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Mixed Clastic–Carbonate Cycles and Sequences: Quaternary of Egypt and Carboniferous of England

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Abstract

There are various types of mixed clastic–carbonate sequences and parasequences in the geological record and sea-level change is one of the major controls on their development, as well as the obvious availability of terrigenous material. Mixed-lithology sequences are especially well-developed in icehouse times, as in the Permo–Carboniferous and Quaternary. The two major types, lower carbonate – upper clastic and lower clastic – upper carbonate sequences, reflect the rates of sea-level change and the source of clastic sediment – whether it is brought across the carbonate platform from the adjacent landmass or supplied axially to the basin. Two examples of carbonate–clastic high-frequency sequences are discussed: 1) from the Red Sea coast of Egypt, Quaternary transgressive/highstand shallow-water carbonates and late highstand/falling-stage/lowstand clastics deposited in incised-valley fills and fan deltas, and 2) from northern England, mid-Carboniferous 'Yoredale' cycles of transgressive shelf carbonates passing up into highstand coarsening-up deltaic and shoreline clastics, capped by palaeosoils and coal. Locally, falling-stage incised-valleys supplied sediments to the adjoining basin. One significant difference between these two examples is the palaeoclimate: arid in the Red Sea leading to the episodic supply of sand and gravel, and humid in the Carboniferous resulting in the more continuous supply of mud and sand, each having a different effect on carbonate deposition.

1. INTRODUCTION

In the geological record one tends to think of formations composed of either limestones or sandstones, but rarely both. In fact, there are many cases of interbedded clastics and carbonates in repeated cyclic arrangements. Such units occur on the small-scale (metre-thick cycles or parasequences, $4^{th}/5^{th}$ order), and on the larger-scale (10's metre-thick, 4^{th} order high-frequency sequences and 100's metre-thick, 3^{rd} order sequences). Mixed lithologies, namely sandy limestones and calc-arenaceous sandstones are relatively rare rocks, or at least they are rarely described and classified properly.

Terrigenous input is dominantly a function of clastic availability and relative sea-level change, with the rate of change of major significance (see MOUNT, 1984 and papers in DOYLE & ROBERTS, 1988). Mixed-lithology cycles and sequences are perhaps more typical of icehouse periods. At these times of higher amplitude sea-level falls, terrigenous debris is supplied in abundance to shelves and basins, and with subsequent sea-level rises and flooding of coastal plains, carbonates are deposited extensively. Thus, mixed carbonate–clastic sequences are more common in Permo–Carboniferous and Quaternary successions, although they do occur in other periods too.

In this personal review, clastic–carbonate interaction is briefly considered on two levels: a) mixed clastic–carbonate sediments and their penecontemporaneous deposition and b) interbedded clastic–carbonate cyclic sediments on the parasequence (metre-thick) and sequence (10's–100's metre-thick) scale. Two case studies are then presented to illustrate the general principles, from the Quaternary of the Red Sea coast in Egypt, and the mid-Carboniferous of northern England.

2. MAJOR CONTROLS ON CLASTIC AND CARBONATE DEPOSITION

The supply of clastic sediment to a sedimentary basin is largely controlled by the relief and erosion of the hinterland and the climate. On a large-scale, relief is created by geotectonics which determine uplift rates and topography. The generation of terrigenous debris itself is determined by the rock-types exposed, their break-up-ability, and the climate again, which controls the degree of weathering and the type and frequency of sediment transport by ice, wind and water. With regard to climate, a more humid regime leads to persistent mud-rich systems through more intense chemical weathering, the development of soils and presence of vegetation; a more arid climate leads to erratic sand/gravel-rich systems, through a more physical type of weathering and less influence from soils and vegetation. A medium-scale control is sea-level change, which affects position of base-level and gradients, and so sediment supply to the shoreline. Falling sea-level leads to river entrenchment and downcutting, resulting in more clastic input to the basin; rising sea-level on the other hand, causes deposition in higher reaches of a fluvial system and so less sediment reaching the basin.

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Like clastic deposition, carbonate deposition is controlled by many factors, of which latitude, climate, environment (notably the absence of clastics, plus salinity, temperature, nutrient supply, depth and turbulence), sea-level change and tectonics, are the most important. These parameters are often inter-linked of course. The highest levels of productivity occur in the shallow, warm waters of the tropics, especially along high-energy platform margins.

3. EFFECTS OF TERRIGENOUS SEDIMENT ON CARBONATE-SECRETING ORGANISMS

Terrigenous material generally has a detrimental effect on carbonate production, affecting the carbonate-secreting organisms in several ways. Turbidity brought about by fine-grained material in suspension affects organisms by reducing light penetration, causing animals and plants to live at shallower depths, and bunging up their feeding mechanisms. Sudden influxes of mud and sand can smother and bury organisms, and high nutrient levels often accompany terrigenous input and lead to flourishing microbial activity. This has a deleterious effect on many higher organisms which are often oligotrophic.

There are various responses of carbonate organisms to terrigenous input. Some organisms have adapted to move quickly or extricate themselves from under a cover of sand or simply to fling the sediment off their growing surface. Skeletons may be adapted to keep above a mobile sandy substrate, as in finger corals. Others have adapted to soft muddy substrates by having flatter shells, as some bivalves and brachiopods. Animals have also adapted to lower light levels, as in certain corals, by developing a more leafy or platy shape to increase their surface area. Some organisms are adapted to low salinities, which often result from freshwater influx associated with terrigenous material.

4. CONTEMPORANEOUS CLASTIC–CARBONATE DEPOSITION

There are a good number of locations around the world where clastics and carbonates are being deposited in close proximity.

4.1. Delta-front reefs

There are many places where corals and coralline algae are able to tolerate the presence of terrigenous mud and this can lead to the development of local patch reefs. One recently described modern example is the Mahakam Delta, Indonesia, where patch reefs dominated by platy corals are growing on the seaward-margins of abandoned mouth bars, surrounded by terrigenous mud (WILSON & LOCKIER, 2002). The reefs are forming in very shallow-water (<10 m) since light penetration is reduced by turbidity from the terrigenous mud. Patch-reef growth in a deltaic setting can affect the delta development itself by redirecting turbid flows and bottom currents.

Tertiary examples of reefs in a deltaic setting also occur in the subsurface of Indonesia and in Spain, where they grew on fan deltas in the Pyrenean foreland basin (SANTISEBAN & TABERNER, 1988) and Granada Basin (BRAGA et al., 1990).

4.2. Patch-reefs and carbonate sands on clastic shelves

Coral patch reefs growing on clastic shelves are well developed off eastern Australia in the inner-shelf area of the Great Barrier Reef (LARCOMBE et al., 2001). Here the shelf is mostly covered by relict alluvial sediment from earlier sea-level lowstands and reefs grow in areas of coarser, more stable, sands and gravels. Wide expanses of carbonate sand, mostly of calcareous algal origin, occur on the shelf off NE Brazil, where quartz-rich sands were deposited at times of glacially-lowered sea-level (TESTA & BOSENCE, 1998). Mixing is now taking place in many areas through the strong current and wave activity.

Carbonate sands dominated by bivalve, barnacle and serpulid debris occur extensively along the western seaboard of Britain, especially on the West Shetland shelf, where there is now an absence of clastic influx (LIGHT & WILSON, 1998). In both the Brazilian and British shelf cases, the carbonates have formed since the post-glacial (Flandrian) transgression. In fact in any area of clastic sediment starvation, carbonate sediments are likely to accumulate. The well-known white beaches of the Inner and Outer Hebrides with 'coral' sands of comminuted coralline red algae are a case in point, and these occur all the way up to Finnmark, northern Norway.

5. MIXED-LITHOLOGY PARASEQUENCES AND SEQUENCES

Mixed-lithology metre-scale cycles (parasequences) and the much thicker mixed-lithology sequences and high-frequency sequences come in two broad types. In some cases the clastics, generally coarse grained, occur above the carbonates at the top of the parasequence/ sequence (*lower carbonate – upper sandstone cycles*), whereas in others, the clastics, usually mudrocks, occur in the lower part of the units, beneath the carbonates (*lower mudrock – upper carbonate cycles*). These mixed-lithology cycles are developed where carbonate platforms are attached to terrigenous source areas or where there is an axial supply of clastic material to the basin. The clastic input is mostly controlled by sea-level and base-level changes, less commonly through fault-related uplift.

5.1. Lower mudrock – upper carbonate cycles

In metre-scale (4th/5th order) carbonate cycles (parasequences) with lower mudrock beds, the clays are usually deeper-water marine or lagoonal facies, derived from reworking of muddy coastal plains and supplied by rivers. The upper carbonates are oolitic-bioclastic grainstones or peritidal fenestral microbial lime mudstones. Overall, the parasequences themselves are generally shallowing-upward cycles generated by progradation of tidal flats or the shoreface–foreshore over the deeper-water muds. Many of these mudrock–limestone parasequences were subtidal cycles, not subject to subaerial exposure. The depth of deposition of the mudrocks would have been a few to several 10s of metres, and they frequently contain thin storm layers (tempestites), generating ribbon rocks. This type of parasequence tends to be more common in the transgressive parts of cyclic platform successions, or in the deeper-water, more distal parts of carbonate ramps. They are common throughout the geological record, and examples occur in the Cambro-Ordovician of North America (OSLEGER & READ, 1991; JENNETTE & PRYOR, 1993) and China (MENG et al., 1997), Mississippian of northwest USA (ELRICK & READ, 1991) and Triassic Muschelkalk of western Europe (e.g., AIGNER, 1984).

On a larger (3rd order) sequence scale, there are many examples of basinal mudrock–shallow-water limestone sequences. They are rather typical of carbonate ramp successions, and of course may themselves contain an internal smaller-scale cyclicity. Examples of these occur within the Carboniferous strata of South Wales (BURCHETTE & WRIGHT, 1992) and the Cretaceous of the central and western Pyrenees (SIMO, 1989; LENOBLE & CANEROT, 1993) and Austrian Alps (SANDERS & HÖFLING, 2000). Broadly, the deeper-water mudrock lower parts represent transgressive facies, with the upper carbonates being prograding shallow-water highstand facies. The ‘Grand Cycles’ of the Cambrian of the Rocky Mountains (Canada), Appalachians (USA; GLUMAC & WALKER, 2000), China (MENG et al., 1997) and elsewhere, are of this type. The terrigenous muds may well be supplied axially into the basin, rather than across the drowned carbonate platforms. This is particularly the case with foreland basins and narrow extensional basins, where carbonate platforms may be preferentially developed on one side.

5.2. Lower carbonate – upper sandstone cycles

Thin sandstone beds at the top of metre-scale carbonate cycles were generally deposited in fluvial, clastic sabkha and aeolian environments when the carbonate platform was exposed; in some cases these sands were reworked into the basal layers of the next parasequence. Sand layers are most common in the lowstand parts of cyclic successions, close to the sequence boundary zone. Minor and major channels may have been cut into the platform during more significant sea-level falls. Such thin sandstone beds are well described from the Permian in Texas, as in the Yates Formation (BORER & HARRIS, 1991), the Permo-Carboniferous in Texas (SALLER et al., 1999) and the Pennsylvanian of the Paradox Basin (GOLDHAMMER et al., 1994). Minor sandstones also occur in the lowstand parts of lower Palaeozoic cyclic platform carbonates.

On the larger sequence-scale, after transgressive and highstand platform-carbonate deposition, often involving progradation through clinoforms, clastic sediments are commonly deposited during the lowstand, occurring within incised valleys cut during the falling stage, and as lowstand wedges on the foreslope of the platform and on the basin floor. This is the notion of reciprocal sedimentation: lowstand shedding of clastics and highstand shedding of carbonates. This pattern is well seen in the slope and basinal deposits of the Quaternary of the Caribbean area (SCHLAGER et al., 1994) where clastic input to the deep-sea was much greater during glacial times and carbonate input was higher during the interglacials, when carbonate platforms were flooded. Ancient examples are documented from the Cambrian of northern Greenland (INESON & SURLYK, 2000), Devonian of the Canning Basin (SOUTHGATE et al., 1993), the Permian of Texas (e.g., Bone Spring Sands, SALLER et al., 1989), and the Tertiary of northeast Australia and Gulf of Papua (DAVIES et al., 1989).

A further type of carbonate–clastic sequence is where the limestones were deposited during the relative sea-level rise, and clastics deposited during the highstand/stillstand. The lower carbonates were initiated by a rapid sea-level rise such that there was little time for reworking of the coastal plain. However, a plentiful supply of terrigenous material is necessary in this scenario to generate the upper clastic unit, which is usually a coarsening-upward deltaic or shoreline deposit. This type of sequence is well-known from the mid-Carboniferous of America (e.g., SOREGHAN, 1997; RANKEY et al., 1999; MILLER & ERIKSSON, 2000; SMITH & READ, 2001) and western Europe (see Section 7 below).

To illustrate the variety of clastic–carbonate sequences, two case studies are briefly presented of work that the author has been involved in over the last few years and which will be published in detail elsewhere. These are the Quaternary deposits of the Red Sea coast of Egypt where highstand carbonates are associated with lowstand clastics, and the mid-Carboniferous Yoredale cycles of northern England, where transgressive carbonates are succeeded by highstand clastics.

6. QUATERNARY OF THE RED SEA COAST

Modern fringing reefs are beautifully developed along the Red Sea coast of Egypt and in the Gulfs of Suez and Aqaba, but they are also closely associated with episodic clastic influx. There are also fine examples of clastic–carbonate interaction in the Pleistocene sequences exposed along the coast. This case study is based on visits to Marsa Alam, ~200 km south of Hurghada on the Egyptian Red Sea coast (location in Fig. 1), in a collaborative project with the University of Assiut. In this region, fringing reefs are well developed, attached to a low-cliffed shoreline (Plate I, Fig. 1) with major and minor dry river valleys (wadis) dissecting the coastal plain (Plate I, Figs. 2–4). The latter is 5 to 20 km wide and composed of Quaternary and Tertiary clastic and carbonate formations, backed by the Red Sea Hills of Precambrian metasediments and intrusives.

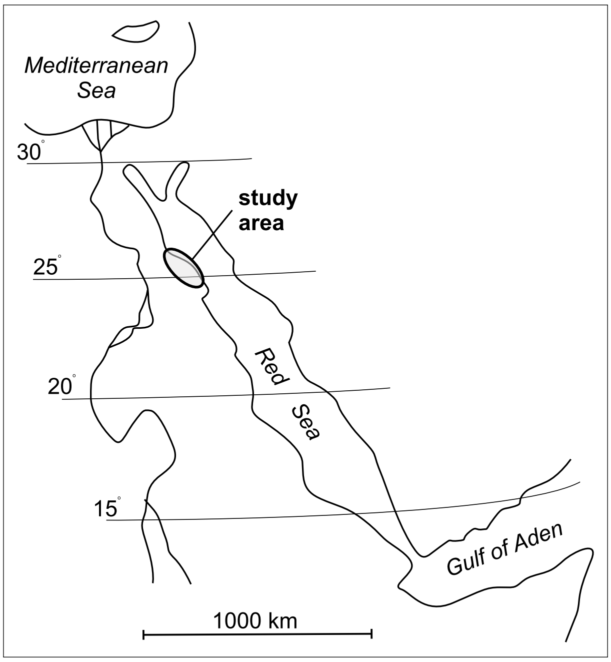

Fig. 1 Location of field area near Marsa Alam, Egypt.

6.1. Recent carbonate deposition

Reefal organisms are growing luxuriously in 0.5 to 30 m of water, along a generally steep to vertical reef-front. A great variety of corals is present, along with all the usual reef-associated fauna and flora. In many places the reef-front itself is indented with grooves and channels, and penetrated by tunnels and caves (Plate II, Fig. 1). These features are cut into the late Pleistocene (MIS 5e) reefal limestone, upon and against which the modern reef is growing, and they relate to fluvial erosion and karstic dissolution during the last lowstand of sea-level (120 kyr–10 kyr BP) (see Figs. 2, 3).

The reef-flat immediately behind the reef-crest is a smooth to uneven rock surface that extends shorewards up to 100 metres (Plate I, Figs. 1, 4). Much of this wave-cut platform is exposed at low spring tides and it is basically planed-off reefal limestone where corrosion and bioerosion are taking place. There is only very minor coral and coralline algal growth there. The reef-flat may extend to the shoreline to be covered by foreshore sands (clastic dominated) or there may be a mixed clastic, lime sand-floored lagoon, water depth <2 m, before the beach.

6.2. Recent clastic deposition

Major wadi systems originating in the Red Sea Hills deliver terrigenous sediment directly to fan deltas along the coast during floods (Plate I, Figs. 3, 4). The wadis cut through the fringing-reef system to form re-entrants (sharms), every 5–10 km along the coast. Fan-delta sediments are reworked in shoreface and foreshore environments at wadi mouths and are mixtures of clastic and carbonate grains. Ooids are locally precipitated in the shoreface areas here.

Minor wadi systems occur all along the coast (Plate I, Fig. 2), with spacings of 50–500 metres, but they do not disrupt the fringing reef. Flash floods deposit sand and gravel at the shoreline and on the reef-flat, and fine material is carried over the reef-crest if the reef-flat is narrow with no lagoon to act as a sink. After a flood, terrigenous sediment on the reef-flat is reworked in the ensuing months and the fine material redistributed, either shorewards to form beaches or seawards to the fore-reef. Clastic grains are also incorporated into reef-flat limestones (Plate II, Fig. 2). Gravels on the reef-flat are wave-reworked to form bars and beaches, and then cemented and blackened (Plate I, Fig. 2).

At the present-time, minor floods occur at any one location around once every 5 years and major floods every few decades. During a flood, the sea close to a wadi is coloured bright red from the suspended clay and this is deposited upon the corals over the ensuing few days. Modern corals do have layers of clay and silt within their skeletal structure. The sediment transported through the wadis to the coast is relatively coarse-grained (reflecting the arid climate and dominant physical weathering), and the flood frequency is low at the present-time. Over the long term the organisms on the reef-front do not appear to be affected by the floods, although corals close to the subaqueous wadi margins are frequently broken.

6.3. Discussion of Recent deposition

The modern Red Sea coast does provide a cool example of syn-deposition of clastics and carbonates, as described earlier by PURSER et al. (1987), and several papers in PURSER & BOSENCE (1998). However, at the present time, with an extremely arid climate in the region and a relative highstand of sea-level following termination of the last ice age, the clastic–carbonate

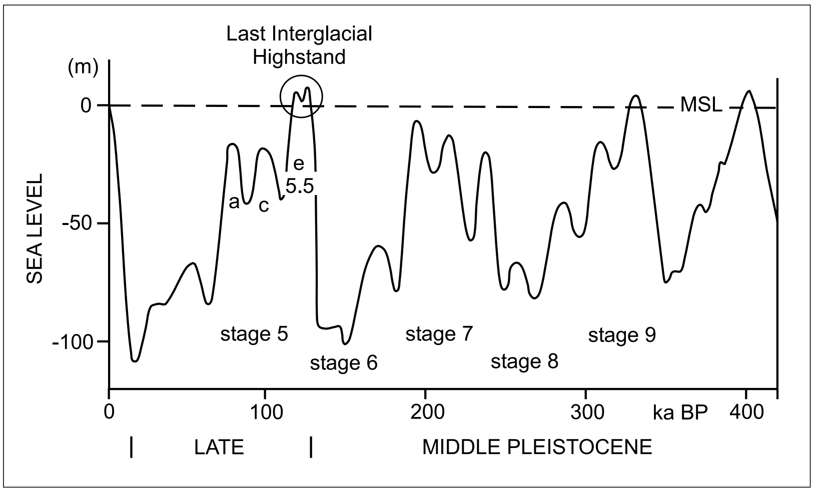

Fig. 2 Sea-level curve for last 500,000 years (after SHACKLETON, 1987).

interaction is relatively minor: a) clastic beaches at the back of the carbonate platform with the terrigenous sediment derived from minor wadis draining the coastal plain, and b) clastics within major wadis cutting through the carbonate platform and feeding fan deltas. Figure 4 presents a facies model summarising this clastic–carbonate system.

On a longer-term perspective of a cycle of sea-level change, such as a glacial–interglacial cycle, the facies model will evolve. During a relative sea-level fall, carbonate sedimentation would be terminated as the platform and the reef-front became exposed. Initially some clastics may be deposited across the reef-flat but with little and then decreasing accommodation space there, it could only be a thin layer. The platform would be subjected to karstification, and platform-margin collapse generating megabreccias would be likely. Reefs might be established again when sea-level stabilised at its low point, although this would depend on the angle of the slope.

The fluvial system would become incised during the forced regression of the falling stage, such that more terrigenous sediment would be supplied to the marine fan delta. Whether more sediment would be generated in total would depend on the climate and frequency of floods. Evidence from the region suggests that during the last glacial episode the climate was indeed wetter (LEZINE & CASANOVA, 1991; PLAZIAT et al., 1998), such that more clastic sedimentation would have been likely.

The sequence model for this system is thus one of a highstand prograding reefal carbonate platform, with minor interbedded clastics at the shoreline, immediately overlain by very thin shoreface–foreshore clastics, and then fluvial facies, of the late highstand/early falling stage. Fan deltas will be especially active during lowstands, particularly if the climate was more humid and flood frequency increased. During a subsequent sea-level rise, reworking of the clastics on the platform-top would provide the foundation for the next transgressive/highstand carbonate platform.

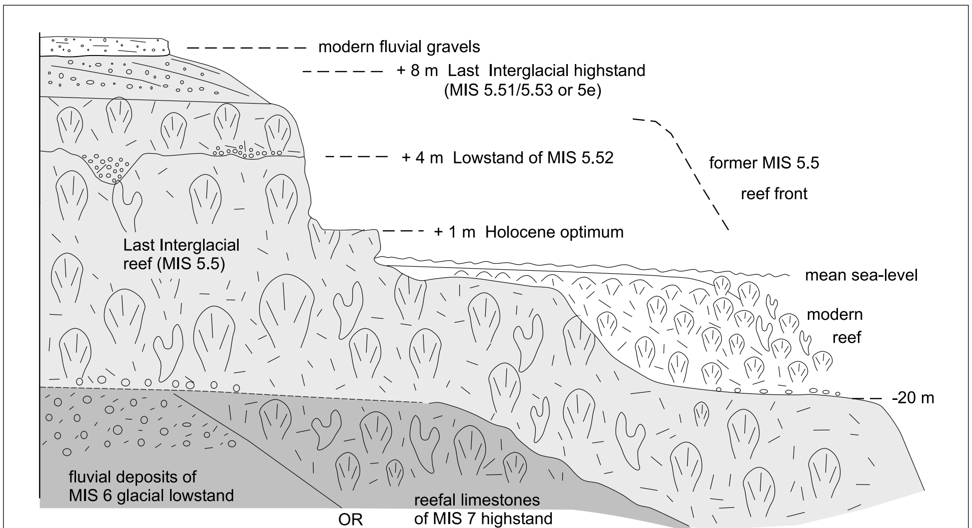

Fig. 3 Stratigraphy of the Quaternary of the Red Sea coast, Marsa Alam, Egypt.

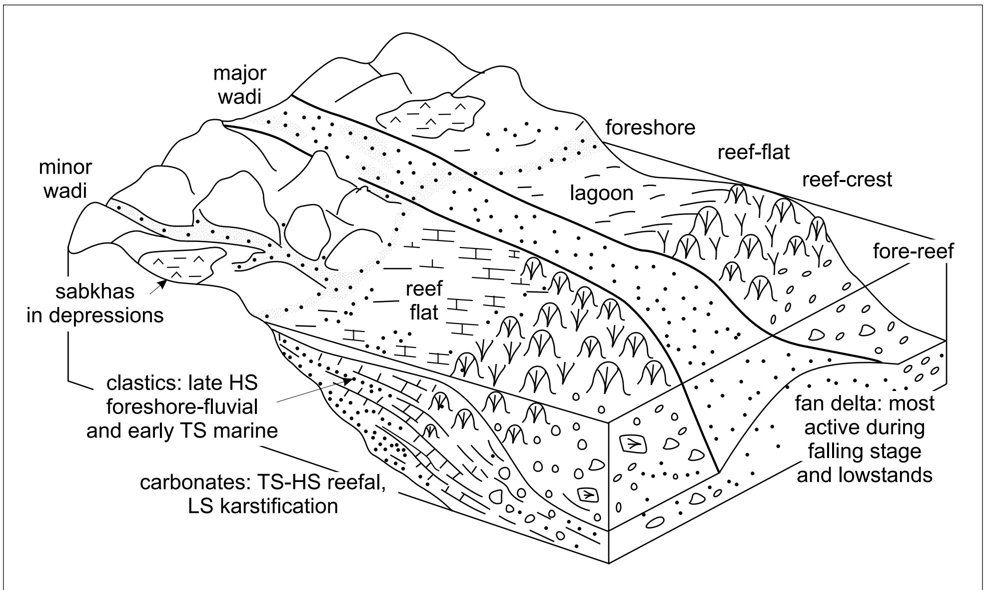

Fig. 4 Facies model for clastic–carbonate interaction, Recent, Red Sea coast.

6.4. Pleistocene of the Red Sea

Coral reefs were well developed during the Pleistocene of the Red Sea region and are now well-exposed along the coastal plain in Egypt, adjacent to the modern fringing reefs. The reefs were deposited during interglacial highstands of sea-level, of which there were four during the last 500,000 years (see Fig. 2 and papers in PURSER & BOSENCE, 1998). Interbedded with the Pleistocene carbonates are terrigenous clastics of a variety of facies, but mostly well-sorted lithic sands and pebble conglomerates, with cross-bedding and lenticular bedding. These were deposited in shoreface–foreshore and fluvial environments, either contemporaneous with reef sedimentation, or during subsequent lowstands. This section focuses on the last-interglacial reefal unit exposed in the Marsa Alam area, which was deposited around 120–130,000 years ago, i.e. marine isotope stage (MIS) 5e or 5.5 (Figs. 2, 3). It shows some awesome features of clastic–carbonate interaction. This is an area where there has been no tectonic uplift for at least 1 million years.

6.5. Last-interglacial reefal carbonates

The MIS 5e reef was deposited when sea level was up to 8 metres higher than present and so the deposits are well exposed in low cliffs along the modern coast. However, within the reefal unit there is clear evidence for a minor sea-level fall and rise, dividing the last-interglacial reef into two parts: the lower deposited during MIS 5.53 and the upper during MIS 5.51. This minor sea-level perturbation in MIS 5e has been recorded elsewhere (Bermuda, HEARTY, 2002; Bahamas, KINDLER & HEARTY, 1996; and Sardinia, KINDLER et al., 1997). Indeed, along the Red Sea coastal plain subaqueous gypsum was deposited in lakes and bays at the time of the lowstand in the depression which was the former lagoon behind the reefs (ORSZAG-SPERBER et al., 2001).

The MIS 5e reefal carbonates consist of large coral colonies up to several metres in diameter composed of *Montastrea, Porites* and *Galaxea* (e.g., Plate II, Fig. 3). There are many smaller corals, as well as molluscs, echinoids, calcareous algae and serpulids. There are also pockets and lenses of carbonate sand and gravel, with varying amounts of fine terrigenous material. Landwards, the reefal unit passes into foreshore/shoreface conglomerates with a transition zone of mixed carbonates and clastics (Plate II, Fig. 4). The reefal limestone appears to have grown on coarse pebbly–sandy terrigenous debris with marine shells and other fossils, although the base of the 5e reef is rarely seen.

6.6. Clastics within MIS 5e reefal carbonates

Within the last-interglacial reefal limestone, there is a marked disconformity at about 4 metres above the base, reflecting a sea-level fall. The disconformity can be found in many localities and is mostly a planar surface which can be followed for up to 100 metres in wadi-cliff exposures. It is interpreted as a wave-cut platform. In one locality (Wadi Mouran), there are low-angle dipping limestones below and horizontal coral-rich limestones above. At another locality (Wadi Shagra), the disconformity terminates landwards (500 metres from the present shoreline or 1000 metres from the modern reef-crest) at a well-developed wave-cut notch (Plate III, Fig. 1). The surface here is overlain by gently offshore (eastward) dipping foreshore conglomerate and sandstone (up to 1.5 m thick), banked into the notch. Traced laterally the clastics thin to less than 0.5 m. Limestone with corals occurs above the clastics on the disconformity, and indicates a sea-level rise and resumed carbonate sedimentation.

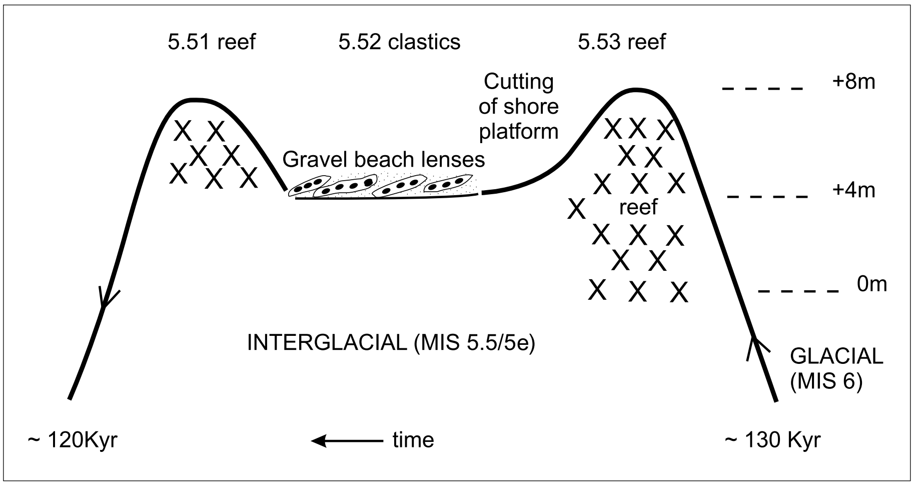

Fig. 5 Sea-level change and deposition, last interglacial reef (MIS 5e/5.5), Red Sea.

There are also channel structures locally cut into the reef (e.g., Wadi Mouran), at the horizon of the disconformity, filled with well-sorted and rounded mixed clastic–carbonate sand (Plate III, Fig. 2). These channels are interpreted as having been cut during the sea-level fall and filled during the subsequent MIS 5.51 sea-level rise, which was then followed by the second stage of reefal limestone growth.

In exposures in Wadi Samadai, several shingled, low-angle dipping conglomeratic lenses, prograding seawards, are present on the disconformity surface (Plate III, Figs. 3, 4). They consist of well-sorted terrigenous gravel and lenses of sand, crudely bedded, with dispersed fossils of molluscs and coral fragments. These units are clearly foreshore deposits passing laterally (seawards) into thin lithic sand-dominated shoreface sediments. These marine deposits are a series of prograding clastic beaches upon a wave-cut platform, developed at a time of sea-level stillstand after the cutting of the wave-cut platform (Fig. 5). The lenticular nature of the conglomerates suggests that there were periodic influxes of terrigenous gravel and sand to the shoreline. Most likely these would have been brought to the shoreline by longshore drift from a major wadi. The regular arrangement of the beach lenses could indicate periodic climatic changes, and these would have been on the millennial scale.

Thus the latest Pleistocene reefal unit of the Red Sea coast presents a useful example of clastic deposition within an overall carbonate succession and this was the result of a relatively small sea-level fall (probably the order of 3–4 metres).

7. MIXED CARBONATE–CLASTIC HIGH-FREQUENCY SEQUENCES, MID-CARBONIFEROUS, NORTHERN ENGLAND

High-frequency sequences are a feature of the mid-Carboniferous of Europe and farther afield and carbonate–clastic cycles referred to as Yoredale cycles are particularly well-developed in northern England. They occur within the Carboniferous Limestone and Scremerston Coal Groups (Fig. 6) (Holkerian, mid-Viséan, to mid-Namurian) across the Northumberland and Stainmore Basins and Alston and Askrigg blocks (Fig. 7). There are up to 60 cycles with an average thickness of around 25 metres, and they are generally

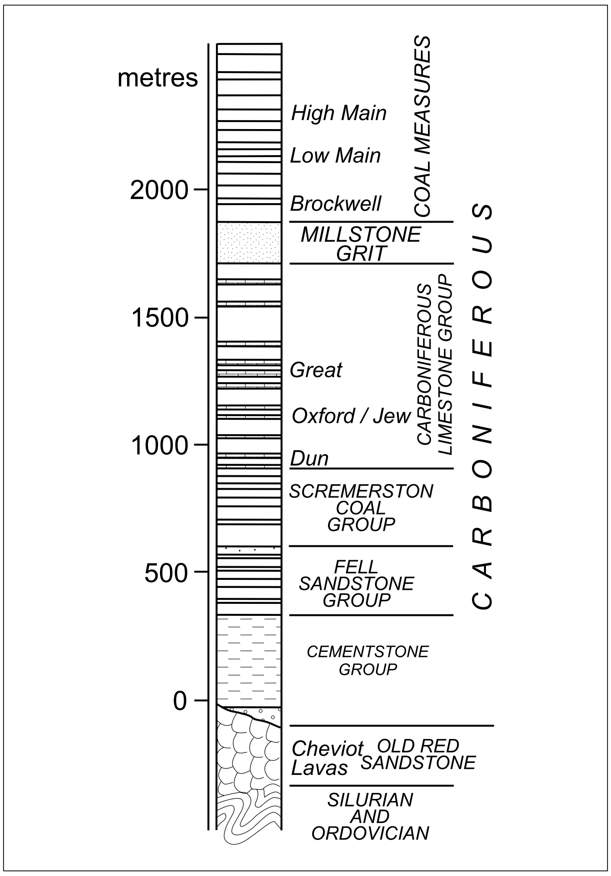

Fig. 6 Stratigraphy of the Carboniferous of N.E. England. Yoredale cycles occur within the Scremerston Coal Group and Limestone Group, where lines represent limestone units. Lines within the Coal Measures are major coal seams.

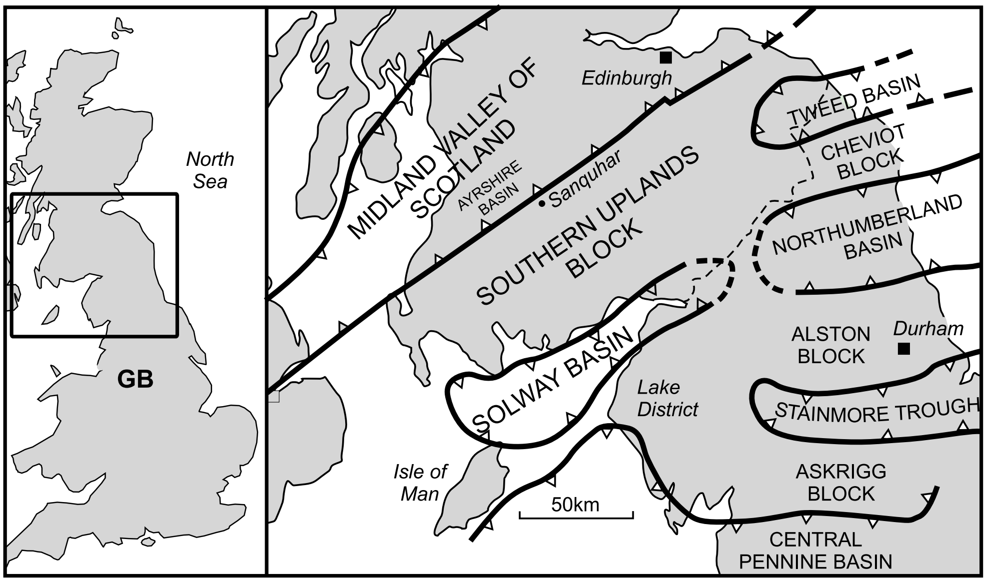

Fig. 7 Location and palaeogeography, mid-Carboniferous, northern England/southern Scotland.

thicker in the basins and thinner on the blocks. There was no surface expression of the boundaries between blocks and basins; they were simply areas of differential subsidence, although bounded by faults. The platform margin was located on the south side of the Askrigg block in central Yorkshire, with the deeper-water Bowland/Central Pennine Basin to the south.

The Yoredale cycles typically consist of a lower limestone unit, which can be correlated over several 100 sq km, and an upper coarsening-upward clastic succession of mudrocks to sandstones (see Fig. 8 and Plate IV). In many cases there is a palaeosoil and thin coal seam at the top, or several minor (metre-scale) cycles.

7.1. Carbonate deposition

Typically, the Yoredale limestones are well-bedded muddy bioclastic packstones–wackestones 1–20 metres thick (Plate IV, Fig. 1). Corals, crinoids and brachiopods are the most abundant fossils, but calcareous algae, foraminifera, molluscs and bryozoans are also common. The limestones contain lenses and discontinuous layers of skeletal debris, probably the result of storm reworking. Bioturbation is ubiquitous, mostly cm-sized burrows, some with pelleted walls. Locally there are small biostromes of larger colonial corals (0.3 m diameter), of *Siphonodendron* especially, some of which may be overturned, or beds of the solitary coral *Dibunophyllum* as in the famous Frosterley 'marble'. The basal bed (up to 0.5 m thick) of some limestones (also the basal bed of the cycle) is a prominent sand-rich or clay-rich bioturbated packstone with fish scales, crinoids and brachiopods. The clastic material here is derived from reworking of the top of the cycle below.

The limestones were probably deposited in water depths of 10–40 metres, in a generally quiet environment with only occasional storms. This was effectively an extensive and flat, low-energy platform, probably 150 km across, with a gentle slope with mud mounds and debrites into deeper water of the Central Pennine Basin to the south.

7.2. Clastic deposition

Two main types of clastic package occur above the limestone in a Yoredale cycle (Fig. 8): (1) a dominantly deltaic unit of prodelta mudrocks passing up into distal mouth-bar then proximal mouth-bar sandstones (Fig. 8a; Plate IV, Figs. 2, 3). In some cases a channel sand-body cuts down into mouth-bar sandstone (Plate IV, Fig. 4). (2) a deep to shallow-marine succession of mudrocks to sandstones with tempestites and HCS from storms and a range of trace fossils, and then shoreface–foreshore cross- and flat-bedded sandstones (Fig. 8b).

At several horizons in the succession, major lenticular sand bodies composed of cross-bedded medium to very coarse sandstone cut down 10 metres or more into the coarsening-upward unit, almost reaching the limestone at the base of the cycle (Fig. 8c; Plate IV, Fig. 4). These shoestring sand-bodies show a fining-up of grain-size and a decrease of cross-bed set thickness, and in some cases wave-ripples and burrows towards the top. These sandstones are interpreted as incised-valley fills.

At the top of the Yoredale cycles, there is usually a palaeosoil (seatearth, fireclay, underclay, ganister) of variable grain-size, colour, thickness and texture. Rootlets, nodules (siderite or calcrete), and/or polygonal cracks may be present, depending primarily on climate. A thin coal seam may complete the cycle (Fig. 8), but is often absent. One or several metre-scale ('minor') coarsening-upward cycles may also occur at the top of the Yoredale cycle (as in Fig. 8a). These coastal-plain facies result from small deltas filling lakes and bays.

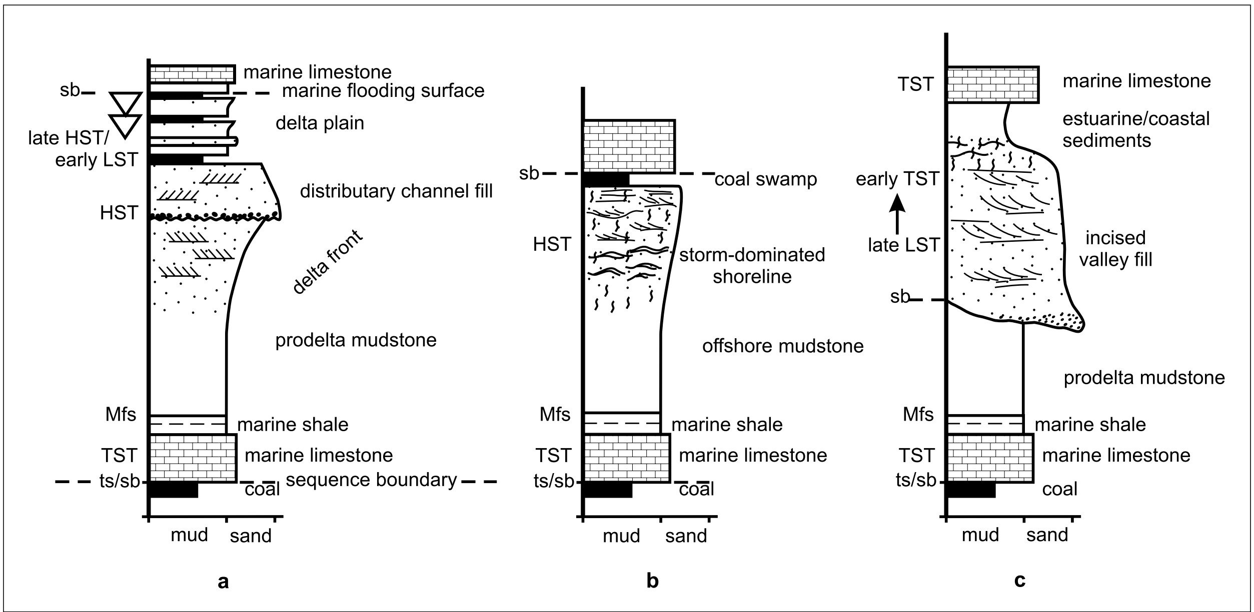

Fig. 8 Varieties of carbonate–clastic Yoredale high-frequency sequence: a) limestone–deltaic clastics sequence with minor cycles at top; b) limestone–shoreline clastics sequence, c) incised-valley sandstone–limestone–deltaic clastics sequence.

7.3. Origin of cyclicity

The origin of the Yoredale cycles has been much discussed with tectonic, eustatic and sedimentary mechanisms all put forward (e.g., LEEDER & STRUDWICK, 1987). Plots of cycle thickness variation through the succession (Fischer plots) for several localities from both block and basin areas reveal a similar pattern, supporting the role of eustasy and/or regional tectonics (subsidence), but ruling out a local tectonic (i.e., fault) or sedimentary control. There is also a pattern through the succession in the facies distribution within cycles, with more carbonate-dominated cycles in the lower part of the succession and more clastic-dominated cycles in the upper part. There is also a trend in the clastic grain-size, with more coarse clastics in the upper Asbian cycles and finer clastics in the cycles above and below. These patterns are related to the general decrease in marine influence and increase in clastic supply through the upper Dinantian–Namurian, a function of plate-scale tectonics, and a more arid climate in the upper Asbian.

Although there is much uncertainty in the Carboniferous time-scale, the duration of the Yoredale cycles would appear to be the order of one to several 100,000 years. The mid-Carboniferous was a period of glaciation in the southern hemisphere so that it is very likely that eustasy exerted a strong control on sedimentation. The cycles are interpreted as the result of the eccentricity orbital rhythm, most likely the long (400 kyr) one.

7.4. Sequence stratigraphy

From a sequence stratigraphic point of view, the Yoredale cycles are interpreted as high-frequency sequences (model presented in Fig. 9). The limestone units were clearly the result of rapid flooding and transgression across a low-relief coastal plain, with only local reworking of underlying sediments. A glacioeustatic mechanism best explains this. The carbonates are thus the transgressive systems tract. The progradation of deltaic shorelines or storm-dominated shorefaces, which led to the coarsening-upward clastic units, is the product of highstand deposition. The influx of the prodelta clay terminated carbonate production. The palaeosoils represent the late highstand, falling-stage and lowstand intervals, which may have been quite short periods of time judging by rates of sea-level change in the Quaternary. The coals could have been generated during the earliest stages of sea-level rise, as accommodation space was beginning to be created, but their thin nature (or absence) followed by widespread deposition of the limestones suggests rapid sea-level rises.

The major downcutting sand-bodies which occur at specific stratigraphic horizons are interpreted as incised-valley fills. They represent times of sharper and deeper glacioeustatic sea-level falls. The valleys would have fed lowstand fans in the Central Pennine Basin to the south.

8. DISCUSSION: GENERAL PATTERNS AND TRENDS

With the different types of mixed-lithology cycle, the lithofacies succession depends on the rate of sea-level change and availability of clastics. Slow sea-level rises can lead to extensive reworking of coastal-plain clastics and so well-developed clastic lower parts to cycles. More rapid sea-level rises cause flooding of coastal plains and so little reworking of sediment, especially if

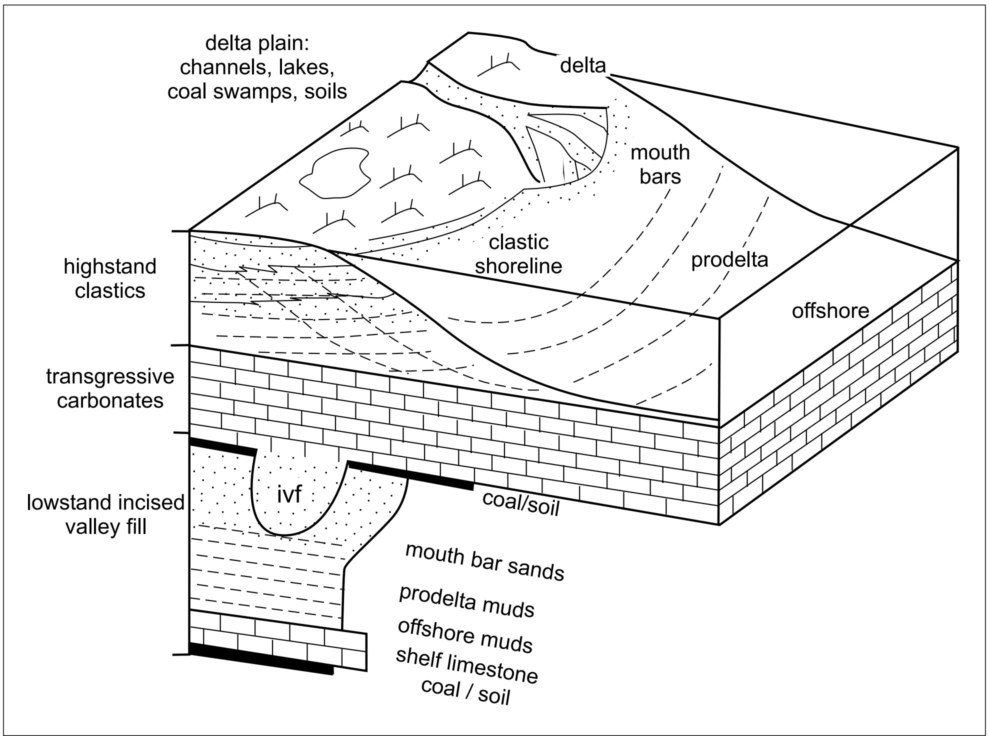

Fig. 9 Depositional model for lower carbonate–upper clastic sequence based on Yoredale cycles.

there had been extensive pedogenesis and/or vegetation cover, such that ravinement erosion was limited. At the other end of the sea-level cycle, stillstands allow alluvial-plain, shoreline and deltaic facies to prograde over highstand carbonates, with accommodation space determining thickness. A forced regression and the falling stage systems tract lead to platform exposure, river incision and the formation of lowstand fans and wedges on the basin-margin and incised-valley fills on the platform-top.

Mixed carbonate–clastic sequences are best developed at times of high amplitude sea-level change, and since these are typical of icehouse conditions, they are well-represented in the Quaternary and Permo–Carboniferous. During these times the high-frequency sea-level fluctuations were on the scale of 10's of metres and this was sufficient to bring terrigenous sediment into the depositional environment during a sea-level fall. The Permo–Carboniferous was also a time of first-order sea-level lowstand, in other words there were more of the continental landmasses exposed for weathering, erosion and denudation than at other times. The late Palaeozoic was also a period of supercontinent assembly, when mountain ranges were forming, being uplifted and eroded.

During greenhouse times, lower and mid-Palaeozoic and Mesozoic, low amplitude sea-level changes were the norm and extensive carbonate platforms and clastic shelf seas were typical. Most shallow-marine, continental-shelf sequences of these periods are composed of single, uniform lithofacies, all clastic or all carbonate. The mixed carbonate–clastic sequences discussed here were rarely developed.

Mixed-lithology sequences may also involve cool-water carbonates, which are being increasingly recognised in the geological record and were deposited extensively around the Mediterranean in the Tertiary. However, it has recently been shown that these sediments respond in different ways to sea-level change with wave action generating shell beds during lowstands and sandstone units formed during the sea-level rise (BRACHERT et al., 2003). Thus, here it is a case of lowstand carbonates and highstand sandstones.

The two examples of mixed clastic–carbonate formations discussed in this paper illustrate the variety that is encountered in the sedimentary record. However, much of this is due to the completely different climatic regime of the arid/semi-arid Red Sea in the Quaternary versus equatorially-humid England in the Carboniferous. In large part this is responsible for the difference in dominant clastic sediment type: coarse (sand–gravel) in the Red Sea versus fine (mud–sand) in the Carboniferous. In both cases, carbonates were deposited during rising sea-level, after some reworking of coastal plain clastics. In the case of the Red Sea, carbonate deposition continued into the highstand with some minor intercalation of clastics along the shoreline from local fluvial input under the arid climate. In the Carboniferous case, once sea-level had peaked, then, under the humid climate, clastic shorelines and deltas prograded rapidly across the platform during the highstand, and terrigenous prodelta mud inhibited and then terminated carbonate production. In both cases, during the falling stage and lowstand of sea-level, terrigenous clastics were funnelled through major wadis and incised valleys to fan deltas and lowstand wedges at the basin-margin. In the Red Sea, the exposed carbonate platform was karstified, whereas in the Carboniferous, extensive palaeosoils developed on the subaerially-exposed coastal-fluvial plain.

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Plate I

Carbonate–clastic interaction, Recent, Red Sea coast, Egypt

1 Fringing reef and reef-flat along the coast near Marsa Alam and low cliffs of late Pleistocene reef.

2 Minor wadis supplying sediment to the shoreline. Reef in mid-distance with reef-flat and lagoon in near-distance.

3 Major wadi supplying terrigenous sediment to a fan delta.

4 Major wadi entering the sea, cutting through fringing reef and feeding submarine fan delta.

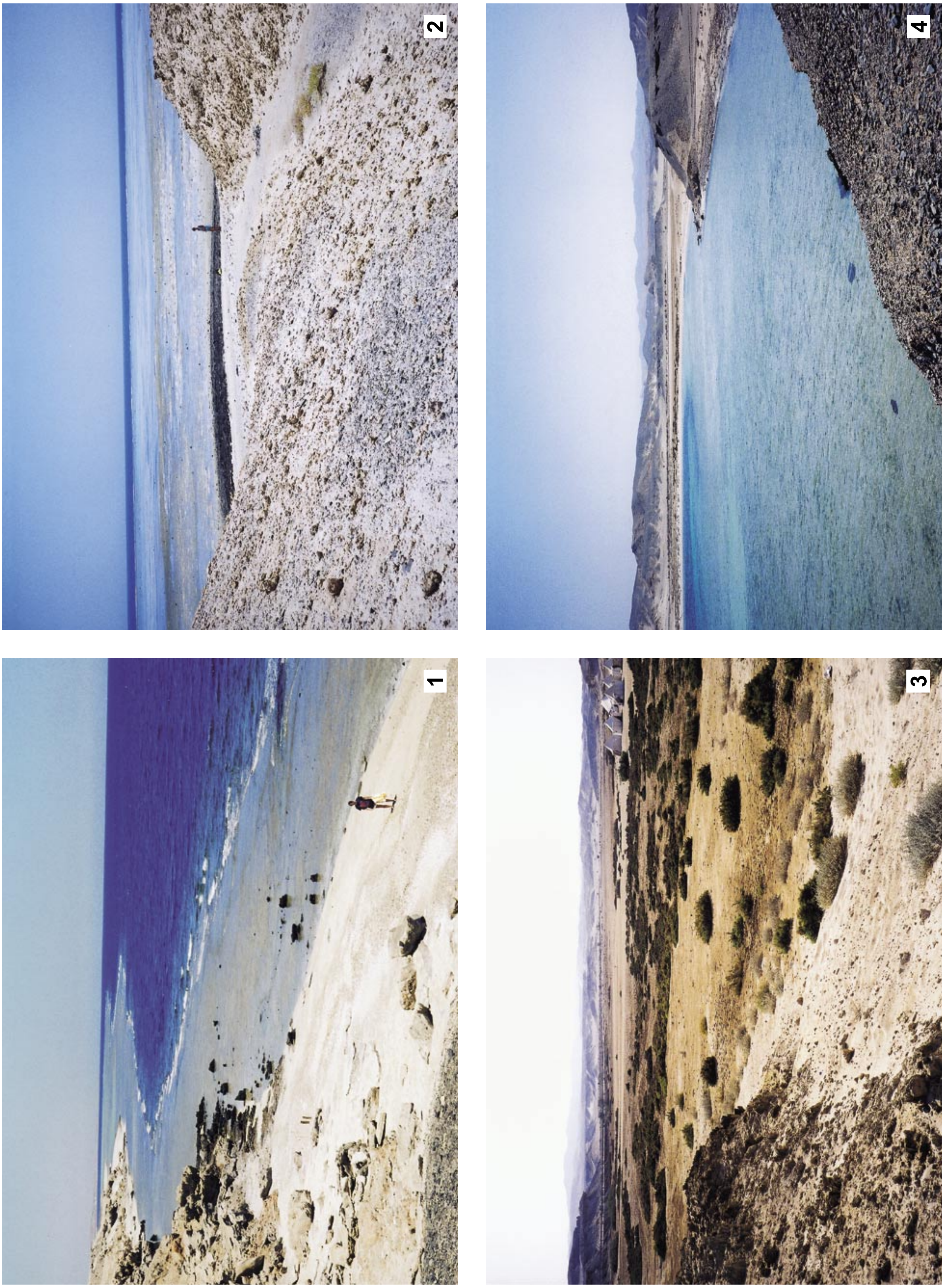
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Plate II

Carbonate–clastic interaction, Recent and Pleistocene, Red Sea coast, Egypt

1 Modern reef-front with channels and tunnels cut into last interglacial, highstand reef during last glacial lowstand.

2 Silt grains within modern reef-flat coral.

3 Large coral colonies within last interglacial (MIS 5e/5.51) reef.

4 Large coral colonies in foreshore conglomerates and sandstones. Last interglacial (MIS 5e/5.51) reef (late Pleistocene).

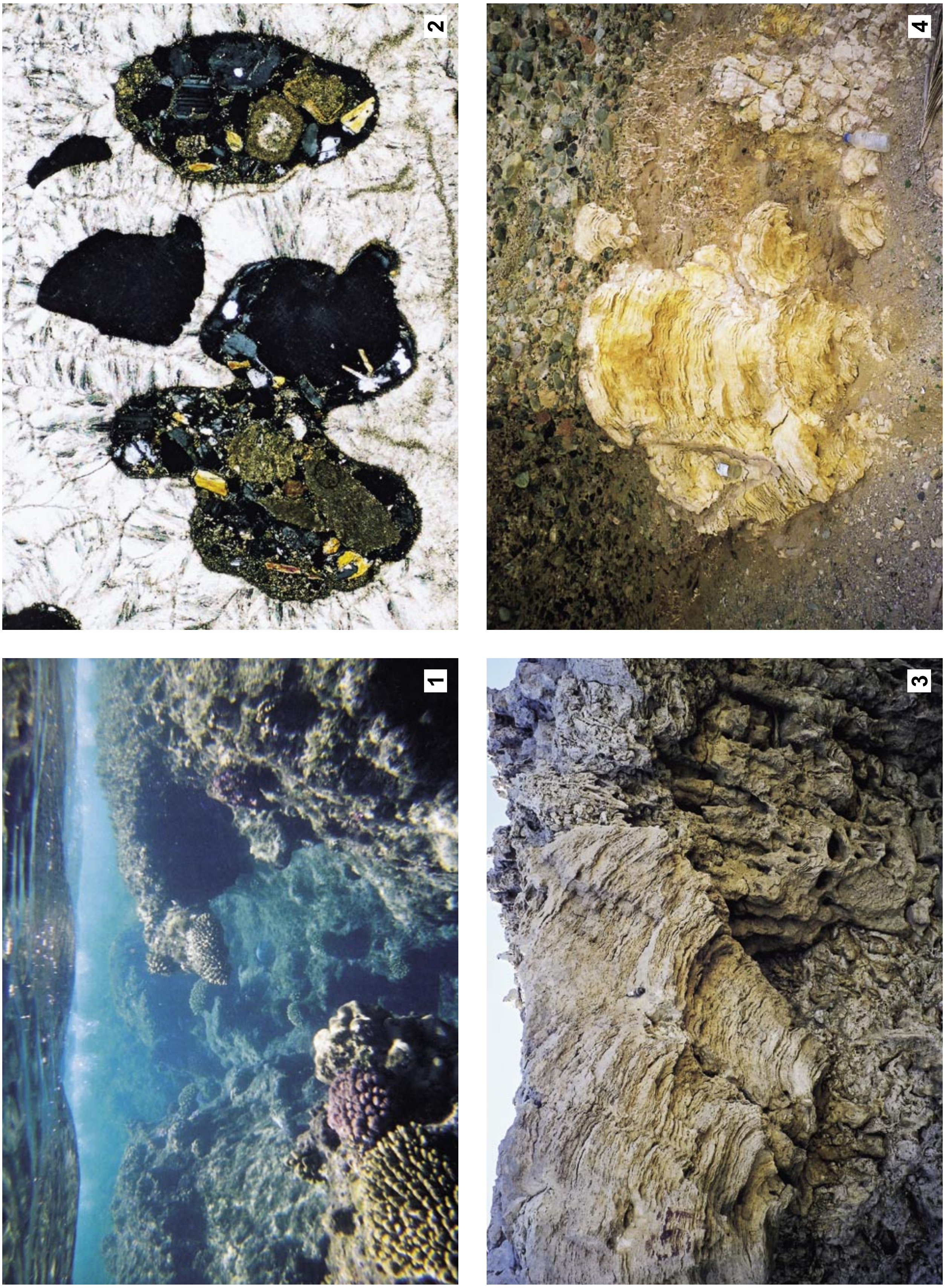
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Plate III

Carbonate–clastic interaction, Pleistocene, Red Sea coast, Egypt

1 Reefal limestones with wave-cut platform and wave-notch overlain by beach gravels and sands. Last interglacial (MIS 5e/5.5) reef.

2 Reefal limestone with a small incised channel of sandy-grainstone.

3 Reefal limestones within which are shingled beach conglomerates upon a wave-cut platform.

4 Two shingled beach conglomerate lenses upon reefal limestone (MIS 5.51 reef).

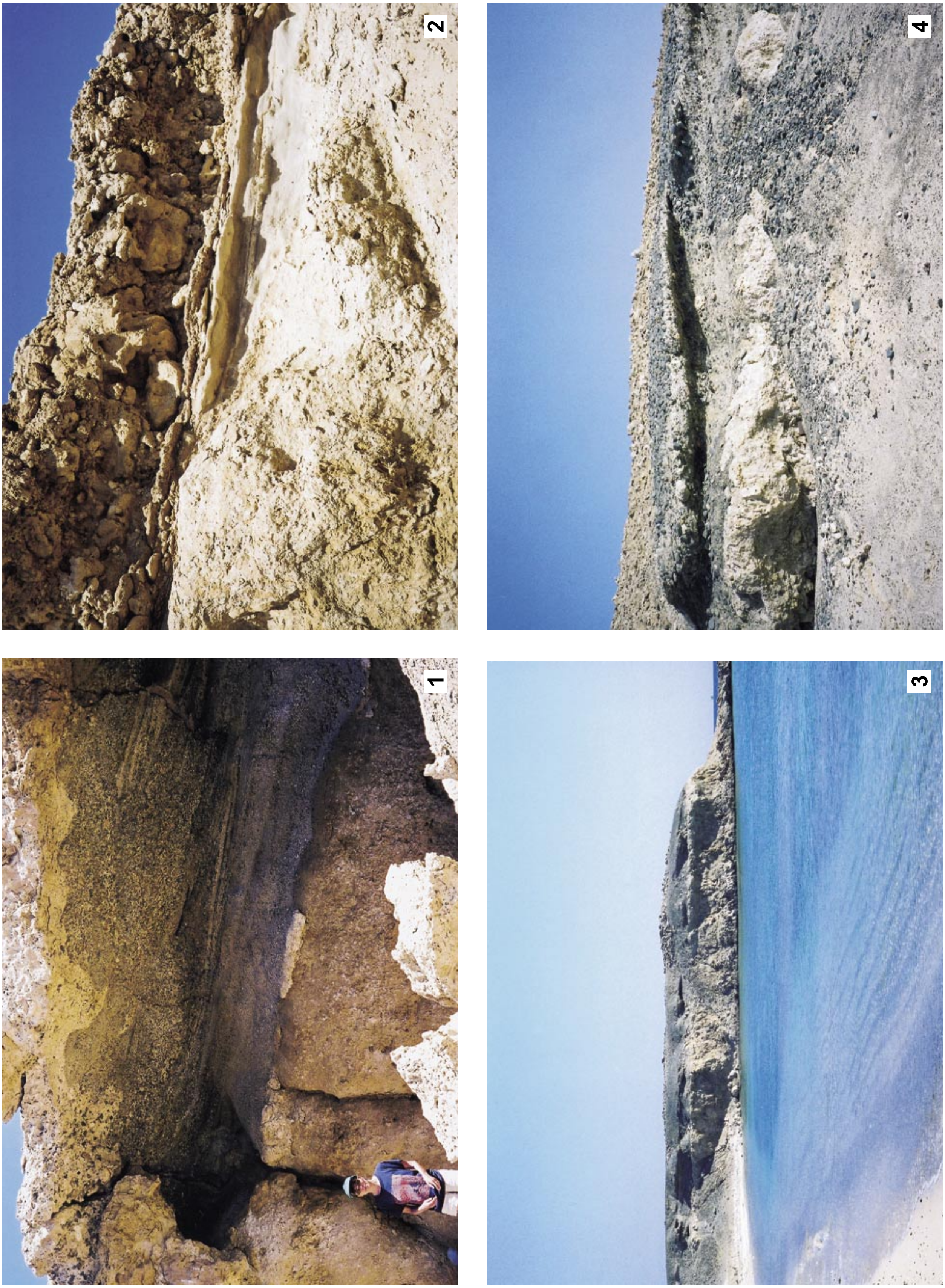
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Plate IV

Mid-Carboniferous high-frequency sequences (Yoredale cycles), NE England

1 The Great Limestone – the thickest carbonate (~20 m) of the Yoredale cycles. Weardale, Co. Durham.

2 Coarsening-upward prodelta mudrock to mouth-bar sandstone above the Howick Limestone. Howick, Northumberland.

3 Limestone (upon a palaeosoil) overlain by marine mudrock, then prodelta mudstone passing up into deltaic sandstone and palaeosoil/coal, before next limestone. Scremerston, Northumberland.

4 Channel cutting into top part of Yoredale cycle; basal limestone marked. Howick, Northumberland.


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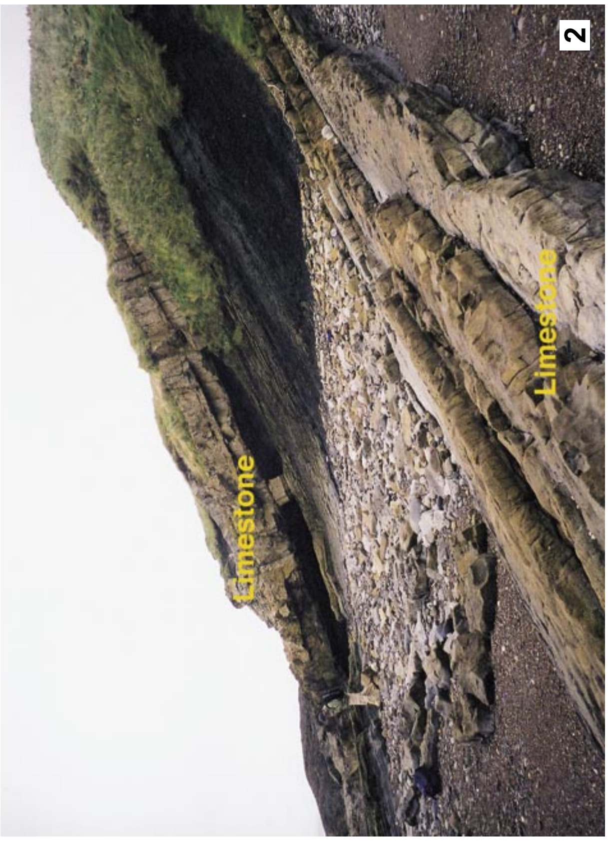
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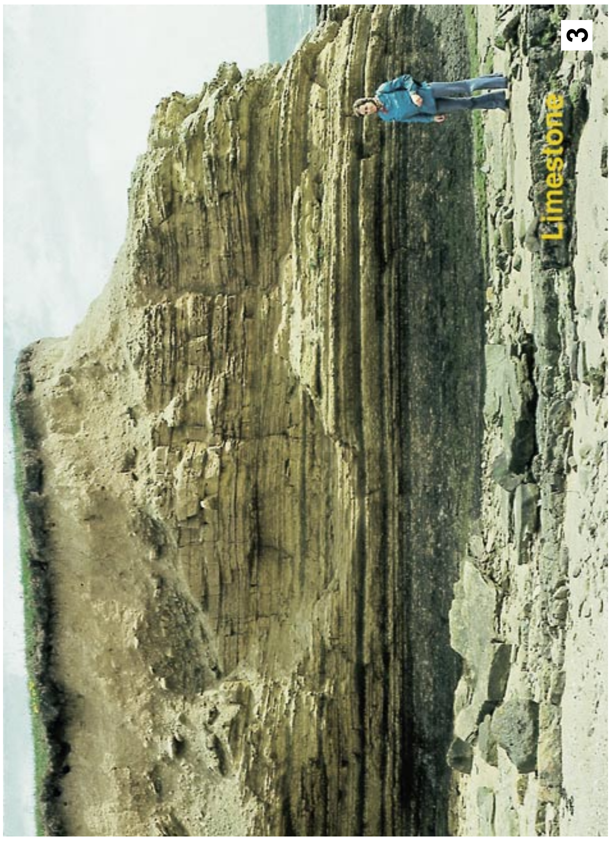
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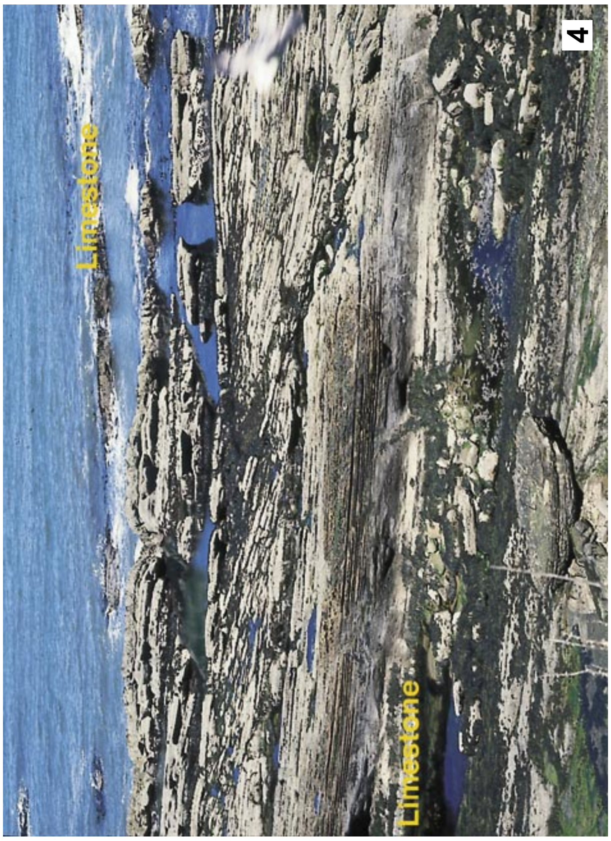
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