragment. Six such marks are located on the dorsal surface of the rib, and another is located on the ventral central surface of the rib (Fig. 2.A). The incisions range from 5 to 29 mm in length and are often associated with parallel streaks with spacings of about 0.5-1 mm. Four 'V-shaped', type II incisions are prominent (Fig. 2.B). One is particularly long and is incised deeply into the bone ; its internal surface is scored with light, parallel streaks (Fig. 2.C-D). Near the anterior margin of the rib, type III and IV surficial marks with deep, parallel grooves are also present (Fig. 2.D-E). A shallow type I mark occurs on the posterior margin of the rib (Fig. 2.A). Several type II marks are characterized by crenulations of the inner surface. The edges of five type II marks are irregular and indicate the detachment of small bone splinters caused by the impact of the tooth (Fig. 2.B). The 'V-shaped' marks are especially deep and cluster on the surface of the bone, exhibiting both concave and convex morphologies.

Figure 2: VT0173, tooth-mark-bearing rib fragment of Cetacea indet. from the Buca della Balena locality. A) The rib fragment in dorsal and ventral views (arrows indicate the tooth marks); B) four different type II tooth marks; C) close-up of some clearly serrated tooth marks; D) two tooth marks belonging to types III and IV; E) type IV. Different tooth marks are identified by different lowercase letters. Scale bars measure 10 mm.

5. Discussion and conclusions

The tooth marks described in this study are interpreted to be the result of the bite of a selachian predator or scavenger. On the basis of morphological and dimensional considerations, the parallel grooves evident on the bone fragment studied indicate production by the large, coarsely serrated teeth of the white shark, *Carcharodon carcharias* (see also Cigala-Fulgosi, 1990; Jacobsen & Bromley, 2009; Schouten, 2017). From an ichnotaxonomic viewpoint (Jacobsen & Bromley, 2009), such tooth marks can be classified within the ichnogenus *Linichnus*, and specifically as *Linichnus serratus*.

The Piacenzian marine setting reflected by the BDB succession was offshore and neritic (Cau *et al.*, 2019, 2020; Freschi *et al.*, 2019). Thus, the BDB palaeoenvironment may have been: 1) frequented by white sharks (Chapple *et al.*, 2011; Jorgensen *et al.*, 2012) as well as by cetaceans (including both odontocetes and mysticetes), and 2) characterized by the transport and/or deposition of cetacean carcasses (Dominici *et al.*, 2020; Moore *et al.*, 2020). This scenario suggests that scavenging activity by mammalophagous sharks was likely to occur (Klimley, 1994; Long & Jones, 1996; Bianucci *et al.*, 2010; Fallows *et al.*, 2013; Collareta *et al.*, 2017; Tucker *et al.*, 2019).

Although VT0173 consists only of a small rib fragment, it exhibits several tooth marks. Similar traces have also been observed on more complete fossil cetacean skeletons, where more than ten tooth marks have been locally observed on a single rib (CIGALA-FULGOSI, 1990; BIANUCCI *et al.*, 2010). The rib from the BDB locality displays a high number of tooth marks with different orientations, which could indicate that the abdomen of the cetacean was bitten multiple times by one or more white sharks (LEA *et al.*, 2018). The abdominal region of a small cetacean is the most voluminous part of the animal – one that comprises layers of fat, internal organs, and muscles (LITCHFIELD *et al.*, 1974). As scavengers, white sharks famously feed by drawing on highly nutritious food sources with minimal effort (HEITHAUS, 2004; BENITES-PALOMINO, 2022).

White shark tooth marks are relatively rare compared to the abundance of cetacean finds from the Pliocene epoch, during which *Carcharodon carcharias* spread worldwide (LEONE *et al.*, 2020). In the Mediterranean Basin, only two other finds of fossil cetacean bones with tooth marks have been described so far, both originating from the Pliocene. The first consists of bite marks on the ulna of *Eschrichtioides gastaldii* (BISCONTI, 2008; see also PORTIS, 1883) from the "Sabbie Gialle Astigiane" of Piedmont. The second such find is an almost complete skeleton belonging to *Hemisyntrachelus cortesii* (DEL PRATO, 1897; BIANUCCI, 1996), which was described in great detail by CIGALA-FULGOSI (1990). This specimen, where 80 different white shark tooth marks were observed, was discovered at the Rio Stramonte locality, a few hundred meters from the BDB section.

Several bone fragments incised by white shark tooth marks have been documented from the southern Atlantic. GOVENDER and CHINSAMY (2013) and GOVENDER (2015, 2019) reported on 14 fragmentary cetacean specimens showing abundant evidence of predation or scavenging from the South African Cape Basin. The concentration of discoveries in this specific area along the southeastern Atlantic coast suggests that white shark populations in the Cape Basin were abundant and engaged in the predation of marine mammals as early as Pliocene times.

Two additional discoveries from the northeastern and central-eastern Pacific margins contribute to the understanding of white shark tooth marks on fossil cetacean remains. DEMÉRÉ and CERUTTI (1982) described tooth marks attributed to a great white shark on a posterior portion of the mandibular ramus of a specimen of *Herpetocetus*, a small (~5 m long) baleen whale, from the San Diego Formation of California (Eastern USA). CORTÉS *et al.* (2019) documented remains of a fossil whale from Panama, specifically appendicular remains of a baleen whale belonging to the family Balaenopteridae. These remains were recovered from the sediments of the Upper Pliocene Burica Formation and, according to CORTÉS *et al.* (2019), they exhibit two distinct types of shark tooth marks on the whale forelimb bones, indicating scavenging activity by at least two great white shark individuals.

Continued research on white shark tooth marks contributes significantly to our knowledge of the paleoecology and distribution of this iconic shark species during the Neogene period. The roughly coeval appearance of teeth and tooth marks from different oceanic regions underscores the rapid dispersal of *Carcharodon carcharias* (COLLARETA *et al.*, 2023a, 2023b). This dispersal was likely facilitated by the gradual disappearance and extinction of the megatoothed shark, *Otodus megalodon*, reducing ecological competition, and by favorable climatic conditions established around 3 million years ago that supported this cosmopolitan top predator (EHRET *et al.*, 2012).

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