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The Great Pearl Bank Barrier of the Arabian Gulf as a Possible Shu'aiba Analogue

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ABSTRACT

Within the Arabian Peninsula, the Shu'aiba Formation is one of three Cretaceous carbonate formations in which rudist bivalves are an important component. The favourable hydrocarbon reservoir properties of these carbonates are primarily attributed to the presence of the rudists and their associated debris, which accumulated along the margins of an intra-shelf basin. The rudist banks caused differentiation of an earlier carbonate platform into lagoon, back-bank, bank, fore-bank and open marine environments. Understanding of the orientation of these banks has been significantly assisted by micropalaeontological analysis of the rudist-associated sediment, but may be additionally enhanced by the study of Recent large bivalves, such as the 'fan mussel' *Pinna* spp. The depositional geometries of the rudist-dominated facies of the Shu'aiba Formation may be better understood by studying the Great Pearl Bank Barrier, located on the southern flank of the Arabian Gulf, as this may present a Recent analogue for variations in sedimentation and bioclast distribution.

The Great Pearl Bank Barrier complex includes a submarine ridge that extends for approximately 200 kilometers between the Qatar Peninsula and Abu Dhabi, and lies in water depths of less than 8 meters, together with a deep lagoon and barrier flank facies. The submarine barrier complex and the back island lagoons consist primarily of bivalve shells, sands and mud, in which are embedded locally dense populations of the large bivalve species *Pinna bicolor* Gmelin and *P.mururicata* (Linnaeus). These forms may serve as Recent counterparts for the extinct Aptian constratal elevator rudists, such as *Glossomyophorus costatus* Masse, Skelton and Sliskovic, with a form that resembles *Pachytraga* sp., and *Agriopleura blumenbachi* that characterise the back-barrier and lagoonal facies, respectively, of the Shu'aiba Formation in the region. The oysters that have colonised the barrier crest have a clinging habit and may occupy a niche that equates with the Aptian recumbent rudist *Offneria murgensis.*

INTRODUCTION

The Lower Cretaceous, Aptian, Shu'aiba Formation carbonates in the Arabian Peninsula display high-quality hydrocarbon reservoir properties that have developed within facies dominated by, or closely associated with, the now extinct group of bivalves known as rudists. These rudists contributed to the formation of a barrier, that is considered to be an enlarged sediment bank, in the sense of Gili et al. (1995a), rather than a biologically constructed reef. As the rudist bank complex aggraded, prograded and retrograded in response to changes in sea level, it differentiated the previously unrimmed platform into lagoon, back-barrier flank, barrier crest, fore-barrier flank and open marine regimes with their associated sediment variations. An ability to predict the architectural trend of these rudist banks, and their associated lithofacies, would provide considerable support towards improving reservoir facies prediction, generating the best reservoir model and thereby optimise the exploitation of the hydrocarbon content. Such understanding of the mode of life of extinct rudists may be assisted by the application of a modern analogue with similar large bivalve faunas, such as the Great Pearl Bank Barrier of the southern Arabian Gulf.

The Great Pearl Bank Barrier consists predominantly of bivalve debris, together with the extraordinarily large constratal bivalve species *Pinna bicolor* Gmelin and *P. muricata* (Linnaeus), and these species may represent modern analogues for the elevator rudists (Masse, 1979; Skelton et al., 1995). Shu'aiba Formation details, as considered in this study, are based upon a comprehensive review of numerous

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publications, and by the author's intensive micropalaeontological and rudist investigations in Saudi Arabia. Knowledge of the detailed distribution of *Pinna* in the Great Pearl Bank Barrier complex is, unfortunately, rather limited and requires further investigation.

PREVIOUS WORK

Aptian Rudist Banks of the Arabian Gulf Region

Aptian rudist carbonates of the Middle East have received considerable attention because of their importance as hydrocarbon reservoirs. Numerous publications have discussed their stratigraphy and palaeoecology based on the micropalaeontological and macropalaeontological components. Important Middle Eastern references to the depositional history of the Shu'aiba Formation include Aldabal and Alsharhan (1989), Alsharhan (1983, 1985, 1987, 1990, 1995), Alsharhan and Nairn (1986, 1988, 1990, 1993), Azer and Toland (1993), Banner and Simmons (1994), Frost et al. (1983), Hamdan and Alsharhan (1991), Harris and Frost (1984), Litsey et al. (1986), Murris (1980), Scott (1990a), Simmons (1994), Simmons and Hart (1987) and Witt and Gokdag (1994). Descriptions of the Late Cretaceous carbonate ramp of the southern Arabian Gulf in general by Burchette (1993) and Burchette and Wright (1992) are of regional value. Marzouk and El Sattar (1995) have considered the distribution of rudists banks within the Shu'aiba Formation to have been possibly influenced by rather weak evidence for wrench faults. Outside the Arabian region, relevant studies of rudist build-ups and their associated biofacies include those of Carbone and Sirne (1981), Masse and Philip (1981), Polsak (1981), Achauer (1983), Bay and Bebout (1983), Frost et al. (1983) and Scott (1990b).

The Great Pearl Bank Barrier

The Great Pearl Bank Barrier of the Arabian Gulf has received only limited attention, but is widely considered to provide a good example of a carbonate ramp (Wilson and Jordan, 1983; Emery and Myers, 1996; Burchette and Wright, 1992). One of the earliest detailed studies was a study of the surface sediment type and distribution near the Qatar Peninsula (Houbolt, 1957). The comprehensive multidisciplinary study of Purser (1973) focused on Holocene carbonate sedimentation and diagenesis of the shallow epicontinental sea of the Arabian Gulf, and the Great Pearl Bank Barrier. Regional foraminiferal distributions have been investigated by Houbolt (1957), Evans et al., (1973), Hughes Clarke and Keij (1973), Ahmed (1991), Basson and Murray (1995), Murray (1965; 1966a; 1966b; 1966c; 1991) and Al-Zamel et al. (1996). Recent satellite image interpretation of sediment type and distribution along the eastern extension of the Barrier and the adjacent Abu Dhabi coastline (Harris and Kowalik, 1994) provides additional information on the patterns of sediment distribution and their relationship to channels, islands and coastal features.

COMPARATIVE PHYSIOGRAPHY AND SEDIMENTOLOGY

Aptian Rudist Banks of the Arabian Gulf Region

The Cretaceous succession of Abu Dhabi is made up of three major cycles of carbonate deposition, that include the Shu'aiba, Mishrif and Simsima formations, each of which is terminated by an unconformity and coincides with a major marine regression (Scott, 1988; Alsharhan and Nairn, 1993; Figure 1). An episode of rudist colonisation, expansion and bank development characterises the final, shallowing stage of each of the three cycles, located at submarine shelf-slope breaks. The Shu'aiba Formation is the earliest of these carbonates, of which the rudist and associated facies were deposited on the shallow flanks of an intra-shelf basin that was itself located within a broad, stable shelf that extended over the eastern Arabian Peninsula during the Early Aptian. This was coincident with the maximum extent of the Neotethys Ocean (Hooper et al., 1995; Dercourt et al., 1993). The intra-shelf basins were probably separated from the deep open sea by shallow shelf areas, but it is possible that there was some limited connection through narrow channels (Murris, 1980; Grabowski and Norton, 1995; Fischer et al., 1995; Hooper et al., 1995).

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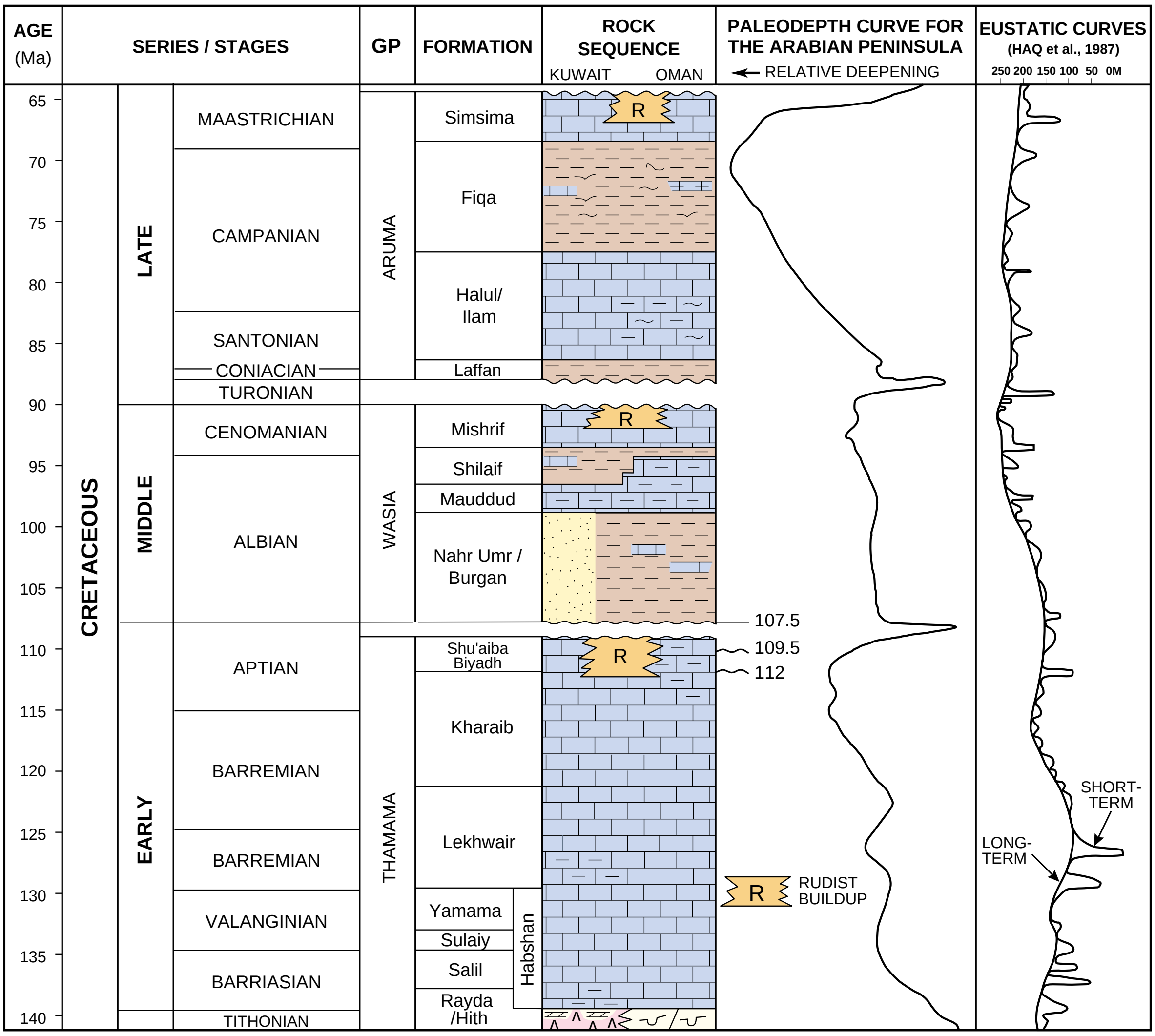

Figure 1: Cretaceous lithostratigraphy of the Arabian Gulf region to illustrate the relationship between the rudist build-ups (R) and the peaks of relative sea level (adapted from Alsharhan and Nairn, 1993) (Balkema).

In broad terms, the Shu'aiba Formation consists of three stacked genetic carbonate units that are principally differentiated by their biocomponent variation. The lower unit consists of a regionally extensive, laterally homogeneous, algal-dominated platform facies, that is dominated by foraminifera. The thicker rudist-bearing middle unit is both horizontally and vertically heterogeneous and includes algal-dominated lagoon, rudist-bank and open-marine biofacies and may possibly have been initiated by rejuvenation of basement blocks, creating fault-controlled palaeobathymetric variations, although there is no evidence for such activity. The rudist barrier-bank complex, together with the fore-bank and back-bank flank deposits, aggraded and subsequently prograded into the basin and retrograded into the lagoon. There is evidence that an episode of emergence followed the development of the main rudist build-up in Oman (Witt and Gokdag, 1994), but this event is not necessarily detected over the region. The upper unit is not preserved throughout the region, but in places is characterised by the extensive development of a lagoon, with associated locally developed rudist and open marine facies. There is a marked lithological change at the top of the Shu'aiba Formation, where the cream-to-white limestones are unconformably overlain by dark brown-to-green calcareous shales and mudstones of the Nahr Umr Formation. This post-Shu'aiba unconformity is of intra-Upper Aptian age, based on calcareous nannofossil evidence (personal communication, Varol, 1996).

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The predominance of rudistid bivalves instead of corals along the intra-shelf margin suggests proximity to intra-shelf basinal restriction associated with nutrient-rich, suboxic to anoxic submarine conditions (Scott, 1988; Ross and Skelton, 1993; Gili et al., 1995b). Within the region, rudists and corals are not found together. Possible causes for coral scarcity include hypersalinity, turbid water conditions and lack of a firm substratum, although some well-adapted corals are able to survive such conditions (personal communication, Thomassin, 1996).

In Caribbean Cretaceous platforms, rudists co-existed with corals in shelf-margin reef systems but each occupied a separate habitat. Corals, algae and stromatoporoids built the reef-frame below wave base, and caprotinid, caprinid and radiolitid rudists occupied the shallower high wave-energy zone (Scott, 1990b). Mixed coral-algal-rudist assemblages have been described from bioherms and biostromes on shelf margins and isolated platforms (Camoin, 1990). Kauffman (1990) considered that rudists displaced corals following a change in the local ocean and climate system, although this is not accepted by most rudist workers (Gili et al., 1995b). At Zibara and Jarn Yaphour in onshore Abu Dhabi, together with many other wells and areas, the Shu'aiba consists of small intervals of coral-algal build-ups and may indicate proximity to more agitated conditions. It has been speculated that some of these build-ups may have originated upon local palaeobathymetric highs formed by salt diapirs, although it is not considered that diapiric movement is responsible for all of the Shu'aiba rudist distribution (Alsharhan, 1985; Alsharhan and Kendall, 1991).

Figure 2 is an adaptation of the biotic components of the Aptian rudist complex of Bu Hasa field, Abu Dhabi (Alsharhan and Nairn, 1993; Alsharhan, 1995). The 'shelf lagoon' is the most shoreward regime, suggested by these authors to be less than 7 meter (m) deep and characterised by lime mudstones and localised medium- to coarse-grained packstone-grainstones. This low energy regime supported miliolid foraminifera and high conical forms of *Palorbitolina lenticularis* together with stromatoporoids, corals, shell and echinoid fragments and rare codiacean calcareous algae. Seawards of this regime, but separated from the open marine environment by a rudist barrier, lies the 'back barrier slope'. This

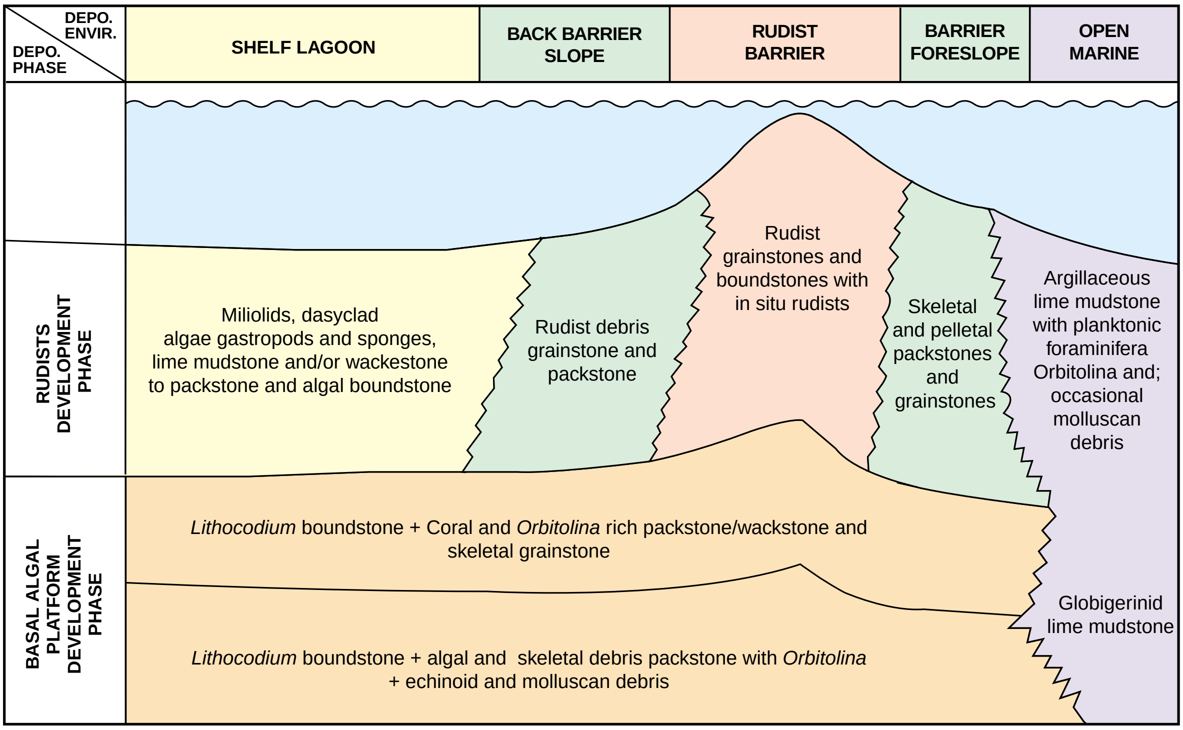

Figure 2: Schematic diagram showing the palaeoenvironments and facies distribution of the Shu'aiba build-up in the Bu Hasa field (from Alsharhan, 1995) (Balkema).

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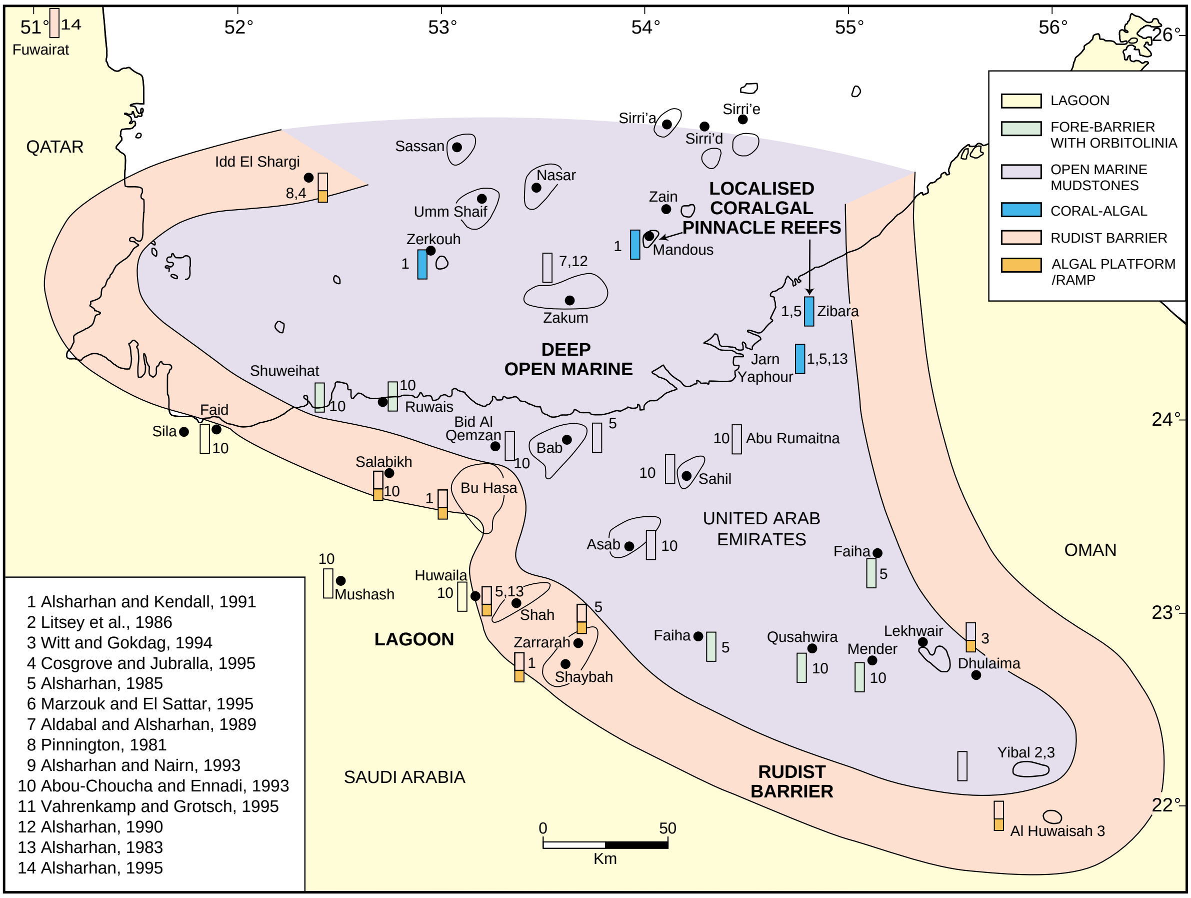

Figure 3: The shelf-margin trend of the Shu'aiba Formation rudist barrier during the Aptian (based upon Alsharhan and Kendall, 1991) (Balkema).

feature is composed of lime mudstones-wackestones and packstones-grainstones transported from the rudist barrier under low to medium energy conditions suggested to be between 3 and 7 m water depths. The biocomponents include rudist debris transported by tidal swash or storms mixed with 'shelf lagoon' benthonic foraminiferal forms, ostracods and echinoid debris, supplemented by the calcareous alga *Lithocodium aggregatum* Elliot. The 'rudist barrier' is a positive sedimentary accumulation feature, but not a reef, composed of rudist shells and rudist fragments of various sizes, that accumulated at water depths suggested to be between 2 to 5 m with medium- to high-energy levels. Undifferentiated echinoid debris, *Lithocodium aggregatum* and rare isolated small corals are present.

The 'barrier foreslope' is essentially equivalent to a fore-reef talus apron, and resulted from the debris transported oceanwards from the rudist barrier, possibly by storms or tidal backwash under medium to low energy levels, with water depths suggested to be between 10 and 20 m. It consists predominantly of coarse-grained packstone-grainstone debris of rudists, together with lime mudstones-wackestones with calcareous algae, low conical forms of *P. lenticularis*, and echinoids; localised mudstones contain planktonic foraminifera. The 'open-marine' regime contains lime mudstones with planktonic foraminifera, low conical *P. lenticularis*, small miliolids, sponge spicules and small rotalid benthonic foraminifera. Deeper in the basin, dark grey mudstones of the Bab Member of the Shu'aiba Formation contain planktonic foraminifera with ammonites, and were deposited under reduced circulatory conditions (Aldabal and Alsharhan, 1989). Low energy conditions would have prevailed, with water depths exceeding 20 m. The configuration of the Aptian shelf-margin rudist barrier trend (Figure 3) is based on published biotic components of regional wells and is a modification of the model by Alsharhan and Kendall (1991).

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The Great Pearl Bank Barrier

Physiographically, the Arabian Gulf is an almost enclosed subrectangular basin, approximately 850 km in length and a maximum width of 330 km, that trends in a northwest-southeast direction. The basin floor is markedly asymmetrical, forming a ramp that dips gently (35 cm per km) away from the tectonically stable Arabian side (average depth 20 to 40 m), but steeply (175 cm per km) away from the tectonically active Iranian side (40 to nearly 100 m). The greatest depth (100 m) is reached near its entrance, at the Straits of Hormuz (Purser and Seibold, 1973; Figure 4). In terms of its regional tectonic setting, the Arabian Gulf is an epicontinental sea within a foreland basin, between the geologically stable, low-lying, Precambrian Arabian Shield and the high, geologically unstable Tertiary fold belt of the Zagros Mountains of Iran. The latter result from compression associated with subduction of the Arabian Plate beneath the Eurasian Plate along the Zagros Thrust Zone since the Early Miocene (Stöcklin, 1974; Stoneley, 1974). The bathymetric asymmetry results from Pliocene to Quaternary tectonic loading on the Iranian side, and tilting of the Arabian Peninsula in the Neogene, during the opening of the Red Sea. The southeastern part of the Arabian Gulf is a very gently sloping ramp (Wilson and Jordan, 1983). The Qatar Peninsula forms a distinct feature on the near-linear Arabian coastline, and causes anomalous trends in current direction, and possibly of sedimentation, along the southeastern Gulf. Shallow seismic investigations (Kassler, 1973) indicate that the northern limit of the barrier is represented by a 'hinge line', that approximately coincides with a gravity anomaly and may suggest fault-control.

The Gulf waters are hypersaline, with salinity values generally exceeding 39 ppt (parts per thousand), with values up to 66.9 ppt in the inner lagoon (Evans et al., 1973). This hypersalinity is the result of a combination of frequent winds (mostly from between 315° and 15°), high temperatures (45 to 50°Centigrade), low precipitation (less than 5 cm a year), low fluviatile input (except for the Tigris,

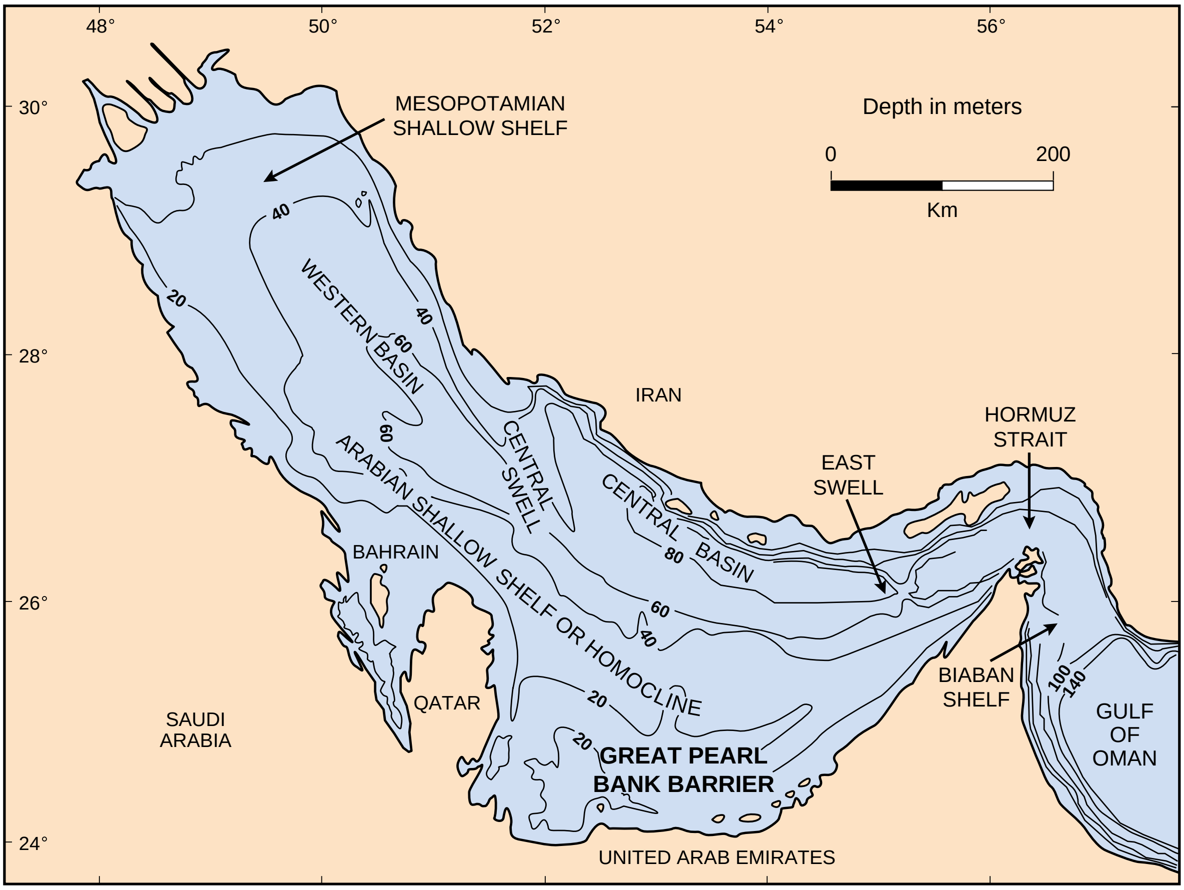

Figure 4: The principal bathymetric provinces of the Arabian Gulf (after Purser and Seibold, 1973).

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Euphrates and Karun rivers in the extreme north) and the restricted connection with the normal salinity waters of the Indian Ocean. Surface water temperatures vary from 23-24°C in the nearshore non-restricted areas to 22-36°C in the inner lagoon (Evans et al., 1973).

The Arabian Gulf is unique in being the only shallow inland sea in which carbonate deposition is currently taking place and this is attributed to its low latitudinal position and sufficiently clear water, resulting from low terrigenous input, conducive to considerable carbonate-secreting biological activity (Wilson and Jordan, 1983). Pure carbonate sediments characterise the Arabian flank of the basin, but some siliciclastic input in the north and western parts is provided by the Shatt Al Arab delta and smaller rivers from the Iranian coast (Houbolt, 1957; Stoffers and Ross, 1979). The depth of the euphotic zone is approximately 20 m in the turbid waters above the muddy sediments along the Abu Dhabi coastline, but increases to 30 m in the clearer waters in the axial parts of the basin.

The Arabian Gulf has experienced a number of desiccations and flooding events in its recent history. At 20,000 years before the present (BP), sea level fell to -120 m, flooding the site of the Great Pearl Bank Barrier at about 10,000 years BP (Uchupi et al., in press). At about 6,000 years BP, sea level had risen to 10 m above present level but fell to the present sea level 1,000 years ago (Glennie et al., 1994; Glennie, 1995).

The Great Pearl Bank Barrier is an irregular, asymmetrical submarine ridge with a maximum width of 50 kilometers (km) that extends in a discontinuous northwest-southeast trend off the Saudi Arabian coast from Tarut Bay, where it forms the Bahrain Ridge, to west Qatar, and from east Qatar 200 km to Abu Dhabi (Figures 4 and 5). Although generally continuous, there is a pronounced break in the barrier west of Bu Tini Island, where a northwest-southeast-trending channel connects the lagoon

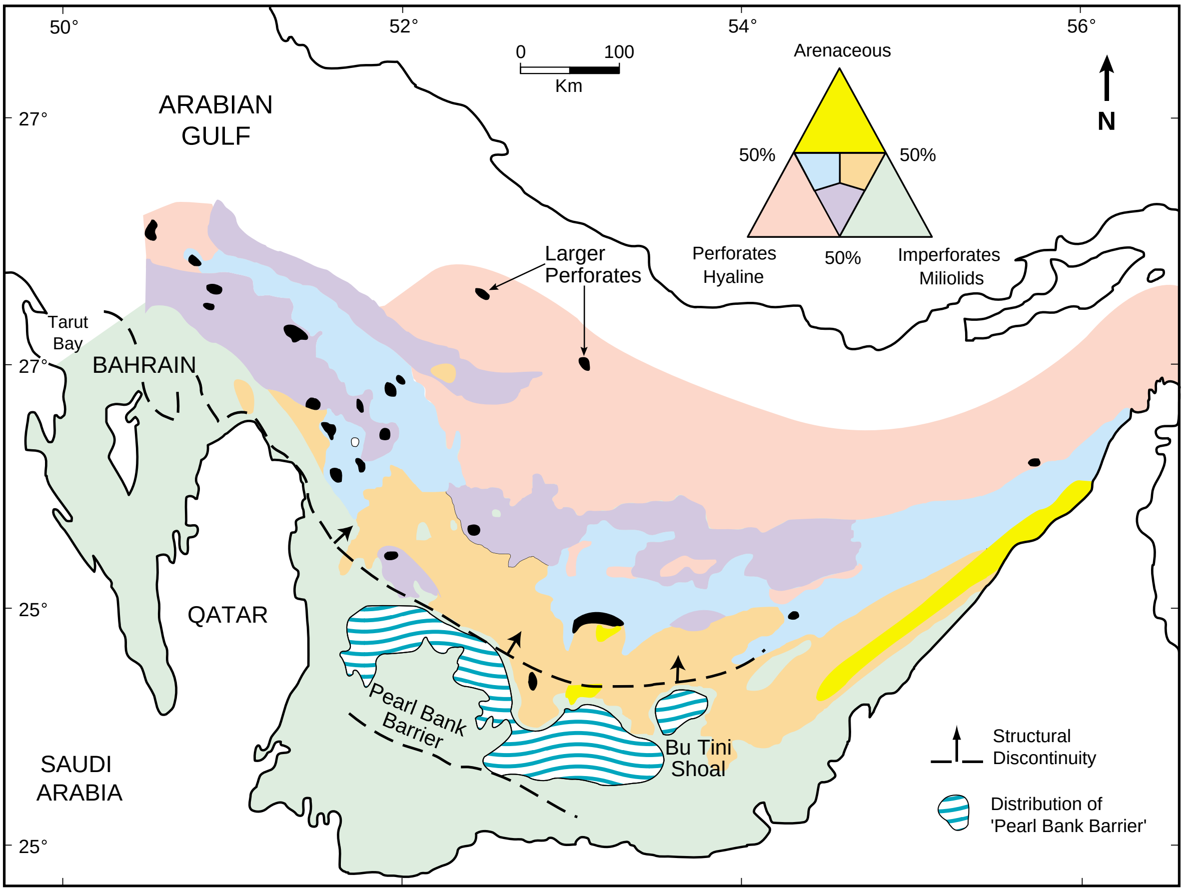

Figure 5: The southern Arabian Gulf showing the location of the Great Pearl Bank Barrier and foraminiferal components of the sediments (from Hughes Clarke and Keij, 1973) (Balkema).

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with the open waters of the Gulf. The average depth of the top of the barrier is between 5 m and 10 m in the west, where it is covered by skeletal sands, but shallows to less than 2 m towards the east where it supports a series of sand shoals and small islands such as Bu Tini and Zirko (Figure 8). As the barrier lies oblique to the shoreline, the Khor Al Bizm lagoon is nearly 140 km wide and more than 40 m deep in the west, but narrows to less than 10 km, and shallows to less than 4 m east of Yas Island. The barrier finally merges with the coast east of 54° longitude, and displays a trend that is associated with the structural axis of the Gulf and therefore related to the Zagros, or 'Iranian' trend (Purser and Evans, 1973). Kassler (1973) has also recognised an 'Arabian Trend' of structures such as the Qatar and Bahrain anticlines with north northeast-south southwest axes.

The barrier becomes a broad ridge covered by a series of carbonate sand shoals and islands, which become increasingly numerous and larger eastward. The lagoon, however, becomes increasingly narrow, shallow and hypersaline to the east which limits faunal diversity and sediment type. It eventually transforms into a series of small isolated lagoons separated by the downwind sediment 'tails' that have accreted from the barrier islands (Purser and Evans, 1973).

Twelve carbonate associations have been recognised by Wagner and Van der Togt (1973). From shallow to deep, these facies can be summarised as including rounded mollusc and gastropod grainstones, angular molluscan grainstones, molluscan wackestones and packstones, and dark argillaceous carbonate mudstones and wackestones. The relatively small area of the Arabian Gulf inhibits the development of long swell waves and the depth of wave influence is directly controlled by wind-blown waves. Mud content increases in sediments in exposed areas below 50 m, and this is attributed to strong shamal-influenced water movement. Much of the mud in the lagoon is considered to be the product of post mortem mechanical bioerosion of shells by worms, fishes, etc. (Houbolt, 1957). Irregular and regular echinoderms alone account for the production of 0.5 gm. per day of carbonate sand (Evans et al., 1973). Carbonate mud also typifies the deeper parts of the region, with bioclastic, bivalve-dominated, grainstones, muddy packstones and coralgal grainstones on the higher areas. The three major geomorphologic elements which characterise a barrier system, according to Reinson (1984, 1992), may be recognised at the Great Pearl Bank Barrier. These include the sandy subtidal to subaerial barrier-island chain itself, the enclosed lagoon on its shoreward side and the channels which cut through the barrier and which connect it to the open sea through tidal inlets.

The gradual shallowing of the barrier from west to east is accompanied by a transition from bivalve to coral and calcareous algal biocomponents with corals restricted to the seaward side. Sediments are swept across the southern margin of the barrier-bar complex and spill into the muddy Khor Al Bizm lagoon where they form steep triangular accretion slopes or small deltas (Purser and Evans, 1973). These features are comprised of a vertical succession with a sharp transition between *in situ* lagoon muds and the overlying transported sands. The sediment 'tails' are separated by large inter-tail depressions, up to 10 m deep and several kilometers wide, that may represent intertidal channels. Longshore currents have also caused spit development in the lagoon, and these are aligned both normal and parallel to the barrier. These spits have caused near coalescence of the seawards margins of the 'sediment tails' to form islands which trend parallel to the Barrier, and which are separated by tidal channels up to 10 m deep. Pelloids and bioturbation, mostly by crabs, are common features of the lagoon sediments (Evans et al., 1973), and also bioturbation by thalassinid shrimps and worms (personal communication, Thomassin, 1997).

Sedimentation on both the salt-pillow induced bathymetric highs, and the other positive areas, is affected by wind-driven waves and currents. Shoals, such as the Bu Tini shoal, are flat-topped, above wave base, and surrounded by poorly developed fringing reef, except on the windward, northern side. Reef-derived sands contribute to the development of the Barrier complex within the deeper water seaward of the fringing reefs. Individual bars within the barrier system are stabilised locally by hard-grounds. Small islands have formed where bars have coalesced, and the islands are growing leeward by tidal-flat accretion, and laterally by spit growth (Purser and Evans, 1973). Leeward of the barrier-bar complex, peloidal sands and lagoon muds are accumulating. The mainland coastline of Abu Dhabi Emirate is characterised by Holocene sabkhas. Satellite image interpretation of the eastern part of the barrier (Harris and Kowalik, 1994) indicates an offshore complex of reefs, skeletal sand shoals, tidal channels and islands.

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It is likely that the vast bivalve sand-dominated Great Pearl Bank Barrier originally formed as a belt of active bars and tidal channels. The scarcity of siliciclastic sediments precludes an origin that involved spit progradation parallel to the coast from the aeolian siliciclastics of Qatar. A reasonable mechanism for the origin of the barrier may be the submergence of beach-dune complexes during the overall rise in sea level during the Holocene (Swift, 1975; Field and Duane, 1976). It is not inconceivable that the steep northern margin to the Great Pearl Bank Barrier, or 'hinge line' of Kassler (1973), may be fault controlled, and that this provided the required submarine topography within which bivalves could flourish and thereby provide shell debris for the aggradation of the barrier.

BIOCOMPONENTS OF THE APTIAN RUDIST BANKS OF THE ARABIAN GULF REGION AND OF THE GREAT PEARL BANK BARRIER: COMPARED AND CONTRASTED

The elevated salinity of the Arabian Gulf is considered to be a major factor responsible for the reduced species diversity of calcareous biological components in the studied region. The wide lagoon west of the Khor Al Bizm has 40 ppt salinity with faunal components similar to those of the offshore Gulf. In the lagoons east of the Khor, however, more restricted conditions and higher salinity (50 ppt) have caused a depletion of the biological components, in which corals, calcareous algae and echinoderms become rare, while gastropods and miliolid foraminifera become abundant.

Molluscs

Shu'aiba Formation

Rudist bivalves dominate the mollusc component of the Aptian carbonates of the Arabian Gulf Region, although chondrodontid oysters are locally present. Rudists were sessile, and were only able to adjust to local sedimentation by shell growth. Three rudist morphotypes have been defined and are termed 'elevators', 'recumbents' and 'clingers' (Skelton, 1991; Skelton and Gili, 1991), each of which is considered to be an adaptation to particular combinations of ambient hydraulic energy and sediment transport. Elevators typically have a long-conical, elongate-cylindrical or large cylindrical attached valve; a flat or slightly concave or convex free valve; and are therefore typically uncoiled (Figure 6a). The entire growth margin of the attached valve was involved in upward growth. Stability in these vertically elongate forms relied upon support from the surrounding sediment; a mode of growth termed 'constratal' (Gili et al., 1995a). This particular morphotype was associated with originally soft, muddy sediment, with positive net accumulation and only sporadic episodes of sediment removal during the animal's lifetime. It is implied, therefore, that this morphotype was restricted to low to moderately low hydraulic energy levels, and was able to grow vertically and keep pace with sedimentation. They are considered to

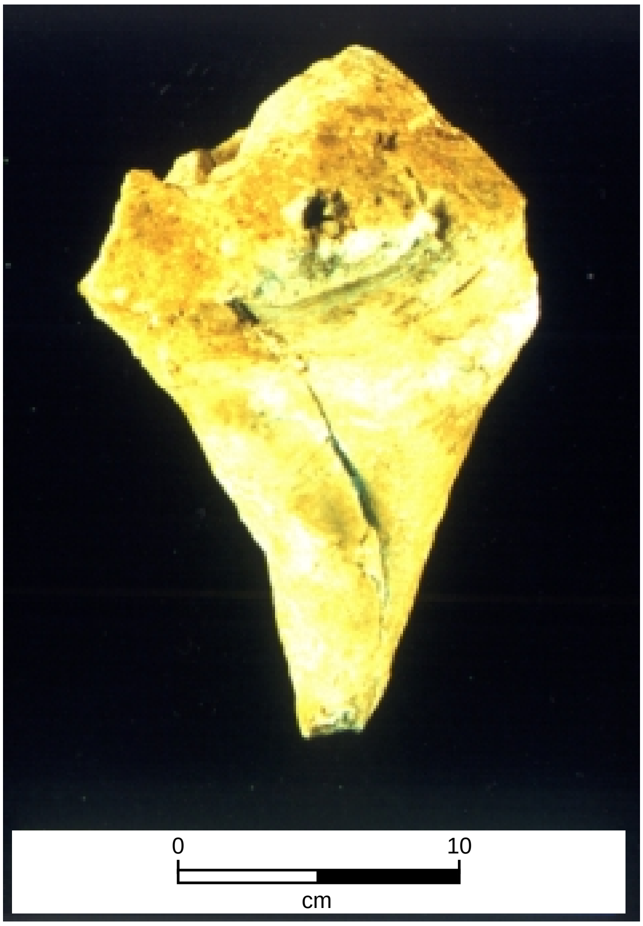

Figure 6a: An elevator rudist from the Shu'aiba Formation of Saudi Arabia. Note the smooth, uncoiled lower valve.

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have occupied moderately shallow conditions as fossil assemblages are frequently disturbed, possibly by storm-wave action, and include the Radiolitidae, Caprotinidae and Caprinidae. Elevator monopleurid beds in Texas display dinosaur footprints which have been used to conclude tidal water depth variations from 1 to 4 m (Perkins, 1974). In the Shu'aiba Formation, the caprotinid elevator species *Glossomyophorus costatus* Masse, Skelton and Sliskovic is particularly well represented (Masse et al., 1984) together with *Agriopleura blumenbachi* (unpublished report, Skelton, Saudi Armco, 1997).

Recumbent rudists are uncoiled and arcuate with both valves extended to maximise the virtual area of contact, and best adapted for living upon a mobile substrate within a high-energy regime, such as on a mobile carbonate sand bank. This extended growth was assisted by the development of pallial canals in caprinids such as *Offneria murgensis* Masse, and form a spongy thick shell wall, thus maximising the available calcium carbonate budget. In the Shu'aiba Formation of Oman, *Offneria murgensis* Masse is particularly well represented (Simmons, 1994). Clingers are characterised by a broad basal surface which enables close contact to be maintained with the substrate. As these forms are typically coiled, they are not easily able to adjust their position, and are therefore also typical of localities with low sedimentation rates, although they were able to respond to spasmodic sediment input by preferential growth of the attached valve margin.

Rudist colonies within the Aptian inner-shelf basin with prograding margin complexes have been studied by numerous authors, a synthesis of which is presented in Ross and Skelton (1993). Shallow basin margins are considered to be characterised by high current energy with grainstone accumulation and biostromes of recumbent and clinger rudists. Frost et al. (1983) described the Shu'aiba bank, or 'biohermal framework' as being characterised by an early development of mostly monopleurid rudists within a lime-mud matrix, and here interpreted as elevators, that became better sorted and winnowed upwards as the bank shallowed-up to within wave base. Above this level, the higher energy conditions are considered to have terminated vertical growth of the bank, and initiated lateral growth and the development of flank beds of broken rudist debris on the slopes of the rudist mounds. Lower energy conditions behind, and possibly downslope of, this margin enabled muddy build-ups with elevator rudists, mostly below wave base. The lagoonal inner shelf areas are characterised by lime-muds with marly wackestone to packstone and supported laterally extensive rudist biostromes, with very low diversity primitive elevators such as species of *Monopleura* and *Agriopleura* (personal communication, Skelton, 1996).

Great Pearl Bank Barrier

In the Great Pearl Bank Barrier, molluscs are particularly common, with gastropods being preferentially concentrated in the lagoons, and bivalves on the offshore marine high of the barrier (Houbolt, 1957; Hughes Clarke and Keij, 1973). Large, sturdy specimens of pearl oysters are especially concentrated within the effects of normal wave turbulence, and molluscs generally are the most abundant organisms in the sediments offshore Qatar (Houbolt, 1957). The sediments of the lagoons contain common infralittoral molluscs. Intertidal sediments are dominated by *Cerithium* spp., and high-energy regions contain epifaunal species of *Chama, Spondylus, Arca* and the oyster *Pinctada radiata* (Leach). With the exception of the large-shelled *Pinna bicolor*, or 'rough pen shell' and *P. muricata*, none of the large Indo-Pacific molluscs are present within the region (Hughes Clarke and Keij, 1973).

The genus *Pinna* is characterised by being wedge-shaped with a straight or concave ventral margin, a well-defined median ridge and a sculpture of radial ribs or rows of scales (Figure 6b). It lives in tropical or subtropical shallow bottom seas. Most Pinnidae live with the pointed anterior end of the shell buried in soft sediment anchored at their base by byssal threads to underlying stones, shell fragments or other objects. The hinge margin and commisure of the valves is more or less vertical, with the wide posterior end typically exposed. *P.muricata* (Linnaeus) can, however, live completely buried (personal communication, Thomassin, 1997). This growth attitude closely resembles that of the Cretaceous 'elevator' rudists, as described above, and is best described as displaying constratal growth, in the sense of Gili et al. (1995a). *P. bicolor* Gmelin reaches at least 35 cm length and lives three quarters buried, often in dense populations, in the muddy sands of the lagoons and shallow shoals. It is found nearshore, less than 10 m deep, and also in the outer lagoon of the Great Pearl Bank Barrier complex (Evans et al., 1973; Hughes-Clarke and Keij, 1973). In Tarut Bay, Saudi Arabia (Basson et al., 1977), a

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Figure 6b: Two specimens of *Pinna bicolor* from the Arabian Gulf (Bosch et al., 1995). Length approximately 25 cm.

specimen of *Pinna muricata* 40 cm. long, with a commisural gape of 15 cm was found buried in the sand in the seagrass-covered sandy areas with only the open end of the shell protruding. Forms resembling *P. muricata* Linnaeus are present within fine muds at 10 m water depth in the Arabian Gulf in the Safaniya area. *Pinna* are also recorded (personal communication, T. Kirkham, 1997) from the outer lagoon between Abu Dhabi and Baraini Island.

The oyster *Pinctada radiata* (Leach) Order Pteroida, Superfamily Pteriidae, is found in the offshore and outer lagoon areas of the Barrier (Evans et al., 1973). The growth attitude of oysters closely resembles that of the Cretaceous ‘clinger’ rudist morphotype as described above. Unlike normal bivalves, which are capable of moving on or in a substratum, oysters are permanently immobilised, and have no direction of movement. The pearl oysters of the Bahrain and Great Pearl Bank Barrier are assigned to the species *P. radiata* (Basson et al., 1977) , although the black-lipped *P. margaritifera* is also present in the region (Bosch and Bosch, 1983).

Foraminifera

Shu’aiba Formation

Within the Shu’aiba Formation, foraminifera have proved to be useful for age determination, palaeobathymetric interpretation, vertical and lateral palaeoenvironmental interpretation, recognition of marine flooding surfaces and subdivision into a number of layers which may prove to be reservoir

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layers. Planktonic foraminifera, such as *Hedbergella delrioensis* (Carsey) and *H. planispira* (Tappan) are found within the open marine facies of the deeper facies of the Shu'aiba Formation. Their sporadic occurrence within the lagoonal facies indicates only partial restriction with episodic marine access either between the build-ups or over the build-ups during short marine transgressions. Benthonic foraminifera are present throughout most of the Shu'aiba Formation, the most significant being miliolids and the agglutinated forms *Debarina hahounerensis* (Fourcade, Raoult and Vila), *Trocholina* sp., *Vercorsella arenata* (Arnaud-Vanneau), *Praechrysalidina subcretacea* (Sinni), *Orbitolina* spp. and *Textularia* spp. Discorbid and rotalid benthonics are locally present, and are associated with the planktonics and typically deeper, normal salinity conditions.

Specimens of the conical form *Orbitolina* are often abundant, and are characterised by their triangular appearance in cross-section, although accurate palaeoenvironmental interpretation of this extinct genus is difficult. Moullade et al. (1985) stated that the high conical forms are typically found within the carbonate facies of the inner shelf and occur only exceptionally in outer shelf facies. The low, larger, conical forms are not so restricted, however, and have been found within carbonate shelf facies and also in the outer basin. Low conical forms seem to have been tolerant of cooler and possibly deeper conditions, as they are recorded from the northernmost latitudes. Other authors (Sartorio and Venturini, 1988) place the orbitolinids within both the inner shallow platform and the outer platform, but absent from the rudist-dominated build-up on the edge of the inner platform. A general platform habitat is, nevertheless, suggested for the Upper Barremian-Lower Aptian carbonates of southeast Spain (Vilas et al., 1995). By using the depth ranges of associated algae, Banner and Simmons (1994) have suggested depth ranges for *Orbitolina (Palorbitolina) lenticularis* (Blumenbach) of 5 to 60 m, with a preferred range of 10 to 60 m.

Miliolids are well represented throughout most of the Shu'aiba Formation and were present in most water depths, but are preferentially concentrated within lagoonal carbonates where possible elevated salinity levels tended to exclude other foraminifera. Calcareous hyaline forms typically include smooth and costate discorbids, *Lenticulina* spp. and uniserial genera Nodosaria and Dentalina, and are therefore associated with moderately deep depositional environments.

Great Pearl Bank Barrier

Foraminifera recorded within the Great Pearl Bank Barrier region include the agglutinated forms *Textularia*, *Clavulina*, and encrusting *Placopsilina*. Miliolid forms include small and large genera such as *Peneroplis* and *Sorites*. Small rotalid genera include *Elphidium*, *Cibicides*, *Discorbis* and *Cancris*, and include larger genera *Operculina*, *Heterostegina* and *Amphistegina*. Locally developed rises on the submarine terraces offshore Qatar contain enormous numbers of *Heterostegina qatarensis* (Houbolt) which occupy up to 50% of the total sediment volume (Houbolt, 1957); this large benthonic species is considered to live in great abundance at depths below normal wave base. *Heterostegina* and *Operculina* species possibly represent modern analogues for *Orbitolina*, as no other larger genera were present in the Aptian.

The distribution of the relative proportions of miliolid, agglutinated and rotalid benthonic foraminifera was displayed as three broad zones by Hughes Clark and Keij (1973) (Figure 5). A predominantly miliolid assemblage (>50%) is found on and shorewards of the Great Pearl Bank Barrier, and is characterised by the larger forms *Peneroplis* and *Sorites*, although the larger rotalid forms *Operculina* and *Pseudorotalia* also occupy the deeper parts of the back-barrier area; foraminiferal abundance is high. Miliolid-dominated assemblages characterise the Shu'aiba restricted lagoon sediments inland of the best developed rudist build-ups. Offshore to the Great Pearl Bank Barrier is a belt, approximately 50 km wide, dominated by a mixture of agglutinated and miliolid forms, although smaller and larger rotalids are locally distributed within this field. *Operculina* and *Pseudorotalia* are particularly concentrated within this belt.

Foraminiferal recovery is rich, particularly at the foot of the barrier. Further offshore is a more differentiated area which ranges from 25-100 km wide, in which variable admixtures of agglutinated, miliolid and rotalid forms are found, including *Ammonia*. Foraminiferal recovery is generally low in this belt and rare planktonic foraminifera are present.

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Calcareous Algae

Shu’aiba Formation

Lithocodium aggregatum Elliot, synonymous with *Bacinella irregularis* (Banner et al., 1990), is an encrusting green alga (Codiaceae) particularly common in the Shu’aiba Formation of the Arabian Gulf Region, where it formed layered calcified lamellae over the surface of the sediment, and also as localised nodules enclosing micro- and mega-faunal remains. In addition, *Salpingoporella dinarica* Radoicic (Dasyclad), *Arabicodium aegagrapiloides* Elliot (Codiaceae) and *Coptocampylodon lineolatus* Elliot (?Dasyclad) are locally concentrated in the uppermost and lowermost parts of the Shu’aiba Formation. Banner and Simmons (1994) considered that the micritic matrix of *Lithocodium* indicates low palaeocurrent velocities (less than 10 cm. sec) and unlikely, therefore, to be common in shallow palaeoenvironments. A more likely habitat would have been in deeper water where it was associated with green algae such as *Salpingoporella dinarica* (Phylum Chlorophyta, Family Dasycladaceae).

The palaeoenvironment favoured by *Lithocodium* is concluded to be warm, fully marine, well-oxygenated, calcium carbonate-rich, mid-shelf sea with possible palaeo-depths of abundant in situ specimens ranging from approximately 15 to 60 m. The *Lithocodium*-dominated facies are typically associated with the benthonic foraminifera *Lenticulina, Pseudocyclammina* and *Trocholina,* echinoid debris and occasional small planktonic foraminifera. It is suggested that such beds developed in moderate water depths, and as they are often underlain by sediments rich in planktonic foraminifera, it is possible that they represent relatively shallower conditions, possibly resulting from aggradation.

Great Pearl Bank Barrier

In the Great Pearl Bank Barrier, an abundance of calcareous red algae is noted in depths less than 10-15 m, where *Lithothamnion*, *Lithophyllum* and *Goniolithon* species bind unconsolidated coral rubble. Encrusting algae occasionally developed into large concretions and form irregular nodules and branches in deeper water.

Corals

Shu’aiba Formation

Corals are only locally well-represented in certain facies of the Aptian Rudist Banks of the Arabian Gulf Region, possibly because of the abundance of nutrients and the turbid water (Gili et al., 1995b). Corals are sparsely distributed as solitary forms, or possibly broken fragments of branched forms, within the main facies of the Shu’aiba Formation, where they are mostly represented within the *Lithocodium aggregatum* and / or lagoonal facies. Although rare, phaceloid and microselenid corals are present within certain facies of the Shu’aiba Formation (personal communication, Skelton, 1996). Localised coral reefs founded upon salt diapirs were described by Alsharhan and Kendall (1991) for the Zerkouh, Mandous, Zibara and Jarn Yaphour fields of Abu Dhabi.

Great Pearl Bank Barrier

Fringing reefs are localised, and distributed close to island shores and along the northern margins of some shoals in the Great Pearl Bank Barrier. Large coral bioherms are reported from the very shallow water around the Qatar Peninsula, islands and in the rubble shoal flanks (Houbolt, 1957). Solitary corals are usually found attached to large molluscs and within the ‘rounded calcarenites’, but are rare within all other sediment types (Houbolt, 1957). Solitary and colonial corals are moderately widespread in the Gulf, but display a low species diversity. The most common types include the branching form *Acropora* spp., the massive form *Porites* spp. and the brain coral *Platygyra* spp. Solitary epifaunal corals include *Heterocyathus aequicostatus, Heteropsammia michelini* and *H.cochlea* (Hughes Clarke and Keij, 1973; personal communication, Thomassin, 1997), and resemble the forms most commonly found in the lagoonal Shu’aiba carbonates.

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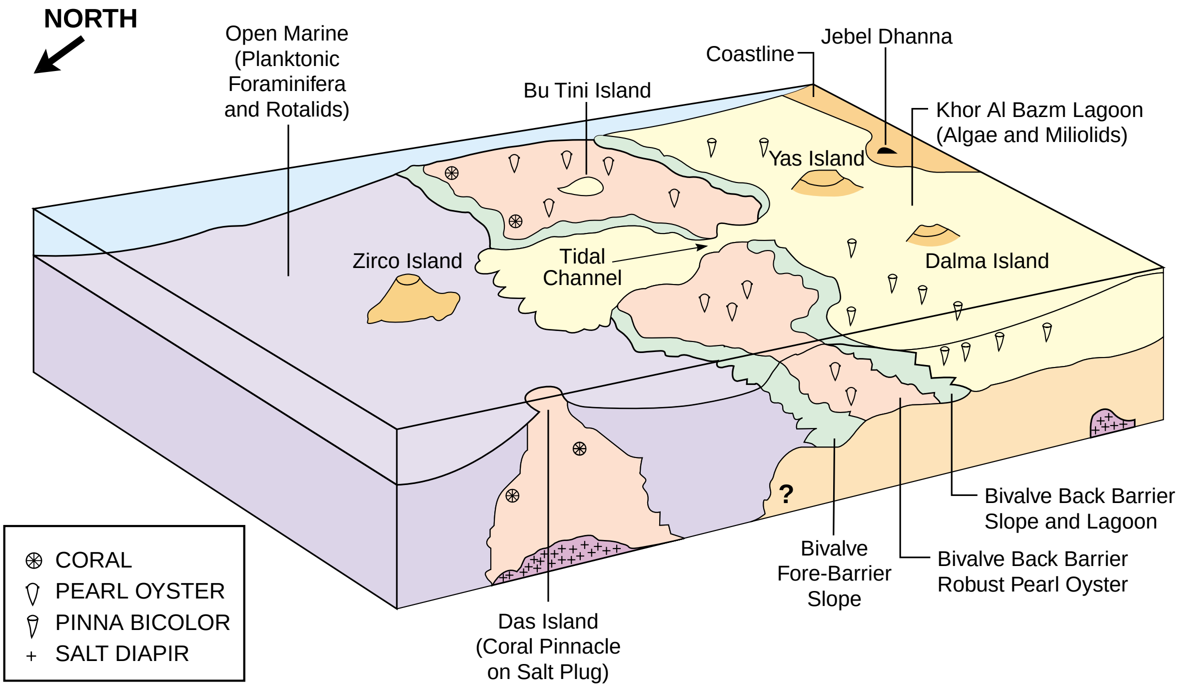
GREAT PEARL BANK BARRIER



APTIAN RUDIST RIMMED PLATFORM

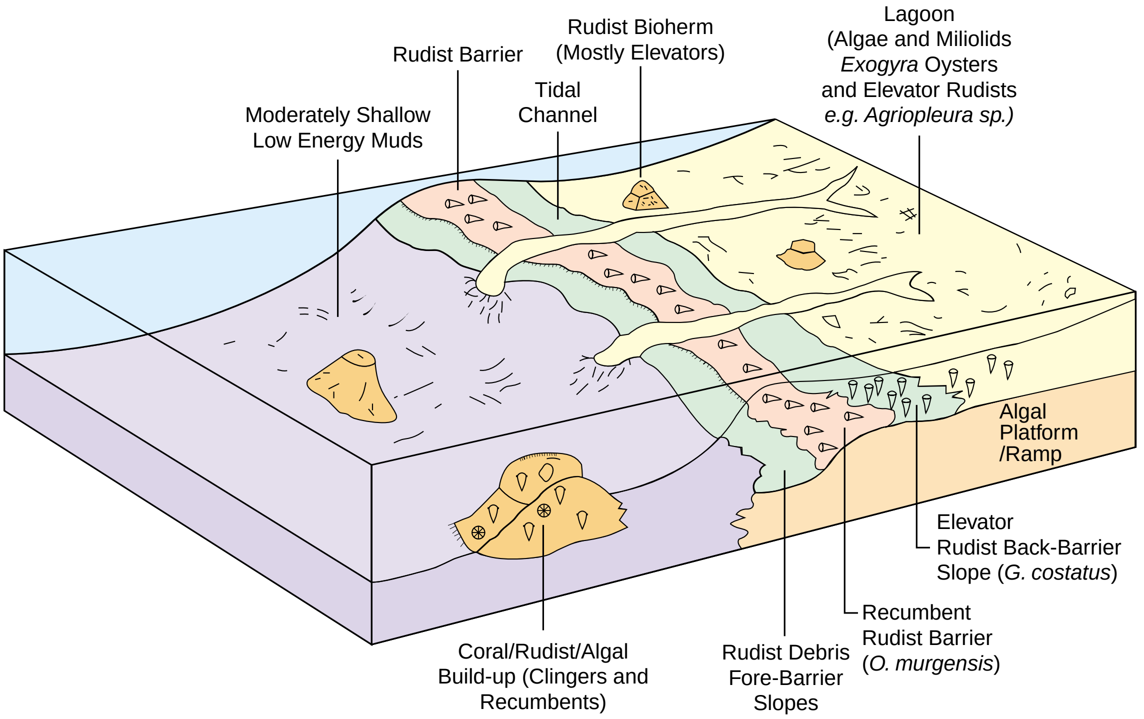


Figure 7: Diagrammatic comparison of biocomponents, energy levels and textures of the Great Pearl Bank and the Aptian rudist bank (Balkema).

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Echinoderms

Shu'aiba Formation

Undifferentiated echinoderm debris is well represented within the Shu'aiba sediments of the Arabian Gulf Region. Echinoderm plates and spines are abundant within the lagoonal and fore-bank deposits, but less well represented within the rudist barrier itself. Finely costate spines are common in the basinal sediments (Hughes, in preparation).

Great Pearl Bank Barrier

Echinoderms are common in the Great Pearl Bank Barrier, but display a low species diversity that is considered to be controlled by salinity. Houbolt (1957) found echinoid spines all over the area, and in all sediment types.

Coccoliths

Shu'aiba Formation

There is limited information on the calcareous nannofossil content of Shu'aiba-associated facies of the Arabian Gulf Region. In the 'upper Shu'aiba' of the Yibal field, Witt and Gokdag (1994) described abundant nannofossils from the pelleted matrix of bioclastic wackestones and packstones.

Great Pearl Bank Barrier

In the Great Pearl Bank Barrier, a sample of carbonate mud collected 85 km offshore Sabkhat Matti consisted of over 70% of the coccolith *Gephyrocapsa oceanica* (Hughes Clarke and Keij, 1973) and would typically indicate considerable open marine influence. Coccoliths are rarely present in the muddy sediments of the nearshore and lagoonal areas of the Abu Dhabi area (Evans et al., 1973). Conditions conducive for such concentrations, however, also include lagoonal and low-energy nearshore conditions (Scholle and Kling, 1972; Conley, 1979; Varol, 1984; Noel et al., 1993). Coccolithophorid communities in marginal seas are dominated by *Gephyrocapsa oceanica* rather than *Emiliania huxleyi* (Okada and Honjo, 1975; Varol, 1984).

SUMMARY

Recent Analogues for Carbonate Geological Formations

The search for modern analogues for fossil carbonates is not new. Comparisons between modern carbonate environments and their fossilised equivalents began with studies of the Great Bahama Banks sediments (Black, 1930; Field, 1930). Bay and Bebout (1983) similarly considered the White Bank sand shoal, on the South Florida carbonate shelf, to be an excellent Holocene analogue to the rudist-bearing Lower Cretaceous, Lower Glen Rose Formation of Texas. Recent Arabian counterparts to the Aptian rudistid banks have, however, received little attention. Surface sediments off the north coast of Qatar have been used as a modern analogue for the American Mississippian and Albian facies belts (Wilson, 1975). Baumann (1983) compared the geological model of the Al Huwaisah oil field of Oman with the localised carbonate shoals around Bu Tini island, in the Arabian Gulf. Burchette and Wright (1992) and Harris and Kowalik (1994) consider the Abu Dhabi area as a modern analogue for a carbonate ramp. Palaeontological and biological information on the Aptian Shu'aiba Formation and the Great Pearl Bank Barrier, respectively, suggest that there are many features in common and support the concept that the Great Pearl Bank Barrier may serve as an appropriate analogue as a depositional model for the Shu'aiba Formation.

The Great Pearl Bank Barrier and Aptian Carbonate Banks

The Great Pearl Bank Barrier is here proposed as a potentially useful analogue for the Aptian rudistid barrier, and as such could assist in both biostratigraphic and sedimentological interpretations of the latter. The 'fan mussels' of the genus *Pinna*, including *P. bicolor* and *P. muricata,* are considered to be potentially valid analogues for the extinct elevator rudists of the Aptian carbonate banks. The palaeoenvironmental preferences of bio-components of both depositional forms are illustrated in Figure 7. Figure 8 illustrates idealised views of the physiographic features of the Aptian rudist-rimmed platform and its similarity to that of the Great Pearl Bank Barrier.

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Similarities

A number of similarities exist between the Great Pearl Bank Barrier and the Aptian rudist banks. The Great Pearl Bank Barrier lies on the south side of a restricted basin; rudistid build-ups of the Shu'aiba Formation are considered to have rimmed the ?southern flank of an intra-shelf basin. The Great Pearl Bank Barrier is a linear form that may have been influenced by faults, although there is no currently available evidence to support this origin. The position, orientation and overall geometry of rudist build-ups of the Shu'aiba Formation are also considered to have been influenced by faulted blocks (Marzouk and El Sattar, 1995). It is suggested that both barriers may be genetically linked with the growth of unusually large, constratal bivalve molluscs and the accumulation and entrapment of sediment of bivalve or associated faunal/floral origin between the bivalve shells.

The Recent *P. bicolor/muricata* is considered to be possibly analogous to the Lower Cretaceous elevator form *Glossomyophorus costatus*. Oysters on the bank crest may occupy an environmental niche analogous to that occupied by the recumbent rudist *Offneria murgensis*. Neither barrier is the product of coral growth and its characteristic constructive architecture, although localised coral may be present. It is probable that a good nutrient supply within the inner-shelf basin of the Aptian and of the present day Arabian Gulf may have preferentially discouraged the establishment of profuse coral growth. Both barriers have provided physical differentiation of otherwise undifferentiated shelf/ramps. Low energy, protected lagoon, moderately high energy back-barrier and fore-barrier regimes have been created by the presence of this wave-energy baffles.

Areal and vertical variations in sediment textures and grain size are a natural response to these energy and water depth variations. Inter-barrier channels are present in the recent barrier, and should be expected in the Aptian barrier complex. In such cases these have enabled the lagoon to maintain its biotic activities, and hence establish specific biological communities. Intra-lagoonal banks are present behind the Recent barrier, and there is some suggestion of their presence in the Aptian barrier. The presence of rare planktonic and deeper marine benthonic foraminifera further offshore in the Arabian Gulf compares well with similar forms in the open marine Bab Member of the Shu'aiba Formation (Aldabal and Alsharhan, 1989).

Possible Dissimilarities

The apparent similarity of the Recent and Aptian mollusc banks, as discussed above, should be considered with a review of the possible dissimilarities. In this attempt to increase our understanding of the extinct Aptian biocomponents, rudists may not physiologically equate with pinnate bivalves, and there are no present day equivalents to the pallial canal-bearing caprinid rudists. Extinct Cretaceous foraminifera, such as *Orbitolina* spp. and *Trocholina* spp, and calcareous algal genera, such as *Lithocodium aggregatum*, *Salpingoporella dinarica* and *Coptocampylodon lineolatus*, may have occupied environments which are not present today, and a direct comparison with living morphological counterparts may be unjustified. Areas of elevated salinity and coastal sabkhas are present in the Arabian Gulf, but there is no indication of such hypersaline sediments associated with the Shu'aiba Formation.

A further dissimilarity which may be of significance is the rate of carbonate productivity in the Aptian compared with the Recent. During the Aptian, the carbonate platform under consideration would have been centered on 5° south (Beydoun, 1991) with semi-arid or humid equatorial conditions under a regime in which the temperature belts were expanded polewards during the 'Cretaceous greenhouse' (Frakes, 1977).

Glennie (1995) suggests that the equatorial 'doldrums' belt may have expanded to 15° south during such greenhouse episodes. Prevailing wind conditions would, therefore, be expected to be weak, and predominantly from the south-east. South-easterly winds are also suggested by Burchette (1993) during the deposition of the Cenomanian-Turonian rudistid carbonates of the Mishrif Formation of the southern Arabian Gulf. The Great Pearl Bank Barrier presently lies near 25° north in the tropical, evaporitic belt, and experiences winds predominantly from the northwest. Such differences may account for any relative distributional differences of the palaeontological and biological components.

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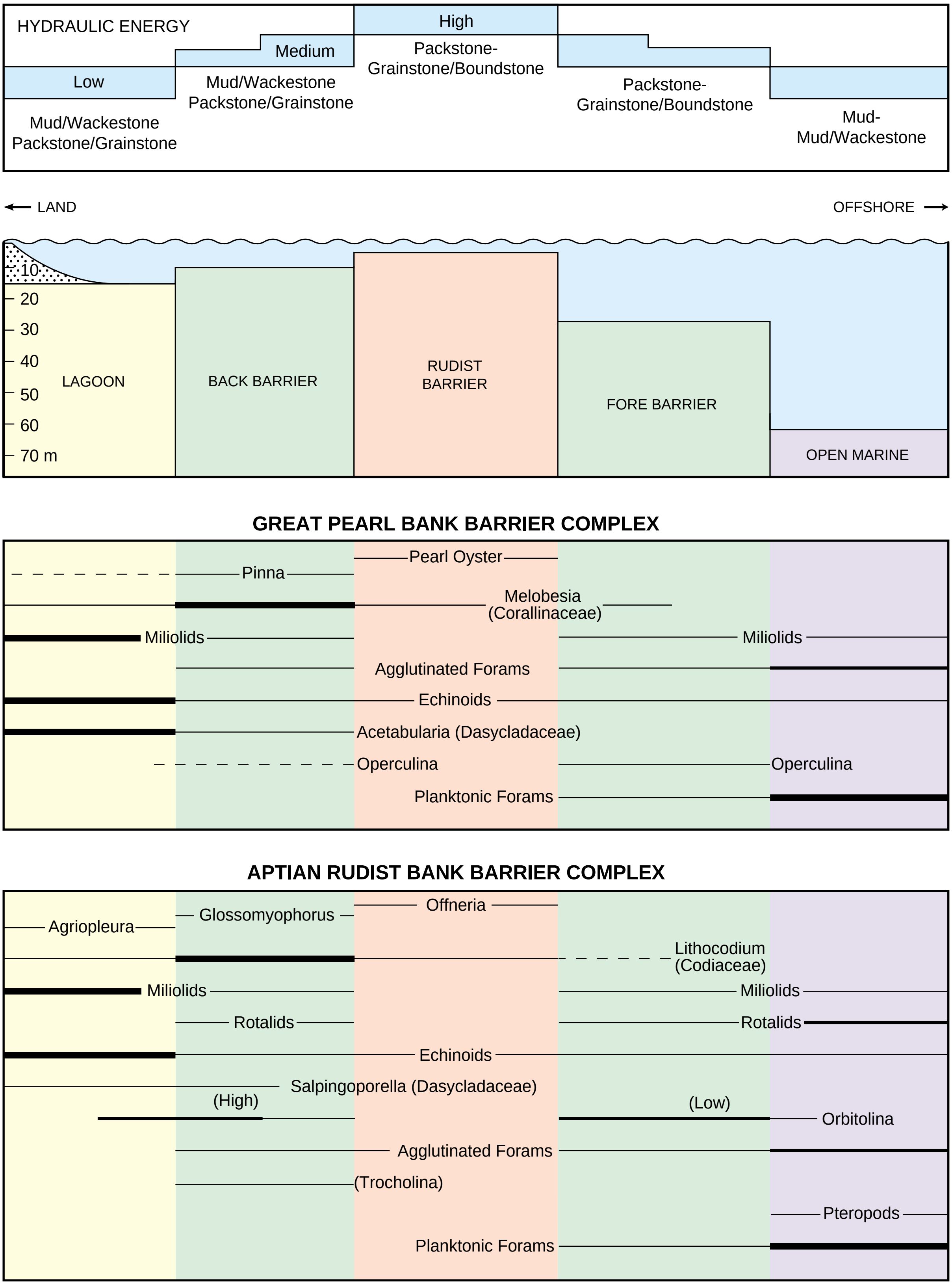

Figure 8: Idealised views of the physiographic features of the Aptian rudist rimmed platform and that of the Great Pearl Bank Barrier to illustrate the similarity between both features (Balkema).

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CONCLUSIONS

The numerous aspects discussed above cannot conclusively validate nor invalidate the comparison between the physiological, biological and sedimentological aspects of the present day and Lower Cretaceous submarine barrier/bank differentiation of the shelf. It is considered here, however, that there are sufficient features of the Great Pearl Bank Barrier that may help visualise and improve our understanding of the distribution of the extinct bioclasts present in the economically valuable hydrocarbon rudistid carbonate reservoirs of the Middle East. Such an aid is of great significance for the Shu'aiba Formation carbonates, where seismic profiles lack clear geometric features (Boichard et al., 1995), and therefore preclude detailed mapping of reservoir facies.

Rudistid hydrocarbon reservoirs of Cretaceous age are being either explored or developed in the Emirates, Oman and Saudi Arabia. Reservoir quality is highly dependent upon the character of the bioclasts, their size and degree of sorting, as well as diagenetic alterations to the original porosity and permeability.

Application of the Great Pearl Bank Barrier as a modern analogue could improve reservoir exploitation by assisting prediction of the lateral extent of good quality, high permeability reservoirs in the coarse-grained rudist banks, back-barrier and fore-barrier regimes. The Great Pearl Bank Barrier physiography would suggest lateral discontinuities within the rudist bank reservoir facies such as the presence of intra- and inter-barrier channels, with possible excellent facies on the lateral flanks of such channels. Coarse-grained debris flows in the muddy open marine regime, which may have been deposited during the process of 'highstand shedding', especially offshore to channels in the rudist barrier, may be locally preserved within the Arabian carbonate reservoirs. Coarser-grained intra-lagoonal rudistid bioherms may exist within the otherwise muddy lagoonal sediments, such as the locally-developed shoals within the lagoon south of the Great Pearl Bank Barrier complex. The back-barrier triangular debris deposits resulting from wave across the Great Pearl Bank Barrier may have fossil coarse-grained equivalents with potentially good porosity. As unfilled medulla cells of *Lithocodium aggregatum* are known to act as a good reservoir facies within the region (Banner et al., 1990), areas of preferential development of this alga should be mapped.

This living laboratory on the doorstep of the Arabian Peninsula should be fully exploited in view of the potentially significant contribution for hydrocarbon exploration and reservoir modelling. Three-dimensional sedimentological facies distribution of this modern analogue could improve the exploration and exploitation of reservoirs developed in rudistid and associated facies within the region. Investigation into the palaeontological and sedimentological history of the Great Pearl Bank Barrier should incorporate analysis of Recent sediments and biocomponents recovered during exploration and development drilling within the region. The University of Aberdeen is currently initiating a study of selected aspects of the Great Pearl Bank Barrier. Biologically-based field analysis of the distribution of pinnate bivalves and oysters should be undertaken to confirm whether they are the major source for the extensive bivalve sand and muddy sand deposits of the barrier, and also to test the validity of their use as analogues for the rudistid bivalves.

If these investigations confirm the analogue hypothesis, then the sedimentological aspects of the Great Pearl Bank Barrier should be studied carefully in order to better understand the lateral and vertical biological and lithological variations observed in the sparse borehole data available for the Shu'aiba Formation. Such a combination of palaeoecology and sedimentology could then be applied to the palaeontological and lithological data from the Shu'aiba Formation, where it would contribute greatly towards an optimum hydrocarbon exploitation strategy within the Shu'aiba and other rudistid reservoirs within the Middle East.

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