Diversity in the geomorphology of shallow-water carbonate depositional systems in the Saudi Arabian Red Sea

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A R T I C L E   I N F O
Abstract
Coral reefs and their associated accumulations of carbonate sediment adopt particularly complex planform geometries atop the coastal shelf of the Saudi Arabian Red Sea. By assembling 95,000 km² of remote sensing data into a GIS, this study aims to relate the morphology of these shallow-water depositional environments to processes that sculpt the coastal zone. A typology that sorts carbonate systems into end-members on the basis of their morphology and relationship to the coastline is developed. The resulting GIS was interrogated for spatial patterns in the distribution and abundance of the end-members. While several depositional morphologies are present throughout the length of the Saudi Arabian Red Sea, the occurrence of others is restricted to narrow regions of latitude. Such differences in distribution can be explained in process-terms by the rift tectonics of the Red Sea basin, spatial variability in the presence of sub-seafloor evaporites, and the input of siliciclastic detritus onto the coastal shelf via wadis. This paper provides a foundation for understanding the morphological diversity of shallow-water carbonate systems in both the modern ocean and rock records.

1. Introduction

The classification of coral reef morphology has a long history, starting with Darwin (1842) who defined the three broad classes ‘fringing reef’, ‘barrier reef’, and ‘atoll’, terms still used to this day. Later works have strived to capture more subtle morphological variations. For example, the typology of Hopley et al. (1989) splits the Great Barrier Reef (GBR) into nine classes while more than a thousand reef types have been defined by Andréfouët et al. (2006) at the global scale. The span in number of classes presented by these studies is indicative of the morphological complexity of coral reef systems. Coral reefs are not by any means made of corals alone. Many other calcareous organisms, both animal and plant, contribute to the volume of a reef (Hart and Kench, 2007). A “carbonate system”, as defined in this paper, therefore considers the shallow-water (<30 m) accumulation of both reefs and associated carbonate sediments. Carbonate systems can be partitioned on the basis of planform morphology of reefs and sediments into distinct ‘morphological end-members’.

The classification of carbonate systems is relevant to a number of disciplines. Coral reef managers often lack knowledge on the diversity of carbonate systems over which they preside, their size, and how carbonate systems are connected with one another (Andréfouët et al., 2006). A knowledge deficit is problematic because the morphology of carbonate systems influences the biogeographic patterns of reef associated species (Bellwood and Hughes, 2001), and is an important consideration in the design of marine protected areas (McLeod et al., 2009). Modern carbonate systems also serve as analogs for understanding ancient carbonate systems (Montaggioni et al., 1986; Rankey, 2002; Purkis et al., 2007; Harris et al., 2011; Purkis et al., 2012a, 2012b; Harris et al., 2013). The definition of carbonate systems can also be used to structure comparative analyses. For example, carbonate systems that are similar in their appearance may be expected to exhibit similar carbonate production values (Perry et al., 2008; Leonard and Woodroffe, 2013). Finally, carbonate system morphology provides much needed context for more detailed mapping of seabed habitats at fine spatial resolution (Andréfouët et al., 2006; Rowlands et al., 2012).

Diversity in the morphology of carbonate systems can sometimes be explained in terms of underlying tectonics, the action of wind, waves and currents, changes in the position of sea-level, antecedent topography, and climate (Darwin, 1842; Fairbridge, 1967; Maxwell, 1970; Purdy, 1974; Hopley, 1982; Bosence, 2005; Purkis et al., 2010; Harris et al., 2011; Purkis et al., 2012a; Leonard and Woodroffe, 2013). The morphology of a carbonate system is not static through time. For instance, considering the carbonate systems of the Australian GBR, Hopley (1982) recognizes an evolutionary progression through different morphological end-members from juvenile (unmodified antecedent platforms, submerged reefs, irregular patch reefs), to mature (crescentic reefs, lagoonal reefs) and finally to senile (planar reefs). Morphology is therefore a temporally dynamic property of a carbonate system.

This study considers the morphological diversity of carbonate depositional systems in the Saudi Arabian Red Sea (Fig. 1), which Bosence
broadly explains in terms of the input of siliciclastics as controlled by the hyper-arid Arabian climate, combined with the action of rift-related tectonics. Despite the relatively small size of the Red Sea, a wide variety of carbonate systems have been documented (Sheppard et al., 1992; Dullo and Montaggioni, 1998; Bosence, 2005). Nonetheless, there has not been an effort to collate this morphological diversity into a logical scheme of classification, nor to analyze the spatial distribution of this morphological diversity, as, for example, has been undertaken in the GBR (Hopley et al., 1989) and Torres Strait (Leon and Woodroffe, 2013), Australia.

This study will firstly propose a robust typology for identifying morphological end-members of the carbonate systems of the Saudi

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Fig. 1. a) The Red Sea basin. Note rotated north axis. Letters and boxes indicate position of image subsets shown below; b) subsets of QuickBird satellite imagery that illustrates the sixteen morphological end-members of the Saudi Arabian Red Sea typology (Fig. 2). In each image, the horizontal scale bar represents 1 km. First row (A–E) are carbonate systems with an ‘Attached Form’, second row (F–I) are carbonate systems in the ‘Tower Group’, third row (J–M) are carbonate systems in the ‘Platform Group with an Aggraded Edge’ and forth row (N–P) are carbonate systems in the ‘Platform Group with a Non-aggraded Edge’. Names of Carbonate Systems in key are abbreviated; see Fig. 2 for details.
Arabian Red Sea. Second, through the development of a geographic information system (GIS), the spatial distribution of the morphological end-members will be quantitatively analyzed for trends and patterns. Thirdly, the spatial distribution of the coastal shelf, sub-seafloor evaporite thickness, and terrestrial drainage basins feeding into the Saudi Arabian Red Sea are mapped into the GIS. Lastly, this study aims to explain the spatial distribution of the carbonate system morphological end-members in process-terms.

2. Material and methods

2.1. Development of a typology for Saudi Arabian Red Sea carbonate systems

To quantify the diversity of carbonate systems, a typology that sorts Saudi Arabian Red Sea carbonate systems into morphological end-members is developed (Figs. 1 and 2). This contrasts typologies geared to different goals, such as Andréfouët et al.’s (2001) hydrodynamic classification of Pacific atolls. The typology of this paper is built upon the visual interpretation of satellite and aerial imagery (Fig. 1). Remote sensing data have been shown to be a viable and efficient means to classify carbonate systems in other regions (Hopley et al., 1989; Purkis and Pasterkamp, 2004; Andréfouët et al., 2006; Harris et al., 2011; Purkis et al., 2012a; Leon and Woodroffe, 2013). Because the waters of the Red Sea are so clear, seabed morphology can be appraised down to depths of at least 30 m using satellite imagery. This study draws on a 95,000 km² collation of QuickBird (2.5 m pixel; DigitalGlobe) and Landsat (30 m pixel; USGS) satellite imagery acquired under clear and calm sea conditions (Bruckner et al., 2011; Rowlands et al., 2012). This vast archive of remote sensing imagery encompasses all shallow water carbonate systems of the Saudi Arabian Red Sea. As detailed by Bruckner et al. (2011), in the rare cases where the quality of these images did not allow the shallow seabed to be appraised, the clarity of the imagery was improved through the processing of atmospheric and water surface effects. The satellite data were augmented with the public-domain imagery available as an ESRI ArcGIS base-layer and through Google Earth, as well as georeferenced British and Saudi Arabian nautical charts.

The typology of Saudi Arabian Red Sea carbonate systems takes the form of a decision tree (Fig. 2). The criteria for branch-points in the tree are objective and reproducible. Criteria include differences in the spectral content and texture of satellite image pixels, measurements of the size and shape of carbonate systems as measured in the GIS, and water depth assessed from nautical charts. At the top of the decision tree are two ‘Forms’, which split to four ‘Groups’, under which nest the sixteen morphological end-members (Fig. 1b).

The logic of the decision tree proceeds as follows (Fig. 2). The ‘edge’ of a carbonate system is defined by its boundary with either land or

Fig. 2. Typology of Saudi Arabian Red Sea Carbonate Systems. Boxed text represents different types of Carbonate System, while unboxed text is a decision point in the typology. Shaded boxes represent the sixteen morphological end-members of the decision tree (Fig. 1).
deep water. The system’s ‘interior’ lies inboard of the edge. ‘Attached’ or ‘Detached’ represents a logical place to start the typological hierarchy since it distinguishes systems where the main geological foundation – coastal shallows – is apparent, from offshore systems that require an antecedent platform or mechanism of geologic uplift to explain their formation. The distinction also separates attached systems which receive terrestrial sediments from detached systems which do not. A carbonate system is defined as having a ‘Detached Form’ if separated from a landmass by water deeper than 50 m, the most appropriate contour seaward edge of the system and the coastline. The reef terrace may therefore encompass a number of recognizable features such as reef crests, back-reefs, shallow lagoons, patch reefs, small islands, and sand cays. The term ‘fringing’ is used in naming both narrow system morphological end-members (Fringing, Fringing with embayment), which have a simple morphology consistent with the common use of the term (Smithers, 2011). Various thresholds were tested and 2 km was found to be the most logical to differentiate these simple fringing morphologies in the GIS from more complex forms. Though both ‘Dendritic Systems’ and ‘Unorganized Systems’ exhibit shallow water extending outboard from the coastline, in the latter case, reef growth is less pronounced and often punctuated by channels running parallel to the coastline.

Within the typology (Fig. 2), carbonate systems with a Detached Form fall into two groups. Detached Form carbonate systems that are circular in plan-view fall into the ‘Tower Group’. To facilitate rapid assessment of systems in the GIS, circular was defined as having rounded edges and a ratio of length to width of <3. The remaining carbonate systems with a Detached Form are encompassed by the ‘Platform Group’. Carbonate systems in both the Tower and the Platform Groups fit into the typology based on the characteristics of their edge and interior. The approach to classifying morphological end-members outlined in this paper therefore follows that of Hopley (1982) and Harris and Vlascwinkel (2008) from whom many terms in this work are taken. For example, the term “aggraded” relates to the situation where reef and/or sediment has filled the available accommodation space and built to, or above, sea-level. Features of a carbonate system that are built to, or above, sea-level. Features of a carbonate system that are and/or sediment has filled the available accommodation space and built to, or above, sea-level. Features of a carbonate system that are aggraded include reef crests, shallow reef flats, back reefs, small islands and sand cays. Because of the differential absorption of light through the water column, aggraded coral reef frameworks and sediments can be identified by a strong spectral response in the red band of the satellite imagery. Aggraded coral frameworks appear honey-brown to green in color in an image composed of the red, green and blue satellite bands. Breaking waves may indicate aggraded structure, but since our images were acquired under clear calm sea conditions, they are not always present and therefore not a necessary criterion. Shallow (<1 m) water depths from nautical charts provide further evidence for the occurrence of aggraded coral frameworks and sediments.

Morphological end-members with a Detached Form are identified based on how much and where (edge vs. interior) the system that has aggraded. The term ‘fully-aggraded’ describes cases where >80% of the carbonate system’s edge or interior has built to sea-level. Occurrences of deep water (greater than ~15 m), such as narrow channels and reentrants, are permitted within areas of seabed classified as fully-aggraded provided deep waters do not occupy >20% of the total system area. ‘Partially-aggraded’ describes cases where between 30% and 80% of the carbonate system’s edge or interior has built to sea-level. The occurrence of aggraded coral framework and sediment is patchy and often interspersed with deep water channels, which may attain widths of several hundred meters. ‘Non-aggraded’ describes cases where <30% of the carbonate system’s edge or interior has built to sea-level. Use of the term ‘ribbon’ to describe ‘Ribbon Platform Systems’, is consistent with the “linear, long, winding” aggraded central axis (Andréfouët and Cabioch, 2011).

To illustrate the use of the typology, consider how the following carbonate system would be handled in the decision tree (Fig. 2). The system is separated from land by a structural low of several hundred meters in depth and is therefore deemed in the typology to have a Detached Form. The system is not circular and therefore it falls into the Platform Group. Because all the edges of this carbonate system are fully-aggraded but the interior is only partially-aggraded, its morphological end-member classification is a ‘Platform System with Lagoonal Patches’ (Fig. 1b-L).

2.2. Spatial distribution of carbonate systems

On the basis of the typology, carbonate systems throughout the Saudi Arabian Red Sea were mapped from satellite imagery and nautical charts using a 1 km × 1 km grid (Fig. 3). This grid is hereafter referred to as being composed of ‘GIS grid cells’. Only GIS grid cells intersecting a carbonate system were retained for analysis. This process yielded 20,505 cells across the extent of the Saudi Arabian Red Sea. The GIS grid was overlain on the satellite imagery and carbonate systems were then classified using the typology (Fig. 2). Distance attributes critical to decision points and thresholds were measured in the GIS. A numerical code specific to the type of carbonate system was then appended to each GIS grid cell. When a GIS grid cell overlaid multiple morphological end-members, the numerical code of the system occupying the majority of that grid cell was appended as an attribute. This situation was rare, affecting only 4.3% of attached system grid cells and 0.7% detached system cells.

The abundance (km2) and distribution of carbonate systems was assessed through a tally of the GIS grid cells. An analysis of the distribution of Saudi Arabian Red Sea carbonate systems was structured according to width of the coastal shelf. The coastal shelf is defined as lying inboard of the 500 m depth contour as measured from nautical charts (Figs. 4 and 5). On the basis of width, the shelf breaks into three logical ‘precincts’, which are denoted A, B, and C. The coastal shelf in precinct A has a mean width of 4.4 km (SD: 1.0 km); precinct B has a mean width of 27.9 km (SD: 12.8 km); precinct C has a mean width of 129.2 km (SD: 10.2 km). Each shelf-width precinct was sub-divided into ‘sectors’ of approximately equal N–S length (75 km ± 3 km). The selected N–S length reflects a compromise that allows most carbonate systems to be encompassed by a sector in their entirety, yet small enough to identify distinct latitudinal patterns. Sectors extend from the coastline to the seaward edge of the coastal shelf. Patterns in the distribution of carbonate systems across the coastal shelf were assessed by measuring the distance of each GIS grid cell in a carbonate system from the coastline. Satellite imagery was consulted to digitize the coastline, a process that yielded a ‘coastline vector’. The coastline vector was resampled with nodes placed every 250 m along its length. The distance of each GIS
grid cell from the coast was calculated as the minimum distance between the centroid of a GIS grid cell and a node of the coastline vector and appended as an attribute to each GIS grid cell.

2.3. Factors creating shallow-water carbonate depositional environments in the Red Sea

The Red Sea is a rift basin flanked by mountains and the climate of the region is hyper-arid. In common with other tropical seas, carbonate production is most productive where the seabed is shallower than ~30 m (Kleypas et al., 1999). Bosence (2005) identifies three seabed configurations as important in the formation of Red Sea carbonate systems; (1) fault-block, (2) salt diapir and (3) delta-top.

As the Red Sea rifts, “fault-blocks” slip back towards the axial trough and tilt (Bosence, 2005), producing bathymetric highs. “Salt diapirism” describes the subsurface movement of evaporite rock formations. Red Sea evaporites, known as the Zeit and South Gharib formations, were laid down during the Mid- and Upper-Miocene (16.4–5.3 Ma) during a period when the Red Sea basin was restricted at its southern limit, the Bab el Mandeb (Mitchell et al., 1992). These evaporites are sandwiched beneath Pliocene siliciclastics, above which sit the Pleistocene and Holocene carbonates (Brown, 1970; Mitchell et al., 1992; Bosence et al., 1998). Evaporites, which are less dense than the rock layers above them, tend to rise upwards and distort or pierce the overlying strata, generating bathymetric highs. These highs, termed “diapirs” tend to have a domed morphology and may be topped by islands (Bosence, 2005). Areas where seabed morphology is controlled by salt diapirs may consist of complex arrangements of shallow water separated by deep structural lows (Bosence et al., 1998). In the cases where salt diapirs have pierced the seabed and are subaerially exposed, as is common during sea-level low-stands, meteoric dissolution of the evaporite rock may lead to the formation of a void through collapse. The resultant depressions, termed “dolines”, have characteristic circular or semi-circular shapes (Fig. 5b; Bosence, 2005). Boreholes have been drilled throughout the Red Sea that extend into, and in most cases through, the Miocene evaporite layer (Fig. 5a; Mitchell et al., 1992;
Bosence et al., 1998). Mitchell et al. (1992) arrange cores from these boreholes chronologically based on ageing of samples and the depth of the pre-evaporite “basement”.

Using the GIS database, several lines of evidence were developed to assess the distribution of evaporite in the Saudi Arabian Red Sea. Stratal evaporite thickness underlying the mapped carbonate systems was estimated using an inverse distance weighting interpolation of the vertical thickness of these rock formations measured within published exploratory bores (Mitchell et al., 1992; Bosence et al., 1998). This interpolation produces a continuous map layer within the GIS (Fig. 4a). Bores in Yemen were included to extend the evaporite thickness map layer to the south and through the entire Saudi Arabian Red Sea. As further evidence for the spatial distribution of evaporite, dolines were identified in the satellite imagery and their position entered into the GIS.

The “delta-top” carbonate systems defined by Bosence (2005) occur where terrestrial siliciclastics accumulate in the coastal zone to form topographic highs that extend into the photic zone. If sufficiently undisturbed (10s–100s years; Hayward, 1982), these highs may host considerable carbonate deposits. Siliciclastics are mobilized during heavy rainfall and runoff events and are transported seaward within alluvial flows. The word ‘wadi’ is an Arabic term used to describe a valley or dry ephemeral riverbed. In the hyper-arid Arabian climate, wadis typically only contain water during heavy rain events. Rainfall within a drainage basin is channeled through a network of wadis on its way to the sea (Fig. 6a). Neighboring drainage basins can vary substantially in terms of area, relief and bedrock type (Blair and McPherson, 2009). To estimate the potential for sedimentary input, drainage basins of wadis feeding into the Saudi Arabian Red Sea were mapped into the GIS. This task was accomplished using the ESRI ArcGIS hydrology tool box applied to ASTER GDEM v2 satellite-derived elevation data (product of METI and NASA; Fig. 6c). Within the GIS, drainage basins were defined for wadi systems measuring >5 km in length. The planar area, gradients, and elevations encompassed by each drainage basin were assessed and tallied as attributes within the GIS.

Lineated Systems are comprised of repeating linear coral reefs aligned parallel to the coastline (Fig. 1b-E). Analysis of satellite and aerial imagery in the North of Saudi Arabia (28°09′ N, 31°48′ E) revealed a terrestrial morphology, dune ridges, with similar repeating linear units. Dune ridges occur sporadically throughout the length of Western Saudi Arabia (Jado and Zötl, 1984), and when submerged, have been shown to be the nucleating point for coral reefs in other seas (Banks et al., 2007). To test the hypothesis that submerged sand dunes might underlie Lineated Systems, the crest-to-crest distance of the parallel coral reefs was measured and compared to the crest-to-crest distance of terrestrial dune ridges. These measurements were made along transects, overlaid on satellite imagery, and running normal to the long axis of the dunes and coral reefs. Four, 5 km long, transects were laid across dune systems, while eleven transects, extending from the coastline to the outermost coral reef crest were placed across Lineated Systems.

3. Results

3.1. Geological influences on shallow-water carbonate depositional environments in the Saudi Arabian Red Sea

The evaporite layer is distributed unevenly beneath the coastal shelf of the Saudi Arabian Red Sea (Fig. 5a). The thickest evaporites are located beneath the Salif-2 borehole offshore of Yemen, to the south of Saudi Arabia (Bosence et al., 1998). An approximately 1 km thick layer of evaporite underlies precinct C, in the south of Saudi Arabia. A 2 km

![Diagram of a drainage basin feeding an alluvial fan](image1)

**Fig. 6.** a) Diagram of a drainage basin feeding an alluvial fan (adapted from Blair and McPherson, 2009). The word ‘wadi’ is an Arabic term used to describe a valley or a dry ephemeral riverbed; b) Examples of alluvial fans found just inland of the Saudi Arabian Red Sea coast. Black dashed outline depicts separate alluvial fan systems; c) Distribution of Saudi Arabian drainage basins mapped in the study GIS. Those drainage basins associated with Dendritic Systems (e.g. Fig. 1b image C) are highlighted as shown in key. Within the GIS the Saudi Arabian Red Sea is split into three shelf-width precincts (A, B, C) divided into sectors of approximate equal length (x-axis).
thick evaporite layer underlies the Al Kurmah borehole in sector B1 (Mitchell et al., 1992). In sector B1, between the Al Kurmah and Barquan-1 boreholes, the evaporite layer is < 100 m thick. South of the Barquan-1 borehole, in sectors B2–B13, the evaporite layer ranges in thickness from 100 m to 500 m. The distribution of dolines recorded in the GIS is in good accordance with the interpolated distribution of sub-seabed evaporite (Fig. 5b). The greatest number of dolines is seen in the mid-coastal shelf in sectors C2–C8 (Farasan Banks and Farasan Islands). Though a doline is evident in the satellite imagery in sector B1 near the Al Kurmah borehole, dolines are otherwise absent in precinct B where the evaporite layer is thinner than 500 m.

A total of 2120 drainage basins were mapped within the GIS, with a combined area of 258,574 km² (Fig. 6c). 80% of this area is drained by only 10% of the drainage basins. In precinct A (Gulf of Aqaba), the northern mountain range abuts the coastline. Drainage basins entering precinct A are small (mean area: 15 km²; SD: 75 km²). However, mountains within these drainage basins attain heights of 1863 m and their slopes are steep, with gradients of up to 56°. In precincts B and C, 87% of the drainage basins have an area < 15 km², but these basins are restricted to the coastal plain where slopes are gentle (mean gradient: 3°; SD: 1°). The remaining 13% of drainage basins in precincts B and C are much larger (mean area: 930 km²; SD: 6416 km²). These large drainage basins extend into the coastal mountain belt, and elevations attain 2989 m, while slopes have gradients of up to 69°. The largest drainage basin has an area of 104,977 km² and feeds into the Saudi Arabian Red Sea in sector B5, approximately 200 km north of the port of Yanbu, in a region named Al Wajh.

The distance between terrestrial dune crests ranged from 80 m to 426 m, and had a mean of 231 m (SD: 91 m). By contrast, the distance between submerged reef crests in Lineated Systems ranged from 322 m to 2300 m, with a mean of 1260 m (SD: 662 m).

3.2. Abundance and distribution of carbonate systems in the Saudi Arabian Red Sea

The latitudinal distribution of carbonate systems through the Saudi Arabian Red Sea is highly variable (Fig. 7). Carbonate systems in the Narrow Group (Fringing; Fringing with embayment) are found in all sectors of all precincts. Indeed, carbonate systems in precinct A are entirely of the Narrow Group. Other morphological end-members are restricted to distinct regions of the Red Sea. For instance, Dendritic Systems are restricted to the northern half of precinct B, while Lineated Systems are found in the southern half of precinct B, and the first sector (C1) of precinct C. Unorganized Systems are found in two clusters in the north of precinct B (sectors B1 and B5–B7) and throughout most of precinct C. Over 97% of carbonate systems in the Tower Group are found outside of precinct C (sectors C2–C5). The few carbonate systems in the Tower Group found outside of precinct C (sectors B6 and B7) are exclusively of the Planar type. Partially-aggraded Platform Systems are only found in precinct C in the very south of the Saudi Red Sea (sectors C3–C8). Planar Platform Systems are found throughout much of precincts B and C, where mountains within these drainage basins attain heights of 1863 m and their slopes are steep, with gradients of up to 69°. The largest of these drainage basins extend into the coastal mountain belt, and elevations attain 2989 m, while slopes have gradients of up to 66°. These large drainage basins attain an area of 104,977 km² and feeds into the Saudi Arabian Red Sea in sector B5, approximately 200 km north of the port of Yanbu, in a region named Al Wajh.

The area occupied by each of the sixteen morphological end-members is variable (Fig. 8). Attached Forms are slightly more abundant than Detached. The Expansive Group accounts for 66% of carbonate systems with an Attached Form. However, this area abundance is spread across fewer distinct systems. Carbonate systems in the Platform Group account for 96% of Detached Forms. Platforms with Non-aggraded Edges account for 67% of systems in the Platform Group. Three of the sixteen morphological end-members account for half of all carbonate systems, (1) Unorganized Systems, (2) Partially-aggraded Platform Systems and (3) Non-aggraded Platform Systems.
The combined area of all carbonate systems is highest in precinct C of the Saudi Red Sea (Fig. 9a). This shelf precinct corresponds to a widening of the coastal shelf (Fig. 4). The proportion of the continental shelf occupied by carbonate systems is variable by latitude and shows no trend of increasing to the south (Fig. 8a); depending on the sector, carbonate systems occupy between 22% and 85% of shelf area. Sectors with a high proportion of the shelf occupied tend also to have large carbonate systems in the Expansive Group (Fig. 7). In precincts A and B, the outermost carbonate systems are found closer to the seaward edge of the coastal shelf (Fig. 9b). In precinct C, the shelf is wide, extending to between 70 km and 125 km offshore. Though carbonate systems in precinct C are found up to 111 km offshore, the majority of systems are located mid-shelf between 25 km and 75 km from the coast.

System morphology stratifies with distance offshore. Trends and patterns in cross-shelf distribution are most apparent when carbonate systems are analyzed in terms of Groups rather than the sixteen morphological end-members of the Saudi Arabian Red Sea typology (Fig. 2). As is expected by their definition, the Narrow Group of carbonate systems is found closest to the coastline in most sectors (Fig. 9b). The exception to this rule is found in sector C2 where, due to the presence of small offshore islands, narrow systems tend to be found farther from the coastline. Moving offshore in precincts B and C, the Narrow Group is followed by the Expansive Group, which is in turn followed by carbonate systems in the Platform Group with Non-aggradated Edges. In most sectors, carbonate systems in the Platform Group with Aggradated Edges are situated furthest offshore. The exception to this trend occurs in sectors B6–B7 and sectors C2–C5 (Farasan Banks; Fig. 7), where the offshore progression ends with the Tower Group of carbonate systems. In sectors C7 and C8 (Farasan Islands; Fig. 7), the Narrow and Expansive Groups of carbonate system are found 30 km to 60 km offshore (Fig. 9b). Carbonate systems in the Tower Group, and those of the Platform Group with Aggradated Edges, are absent from the two southernmost sectors of the Red Sea. In sectors C7 and C8 the offshore progression therefore ends with carbonate systems in the Platform Group with Non-aggradated Edges.

4. Discussion

This study identifies several trends in the spatial distribution and abundance of Saudi Arabian Red Sea carbonate systems. This insight is achieved by developing a typology of sixteen morphological end-members and then mapping the occurrence of these systems within a GIS (Figs. 1 and 2). Many of the systems mapped for Saudi Arabia have a similar morphology to those identified in the GBR and Torres Strait, Australia (Hopley, 1982; Hopley et al., 1989; Leon and Woodroffe, 2013). The greater number of morphological end-members in the Red Sea, as compared to Australia, can be accounted for by a higher level of diversity of Attached Forms, as well as our recognition of the Tower Group of carbonate systems as distinct from the Platform Group. In Hopley’s (1982) terms, a similar spectrum of maturity is visible in this study from juvenile (non-aggradated systems), to mature (crescentic and lagoonal platform/tower systems), and senile morphological end-members (planar platform/tower systems).

Variation in relative sea-level over geological time-scales facilitates or resets the evolutionary development of a carbonate system (Hopley, 1982). If carbonate budgets are positive and relative sea-level is stable, then systems can be expected to fill available accommodation space and transition towards more mature morphologies. Records of sea-level along the Red Sea margins are incomplete, but often depart from a simple eustatic model by tens of meters (Sheppard et al., 1992;
Detached Forms nucleated atop fault-blocks. Most morphological end-discriminate between Detached Forms nucleated atop salt diapirs and diapir and (3) delta-top. The typology of the Saudi Arabian Red Sea in the formation of Red Sea carbonate systems; (1) fault-block, (2) salt host shallow-water carbonate depositional systems (Figs. 4 and 6; ous topographic highs in precinct C that extend into the photic zone and (Fig. 5), salt diapirism seems the most likely factor creating the numer-
Based on the distribution of evaporite and the presence of dolines
associated with precinct C where the underlying evaporite is thick.

The occurrence of carbonate systems varies through the latitudinal
range described in the GIS (Fig. 7), while the areal abundance of carbon-
ate systems increases from north to south in the Saudi Arabian Red Sea
(Fig. 9a). Low winter temperature has been proposed as a reason for de-
clining reef growth to the north in other high latitude coral reef settings
(Kleyapas et al., 1999). Periodic cold winds blowing off Eastern Europe
lower sea surface temperatures in the Red Sea (Sheppard et al., 1992; Purkis et al., 2010). On tidal flats in the Gulf of Aqaba (precinct A), tem-
perature lows of 7 °C have been recorded, while a low of 14.5 °C has
been recorded as far south as Jeddah (sector B12; Sheppard et al., 1992). However, unlike the much shallower Arabian Gulf where coral
reef growth is reset by cold water anomalies on a decadal basis
(Purkis and RiegI, 2005), cold water events in the Red Sea tend to be
short in duration. The thermal environment of the Red Sea is buffered
by vertical mixing from perennially warm deep waters (Sheppard et al., 1992). As Hopley et al. (2007) documented for the GBR, the abun-
dance of Saudi Arabian Red Sea carbonate systems is closely associated
with the width of the coastal shelf (Fig. 9).

Bosence (2005) identifies three seabed configurations as important
in the formation of Red Sea carbonate systems; (1) fault-block, (2) salt
diapir and (3) delta-top. The typology of the Saudi Arabian Red Sea
carbonate systems presented in this paper (Figs. 1 and 2) is unable to
discriminate between Detached Forms nucleated atop salt diapirs and Detached Forms nucleated atop fault-blocks. Most morphological end-
members that are found in precinct C, where sub-seafloor evaporite is
thick, are also found in precinct B where the evaporite layer is thin
(Figs. 5a and 6b). The Tower Group of carbonate systems and Partially-aggregated Platform Systems are, by contrast, preferentially
associated with precinct C where the underlying evaporite is thick.
Based on the distribution of evaporite and the presence of dolines
(Fig. 5), salt diapirism seems the most likely factor creating the numerous
topographic highs in precinct C that extend into the photic zone and host shallow-water carbonate depositional systems (Figs. 4 and 6; Gúilcher, 1988; Sheppard et al., 1992). Salt diapirism has not led to, in the terms of Hopley (1982), systems that are either more or less mature. Rather, in the Saudi Arabian Red Sea it seems to have increased the diversity of carbonate systems present.

The interpolated evaporite thickness GIS layer informs on the latit-
dinal variation in the distribution of sub-seafloor evaporite (Fig. 5a).
However, given the spacing between the available boreholes, our inter-
polation is not deemed to capture the variability in evaporite thickness
across the coastal shelf. The cross-shelf patterns in evaporite thickness
are better known for the western Red Sea shelf, where Mitchell et al.
(1992) document an area at equivalent latitude to the Farasan Islands
(sectors C7–C8). It is worthwhile considering the cross-shelf transect
described by Mitchell et al. (1992) that runs from the coastline of Eritrea, beneath the Dahlab Islands (Fig. 7), and on towards the deep Red Sea axial trough. Along this transect, the evaporite layer steeply
thickens away from the Eritrean coast, before passing into a “salt-
zone” at the main axis of the evaporite basin (Mitchell et al., 1992). In this salt-zone, evaporite thickness ranges from 2000 m to 4000 m. To-
wards the axial trough, evaporite “thins and interfingers with volcanics in a transitional zone” (Mitchell et al., 1992). Although there are no
boreholes in the mid- and outer-coastal shelf of the Farasan Islands
and Farasan Banks (Fig. 5a; precinct C), the density of dolines in these
areas suggests the presence of a significant salt basin — an “eastern
salt-zone” (Fig. 5b). Most carbonate systems in the Tower Group are
located along the outer edge of this eastern salt zone and may be asso-
ciated with a similar thinning of the underlying evaporite layer. Uplifted
through salt diapirism, the Farasan Islands increase the length of coast-
line in sectors C7 and C8 by a factor of four. This increase in the length of coastline accounts for an almost doubling of the area occupied by carbonate systems with an Attached Form in sectors C7 and C8, and the distribution of these systems tens of kilometers offshore (Fig. 9a).

The three morphological end-members that comprise the Expansive
Group, Dendritic Systems, Unorganized Systems, and Lineated Systems
occur in different regions of the Saudi Red Sea (Fig. 7). Different processes of formation can account for these differences in latitudinal distribution. The delta-top model proposed by Bosence (2005) considers the spatially variable delivery of terrestrial siliciclastic sediment into the Red Sea. The delta-top model should not be confused with the “deltaic” systems identified by Maxwell (1970) in the Pompey Complex of the GBR which form atop debris accumulated by ebb and flow tidal deltas. Of all the carbonate systems in the Expansive Group, Dendritic Systems bear the closest resemblance to alluvial features. These systems project offshore in a manner reminiscent of “bird’s foot” river deltas (Fig. 1b image C; Coleman et al., 1998). Bird’s foot river deltas tend to be associated with large river channels and the continuous delivery of fine
sediment (Blair and McPherson, 1994). Such persistent sediment loads
have been shown to retard coral reef development (Fabricius, 2005).
However, in the hyper-arid Middle East, alluvial flows are of a different type. Red Sea wadi systems only activate episemically, typically during rare but intense rain storms (Dullo and Montaggioni, 1998). Such punished outbursts of activity, with long periods of stasis in between, repre-
sent a highly episodic delivery of siliciclastics out of the wadi mouth
and into the Red Sea. Coral communities may be temporarily destroyed through sediment stress at the time of such outbursts, but given that the violent alluvial disturbance is rare (occurring at time scales of hundreds of years — Hayward, 1982) the coral community is able to recover and persist (Dullo and Montaggioni, 1998).

The outflow and accumulation of siliciclastics creates bathymetric
highs on the coastal shelf. These highs take the form of channel levees
and debris deposits of alluvial fans (Fig. 6a and b) which represent a vi-
able substrate for the initiation of coral growth (Perry and Smithers,
2009). The morphological similarity between the Dendritic Systems
identified in the typology and alluvial fans suggests that the two may be
linked in process-terms (Figs. 1b image C, 5c). For this link to be
feasible, there are several conditions that must be satisfied. First, the
morphology of the fan must be preserved in a submerged form atop
the coastal shelf, such as would occur if deposition coincides with a
sea-level low-stand. Second, the drainage basin landward of the fan
must be large and steep, such that it is able to feed sufficient volume
of sediment to build a coherent system of channel levees. Third, episodic
heavy rainfall is required to mobilize quantities of sediment into the fan
system. Finally, the alluvial fan must have sufficient area on the coastal
shelf in which to form (Fig. 6a). There are several large (>1000 km²)
drainage basins with steep (>25°) slope gradients that feed into the Red Sea along the Saudi Arabian coast (Fig. 6c). The GIS reveals that
Dendritic Systems only occur in the northern half of precinct B
(Fig. 7). While hyper-arid today, during the Mid Holocene, rainfall in
the Red Sea was greater in the north than the south of Saudi Arabia be-
cause of the influence of Mediterranean weather systems (Purkis et al.,
2010). This difference goes some way to explaining why Dendritic Sys-
tems may be more prevalent in the north than in the south of the basin.
It should be noted, however, that Dendritic Systems are absent in the
Gulf of Aqaba (precinct A), but here the coastal shelf is narrow and the
absence of the morphology can be explained by a lack of space in
which it could develop (Tibor et al., 2010).

Earlier in this paper, the similarity between the morphology of
Lineated Systems and that of terrestrial dune ridges was recognized.
Investigation of this similarity within the GIS reveals that the crest-to-
crest distance of parallel coral reefs in Lineated Systems is five times
farther than the distance separating terrestrial dune ridges in the desert of northern Saudi Arabia. The separation distance of the dune ridges, which varies between 80 m and 426 m, is typical for such morphologies (Levin et al., 2004) and can therefore be considered as representative. Because of these differences, a morphology other than dune ridges must be sought to explain the formation of Lineated Systems. Bosence (2005) recognized a situation in the Red Sea whereby carbonate deposition proceeds atop the bathymetric highs created by fault-blocks. Carbonate systems with a Detached Form nucleate atop highs and are separated by areas of deep water (structural lows) defined by large-scale faults (Guilcher, 1988). Widths between offshore structural highs range from 4 km to 15 km, which is much greater than the distance separating reefs within the Attached Lineated Systems. However, the fault-block concept of Bosence (2005) can be extended to smaller-scale faults associated with horst and graben structures. This may offer an explanation for the morphology of Lineated Systems, as previously suggested by Guilcher (1988) and Sheppard et al. (1992).

5. Conclusions

In the Saudi Arabian Red Sea, processes act across a variety of spatial and temporal scales to deliver diverse morphologies of shallow-water carbonate depositional systems. Seafloor topography is influenced by the tectonics of the Red Sea rift basin, and the spatially variable occurrence of salt diapirs. Changes in relative sea-level can in


