

Evolution, Ecology, and Body Size of *Otodus megalodon*



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A quick introduction...



SHARKS!

SINK YOUR TEETH IN!



Calvert Marine
MUSEUM



➤ **What?**

New exhibit on
Maryland sharks

➤ **Where?**

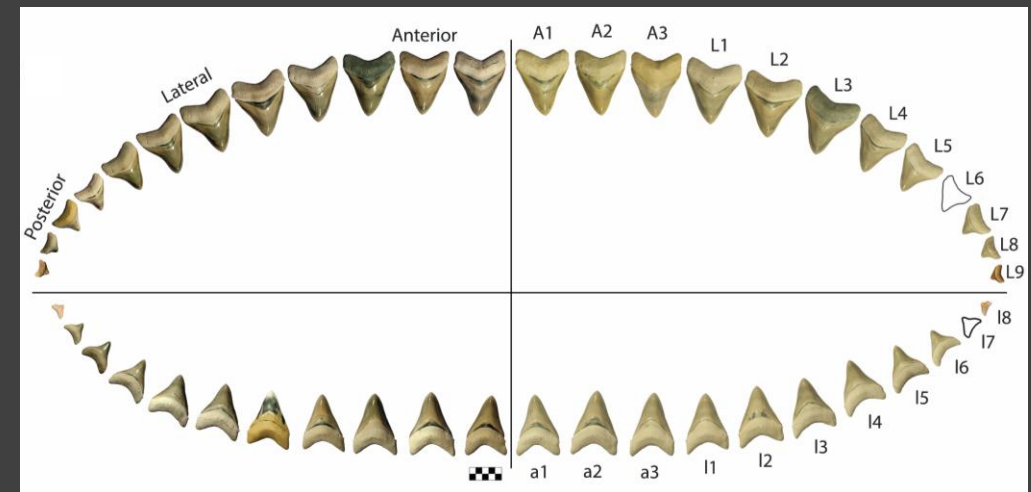
Calvert Marine Museum
Solomons, MD

➤ **When?**

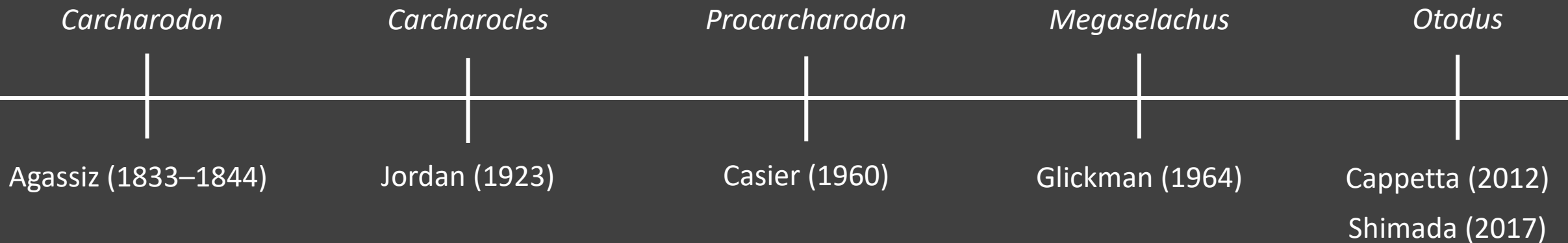
July 2021 – December 2022

Outline

1. Who did Megalodon evolve from?
2. What did Megalodon eat?
3. How big was Megalodon?



Who did Megalodon evolve from?



The different names proposed for the genus of Megalodon refer to different theories about its evolutionary relationships.

Megalodon vs. Great White



1 cm

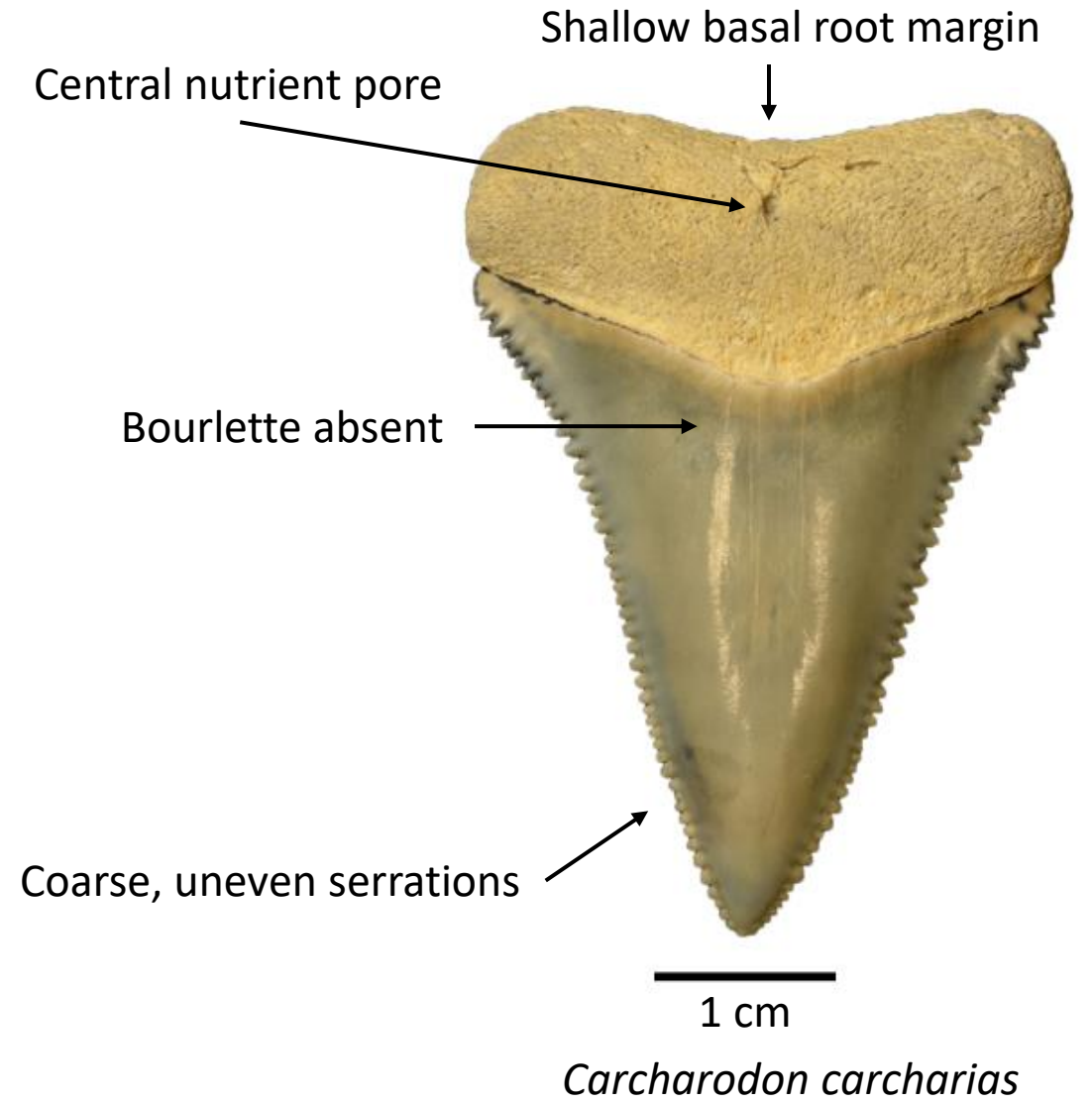
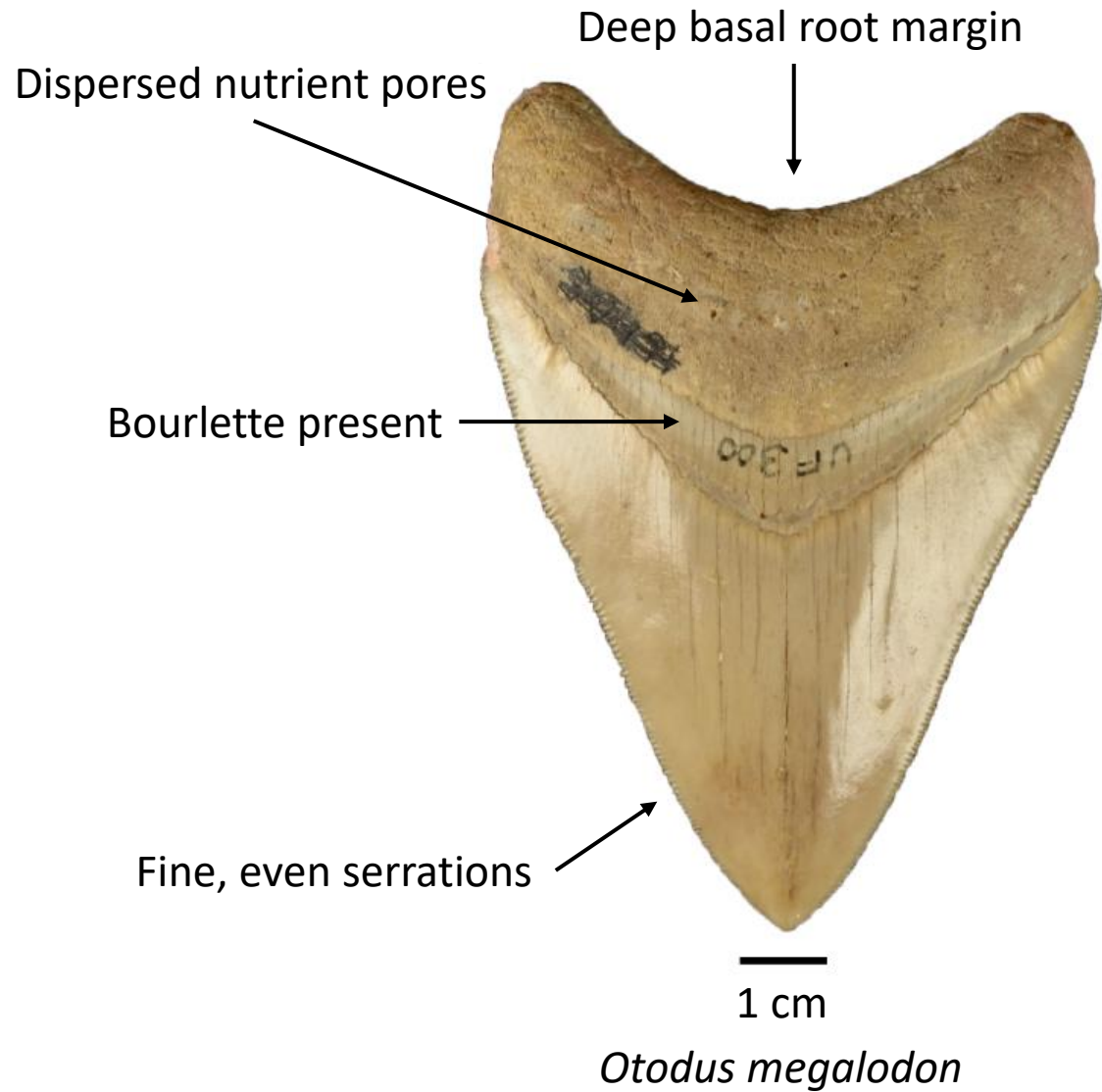
Otodus megalodon



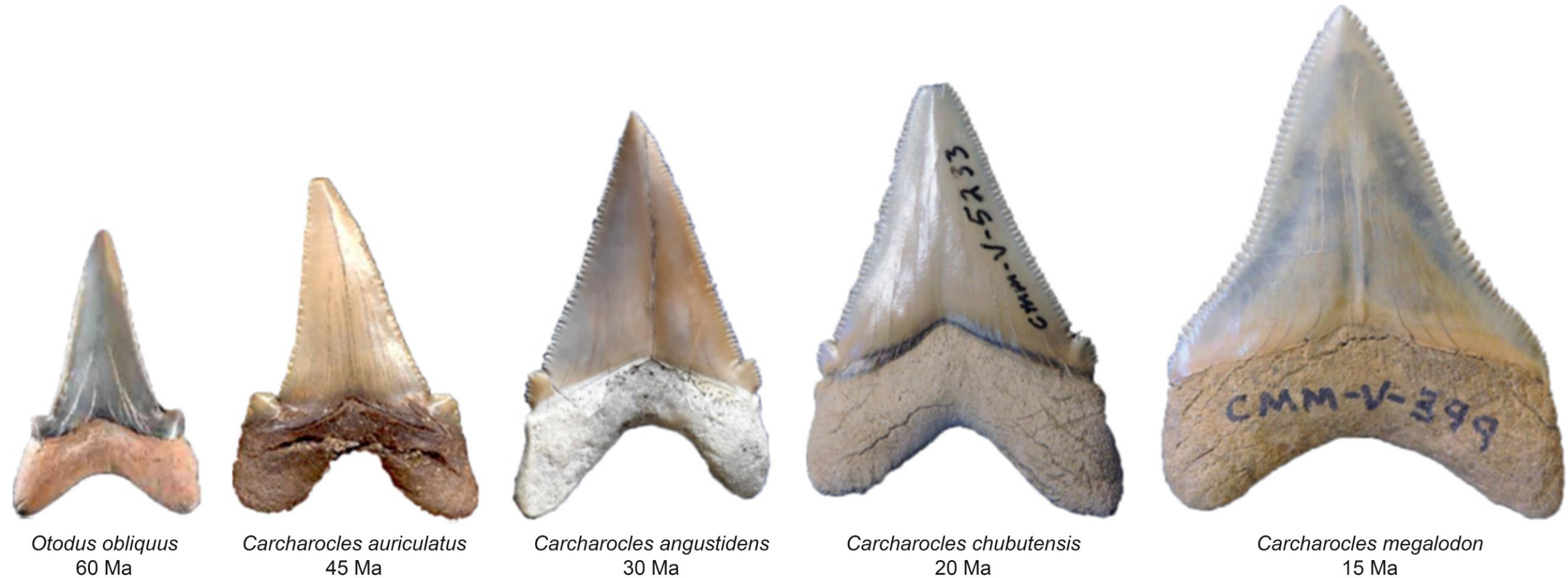
1 cm

Carcharodon carcharias

Megalodon vs. Great White



Megalodon Evolution: Megatooth Shark Lineage



Otodus obliquus
60 Ma

Carcharocles auriculatus
45 Ma

Carcharocles angustidens
30 Ma

Carcharocles chubutensis
20 Ma

Carcharocles megalodon
15 Ma

Great White Evolution: White Shark Lineage



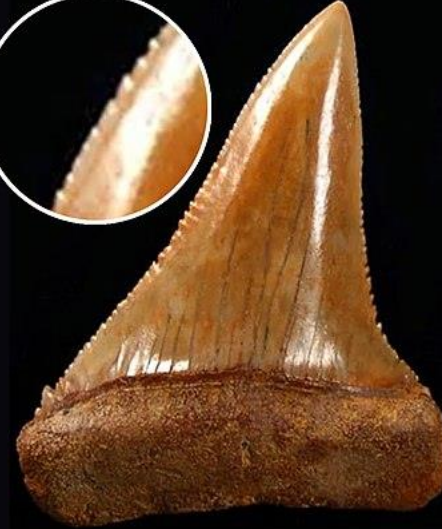
Serrations absent

Carcharodon hastalis



Developing serrations ~8-5 m.y.a.

Carcharodon hubbelli

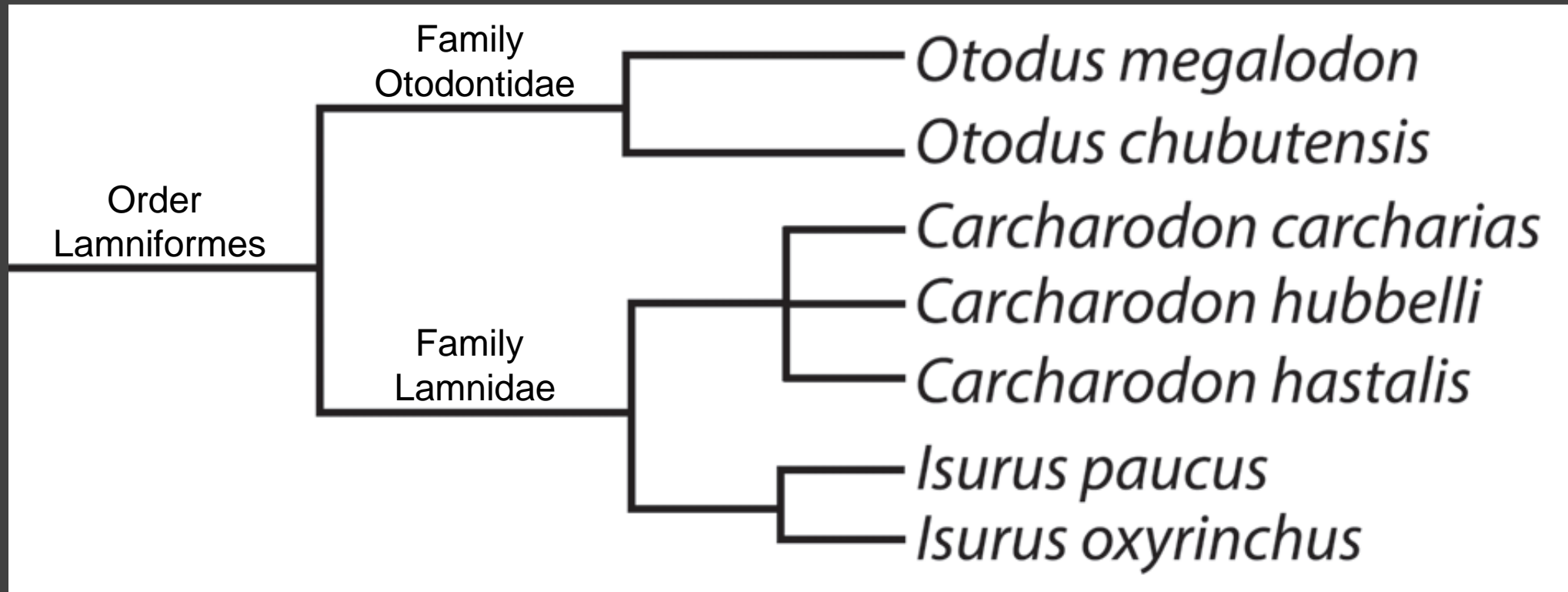


Full serrations

Carcharodon carcharias



Evolutionary Relationship



- Megalodon and the Great White are in two separate taxonomic families
- Their last common ancestor was in the Cretaceous (>65 million years ago)

Relevant Publications

Journal of Vertebrate Paleontology 26(4):806–814, December 2006
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TRACING THE ANCESTRY OF THE GREAT WHITE SHARK, *CARCHARODON CARCHARIAS*, USING MORPHOMETRIC ANALYSES OF FOSSIL TEETH

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ABSTRACT—The evolutionary origin of the great white shark (*Carcharodon carcharias*) is unclear, with debate centering around two principal hypotheses. The first, based on similarity in tooth shape, claims that *C. carcharias* originated from a group of extinct mako sharks that includes *Isurus hastalis*. The second hypothesis, based mostly on cladistic evidence, claims that *C. carcharias* originated from the same lineage as the giant megalothooped sharks, sharing a close evolutionary ancestor with the extinct *Carcharodon megalodon*. To distinguish between the two hypotheses we performed several morphometric analyses. In the first analysis, we used Procrustes method and principal components analysis to quantify variation between *C. carcharias*, *I. hastalis*, and *C. megalodon* in four different positions within the dentition. The results indicate no significant difference in tooth shape between *C. carcharias* and *I. hastalis*. In the second analysis, correlating tooth size with age, we analyzed teeth from upper anterior and lower anterior positions. For both tooth positions, we show that the growth rate of *C. carcharias* is more congruent with the growth rate of *I. hastalis* than that of *C. megalodon*. Finally, we used scanning electron microscopy to show that the tooth serrations of *C. carcharias* are distinct from those of the megalothooped and more similar in size to those of slightly serrated mako teeth. Taken together, these results indicate that *C. carcharias* originated from an extinct group of mako sharks and not from the megalothooped sharks.

INTRODUCTION

Despite more than a century of scrutiny, the evolutionary origin of the great white shark, *Carcharodon carcharias*, is still in dispute. The two leading hypotheses posit an ancestry on the one hand from the extinct megalothooped sharks, including *Carcharodon megalodon*, and on the other from *Isurus hastalis*, an extinct mako shark. It is difficult to argue effectively that one species is directly descended from another, particularly in the case of fossil sharks with their dearth of diagnostic material, so we will describe the two theories in terms of sharing more recent common ancestors (Smith, 1994).

The older and more accepted hypothesis is that *C. carcharias* is descended from the extinct megalothooped sharks that include species such as *Carcharodon auriculatus*, *Carcharodon subsauriculatus*, and *C. megalodon*. In other words, this hypothesis proposes that *C. carcharias* shares a more recent common ancestor with *C. megalodon* than with *I. hastalis*, a view shared by Applegate and Espinosa-Arribarrena (1996), Gottfried and colleagues (1996), and Purdy and colleagues (2001). We will refer to this as the megalodon hypothesis (Fig. 1A). The more recent hypothesis is that *C. carcharias* is descended from the extinct mako sharks that include *I. hastalis*. That is, *C. carcharias* shares a more recent common ancestor with *I. hastalis* than with *C. megalodon*, a view that is shared by Casier (1960), Muizon and DeVries (1985), and Cappetta (1987). We will subsequently refer to this as the *hastalis* hypothesis (Fig. 1B).

In 1835, Louis Agassiz formally introduced *Carcharodon megalodon* based on morphological similarity of tooth shape with *C. carcharias*. Since then, several lines of evidence have been advanced to support the megalodon hypothesis. Applegate and Espinosa-Arribarrena (1996), Gottfried and colleagues (1996), and Purdy and colleagues (2001) identified tooth shape

similarities in *C. carcharias* and *C. megalodon*, including shared symmetries of particular positions and orientation of root lobes. While no formal cladistic analysis has been performed on these species, several non-shape synapomorphies also support the megalodon hypothesis (Applegate and Espinosa-Arribarrena, 1996; Gottfried et al., 1996; Purdy et al., 2001).

Proponents of the megalodon hypothesis view the evolution of *C. carcharias* from the megalothooped sharks as a case of heterochrony, where large *C. carcharias* teeth are similar in morphology to similar sized teeth in *C. megalodon* and other megalothooped sharks (Gottfried et al., 1996). This could explain the lack of lateral denticles in juvenile *C. megalodon* versus the presence of lateral denticles in juvenile *C. carcharias* (Applegate and Espinosa-Arribarrena, 1996).

Although both *C. carcharias* and *C. megalodon* have serrated teeth, Purdy and colleagues (2001) maintain that this is not a useful character for establishing phylogenetic relationships because serrations have evolved many times independently (Applegate, 1967; Compagno, 1988). Purdy and colleagues (2001) also argue that the transition from the extinct makos to *C. carcharias* is not possible because a key hypothesized transitional fossil (Muizon and DeVries, 1987) is from the late Miocene, after the emergence of early *C. carcharias* in the middle Miocene. Furthermore, Purdy (1996) suggests that a similarity in tooth shape between *C. carcharias* and *I. hastalis* could be due to convergent evolution in response to shared pinniped predation.

Casier (1960) submitted the first legitimate challenge to *C. megalodon*'s ascription in the genus *Carcharodon*. Noting the similarity in overall shape, he argued that the serrated-toothed *C. carcharias* evolved from the smooth-toothed broad-form *I. hastalis*, a subset of *I. hastalis* teeth categorized as *I. xiphodon* by Purdy and colleagues (2001). Casier pointed to a shared labiolingual flattening in both *C. carcharias* and *I. hastalis* as a shared, derived character distinct from *C. megalodon*. He also noted the appearance of marginal serrations in some specimens of *I. hastalis*, which look suspiciously like the teeth of *C. carcharias*, and believed he had identified a possible transition species, *Oxyrin-*

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ORIGIN OF THE WHITE SHARK *CARCHARODON* (LAMNIFORMES: LAMNIDAE) BASED ON RECALIBRATION OF THE UPPER NEOGENE PISCO FORMATION OF PERU

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Abstract: The taxonomic origin of the white shark, *Carcharodon*, is a highly debated subject. New fossil evidence presented in this study suggests that the genus is derived from the broad-toothed 'mako', *Carcharodon (Cosmopolitodus) hastalis*, and includes the new species *C. hubbelli* sp. nov. – a taxon that demonstrates a transition between *C. hastalis* and *Carcharodon carcharias*. Specimens from the Pisco Formation clearly demonstrate an evolutionary mosaic of characters of both recent *C. carcharias* and fossil *C. hastalis*. Characters diagnostic to *C. carcharias* include the presence of tooth serrations and a symmetrical first upper anterior tooth that is the largest in the tooth row, while those indic-

ative of *C. hastalis* include a mesially slanted third anterior (intermediate) tooth. We also provide a recalibration of critical fossil horizons within the Pisco Formation, Peru using zircon U-Pb dating and strontium-ratio isotopic analysis. The recalibration of the absolute dates suggests that *Carcharodon hubbelli* sp. nov. is Late Miocene (6–8 Ma) in age. This research revises and elucidates lamnid shark evolution based on the calibration of the Neogene Pisco Formation.

Key words: *Carcharocles*, *Cosmopolitodus*, geochronology, Miocene, *Isurus*, strontium.

NEOSELACHIANS are well represented in the fossil record worldwide during the Neogene and most of the fossil material found consists of isolated teeth. Shark teeth are shed by the thousands over an individual's lifetime and have an enameloid crown that acts as a protective layer during fossilization. The cartilaginous skeleton of chondrichthyans does not typically preserve except in rare instances where calcified vertebral centra, portions of the neurocranium and fin rays have been described (Uyeno et al. 1990; Shimada 1997; Siverson 1999; Gottfried and Fordyce 2001; Shimada 2007; Ehret et al. 2009a). The lack of more complete specimens of most fossil taxa has led to conflicting interpretations about the taxonomy and anatomy of many species. Such problems have caused much confusion in the nomenclature (including generic and specific names) and terminology (i.e. dental homologies) of fossil neoselachians.

One of the most debated enigmas within the neoselachians focuses on the evolution and taxonomic placement of the white shark, *Carcharodon carcharias* (Linnaeus, 1758), within the Lamniformes. There are two distinct hypotheses regarding the evolution of *C. carcharias* that have been proposed in the literature. The first hypothesis places all large, serrated megalothooped sharks within the genus *Carcharodon*, including *C. carcharias* as well as those species referred to as *Carcharocles*, for example, *Carcharocles megalodon* (Jordan and Hannibal, 1923) and its related taxa. Based on this taxonomy, the lineage of *C. carcharias* branched off as smaller forms of the megalothooped sharks and co-evolved alongside the truly large taxa, such as *C. megalodon* (Applegate and Espinosa-Arribarrena 1996; Gottfried et al. 1996; Purdy 1996; Gottfried and Fordyce 2001; Purdy et al. 2001).

The second hypothesis proposes that *C. carcharias* evolved from the broad-toothed 'Oxyrinus' (*Cosmopolitodus*)

What did Megalodon eat?

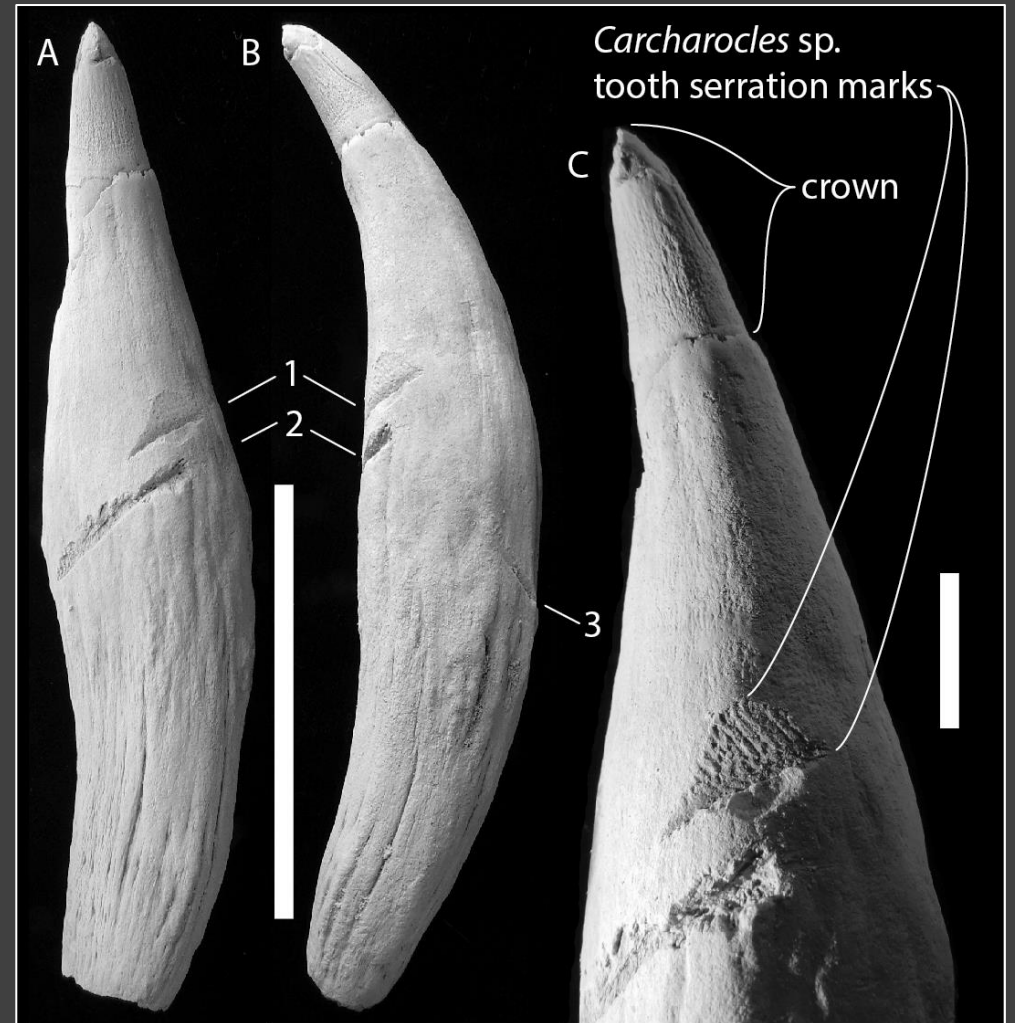


Megalodon's Menu Items

- Marine mammals
 - whales, dolphins, seals, manatees
- Large bony fish
- Other sharks
- Marine reptiles
 - turtles and crocodiles

Megalodon has cutting-type teeth, which help to dismember prey!

Direct Evidence of Predation



Megalodon Daily Diet

It was estimated that Megalodon would require 2500 pounds of food per day to support its large size!



Florida Museum travelling exhibit on Megalodon

Interpreting Diet from Teeth



Tooth Shape



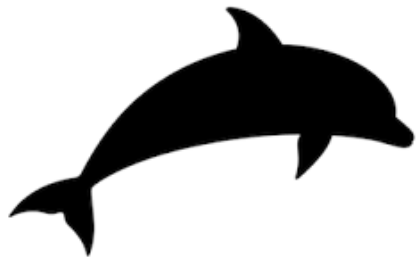
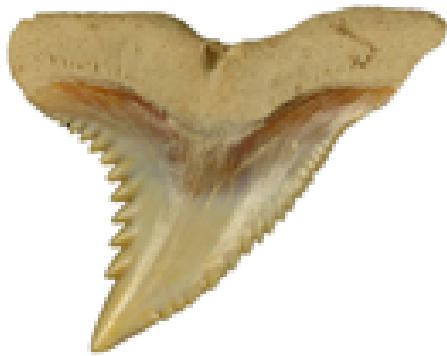
Tooth Function



Diet

Chondrichthyan Tooth Functions

Cutting



Large, fleshy prey

Grasping



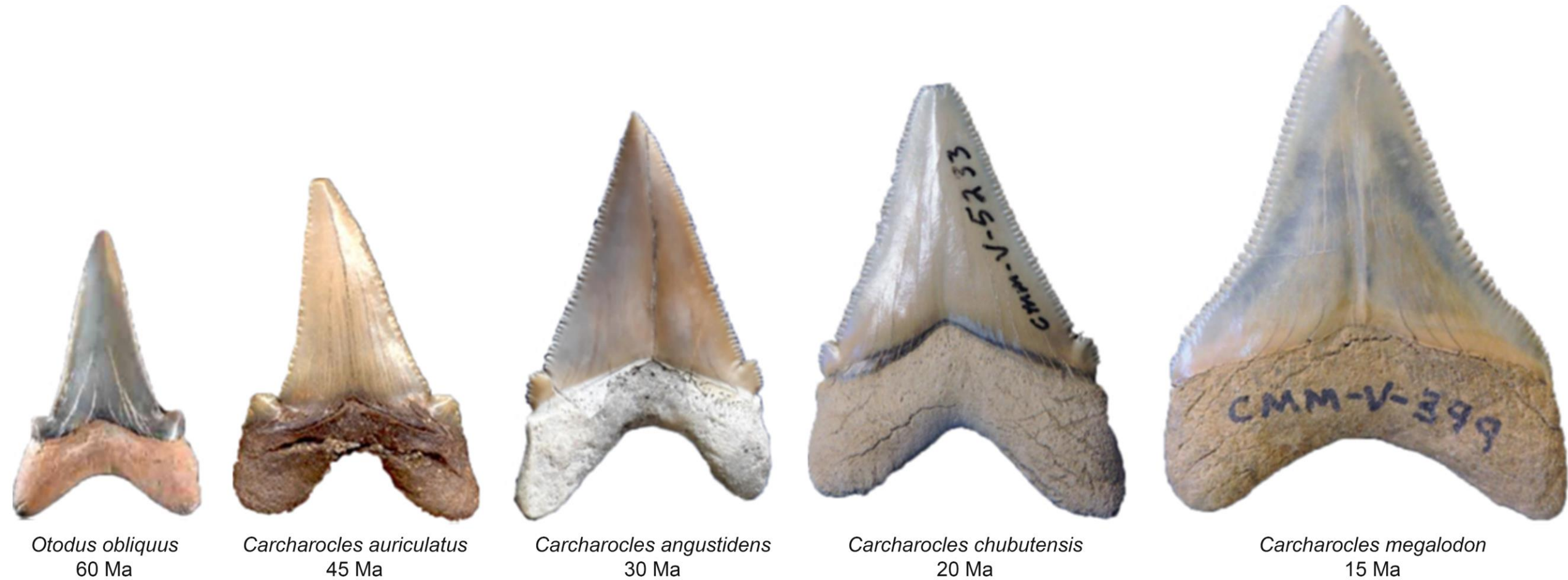
Small, swift prey

Crushing



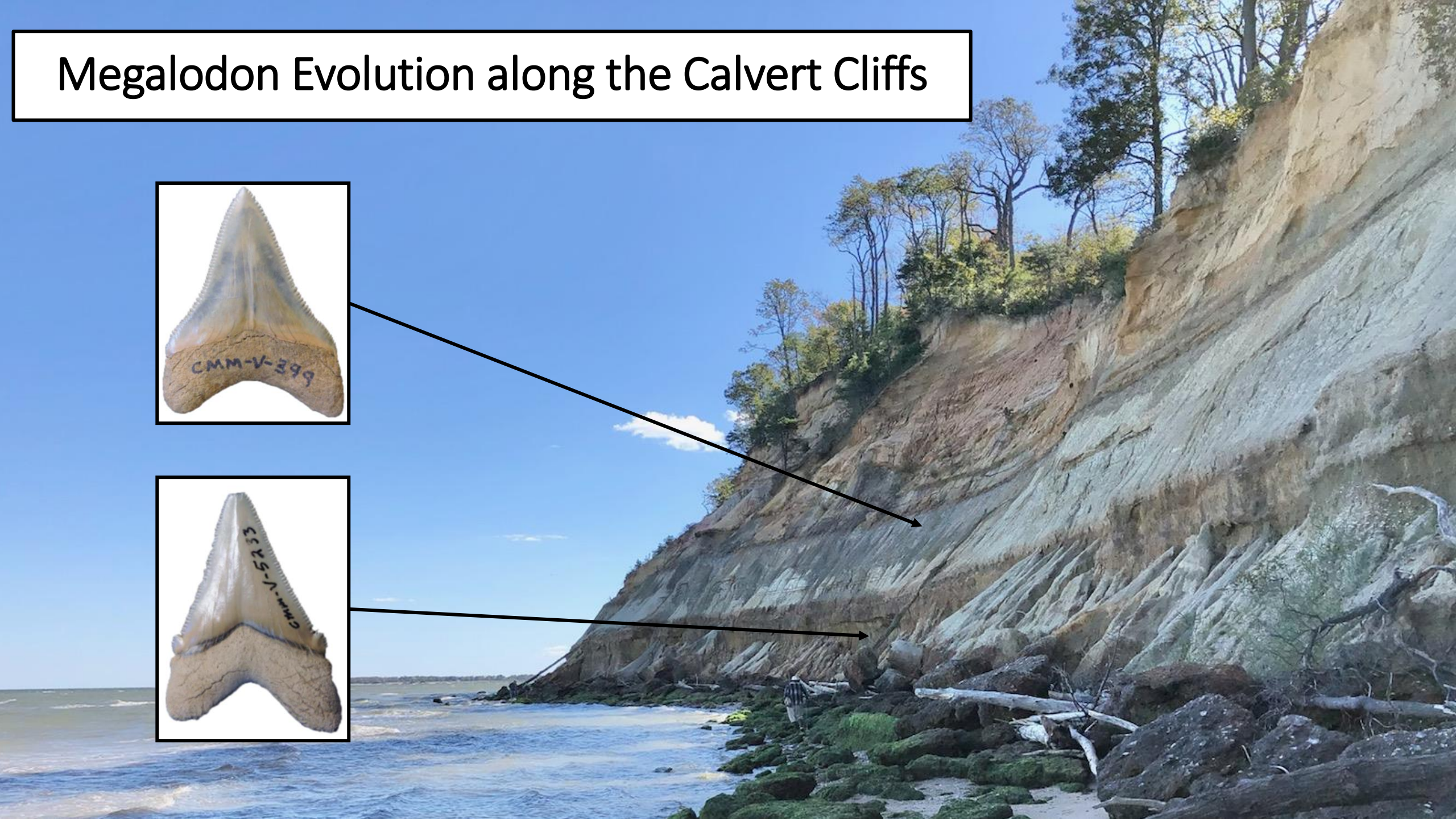
Hard-bodied prey

Evolution and Ecology



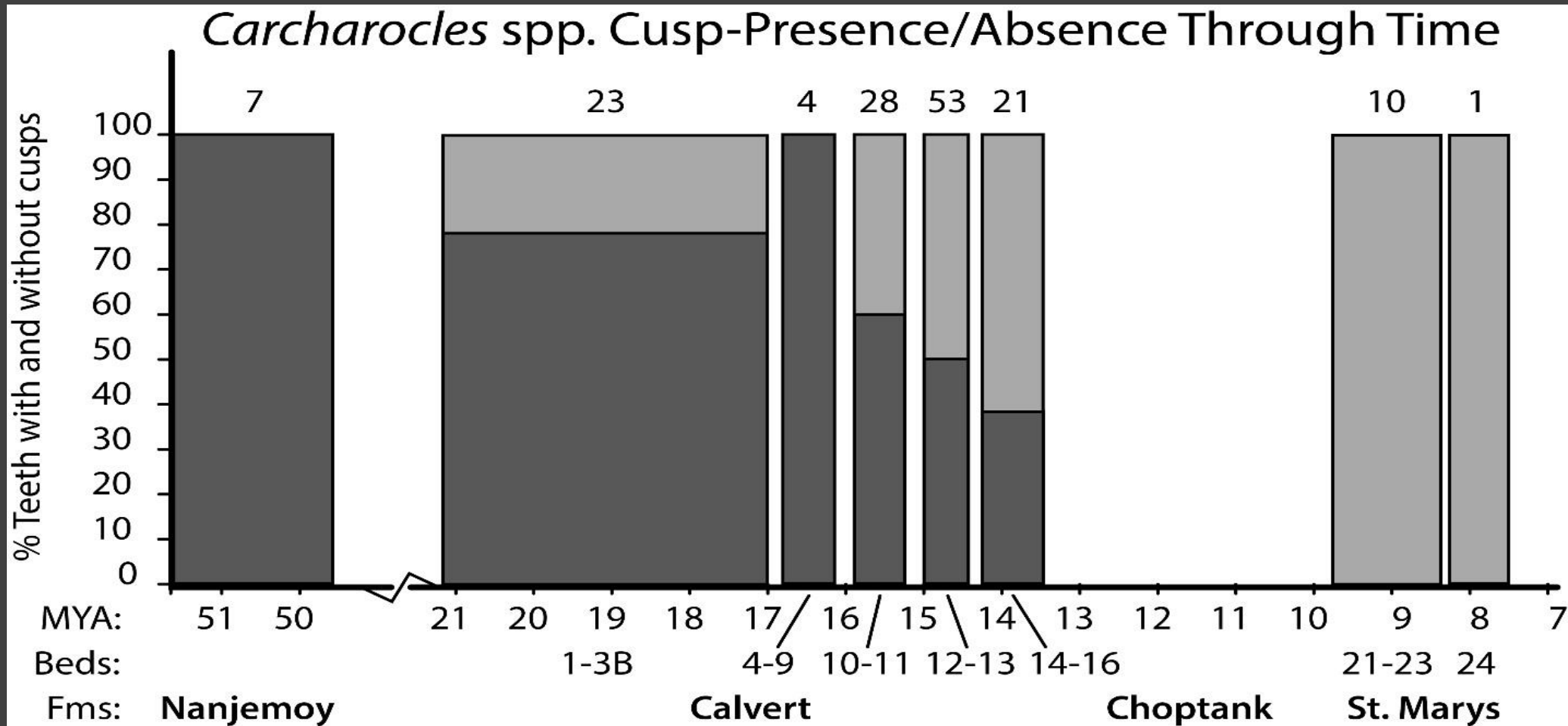
Did Megalodon's ancestors have the same diet?

Megalodon Evolution along the Calvert Cliffs

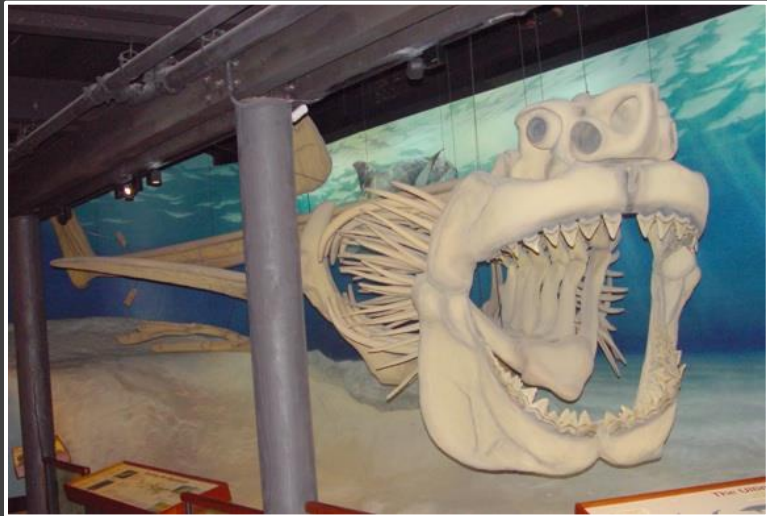




Local Megalodon Evolution



How big was Megalodon?



Calvert Marine Museum
Solomons, MD



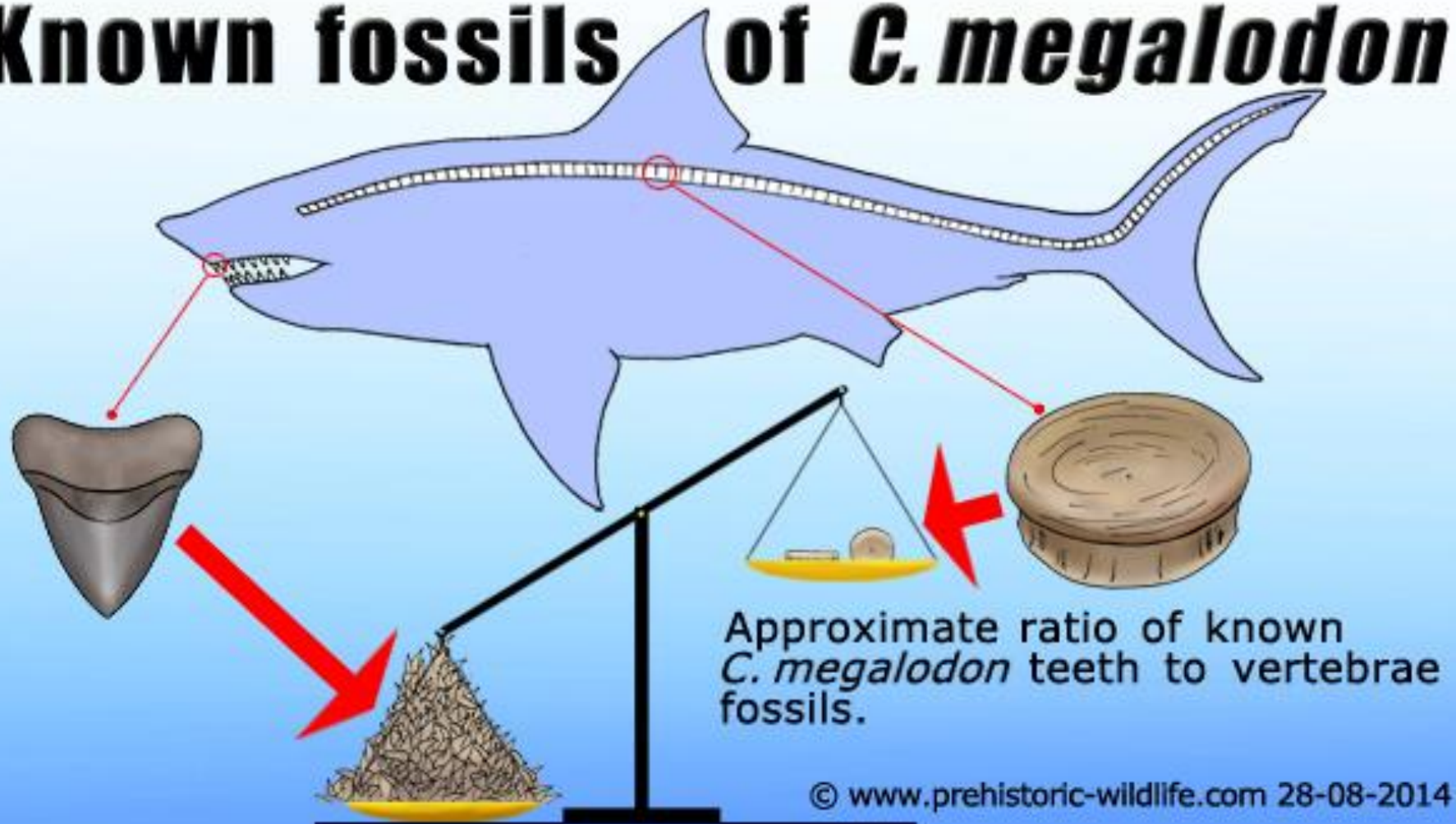
Smithsonian
Washington, DC



Western Australian Museum
Perth, AU

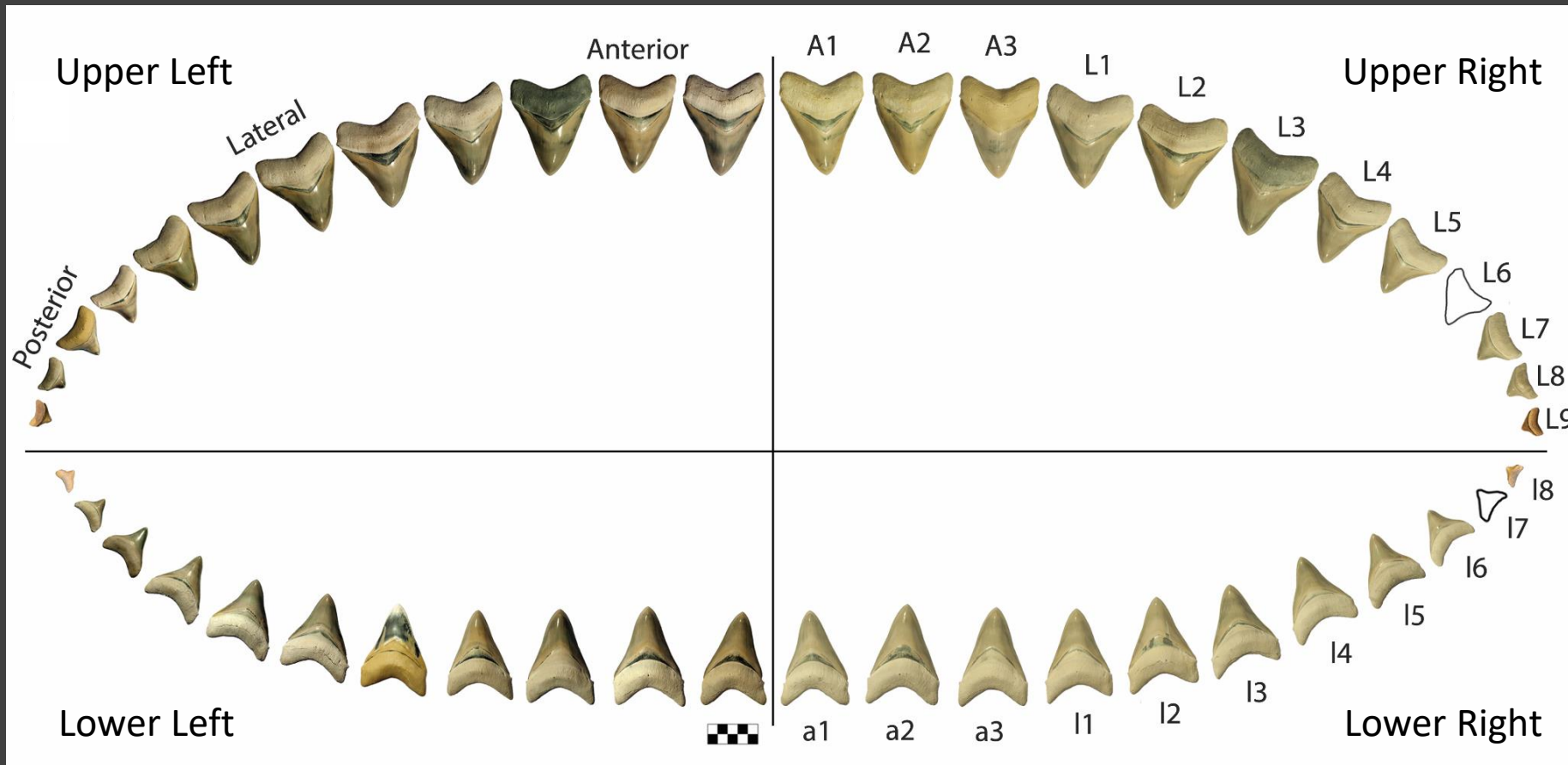
Megalodon Fossil Record

Known fossils of *C. megalodon*



Body Size Myth

Every inch of tooth equates to 10 ft of length



Associated Dentition – multiple teeth found together that came from one individual

Popular Method

The relationship between the tooth size and total body length in the white shark, *Carcharodon carcharias* (Lamniformes: Lamnidae)

SHIMADA, Kenshu*

Abstract

The relationship between the height of tooth crown (CH) and total body length (TL) in the modern great white shark, *Carcharodon carcharias* (Linnaeus) (Lamniformes: Lamnidae) is examined using regression analyses. The results suggest: 1) that an increase in the CH of each tooth through replacement is proportional to the increase in the TL, 2) that the CH can be used to predict the TL, and 3) that distally located teeth develop faster through replacement compared to mesially located teeth. A comparison with previous data suggests that the "growth rate" between the crown and root is perhaps not isometric. These data can be applied to paleontological practices.

Key words: dentition, elasmobranch, growth, lamnoid, morphology, variation

Introduction

The presence of intraspecific variation in tooth morphology is known in various elasmobranchs. Common examples (other than pathologic or abnormal teeth: e.g., Gudger, 1937) include ones caused by sexual differences (e.g., Springer, 1966; Kajiura and Tricas, 1996) and ones by ontogeny (e.g., Reif, 1976; Shimada, 2002b). However,

data on morphological variation are still scarce for most elasmobranchs. Some have examined intraspecific variation of one or a few selected teeth quantitatively, but none of them evaluated the dental homology critically (e.g., Applegate, 1965; Randall, 1973). Indeed, the inability to recognize homologous teeth across conspecific individuals has hampered investigators to conduct rigorous analyses on

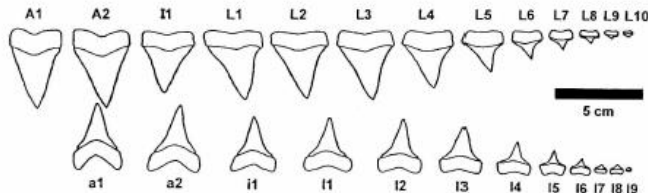
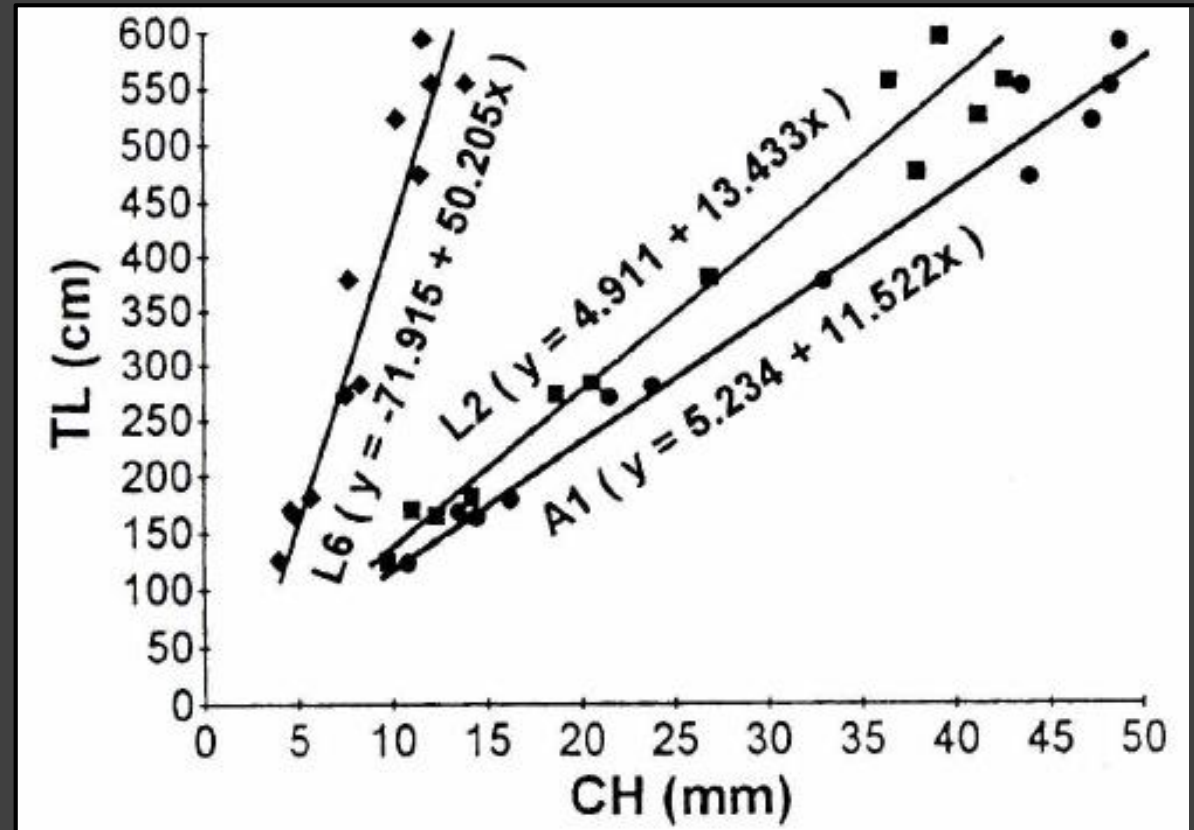


Fig. 1. Representative upper and lower dental series of modern great white shark, *Carcharodon carcharias* (mesial to the left: labial view). Tooth types: A, upper anterior tooth; a, lower anterior tooth; I, upper intermediate tooth; i, lower intermediate tooth; L, upper lateral tooth; l, lower lateral tooth. Illustration traced from Uyeno and Matsushima (1979, fig. 2); tooth type identification based on Shimada (2002a).

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Shimada (2002)

Ancient Nursery Area for the Extinct Giant Shark Megalodon from the Miocene of Panama

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Abstract

Background: As we know from modern species, nursery areas are essential shark habitats for vulnerable young. Nurseries are typically highly productive, shallow-water habitats that are characterized by the presence of juveniles and neonates. It has been suggested that in these areas, sharks can find ample food resources and protection from predators. Based on the fossil record, we know that the extinct *Carcharodes megalodon* was the biggest shark that ever lived. Previous proposed paleo-nursery areas for this species were based on the anecdotal presence of juvenile fossil teeth accompanied by fossil marine mammals. We now present the first definitive evidence of ancient nurseries for *C. megalodon* from the late Miocene of Panama, about 10 million years ago.

Methodology/Principal Findings: We collected and measured fossil shark teeth of *C. megalodon*, within the highly productive, shallow marine Gatun Formation from the Miocene of Panama. Surprisingly, and in contrast to other fossil accumulations, the majority of the teeth from Gatun are very small. Here we compare the tooth sizes from the Gatun with specimens from different, but analogous localities. In addition we calculate the total length of the individuals found in Gatun. These comparisons and estimates suggest that the small size of Gatun's *C. megalodon* is neither related to a small population of this species nor the tooth position within the jaw. Thus, the individuals from Gatun were mostly juveniles and neonates, with estimated body lengths between 2 and 10.5 meters.

Conclusions/Significance: We propose that the Miocene Gatun Formation represents the first documented paleo-nursery area for *C. megalodon* from the Neotropics, and one of the few recorded in the fossil record for an extinct selachian. We therefore show that sharks have used nursery areas at least for 10 millions of years as an adaptive strategy during their life histories.

Citation: Pimiento C, Ehret DJ, MacFadden BJ, Hubbell G (2010) Ancient Nursery Area for the Extinct Giant Shark Megalodon from the Miocene of Panama. PLOS ONE 5(5): e10552. doi:10.1371/journal.pone.010552

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Competing Interests: The authors have declared that no competing interests exist.

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Introduction

Sharks, especially large species, are highly mobile organisms with a complex life history and wide distribution. During their lifetime they generally utilize three types of areas: adult feeding, reproduction and nurseries [1]. In modern species, nursery areas are historically defined by the presence of gravid females and free-swimming neonates. It is also an area that can be shared by several shark species, where young sharks spend their first weeks, months or years [2]. More recent studies have defined nursery areas as geographically discrete essential zones for shark survival [3] that provides them with two types of benefits: protection from predation (mainly larger sharks [2]) and abundant food resources. Productive, shallow-water ecosystems thus provide sharks significant protection from larger predators and/or abundant food resources, both of which are essential to survival [4].

The Gatun is a highly fossiliferous Neogene formation located in the Isthmus of Panama (Figure 1) with a diverse fauna of sharks [5–7]. It was located within a marine strait that connected the Pacific Ocean and the Caribbean Sea during the late Miocene (~10 Ma) [8]. Studies of different taxa, including the exceedingly diverse molluscan fauna, indicate that it was a shallow-water ecosystem (~25 m depth) with higher salinity, mean annual temperature variations, seasonality and productivity relative to modern systems in this region [7,9–13]. Over the past 20 years, the Gatun Formation localities have been extensively used to extract sediment for construction. During the more recent years, these extraction activities have increased substantially. Based on our observations made during the two past years of fieldwork, we predict that these outcrops will soon likely be excavated completely. Therefore it is timely and urgent to study the fossils occurring in these outcrops before they are no longer available to science.

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DOI: 10.1017/pab.2015.16



Body-size trends of the extinct giant shark *Carcharocles megalodon*: a deep-time perspective on marine apex predators

Catalina Pimiento and Meghan A. Balk

Abstract.—The extinct shark *Carcharocles megalodon* is one of the largest marine apex predators ever to exist. Nonetheless, little is known about its body-size variations through time and space. Here, we studied the body-size trends of *C. megalodon* through its temporal and geographic range to better understand its ecology and evolution. Given that this species was the last of the megatooth lineage, a group of species that shows a purported size increase through time, we hypothesized that *C. megalodon* also displayed this trend, increasing in size over time and reaching its largest size prior to extinction. We found that *C. megalodon* body-size distribution was left-skewed (suggesting a long-term selective pressure favoring larger individuals), and presented significant geographic variation (possibly as a result of the heterogeneous ecological constraints of this cosmopolitan species) over geologic time. Finally, we found that stasis was the general mode of size evolution of *C. megalodon* (i.e., no net changes over time), contrasting with the trends of the megatooth lineage and our hypothesis. Given that *C. megalodon* is a relatively long-lived species with a widely distributed fossil record, we further used this study system to provide a deep-time perspective to the understanding of the body-size trends of marine apex predators. For instance, our results suggest that (1) a selective pressure in predatory sharks for consuming a broader range of prey may favor larger individuals and produce left-skewed distributions on a geologic time scale; (2) body-size variations in cosmopolitan apex marine predators may depend on their interactions with geographically discrete communities; and (3) the inherent characteristics of shark species can produce stable sizes over geologic time, regardless of the size trends of their lineages.

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Introduction

The extinct megatooth shark *Carcharocles megalodon* is the largest shark ever to exist (Gottfried et al. 1996). From its tooth size and morphology, it was inferred to have been an apex predator that reached up to ~18 m of total length (TL) (Gottfried et al. 1996; Pimiento et al. 2010; Pimiento et al. 2013a). Furthermore, given the nearly global distribution of its fossil record, *C. megalodon* is considered to have been a cosmopolitan species that lived from ca. 15.9 Ma (middle Miocene) to ca. 2.6 Ma (Pliocene/Pleistocene boundary) (Applegate and Espinosa-Arrubarrena 1996; Gottfried et al. 1996; Purdy 1996; Purdy et al. 2001; Cappetta 2012; Pimiento and Clements 2014).

Apex predators are animals with no predatory pressures. Usually they are large-bodied vertebrates that can move over large areas, thus interacting with different communities. Most

importantly, apex predators are pivotal in maintaining ecosystem stability, and their elimination can produce cascading effects throughout entire food webs (Myers et al. 2007; Terborgh et al. 2010; Estes et al. 2011). Accordingly, the extinction of *C. megalodon* potentially affected the structure and function of ancient ecosystems (Pimiento and Clements 2014). The causes of its extinction are still unknown.

The phylogenetic relationships of *C. megalodon* have mainly been studied on the basis of its relatedness to the great white shark, *Carcharodon carcharias* (e.g., Long and Waggöner 1996; Martín 1996). To our knowledge, no phylogenies for this species have ever taken into consideration all its ancestors. Thus, the taxonomy of *C. megalodon* has long been debated, with a number of possible interpretations. For instance, some authors place it in the genus *Carcharodon* (family Lamnidae) (e.g., Applegate and Espinosa-Arrubarrena 1996; Gottfried et al. 1996; Purdy

BIOLOGY LETTERS

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Research

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Palaeontology

Use of nursery areas by the extinct megatooth shark *Otodus megalodon* (Chondrichthyes: Lamniformes)

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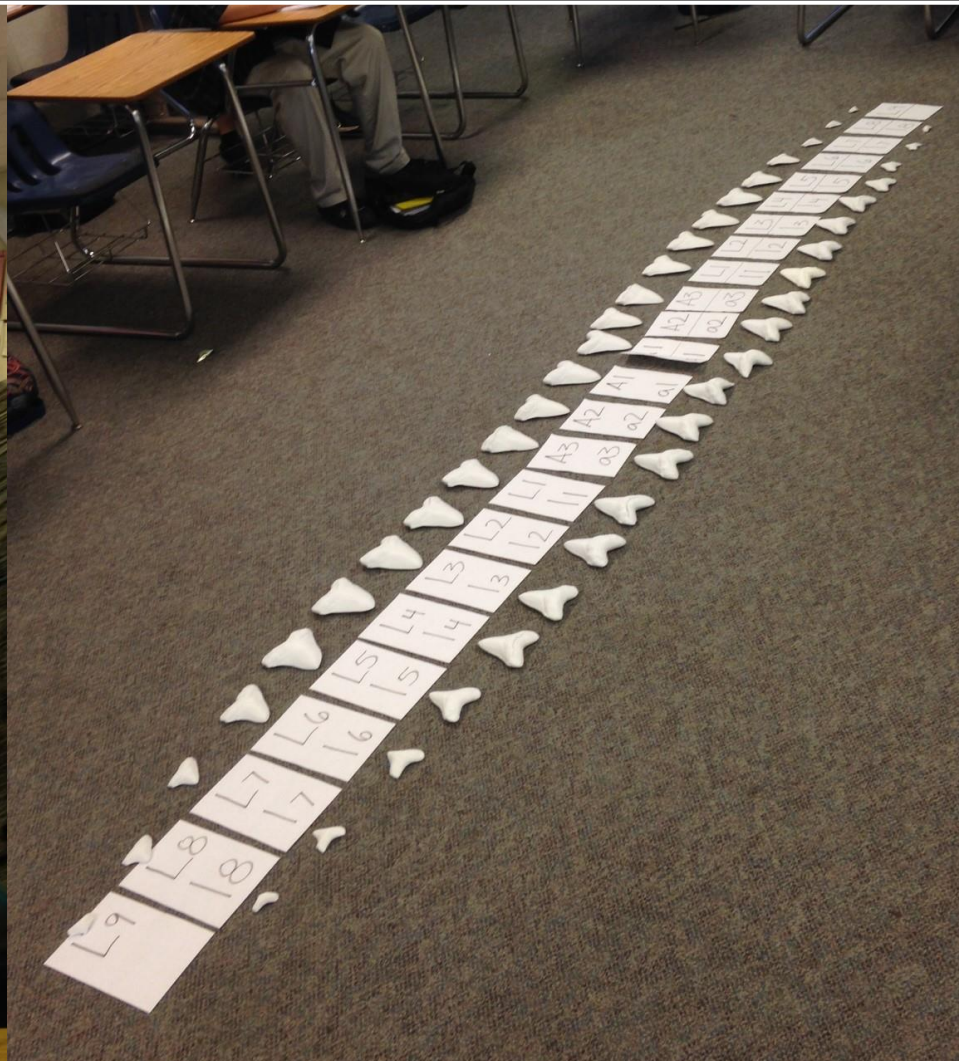
Nursery areas are fundamental for the success of many marine species, particularly for large, slow-growing taxa with low fecundity and high age of maturity. Here, we examine the population size-class structure of the extinct gigantic shark *Otodus megalodon* in a newly described middle Miocene locality from Northeastern Spain, as well as in eight previously known formations (Tembor, Calvert, Pisco, Gatún, Chucunaque, Bahía Inglesa, Yorktown and Bone Valley). In all cases, body lengths of all individuals were inferred from dental parameters and the size-class structure was estimated from kernel probability density functions and Gaussian mixture models. Our analyses support the presence of five potential nurseries ranging from the Langhian (middle Miocene) to the Zanclean (Pliocene), with higher densities of individuals with estimated body lengths within the typical range of neonates and young juveniles. These results reveal, for the first time, that nursery areas were commonly used by *O. megalodon* over large temporal and spatial scales, reducing early mortality and playing a key role in maintaining viable adult populations. Ultimately, the presumed reliance of *O. megalodon* on the presence of suitable nursery grounds might have also been determinant in the demise of this iconic top predatory shark.

1. Introduction

Otodus megalodon is the largest macropredatory shark to have ever lived, with body length estimates of up to 15–18 m for the largest adult individuals [1–4]. This species inhabited the warm and temperate waters of all major ocean basins, spanning a range of almost 20 Myr, from the early Miocene to the Pliocene [5–7]. Most of the studies assessing the causes of the cosmopolitan distribution, the evolution of gigantism, and the extinction of otodontid sharks have focused on the impact of climatic factors and/or the abundance and migration patterns of their potential prey [1,8–11], competition with other macropredatory taxa [7,12], the availability of suitable habitats [13] and the presence of regional endothermy [6,14–16]. However, much less attention has been paid to important aspects of their reproductive biology [17].

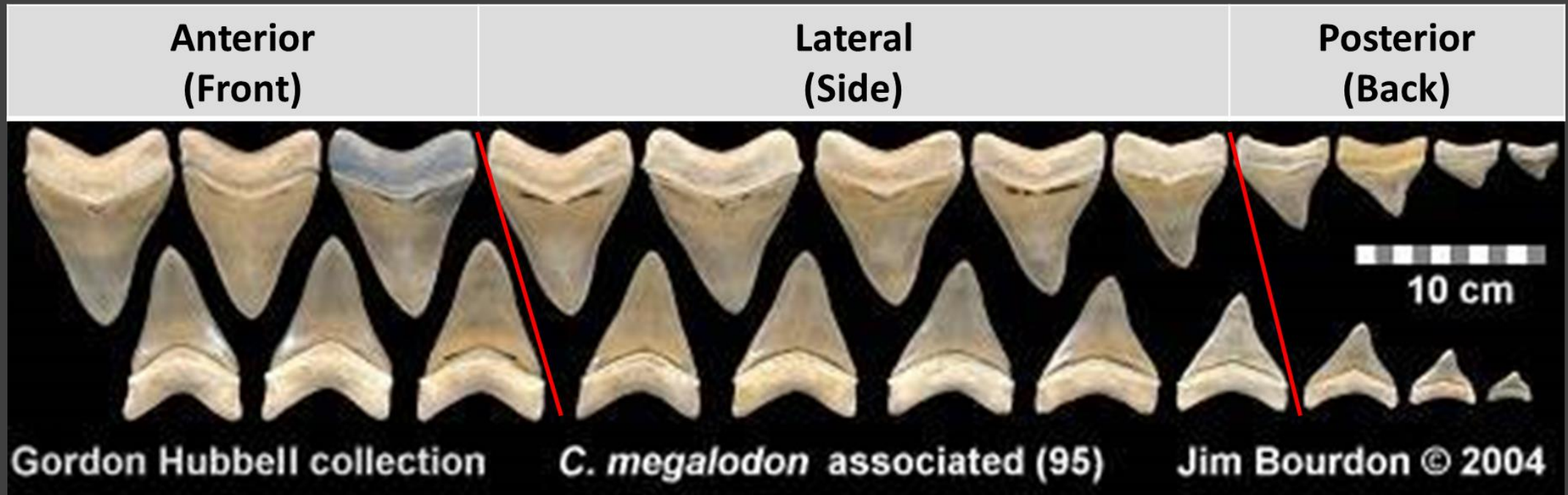
Nursery areas are crucial for several marine groups, as they improve the probability of survival of juveniles and allow a greater persistence and recruitment to the adult populations [18,19]. Shark nurseries are usually located in geographically discrete zones with high primary productivity, being defined by a comparatively high abundance of juveniles that tend to remain or return for extended periods of time [20,21]. The use of these areas has been

Testing the Method



Results: How big was Megalodon?

Jaw Position	Tooth Position	TL Range (ft)	TL Mean (ft)
Anterior	A1-A3; a1-a3	40.3 – 52.3	44
Lateral	L1-L5; l1-l5	44.2 – 108.2	64
Posterior	L6-L9; l6-l8	87.1 – 147.6	110



3-D FOSSILS FOR K–12 EDUCATION: A CASE EXAMPLE USING THE GIANT EXTINCT SHARK *CARCHAROCLES MEGALODON*

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ABSTRACT.—Fossils and the science of paleontology provide a charismatic gateway to integrate STEM teaching and learning. With the new Next Generation Science Standards (NGSS), as well as the exponentially increasing use of three-dimensional (3-D) printing and scanning technology, it is a particularly opportune time to integrate a wider variety of fossils and paleontology into K–12 curricula. We describe a curricular prototype that integrates all four components of STEM (Science, Technology, Engineering, Math) into authentic research using dentitions of the Neogene giant shark *Megalodon* (*Carcharocles megalodon* Agassiz, 1843). This prototype has been implemented in two middle and two high schools in California and Florida. Consistent with prior evidence-based research, student engagement increases when they have hands-on experiences with fossils, particularly with a charismatic species such as *Megalodon*. Access to museum specimens helps students understand big ideas in ‘Deep Time.’ In addition to engaging students in authentic STEM practices and scaffolding development of content knowledge, paleontology is an integrative science that connects and informs socially relevant topics, including long-term (macro-) evolution and climate change. The application of 3-D printing and scanning to develop curricula using fossils has immense potential in K–12 schools in the U.S.

INTRODUCTION

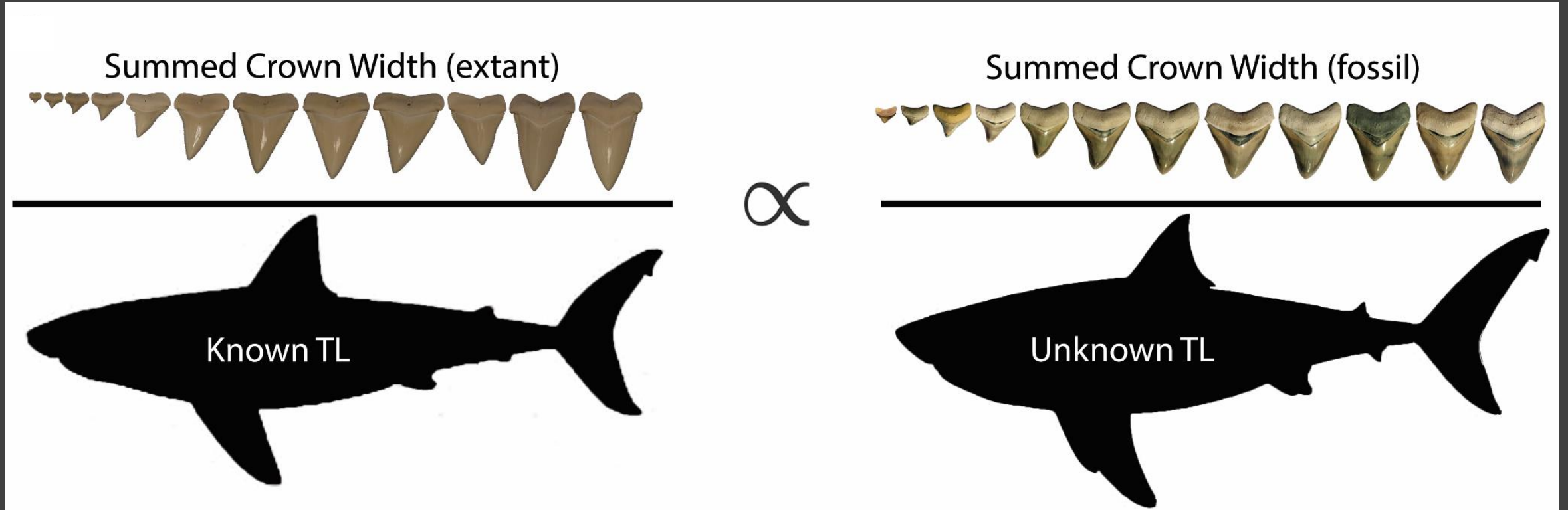
The rapidly increasing need for an adequately prepared science, technology, engineering, and mathematics (STEM) workforce in the twenty-first century requires meaningful integration of STEM disciplines in K–12 education. It is widely recognized that this is an important, but highly challenging, goal (Honey et al., 2014). Historically, students in the U.S. have learned individual STEM disciplines in isolation, which is counter to the common practices in the professional STEM fields today (Roehrig et al., 2012), and STEM teaching in the U.S. has not succeeded in integrating underrepresented groups (Meyer et al., 2012). In this paper, we describe our work to expand and extend understanding of

integrated STEM learning with fossils and paleontology while exploring the associated benefits and challenges. Specifically, we propose a novel curricular model for integrating all four STEM domains in K–12 education. This is being done through the lens of using three-dimensional (3-D) scanning and printing technologies that are increasingly finding their way into K–12 schools (Thomburg et al., 2014). This integration can be achieved in the context of a highly relevant, but heretofore unexplored, educational pathway to STEM in K–12 education using fossils and paleontology.

The relevant background on STEM learning, 3-D scanning and printing technologies, and paleontology as they relate to the goal of advancing integrated STEM education in K–12 is reviewed, and we



New Method

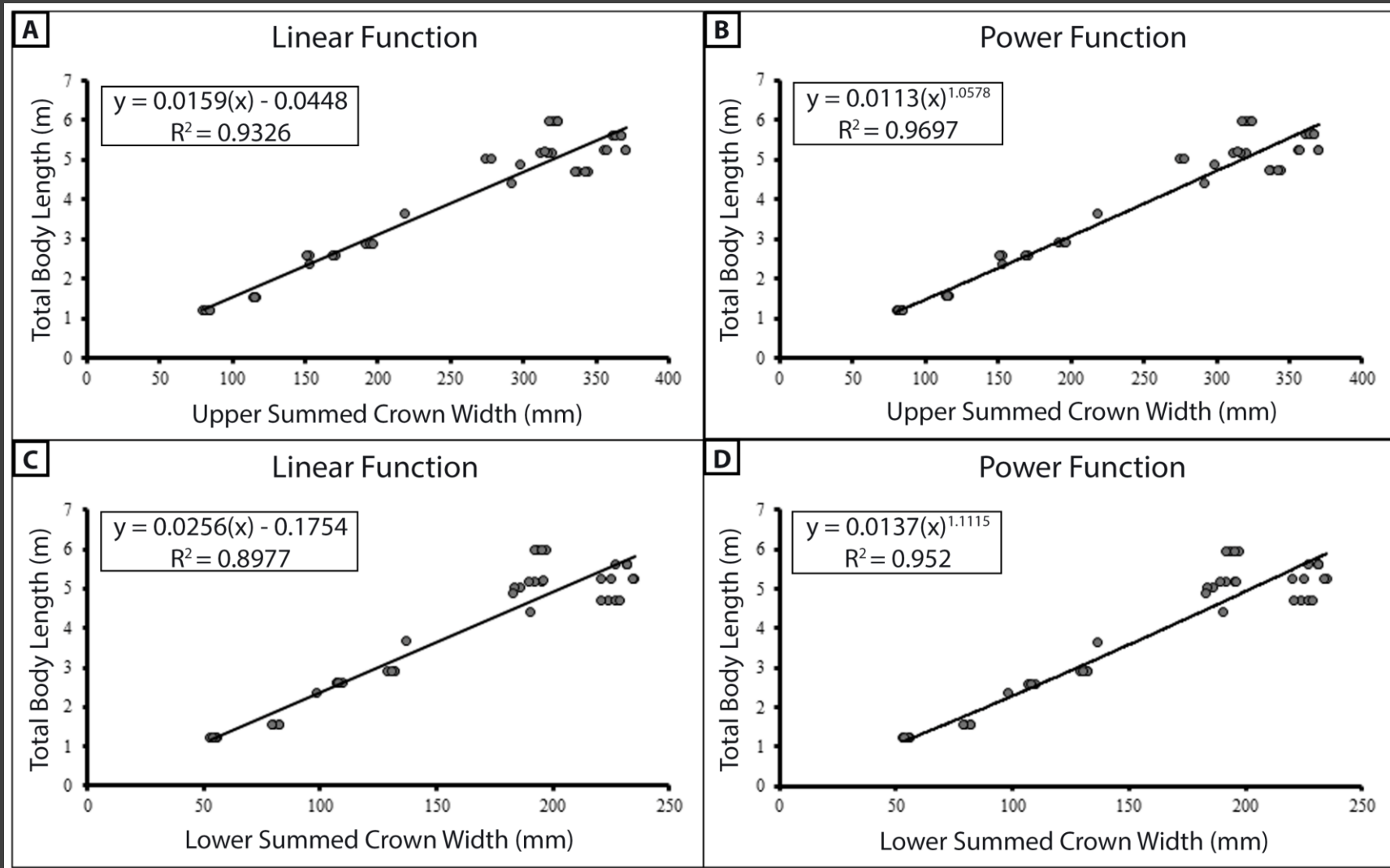


$$\frac{a}{b} = \frac{c}{x}$$

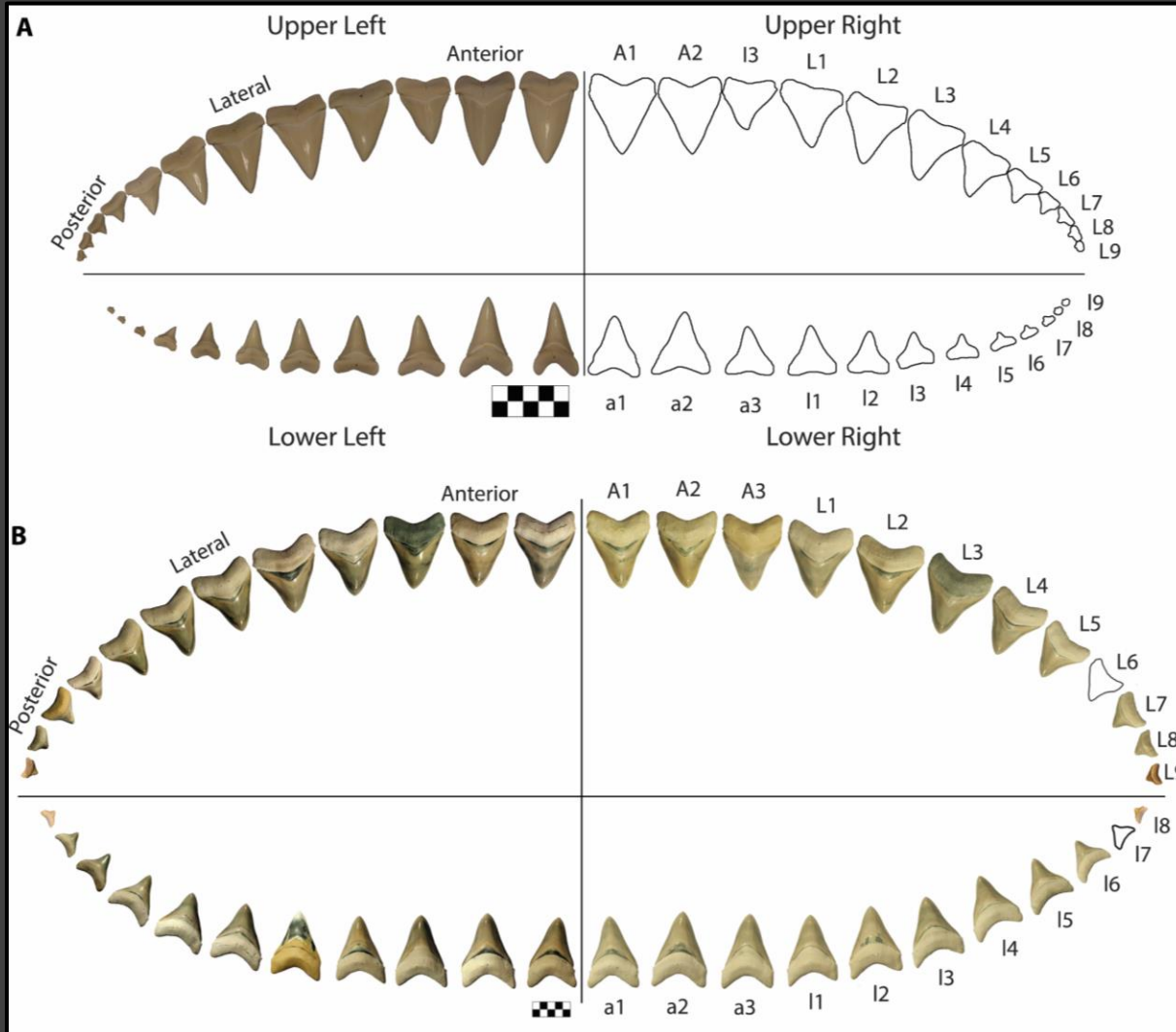


$$x = \frac{b * c}{a}$$

New Method



Megalodon vs. Great White



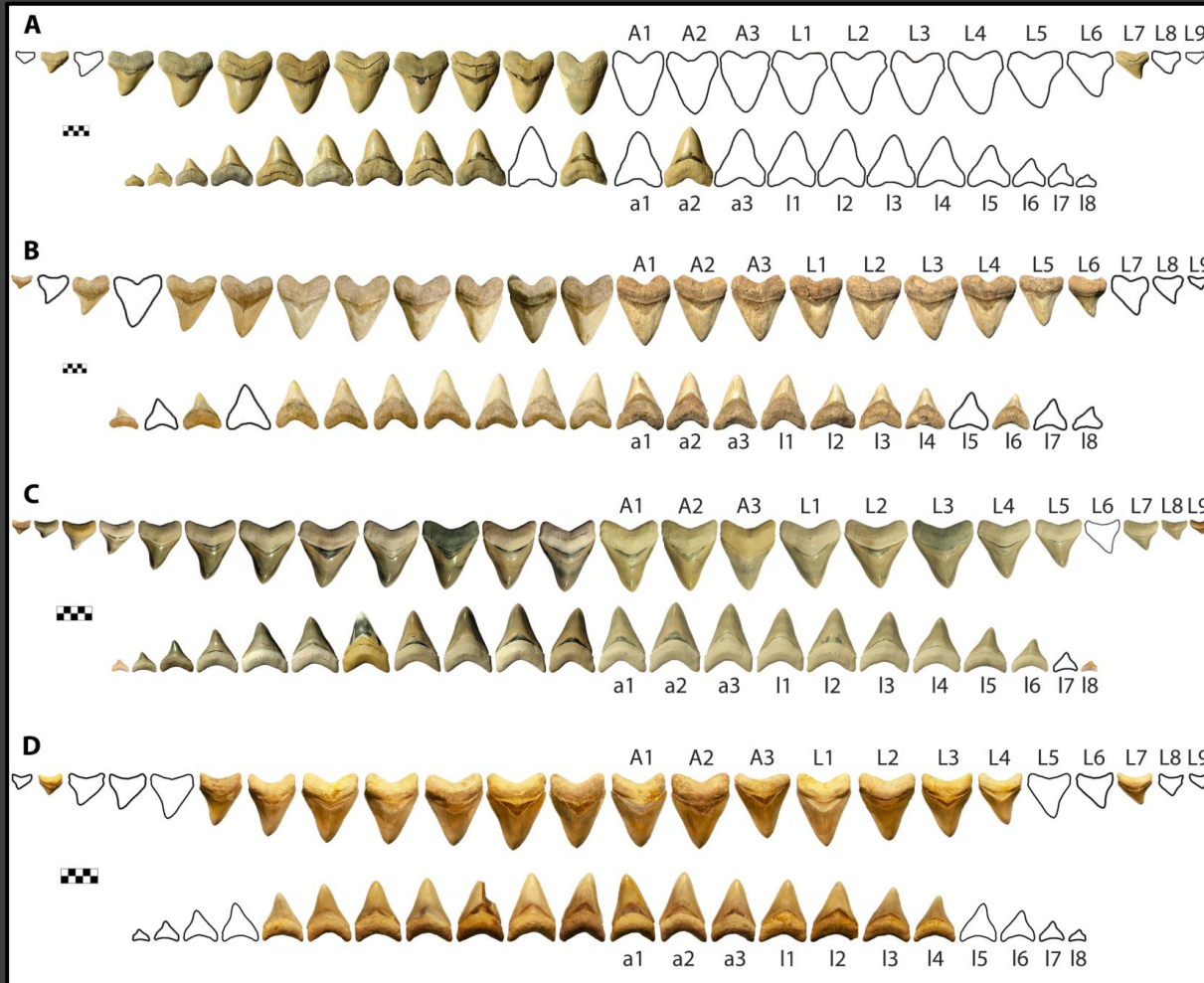
Carcharodon carcharias

- Upper Jaw = 24 teeth
- Lower Jaw = 24 teeth
- Intermediate tooth present

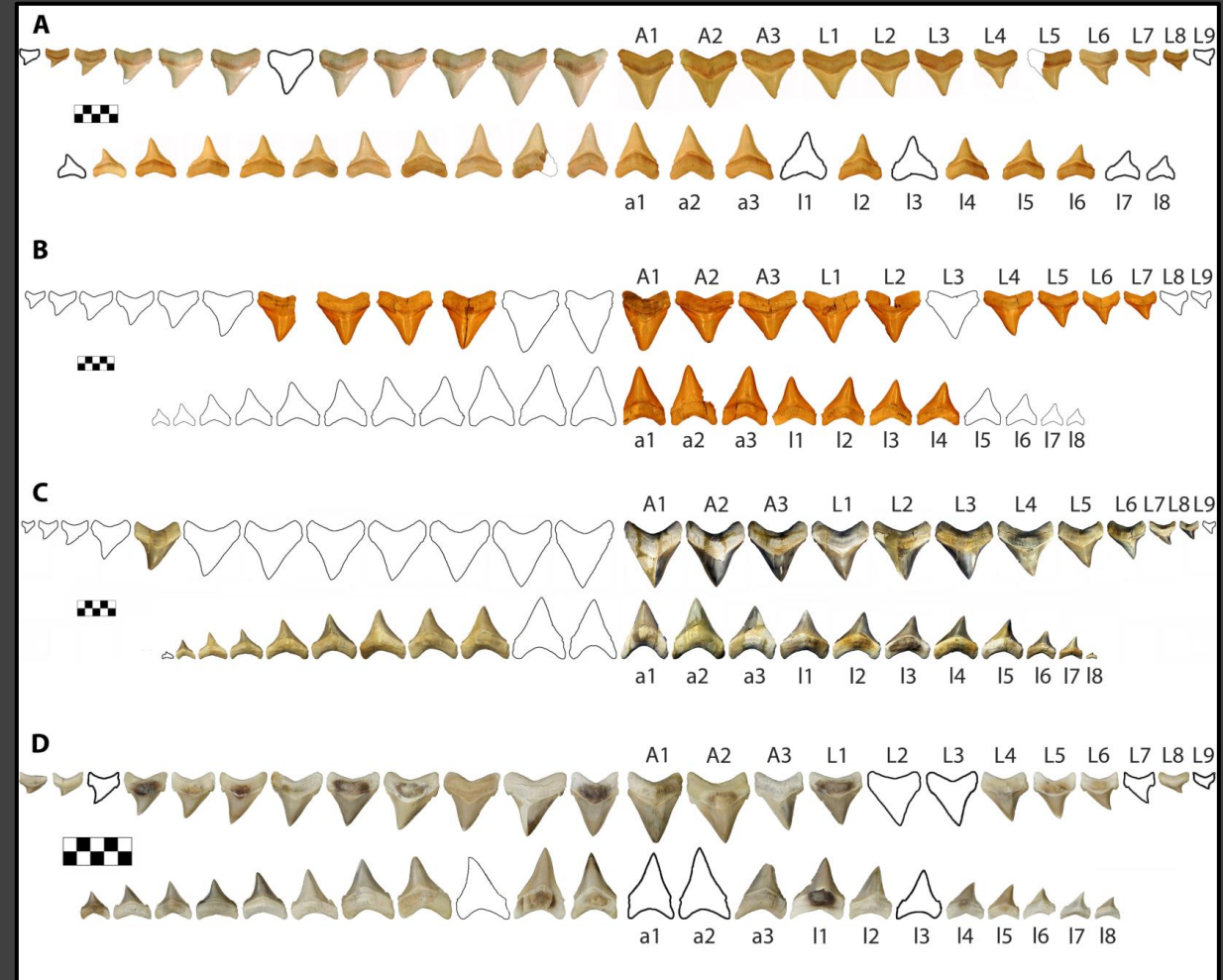
Otodus megalodon

- Upper Jaw = 24 teeth
- Lower Jaw = 22 teeth
- Intermediate tooth absent

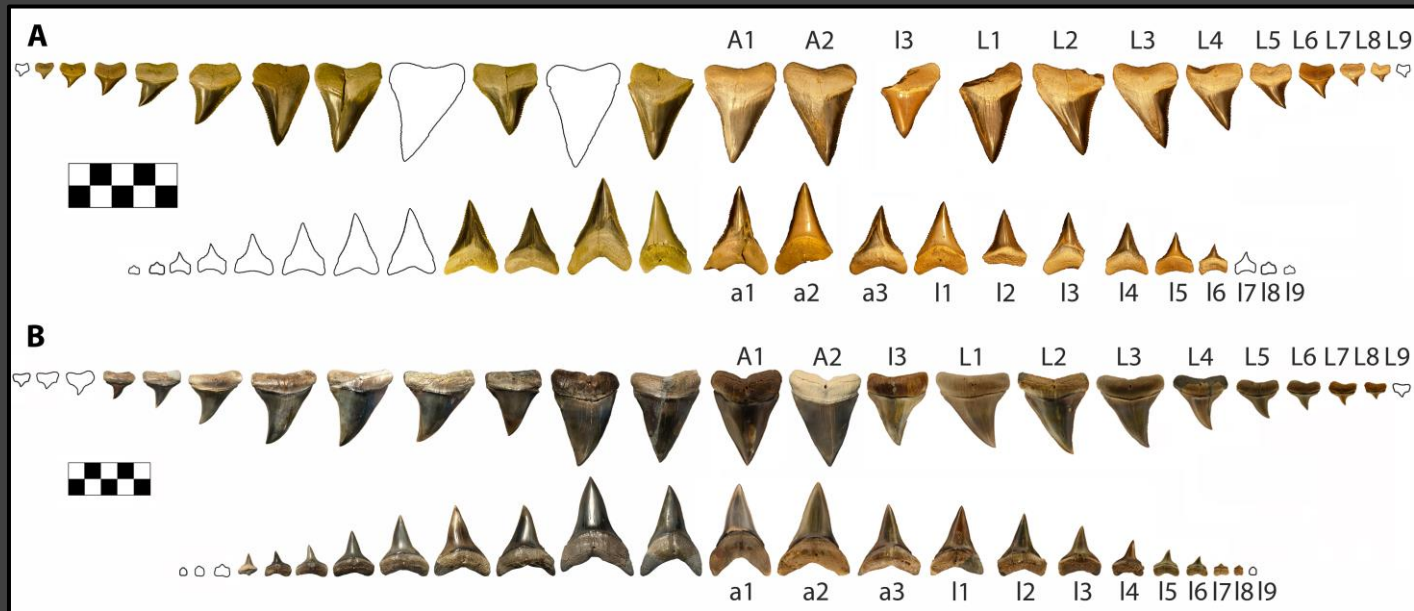
Otodus megalodon



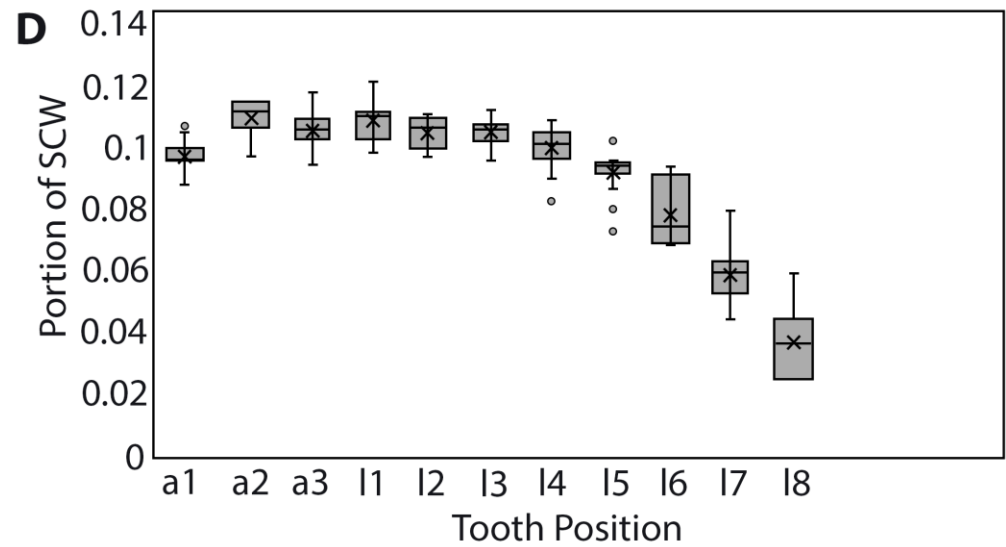
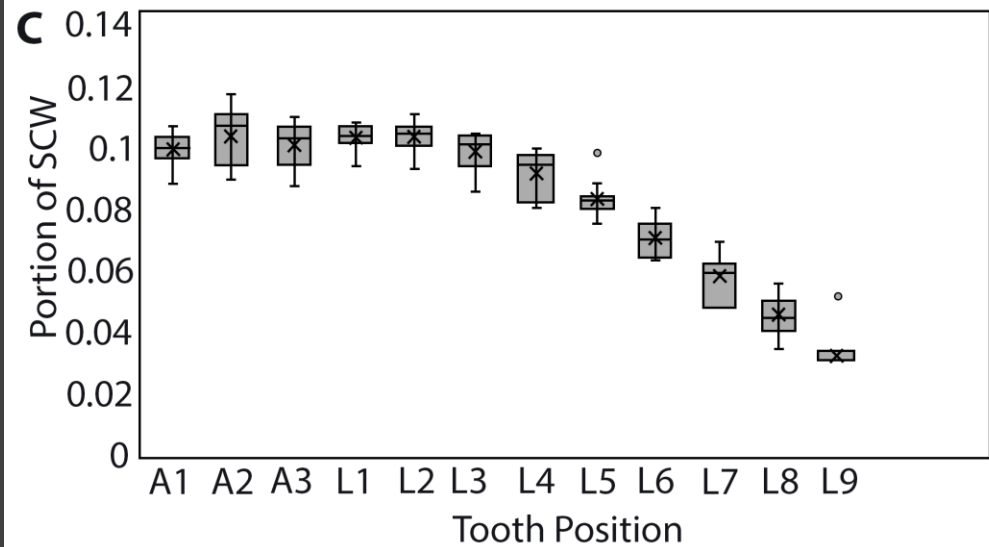
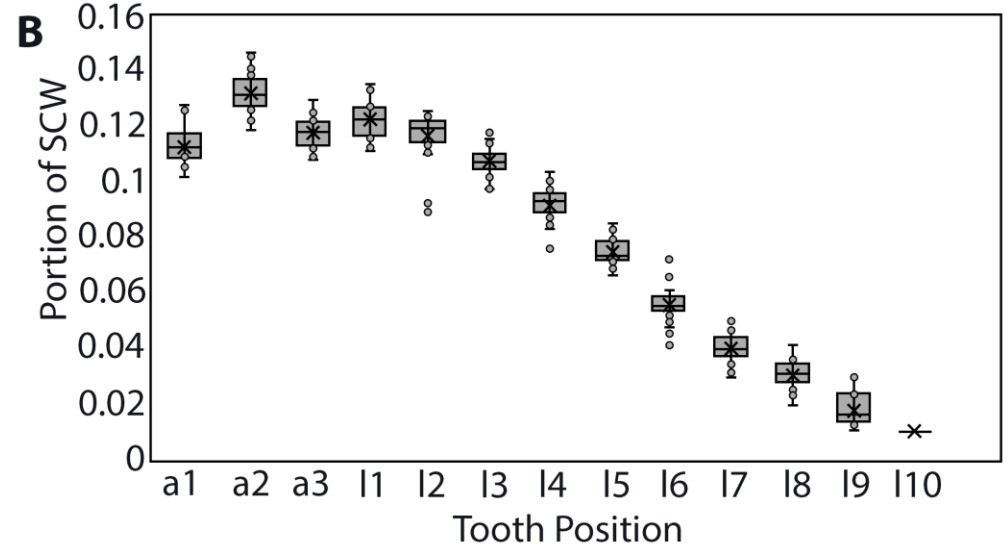
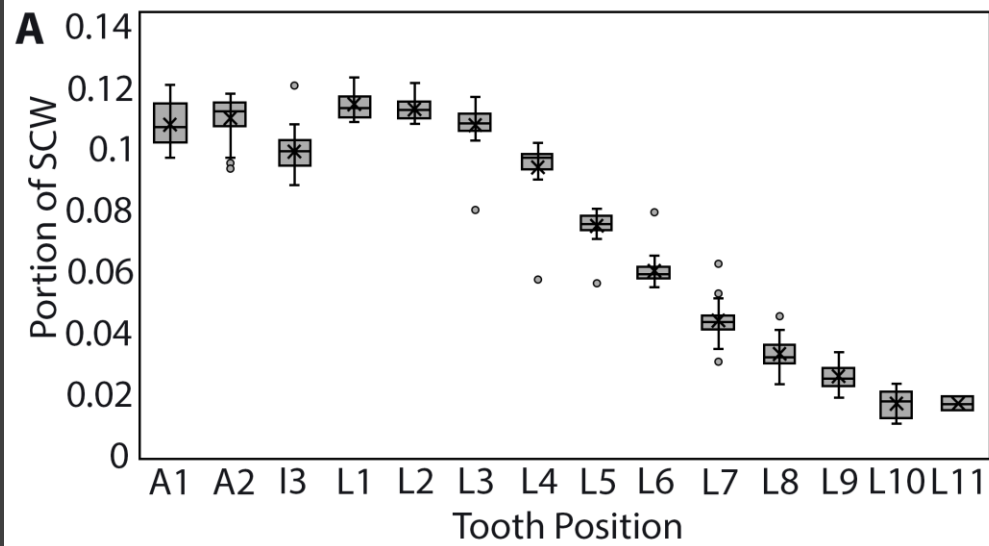
Otodus chubutensis

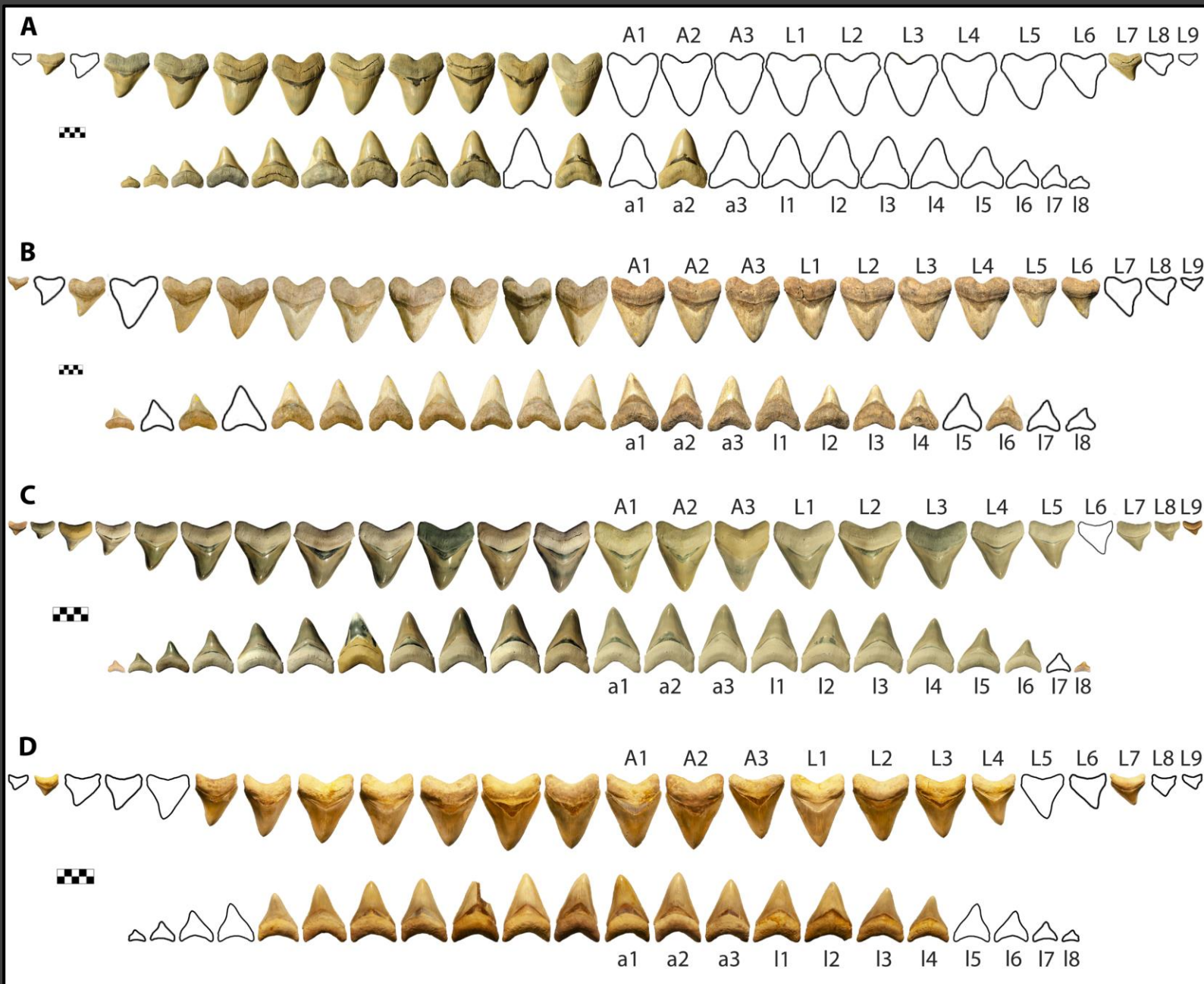


Carcharodon spp.



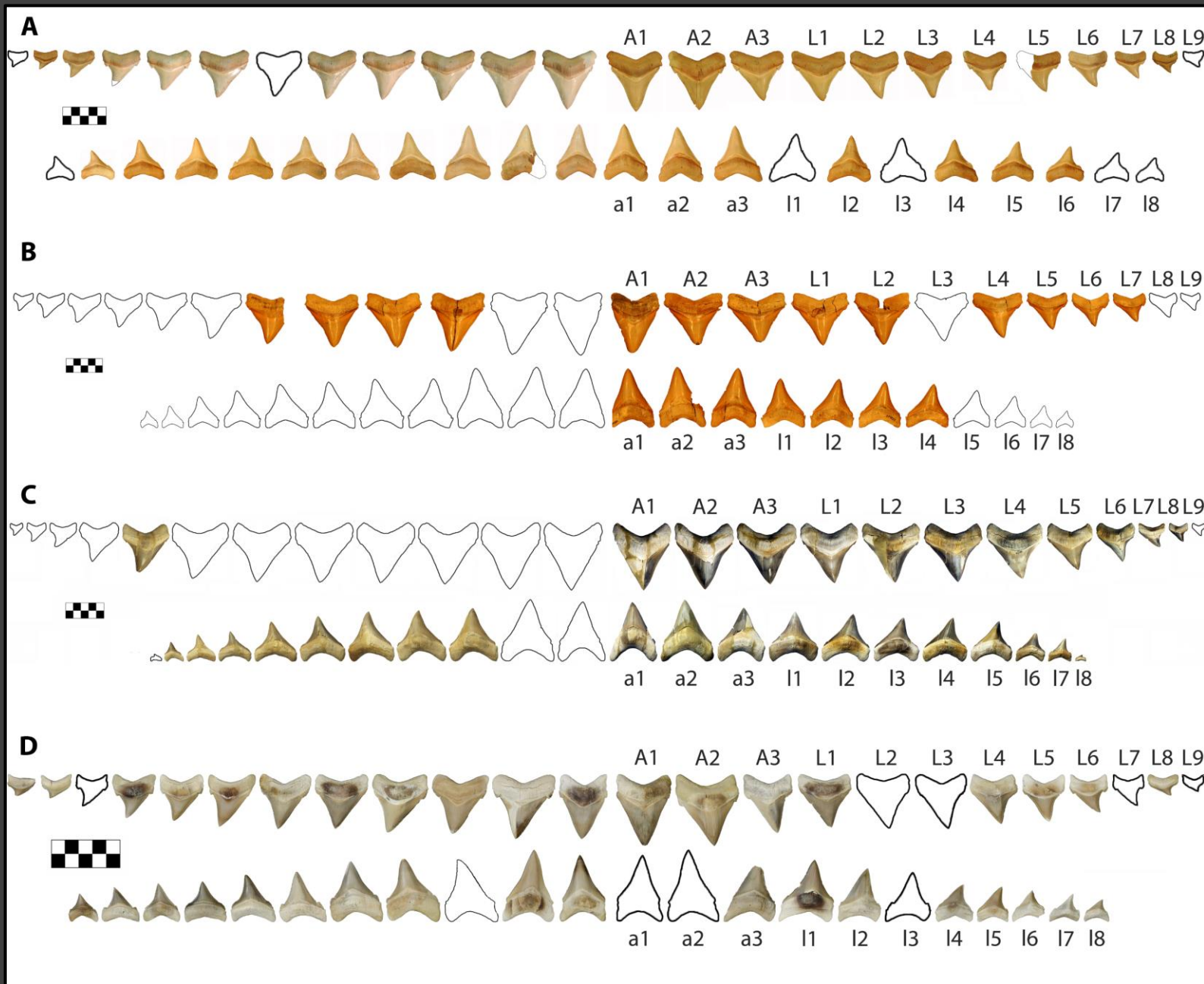
Accounting for Missing Teeth





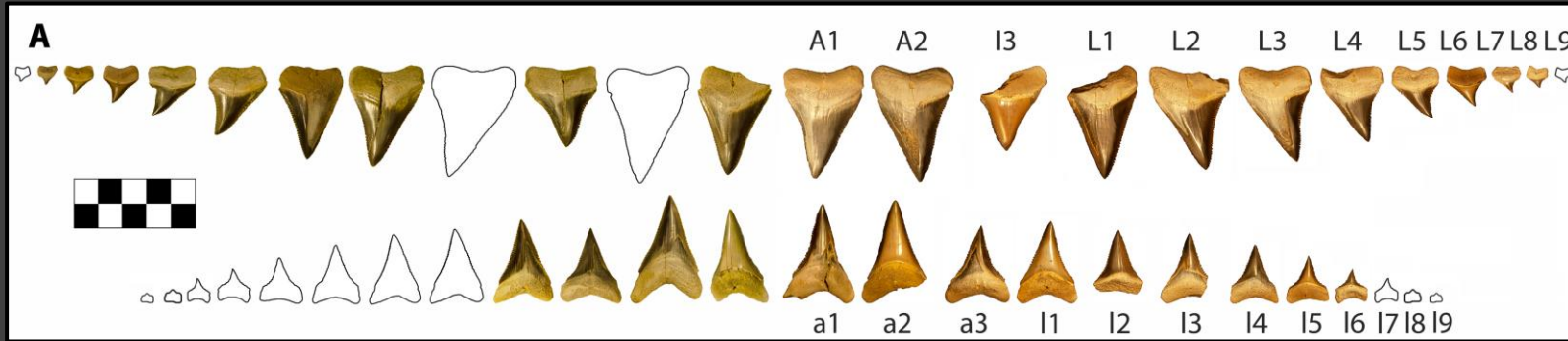
	<u>Range</u>	<u>Mean</u>
U:	15.1 – 20.3 m	17.3 m
L:	17.6 – 26.2 m	20.8 m
U:	15.2 – 20.3 m	17.3 m
L:	16.2 – 24.9 m	19.8 m
U:	10.8 – 14.7 m	12.4 m
L:	12.6 – 18.8 m	15.0 m
U:	9.4 – 12.9 m	10.9 m
L:	11.2 – 16.8 m	13.3 m

Otodus megalodon



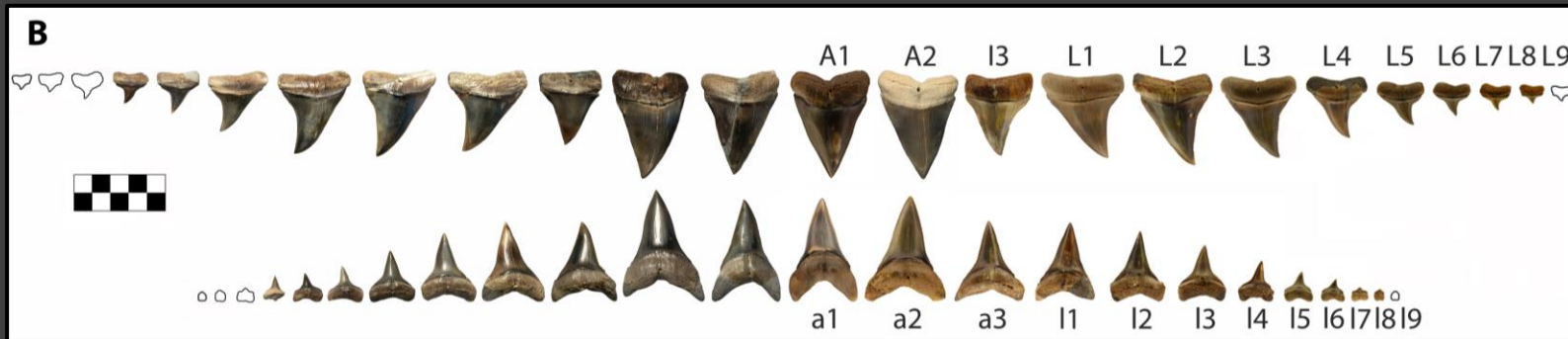
	<u>Range</u>	<u>Mean</u>
U:	9.4 – 12.9 m	11.0 m
L:	11.0 – 16.3 m	13.0 m
U:	9.5 – 13.1 m	10.9 m
L:	10.3 – 16.7 m	13.3 m
U:	7.5 – 10.6 m	9.0 m
L:	8.9 – 13.9 m	11.1 m
U:	5.2 – 7.0 m	5.9 m
L:	6.3 – 10.3 m	8.2 m

Otodus chubutensis



Carcharodon carcharias

	<u>Range</u>	<u>Mean</u>
U:	3.5 – 4.8 m	4.0 m
L:	3.9 – 6.0 m	4.8 m



Carcharodon hastalis

U:	4.6 – 6.2 m	5.3 m
L:	4.5 – 7.8 m	6.2 m



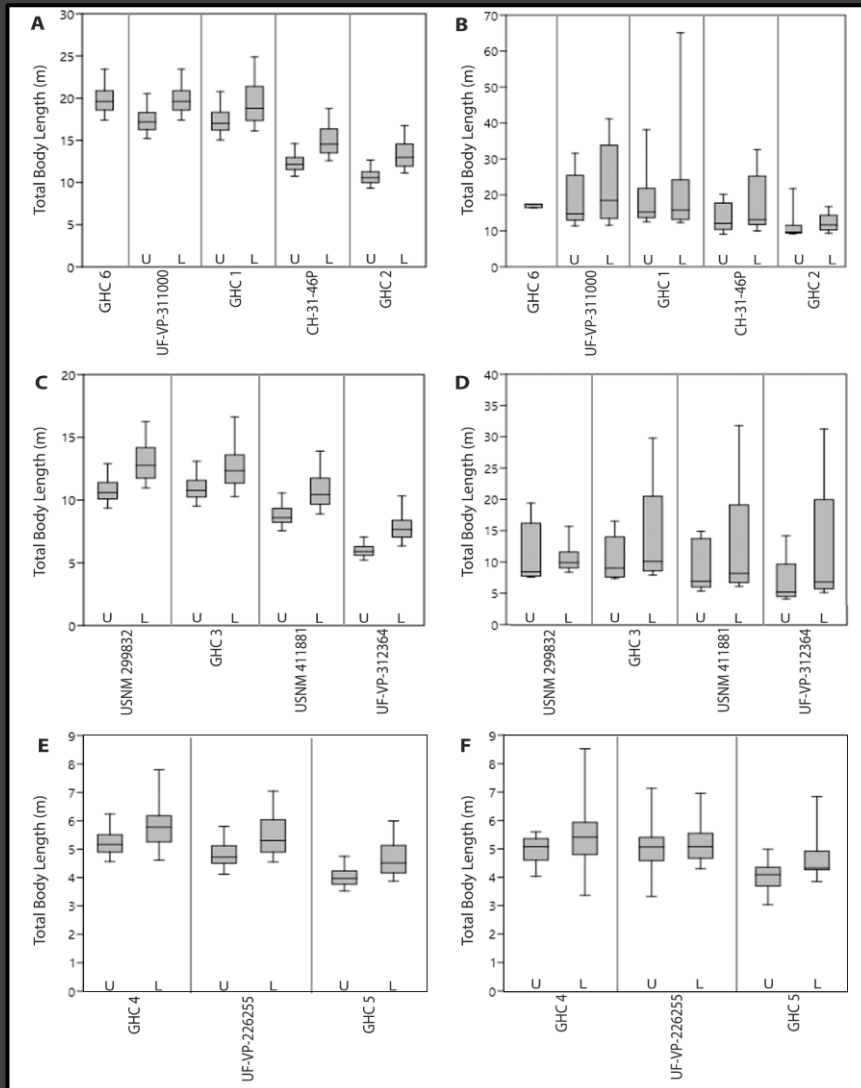
GREAT WHITE SHARK
Carcharodon carcharias
This 5 million year old specimen was collected in Saco, Peru in February, 1985. The total length of the specimen is estimated to be about 6 meters. This is the only complete fossilized skull of a Great White shark that has ever been recovered.

Carcharodon hubbelli

	<u>Range</u>	<u>Mean</u>
U:	4.1 – 5.8 m	4.9 m
L:	4.5 – 6.8 m	5.6 m

Vertebral estimates ranged from 4.7 to 5.2 m, with an average estimate of 4.9 m.

Summed Crown Width vs. Crown Height



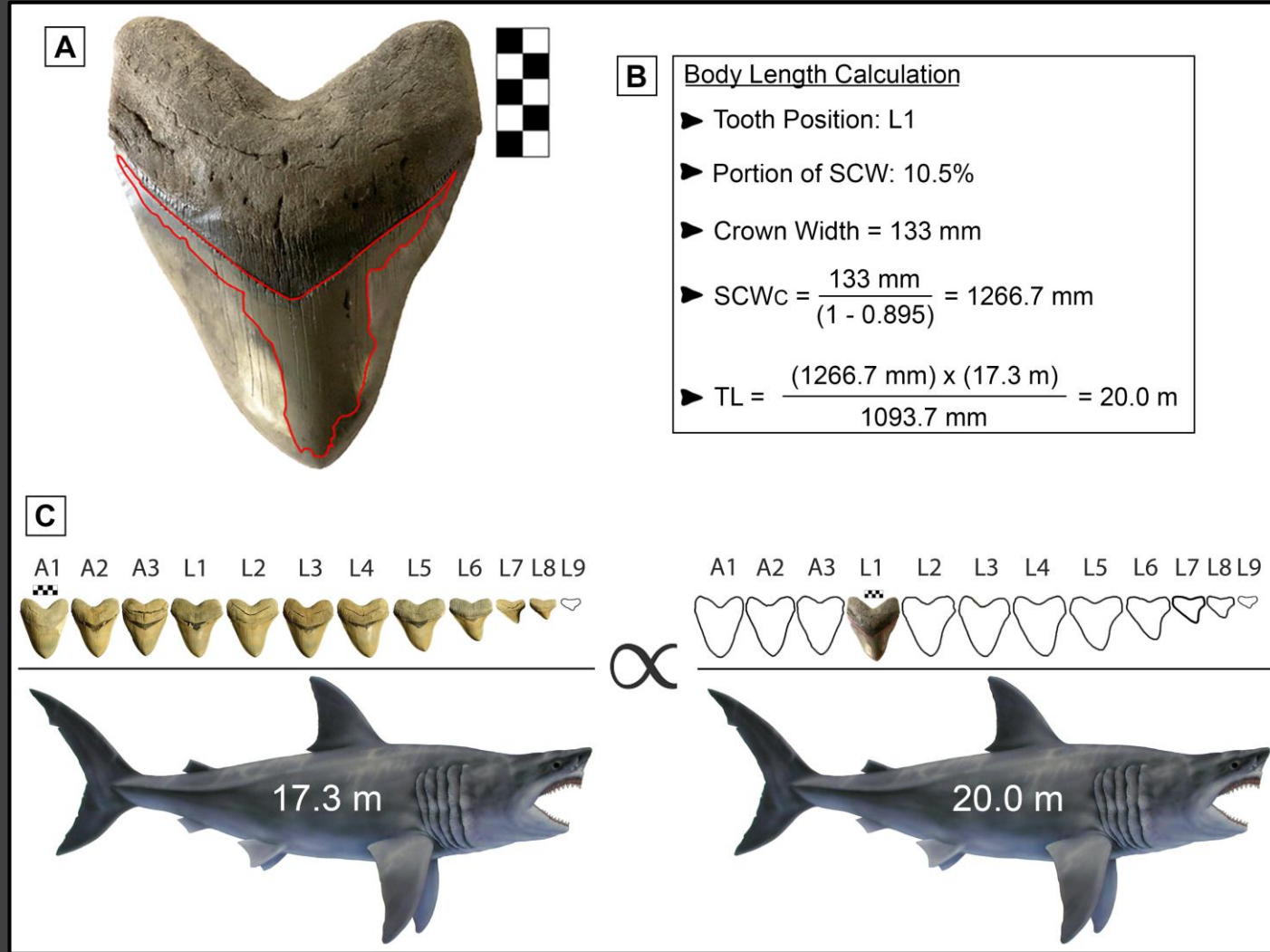
SCW

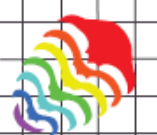
CH

Highlights

- ❖ SCW offers more constraint than CH
- ❖ Lower teeth result in overestimates and greater uncertainty
- ❖ There is greater uncertainty with larger individuals

Extrapolating the Method





Body length estimation of Neogene macrophagous lamniform sharks (*Carcharodon* and *Otodus*) derived from associated fossil dentitions

Victor J. Perez, Ronny M. Leder, and Teddy Badaut

ABSTRACT

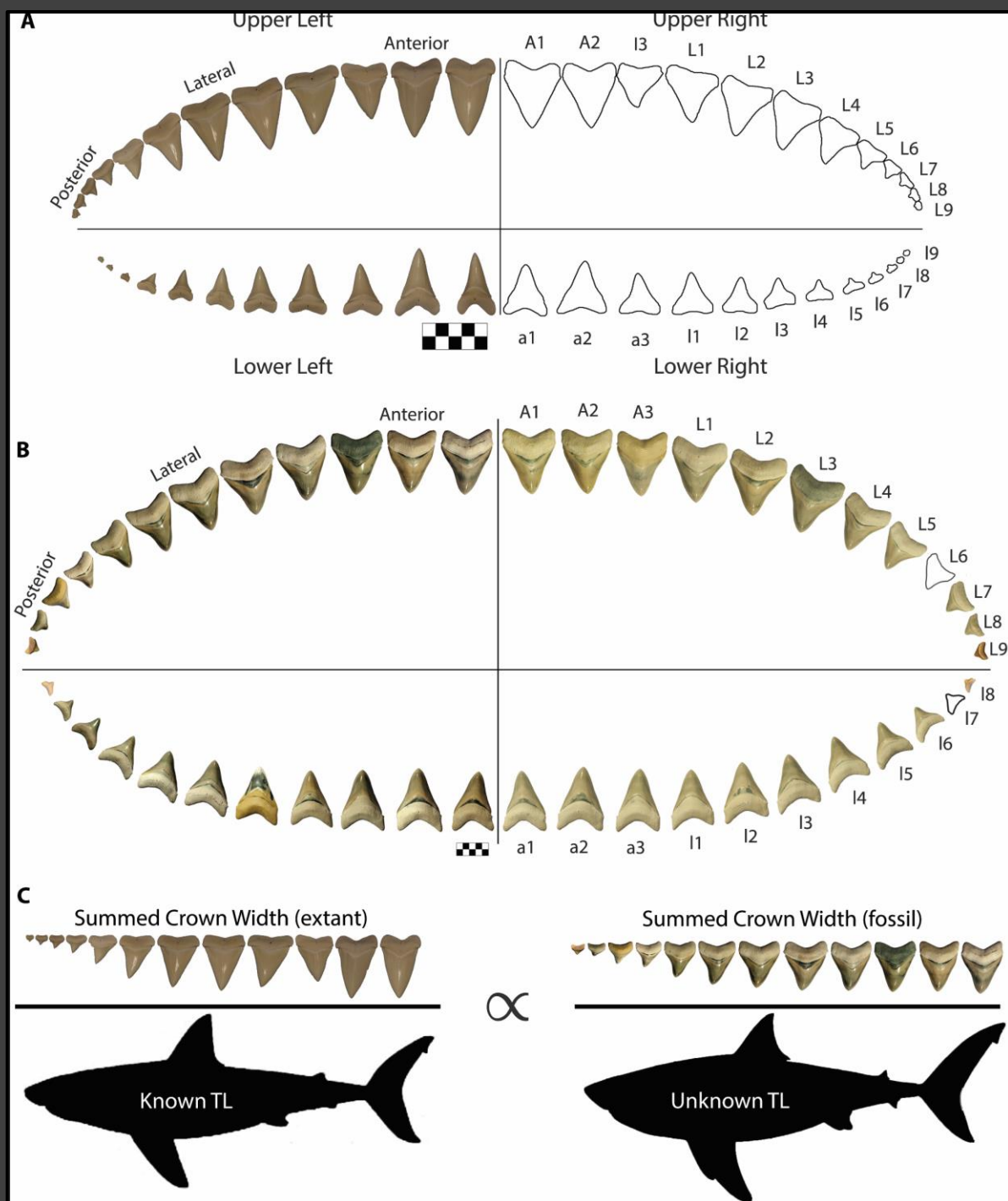
The megatooth shark, *Otodus megalodon*, is widely accepted as the largest macrophagous shark that ever lived; and yet, despite over a century of research, its size is still debated. The great white shark, *Carcharodon carcharias*, is regarded as the best living ecological analog to the extinct megatooth shark and has been the basis for all body length estimates to date. The most widely accepted and applied method for estimating body size of *O. megalodon* was based upon a linear relationship between tooth crown height and total body length in *C. carcharias*. However, when applying this method to an associated dentition of *O. megalodon* (UF-VP-311000), the estimates for this single individual ranged from 11.4 to 41.1 m. These widely variable estimates showed a distinct pattern, in which anterior teeth resulted in lower estimates than posterior teeth. Consequently, previous paleoecological analyses based on body size estimates of *O. megalodon* may be subject to misinterpretation. Herein, we describe a novel method based on the summed crown width of associated fossil dentitions, which mitigates the variability associated with different tooth positions. The method assumes direct proportionality between the ratio of summed crown width to body length in ecologically and taxonomically related fossil and modern species. Total body lengths were estimated from 11 individuals, representing five lamniform species: *Otodus megalodon*, *Otodus chubutensis*, *Carcharodon carcharias*, *Carcharodon hubbelli*, and *Carcharodon hastalis*. The method was extrapolated for the largest known isolated upper tooth of *O. megalodon*, resulting in a maximum body length estimate of 20 m.

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palaeo-electronica.org/content/2021/3284-estimating-lamniform-body-size

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Summary

1. Megalodon evolved from *Otodus obliquus* and is not directly related to the modern Great White Shark.
2. Megalodon fed on large fleshy prey, such as marine mammals and large fish.
3. Megalodon likely reached a maximum body size of 65 ft (=20 m).

SHARKS!

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Calvert Marine
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New exhibit on
Maryland sharks

➤ **Where?**

Calvert Marine Museum
Solomons, MD

➤ **When?**

July 2021 – December 2022