Marine Geology 456 (2023) 106985

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Letter

Controls on carbonate-siliciclastic relationships in quaternary deposits of the Midyan coast of the Gulf of Aqaba, Saudi Arabia

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ARTICLE INFO

Editor: Edward Anthony

Keywords:
Carbonate deposits
Controls on carbonate productivity
Sea level
Red Sea

ABSTRACT

Quaternary deposits of the Midyan coast of Saudi Arabia include coral-bearing limestones interbedded with sheet-flow siliciclastic sands and gravels, interpreted as braid-delta fan deposits. The limestones and their contained faunas provide evidence of periodic local stabilization of gravel surfaces and effective starvation of siliciclastic supply. Some indicate growth and deposition in waters a metre or so deep whereas others were substantially deeper. An additional group reflects initial deposition in shallow waters with resedimentation downslope by storm or other 'delta-front' processes. The surfaces of the fans provided morphological and environmental analogues to fore- and back-reef situations in which corals, calcareous coralline algae, molluscs, and echinoderms flourished, but in this area did not form independent reefs. The dominant controls on the changes from siliciclastic- to carbonate-dominated deposition were not transitional, and primarily related to channel and fan-lobe migration rather than tectonic or eustatic sea level changes. Similar variations in the distribution of siliciclastic sediments may control carbonate occurrence in other mixed sequences.

1. Introduction

There has long been a view that the accumulation of carbonate sediments, and thus rocks, is governed not so much by the productivity of the generating system but by the absence of anything else. Selly (1985) outlined three circumstances in which this might come about: A low input of terrigenous sediment might be due to low run-off, or low siliciclastic sediment availability, where the hinterland is low-lying, or where the shoreline itself has a low gradient. In each of these, the supply of siliciclastic sediment is effectively cut off. But this is only part of the solution to the problem. Typical siliciclastic processes call for bedding units to be formed on timescales that range from a few hours to weeks or months, although such events may only occur at intervals of decades. In geological terms the delivery of such material, when it occurs, is instantaneous, and largely precludes the accumulation of carbonate deposits, where production of a single mollusc shell may take years and a 1 m *Porites* colony a hundred years. Although the processes of siliciclastic transport may generate some mixing, for substantial thicknesses of carbonate sediments to be deposited, it is necessary that there should be very low or no siliciclastic input. In the part of the Red Sea coast described here, where differences in age between carbonate and siliciclastic deposits are small, this seems to require on-off switches, as observations indicate a system in which deposition of these supposed end members was concurrently either on or off in adjacent areas.

Eustatic and tectonic controls on the deposition of hybrid carbonate-siliciclastic sequences in basin settings were examined by Dolan (1989), who concluded that deposition of basinal sediments along platform margins is broadly controlled by sea level. At high sea level stands shelves are flooded and the relative elevation of the hinterland reduced. After a lag, in which a biota can become established, carbonate deposits are generated, that form the 'overproduction' of Neumann and Land (1975), and Boardman and Neumann (1984), and may be transported to accumulate downslope. By contrast, as sea level falls, there is a relative elevation of siliciclastic supply areas, commonly resulting in exposure of the shelf or upper ramp, and concomitant increased erosion and sediment transport, restricting the area available for carbonate production. Thus, only siliciclastic sediment is delivered to the slope.

This model has a compelling simplicity but unfortunately does not seem to apply to areas within the shelf or upper ramp. In these, relatively shallow waters, small changes in sea level moderate changes within the accumulating sequence. But although these may arrest or reset cycles, as in Hardie (1986), they seem unlikely to exercise precise control over gross siliciclastic input because their effects are insufficiently widespread. Where sea level changes are large, positive movements may

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https://doi.org/10.1016/j.margeo.2022.106985
Received 12 November 2022; Received in revised form 20 December 2022; Accepted 23 December 2022
Available online 26 December 2022

result in flooding of shelves and reduced sediment supply. Conversely, relative lowering of sea level results in shelf emergence and deep incision, such that areas are by-passed by the terrigenous sediment generated. Thus, to be effective, controls must operate within a limited scale that avoids these extremes, as in autocyclic sequences.

2. Location

Sediments of the western coastal zone of Saudi Arabia, bordering the Red Sea, are dominated by siliciclastic deposits derived from the uplifted shoulders of the Red Sea Rift. At times during the Pleistocene, when sediment input to coastal areas was low in areas to the south, reef systems were able to form and locally reef growth remains active. However, in the Gulf of Aqaba (Hayward, 1985; Roberts and Murray, 1988), small outcrops of Pleistocene limestone fringe extensive alluvial fans with few areas of Holocene reef formation. In the Maqna area, latitude 28° 24′ 20″ N longitude 34° 44′ 45″ E, close to the town of Maqna (Fig. 1), where basement mountains locally reach the sea, there is a discontinuous interbedding of siliciclastic and thin carbonate deposits. Satellite images are available through Google maps and the United States Geological Survey: https://earthexplorer.usgs.gov. In the latter it is sufficient to enter the coordinates with the location found automatically.

At present, the highland areas close to Maqna. including Jebal Tayran, Jebel Amrah, Jebal Musayr and Jebel Nutaysh, are drained by extensive wadi systems; Wadi Saak, Wadi El-Hamid, and Wadi Kharaj, that spread alluvial fans and braid-plains across the narrow coastal plain. Although these appear to inhibit present-day reef growth in this area, their progradation is restricted by wave action and longshore transport, but also by the relative steepness of the offshore slope. Unlike the examples described by Hayward (1985) and Gvirtzman and Buchbinder (1978), in this area, they do not have a seawards expression as fan-deltas.

Along both margins of the Red Sea, reef flats are locally crossed by narrow channels, sharms, incised 30–40 m through underlying Pleistocene substrates during low sea-level stands (Braithwaite, 1982, 1987). Maqna is situated on a similar embayment (Gvirtzman and Buchbinder, 1978).

The Quaternary carbonate deposits described here comprise an intermittent series of coastal terraces rising metres above present sea level and dissected by channels emerging from wadis. However, fans do not form continuous aprons and locally rocky ridges extend to the shore.

Fig. 1. Map of the area including the Gulf of Aqaba showing the position of the localities described. For satellite image see: https://earthexplorer.usgs.gov

3. Field descriptions

In the southern Red Sea, the Gulf of Suez, and the northern Red Sea (see articles in Purser and Bosence, 1998) extensive Pleistocene carbonate deposits form well-defined terraces at consistent elevations and provide multiple age dates (referenced below). Here attention is focussed on features of discontinuous limestones on the Midyan coast of the Gulf of Eilat that offer evidence of synchronous relationships between carbonate and siliciclastic deposition. In this area, Quaternary and Recent alluvial fans spread from adjacent igneous massifs across a narrow coastal plain. Deposits are dominated by conglomerates with relatively small proportions of interbedded sandstones. Clasts include a variety of rock types correlated with the adjacent exposed basement. Coarser grain-sizes are commonly well-rounded but finer-grained gravels are dominated by angular scree-like fragments. Lamination on a scale of tens of centimetres parallels low angle surfaces, reflecting sheet-flow transport and accumulation in low-relief longitudinal bars. Centimetre- to metre-thick, beds are commonly poorly sorted. In total, siliciclastic deposits are tens of metres thick, considerably more than any associated limestones.

3.1. Locality 1. Wadi Saak

Two limestones are present within the siliciclastic succession on the coast south of Wadi Saak, latitude 28° 31′ 39″ N, longitude 34° 48′ 18″ E. The lower unit is about 2.5 m thick, with a loose accumulation of coral and algal debris at the base on which a thin but well-defined coral growth frame became established. However, growth was not sustained for long and was overlain by transported coral and coralline algal rubble. Corals include *Porites, Favia, Favites, Hydnophora, Fungia, Galaxaea, Echinopora, Pocillopora damicornis, Leptoria* and *Lobophyllia.* A similarly diverse molluscan fauna includes the gasteropods *Lambis, Murex, Conus* spps, and *Cypraea* spps, with bivalves, *Tridacna, Arca,* and *Spondylus*. Together these suggest a near-shore shallow water environment. The overlying unit, about 3 m thick consists of poorly sorted fine-grained siliciclastic conglomerate, containing clasts with lithologies related to the exposed igneous basement to the east. Conglomerates at the top of the sequence contain intermixed coral fragments, and the surface is overgrown by massive corals, including *in situ* colonies of *Porites,* some of which are more than a metre in diameter (Fig. 2), that together suggest deeper water. Outcrops about 50 m to the east of these

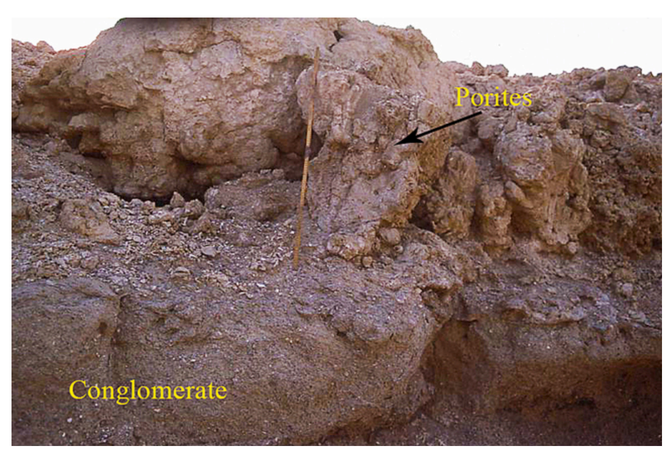

Fig. 2. Coast south of Wadi Saak, latitude 28° 31′ 39″ N, longitude 34° 48′ 18″ E. Pleistocene siliciclastic conglomerate overlain by large, *in situ*, *Porites.* Scale is 1 m rule.

include a third limestone. This also rests on conglomerate, but only a few centimetres of this are visible. The base of the limestone consists largely of coral rubble, overlain by a well- bedded sequence (Fig. 3) including small bushy growths of *Pocillopora damicornis* and *Acropora formosa,* implying deposition in relatively shallow water. All three limestones taper for about 100 m to the east between thickening wedges of siliciclastic conglomerates with well-rounded pebbles. An important feature of this group of deposits is that the corals appear to be diagenetically similar and although they cannot be physically correlated are probably of broadly similar ages.

3.2. Locality 2. Headland between Wadi Saak and Wadi Qsarah

More outcrops of coral-bearing limestone are present on a headland at latitude 28° 31′ 08″ N, longitude 34° 48′ 05″ E, between Wadi Saak and Wadi Qsarah. The main outcrop, 5 to 7 m above present sea level, is about 8 m thick on the south side of the headland, sloping at about 25° and tapering seawards (westwards), reaching about 4 m thickness within 3 to 4 m of present sea level. Intercalations of siliciclastic conglomerate up to 50 cm thick occur at the base and are associated with metre-size boulders of cemented older conglomerate where adjacent conglomerate outcrops are generally uncemented. On the north side of the headland the base of the sequence consists of conspicuous areas of coral growth frame form. However, although some corals appear upright, effectively growing in or on the conglomerate, many seem to have been transported downslope from a shallower environment. Corals in the thicker, southern, outcrop of the limestone include colonies of *Porites*, up to 3 m diameter, with robust club-like branches (Fig. 4). Locally, patches on the north side of the headland contain numerous spines of the echinoderm *Heterocentrotus*.

3.3. Locality 3. Headland to the South

Thick limestones, superficially resembling those on the Wadi Saak headland, are present on a similar unnamed headland at latitude 28° 30′ 44″ N, longitude 34° 47′ 49″ E, but represent a distinct sedimentary environment. They include metre-size blocks of sandstone containing numerous shells of the bivalve *Fragrum,* associated elsewhere with restricted higher salinity environments. Blocks several metres in diameter were already well-cemented at the time of derivation. South of this locality additional outcrops expose up to 12 m of limestone. Most of this is a coarse carbonate sand with comparatively few large corals. The paucity of corals suggests a more restricted environment, but the coarser grain-size implies one that was hydrodynamically active with a source of shelly material nearby. The lack of bedding may reflect bioturbation, but no trace-fossils have been identified. Small bushy species of *Acropora* are common at the base of the unit, with scattered *Lobophyllia*? Commonly, fragments of coral branches are encrusted with coralline algae. The presence of *Nerita* and a few bivalves may indicate proximity to a rocky shore. The top 2 m of the limestone form a distinctive fine-grained subunit, overlying a well-defined planar erosion surface.

Fig. 4. Headland between Wadi Saak and Wadi Qsarah, latitude 28° 31′ 08″ N, longitude 34° 48′ 05″ E. Sequence of *in situ* massive corals, intercalated with coral-rubble bearing conglomerates. Figure for scale.

3.4. Locality 4. South of Wadi Qsarah

Limestones are present on two headlands south of Wadi Qsarah, latitude 28° 29′ 58″ N and longitude 34° 47′ 31″ E. On the northern headland, coral-bearing limestones overlie the eroded surface of steeply dipping Miocene deposits 10–12 m above present sea level. However, on the seaward (western) face of the headland, parts of the cliff comprise interbedded sandy siliciclastic conglomerates and coral-rubble-bearing conglomerates (Fig. 5). Lower units contain greater proportions of coral debris, arguably swept from a shallower area and transported downslope by discrete turbulent events. Locally, these make up about two-thirds of the section with the remainder consisting of more typical coral-bearing limestone, but the eastern margin of the outcrop includes blocks of sandstone up to 2 m in diameter.

Patchy outcrops of similar limestones appear on the coast both north and south of the debouchement of a prominent wadi, Abu Hasah, latitude 28° 12′ 00″ N, longitude 34° 39′ 22″ E. South of the main group,

Fig. 3. Coast south of Wadi Saak latitude 28° 31′ 39″ N, longitude 34° 48′ 18″ E. Bedded sequence of Pleistocene Limestones with corymbose growths of corals including *Acropora* and *Pocillopora*. Scale is a 1 m rule.

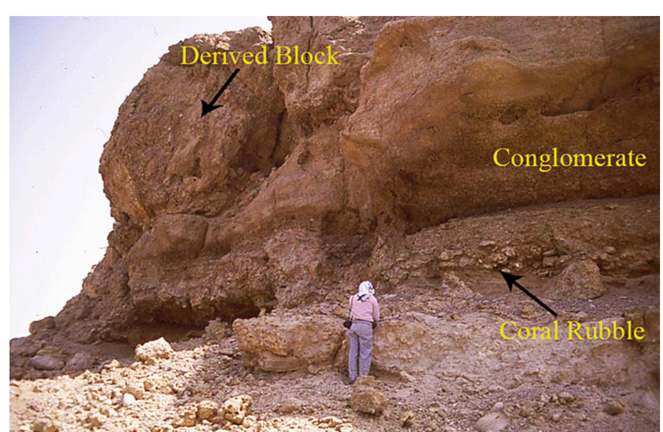

Fig. 5. Headland between Wadi Saak and Wadi Qsarah, latitude 28° 31′ 08″ N, longitude 34° 48′ 05″ E. Bedded intercalations of coral-rubble and siliciclastic conglomerates. Figure for scale.

some of these contain little limestone, and what there is commonly rests directly on Miocene rocks, and locally occupying shallow channels and grooves cut into the surface of these. There is little differentiation of the boundaries between the various alluvial fan systems in outcrops, but it seems that the limestones are separate occurrences within individual fans. The corals present are not *in situ* and, with other debris, appear to have been transported some distance.

3.5. Locality 5. Sharm Dabbah

Limestones are absent for several hundred metres to the south, but reappear north of Sharm Dabbah, latitude 28° 11′ 26″ N, longitude 34° 39′ 51″ E. Here 10–12 m of limestones and coral-bearing conglomerates again fill channels cut into the surface of Miocene rocks (Fig. 6). Large coral masses, some of which may be boulders, are present at the base together with rounded siliciclastic pebbles that are found several metres above the base of the limestone. Locally, groups of corals form areas of growth frame with coralline algae, some of which appear to be blocks derived from areas of similar lithologies (Fig. 7), implying an essentially syndepositional lithification of the limestones. Other areas are simply carbonate sands with only small, disoriented, fragments of corals and molluscs. Overlying limestones, include a prominent mound with large corals, including one exceptionally large colony *cf. Lobophyllia*, extending almost the full thickness of the 'bed' (Fig. 8), accompanied by smaller colonies of *Galaxaea,* club-like *Porites*, and *Hydenophora.* Large *Lambis* and *Tridacna* are scattered on the surface and are presumably derived from the limestone. One mound area of growth frame 7–8 m high, is overlain by thin conglomerate and a thin rubbly limestone, tilted to the west, and potentially reflecting mass movement.

3.6. Locality 6. Maqna

Outcrops of Holocene and Pleistocene alluvial fans spread westwards from the igneous massif about 1 km south of Maqna, latitude 28° 24′ 22″ N, longitude 34° 44′ 24″ E. The surface of these deposits forms a gentle slope, reflecting sheet-flow transport that has formed a thinly bedded sequence on a scale of tens of centimetres. Much of the coarser debris is angular scree-like clasts with few rock types, dominated by 'granite' and basic intrusive rocks. The section is capped at about 30 m by coarse conglomerates and sands, potentially derived from older fans. Although clasts in the coarser deposits are commonly more rounded, they retain a sheet-like architecture. At the base, about 50 cm of siliciclastic conglomerate containing coral debris, rests on the irregular surface of the igneous basement, with the surface sloping gently and the bed thickening rapidly to the west, but thinning to the east, disappearing within about 20 m. Boulders at the base are predominantly granite but many are coated by crustose coralline algae (Fig. 9), and locally, by growths of *Millepora*. These are associated, at intervals, with colonies of *Favia sp.*, *Porites,* and *Acropora*, *sp.* 20–30 cm in diameter, with a sheet-

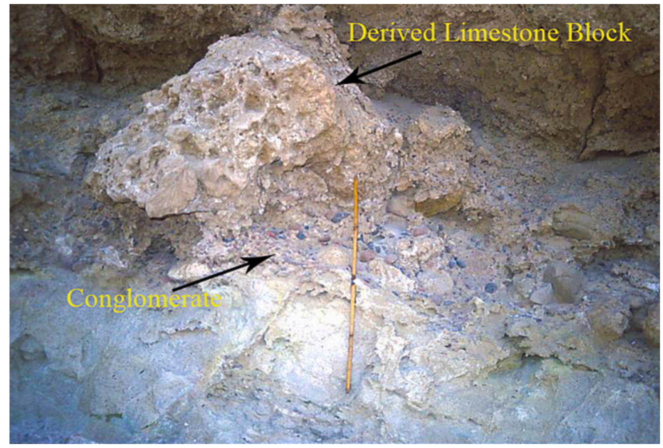

Fig. 7. Sharm Dabbah, latitude 28° 11′ 26″ N, longitude 34° 39′ 51″ E. Derived blocks of coral frame within siliciclastic conglomerates. Scale is 1 m rule.

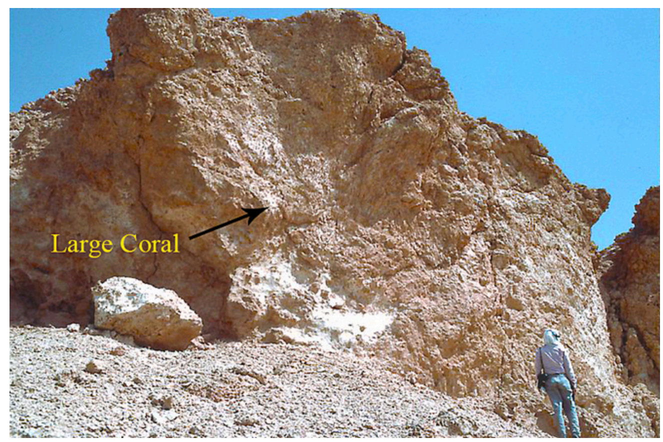

Fig. 8. Sharm Dabbah, latitude 28° 11′ 26″ N, longitude 34° 39′ 51″ E. Coral-bearing mound with large corals extending nearly the full thickness of the unit. Figure for scale.

Fig. 6. Abu Hasah, latitude 28° 12′ 00″ N, longitude 34° 39′ 22″ E Pleistocene limestones with transported coral assemblage, overlying tilted Miocene rocks. Scale provided by vehicle.

Fig. 9. Coast, about 1 km south of Maqna, Coralline algae encrusting surfaces of siliciclastic boulders incorporated into the base of the unit, overlain by additional conglomerate without carbonate clasts. Metre rule provides scale.

like form resembling *Acropora hyacynthus,* together with *Leptoseris(?)* and numerous calcareous algal fragments. Scattered large molluscs include *Lambis, Turbo*, and *Tridacna.* Although the coralline algae encrusting the boulders are probably *in situ*, most of the corals and other algal fragments appear to be derived.

A few hundred metres to the south, outcrops are predominantly of siliciclastic conglomerates but, include about 1.5 m of poorly sorted limestone, consisting largely of randomly orientated fragments of coralline algae, and scattered *Porites* > 50 cm diameter. Importantly, the upper surface of this limestone has been truncated by erosion, with siliciclastic conglomerate occupying shallow channels cut into what must have been a lithified limestone surface (Fig. 10). This may account for the attenuation of the unit but within about 20 m to the north it is replaced by conglomerates that include scattered massive corals, with *Porites* up to 1.5 m diameter, forming patches several metres across.

About 500 m to the south, another thin limestone outcrops include colonies of *Porites* up to 2 m diameter (Fig. 11) together with *Hydnophora (?)* colonies 20–40 cm in diameter. These are important because they include a several colonies with sharply truncated upper surfaces, sculpted by numerous borings of *Lithophaga*, Sipunculids, and *Cliona,* and resembling micro-atolls. These indicate proximity to the water surface during growth but, like others, the limestone thins laterally and disappears within a short distance.

Patches of limestone appear again to the south, decreasing in altitude, and within another 500 m are only 10–15 m above present sea level. Very large, *in situ Porites,* are also present in this area but, in contrast to those described above, they have few borings and are associated with numerous fragments of encrusting coralline algae that become more common upwards in the succession. Areas between corals are packed with algal clasts and bivalves, including *Arca* in particular, perhaps suggesting a sandy lagoonal environment. The surface of this outcrop slopes gently seawards but is essentially flat, suggesting that it is an erosion surface. However, this raises the question of whether the surface formed as a slope during deposition or reflects tectonic or landslip disturbance. The limestone at the southernmost end of these outcrops consists largely of coral rubble that includes *Acropora cf.* A. *hyacynthus* sheets, and small *Galaxaea, Porites* and *Fungia*. There are scattered colonies of a corymbose *Acropora* and of *Pocillopora cf. damicornis.* Large molluscs include *Tridacn*a, *Lambis, Spondylus*, and *Terebra.*

4. Dating deposits

The importance of these limestones lies in their relationship to the siliciclastic fans with which they are associated. They probably vary in age but can be compared to published data on other Red Sea coasts. Ages determined (typically by U-Th methods) range from 6 ka (Gvirtzman, 1994) to 340 ka (Dullo, 1990). Most reports recognize only two or three stages, but Gvirtzman (*ibid*) listed 10 separate depositional events related to sea level changes in southern Sinai, dated at 331, 193, 124, 111, 99, 91, 79, 64, 18, and 6 ka (elevations of +2.9, −1.4, +6.5, −29, −1.5 -28, +0.3, −65, −122, and + 0.5 m respectively). Numbers vary between localities, and minus values are below present sea level. The dominant group in all localities relates to MIS 5e, 128–117 ka BP. But Butzer and Hansen (1968) recorded 80 ± 8 ka from deposits 5–6 m above present sea level, and Berry et al. (1966) recorded 91 ± 5 ka from 9.8 m elevation outcrops 42 km north of Port Sudan. In the Gulf of Aqaba, Gvirtzman and Buchbinder (1978) recorded dates of >250, 250–200, and 140–108 ka and Hoang and Taviani (1991) also found older ages, of 300–290, 200, and 138–125 ka at elevations varying between 10 and 15, 17, and 6–8 m respectively, above present sea level. Results by Dullo (1990) also indicated some older ages of 340–290, 250–200, and 118–86 ka. More recent dates, by Yehudai et al. (2017), Bar et al. (2018), Taviani et al. (2019), and Plaziat et al. (2012) are all within similar lower limits, with the emphasis on the last interglacial. To underline this, work by Manaa (Manaa, 2016; Manaa et al., 2016) provided $^{230}Th/^{238}U$ dates, including Open System models, from around 40 localities on the Red Sea coast, mostly to the north of the present study area but extending south to Jeddah and the Farasan Islands. These ranged between 131 and 108 ka, but all fall within MIS 5e. It is likely that new dates would fall within the same interval but are likely to be just as varied.

These data and the above descriptions show that deposits vary in elevations that are arguably related to environmental positions relative to existing topographies, although they nevertheless also reflect their contemporary sea level. If this is correct, there is no precise correlation between age and elevation because deposits of the same age formed in environments at different elevations, and deposits at the same elevation may have formed at different times.

Fig. 10. Coast south of Maqna, latitude 28° 24′ 22″ N, longitude 34° 44′ 24″ E. Sheet-flow conglomerates, note aligned texture, resting on the channelled surface of Pleistocene coral bearing limestones. Hammer, approximately 30 cm long provides scale.

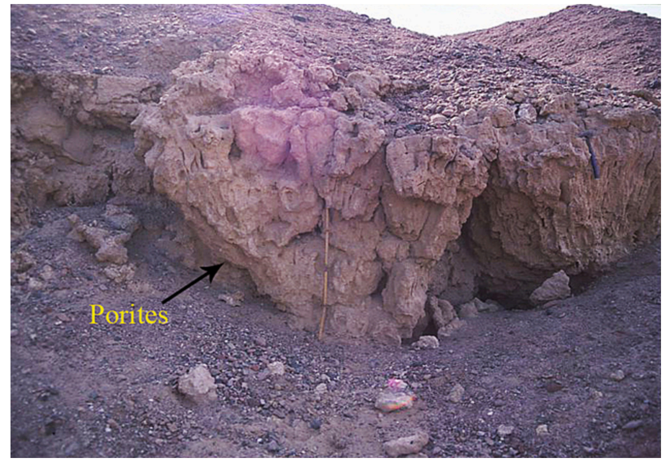

Fig. 11. Coast south of Maqna latitude 28° 24′ 22″ N, longitude 34° 44′ 24″ E. Massive, *in situ, Porites,* locally with flattened tops, forming microatolls. Scale is 1 m rule.

5. Discussion

Quaternary alluvial fans in the Maqna area are characteristically coarse-grained deposits, dominated by gravels, and sometimes containing boulders of metre dimensions. Typically, coarse sands and pebble beds are interleaved in sheet flow lamination. There is relatively little fine-grained sand and silt, and clay size material is essentially absent.

Bull (1972) outlined a general geometry for fan systems that characteristically form along fault scarps and at the debouchement of narrow valleys. Spreading laterally from the point source, they assume a fan shape, forming a wedge in cross-section with an upper surface on which grain-size shows a positive co-variance to slope. Steep proximal slopes at the head of the structure are generally coarser-grained whereas low slopes on the distal margin are finer-grained. However, McPherson et al. (1987) noted a general similarity between the deposits of alluvial fan systems and those of some braided streams and reserved the term "fan-delta" for gravel-rich structures formed where an alluvial fan is deposited directly into standing water. By contrast, "braid-deltas" may also be gravel-rich but are deposited where a braided fluvial system progrades into a standing body of water.

In the Maqna area, Wadi El-Hamd, Wadi Kharaj, and Wadi Saak form extensive alluvial fans feeding braid systems, that reach the sea along their western margins. It seems likely that during the last interglacial, with sea-level close to that at present, Quaternary sediments were of similar architecture, with braid systems spilling onto the coast. As McPherson et al. (1987) noted, braid-delta deposits generally show increased roundness, improved sorting and better orientation of grains compared to those of fan-deltas and typically lack a muddy matrix. Their geometry is dominated by low-angle sheets with high lateral continuity, as demonstrated by the Maqna deposits. The debris-flows and mud-flows typical of many alluvial fans are absent in braided river deposits and are also absent from the coastal sequences at Maqna.

Because coarse-grained deltas are characterized by high rates of sediment input it might be expected that they would be less influenced by factors such as wave action than their fine-grained equivalents. However, the present sea-surface expression of the braid-delta building from Wadi Saak shows little seawards projection (unlike those figured by Hayward, 1985) and implies significant reworking and (presumably) substantial long-shore redistribution.

The conglomerates associated with the Quaternary limestones near Maqna commonly contain well-rounded pebbles. McPherson et al. (1987) regarded these as a feature of braid-deltas. However, the sediments and some structures resemble deposits described by Postma and Nemec (1990) in south-western Crete and attributed to wave reworking of Pleistocene alluvial fans. We might expect similar reworking of both Pleistocene and contemporary fans, and this, rather than prolonged transport, may explain the well-rounded materials. However, it seems that limestone blocks, whatever their size, were not reworked in this way, pointing to the independence of their depositional systems. Wescott and Etheridge (1980) noted the dominance of marine reworking on the coastal margin of the Yallahs River fan in Jamaica. Discharge from the Yallas River is strongly seasonal and this feature is important for arid systems where the erratic supply of sediment allows much longer periods of reworking. Postma and Nemec (1990) noted that where marine reworking occurs, the lower beach face may extend to depths of 2–3 m below sea level, a significant datum because it brings the depositional surface within the depth range implied by some of the limestones, which we will now consider.

The limestones examined are laterally discontinuous. Thicknesses vary from a few centimetres to a little over 10 m but although they locally include coral growth assemblages, they are not in any sense reefs. Notwithstanding the occurrence of obvious erosion surfaces, much of the variation in thickness reflects local variations in the volume of material deposited, whether that represents differences in transport or production. Hayward's (1985) descriptions suggest an active stabilization of gravel surfaces by a variety of encrusting organisms, but principally by coralline algae. He considered that this allowed the subsequent colonization of the surfaces by corals. However, these views do not accord with observations of the Maqna limestones. Here it seems that gravel surfaces must already have been inactive, and therefore stable, before any coating of pebbles became possible. Although we may expect encrusting coralline algae to "prefer" a relatively high-energy milieu it is nevertheless unlikely that they would coat surfaces that were moving and subject to mutual attrition of pebbles. Together with colonies of *Millepora* they bind previously mobile clasts in areas of no additional siliciclastic input. However, it is important to note the occurrence of both coral and algal clasts entrained in some conglomerates.

Masses of broken coralline algae and corals indicate periodic temporary increases in hydrodynamic energy. The limestones locally include, or consist predominantly of, derived materials. Poorly sorted sheet-like units suggest storm transport, essentially like that redistributing siliciclastic sediment on the surfaces of the fans. Hayward (1985) noted the occurrence of large coral blocks in poorly sorted gravels of storm berms, reinforcing the view of reworking on the shallow seaward faces of the fans. The Maqna limestones are characteristically poor in siliciclastic components and therefore imply a temporary halt in their delivery. It may be significant that in the Gulf of Eilat, Hayward (1985) suggested that up to 50% of reef structures may rest on siliciclastic foundations. Progradation of gravel lobes washed onto tidal flats results in coarse debris spilling through channels onto the nearshore shelf where it mixes with bioclastic components from within the system. Not only was there little siliciclastic material contributed to areas where the Quaternary limestones formed, but these had sometimes been cemented and eroded before any further gravel increments were delivered. Evidence for this is seen in the presence of erosion surfaces within the limestones and of derived cemented limestone blocks.

The proportion of carbonates in the Maqna sequence is small, perhaps only 10– 15%, but is significant. They are limited in area and variations in thickness indicate that they were also temporally limited. Sea level was higher when they were deposited and shelf areas must also have been larger, covering the present coastal plains, but there remains the difficulty of isolating production from contemporary siliciclastic deposition. The productivity of corals or of other large organisms can be misleading if we correlate occurrence directly with areas of growth. The much larger volumes of finer-grained carbonate produced by the biota argue for significant areas of more general production from which siliciclastic deposits were excluded. It is equally obvious, where limestones are resedimented, that their deposits were ultimately dependent on extensive 'carbonate factories' from which siliciclastic deposits were excluded during both production and derivation. Thus, even where there are no overt erosion surfaces, substantial volumes of carbonate sediment have been separated from their point of origin and are not preserved in place. The volume of resedimented material in present outcrops does not adequately account for the deficit.

Although Gvirtzman and Buchbinder (1978), recorded three separate limestone terraces dated at >250, 200–250 and 108–140 ka there is no morphological basis for such a distinction in the Maqna area. There is no obvious separation in altitude and few petrographic (diagenetic) differences between the limestones described. Without accurate radiometric dating it is not possible to discriminate between deposits of different ages and those formed at different depths on the same fan slope. There is no evidence in fan sequences of subaerial influence, and it is therefore likely that accretion was related to a 'catch-up' phase following sea level rise (compare Hardie, 1986). If this is so, there remains the problem of the processes that switched either carbonate or siliciclastic deposition on or off.

Friedman (1988) suggested that interbedded limestones and siliciclastics on alluvial fans in the Gulf of Eilat (Aqaba) were produced where "carbonate secreting organisms overcome the inhibiting effects due to sediment coarseness and the long periods of quiescence between flashfloods". However, the relative thicknesses of the limestones that accumulated in the Maqna area, together with the sizes of the *in situ* corals contained within them, and the presence of erosion surfaces, all point to deposition over many decades or even hundreds of years. Whereas droughts may extend over such periods, cycles of rainfall are typically very much shorter (some data on present rainfall are available in Edwards, 1987). In addition, if climate were the primary control, then we would expect some degree of synchroneity from place to place in both the timing and volume of carbonate increments.

It seems unlikely that variation could have been controlled by repeated eustatic changes in sea level, since neither these nor tectonic events generate localised abrupt on-off-on changes on the required time scale. Recent faulting is reported in the Gulf of Suez (Plaziat et al. 1998) but the general assumption that the limestones throughout the Red Sea are all the same age or, further north, of three separate ages, points to controls acting in relation to relatively stationary sea levels. The problem is analogous to that of the repeated shallowing-up cycles seen in deltaic sequences, where there is an abrupt return to a relatively deep environment, and may be resolved in a similar way. Notwithstanding the characteristic high lateral continuity of lithofacies in braid-deltas, the discharge does not simultaneously occupy the entire surface of a fan, even subaqueously. Hayward (1985) noted that many fans in the Gulf of Aqaba have one or more entrenched channels and, where accretion has reached its effective hydrodynamically defined limits, these represent the only access to the foreslope. As in subaerial systems, such flows periodically choke on their own debris and are diverted. Thus, as flow paths migrate across the fan surface, segments are abandoned by or shielded from siliciclastic input. As Roberts and Murray, 1988 Fig. 10 shows, it is distribution that is the key to carbonate accumulation rather than temporal variation in siliciclastic supply. In support of this view, Santisteban and Taberner (1988) described reef growth related to bar-finger sands within an advancing delta, pointing to channel avulsion as the principal means of diverting detrital sediment and allowing the coralgal community to become established.

Bypassed areas are not initially characterized by low hydrodynamic energy, because they remain subject to marine influence. They may become so by subsidence, by a progressive eustatic sea level rise, or by progradation of the fan around them, or may be built up by carbonate deposition to occupy a higher energy zone. The truncated colonies of *Porites* in the Maqna limestones reflect a shallow-water low hydrodynamic system. By contrast, thicker sequences showing an upwards transition to an *Acropora*-dominated association reflect establishment in deeper water, building to a shallower zone with greater water movement.

The work of Rosen (1971, 1977), and others, has highlighted the close relationships between coral associations and particular positions on a reef. The steep environmental gradients of the reef system result in marked biological zonation. Rosen's work was especially important in showing that similar environmental conditions may generate similar assemblages in more than one location on a reef. Elsewhere, Braithwaite (1987) argued that the observed biota of the reef environment should be dissociated from the morphological concept of the reef. In the Quaternary limestones of the Maqna area we see the implications of this dissociation.

The morphology of the depositional system was provided by braid-deltas. In some respects, these are analogous to reefs. The upper surfaces are characterized by shallow 'topset' environments equivalent to a backreef. Breaks in slope, where marine reworking is dominant, with or without distributary mouth bars, are analogous to reef crests, and 'foreset' slopes compare to fore-reefs. It is not surprising therefore that, where the delivery of siliciclastic material fails, the biota that colonizes the surface is that relating to the appropriate reef position (compare again Santisteban and Taberner, 1988). Given sufficient time, as was apparently available during accretion of the Gulf of Aqaba Limestones described by Hayward (1985), a biologically dominated reef may develop, but this did not occur in the Maqna area. It seems that here most of the limestones formed in a 'topset' or effectively 'backreef' environment, a shallow lagoon, although locally substantial amounts of carbonate sediment were shed to deeper slopes. Santisteban and Taberner (1988) described an analogous zonation in a Miocene fauna adjusted to growth on a fan-delta lobe.

6. Conclusions

The accumulation of limestones within the braided Quaternary alluvial fan sequences of the Saudi-Arabian coast of the Gulf of Aqaba was controlled by channel-switching on fan surfaces. Faunal evidence suggests that the positions of carbonate accumulations on fans was morphologically and environmentally analogous to positions on a reef but sedimentologically distinct. As in well-known autocyclic sequences in deltaic and other environments no tectonic or individual sea level controls were necessary. Against a background of stationary or only gently rising sea level, distributary migration can locally cut off siliciclastic supply and allow carbonate sediments to accumulate. Similar variations in the distribution of siliciclastic deposits may control the occurrence of carbonates in other mixed sequences.

Data

All data relating to this manuscript are either contained within the text or in referenced public material.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

I am indebted to Rushdi Jamal Taj and the Faculty of Earth Sciences of King Abdulaziz University in Jeddah, Saudi Arabia for logistical support of the fieldwork, undertaken in parallel with a larger project in the Maqna area, and for the co-ordinates of localities. The careful work of an anonymous reviewer, noting points that needed explanation and correcting typographical errors has greatly improved the manuscript.

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