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EXAMPLES OF THE REPLACEMENT OF LIMESTONE BY CLAY

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Abstract

The thick masses of clay on limestone and the clay filling of caves, commonly considered residual material left by solution of calcium carbonate, may instead be a replacement produced by action of acidic water that contains quantities of silica, alumina, and iron oxide. Fossil shells near Pontotoc, Mississippi, have been replaced by beidellite that preserves all the internal structure of the originally calcareous shells. Slightly glauconitic limestone in Wayne County, Mississippi, is overlain by slightly glauconitic montmorillonite that appears to have replaced the limestone. The geochemistry of the replacement process is still not understood.

Introduction

The source of the thick masses of montmorillonitic or kaolinitic clay that in places cover limestone terranes and are usually called "residual clay" has long constituted a controversial question, especially when the clay rests on limestone that is nearly pure calcium carbonate. At some places the clay is as thick as or nearly as thick as the limestone from which it is supposed to be residual. Where the parent limestone consists of 95 percent or more of calcium carbonate, the term "residual" is patently so absurd that some other explanation has been sought to explain the presence of the clay. The most common explanation has been that the clay is material that has been washed or blown over the limestone.

Another explanation for the origin of the thick clays is suggested in an article by Ross and Stephenson (1939) in which they report the "formation of an unusually pure clay mineral of the montmorillonite group by replacement of calcareous shells" at a locality near Pontotoc, Mississippi.

Belgian geologists (Corin and Huge, 1949) have observed deposits of clay or shale that they can only explain as replacements of limestone. The present paper reviews these and other cases of replacement of limestone by clay and suggests geochemical studies to test the hypothesis.

Replacement of Fossil Shells by Clay

In 1910 Stephenson (1939) discovered in a railroad cut about 800 meters (half a mile) south by west of Pontotoc in northeastern Mississippi a suite of molluscan shells that had been completely replaced by clay. The clay-replaced shells occur in yellowish-brown, medium-grained sand at the base of the Clayton Limestone of the Midway Group of Paleocene age, which immediately overlies the Owl Creek Formation of Late Cretaceous age. Ross and Stephenson (1939, p. 393-394) describe the occurrence as follows:

"The fossil shells are in a good state of preservation, but are very soft and easily damaged. The clay contains a large proportion of excess water, which quickly evaporates on exposure to the air, and the shells shrink and shrivel into thin flaky fragments. Even when packed in damp sand, and allowed to dry slowly for nearly a year, the final state of preservation is very poor. The shells have been reworked and redeposited from an underlying Cretaceous bed which is not exposed in the immediate vicinity, but which must have been nearby, for the shells show little evidence of wear by transportation. Therefore, this transportation must have occurred before their replacement by fragile clay material.

"The shells are dull olive-gray when moist, and gray to brownish-gray when dry. The material is unusually translucent and resembles horn when dry. The original structure of the shells is very perfectly preserved in the clay material. In one specimen the minute lamellae of the clay material average about 0.015 millimeter in width, but are sharply distinguishable by the different crystallographic orientation in adjoining areas."

A photomicrograph showing the finely laminated structure of a fragment of a bivalve molluscan shell replaced by clay is shown on page 394 of the paper by Ross and Stephenson. On page 394 they describe the clay mineral as biaxial, negative, with a variable axial angle, a birefringence of about 0.03, and a mean index of refraction of about 1.53, a little high for minerals of the montmorillonite group, perhaps due to the high iron content.

They also give a chemical analysis of the clay material, which is included with others in the table.

On the basis of petrographic studies and of the chemical analysis, Ross concludes that the clay is composed of the following molecules recalculated to 100 percent:

$Al_2Si_4O_{10}(OH)_2$	Montmorillonite	30
$Al_2AlSi_3O_9(OH)_3$	Beidellite	53
$Fe_2Si_4O_{10}(OH)_2$	Nontronite	7
$Mg_3Si_4O_{10}(OH)_2$	Hector clay	6
$KAl_2AlSi_3O_{10}(OH)_2$	Muscovite	4

Margaret D. Foster also collected some of the material in 1951 and analyzed it herself (see Table). On the basis of her calculations she considered the material beidellite with the layer charge predominantly on the tetrahedral sheet, rather than on the octahedral sheet, as in montmorillonite. She considered the formulas rational only if at least some of the MgO in the analyses is considered to be in exchange positions.

The complete replacement of the calcium carbonate of the fossil shells by clay is accentuated by the virtual absence of calcium oxide in the clay.

The shells at Pontotoc are in a highly weathered, ferruginous, clayey, medium sand that contains abundant, highly polished, small, ovoid, hollow concretions of goethite up to a millimeter long. The quartz sand and possibly the goethite concretions are probably residual material from an original bed of sandy limestone. Very sandy, friable limestone that contains abundant reworked Cretaceous shells composed of calcite is present at the same stratigraphic position at several places from Tippah County, farther north, to the northern part of Chickasaw County, south of Pontotoc. One of these outcrops is described by Ross and Stephenson (1939, p. 397):

"About 14 miles north of Pontotoc and 3 1/4 miles south of New Albany, there is a bed that contains abundant reworked Cretaceous shells and occupies the same position at the base of the Eocene [Paleocene]. Here the shell bed is from 2 to 3 feet thick, and is a greenish-gray, sandy, coquina-like, friable limestone. The matrix between the shells contains abundant limonitic oolites, and a few spherical grains of calcite. The shells are for the most part calcium carbonate, but here and there the calcium carbonate has been partly replaced by clay material of the same type previously described."

In August 1966 I visited the Pontotoc locality and collected a number of the clay-replaced shells, which were packed for shipment in the damp quartz and limonitic sand in which they occur. Efforts to seal the cartons containing the replacements were not very successful, however, so that when the material was unpacked in San Juan, Puerto Rico, a month later, most of the replacements had dried out to clay flakes.

TABLE 1 (table from Monroe, 1974)
Chemical analyses of limestone and associated clay from Mississippi

Field Number	PON—A	PON—B	WAY—AL	WAY—AM	WAY—AC
Material	Clay replacing fossils	Clay replacing fossils	Limestone	Transitional limestone	Clay above limestone
SiO_2	46.95	48.61	3.1	27.7	50.6
Al_2O_3	27.26	25.06	1.2	9.4	19.3
Fe_2O_3	2.26	3.13	.90	5.8	9.2
FeO	0.32	.33	.09	.06	.04
MgO	1.39	2.24	1.4	1.3	2.2
CaO	None	.85	50.3	26.0	1.2
Na_2O	0.20	.09	.00	00	.04
K_2O	0.36	.04	.20	.90	.90
H_2O^-	11.10	12.83	.52	5.7	8.5
H_2O^+	10.55	7.09	.68	3.5	7.0
TiO_2	None	0.04	.07	.37	.56
P_2O_5	0.03	.20	.08	.24	.19
MnO	0.01	.02	.08	.14	.09
CO_2	-------	-------	41.2	18.7	.05
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Sum	100.43	100.53	100.00	100.00	100.00

Analysts : PON-A, J.G. Fairchild (1937); PON-B, M.D. Foster (1951); all others in 1967 by Paul Elmore, H. Smith, S. Botts, G. Chloe, L. Artis, and J. Glenn.

Localities : PON-A and PON-B, west side of cut of Gulf, Mobile, and Ohio Railroad, 1/2 mile south by west of railroad station at Pontotoc, Miss. — WAY-AL, WAY-AM, and WAY-AC. Roadside outcrops on secondary road near north edge sec. 13, T. 9 N., R. 6 W., 3/4 mile north of Tokio, Wayne Co., Miss. AL is unweathered Mariana Limestone; A.M. is material transitional between limestone and clay; AC is clay about 1 foot above top of limestone.

Nevertheless I picked these flakes out of the sand matrix, cleaning the sand and limonite from them. The flakes were then studied by Paul D. Blackmon of the U.S. Geological Survey. He found that about eight tenths of the material consists of beidellite-montmorillonite (over 50% beidellite) with a high aluminum-interlayer content, a little less than one tenth is goethite, and the rest consists of trace amounts of kaolinite, interlayered kaolinite-montmorillonite, illite, and mixed-layered illite-montmorillonite. His determinations are very close to those computed by Ross many years earlier. I also sent Dr. Blackmon some of the sand with the flakes of clay loose in it. He dried this material, dispersed it in water, and then determined the percentage composition of sand, silt, and clay. He then determined by X-ray the minerals present in each fraction. The minerals present in these fractions are similar to those in the handpicked sample, except that there is an appreciable quantity of quartz, and a considerably larger quantity of goethite.

Clay resting on limestone in southern Mississippi

Clay that superficially, at least, resembles the clay formed by replacement of the fossil shells at Pontotoc in northern Mississippi rests on the Marianna Limestone of Oligocene age in shallow road cuts at the top of a hill south of Dry Creek, about 1.2 kilometer (3/4 mile) north of Tokio, near the north edge of Sec. 13, T. 9 N., R. 6 W., Wayne County, in southeastern Mississippi.

At the base is cream-colored to white, glauconitic limestone typical of the Marianna. The upper few centimeters of the limestone is soft, but still contains grains of glauconite scattered at about the same distances as in the underlying harder, purer limestone. The contact between the hard limestone and the softer limestone is gradational and the latter seems to be a weathering product of the former. The soft limestone is overlain transitionally by yellow to gray, slightly manganiferous clay, which also contains grains of glauconite scattered through it in the same density pattern as in the underlying limestone. The clay is overlain disconformably by yellow clayey sand, which grades upward into coarse red sand. Pinnacles of the underlying clay as wide as 60 centimeters and up to 15 centimeters high project upward into the clayey sand. These pinnacles resemble pinnacles of limestone seen elsewhere, but here they consist of the yellow to gray smooth clay.

The yellow to gray clay appears to be a weathering product of the limestone as evidenced by the transitional soft limestone; it is certainly not a separately deposited clay, much less an overlapping deposit of bentonite of another formation, as the outcrop was originally considered (Blanpied, Oldham, and Alexander, 1934, p. 11-14), for the clay is much more plastic than the bentonite deposits found nearby in an overlying clay formation.

The chemical analyses in the Table show that the fresh limestone (WAY-AL) contains about 91.5 percent calcium carbonate. The transitional material (WAY-AM) contains only about 44.7 percent calcium carbonate and the relative percentages of silica, alumina, and ferric oxide have increased appreciably over the amounts contained in the fresh rock. Almost no calcium carbonate is present in the clay (WAY-AC). This pattern of change is consistent with weathering of the Marianna Limestone, but the distribution of glauconite grains suggests that there has been no change in volume of the material upon weathering, and the amount of noncarbonate material in the original limestone is insufficient to account for the mantle of clay without a change in volume.

Dr. Blackmon studied two samples from this locality, one from the clay about a foot above the limestone (WAY-AC) and the other from the transitional bed between the limestone and the clay (WAY-AM). He found that the clay fractions of both samples were much the same: montmorillonite constitutes about 7/10 of the transitional bed and 8/10 of the clay, kaolinite is about 1/10 of each sample. Traces of illite, illite-montmorillonite, mixed-layered, anastase, goethite, quartz, and vermiculite (?) are present in both samples. The transitional material also contains traces of calcite and siderite; the clay above contains traces of nontronite. As can be seen this clay resembles that replacing the shells at Pontotoc, and the two probably have a similar origin.

Replacement of limestone by clay in the Congo

In the Congo (Zaire) Corin and Huge (1949) observed several outcrops where a core of limestone in the center of a hill passed laterally into clay or shale in every direction without much change in volume. In a cut near Kimpese on the railroad from Matadi to Leopoldville (1949, p. 66-67) they described about 3.5 meters of limestone consisting of more than 40 percent calcium carbonate, stratified into light-gray beds from 10 to 20 centimeters thick alternating with dark beds from 2 to 5 centimeters thick. Two outcrops of the limestone are surrounded and overlain by 1.5 meter or more of noncalcareous yellow and red clay ("schiste") in beds 5 to 10 centimeters thick. Careful study of the limestone and the clay at the site showed that individual beds in the limestone could be traced into the clay without interruption. This clay is overlain by 1 to 2 meters of yellow clay ("argile") that is compact and resistant to slumping. Resting on the yellow clay is a 1.5 centimeter bed made up of blocks of white chert arranged in a regular pattern that suggests a formerly continuous bed. The chert bed follows the undulation of the limestone and the associated clay with only slight downwarping over places where the limestone is replaced by clay. Corin and Huge considered the evidence of replacement of the limestone by the clay conclusive.

At Lukala Corin and Huge (1949, p. 63-66) studied a quarry of cement rock in which a central mass of thin-bedded limestone grades laterally in all directions into thin-bedded shale with very little change in thickness. The limestone contains two thin beds of chert that pass into the shale and continue to the edges of the quarry. They consider evidence conclusive that the limestone has been altered in place into shale, and that the lack of settling apparent in the chert beds indicates replacement of the limestone by clay rather than simple solution.

A summary of observations of replacement of limestone and dolomite by clay and of oolites by silica is reported in the same bulletin by Corin, Egoroff, Huge, and Waegemans (1949).

Clay fills in caves

The alteration of limestone to clay by replacement may explain the anomalous deposits of clay in caves. Bretz (1942, p. 774) distinguished between alluvial deposits in caves and "clay fills," which he stated "have so commonly filled the caverns to the ceiling and are so universally of unctuous clay, without sand, gravel or flowstone, that they ... clearly record an epoch between Davis' first and second, that is, between the epoch of solution and the epoch of dripstone and flowstone deposition." Bretz observed that streams could not have brought the clay into the cave, for in Meramec Cave, Missouri, a stream has cut terraces in the clay, and downstream "the terraces are so wide and so close under the ceiling that a narrow trench in the clay is the only open space. By good inference, Meramec is still completely clay-filled beyond the place of escape of the stream." He also pointed out that "most of Cathedral Cave retains its clay fill, headroom in much of the main chamber being largely due to compaction."

Bretz was puzzled by the origin of the clay. He described its occurrence (1942, p. 775):

"The point has already been stressed that capacious caverns antedated the clay fills and that partial or complete removal has been the task of vadose streams. What conditions determined the intermediate clay-fill epoch?

"The clays commonly are red, like the residual soils above. They lack all evidence of current, they show little evidence of any kind of fluctuations during deposition. Even good lamination is not common. Complete lack of flowstone, dripstone, and rimstone indicates the absence of air while the deposit accumulated. The fills appear to be subterranean lake clays beneath the water table.

"Yet many chambers now or formerly containing them obviously were trunk routes for ground-water discharge. The marked stagnancy required for deposition of the clay in such chambers succeeded a fairly definite flow, though both epochs were phreatic."

He pointed out that "it is impossible to derive complete clay fills from the insoluble material of the limestone which has disappeared, and it is impossible to explain the older cavern forms so gradually being filled at the bottom while being dissolved from the top." He postulated that the clay has been carried down joints and swallow holes from a mantle of residual clay on the surface, but he also pointed out that most streams entering caves have deposited silt, sand, and gravel as well as clay.

Most extraneous material in caves has been brought in by running water, but such deposits contain grains of quartz and other minerals, fragments of carbonized wood, and other material definitely originating outside the caves. The "clay fills" of Bretz consist entirely of unctuous clay, and in places they fill the caves to the ceiling; thus they can not be considered ordinary alluvium. It is possible that they have been brought into the caves during periods of solution by water that came down through minute fractures and carried the clay as cutans that migrated downward along root pipes in soil at the surface. But it is also reasonable, perhaps more reasonable, to ascribe the clay filling to replacement of the limestone by clay in the manner in which the shells at Pontotoc, Mississippi, have been replaced. Replacement explains why some cave chambers are completely filled to the ceiling by clay, why the clay contains little evidence of current or fluctuations during deposition, and why the clay contains no silt, sand, or gravel, whereas at almost every place Bretz observed deposits brought into the cave from outside, he found material coarser than clay.

Geochemistry

Roberts (1971, p. 98) has written, "The weathering process in carbonate rocks appears to be far more complex than that in granitic rocks, in that leaching and replacement are involved; " also " The residual clay retains the volume of the original rock."

The chemistry of the change from limestone to clay is not known, but apparently it takes place by reaction of ground water with limestone. Certainly the clay replacing the calcareous fossil shells at Pontotoc is not residual nor is it material that fills cavities that have been dissolved in the limestone. Rather the action of replacement of the limestone by clay seems to take place molecule by molecule, as Ross and Stephenson show that all the structure of the shells is preserved in the clay replacements (1939, fig. 1, p. 394). Ross believes that the clay is precipitated directly from solution (Ross and Stephenson, 1939, p. 396):

"The replacement of calcareous shells by clay material raises a question as to the chemistry of the process. It is evident that clay-forming material must have been introduced into the shells from the outside and solutions of some kind are the only means for such replacement. Clay is a material that, no doubt, is commonly transported in colloidal solutions, which have small power of penetration, and are ineffective for the removal of replaced material. It, therefore, seems probable that the calcareous shells from near Pontotoc were replaced by solutions carrying the necessary elements for the formation of clay in true chemical solution. These solutions dissolved and removed the calcium carbonate of the shells and at the same time were introducing alumina, silica, a little ferric oxide, magnesium oxide, and unimportant amounts of other elements. In these sands there is no evidence of thermal solutions, and the transfer seems to have been due solely to those acting at normal earth temperatures. The clay mineral contains no calcium oxide, although a small percentage is normally present in minerals of this group. This is surprising, as it shows the complete removal of calcium oxide from the calcium carbonate of the shells."

The examples described in Mississippi have in common the feature that the limestone is overlain by ferruginous, argillaceous sand. Although such a cover may not be essential to the process of replacement, it provides a ready source of the oxides postulated by Ross (Ross and Stephenson, 1939, p. 396). It seems likely, therefore, that the replacement process requires water that is acidic and rich in silica and alumina. The presence of thick masses of terra rossa on beds of fairly pure limestone suggests, however, that an actual cover of ferruginous, argillaceous sand may not be essential, provided that the water attacking the limestone has become enriched in these oxides and in acid through percolation through soil at some stage of its course.

I suggest, therefore, that geochemists having access to limestone and ferruginous sand of the kind present at the localities described in Mississippi carry out an experiment for at least a year placing chips of limestone or fossil shells in or beneath the sand and letting slightly acid ground water percolate slowly through the mixture. Analyses of the water before and after percolation and of the limestone-sand mixture may show some differences. It will be significant also if some of the limestone chips or shells can be exposed to the air occasionally to try to duplicate the conditions described by Ross and Stephenson (1939, p. 397) about 14 miles north of Pontotoc.

Conclusion

The evidence reported in this paper shows definitely that pure limestoné can be replaced molecule by molecule by essentially lime-free clay. In the examples from Mississippi the replacing clay is mostly of the montmorillonite group, but similar replacements in northwestern Alabama observed by me show that the replacing clay may be kaolinite. Dr. C. S. Ross (oral communication, 1966) told me of replacement of pure limestone in Missouri by kaolin in an occurrence much like that in the Congo, in which a bed of chert in the limestone continues through the clay with only slight sagging from the horizontal.

Replacement of limestone by clay will help to explain the thick deposits of terra rossa on masses of pure limestone. It will also help explain the source of the parent material of many of the deposits of bauxite that occur in depressions on pure limestone.

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TEETH OF THE GIANT SHARK *CARCHARODON AURICULATUS* FROM THE EOCENE AND OLIGOCENE OF MISSISSIPPI

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INTRODUCTION

Shark teeth are a favorite among most rock and fossil collectors in Mississippi. Teeth from many shark species can be found in the state's upper Cretaceous and Paleogene marine sequence. Generally, these teeth are less than two and a half centimeters (an inch) in length. Some can barely be seen without magnification. Exceptionally large teeth are rare in Mississippi, and are generally found by chance in marine units of upper Eocene and lower Oligocene age. These beds are found in a relatively narrow band that runs northwest - southeast across central Mississippi. This band is bounded by the towns of Yazoo City and Vicksburg in the west and Shubuta and Waynesboro in the east. The strata range from the early late Eocene (about 42 million years ago) Moodys Branch Formation of the basal Jackson Group to the late early Oligocene (about 35 million years ago) Byram Formation of the upper Vicksburg Group.

The impressive large shark teeth of the Jackson and Vicksburg groups are those of the primitive great white shark *Carcharodon auriculatus*. This must have been a huge and fearsome shark. Its teeth are often twice the size of the largest modern carnivorous shark, *Carcharodon carcharias*, the great white shark.

CARCHARODON AURICULATUS IN MISSISSIPPI

Carcharodon auriculatus has been known in Mississippi since 1828 when the French naturalist Charles A. Lesueur (Figure 1) illustrated two tooth crowns of that species among a group of fossils collected at Vicksburg. Unfortunately, Lesueur's beautiful lithographic plates were part of a report that was never published. These plates have only recently been published (Dockery, 1982a, 1982b). Lesueur's plate 3 shows the crowns (the cutting part of the tooth, as opposed to the root) of two large *Carcharodon auriculatus* teeth in figures 7, e-f, and 8. These specimens were collected from early Oligocene beds of the Vicksburg Group at Vicksburg (probably from either the Mint Spring or Byram Formation).

The first published report of *Carcharodon auriculatus* in Mississippi is Gibbes (1848), the first major study of American fossil sharks. Among the many teeth figured from the Atlantic and Gulf coastal plain is one of *C. auriculatus* (Plate 19, figure 13) from the late Eocene (Jackson Group) of Wayne County in southeastern Mississippi.

Reports of *Carcharodon auriculatus* from Mississippi have been sporadic since 1848. Benjamin L. C. Wailes noted the species (as *Carcharodon "agustidens"* [sic] and *Carcharodon megalodon)* from the late Eocene beds of the Jackson area in the state's first geological survey report (Wailes, 1854). *Carcharodon angustidens* Agassiz, 1843, is now considered to be a junior synonym of *C. auriculatus* (de Blainville, 1818). The second survey report (Harper, 1857) repeated this record and noted that the species (as *Carcharodon* sp.) also occurred on the Chickasawhay River in Wayne County (probably from the Vicksburg Group). The third survey report (Hilgard, 1860) recorded the species as *Carcharodon* sp. from Wayne County and as *C. angustidens*

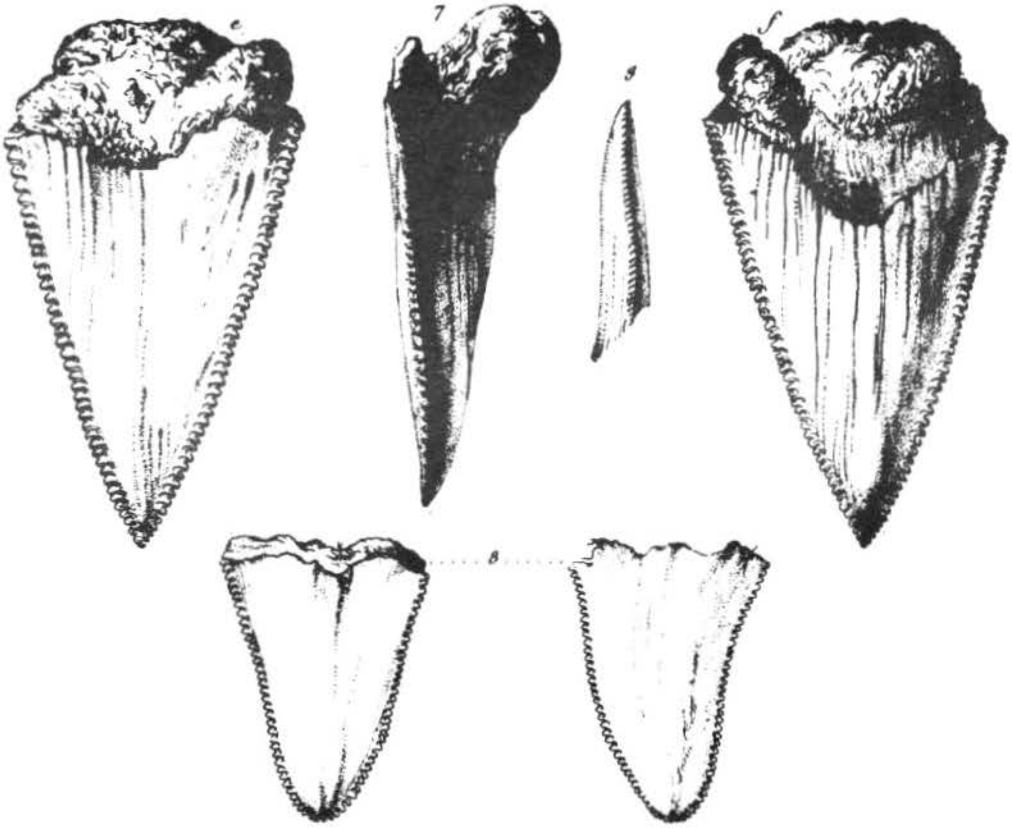


Figure 1. *Carcharodon auriculatus* teeth (crowns only) illustrated by Charles A. Lesueur in 1828 from the Vicksburg Group (lower Oligocene) at Walnut Hills north of Vicksburg, Mississippi.

from the Jackson Group near Jackson and the Vicksburg Group of Warren County. Hilgard reported that the Jackson teeth included specimens four inches in length (1860, p. 132). These teeth are larger than any illustrated in this report, the longest of which is 99.2 mm or 3.6 inches along the anterior edge (Plate 2, figure 1). Hopkins (1871) reported the species as *C. angustidens* from the late Eocene of Jackson and from the Vicksburg Oligocene of the state.

More recent citations include Leriche's (1942) major review of American coastal plain sharks. Leriche reported late Eocene specimens of the species (as *C. angustidens* praemut. cf. *sokolowi*) from 3-4 miles east of Shubuta in Wayne County and from Pachuta in Clarke County. Domning (1969) noted the Mississippi records of the species (as *C. angustidens*) in a review of the literature on Mississippi vertebrate fossils. Breard (1978) recorded teeth of *C. auriculatus* (as *C. angustidens*) from the Moodys Branch Formation at Techeva Creek in Yazoo County.

The most recent citation of *Carcharodon auriculatus* (as *Carcharodon* sp.) material from Mississippi was a brief article and an illustration of a large tooth collected from the Yazoo Formation at Yazoo City by Charles E. Adams of Yazoo City. This article in the June 1981 issue of *Mississippi Geology* (Dockery, 1981) cited the Yazoo City specimen (see Plate 2, figure 2) as one of the largest known from the state. Nelson T. Carr, a fossil collector from Jackson, Mississippi, notified the senior author that he had found a larger one. This tooth (Plate 2, figure 1), which is now part of the Mississippi Petrified Forest museum collection, is indeed longer, but has a lesser weight and volume than the Yazoo City specimen. Due to the interest in these large fossil shark teeth, several *Carcharodon auriculatus* teeth from private and institutional collections in the state were examined and detailed measurements made in order to make more accurate comparisons of the teeth. Photographs of nine of these teeth are given (at their actual size) in plates 1 to 4. Measurements of these teeth are presented in Table 1.

Specimen number	Weight in air (gm)	Weight in water (gm)	Volume (cc)	Specific gravity	Length of anterior edge (mm)	Length of posterior edge (mm)	Height (mm)	Width (mm)	Formation
1	75.0	47.0	28.0	2.68	89.6*	84.0*	82.1*	65.1	Moodys Branch
2	18.8	12.2	6.6	2.85	57.9	49.7	49.0	46.0	
3	77.2	48.8	28.4	2.72	89.3	80.4	78.4	67.4	Yazoo
4	94.4	60.1	34.3	2.75	91.3	89.4	84.4	<u>71.9</u>	
5	76.4	46.6	29.8	2.56	<u>99.2</u>	<u>91.7</u>	<u>90.4</u>	66.3	
6	88.9	57.3	31.6	2.81	88.8	83.8	83.0	68.8*	Marianna
7	<u>99.4</u>	<u>64.6</u>	<u>34.8</u>	<u>2.86</u>	93.5*	89.3*	87.7*	65.3	Byram
8	33.1	19.9	13.2	2.51	77.5	66.8	66.2	56.9	
9	61.2	39.0	22.2	2.76	80.4*	71.8*	70.6*	70.2	

Table 1. Measurements of some Eocene and Oligocene *Carcharodon auriculatus* teeth from Mississippi. Specimen data are provided in the text, and all teeth are figured in Plates 1-4. Underlined measurements are the greatest for each measurement. Those measurements followed by an asterisk (*) are approximate, because the specimens are incomplete.

SPECIMENS STUDIED

Nine *Carcharodon auriculatus* teeth from four formations were graciously loaned to the Mississippi Bureau of Geology by various individuals and institutions for the purposes of this study. These specimens, as shown in Table 1, are given numerical designations (1-9) based largely upon their stratigraphic sequence (oldest to youngest). The oldest specimens (specimens 1 and 2) are from the late middle Eocene Moodys Branch Formation of the basal Jackson Group, and the youngest specimens (specimens 7-9) are from the late early Oligocene Byram Formation of the upper Vicksburg Group. Those specimens (specimens 3-5) from the Yazoo Formation of the Jackson Group were found in the lower part of that formation. Two large *Carcharodon auriculatus* teeth are known to have been found in the upper Yazoo Formation (Shubuta Member equivalent) in the Miss Lite clay pit at Cynthia, Hinds County, Mississippi, but were unavailable for this study.

Data for each of the teeth studied, including the collector, date collected, formation, locality, and present disposition of the specimen, are given below according to the numerical designation of the specimen.

Specimen 1. Collected by David T. Dockery III around 1967 from the Moodys Branch Formation at Town Creek (Mississippi Geological Survey locality 1), right (south) bank just upstream (west) of the South State Street bridge, Jackson, Hinds County, Mississippi. Private collection, Jackson, Mississippi.

Specimen 2. Collected by David T. Dockery III around 1967 from the Moodys Branch Formation at Town Creek (MGS locality 1), Jackson, Hinds County, Mississippi. Private collection, Jackson, Mississippi.

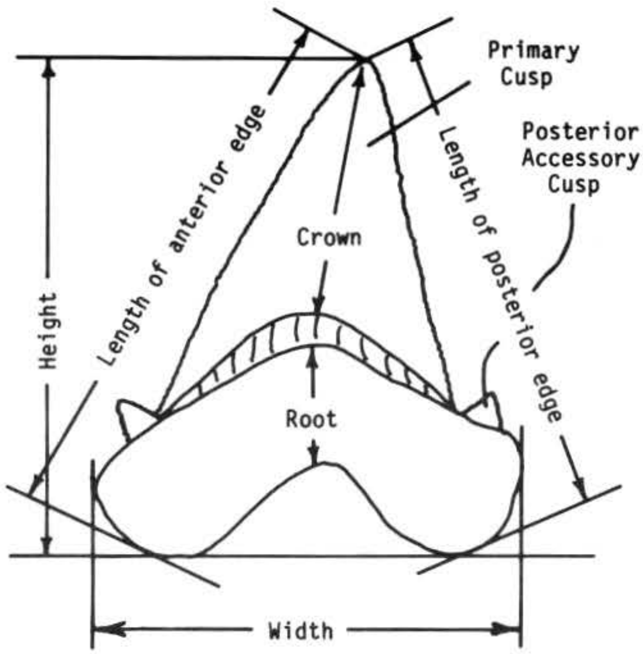


Figure 2. Diagram showing how measurements were taken for this report (see Table 1). Tooth represents a left upper tooth of *Carcharodon auriculatus* in lingual view. Ventral is at the top of the page, and anterior is to the left.

Specimen 3. Collected by Charles M. Adams around 1981 from the Yazoo Formation at Yazoo City, Yazoo County, Mississippi. Private collection, Yazoo City, Mississippi.

Specimen 4. Collected by Charles E. Adams in 1978 from the Yazoo Formation at Yazoo City, Yazoo County, Mississippi. Private collection, Yazoo City, Mississippi.

Specimen 5. Collected by Nelson T. Carr around 1963 from the Yazoo Formation at a culvert excavation just north of the Northside Drive - I-55 interchange on the west side of the interstate in Jackson, Hinds County, Mississippi, during construction of I-55. On display in the museum collection of the Mississippi Petrified Forest, Flora, Madison County, Mississippi.

Specimen 6. Collected by Ralph B. Holt in 1983 from the Marianna Limestone at the South-Central Lime, Inc., quarry (MGS locality 105) at Edwards, Hinds County, Mississippi. Private collection, Pearl, Rankin County, Mississippi.

Specimen 7. Collector unknown. Prior to this study, the specimen was mounted with other fossils on a plaque display labeled as Vicksburg Group, Vicksburg, Mississippi. Mollusks on this plaque are from the Byram Formation, and it is assumed that the tooth is also from that unit. The preservation of the tooth and pyrite mineralization along the root also point to the Byram Formation as its source. The plaque display has been on exhibit at the Millsaps College Geology Department since 1958, so it is assumed that the specimen was collected around 1958 from the Byram Formation at or near Vicksburg, Warren County, Mississippi. Millsaps College Geology Department collection, Jackson, Mississippi.

Specimen 8. Collected by the late Leslie P. Pitts in 1969 from the Byram Formation at the old Marquette Cement Mfg. Co. quarry (MGS locality 98) at Brandon, Rankin County, Mississippi. Private collection of Sue Pitts, Jackson, Mississippi.

Specimen 9. Collected by Brian J. Sims in 1982 from the Byram Formation at the old Mississippi Valley Portland Cement Company quarry (MGS locality 112c) on the east side of Highway 3 north of Redwood, Warren County, Mississippi. Private collection, Jackson, Mississippi.

MEASUREMENTS OF SPECIMENS

Linear measurements of the *Carcharodon auriculatus* teeth given in Table 1 include: (1) length of the anterior edge, (2) length of the posterior edge, (3) height, and (4) width. These dimensions are shown in Figure 2. Because the primary cusp of the tooth points posteriorly, the edges of the teeth are of unequal length. The length along the anterior edge is the longest dimension of the tooth, and the length along the posterior edge is the second longest. This latter dimension was measured along the edge toward which the primary cusp points from the tip of the crown to the end of the root. The measurement of the opposite side gives the dimension of the anterior edge. The height was measured by standing the two roots of the tooth on a flat surface and measuring the greatest dimension perpendicular from that surface to the tip of the crown. The width is the greatest dimension between the root margins and was measured perpendicular to the height.

Each specimen was weighed to the nearest tenth of a gram in air and in water. The difference between the weight in air and weight in water is equal to the weight of water displaced when the tooth is submerged. Since water at room temperature weighs one gram per cubic centimeter, this difference in grams is equal to the tooth's volume in cubic centimeters (cc). To insure an accurate measure of volume, the weight in air was taken immediately after the weight in water while the specimen was still damp with only the surface water removed with a paper towel. This procedure was to account for the

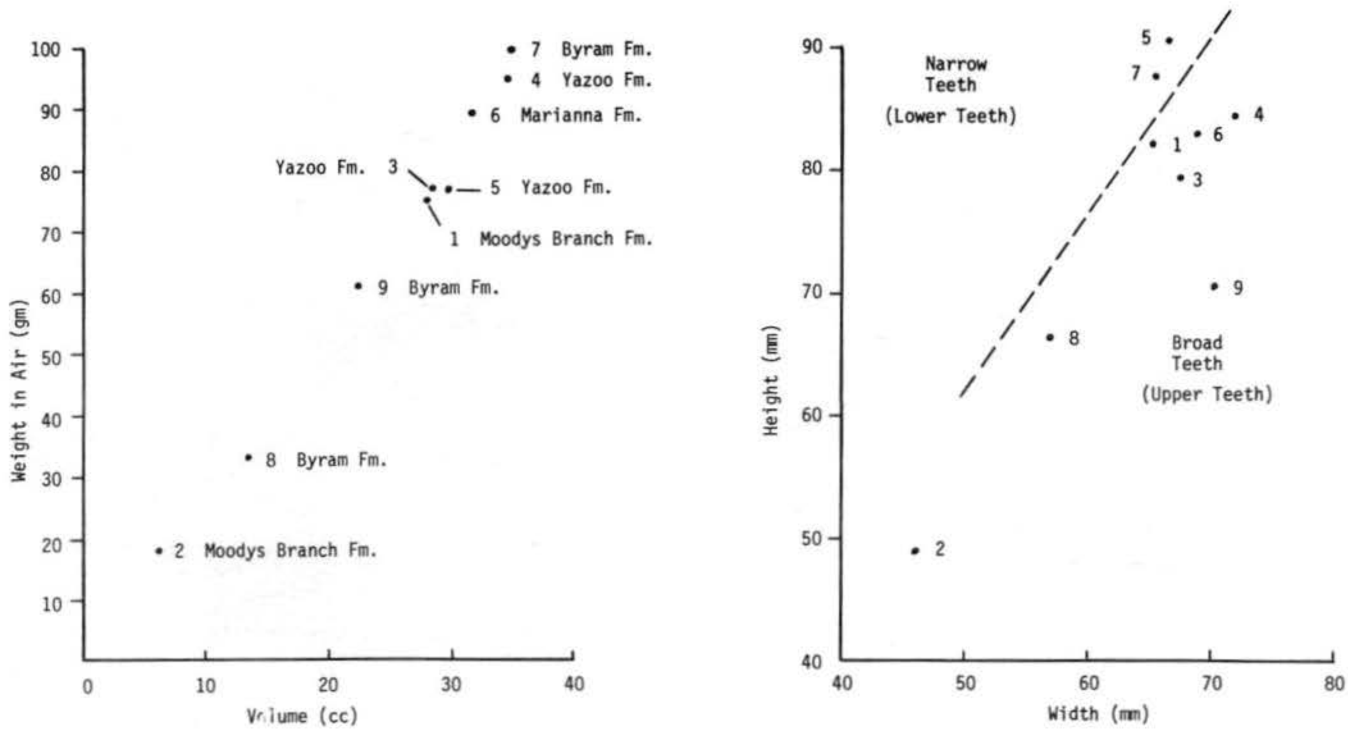


Figure 3. Relative size and proportions of some late Eocene and early Oligocene *Carcharodon auriculatus* teeth from Mississippi. A. Relative size, by weight and volume, of teeth measured in the present study. Weight increases directly with volume. B. Relative proportions of teeth measured in the present study. Lower teeth are narrower than upper teeth and anterior teeth are larger than posterior ones. See data in Table 1.

water that penetrated porous areas of the teeth while submerged, thus adding to their weight in water. Specific gravity, a measure of the tooth's density, was calculated for each specimen. High specific gravities indicate the tooth was either initially dense or that mineralization has occurred in pore spaces. Low specific gravities indicate the tooth was either initially of low density due to porosity or that subsequent leaching has occurred.

INTERPRETATION OF THE TOOTH MEASUREMENTS

Measurements in Table 1 show that three teeth, rather than one, account for the largest values in all the measurement categories. Specimen 5 from the Yazoo Formation has the greatest length and height. The greatest width goes to Specimen 4 from the Yazoo Formation, which also comes in second in weight and volume. The largest tooth by weight and volume is Specimen 7 from the Byram Formation. Specimen 2 is smallest in all categories with the exception of its specific gravity, which is the second highest.

Size

The teeth of a single shark species can vary greatly depending on the size of the shark, whether they are from the upper or lower jaw, and from their position on the jaw. Unlike human teeth, which are replaced only once, those of sharks are constantly replaced. Shark teeth develop in rows, so that when one falls out, the next one rotates forward to take its place. Those at the front of a row, or "tooth whorl," are smaller than those at the back. Young sharks are smaller than adult ones and have smaller teeth. Adults may also vary in size. Specimen 2 from the Moodys Branch Formation (Plate 1, figure 2) is probably small (see Figure 3) due to youth and not because it is an especially early or primitive type. Large teeth of the same species also occur at the same site and same stratum (see Plate 1, figure 1).

Upper and Lower Teeth

Upper and lower teeth of advanced sharks are often very differently shaped, both in the roots and the crown. As a general rule, upper teeth have broader crowns than

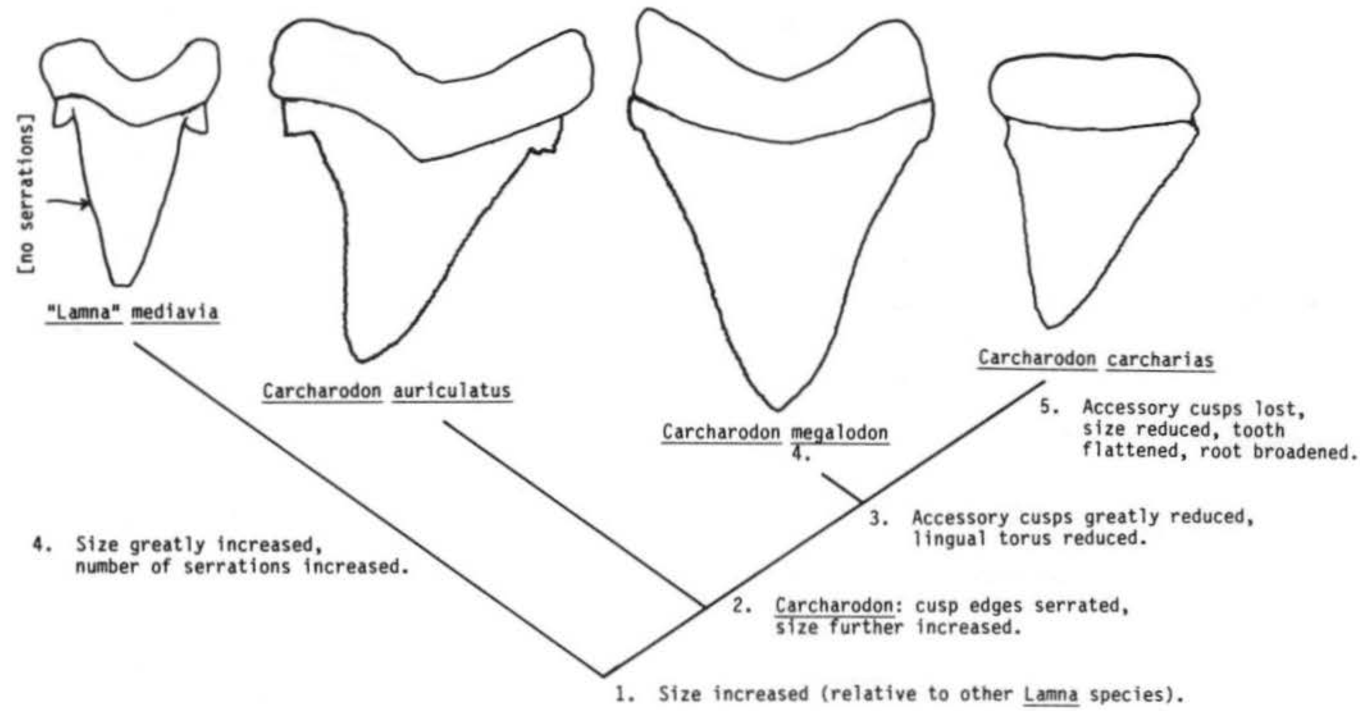


Figure 4. Hypothesis of phylogenetic relationships (cladogram) of some great white shark species. Characters listed at each numbered location are thought to be derived (specialized) at that point. Characters listed at branching points (nodes) are thought to show a close relationship between all taxa beyond that point. For example, because of the characters at node 3, the taxa at numbers 4 and 5 are thought to be more closely related to each other than to either of the other taxa. All figures are modified from Leriche (1942), and have been reduced by 1/3 from natural size.

lower teeth. Think of shark teeth as forks and knives. The narrow lower tooth crowns act like tines of a fork to hold on to the prey. The broad upper teeth act like serrations on a steak knife to cut off chunks of meat. When a shark bites, it doesn't simply bring its jaws together. It lashes its tail back and forth, so that its head moves in an arc from side to side. This allows it to cut out a large plug of meat. Carnivorous sharks swallow their food whole without chewing it. Serrations on the teeth make them even more effective at cutting. The long narrow crowns of specimens 5 (Plate 2, figure 1) and 7 (Plate 3, figure 2) indicate that they are lower teeth (see Figure 3B).

The roots of upper and lower shark teeth are often different as well as the crowns. Compare the tight U-shape of the root of Specimen 5 (Plate 2, figure 1) to the more broadly flaring root of Specimen 4 (Plate 2, figure 2). Because the upper teeth do more cutting and bear greater lateral pressures, they need a broader base of support. To provide this support, the two root ends turn to the sides and the root is flattened from front to back. This is probably why Specimen 9 (Plate 4, figure 2), an upper tooth, is considerably wider than Specimen 7 (Plate 3, figure 2), a lower tooth, even though it is significantly smaller in every other aspect (see Figure 3B). Another

Plates

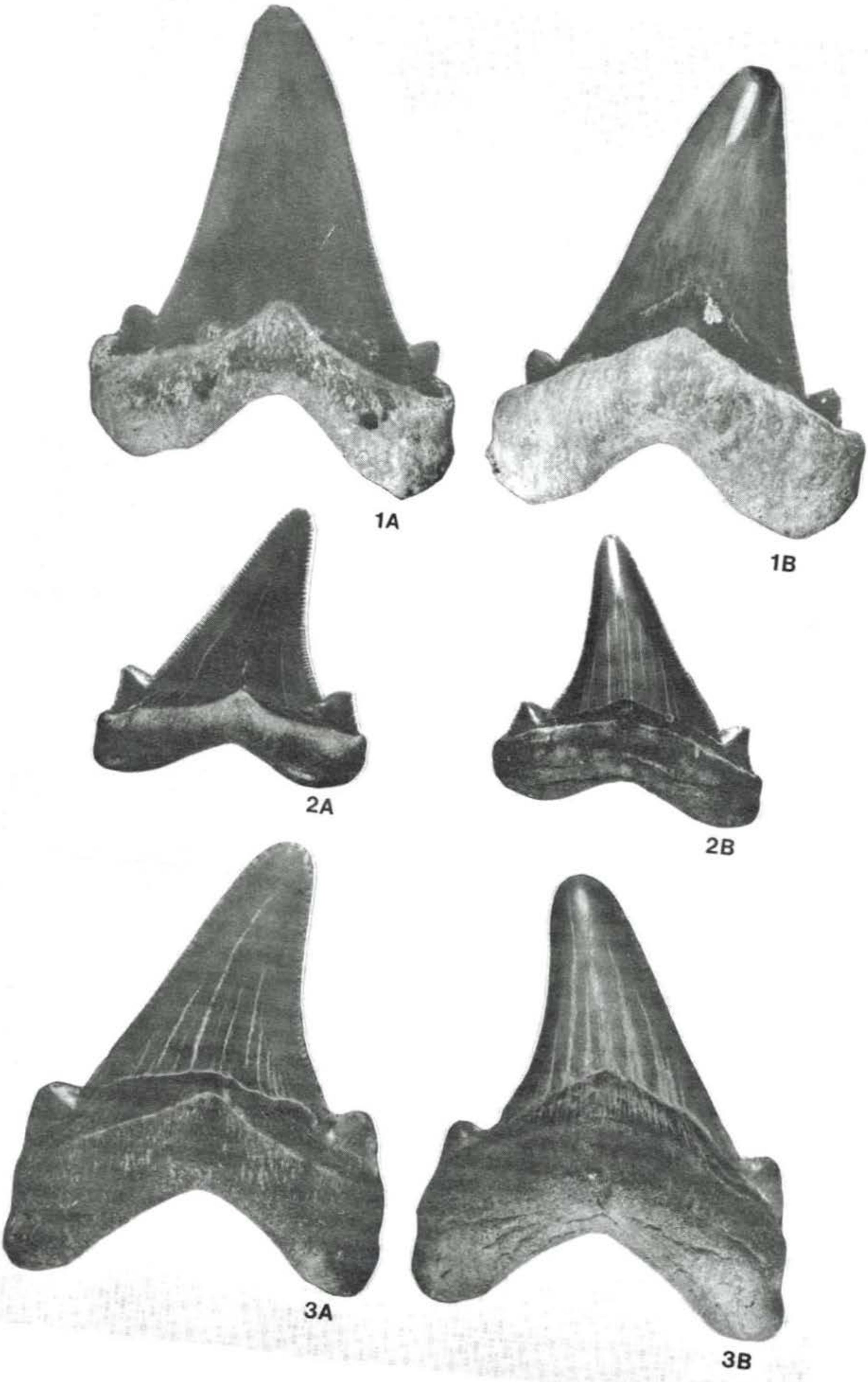
Teeth of late Eocene and early Oligocene *Carcharodon auriculatus* from Mississippi. All "A" figures are in labial view, all "B" figures in lingual view. All figures are x1.

Plate 1

Figure 1. Specimen 1. Left anterolateral upper tooth. Moodys Branch Fm.; Town Creek, Jackson, Hinds County, Mississippi.

Figure 2. Specimen 2. Right lateral upper tooth, juvenile or small adult. Moodys Branch Fm.; Town Creek, Jackson, Hinds County, Mississippi.

Figure 3. Specimen 3. Right posterolateral upper tooth. Yazoo Fm.; Yazoo City, Yazoo Co., Mississippi.


1A
1B
2A
2B
3A
3B

factor that affects the form of the roots of upper teeth is the size of the secondary lobe at the base of the root. This variation in the secondary lobe is illustrated by the contrast of the rounded root ends of Specimen 1 (Plate 1, figure 1) with the very pointed root ends of Specimen 6 (Plate 3, figure 1).

Position in the Jaw

The shape and size of the tooth varies according to its position in the jaw. The main cusp is almost symmetrical (perpendicular to the root) at the front of the jaws, where the left and right sides of the jaw join. Specimen 4 (Plate 2, figure 2) is a good example of an upper anterior tooth. The main cusp barely leans to the side. This is reflected in the small difference between the lengths of the anterior and posterior edges as shown in Table 1, a difference of only 1.9 mm. Many sharks also have very small, oddly shaped teeth near the place where the two sides of the upper or lower jaws meet (this junction is called the symphysis). These are called symphyseal teeth. No symphyseal teeth are among the specimens figured here.

When you look at the outer (labial) side of a shark tooth (usually the flatter side), the main cusp of most teeth leans toward the back of the jaw. The farther back the tooth is positioned, the more it leans. Sometimes the crowns of these posterior teeth are also proportionately smaller (relative to the root) than those of anterior teeth. This explains the shape and proportions of Specimen 3 (Plate 1, figure 3).

Teeth in both upper and lower jaws usually (except for symphyseal teeth) decrease in size toward the back of the jaw. From this it can be determined that Specimen 2 (Plate 1, figure 2) is from a small shark, rather than the posterior tooth of a large shark, because the angle of the main cusp indicates a position on the middle region of the jaw, not the far back. Specimens 1, 4, 5, 6, and 7 are as large as they are partly because they came from the front of the jaw.

Specific Gravity

The specific gravity values of the teeth studied are fairly similar and range from 2.51 to 2.86. Extreme values of this range can readily be attributed to alterations in the teeth after burial. Specimens 5 and 8, with the low values of 2.56 and 2.51 respectively, are bleached by exposure to the sun and show signs of weathering. Leaching of minerals from porous areas of these teeth is responsible for the low specific gravity. Specimen 7 has the highest specific gravity, 2.86, and has pyrite mineralization of the root. With the elimination of end values (as these values are the result of diagenesis), the specific gravity range is from 2.68 to 2.85. The densest tooth within this restricted range (Specimen 2) is the smallest. It is possible that the younger sharks had less porous teeth.

Oligocene Vs. Eocene Teeth

Two of the four Oligocene specimens, specimens 7 (Plate 3, figure 2) and 8 (Plate 4, figure 1), both from the late early Oligocene Byram Formation, are notable in the small size of their accessory cusps when compared to the other specimens (except for Specimen 4, Plate 2, figure 2, in which the accessory cusps have been lost). As the Miocene great white shark *Carcharodon megalodon* has even more reduced accessory cusps, size reduction of the accessory cusp may be part of a trend through the Oligocene and Miocene (see Figure 3).

Another point worth noting is that the largest tooth (Figure 3A) studied here (Specimen 7) is from the youngest stratum. This may suggest a small overall size increase in *Carcharodon auriculatus* from the Eocene to the Oligocene. This hypothesis is supported by the unusually large *C. auriculatus* tooth figured by Gibbes (1848, pl. 19, fig. 14) from the Oligocene of the Ashley River area of South Carolina. Case (1980) reports early Miocene *C. auriculatus* teeth from North Carolina reaching 130 mm in length. These specimens indicate a phyletic overall size increase in the species from late Eocene to early Miocene.

Mississippi's Largest Shark Tooth

The largest shark tooth (volumetrically) studied in this report is Specimen 7 (Plate 3, figure 2). This specimen is not as long as the four inch specimen reported by Hilgard (1860), but the present location of the Hilgard specimen is unknown and thus it is not available for verification of its size and for measurement of its volume. So, for the time being, until a larger tooth is found, Specimen 7 is the largest well documented shark tooth from Mississippi.

There are several factors responsible for the large size of Specimen 7. First, it came from a large individual of the species. Second, it came from the front of the jaw, where the teeth are larger. Third, it is an anterior lower tooth, which may be slightly larger than anterior upper teeth, and may have a more massive root. Fourth, it is from a stratigraphically higher level than most of the other specimens. There appears to be a general trend of increasing size from middle Eocene *Carcharodon auriculatus* to Miocene *Carcharodon megalodon*.

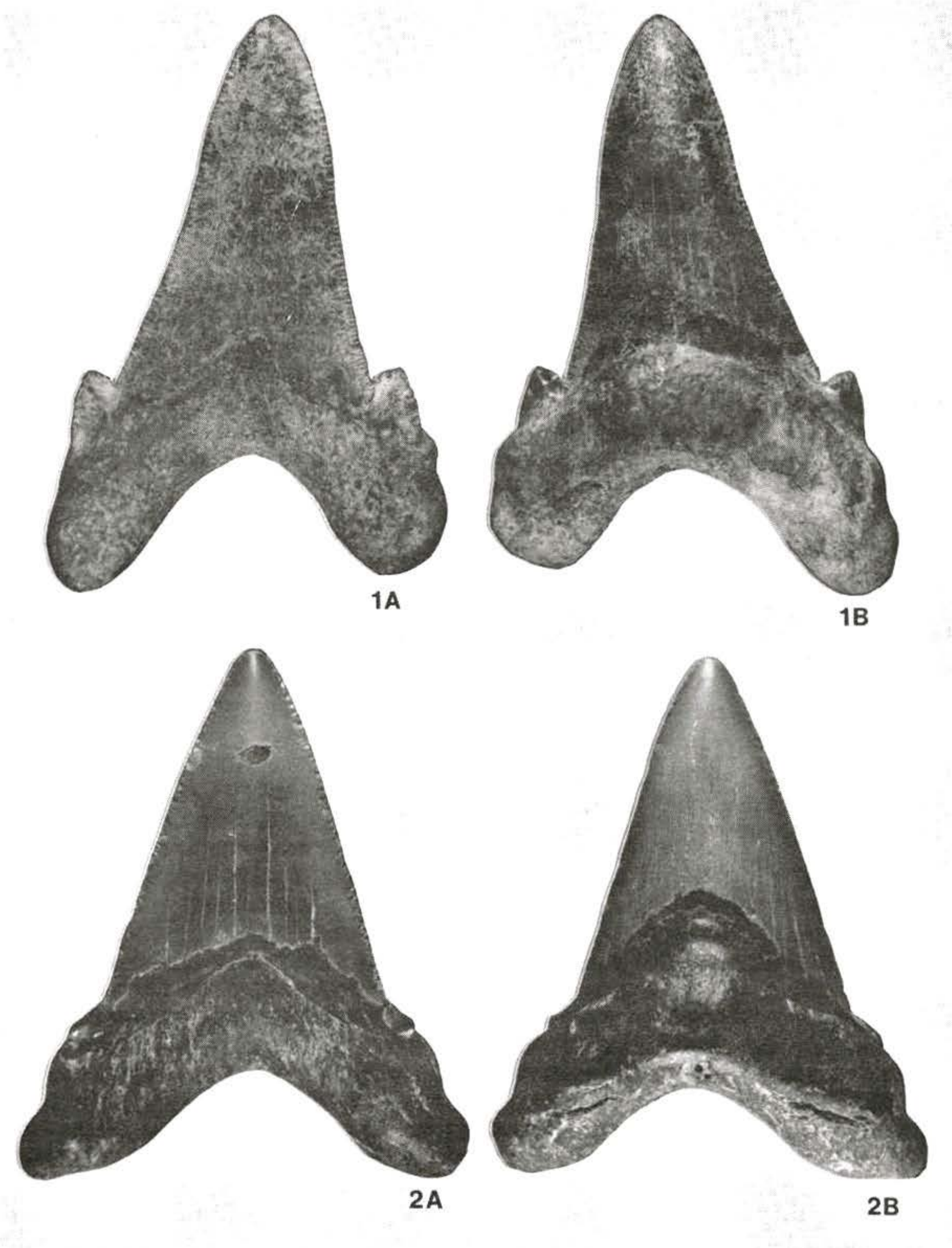


Plate 2

Figure 1. Specimen 5. Left anterior lower tooth. Yazoo Fm.; Jackson, Hinds Co., Mississippi.

Figure 2. Specimen 4. Right anterior upper tooth. Accessory cusps are missing. Yazoo Fm.; Yazoo City, Yazoo Co., Mississippi.

CARCHARODON AURICULATUS IN THE UNITED STATES

Carcharodon auriculatus (de Blainville, 1818) was originally described from Europe. Since then it has been found all over the world. A figure of an American specimen was first published (as *Squalus* sp.) by Morton (1834) from the late Eocene of New Jersey. The species has since been found in nearly the entire length of the eastern Atlantic and Gulf coastal plain. Case (1981, p. 57) gave the range of *Carcharodon auriculatus* as late Eocene to middle Miocene (Helvetian). However, older specimens have been found. Late early Eocene (late Ypresian) specimens of the species have been reported from the upper Nanjemoy Formation of southwestern Maryland and northeastern Virginia by Weems and Horman (1983) and Weems (1985). Middle Eocene (upper Claiborne Group) specimens have been reported from the Castle Hayne Formation of eastern North Carolina by R. L. Meyer *in* Domning, Morgan, and Ray (1982). This formation classically had been considered to be of late Eocene age after its placement as such by Miller (1912) and Kellum (1926). More recent studies, such as that of Ward et al. (1978) and Baum et al. (1978), assign the Castle Hayne a late middle Eocene age and place it in the Claiborne Group.

Late Eocene *Carcharodon auriculatus* teeth have been reported from New Jersey (see review in Fowler, 1911), Maryland (Eastman, 1901), Virginia (Clark, 1896), South Carolina (Gibbes, 1848; Leriche, 1942), Georgia (Case, 1981), Florida (Tessman, 1969), Alabama (Gibbes, 1848; Woodward, 1889; Leriche, 1942; White, 1956), Mississippi (reviewed in this paper), and Louisiana (Hopkins, 1871; Breard, 1978; Manning and Standhardt, 1986). Early Oligocene records of the species are less common. Some specimens reported from South Carolina by Gibbes (1848) may be of that age. Most definite American Oligocene records of *Carcharodon auriculatus* are from Mississippi (this report). Excellent early Miocene (Aquitanian) *C. auriculatus* teeth have been reported from the Trent Formation of eastern North Carolina (Case, 1980).

THE RELATIONSHIPS OF *CARCHARODON AURICULATUS*

Great white sharks (*Carcharodon* spp.) probably evolved from large Paleocene species of *Lamna*, such as *Lamna mediavia*. These shark teeth are similar to those of *Carcharodon auriculatus*, though they are smaller and lack serrations on the edges of the cusps. If this relationship is correct, these large froms should probably not be retained in the genus *Lamna* (which includes the modern mackerel shark). *Lamna* is relatively primitive among galeoid sharks in its retention of large accessory cusps on either side of the primary cusp. Most advanced sharks lose these accessory cusps.

Carcharodon auriculatus and the giant Miocene species *Carcharodon megalodon* have been placed by Casier (1960) in the genus *Procarcharodon*. This genus is not used here because it appears to have been erected on the basis of the shared primitive characters of its component species. Rather than considering *C. megalodon* to be an end member of a now extinct lineage, an argument can be made that it is more closely related to the modern great white shark, *C. carcharias*, than it is to *C. auriculatus* (see Figure 4). Despite its huge size, considered a unique derived character here, *C. megalodon* shares with *C. carcharias* a reduction of the accessory cusps that are so prominent in *C. auriculatus*. It may be that one reason *"Procarcharodon"* is considered to be a lineage separate from *Carcharodon* is that *C. megalodon* coexisted with *C. carcharias* in the middle Miocene (Case, 1980). If phylogeny is seen in terms of closeness of relationship rather than as ancestors and descendants, there is no reason that closely related species cannot coexist and still be more closely related to each other than any other species. The same is true of *C. auriculatus* and *C. megalodon*, which coexisted in the early and middle Miocene. Evolution is better shown by a simple system of interrelationships based on advanced features than by large numbers of short, unrelated lineages.

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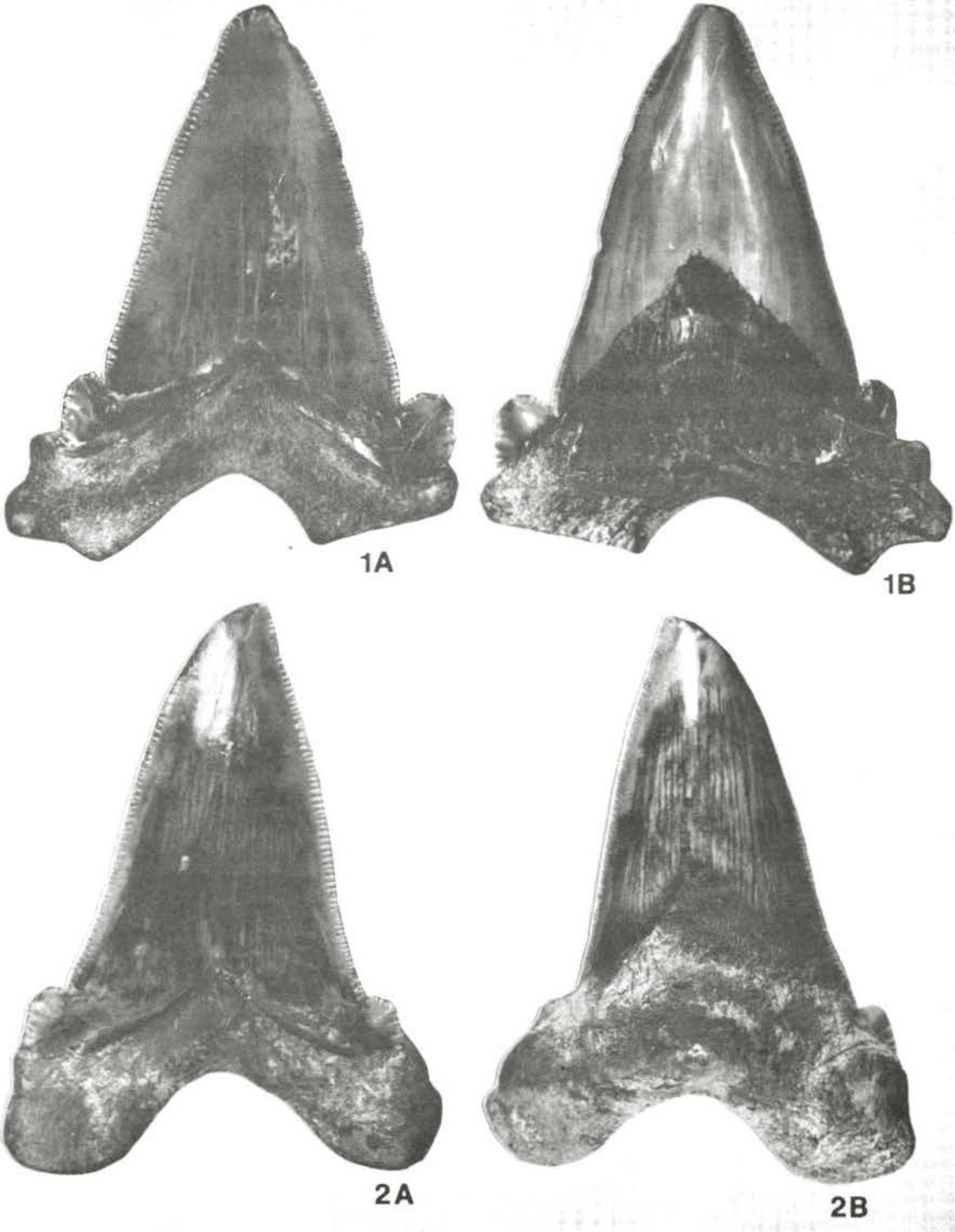

Plate 3

Figure 1. Specimen 6. Left anterolateral upper tooth. The base of the right root is missing. Marianna Limestone; South-Central Lime, Inc., quarry at Edwards, Hinds Co., Mississippi.

Figure 2. Specimen 7. Left anterior lower tooth. The tip of the primary cusp is missing. Byram Fm.; Vicksburg, Warren Co., Mississippi.

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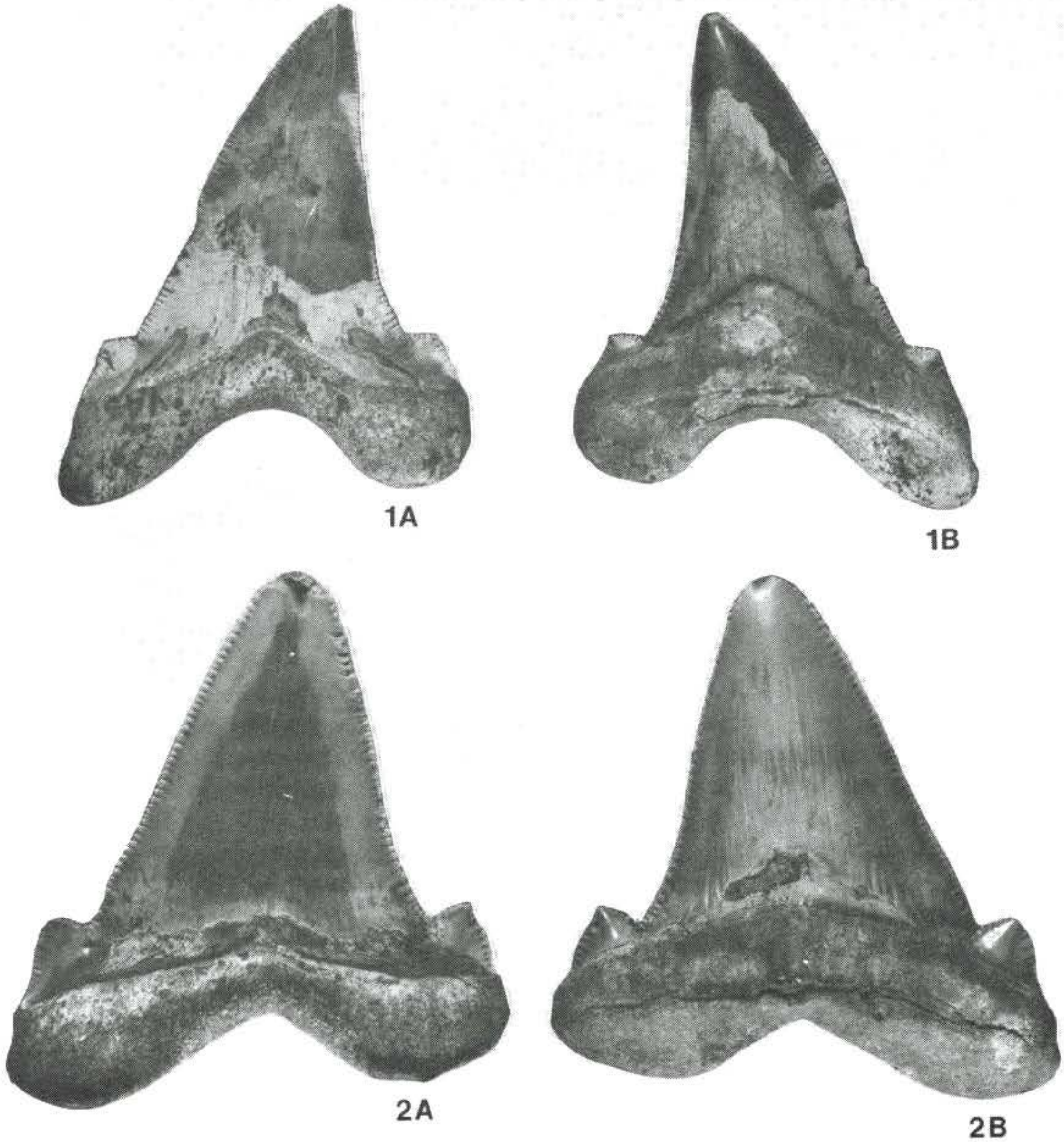

Plate 4

Figure 1. Specimen 8. Right lateral upper tooth. Byram Fm.; Marquette Cement Mfg. Co. quarry, southwest of Brandon, Rankin Co., Mississippi.

Figure 2. Specimen 9. Right lateral upper tooth. Byram Fm.; Mississippi Valley Portland Cement Co. quarry, north of Redwood, Warren Co., Mississippi.

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