Turkish Journal of Earth Sciences (Turkish J. Earth Sci.), Vol. 19, 2010, pp. 757–767. Copyright ©TÜBİTAK
doi:10.3906/yer-0904-15 First published online 22 October 2010

Blending Rudists with Technology; Non-destructive Examination of the Internal and External Structures of Rudists Using High Quality Scanning and Digital Imagery

ANN MOLINEUX[1], ROBERT W. SCOTT[2], JESSIE MAISANO[3], RICHARD KETCHAM[3] & LOUIS ZACHOS[3]

[1] Texas Natural Science Center, The University of Texas at Austin, 2400 Trinity Street Austin, Texas 78705, USA (E-mail: annm@mail.utexas.edu)

[2] Precision Stratigraphy Associates and University of Tulsa, RR3 Box 103-3, Cleveland Oklahoma 74020, USA

[3] Jackson School of Geosciences, The University of Texas at Austin, 1 University Station, C1160 Austin, TX 78712-0254 Texas, USA

Received 27 April 2009; revised typescript received 2 May 2009; accepted 3 November2009

Abstract: Certain formations within the Cretaceous of Texas include zones of silicified rudists. Such diagenetic alteration, combined with the timing of alteration, has preserved many structural features of the rudist suitable for computed tomography (CT scanning). The excellent density differences between those skeletal structures (silica) and the internal sediment (calcitic mud) or later crystallization (calcite), fulfill a fundamental requirement for such analysis. The Jackson School of Geosciences at The University of Texas provides access to a high resolution computed tomography scanning system. This equipment, not identical to medical scanners, provides higher resolution and sophisticated software to analyze the imagery. Several rudist specimens have been scanned, including *Caprinuloidea perfecta*, from the Lower Cretaceous Edwards Formation (Albian) and *Bayeloidea clivi* from the Albian (formerly considered Turonian) of Mexico.

Other rudist specimens are preserved in a different manner. For example, structures may be replaced with single crystal calcite with external skeletal intricacies especially well preserved. Elsewhere the record is one of internal molds or casts, with a reduction of available detail. Cost, diagenesis, and size determine the mode of specimen imagery used in an NSF sponsored project to image and conserve the type and figured specimens in the collection of the Texas Natural Science Center, Non-vertebrate Paleontology.

This paper describes how such imagery can be used to further many aspects of rudist research. CT scanning produces serial sections of minute thickness without destroying a valuable specimen, in contrast to preparing physical serial sections, a more traditional method of analytical study. High resolution digital imagery (35 mm) provides images of great clarity which can be analyzed further and can be used as a surrogate for physical peels of rare or fragile specimens. Both these methods of imagery can be made available on-line and can be studied by scientists throughout the world.

Key Words: rudists, digital imagery, scanning, computed tomography, type collections, Cretaceous

Rudistlerin Teknoloji ile Harmanlanışı: Yüksek Kaliteli Tarama ve Dijital Görüntüleme ile Rudistlerin İç ve Dış Yapılarının Hasarsız İncelenmesi

Özet: Teksas Kretase'sinde bazı formasyonlar silisleşmiş rudist zonları içerir. Bu tip diyajenetik alterasyon, alterasyonun zamanlaması ile de birleşerek rudistlerin birçok yapısal özelliklerinin korunmasını sağlamıştır. Bu olay rudistleri bilgisayarlı tomografiye (BT tarama) uygun hale getirmiştir. İskeletsel yapılar (silis) ve iç tortul (kalsitik çamur) veya sonraki rekristalizasyon (kalsit) arasındaki mükemmel yoğunluk farklılıkları bu tip analizler için zorunlu olan temel gereklilikleri yerine getirir. Teksas Üniversitesi Jackson Yerbilimleri Okulu yüksek çözünürlüklü bilgisayarlı tomografi tarama sistemine erişime izin vermiştir. Medikal tarayıcılardan farklı olarak bu cihaz, yüksek çözünürlük ve görüntüyü analiz etmek için karmaşık bir yazılım içerir. Erken Kretase yaşlı (Albiyen) Edwards Formasyonu'ndan *Caprinuloidea perfecta* ve Meksika Albiyen'inden (daha önce Turoniyen olduğu düşünülen) *Bayeloidea clivi*'nin de aralarında bulunduğu çok sayıda rudist örneği taranmıştır.

Diğer rudist örnekleri farklı oranlarda korunmuştur. Örneğin yapılar, dış iskeletsel ayrıntıların özellikle iyi korunduğu, tek bir kalsit kristali ile yer değiştirmiş olabilir. İç ve dış kalıplarda ise elde edilebilecek ayrıntılar azalmış olabilir. NSF'nin sponsor olduğu ve Teksas Doğa Bilimleri Merkezi, Omurgasızlar Paleontolojisi kolleksiyonunda bulunan tip örnek ve çizilmiş örneklerin görüntülenmesini ve korunmasını amaçlayan proje kapsamında, fiyat, diyajenez ve boyut, örnek görüntülemenin türünü belirler.

Bu yayın, bu tip görüntülerin rudist araştırmalarının birçok alanında nasıl kullanılabileceğini tanımlar. BT tarama, daha geleneksel bir analitik çalışma yöntemi olan fiziksel seri kesit hazırlamayla kıyaslandığında, çok ince kalınlığa sahip seri kesitler üretir ve bu işlem sırasında değerli örneğe zarar vermez. Yüksek çözünürlüklü dijital görüntü (35 mm), daha ayrıntılı çalışmalar için yüksek netlikte görüntüler oluşturur. Bu görüntüler nadir veya kırılgan örneklerin fiziksel dilimlerinin yerine kullanılabilir. Bu görüntüleme yöntemleri online olarak kullanılabilir ve dünyanın heryerindeki bilim insanları tarafından çalışılabilir.

Anahtar Sözcükler: rudistler, dijital görüntüleme, tarama, bilgisayarlı tomografi, tip koleksiyonlar, Kretase

Introduction

This paper records the interim progress of an NSF funded project to image and conserve the type and figured collection at the Non-vertebrate Paleontology (NPL) collections of the Texas Natural Sciences Center (formerly Texas Memorial Museum) at the University of Texas at Austin, with specific emphasis on the results that bear upon the rudist type and figured specimens in that collection (Molineux & Triche 2007; Molineux 2008).

The major goal of the project is to create digital access to specimens and related data (Figure 1) and to achieve that by digital imaging of specimens, labels, peels and any other relevant field data. A critical element, often overlooked by researchers, is the physical conservation of the specimens, including any related paperwork, labels, field notebooks, thin sections, acetate peels, and both early analog and recent digital images. Georeference data for the collection localities is being assembled for general biogeographic mapping or password protected research access for detailed locations. Additional steps include a check of the veracity of catalogue data and an update of taxonomy whenever possible. We encourage the research community to help further with this last objective when they visit the repository and/or when the material is made available online.

The type and figured rudists held at NPL are examined as a segment of the entire collection. These are specimens collected, studied and described by W.S. Adkins, Keith Young, Ralph Myers and many other students, in addition to ongoing research projects (Adkins 1928, 1930; Myers 1965, 1968). The collection mainly represents rudist diversity and evolution on the shallow carbonate shelf of the proto-Gulf of Mexico and the southern extent of the Western Interior Seaway mainly during the Comanchean (127–99 Ma) (Coogan 1973, 1977; Scott 2002; Schafhauser *et al.* 2007). Most specimens were collected from outcrops in Texas and Mexico, although there are a few samples from the subsurface.

During the process of initial description many specimens were cut and polished and acetate peels or thin sections created (Wilson & Palmer 1989). Much of our repository has undergone multiple moves and lacked adequate curation for many years. Specimens became scattered and considerable work in this project has involved the re-connection of split specimens, associated peels and related data.

Methods

Basic project design is shown in a simplified flowchart (Figure 1). This schema can be broken down into three groups relevant to this paper, those dealing with the actual specimens and related materials, those dealing with the procedures and protocols used to acquire and store the digital data, and those dealing with the conservation of the materials. All phases are pertinent to the rudist collection but the order in which they are addressed in this paper does not reflect actual timing. Task order must be flexible enough to take advantage of vital student assistants, cope with highly fragile specimens or take advantage of the availability of a specific imaging device.

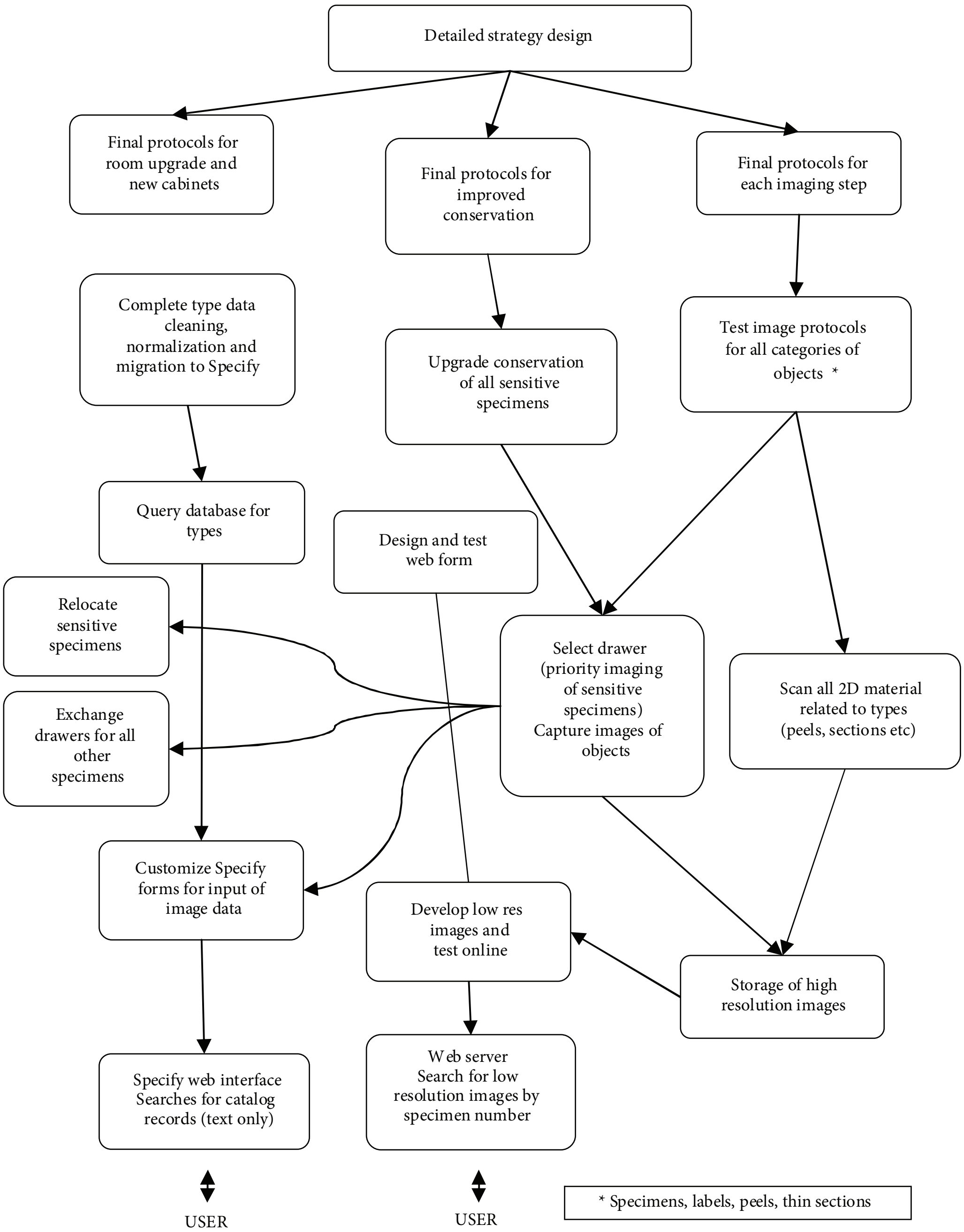

Figure 1. Simplified flowchart of procedures and the strategy of the whole project.

The first phase involves assembling relevant physical specimens and related secondary products (such as peels) and additional written material, such as labels, field note books and maps. Pinpointing relevant specimens in this large repository involves our GIS management system and the task is less arduous for the rudists since they are held as a nascent taxonomic collection and are mostly inventoried. However, separated parts of the same original specimen are often in different storage locations and must be reunited.

A stage of preparation is necessary before the specimens can be imaged. Each must be cleaned to remove dust from the surface layer. Some specimens are reconstructed if they were previously glued and imaged as reconstructions in the original literature. Some specimens are smoked with ammonium chloride (Feldman 1989). This enhances the surface details of the specimen and is quite often used to illustrate intricate details (Figure 2). All acetate peels are cleaned and scanned but they too must be connected to their relevant source specimen. Paperwork relating to specific specimens includes handwritten labels. The task of scanning those labels is well underway but that of updating taxonomy is not yet complete.

The choice of imaging technique depends upon the nature of the specimen and the importance of that specimen (Figure 3). The very rare and fragile specimens are candidates for the Computed Tomography (CT) scanning (Figure 4). This technique basically records density differences so specimens must show a clear difference between the skeletal material and any later matrix infill (Hughes *et al.* 2004; Ketcham & Carlson 2001; Rowe *et al.* 2001). The majority, however, are imaged with a high quality digital camera. Original acetate peels and /or thin sections are scanned using a flat bed scanner with a light source both above and below the specimen.

The second and crucial phase involves selection of imaging techniques and software, the design of data storage, and the preparation of protocols to allow the research assistants to fulfill their tasks. This project uses students, graduate and undergraduate research assistants. The very nature of that impermanent input requires that protocols and procedures are well thought out and clearly written. Those instructions are made available to the assistants in written form and online.

Data storage is critical because the volume is so huge. The file structure was designed to maximize access to the relevant specimens and minimize loss of image files. Current web visibility is limited but will be increasing during the next year. Linkage of basic data with images is not a problem but it is complicated by the change to a completely different data structure.

The equipment in house consists of a high end 35 mm digital SLR camera with various lenses and extensions, and several flatbed scanners, one with upper and lower light sources and a high enough resolution to cope adequately with thin sections and acetate peels. The Computed Tomography (CT) scanner is remote equipment, for which we are charged a usage fee.

The basic camera and scanner software is supplemented with more specialized image handling and multifocal combination software. Specialized java scripts have been created to fulfill several needs such as improving throughput and applying standard scale-bars to images.

The last phase, conservation, is just as relevant and important as the other two. One aspect concerns the physical storage of specimens; the other involves the individual specimens. An important part of this entire NSF-sponsored project is the development of a new, climate controlled room in which the types and figures specimens are stored. This required remodeling of space and acquisition of new metal cabinets and drawers. This facility will ensure that specimens are held in appropriate climatic conditions and in a secure environment.

Each individual specimen is examined and handled carefully during imaging, any containers are acid free and lined with inert foam to protect where needed. In cases where either the specimens or their infilling matrix is chemically reactive appropriate measures are taken to isolate and control further deterioration.

Results

The project has so far generated well over 20,000 images of specimens and labels. Only a fraction of those are rudists but our initial imagery is highly promising. The use of multiple focal plane focusing improves the clarity of these images (Figures 2 & 3).

Development of embedded scaling, the topic of a separate paper, now allows us to send images to researchers from which they can, with appropriate software, make accurate measurements of features visible on the images. Areas can be measured; features counted, linear features measured and all can be recorded in a table beside the image.

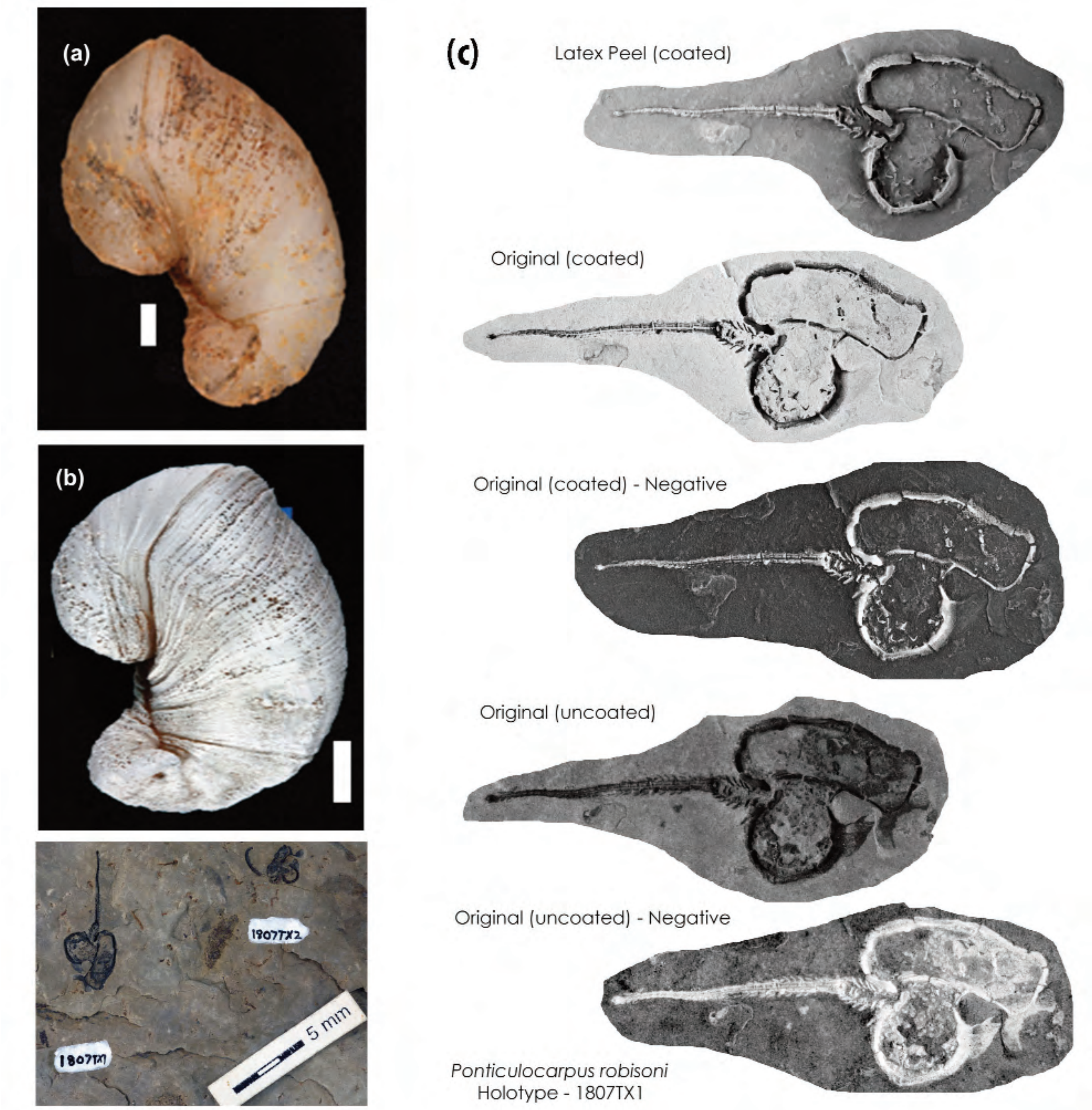

Figure 2. Detail can be enhanced by coating with ammonium chloride. **(a)** is the specimen prior to smoking and **(b)** a similar specimen with the coating. Images in **(c)** are a series from a single specimen including latex peels, specimens, coated and uncoated. In this case the most detailed specimen image is a digital negative of an image of the original uncoated specimen. The series demonstrates new uses for digital imagery, in this particular instance removing the need for creating latex peels.

The CT scanned images are of great relevance in the study of rudists because they provide detailed images of internal structures without destroying the sample. Several rudist preservation styles are amenable to this type of imagery. *Caprinuloidea* provides a good example of such scanning and can be examined in detail on-line (http://digimorph.org/specimens/Caprinuloidea_perfecta/) (Molineux

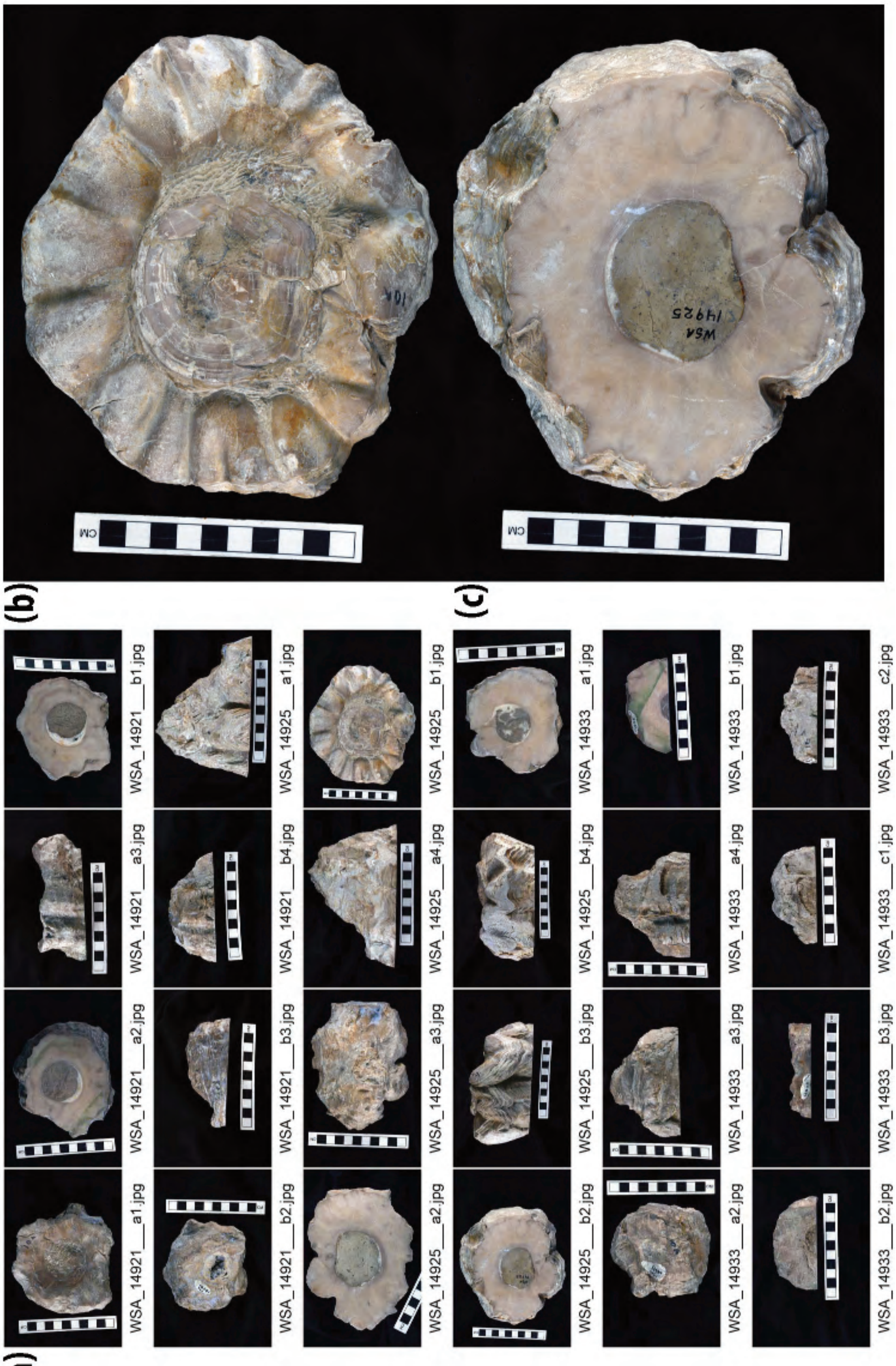

Figure 3. Images of specimens in the Ralph Myers collection. Multiple views and multifocal plane images provide a good view of these specimens. A reference pdf sheet **(a)** provides a quick overview from which to select specific images such as **(b)** and **(c)**. Scale bars are provided but the scale is also embedded into the digital file and is retrievable if the image is to be used for further numerical analysis.

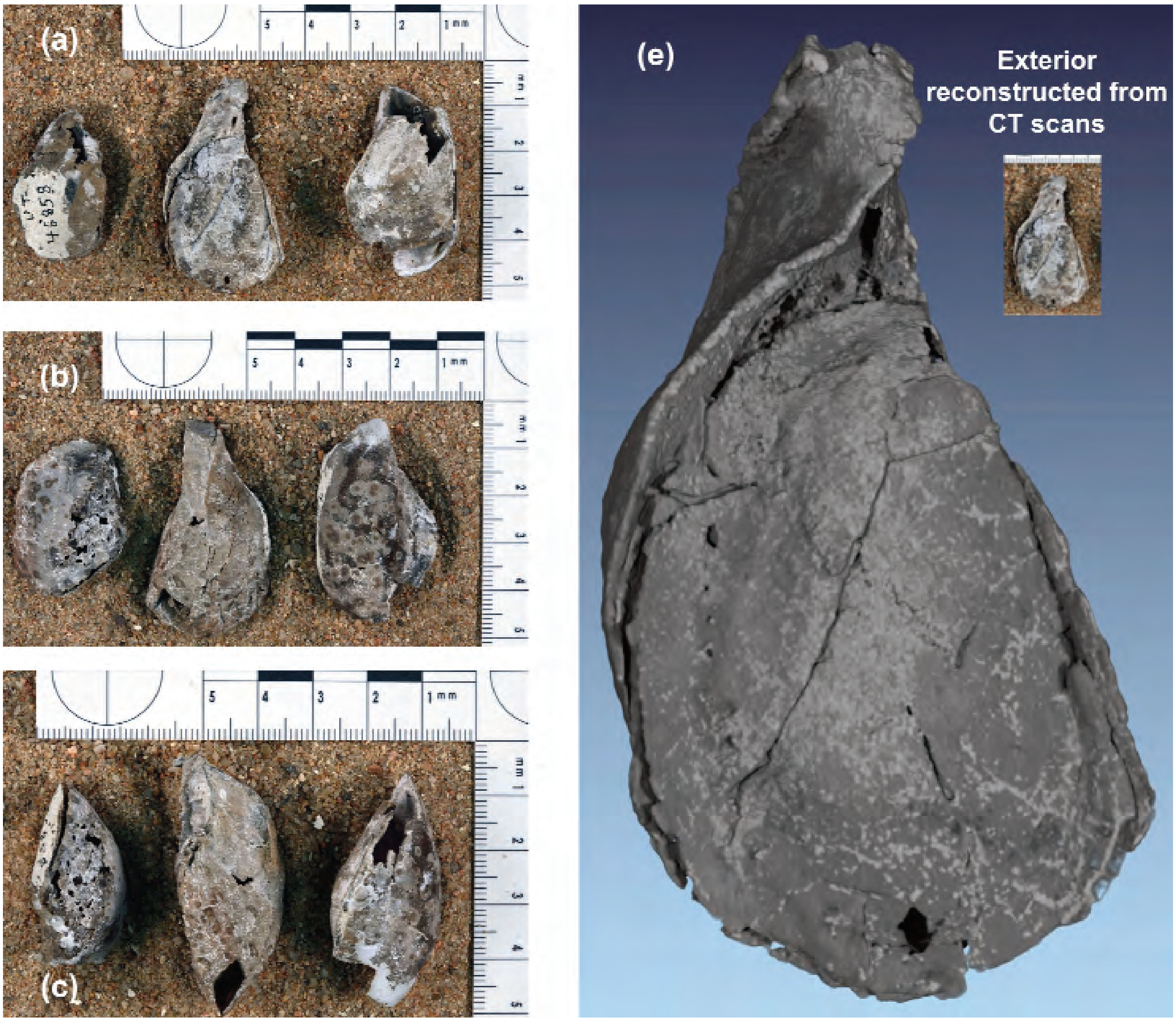

Figure 4. Fragile, silicified specimens of *Bayleoidea clivi* are imaged from multiple perspectives **(a)**, **(b)**, and **(c)**. The central specimen has been CT scanned and **(e)** is a digital reconstruction of the exterior of that specimen.

et al. 2007). The ontogenetic development of pallial canals is observable; the points of insertion can be pinpointed from the hundreds of scans that comprise the whole data set. Further scans of other *Caprinuloidea* were obtained and examined as part of a research project on ontogenetic growth (Scott & Weaver 2008).

The recent CT scan of a silicified and highly fragile *Bayleoidea* further illustrates the point (Figure 4). This specimen could not have been sectioned without injection of epoxy (or similar product) at great risk to the specimen even before slicing. These scans reveal details of internal wall structures not recorded by Palmer (Palmer 1928; Figures 5 & 6). The specimen, *Bayleoidea clivi,* comes from a limestone in Huescalapa, Jalisco, Mexico, and the same section that produced the type specimens described by Palmer. Palmer placed this rudist zone in the Turonian on the basis of the presence of '*Radiolites*' and '*Apricardia*'. His argument, at that time, the first genus was thought to appear in the Turonian and the latter not known above the Turonian. This unit is now considered to be Albian (Alencáster & Garcia-Barrera 2008).

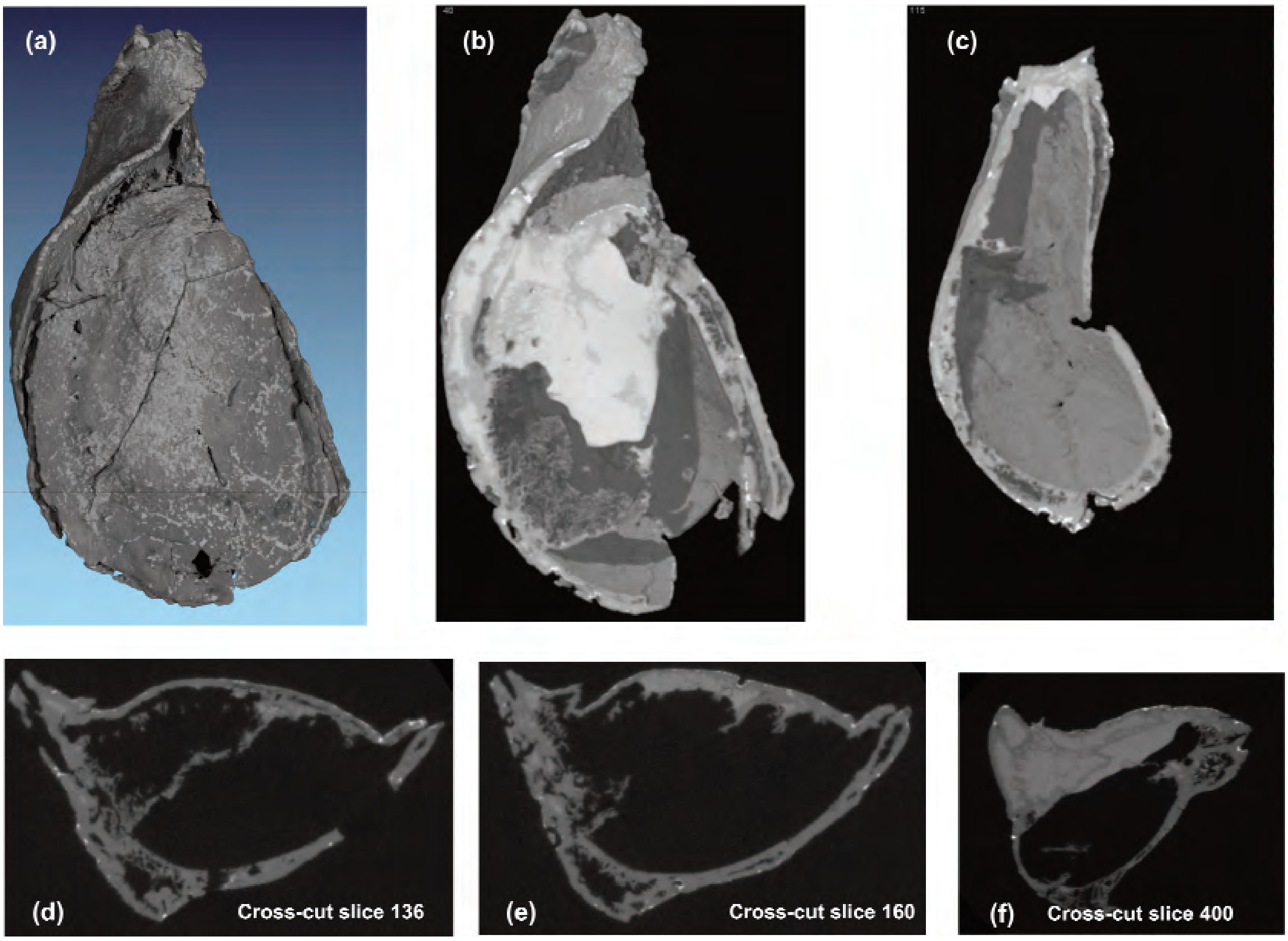

Figure 5. Further slices through the digital model illustrate specific characteristics. Images **(a)**, **(b)** , and **(c)** are the exterior viewed horizontally, facing the smaller and flatter upper valve, **(b)** is a section through the upper and lower valve showing the wall structure, and **(c)** is the anterior of the lower valve beyond the keel. The other three images are cross-sections, approximating to the lines drawn on image **(a)** capturing the relationship of the upper and lower valves. The posterior of the lower valve contains a robust keel and thicker wall which supported the animal on the sediment. It contrasts with the thinner anterior section. Further study of these scans may clarify the myophoral structures which Palmer had trouble examining.

Discussion and Conclusions

Current availability of imagery is by request to the first author, and by online request (http://www.utexas.edu/tmm/npl/research/loan.html) but by the end of the project in 2010 images will also be available through the NPL web site and within a portal so that these collections may be queried alongside other major resources.

There are questions of data storage and long term accessibility. Many of these issues have been addressed by the transfer of our local databases and image files to a central university server system capable of handling the huge amounts of data generated by imagery and dedicated to making that data available over the long term. We are still working to create the most effective interface for web query of the database and we anticipate moving to *Specify 6* in the near future. This is an open source, multi-platform, database structure.

It is true that the process of CT scanning and data manipulation is expensive but, the cost benefit is significant. For a few hundred dollars, more than 600 'slices' were obtained for the 45 mm *Bayleoidea* specimen. It would have been impossible to grind that number of serial sections for the specimen, and

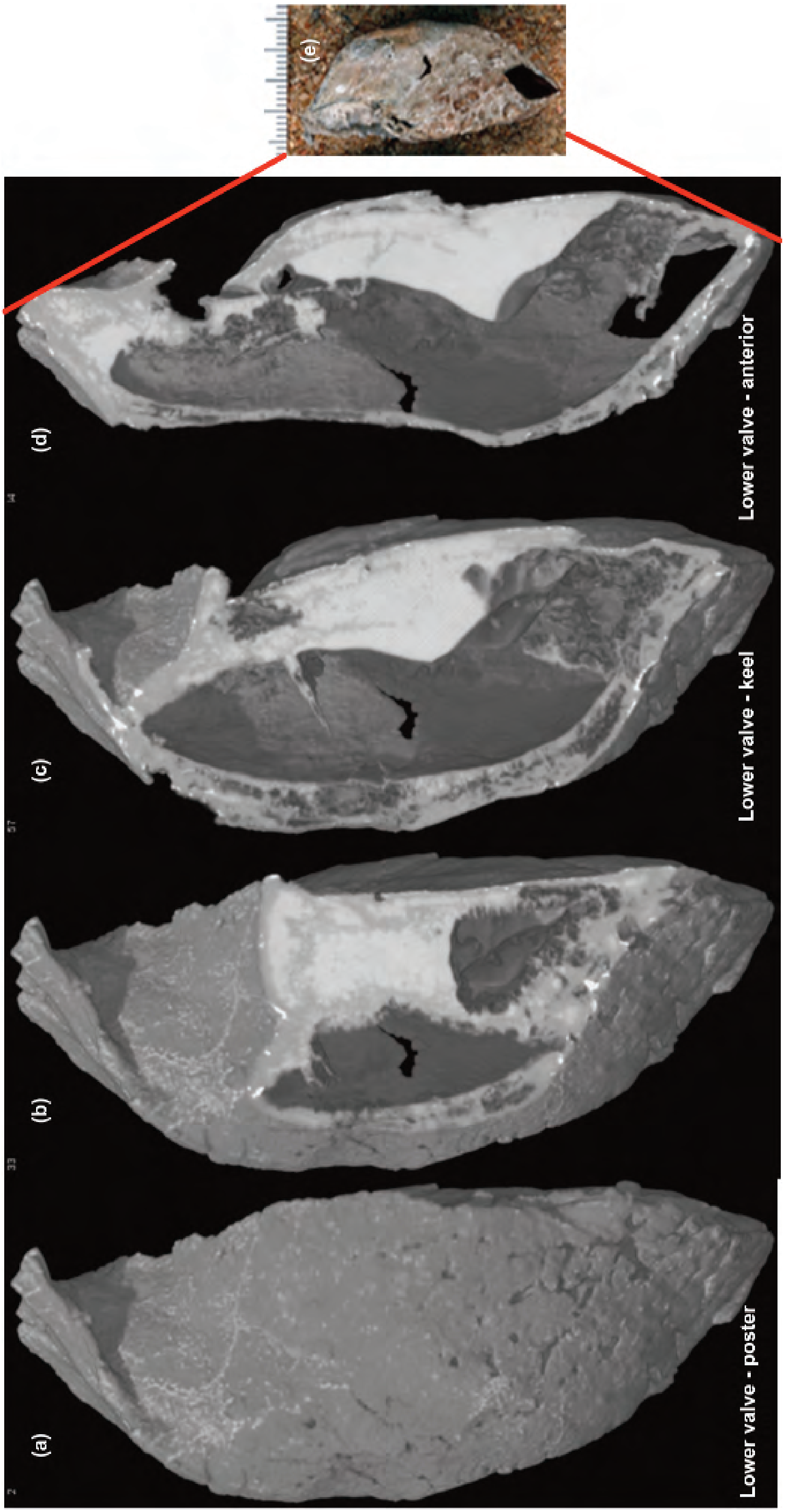

Figure 6. These sections **(a)** though **(d)** are at right angle to those shown in Figure 5 (a) through (b). They pass through the posterior of the lower valve, through the keel to the thinner anterior of the valve. The flatter upper valve is visible. The exterior of the anterior valve, **(e)**, is a digital image and provides scale and orientation.

those serial sections would need to be scanned and manipulated with appropriate software to approach the product provided by the CT scanning facility. The specimen scanned is not destroyed and thus highly fragile or rare material such as the acid prepared silicified specimens can be studied in great detailed without a cumbersome burial in epoxy and destructive sectioning. The data set can be examined in any plane of reference; this is not the case with serial sections where the selection of the plane for section is critical and once cut cannot be regenerated. Individual serial sections may need to be cut where the specimen is unsuitable for CT scanning, the sections can be scanned and the digital files run through a 3D modeling program but that program can only generate a model to the resolution of the original thin sections (Sandy 1989; Chapman 1989). For some studies this may be adequate but for detailed examination of ontogenetic features the availability of such microscopic detail viewed at any angle requested is significant.

Interestingly Palmer (1928) notes that specimens in the source limestone bed for *Bayleiodea* are silicified and that they are only silicified at or close to the surface layers. The same selective silicification was observed by the author when testing a block of Permian limestone from the Glass Mountains in Texas. CT scanning was unable to resolve any density differences except in the case of a few brachiopod specimens at or near the surface of the block. These observations may be valuable for future collection targeting silicified beds.

We believe that CT scanning technique may be relevant for other preservation modes. The earlier scan of *Caprinuloidea perfecta* discriminated silicified structures and also revealed poikilotopic calcite structures. There are other samples that we intend to scan based upon this observation.

Mapping of collection sites using such universal tools as Google earth requires a latitude and longitude for each site. Such 'georeferencing' is underway but there are several caveats. A variety of issues arise under the umbrella of 'privacy', for example, it may be a question of private land or an issue of ongoing research at a specific site, in either instance a generalized area can be used rather than a specific point. The locality is only as accurate as the original data collector and for many historic collection sites that information is provided as a verbal locality description. Georeferencing software programs usually provide a margin of error or level of accuracy given the type of data entered. Such limitations are an integral part of the location data. Even if the verbal localities are plotted by hand on topographical or geological maps, precision remains an issue: any geographical distributions 'mapped' need to be viewed within these known limitations. Such data are transcribed into the database but when the single georeference is extracted for a particular mapping purpose that important data may be inaccessible to the user unless the mapping program can address the additional information.

Imaging is a time consuming procedure and constant practical improvements are made to improve throughput. The challenge to provide research quality imagery is substantial. Images must be of high quality and show useful and relevant characteristics (Skelton & Smith 2000). As these specimen images may be substituting for an actual physical specimen, the researcher must be able to measure with a reasonable degree of accuracy and be able to determine the quality of preservation and hence the relevance of a particular character in the image. There must be a high degree of integrity; images cannot be subject to digital enhancements that would make them far removed from the actual specimens. As the requests for specific images increase and repeat requests are common, we believe that the product has great potential for current and future research. Nothing will replace the study of the physical specimen but where that specimen is unique, too fragile to travel or be manually sectioned, digital imaging could become the only way in which that material can be examined.

Acknowledgements

Funding for this project is provided by the National Science Foundation (NSF) through their Biological Research Collections program (grant DBI 0646468). Computed tomography (CT) scans were partially funded by the NSF and the Texas Natural Science Center. We thank Matt Colbert for additional CT imagery. The Jackson School of Geosciences provided matching funding to improve the cabinetry and is the major source of the research assistants. The Texas Natural Science Center provided matching funds to remodel the type and figured collection room, and enabled a closed climate control system for that space. We thank the editors of this journal for their patience during the production of this paper.

References

Adkins, W.S. 1928. Handbook of Texas Cretaceous fossils. *University of Texas Bulletin* **2838**, 5–385.

Adkins, W.S. 1930. New rudists from the Texas and Mexican Cretaceous. *University of Texas Bulletin* **3001**, 77–100.

Alencáster, G. & Garcia-Barrera, P. 2008. Albian Radiolitid rudists (Mollusca Bivalvia) from East-Central Mexico. *Geobios* **41**, 571–587.

Chapman, R.E. 1989. Computer assembly of serial sections. *In*: Feldman, R.M, Chapman, R.E. & Hannibal J.T. (eds), *Paleotechniques* The Paleontological Society Special Publication **4**, 157–164.

Coogan, A.H. 1973. New rudists from the Albian and Cenomanian of Mexico and south Texas. *Revista del Instituto mexicano del Petróleo* **5**, 51–83.

Coogan, A.H. 1977. Early and middle Cretaceous Hippuritacea (rudists) of the Gulf Coast. *In*: Bebout, D.G. & Loucks, R.G. (eds), *Cretaceous Carbonates of Texas and Mexico*. University of Texas at Austin, Bureau of Economic Geology, Report of Investigations **89**, 32–70. Austin, Texas.

Feldman, R.M. 1989. Whitening fossils for photographic purposes. *In*: Feldman, R.M, Chapman, R.E. & Hannibal J.T. (eds), *Paleotechniques*. The Paleontological Society Special Publication **4**, 342–346.

Hughes, G.W., Siddiqui, S. & Sadler, R.K. 2004. Computerized tomography reveals Aptian rudist species and taphonomy. *Geologica Croatica* **57**, 67–71.

Ketcham, R.A. & Carlson, W.D. 2001. Acquisition, optimization and interpretation of X-ray computed tomographic imagery. *Applications to the Geosciences. Computers and Geosciences* **27**, 381–400.

Molineux, A. 2008. Non-vertebrate Paleontology Laboratory. http://www.utexas.edu/tmm/npl/.

Molineux, A., Scott, R.W., Ketcham, R., & Maisano, J. 2007. Rudist taxonomy using high-resolution X-ray Computed Tomography. *Paleontologica Electronica* **10**, 13A:6p, http://palaeo-electronica.org/2007_3/135/index.html.

Molineux, A. & Triche, N. 2007. Rudist collections as a resource for research at the Texas Natural Science Center. *In*: Scott, R.W. (ed), *Cretaceous Rudists and Carbonate Platforms*. Environmental Feedback SEPM Special Publications **87**, 231–236.

Myers, R.L. 1965. *Biostratigraphy of the Cardenas Formation (Upper Cretaceous)*. PhD Thesis, San Luis Potosi, Mexico [unpublished].

Myers, R.L. 1968. *Biostratigraphy of the Cardenas Formation (Upper Cretaceous)*. San Luis Potosí, Mexico. Paleontologia Mexicana UNAM, Mexico D.F.

Palmer, R.H. 1928. *The Rudistids of Southern Mexico*. Occasional Papers of the California Academy of Sciences **14**. San Francisco, California.

Rowe, T.B., Colbert, M., Ketcham, R.A., Maisano, J. & Owen, P. 2001. High-resolution X-ray computed tomography in vertebrate morphology. *Journal of Morphology* **248**, p. 277.

Sandy, M.R. 1989. Preparation of serial sections. *In*: Feldman, R.M, Chapman, R.E. & Hannibal, J.T. (eds), *Paleotechniques*. The Paleontological Society Special Publications **4**, 146–156.

Schafhauser, A., Goetz, S. & Stinnesbeck, W. 2007. Rudist decline in the Maastrichtian Cardenas Formation (East-central Mexico). *Palaeogeography, Palaeoclimatology, Palaeoecology* **251**, 210–221.

Scott, R.W. 2002. Albian caprinid rudists from Texas re-evaluated. *Journal of Paleontology* **76**, 408–423.

Scott, R.W. & Weaver, M. 2008. Ontogeny and functional morphology of a lower Cretaceous Caprinid, Comanche Shelf, US Gulf Coast. *8th International Congress on Rudists*, İzmir, Turkey, p. 37.

Skelton, P.W. & Smith, A.B. 2000. A preliminary phylogeny for rudist bivalves: sifting clades from grades. *In*: Harper, E.M., Taylor, J.D. & Crame, J.A. (eds), *The Evolutionary Biology of the Bivalves*. Geological Society, London, Special Publications **177**, 97–127.

Wilson, M.A. & Palmer, T.J. 1989. Preparation of acetate peels. *In*: Feldman, R.M, Chapman, R.E. & Hannibal, J.T. (eds), *Paleotechniques*. The Paleontological Society Special Publication **4**, 142–145.