

Shu'aiba rudist taphonomy using computerised tomography and image logs, Shaybah field, Saudi Arabia

G. Wyn ap G. Hughes, Shameem Siddiqui and R. Kumbe Sadler

ABSTRACT

Rudist fossils in cored carbonates from the Shu'aiba reservoir in the Shaybah field have been used to aid the interpretation of lithofacies and reservoir facies in uncored horizontal development wells. The rudists are sufficiently large fossils that they provide well-developed and easily identified images on computerised tomography (CT) scans of cores. The CT images provide valuable information on the rudist orientation prior to damage caused by plugging and slabbing procedures. CT images, combined with the core-based fossil information, are then used to interpret the images on the formation micro-imager (FMI) logs. As the various rudist species are known to have preferentially occupied different environments during the deposition of the Shu'aiba carbonates, depositional environments can now be interpreted from the FMI logs. Specimen orientation in the core provides supplementary information on the depositional environment by discriminating between in-situ and displaced assemblages. Rudist identification in FMI images is a new tool in uncored vertical wells. In long horizontal wells, this is a major achievement and will assist in modelling the 3-D lithofacies and associated reservoir facies distribution for improving the reservoir model.

INTRODUCTION

The hydrocarbon-rich Shu'aiba reservoir of the Shaybah field in Saudi Arabia lies within the Shu'aiba Formation, of early Aptian age (Figure 1). The formation consists entirely of carbonates that were deposited as an extensive blanket on the Arabian Platform (see figure 3.31 in Sharland et al., 2001). Palaeontological and sedimentological analyses have revealed a depositional history that is associated with the initiation and subsequent development of a rudist-rimmed platform (Hughes, 2000; 2001). The rudist-associated facies developed on the southern flank of an intra-shelf basin and caused differentiation from open platform facies into lagoon, rudist bank complex and open marine regimes. Rudist fossils characterise much of the Shu'aiba (Figure 2), and their distribution is directly associated with the depositional environment. The rudists were not reef builders, but sediment dwellers (Gili et al., 1995) that created sedimentary banks with high primary porosity and permeability.

Long horizontal, mostly uncored, development wells demand unconventional information to refine the depositional model, assist interpretation of the depositional facies, and associated reservoir quality. Cored exploration and early development wells have been used to their limit to provide information for reservoir facies distribution. Plugging and slabbing activities, however, often damage the cores and obscure the original rudist fabric. This problem has been overcome by the application of computerised tomography (CT). Previous applications have been focused on the engineering aspects, with scanning windows of 2-inch spacing.

Recent analysis using 1-cm spacing, and optimizing the advantage of the 1-cm beam width, has permitted almost continuous CT scans. Virtual vertical sections through the core using this technique, therefore, have become far more accurate. Core-based rudist identification permits calibration of the CT scans and offers a method rapid palaeoenvironmental interpretation prior to potentially damaging plugging and slabbing. Complementary information can also be gained by formation microscanner images (FMI) in which microresistivity variations of the formation are displayed as high-resolution colour images of variable intensity. FMI logs have been calibrated by using core-based rudist and micropalaeontological data, together with CT-scan image interpretations of in-situ rudists.

Rudist biofacies and palaeoenvironmental significance

Seven rudist species are known from the Shu'aiba Formation in Saudi Arabia (Figure 2) based on analysis of cored wells over the Shaybah field; for additional information on the Shu'aiba rudists, the reader is referred to Skelton and Masse (2000). Their ecological preference in relation to the rudist bank complex is based on co-occurring macrobiocomponents and microbiocomponents (Hughes, 2000; 2001). This approach has provided a useful method of determining sediment type, provenance and associated reservoir quality prediction. A simplified portrayal of the vertical and horizontal distribution of the various biocomponents, including the rudists, is provided in Figure 3 (see figure 8 in Hughes, 2000).

		SAUDI ARABIA	U.A.E./OMAN	
CRETACEOUS	Turonian	Wasia Fm	Natih	Wasia Group
	Cenomanian		Nahr Umr	
	Albian		Shu'aiba	Thamama Group
	Aptian	Biyadh Fm	Kharaib	
	Barremian	Buwaib Fm	Lekhwair	
	Hauterivian		Habshan	
	Valanginian			

Figure 1: Stratigraphy of the Shu'aiba Formation.

The rudist complex includes the recumbent species *Offneria murgensis* Masse that typically grew on the crest of the bank, and represents adaptation to high-energy conditions with no ambient sediment deposition due to sediment by-passing. The presence of pallial canals in the wall of this caprinid species probably permitted rapid growth in a frequently current-swept environment, and its later fragmentation into coarse, highly porous carbonate sediments has significantly contributed to the subsequent development of good reservoir facies within the Shaybah. *Oedomyophorus shaybahensis* Skelton has adapted to the high rate of coarse sediment deposition on the lee side of the bank. In the present study, it is difficult to estimate the dimensions of the rudist banks as well spacing is insufficient to test lateral continuity. Comparison with the Great Pearl Bank Barrier of the Arabian Gulf (Hughes, 1997) would suggest elongate banks, possibly extending in excess of ten kilometers, aligned perpendicular to the prevailing wind direction and broken by inter-bank tidal channels. The width of such banks, including the back-bank zone, is also difficult to estimate but is probably not more than 5 km.

The most extensive and well-developed rudist biofacies is that containing the elongate conical, caprotinid elevator species *Glossomyophorus costatus* (Masse et al., 1984). This species is smaller and less robust than *Oedomyophorus shaybahensis* Skelton, but has developed in response to net sediment deposition in a moderately low energy environment at a greater distance lagoonwards from the *Offneria* bank. The sediment forming the supportive matrix of this species typically includes a high proportion of finely comminuted *Offneria* debris and provides good porosity and permeability reservoir facies. Rare specimens of the long, thin, pencil-like caprinid elevator species *Offneria* sp., cf. *O. nicolinae* Skelton and Masse (2000) are present within this biofacies. Forming a very narrow flank lagoonwards of the above biofacies is a fine-grained belt occupied by the stubby, conical, caprotinid elevator rudist *Agriopleura marticensis* (d'Orbigny). The left valve is not visible laterally because it lies countersunk within the flared open end of the right, or fixed, valve. This species displays an extensive distribution in the uppermost layer of the Shu'aiba Formation at Shaybah field, where it alternates with the related, but elongate, form *Agriopleura* sp. cf. *A. blumenbachi* (Studer) (Hughes, 2002). *Agriopleura* species seem well-adapted to lower energy environments, and although they can occur in a variety of water depths they preferentially occupy the deepest part of the rudist facies.

Many of the rudist depositional cycles commence with rare *Agriopleura marticensis* (d'Orbigny) at the base, overlain successively by *Glossomyophorus blumenbachi* (Masse et al., 1984) and finally by *Offneria murgensis* Masse. On the outer flank of the rudist complex, at younger levels, is located the large, conical elevator rudist genus *Horiopleura* (Douville). This species is considered to be possibly related to *H. distefanoi* (? Boehm) by P. Skelton (oral communication), that has adapted to moderately high rates of sedimentation derived from the tidal backwash of sediment from the adjacent rudist bank complex. Exceptionally large specimens, exceeding 10 inches in length, of the rudist *Offneria murgensis* Masse have been discovered in the outer flank position, where they display a vertical, growth position indicating an elevator mode of life. One of the reviewers of this manuscript has suggested the possibility that these specimens are *Offneria* sp., cf. *O. nicolinae* Skelton and Masse, but their similarity to *O.*

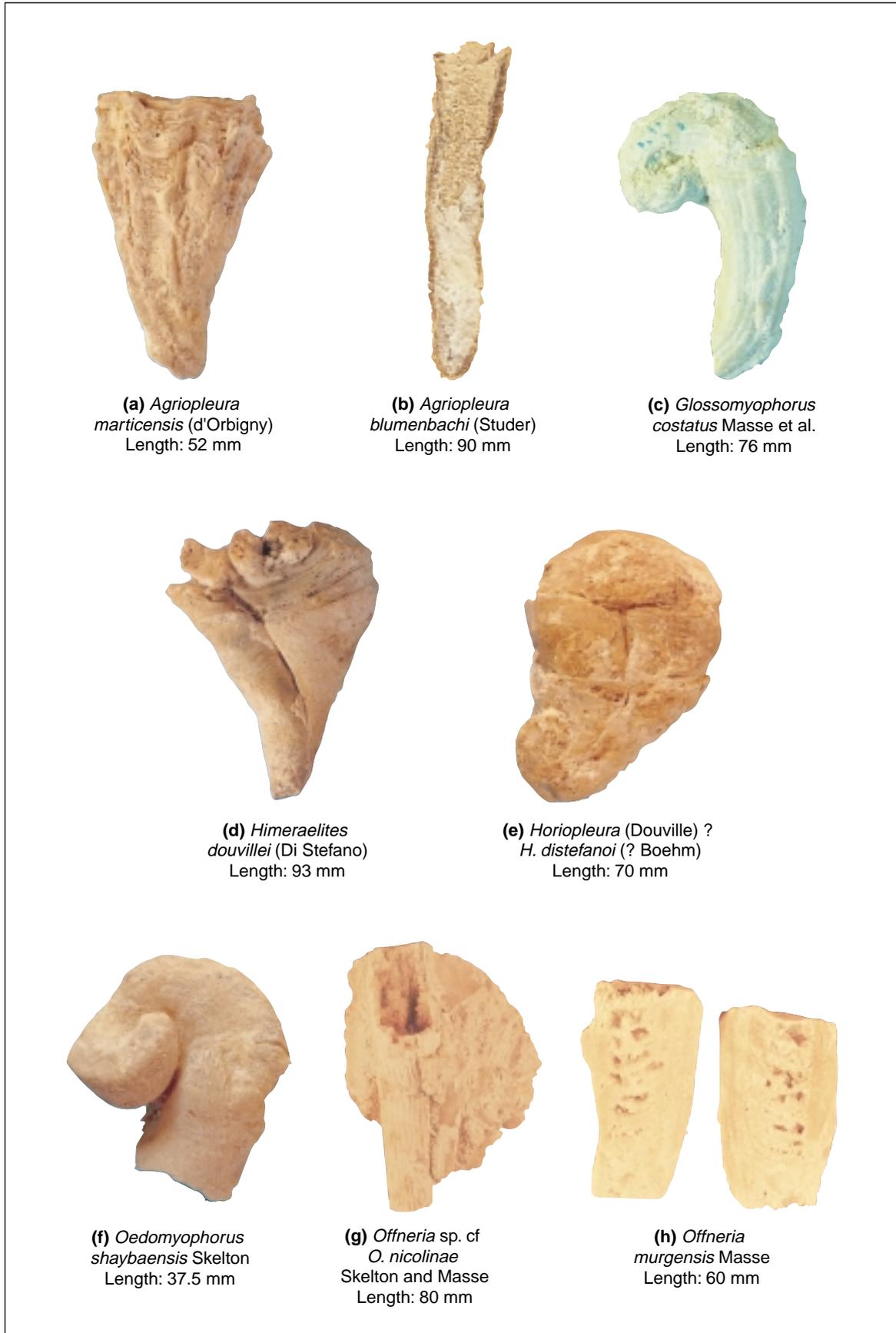


Figure 2: Rudists from the Shu'aiba Formation, Saudi Arabia.

murgensis Masse is convincing to the senior author. Identification of the rudist species therefore provides an important guide to the palaeoenvironment.

Computerised tomography (CT)

Computerised tomography is a non-destructive imaging technique that utilizes X-ray technology and mathematical reconstruction algorithms to view a cross-sectional slice of an object. Since the early 1980s, the oil industry has been using CT-scanners as an effective tool for analyzing reservoir core samples. CT provides a non-destructive, non-invasive way of looking at the cores in 3-D. The particular applications of CT as a reservoir characterization tool include classification of heterogeneity; identification of lithology and broad mineralogy, sand-shale sequences, vugs, fractures and high-density mineral inclusions; measurement of bulk density and porosity; core to log depth correlation; visualization of mud invasion; evaluation of damage in unconsolidated cores; etc. Apart from core characterization, CT is used extensively to visualize and quantify hydrocarbon fluid displacement in cores in simulated laboratory experiments to determine residual oil saturation, to evaluate trapped porosities, to visualize and quantify gravity and viscous effects, etc. Detailed reviews of the application of CT in various core flood experiments can be found in the literature (Kantzas, 1990; Siddiqui, 2001).

Saudi Aramco has been using a medical-based CT-scanner for about seven years, although the applications were limited mostly to the selection of special core analysis samples (SCAL). Recently however, the trend is shifted towards non-destructive core characterization where CT-scanning is increasingly applied for core description, core quality assessment, lithology identification and for quantifying lithological heterogeneity. CT-scanning is also used to address reservoir scale-up issues, matching of conventional core analysis and log analysis data (mostly bulk density and porosity) and broad mineral classifications. A CT-scanner measures the attenuation coefficient of a material. The attenuation of the energy in the X-ray beams is related to the electron density and atomic number of the materials present in the object being scanned. At relatively high X-ray energies the attenuation coefficient becomes mainly a function of the electron density and the latter is a function of the core bulk density (porosity, grain density and fluid saturation) and lithology. CT-scanning also provides that advantage that the data are stored for any future use unlike the cores, which become difficult to use after slabbing and plugging. The 3-dimensional image processing packages such as AVS-Express and OpenDX allow rotation, slicing along any plane and iso-surface mapping.

Rudist identification and taphonomy

CT scan slices of 1 cm thickness were captured and the individual image slices stacked to generate a full 3-dimensional image of the core. As rudists are composed of higher density carbonate than the main ingredients of the rock, a high-density threshold was applied to the CT-derived data. A 2.8 ft length of core from the Shu'aiba Formation has been photographed for comparison with the CT scan and displays large specimens of an elevator rudist, together with smaller fragments of similar rudists (Figure 4). The series of transverse CT scan images in Figure 5 display the primary density data from which the synthetic vertical images of Figure 3 were generated.

The CT image of the same core displays low density areas as cool colours (black to blue) up to 2.0 gm/cc, and high density areas in warmer tones (green through yellow, orange to red) from approximately 2.0 gm/cc to 2.65 gm/cc. Most of the core consists of packstones and grainstones that provide moderately low density values from 1.7 gm/cc to 2.2 gm/cc. The large rudist at the base of the core in Figure 4 is outlined in green, with a yellow centre, as it portrays the dense rudist valve wall together with the denser calcite infilling of the centre of the valve. In the upper part of the core, the rudist fixed, or right, valve is displayed as a yellow image, adjacent to a dark blue area and indicates that the rudist is not filled with calcite cement.

In Figure 5, the calcite-filled large rudist at the base of the core is clearly visible as a subrounded green-rimmed, yellow-filled image that displays interesting observations on the torsional growth of the right valve by its migration laterally in successive images up the lowermost part of the core. The upper part of the core contains calcite-filled rudists, with the characteristic high density yellow fill,

together with valves that are unfilled by calcite cement and appear as dark blue images. Successive migration of the images across the circular sections again provide evidence for the growth habit of the individual rudist specimens and support an in-situ interpretation for these rudist species.

The dimensions of these rudists in the CT scan suggests that the specimens could represent the robust back-bank species *Oedomyophorus shaybahensis* Skelton, but it is difficult to explain the very low density of the inner part of the right valve. Examination of the slabbed core enabled the caprinid rudist *Offneria*

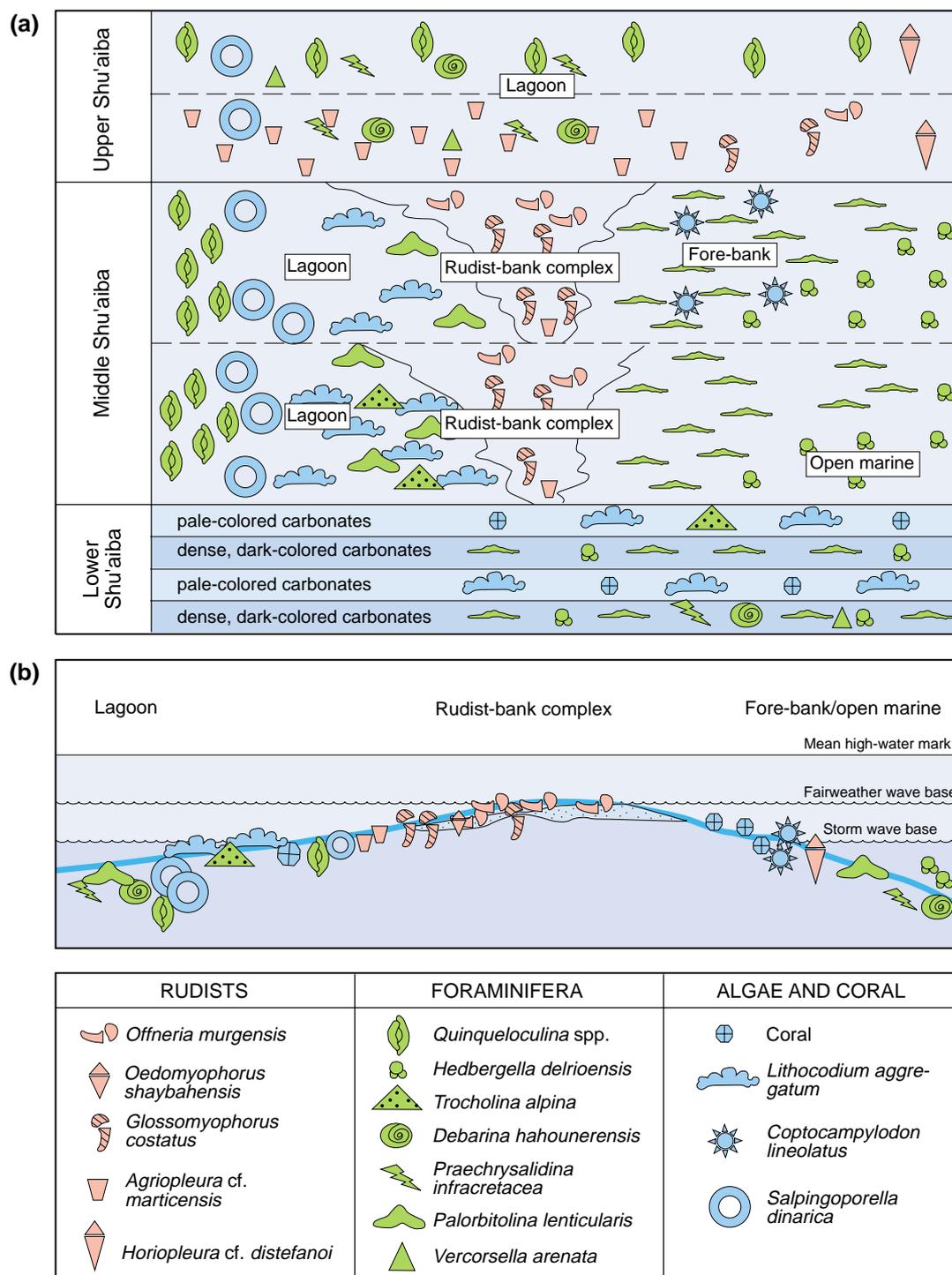


Figure 3: Diagrammatic representation of the distribution of selected macrofossils and microfossils in the Shu'aiba Formation of the Shaybah field and their corresponding palaeoenvironments; (a) through time, and (b) geographically.

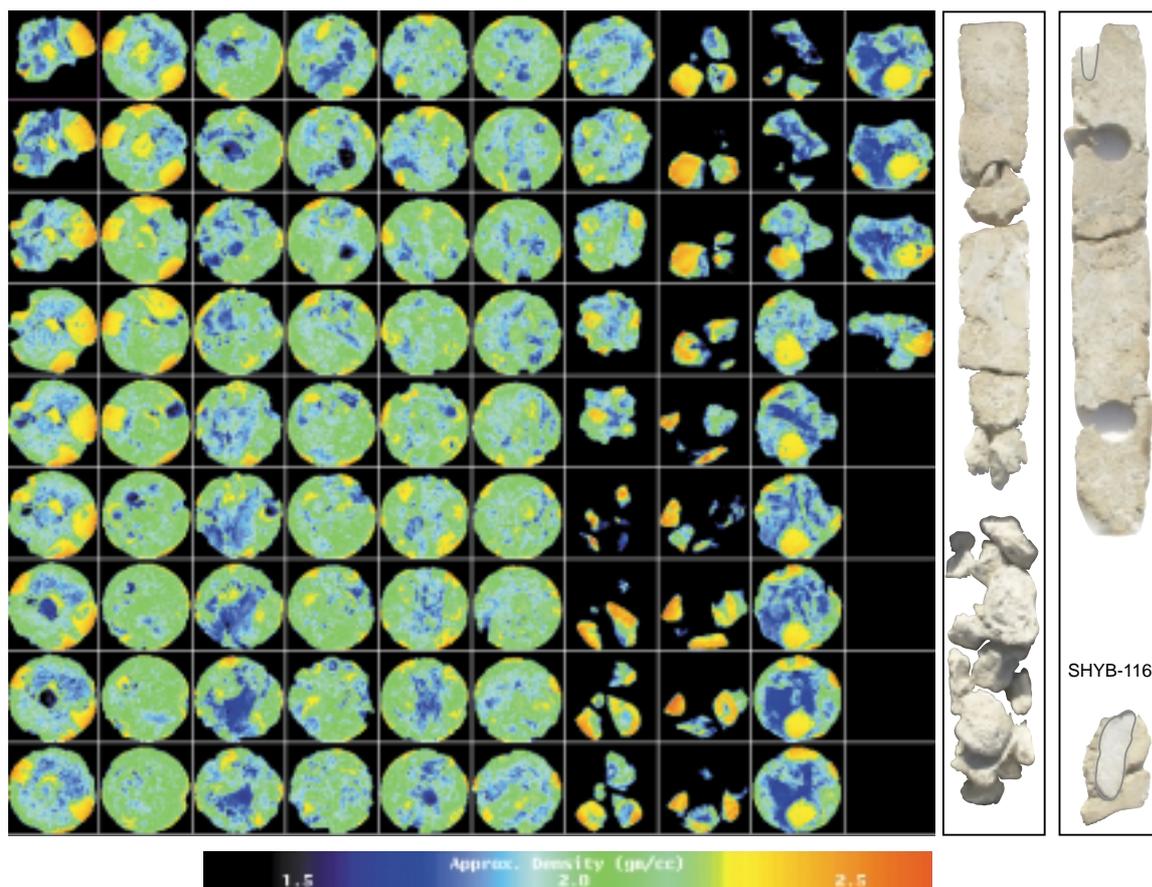


Figure 4: Core photograph with rudist (*Offneria murgensis*) highlighted in the core and in the CT images.

murgensis Masse to be identified. This was a surprise as this species typically displays a horizontal, or recumbent, growth position related to its life position on the high energy bank crest. At the location of this well, it had adopted an elevator life style that has been interpreted to reflect its accommodation to a high rate of sedimentation at a fore-bank locality. The empty fixed, or right, valves of the caprinid rudist *Offneria murgensis* Masse contain thin lateral partitions called tabulae, that serve to subdivide the valve into vertical compartments. The tabulae often serve to inhibit infill by solid crystalline calcite although there may be tabulae-rimming calcite present. It is of interest to note that the lowermost, or earliest formed, part of the right valve is often preferentially filled by calcite owing to perforation of the valve by boring internal bioeroders such as clionid sponges. The uppermost, and last occupied, part of the caprinid valve is also prone to calcite infill as it is left open on *post-mortem* disassociation of the two rudist valves. These features of the internal morphology of *Offneria murgensis* Masse assist in explaining the variation in density variations as depicted in the CT scans of Figures 4 and 5.

Rudist species in the Shu'aiba Formation of Saudi Arabia display characteristic and diagnostic profiles that serve to facilitate identification by the CT scan profile alone. An informal rudist morphological profile typing system (types 1 to 6) is proposed based on morphometry, including degree of fixed valve enlargement and actual dimensional variations. Each rudist species is clearly identifiable in side profile, together with the elevator (vertical) or recumbent (horizontal) life-habit. This scheme is designed to facilitate non-palaeontologists to use the FMI logs to determine the depositional setting. Rudists are arranged in ascending order related to gradually shallower water conditions in Figure 6, together with stylised profiles expected in their autochthonous, or undisturbed life position, as well as in disturbed, displaced, or allochthonous position. It should be noted that the rudist species were not mutually exclusive in their environmental preferences, and that there is often found certain species co-existing in the transitional environmental regimes. Calibration of the various rudist species with depth and sediment type has been facilitated by the use of co-existing microbiocomponents, especially benthonic foraminifera, and various macrobiocomponents (Hughes, 2000). The inclination of the rudist

valves has the potential for revealing the direction of predominant water current direction, when the core has been correctly oriented using the FMI images. Flume tank experiments have revealed (Gili and LaBarbera, 1998) that elevator rudists would, as part of an optimal filter-feeding strategy, preferentially be inclined away from the predominant direction of water flow.

With reference to Figure 6, small, narrow cylindrical or very slowly enlarging forms (Type 1) (less than 10 cm long and 2 cm diameter) include *Offneria* sp., cf. *O. nicolinae* Skelton and Masse and *Agriopleura blumenbachi* (Studer), of which the former is characterised by its smooth sides and very slow rate of fixed valve enlargement; *Agriopleura blumenbachi* (Studer) displays a sinuous profile. With reference to the biofacies model (Figure 3) the presence of vertical *Offneria* sp., cf. *O. nicolinae* Skelton and Masse would indicate a growth position in a back-bank position with relatively rapid rates of sedimentation; whereas *A. blumenbachi* (Studer) would indicate moderately deep, lagoon or open platform conditions with low to very low rates of sedimentation. These environmental interpretations are based on observations of the functional morphology of the shell, as discussed by Hughes (2002).

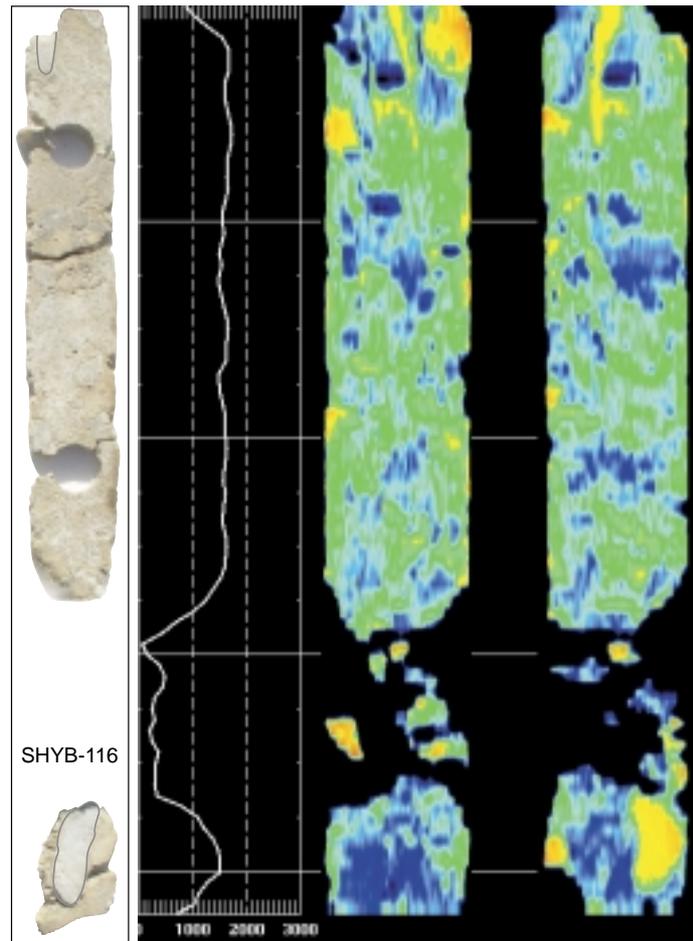


Figure 5: The transverse scans taken from bottom to top of the core are shown from bottom right to top left of the display of circular images on the left. The core and circular scans are 4 inches in diameter.

Large, slowly enlarging narrow conical forms (Type 2) (typically greater than 10 cm long and 4 cm diameter); include *Offneria murgensis* Masse and *Oedomyophorus shaybahensis* Skelton, of which the former displays a slower rate of fixed valve enlargement. The centre of *O. murgensis* Masse often displays patchy infilling of the chamber with sediment or calcite, owing to the baffles created by tabulae which subdivide the fixed (right) valve into compartments; these are absent in *Oedomyophorus shaybahensis* Skelton. *Offneria murgensis* Masse typically displays a recumbent, horizontal growth habit in most of the Shaybah field, and it would typically be difficult to distinguish from a transported assemblage. Along the west flank, however, vertically growing elevator forms have recently been recognised (Hughes, 2003), and so horizontal forms in the vicinity of this regime could provide differentiation of allochthonous from autochthonous forms. Recumbent (horizontal), complete specimens of *Offneria murgensis* Masse are diagnostic of high energy conditions on the crest of a rudist bank with little or no sedimentation; broken horizontal specimens would normally suggest transport, as these shells are relatively easily broken owing to the relatively brittle canaliculate wall structure. Such debris is common within the rudist bank-associated sediments and is considered to result from post-mortem mechanical breakage of the shells within the high energy bank crest regime. Vertical specimens would be diagnostic of the fore-bank environment with rapid rates of sedimentation.

Small, slowly enlarging narrow conical forms (Type 3) (typically less than 10 cm long and 3 cm diameter), include *Glossomyophorus costatus* Masse et al. Vertical specimens would indicate a back-bank position at some distance from the bank crest, with relatively high rates of sedimentation. Horizontal specimens represent transported forms, of which the two valves are normally separated, and would represent an

environment between the back bank and the lagoon. It is not uncommon to find assemblages of transported specimens that consist entirely of either the longer, fixed valve, or of the shorter free valve and this could provide potential additional information for local energy levels during transport.

Medium-sized, rapidly enlarging conical forms (Type 4) (typically less than 10 cm long and 7 cm maximum width) include *Himeraelites douvillei* (Di Stefano). This elevator rudist is typically found in the fore-bank position within areas of moderately low sedimentation rates.

Medium-sized, moderately rapidly enlarging conical forms (Type 5) (typically less than 10 cm long and 7 cm maximum width) include *Horiopleura* (Douville), considered to be possibly related to *H. distefanoi* (? Boehm) by P. Skelton (oral communication). This elevator rudist displays a rather stubby profile, but would not be easy to differentiate from *Himeraelites douvillei* (Di Stefano). It is typically found in the fore-bank position within areas of moderately low sedimentation rates.

Small, moderately rapidly enlarging conical forms (Type 6) (typically less than 10 cm long and 3 cm maximum width) include *Agriopleura marticensis* (d'Orbigny). This elevator rudist is typically found in moderately deep lagoon or open platform conditions with low to very low rates of sedimentation. It is often found as a distinct facies above that dominated by *A. blumenbachi* (Studer) (Hughes, 2002; 2003). Vertical forms are uncommon, as most of the specimens are displaced. A recently discovered horizontal form displaying a clinger habit (Hughes, 2003; Figure 2) provides evidence for the possibility that some horizontal specimens may be in-situ. These can, however, be differentiated by the uneven development of extended growth lamellae on the ventral side; elevator forms would have equal radial development of these extensions.

Imaging Well Bore Walls - FMI logs

In the late 1980s Schlumberger introduced the concept of borehole electrical images by processing variations of the shallow microresistivity of well bore walls recorded by modified versions of its Stratigraphic High Resolution Dipmeter Tool™. Called the Formation MicroScanner™ (FMS), the tool measured closely spaced arrays of focused shallow resistivity readings that are related to changes in rock composition and texture, structure, and fluid content (Serra, 1989, p. 1). Processing the data, in which a range of colours are assigned to the lateral (side to side) and vertical variations of the microresistivity along the well bore, produces an image of the borehole wall. The current generation of tools, called the Fullbore Formation MicroImager™ (FMI), records an array of microresistivity measurements from 192 receivers on eight pads mounted on four orthogonally placed caliper arms. The spacing and position of the pads provides 80% coverage of an 8-inch diameter hole and a resolution of 5 mm. Other oil field wireline service companies have since developed similar high resolution electrical borehole imaging tools. The FMI yields a continuous, high-resolution electrical image of a borehole, and therefore complements whole cores cut in the same well. If the image is of sufficient quality and calibrated against the core, it can provide a continuous survey of the formation in places where core was not cut, there was no core recovery, or when a core has been damaged through handling, transportation, or plugging.

The FMI logs provide valuable information on drilled Shu'aiba carbonates that have not been cored. Ongoing studies are involved in refining the interpretation of the depositional regime in such wells, as there are significant associations between depositional and reservoir facies. The use of core and CT scan - calibrated FMI logs in cored vertical wells is providing valuable assistance to facies determination in the horizontal, uncored development wells where conventional logs cannot yet provide such information. Figure 7 illustrates a comparison between the core, CT scan and FMI images to illustrate the images related to the vertical distribution of macrofossils in the Shu'aiba Formation. The two FMI images (A) illustrate a "wrap-around" pseudo-core view of the cored section in an attempt to closely compare the FMI log with the core photograph (B). Four individual FMI logs for each receiver pad are included (E). Two CT scan synthetic vertical images (C), at 90° have been coloured to closely match the FMI tones and a pseudo "wrap-around" view (F) has also been generated.

The rudists are clearly depicted as highly resistive (light toned) features, and the elevator habit of *Offneria murgensis* Masse, as identified in the core, is clearly seen. The advantage of the FMI log is

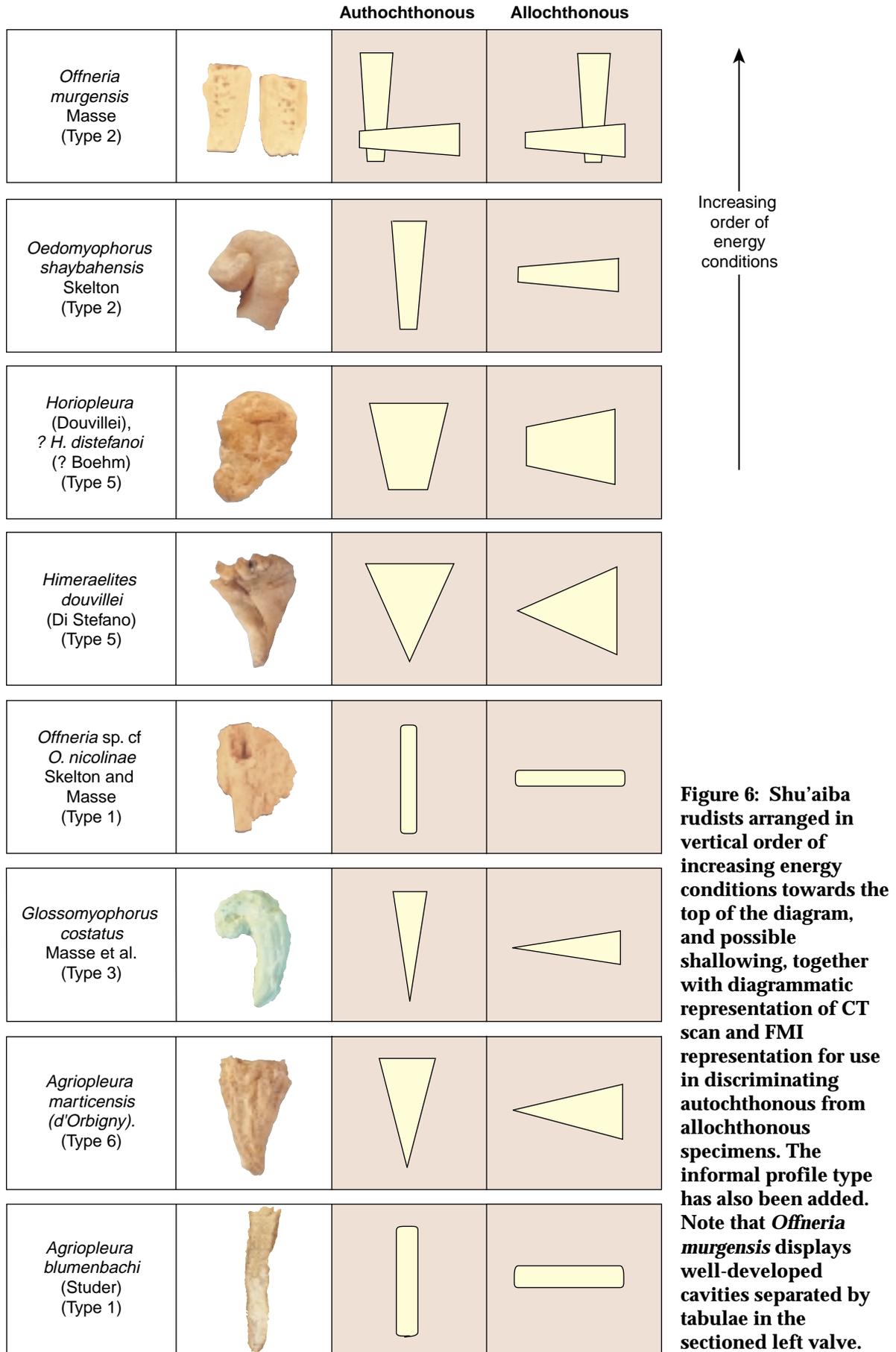


Figure 6: Shu'aiba rudists arranged in vertical order of increasing energy conditions towards the top of the diagram, and possible shallowing, together with diagrammatic representation of CT scan and FMI representation for use in discriminating autochthonous from allochthonous specimens. The informal profile type has also been added. Note that *Offneria murgensis* displays well-developed cavities separated by tabulae in the sectioned left valve.

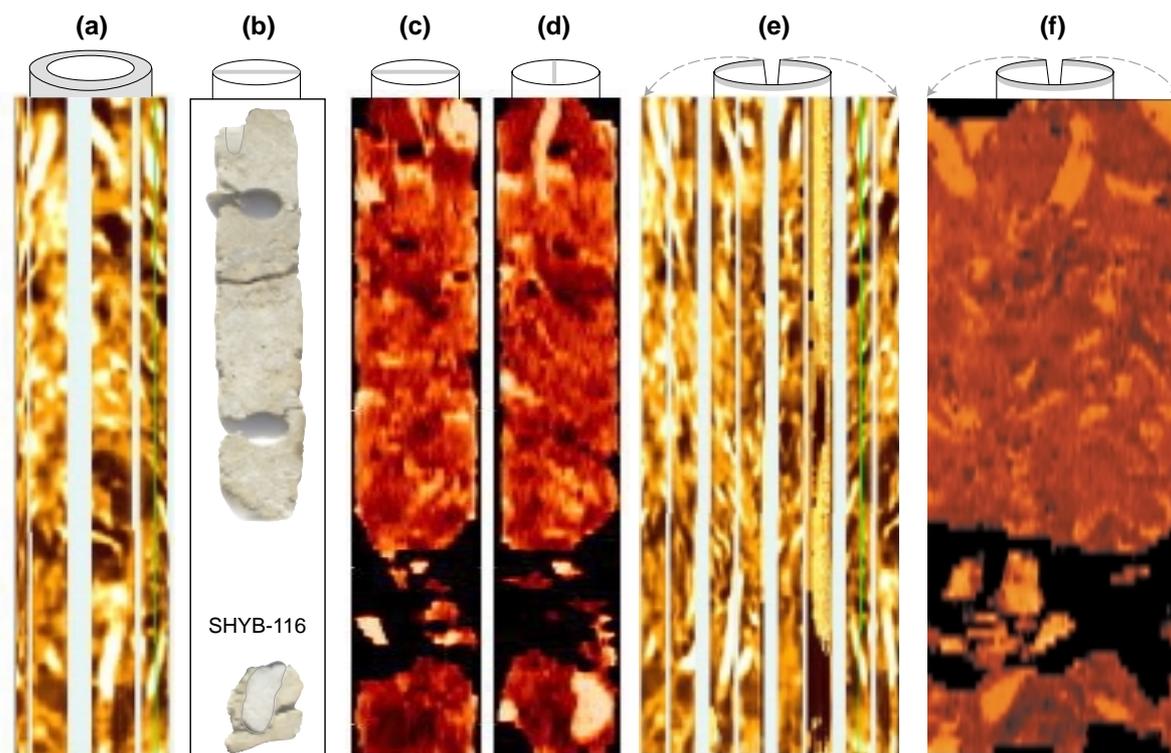


Figure 7: A montage of the images from Core 2, Tray 1 of SHYB-116, total length 2.8 feet. (a) Wrap-around “core” view of the FMI image of the well bore; (b) photograph of the slabbed core; (c) CT scan of the core presented as a cylinder displayed in two dimensions; (d) CT scan of the core presented as a cylinder displayed in two dimensions, but at 90 degrees to C; (e) FMI logs for the cored section; each track represents the images from each of the four receiver pads; and (f) CT image presented as a cylinder opened and displayed in two dimensions. The CT scan image colour scale represents a range of computed densities from zero (black) to high (light orange); the FMI colour scale presents a range of resistivity from conductive (black) to resistive (white).

clearly evident in this example as additional information is provided over the section where actual core coverage is incomplete. Once calibrated in this way, rudists in elevator growth position can be clearly recognised and confidently used to infer a particular depositional environment.

CONCLUSIONS

CT scan images and FMI logs can differentiate rudist bivalves by their high density and high resistivity. Once calibrated with core-based rudist identification, FMI logs can be used alone in uncored wells to provide additional biofacies, depositional facies and reservoir facies information.

An important advantage of the use of CT and FMI is that three-dimensional views of the rudists are depicted, as this primary fabric is often destroyed when friable cores from the Shu’aiba are slabbed for internal description. The orientation of the rudists is always preserved in the images, unlike the core, and assists in palaeoenvironmental interpretation. The three dimensional aspect also has the advantage of revealing rudists that would never be visible in unexposed core surfaces, and thereby enable a taphonomic and palaeoenvironmental interpretations to be made on a higher number of rudist individuals than would normally be visible for study.

In cored wells, the FMI logs permit correct orientation of the core, with important implications for the restoration of the rudist alignment and orientation. This can be used to assist determination of the windward and leeward location of the study well, and thereby provide supplementary information on the wave energy controls on the primary sedimentary facies and also on aspects of the reservoir facies.

The advantage of the present approach lies in the ability to (1) calibrate the CT scan images with the core and (2) calibrate the FMI logs with the CT scan interpretation, thus enabling interpretation of the depositional environment, depositional and potential reservoir facies from FMI logs of vertical and horizontal development non-cored wells

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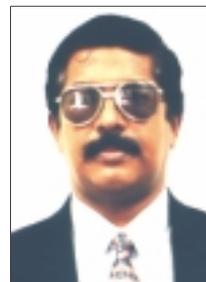
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ABOUT THE AUTHORS

G. Wyn ap G. Hughes is a Senior Geological Consultant in the Geological Research and Development Division of Saudi Aramco. He received his BSc, MSc, and PhD degrees from Prifysgol Cymru, University of Wales. His nearly 30 years of experience in biostratigraphy include 10 years as a Field Geologist/Biostratigrapher with the Solomon Islands Geological Survey, and 10 years as a Biostratigraphic Consultant and Unit Head of the Middle East-India region with Robertson Research International based in Singapore and Wales. Wyn's professional activities are focused on the integration of micropaleontology with sedimentology to enhance sequence stratigraphic interpretations of Saudi Arabian carbonate rocks. He maintains links with academic research through his activities as an external examiner for the University of Wales and as an Adjunct Professor of the King Fahd University of Petroleum and Minerals, Dhahran. Wyn is a reviewer for *GeoArabia*, and a member the British Micropaleontological Society and Dhahran Geoscience Society, and a Fellow of the Cushman Foundation for Foraminiferal Research.
geraint.hughes@aramco.com



Shameem Siddiqui is a Senior Lab Scientist at the R&D Center in Saudi Aramco and heads the CT-Scan Group at the Petrophysics Unit. His research interests include computerised tomography (CT) applications in reservoir characterization, core-log integration, image logs, porosity and pore volume distribution, heterogeneity classification, two- and three-phase relative permeabilities, visualization of reservoir fluids in porous media, and advanced image processing applications with 3-dimensional data. Shameem holds MSc and PhD degrees in Petroleum and Natural Gas Engineering from Pennsylvania State University. Before joining Saudi Aramco in June 1998, Shameem taught Petroleum Engineering at the Colorado School of Mines (CSM) in Golden, Colorado where he also co-directed two of their industry-sponsored research projects. Shameem has more than 20 technical publications. He is a member of the Society of Petroleum Engineers (SPE) and the Society of Core Analysts (SCA) and has been a Technical Editor for the SPE since 1997.
shameem.siddiqui@aramco.com



R. Kumbé Sadler is presently a Geological Specialist in the Reservoir Characterization Department of Saudi Aramco assigned to the Shaybah Field of southeastern Saudi Arabia. He began his career as a Petroleum Geologist in 1980 with Chevron USA, working on offshore and onshore fields of California. He joined Saudi Aramco as a secondee in 1991 and transferred employment to Saudi Aramco in 1996. He earned an MSc in Geology from Oregon State University, an MA in Earth Science from the University of Northern Colorado, and a BA from Susquehanna University. In his twenty years of experience he has worked with clastic and carbonate reservoirs in both gas and oil provinces. He is a member of the AAPG and the Dhahran Geoscience Society.
roy.sadler@aramco.com



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