

RUDIST TAXONOMY USING X-RAY COMPUTED TOMOGRAPHY

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ABSTRACT

X-ray CT provides three-dimensional (3-D) representations of internal features of silicified caprinid bivalves from the Lower Cretaceous (Albian Stage) Edwards Formation in Texas. This technique enables the specific identification of caprinid rudists that otherwise could only be identified by sectioning the specimen. The abundant Edwards species is *Caprinuloidea perfecta* because it has only two rows of polygonal canals on its ventral and anterior margins. Ontogeny of these unusual gregarious bivalves is also demonstrated by means of these images.

KEY WORDS: Rudists; Caprinidae; Cretaceous, Lower; X-ray, CT

INTRODUCTION

The examination of internal structures of three-dimensional megafossils such as caprinid bivalves and brachiopods without destruction of specimens has been a challenge. Serial sections spaced at intervals as close as 0.1 mm provide a succession of two-dimensional cross sections that reveal the internal morphology (Ager 1965), but result in the destruction of specimens. X-radiography also has been used to reveal internal struc-

tures, and by shooting stereoscopic pairs, a 3-D image can be obtained (Zangerl 1965). X-ray computed tomography (CT) scans of limestone cores show the general outlines of rudists and successive slices can be stacked by computer to form 3-D images (Hughes et al. 2004). The attenuation of X-rays through carbonates presented as colored images reveals density patterns that relate to bulk density and lithology. This technique has also been applied to many studies of vertebrates (e.g., Rowe et al. 2001), and to examination of other organisms

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et al. 2001), and to examination of other organisms such as calcareous algae (Torres et al. 2003) and calcareous fossils (Dominguez et al. 2002).

Here we report on the application of X-ray CT scanning to the study of caprinid bivalves from the Lower Cretaceous (Albian Stage) Edwards Formation in Travis County, Texas. This technique enables the specific identification of silicified caprinid rudists that otherwise could only be identified by sectioning the specimen. Furthermore, this technique provides a full 3-D representation that can be inspected from many positions so that a variety of internal features can be seen.

TECHNIQUE

X-ray CT is a non-destructive technique for visualizing structures in the interior of opaque objects that enables paleontologists to acquire digital information about the 3-D structural geometry of specimens. Its ability to resolve details as fine as a few tens of microns in objects made of high density material distinguishes this technique from traditional medical CAT-scanning. Complete details of the technique have been published and are available online (Ketcham and Carlson 2001; <http://www.ctlab.geo.utexas.edu/overview/index.php#anchor2-2>).

The spatial resolution of a CT image is determined principally by the size and number of detector elements, the size of the X-ray focal spot, and the source-object-detector distances. As a rule of thumb, a CT image should have about as many pixels in each dimension as there are detector channels. Thus a 1024-channel linear detector array justifies a 1024x1024 pixel reconstructed image. Resolution in the third dimension is governed by detector aperture or thickness (for single-slice scanners) or vertical spacing (for multi-slice scanners).

No specimen preparation is required prior to scanning, other than the need for the specimen to fit in the field of view. Because the full scan field is a cylinder, the most efficient geometry to scan is a cylinder. Commonly specimens are placed inside a cylindrical container with appropriate filler. This technique in many cases cannot be used successfully if the specimen contains matrix that has a density similar to the specimen. The rudist specimen scanned here is silicified, and its matrix is carbonate mud, providing an excellent contrast (Figure 1.1, see Figure 2, 3-D movie).

Scanning was done by Richard Ketcham at the University of Texas High-Resolution X-ray CT Facility. The specimen was first scanned with the

high-energy 420-kV scanner subsystem in its longitudinal direction (Figure 1.2) to test for the presence of differentiable details. Following this successful test, the specimen was scanned perpendicular to its long axis (Figure 1.3) on 19 August 2005 using the microfocal subsystem, with X-rays set at 180 kV and 0.133 mA to provide a focal spot of 30 μm . A total of 930 1024x1024 slices were obtained with a slice thickness and inter-slice spacing of 0.1433 mm and a field of reconstruction of 66 mm (Figures 1.3, Figure 3). Image processing and visualization (Figure 1.4) was completed by Jessica A. Maisano. The scan can be examined on the DigiMorph site, an NSF Digital library at The University of Texas at Austin, http://digimorph.org/specimens/Caprinuloidea_perfecta/.

INTERNAL CAPRINID MORPHOLOGY

Rudists were aberrant sessile suspension feeding marine bivalves that lived from the Late Jurassic to the end of the Cretaceous. Together with corals and sponges, rudists were important organisms in shallow-water Cretaceous buildups (Masse and Philip 1981; Burchette 1993; Scott 1981, 1990). Their shell structure and form evolved from a pair of coiled valves having a thin calcitic outer layer and a thick aragonitic inner shell layer to very inequivalved forms, in which the unattached valve varied from cap-shaped to operculiform to elongate. Uncoiling enabled shell accretion along the entire mantle margin and, hence, the growth of conical forms (Skelton 1978).

One of the most abundant and diverse Lower Cretaceous rudist families is Caprinidae d'Orbigny (1847). It is divided into two subfamilies, Caprininae d'Orbigny (1847) and Caprinuloidinae Mac Gillavry (1970). These two taxa are differentiated by the cardinal apparatus, ligament, posterior accessory cavity, pallial canals, and the relative protrusion of the posterior myophoral plate, besides other, minor dental differences (Skelton and Masse 1998; Skelton and Smith 2000). The posterior myophore is a salient plate on either the left-free valve (LV-FV) in caprinuloidinids or the right-attached valve (RV-AV) in caprinids that projects across the commissural plane down into a cavity of the opposing valve (Chartrousse 1998, figure 5.1). The anterior myophore in each valve is an inclined ledge that extends ventrally from the hinge plate across the commissure. In Caprininae the myophore plate projects up from the RV-AV and in Caprinuloidinae it projects down from the LV-FV (Chartrousse 1998). However, in 2-D cross

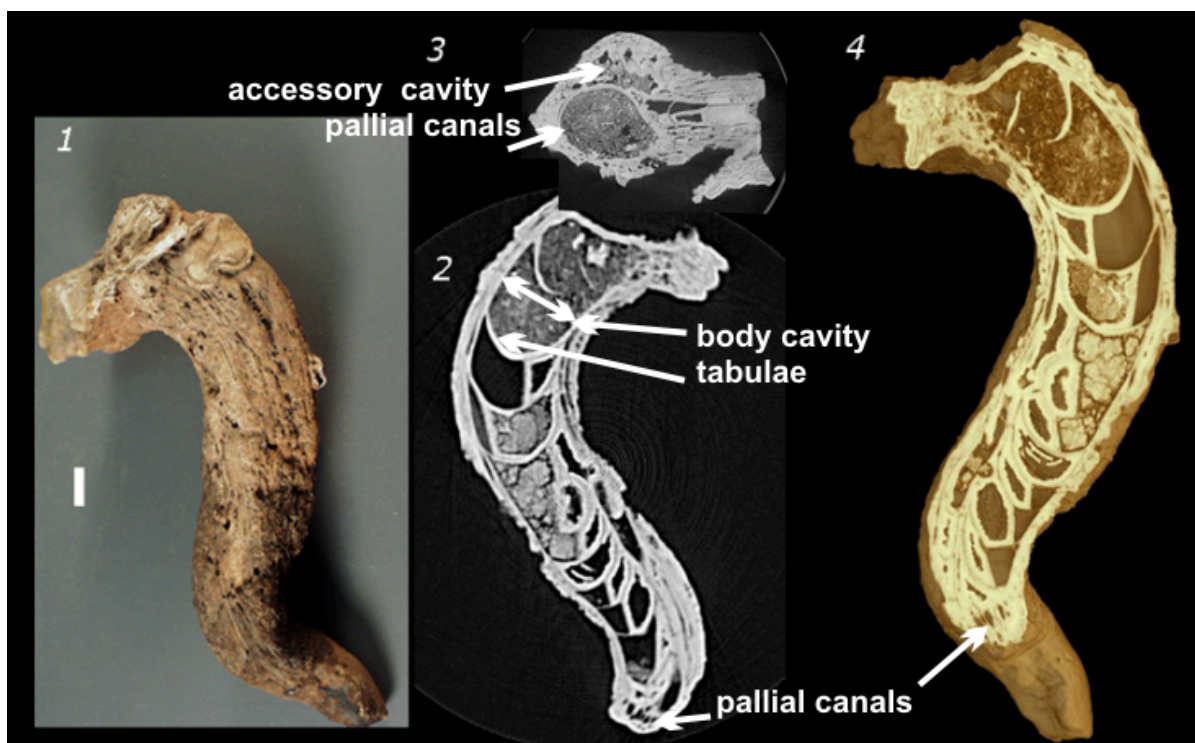


FIGURE 1. *Caprinuloidea perfecta* Palmer, 1928, NPL4387. 1.1, Complete specimen of RV-AV capped by debris. 1.2, Digital slice through the lower right valve (RV-AV) showing concave growth tabulae in the main body cavity, and accessory cavity following the line of the main cavity. Thin tubular pallial canals line the outer walls. 1.3, Digital cross-section through the right valve showing body cavity and accessory cavity. 1.4, Three-dimensional reconstruction with virtual cutaway revealing internal details, colored to approximate actual fossil specimen. The slice is the same orientation as the image of the specimen. Scale bar on 1.1 represents 1 cm and is valid for 1.2 and 1.3.

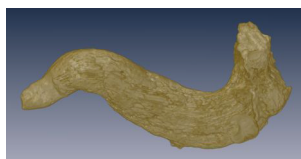


FIGURE 2. QuickTime animation of a 3-D reconstruction of *Caprinuloidea perfecta* derived from the CT data. Animation shows specimen rotating and 3-D cut-aways revealing internal structures along two orthogonal axes: 1. sections transverse to growth direction and 2. longitudinal view; note ligament groove on shell exterior defining dorsal margin. Body cavity opening is covered by shell debris. See the movie online at: http://palaeo-electronica.org/2007_3/135/index.html

sections, as seen in many outcrop specimens, these features cannot be recognized. Thus 3-D views provided by CT images are useful for taxonomic diagnosis (see Figure 1, Figure 2, a 3-D movie).

SYSTEMATIC PALEONTOLOGY

Order HIPPURITOIDA Newell, 1965
 Superfamily HIPPURITOIDEA Gray, 1848
 Family CAPRINIDAE d'Orbigny, 1847
 Subfamily CAPRINULOIDINAE Mac Gillavry, 1970
 Genus CAPRINULOIDEA Palmer, 1928

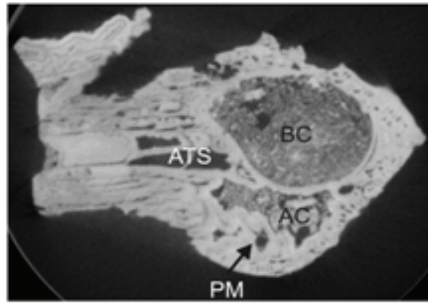
Type species. *Caprinuloidea perfecta* Palmer, 1928, by original designation.

Caprinuloidea perfecta Palmer, 1928
 Figure 1–4

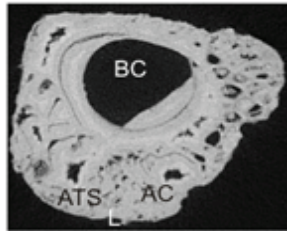
v. 1928 *Caprinuloidea perfecta* Palmer, p. 59-60, pl. VIII, fig. 8; pl. IX, figs. 1, 2; text-fig. 6.

v. 1991 *Caprinuloidea perfecta* Palmer, 1928; Scott and González-León, p. 62; figs. 7C-F; cites previous references.

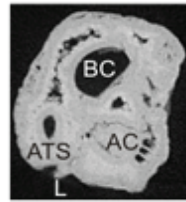
Discussion. The caprinid genus, *Caprinuloidea* Palmer, occurs in Albian rocks in Mexico, Southwestern USA and the Caribbean (Alencáster et al. 1999; Coogan 1973; Payne et al. 2004). Major characteristics of this genus include two teeth in



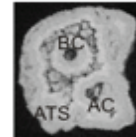
3.1. Coronal slice 100 just below commissure



3.2. Coronal slice 725
-3 cm from apex



3.3. Coronal slice 850
~1.5 cm from apex



3.4. Coronal slice 885
~0.5 cm from apex

FIGURE 3. Close-up umbonal view from inside of valve of oblique cross section through RV-AV showing body cavity (BC), anterior tooth socket (ATS), posterior accessory cavity (AC) and myophoral plate (PM). Longest diameter of cross section is approximately 3.5 cm.

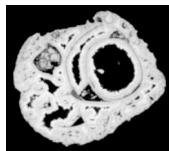


FIGURE 4. QuickTime animation of the original CT slices of *Caprinuloidea perfecta*. Interslice spacing is 0.2866 mm (every other slice has been deleted to minimize movie file size) and field of reconstruction is 66 mm. Grayscale has been adjusted to increase contrast. The movie begins at the juvenile apex of the shell and moves in the growth direction to the mature stage. Dorsal margin is on left side. See movie online: http://palaeo-electronica.org/2007_3/135/index.html

the left-free valve (LV-FV) and one tooth in the right-attached valve (RV-AV), body cavity, accessory cavity, two types of pallial canals, pyriform and polygonal, around both valve margins but not in internal structures, invaginated ligament marked by external groove and muscle attachment sites (myophores) (Skelton and Masse 1998). The two valves are highly unequal in size and have quite different shapes. The RV-AV is long and curved with a slight

rotational twist. The LV-FV is trochospirally coiled with one whorl. The cross-sections of both valves are approximately quadrilateral.

Silicified specimens of *Caprinuloidea perfecta* are quite common in the Edwards Formation of central Texas. Specimen TMM NPL4387 is deposited in the Non-vertebrate Paleontology Laboratory (NPL) of the Texas Natural Science Center at The University of Texas at Austin (its exact location is not recorded). Ann Molineux of NPL made the specimen available to The University of Texas High-Resolution X-ray CT Facility for scanning in order to identify internal structures (Figures 1, 3). The disarticulated RV-AV is well preserved and illustrates diagnostic internal structures. Other caprinid specimens are found in the Lower Albian Glen Rose Formation in Texas.

At least two species of *Caprinuloidea* are recognized in the Caribbean Province and the Gulf Coast: *C. perfecta* Palmer, 1928 and *C. multitubifera* Palmer, 1928 (Scott 2002). Both species range from lowermost Albian to the basal part of the Upper Albian. The two species are differentiated by the number of rows of inner polygonal

canals; *C. perfecta* has two, and *C. multitubifera* has four or more (Coogan 1977). This specimen from the Edwards Formation has only two rows on its ventral and anterior margins (Figure 3). Although Palmer (1928) defined six species of *Caprinuloidea*, only two can be differentiated (Coogan 1977; Scott 2002). Tabulae are present in all of Palmer's species.

The shell structure includes ventrally trifurcating marginal plates cut by radial plates to form two rows of polygonal canals (coronal slice 127) (Figure 1.3). The body cavity is slightly off center, with anterior and posterior tooth sockets separated by the ligamentary infolding on the dorsal side. The ventral side is the thinner side of the skeleton and perhaps the recumbent side or attached side (coronal slice 1205, see Figure 4). The external ligamentary groove marks the trace of invagination of the ligament.

A series of coronal slices from near the apex of the juvenile portion to the commissure shows that the body cavity, accessory cavity and anterior tooth socket are developed early and simply enlarge during growth (Figure 3). The posterior pallial canals, however, are inserted at a stage about 1.5 cm from the apex. Note that the protoconch cannot be observed in this specimen. Although somewhat obscured by silicification, it appears that the pyriform pallial canals develop first, and at the 1.5 cm stage the polygonal canals begin to appear. A separate study in progress is examining additional specimens to clarify the details of these observations.

CONCLUSIONS

The application of high-resolution X-ray CT scanning has the capability to illustrate internal morphological structures of rudists that otherwise could only be studied by destruction of the specimen. Traditional sectioning by a diamond saw requires that the angles and positions of cutting be predetermined. If serial sections are made the specimen is completely destroyed. CT scanning is non-destructive, and specimens may be viewed from many different angles. The enhancement of scanned images may reveal structures that could not be observed in traditional sections. Detailed measurements of different structures are possible in 3-D images 0.1433 mm, or thinner, that cannot be made in thicker traditional serial sections. In addition CT images may reveal minute ontogenetic changes that may be lost in sawed sections.

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