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Reef-island topography and the vulnerability of atolls to sea-level rise

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Abstract

Low-lying reef islands on the rim of atolls are perceived as particularly vulnerable to the impacts of sea-level rise. Three effects are inferred: erosion of the shoreline, inundation of low-lying areas, and saline intrusion into the freshwater lens. Regional reconstruction of sea-level trends, supplementing the short observational instrumental record, indicates that monthly mean sea level is rising in the eastern Indian and western Pacific Oceans. This paper reviews the morphology and substrate characteristics of reef islands on Indo-Pacific atolls, and summarises their topography. On most atolls across this region, there is an oceanward ridge built by waves to a height of around 3 m above MSL; in a few cases these are topped by wind-blown dunes. The prominence of these ridges, together with radiocarbon dating and multi-temporal studies of shoreline position, indicate net accretion rather than long-term erosion on most of these oceanward shores. Less prominent lagoonward ridges occur, but their morphology and continuity are atoll-specific, being a function of the processes operating in each lagoon. Low-lying central areas are a feature of many islands, often locally excavated for production of taro. These lower-lying areas are already subject to inundation, which seems certain to increase as the sea rises. Tropical storms play an important role in the geomorphology of reef islands in those regions where they are experienced. Topographical differences, as well as features such as emergence of the reef flat and the stability of the substrate, mean that islands differ in terms of their susceptibility to sea-level rise. Further assessment of variations in shoreline vulnerability based on topography and substrate could form the basis for enhancing the natural resilience of these islands.

Keywords: atoll; reef island; topography; vulnerability; sea-level rise

1. Introduction

Atolls comprise annular mid-ocean reefs around a central lagoon. The reef rim may contain discrete, or near-continuous, *reef islands* composed of unlithified or poorly consolidated carbonate sand and gravel. Reef islands on atolls appear fragile and are frequently claimed to be some of the most threatened of coastal systems in the face of sea-level rise (McLean and Tysban, 2001; Nicholls et al., 2007).

There have been several preliminary assessments of the vulnerability of atoll reef islands to sea-level rise (e.g. Roy and Connell, 1989, 1991; Lewis, 1989, 1990). The principal impacts anticipated fall into three categories: shoreline erosion, inundation and flooding, and saline intrusion into the water table (Mimura, 1999). Efforts to adapt to the impacts of climate change should be based on the intrinsic capacity of the natural system to adapt, termed autonomous adaptation, supplemented by planned adaptation, which may include coastal protection or other social and infrastructural changes (Klein and Nicholls, 1999; Hay et al., 2003). Reef islands exhibit a degree of physical resilience, and it is important to understand shoreline behaviour so that it can be enhanced by various levels of cultural, or socioeconomic, adjustment by atoll communities in the face of climate and sea-level change (Kay and Hay, 1993; Barnett and Adger, 2003). Best management practice needs to enhance the resilience of the system and reduce both natural and socioeconomic susceptibility (Mimura, 1999).

Sea-level rise is not the only danger that climate change poses for atolls (for example, increased sea surface temperature threatens more widespread coral bleaching, and changes in storm intensity mean more damaging storms may hit islands and cause greater damage, Nicholls et al., 2007). However, sea-level rise has recently been demonstrated in the seas around atoll

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nations, at close to the global average rate (Church et al., 2006), reinforcing the urgency of assessing their vulnerability to this aspect of climate change.

Church et al. (2006) have extended the short observational instrumental record of sea-level change from tide gauges in oceans bounded by 40°S and 40°N, 30°E and 120°W using satellite altimetry. Their approach clearly indicates that monthly mean sea level is rising in this region. Whereas TOPEX/Poseidon data for the period 1993–2001 imply average sea-level rise of 4 mm/yr, this incorporates much variability, especially along the tropical Pacific in response to strong El Niño-Southern Oscillation (ENSO) variability. Church et al. (2006) use tide-gauge data to estimate the amplitude of empirical orthogonal functions (EOF) whose spatial structure was established from the satellite altimetry data (following procedures in Church et al., 2004). Over the period 1950–2001, an average of 1.4 mm/yr was derived using this reconstruction. Although Glacial Isostatic Adjustment (GIA) was included in determining global fields, no GIA component was applied to site-specific records; if it is taken into account then the rate is comparable to the global average rate of sea-level rise. The analysis by Church et al. (2006) provides realistic regional variations of sea level and time series of estimated sea-level change at individual mid-ocean locations over longer periods than generally available from tide-gauge data alone (Fig. 1). The trends show good correlation with the sparse tide-gauge data available, even when individual sites are left out of the reconstruction.

This paper reviews the structure and evolution of the rim of atolls and their response to past sea-level change. It describes the surface morphology and substrate characteristics of reef islands on atolls in the Pacific and Indian Oceans, in order to provide a basis for assessing the implications of anticipated future higher sea levels and the relative vulnerability of different parts of the islands. Prominent ridges along oceanward shores imply that many reef islands have undergone incremental growth in the past, and may continue to accrete sediment rather than experience net erosion of these shorelines. However, lagoonal shores and the low-lying interior of islands are already subject to inundation which is likely to pose an increasing threat to atoll communities. Greater understanding of the morphodynamic development of reef islands is needed to ensure sustainable land use and to increase the natural and socio-economic resilience of these systems.

2. Atoll structure and Quaternary evolution

The term ‘atoll’ is derived from the Maldivian (Dihevi) word *atolu*. Atolls are generally ring-shaped reefs occurring in mid-plate settings in the Pacific and Indian Oceans. Atolls generally form an annular reef around a central lagoon; however, within most archipelagoes of atolls there are also isolated *table reefs*, where only a single island is found on the smaller reef platform, or the lagoon is a residual feature such as a swampy depression. Reef islands vary considerably in size and shape and can occur around the entire rim or may be restricted to one or more margins. It is possible to distinguish sand cays (small sandy islands) and motu (a Polynesian term for island, often applied to those islands composed predominantly of shingle), although the distinction is not always clear (Stoddart and Steers, 1977;

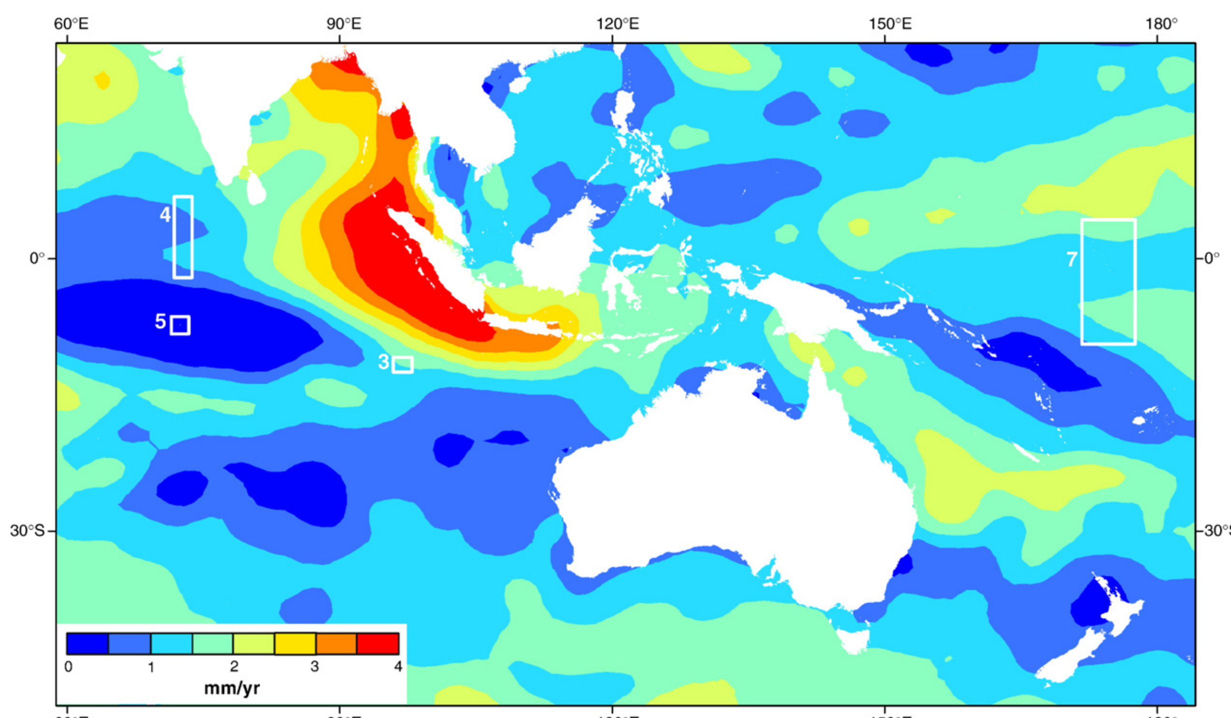

Fig. 1. The pattern of sea-level rise indicated from an analysis of tide-gauge records (based on Church et al., 2006) and the groups of atolls described in this paper: 3, the Cocos (Keeling) Islands (Fig. 3); 4, the Maldives Archipelago (Fig. 4); 5, the Chagos Archipelago (Fig. 5); 7, atolls and reef islands of the Gilbert chain, Kiribati and of Tuvalu (Fig. 7).

Richmond, 1992). The shoreline can be divided into oceanward shores that occur around the perimeter of the atoll and face the open ocean, and lagoonward shores that flank the lagoon. Morphological differences may also occur between windward (facing the prevailing wind) and leeward (away from the wind) margins of the atoll (Stoddart, 1969).

Atoll structure is best understood as a response to gradual subsidence as proposed by Charles Darwin in his theory of coral reef formation. Darwin revised the prevailing view that atolls represented a coral veneer around the margin of submerged volcanic craters, and suggested that there 'is but one alternative; namely the prolonged subsidence of the foundations on which the atolls were primarily based, together with the upward growth of the reef-constructing corals. On this view every difficulty vanishes; fringing reefs are thus converted into barrier reefs; and barrier reefs, when encircling islands, are thus converted into atolls, the instant the last pinnacle of land sinks beneath the surface of the ocean' (Darwin, 1842, p.109). This remarkable deduction, that volcanic islands in mid-ocean undergo subsidence, and that reefs might proceed through a sequence from fringing reef to barrier reef to atoll, as a consequence of vertical reef growth towards sea level had occurred to Darwin after observing evidence of uplift in South America, before he ever saw a reef. His hypothesis was reinforced when he viewed the island of Moorea with its fringing reefs from the slopes of neighbouring Tahiti. Although the *Beagle* passed atolls in the Pacific, it did not stop at any, until Darwin landed at the Cocos (Keeling) Islands in the Indian Ocean on the homeward leg of the voyage in April 1836. He was eager to find evidence to substantiate his ideas, and he considered erosion of the shoreline, as shown by undercut coconut trees, as 'tolerably-conclusive evidence' in support of subsidence.

The subsidence theory of atoll evolution was partly validated by deep drilling on Funafuti in 1896–1898. Although drilling failed to reach the underlying volcanic basement, more than 300 m of shallow-water carbonates were recovered implying subsidence. That volcanic basement underlies atolls was eventually substantiated by drilling on the atolls of Bikini and Eniwetok in the Marshall Islands (see Guilcher, 1988 for a synthesis).

At the time Darwin proposed his theory, the significance of sea-level fluctuations associated with the glaciations was not realised, but it is possible to incorporate such sea-level oscillations into our understanding of the formation of atolls. Sea level has fluctuated over a vertical range of more than 100 m over successive glaciations during the Quaternary (Fig. 2a). Initially, it was considered that reefs were totally planed off at low sea level and that the entire structure of modern reefs was Holocene (Daly, 1934; Wiens, 1959, 1962). However, the antecedent karst hypothesis advocated by Purdy (1974) corrected this mistaken view (Fig. 2b), and it has now been shown that the reef rim on the majority of modern atolls is underlain by older Pleistocene reef limestones (McLean and Woodroffe, 1994; Hubbard, 1997; Montaggioni, 2005).

Drilling on several atolls has demonstrated Pleistocene reef limestone, often dated to the Last Interglacial, at depths of 10–20 m below the modern atoll rim (see McLean and Woodroffe, 1994 and references in Vacher and Quinn, 1997). As a consequence the schematic cross-section shown in Fig. 2c is typical of most atoll rims; a karstified Pleistocene limestone underlies the rim and Holocene limestones form the reef platform on which islands have accreted. When sea level was high during the Last Interglacial (when it appears to have reached an elevation several metres higher than present sea level), an atoll rim similar to the modern existed, although no evidence remains as to whether it contained islands. During glaciations, the reef platforms were exposed by the lower sea level, and the emergent limestone underwent solution (karstification). Atolls appear to be undergoing gradual subsidence associated with plate migration, although locally accentuated by isostatic adjustments and lithospheric flexure. Reef growth re-established when postglacial sea level rose and flooded across the platforms around 8000 yr ago. There are several atolls on which Last Interglacial limestone is exposed at the surface (for example, Aldabra in the western Indian Ocean, Braithwaite et al., 1973; Anna in French Polynesia, Pirazzoli et al., 1988; and Christmas Island in eastern Kiribati, Woodroffe and McLean, 1998), and the extent to which lowering and reshaping of the surface results from subsidence or from solution remains an issue of debate (Purdy and Winterer, 2001, 2006).

Holocene reef growth has been constrained by the pattern of sea-level change since reefs re-established over the karstified Pleistocene limestone platforms around 8000 yr ago. The first stage involved catch-up reef growth, based on drilling and dating results from Tarawa in the Pacific Ocean (Marshall and Jacobson, 1985) and the Cocos (Keeling) Islands in the Indian Ocean (Woodroffe et al., 1994). In some places it has been possible for reefs to keep pace with sea-level rise (keep-up growth), but on atolls they appear to have more often lagged behind, and caught up with sea level as the rate of sea-level rise decelerated (catch-up growth). After reefs caught up with sea level, the predominantly vertical mode of reef growth was superseded by lateral progradation of the reef (Neumann and Macintyre, 1985; Montaggioni, 2005).

The majority of ice melt appears to have been completed by 6000 yr ago. However, ongoing isostatic adjustments mean that the details of relative sea-level history vary geographically (Lambeck, 2002). In particular, uplift in response to northern hemisphere ice sheets and associated changes in ocean volume in the forebulge area around former ice sheets increased the volume of the ocean basins resulting in a fall of sea level relative to far-field continental margins and remote islands, termed ocean siphoning (Mitrovica and Peltier, 1991). The details of sea-level history remain a subject of debate, particularly the extent to which ice melt may have continued beyond 6000 yr ago, and hence whether the sea-level curve at far-field sites peaked abruptly around 6000 yr ago and fell since then (through ocean siphoning) or whether as a result of post-6000-year melt, there was a more gradual peak around 4000 yr (Nunn and Peltier, 2001). Atolls contain little information on this issue because it was necessary for reefs to grow from the surface of the Pleistocene limestone to catch-up with sea level, the timing of which varies geographically.

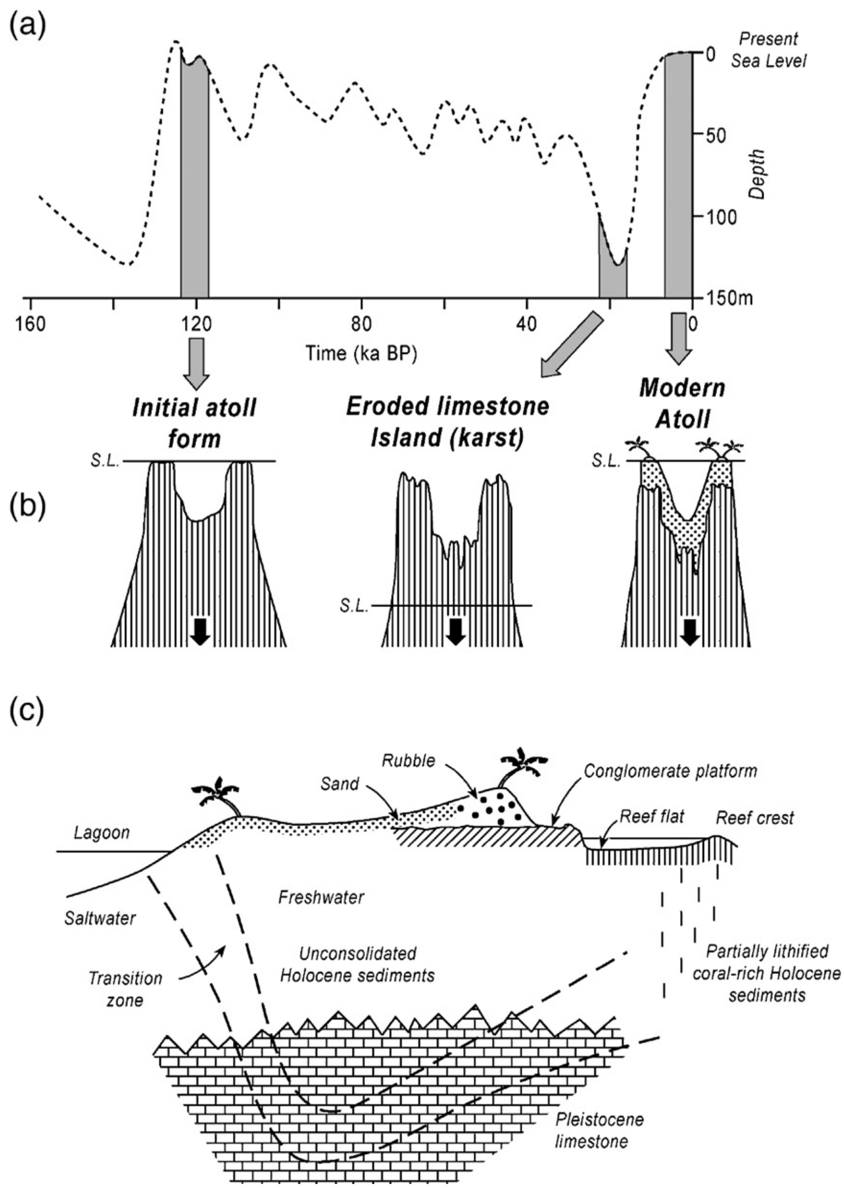

Fig. 2. Schematic illustration of the late Quaternary history of an atoll with respect to (a) variations in sea level, showing (b) gradually subsiding atoll (based on McLean and Woodroffe, 1994), and (c) idealised cross-section of the rim of an atoll showing a reef island, its geomorphology, lithology and sediments, and typical configuration of the freshwater lens.

On many atolls there are outcrops of boulder conglomerate around the reef rim often forming a distinct conglomerate platform that seems to have originated as a reef flat. Radiocarbon ages of 4000–3000 yr BP on corals from within the conglomerate platform around the perimeter of Cocos record this phase of reef flat consolidation at a sea level slightly higher than present. Ages from other atolls are broadly comparable, with evidence for variation in Kiribati–Tuvalu (the Gilbert–Ellice chain), from north (where some corals have been dated as old as 4000 yr BP) to south (where reefs may have reached sea level since 2000 yr ago, McLean and Hosking, 1991). Radiocarbon ages as old as 5500 yr BP have been reported from atoll surfaces in the Tuamotu Archipelago (Pirazzoli and Montaggioni, 1988).

The accretion of reef islands postdates the major phase of conglomerate formation. A number of researchers have suggested that reef-island formation on atolls occurred as a result of a slight fall of sea level (Cloud, 1952; Schofield, 1977a,b). Such an interpretation has been advocated by Dickinson (2004) who suggested that a discrete fall in sea level, based on that inferred in French Polynesia, was the trigger for island initiation.

Two issues need clarification before this view can be substantiated. The first is the detail of sea-level change at any island, and the second is the chronology of island sedimentation. There is a large literature on the former, but less research has been undertaken on the latter (Roy and Connell, 1991). Based on careful mapping of Funafuti, David and Sweet (1904) considered that there was evidence, particularly large *Porites* corals in growth position, which indicated that the sea had been above its present level relative to the atoll in the past. A similar interpretation was proposed for Onotoa in Kiribati by Cloud

(1952) based on *in situ* outcrops of fossil blue octocoral, *Heliopora,* above the elevation to which it presently grows on the reef flat.

There has been an ongoing debate about the extent to which conglomerate was deposited when sea level was relatively higher, or whether it was deposited by storms. An expedition to the Caroline and Marshall Islands (CARMARSEL expedition) specifically to resolve this issue reached no consensus (Shepard et al., 1967; Newell and Bloom, 1970). The preliminary radiocarbon ages reported by Schofield (1977a) from Kiribati and Tuvalu appear to be on corals from the conglomerate that were not in their growth position. The conglomerate in the northern part of the Gilbert chain is composed of a lower unit that contains *Heliopora* in its growth orientation at a few localised sites, overlain by an upper unit of disoriented cemented coral boulders (Falkland and Woodroffe, 1997; Woodroffe and Morrison, 2001). There have been several attempts to infer sea level either geographically (Grossman et al., 1998) or at a site (e.g. Funafuti, Dickinson, 1999), but these have not discriminated the *in situ* corals from the more extensive larger conglomerate outcrops.

Outcrops of conglomerate were used to infer higher sea level in the Maldives (Gardiner, 1903, Sewell, 1936), but there remains debate about the extent to which evidence supports emergence in this archipelago (Woodroffe, 1993, 2005; Mörner et al., 2004; Kench et al., 2005). Based on radiocarbon dating of several *in situ* intertidal coral microatolls of *Porites* around Cocos, a gradual fall of sea level has been demonstrated over the past 3000 yr from an elevation 0.5–0.8 m above present (Woodroffe et al., 1990, 1994).

Although the details of sea-level history and reef-island accumulation are likely to have experienced geographical variations across the region shown in Fig. 1, it is shown below that there are morphological characteristics that recur through these archipelagoes of atolls.

3. Surface morphology and substrate of reef islands

A series of topographic surveys across individual reef islands on atolls in the Indian and Pacific Ocean region are outlined below to support the typical cross-island morphology suggested in Fig. 2c, comprising a distinct oceanward ridge and a lesser lagoonward ridge, with a pronounced swale in the middle.

3.1. Methods

A series of typical cross-sectional profiles have been selected in order to illustrate the topography and substrate characteristics of reef islands. One atoll in each ocean is described in detail, the Cocos (Keeling) Islands in the case of the Indian Ocean and Marakei (Kiribati) in the case of the Pacific Ocean. Both of these atolls contain elongate islands, in the case of Marakei forming an almost continuous doughnut-like rim, which enables a description of reef-island geomorphology on each margin. Cross-sectional surveys are from published surveys, or surveys undertaken by the author. They were completed with an automatic level and were related to a datum of mean sea level (MSL), either through reduction to known benchmarks, or by comparison of still water level with tidal predictions. All are drawn to a standard 1:50 vertical exaggeration, and reduced to the common datum of MSL, so that cross-sections can be easily compared. The various approaches used to delimit MSL vary from island group to island group. Tidal range is generally 1–2 m on these mid-ocean atolls; although each experiences some seasonal and interannual variations in sea level. Water levels are raised further during storm surges, and as a result of wave set-up and runup.

The nature of the underlying sediments is also important. Rubble, shingle and sand are deposited as a result of different processes and differ in their susceptibility to erosion. Prominent on many atolls is a conglomerate of disoriented coral blocks, often forming a highly resistant platform that forms a foundation for reef islands. Lithification of sand can also provide some resistance to erosion. Beachrock is cemented beach sand, preserving the dip of the original beach. Beachrock can be preserved where sand has eroded away, indicating former shoreline positions. Cay sandstone is a less lithified, horizontally-bedded limestone associated with the water table within the island interior on a few islands. The droppings of nesting seabirds have infiltrated into sands in the interior of some islands and lithified sands with phosphatic cement. Island surfaces can also be stabilised by vegetation, which contributes both directly through roots that stabilise sand and humus that gives the soil greater structure.

3.2. The Cocos (Keeling) Islands

The Cocos (Keeling) Islands were probably the best known atoll a hundred years ago as a result of Charles Darwin's visit there in 1836 aboard *HMS Beagle*, the detailed observations made by Guppy during 1888 (Guppy, 1889), and the extensive account by Wood-Jones after a year there as doctor (Wood-Jones, 1912).

The Cocos (Keeling) Islands comprise a southern horseshoe-shaped atoll (South Keeling Islands, henceworth referred to as Cocos) with more than 20 sandy reef islands around a shallow lagoon, and a northern reef island with a small remnant lagoonlet, North Keeling. Darwin drew a schematic cross-section of 'Keeling atoll' (although Darwin's notes indicate that the cross section was not actually of Cocos, but of Whitsunday Atoll) showing the prominent algal rim (at the reef crest), a near horizontal reef flat, the conglomerate platform (which he terms ledge of coral rock), the seaward ridge of the island, steeper on the oceanward side and sloping gradually to the lagoon. Fig. 3 shows a sample of cross-sections from around the atoll rim of Cocos (from Woodroffe et al., 1994; Woodroffe and McLean, 1994).

Cocos is dominated by the southeast trade winds and has persistent swell from the southeast which refracts around the atoll and breaks on the entire perimeter. Tidal range is 1.1 m at springs, and the atoll is influenced by occasional tropical cyclones. Observations during Cyclone Frederic in 1988 indicated that that storm did not undertake significant geomorphological work and there are not storm ridges on Cocos as there are on

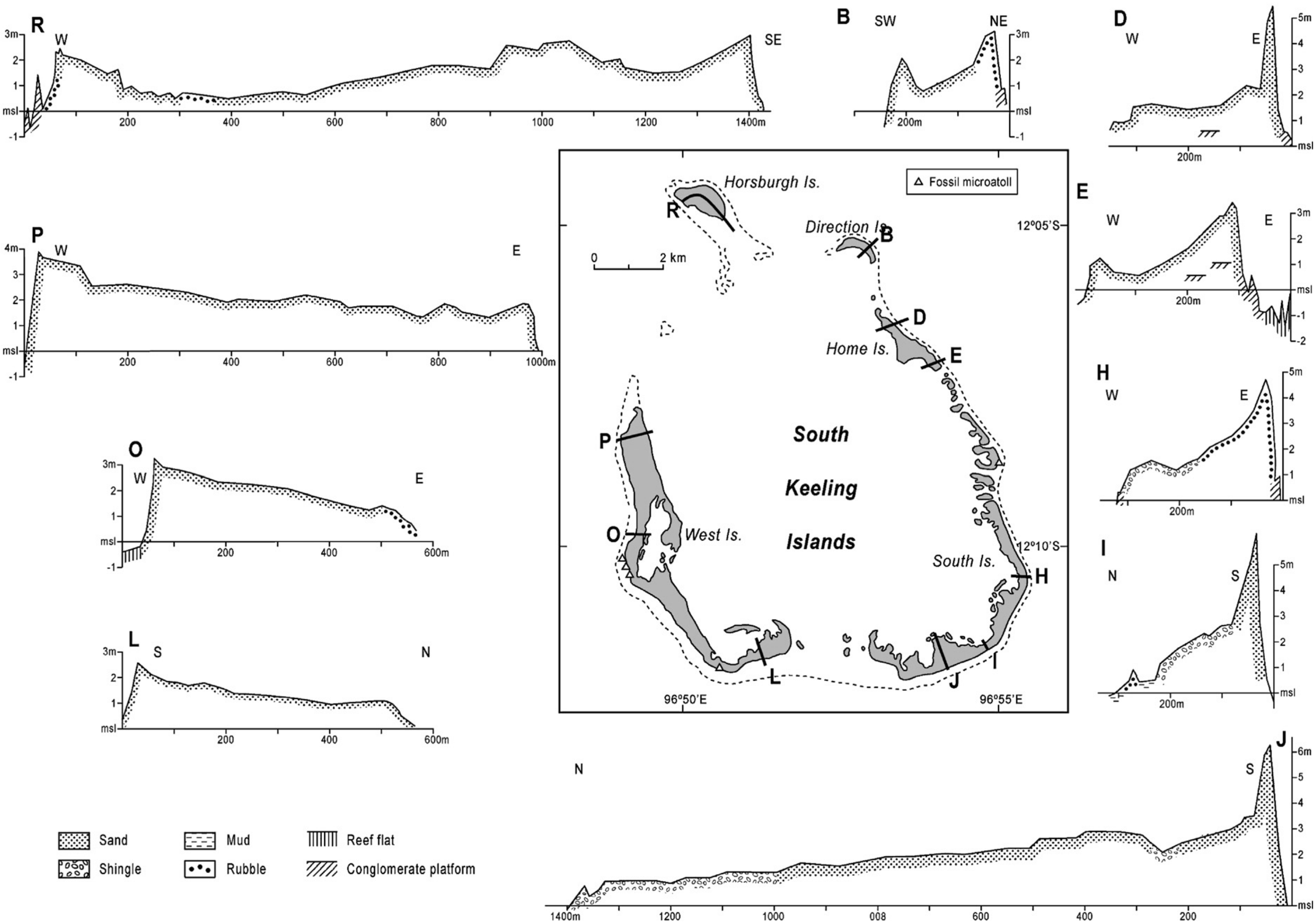

Fig. 3. The Cocos (Keeling) Islands: the South Keeling Islands, forming the southern atoll and selected profiles across reef islands (based on Woodroffe et al., 1994, and Woodroffe and McLean, 1994).

atolls in the Pacific prone to larger storms (such as Funafuti, see Fig. 8).

The majority of islands are perched on a conglomerate platform, which Guppy (1889) suggested represented former reef flat, a view confirmed by Woodroffe et al. (1990). Conglomerate platform (termed brecciated coral rock by Darwin, reef conglomerate by Guppy and breccia platform by Wood-Jones) generally reaches up to 0.5 m above MSL, though locally reaching 1 m, and is inundated by waves at the highest tides. The islands show one of three cross-sectional morphologies: a gradual slope from oceanward ridge crest to lagoon (as shown by Darwin), an oceanward ridge and a lagoonward ridge of lower amplitude, or a series of low-elevation ridges. Islands are predominantly sandy, although with shingle in some places, and coral boulders along the oceanward shore of islands on the eastern rim where the reef flat is narrowest. Beachrock with dipping beds parallel to the modern beachface occurs along many of the oceanward beaches. There are minor lagoonlets, termed teloks, which are open to the lagoon, but are separated from the ocean by a ridge (see transects H, I and O in Fig. 3, which abut a telok).

On Cocos, surveys have been related to mean sea level (MSL) using benchmarks and by level and theodolite survey around the southern perimeter. Fig. 3 shows that there are two major elongate islands, West Island and South Island which occupy about 60% of the horseshoe-shaped southern rim of the main atoll. The remainder are small crescent-shaped islands on conglomerate platform, separated by inter-island passages (similar passages are termed hoa on Polynesian atolls), most of which shoal at low tide. Horsburgh Island on a lone reef at the north of the atoll, is shaped by wave refraction and reaches elevations of 3–4 m.

Darwin inferred different formative processes for islands on windward and leeward sides of the atoll. On the windward (eastern) side he considered that islands accreted solely by addition of material on the oceanward shores, whereas on the leeward (western) side he envisaged that island growth resulted from a combination of oceanward accretion, augmented by lagoonward addition of sediment by waves from the lagoon. By this mechanism, Darwin accounted for the wider islands on the leeward of the atoll. Radiocarbon dating of sand on transects P, O and L supports this view, implying that West Island has accumulated primarily by oceanward accretion, but also with some lagoonward growth (Woodroffe et al., 1999). The islands on the eastern margin of Cocos were described in considerable detail by Guppy (1889) who proposed a model for the growth of these crescent-shaped islands involving spit elongation driven by unidirectional currents through the inter-island channels. This evolutionary model has not been adequately tested by dating.

Islands are highest along their oceanward shores. The oceanward ridge is generally 3–4 m above MSL; however, in some places, fine sand has been winnowed from the beach by wind and the beach ridge is topped by a dune. Such dunes are not typical of atoll reef islands in general. South island has a dune ridge 6–7 m high, reaching as high as 11 m on the southwestern corner of South Island. West Island has an oceanward ridge that is characteristically 3–4 m above MSL (much of the southern part of this island has been altered during runway construction); it rises to 7 m above sea level where the ridge is topped by a dune. On Home island the oceanward ridge generally reaches an elevation of 3 m above MSL, but at one location a dune rises up to 5 m (Woodroffe and McLean, 1994).

3.3. Maldives Archipelago

The Maldives Archipelago consists of a double chain of atolls, comprising about 20 distinct atolls and several individual platform reefs (table reefs), tapering to single atolls to the north and south. There are over 2000 individual reefs from Ihavandiffulu (6°57′N) in the north to Addu Atoll (0°34′S) in the south. To the south of the Maldives Archipelago the lagoons are generally deeper, the rim is more continuous and there are fewer patch reefs but islands fill a greater proportion of the reef rim and individual islands are generally more elongate (Woodroffe, 1993). Reef islands occupy 5.1% of the reef area (Naseer and Hatcher, 2004), and Fig. 4 shows a selection of cross-sections across reef islands from north to south along the archipelago.

The detailed studies by Stanley Gardiner (1903) contain general descriptions of Maldives atolls. Cross-sectional transects of several islands were surveyed in 1989 using an automatic level and, in the absence of a suitable datum on each island, approximate mean sea level (MSL) was estimated by relating still water level at time of survey to tidal predictions (Woodroffe, 1993). MSL has been assumed to be 60 cm above lowest astronomical tide (LAT) to the north of the chain (maximum tidal range 1.2 m), and 70 cm above LAT in the south (maximum tidal range 1.4 m), and tide times were determined by applying appropriate delays to the predictions for Cochin for the northern Maldives, and for Madras for the southern Maldives. Although storms occur, and rubble storm ridges, deposited over the past 3000 yr, are prominent features on islands in Lakshadweep (formerly the Laccadives) to the north of the Maldives (Siddiquie, 1980), the Maldives do not experience such severe storms, and rubble is not a prominent component of island substrates. However, the islands are influenced by a reversal of the monsoons, which causes significant seasonal changes to the geomorphology of some islands (Kench et al., 2006).

The cross-section of Hithadhoo, on the western margin of Addu Atoll, shown in Fig. 4, indicates some similarities to the profile typical of Cocos reef islands, but other cross-sections are less comparable. The oceanward ridge on the western rim of Hithadhoo, was the highest point surveyed on any of the profiles throughout the archipelago (though higher elevation undoubtedly occurs at isolated locations that have not been surveyed), reaching 3.2 m above MSL on an oceanward ridge formed in response to the southwestern monsoon. The village on this island is generally 0.8–1.0 m above MSL. Well-developed ridges are developed on other islands exposed to strong winds from this direction; for example a ridge along the southwestern shore of Foammulah reaches 3.0 m above MSL (Woodroffe, 1993).

Many of the reef islands in the Maldives appear precarious in relation to the sea and susceptible to flooding by extremely high

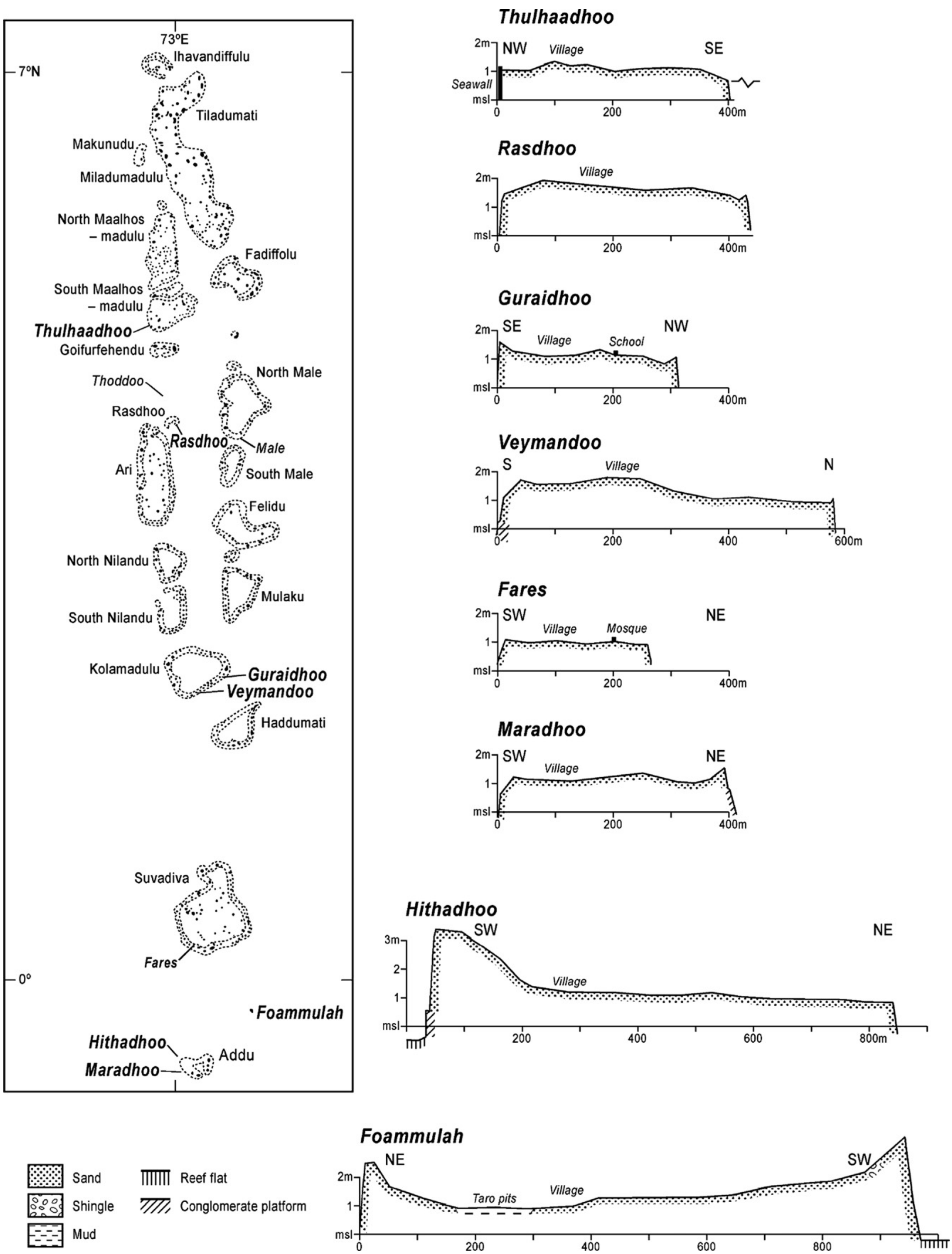

Fig. 4. The Maldives Archipelago, showing the distribution of atolls and table reefs and selected profiles across reef islands (based on Woodroffe, 1993).

water levels under present tidal and sea-level conditions. On islands elsewhere in the chain, the oceanward ridge reaches elevations of 1.5 m above MSL. Fares, a reef island on the southern rim of Suvadiva, reaches a maximum elevation of only 1.05 m above MSL (35 cm above HAT) on the surveyed transect through the village. The island of Thulhaadhoo, South Maalhosmadulu Atoll, looks particularly vulnerable, with a relatively large population (around 1500 — and with an elevation of 1.35 m above MSL in the centre of the island). It has a history of instability; Gardiner recorded the devastating effects of cyclones in 1896 and 1898 just prior to his visit, which had reduced the island to half its previous size, commenting that 'the whole changes at Turadu (sic) serve admirably to illustrate how great may be the action of the sea in a very short period of time' (Gardiner, 1903).

Individual table reefs occur at several locations in the archipelago and their morphology differs. Foammulah is a saucer-shaped island, with a shingle ridge 3–4 m high at its southern end; the centre occurs at an elevation that corresponds to highest tides, with extensive taro pits into which saline intrusion has occurred (Woodroffe, 1993). Other islands on table reefs, such as Thodhoo, do not have a detectable central depression. There are also many small sand cays that occur on patch reefs within the lagoon of atolls, several of which have been developed as tourist resorts.

Large waves in 1987 and 1988 inundated many of the islands and were the trigger for international concern about the vulnerability of these islands. The tragic Indian Ocean tsunami of Boxing Day 2004, resulted in the death of more than 70 people in the Maldives; however, post-event studies have shown that although islands were overtopped, the successive waves performed relatively moderate amounts of geomorphological work (Gischler and Kikinger, 2006).

3.4. Chagos Archipelago

The morphology of islands in the Chagos Archipelago is described in a series of surveys from the 1970s; atolls on the Great Chagos Bank are described by Sheppard (2002) who related elevations to high tide, whereas a detailed geomorphological account of Diego Garcia is provided by Stoddart (1971) who reported surveys reduced to low tide; and a tidal range of 1.6 m at springs. A selection of cross-sections is shown in Fig. 5, redrawn at vertical exaggeration of 50:1 and reduced to MSL. The islands on the Great Chagos Bank, as well as others on Peros Bañhos, Salomon and Egmont are small and show prominent ridges around their margins (Sheppard, 2000, 2002). Diego Garcia is a horse-shoe shaped atoll around which reef islands are often more than 500-m-wide. This atoll is similar to the Cocos (Keeling) Islands, with around 90% of the reef rim occupied by reef island, and with a series of secondary lagoonlets (resembling the teloks on Cocos) separated from the ocean by low ridges, termed barachois. The population of Chagos was relocated in the 1970s after which Diego Garcia became an American air base. Isolated dunes rise up to 5 m high on several of the shores that are exposed to southwesterly winds, rather than on those exposed to the predominant southeasterlies (Stoddart, 1971).

3.5. Kiribati and Tuvalu

In the case of atolls in the Pacific, the chain of atolls that comprise Kiribati and Tuvalu are described in detail. Straddling the equator, these islands are less affected by swell, but experience wind reversals associated with the El Niño-Southern Oscillation (ENSO) phenomenon. Tropical cyclones are important south of about 6° south of the equator, and have played a significant role in construction of islands in Tuvalu; which is also influenced by westerlies in summer. Maximum tidal range is 1.7 m at Funafuti and around 2 m at Tarawa.

Reef-island shape is variable. The rims of some atolls are characterised by elongate islands that parallel the reef crest. Elsewhere small, almost circular, islands appear shaped by wave refraction and the currents that traverse inter-island passages. Larger dumbbell-shaped islands can occur where the reef margin changes direction and material is accumulated from a larger area of reef flat (Richmond, 1992, 1993).

Whereas the Cocos (Keeling) Islands may have been the best-documented Indian Ocean atoll at the beginning of the 20th century, the focus on Pacific atolls gained enormously as a consequence of a series of expeditions in the 1890s to Funafuti (then in the Ellice Islands, but capital of Tuvalu after independence). The Royal Society sponsored a program to drill the perimeter of Funafuti to test Darwin's theory of reef development. The initial fieldwork was led by Professor W. Sollas in 1896; further drilling was undertaken in 1897 together with field mapping by T. Edgeworth David and George Sweet, and the final stage of drilling, though still in shallow-water carbonates was overseen by Alfred Finckh in 1898. Alexander Agassiz visited shortly after the team finished, as part of a voyage aboard the USS Albatross to study reefs in both the Pacific and the Indian Oceans (Agassiz, 1903a,b).

Sollas (1904) drew attention to the similarity of morphology between the profile of Cocos drawn by Darwin and the results of the Royal Society to Funafuti. Although there are broad morphological similarities (the profile of Funafuti in Fig. 7 can be compared with those in Fig. 3), McLean and Woodroffe (1994) point out several contrasts. Rather than outline morphology of Funafuti however, the example of Marakei in northern Kiribati is illustrated in Fig. 6, primarily because this doughnut-shaped atoll has reef islands around its entire perimeter. In this case surveying is relative to the water level in the lagoon, which being connected to the ocean by only two narrow passages shows tidal fluctuations of less than 0.1 m, and thus approximates to MSL.

Marakei has a prominent oceanward ridge, but around much of the lagoon there is also a low ridge, which can be seen as a distinct ridge, or spit, on the map. The cross-sections indicate that the prominent oceanward ridge rises to 3 m above MSL on the eastern shore where it is fronted by a 300-m-wide reef flat (Fig. 6). On the western shore the oceanward ridge is a little lower, but it is evident from the well-developed fringe of vegetation, including substantial trees (20-m tall *Calophyllum*), that the ridge is rarely, if ever, overtopped. The ridge is steep on the seaward face but also slopes away rapidly towards the lagoon. The lagoonward ridge can be seen most distinctly on the southern shore where a distinct ridge reaching up to 0.7 m high

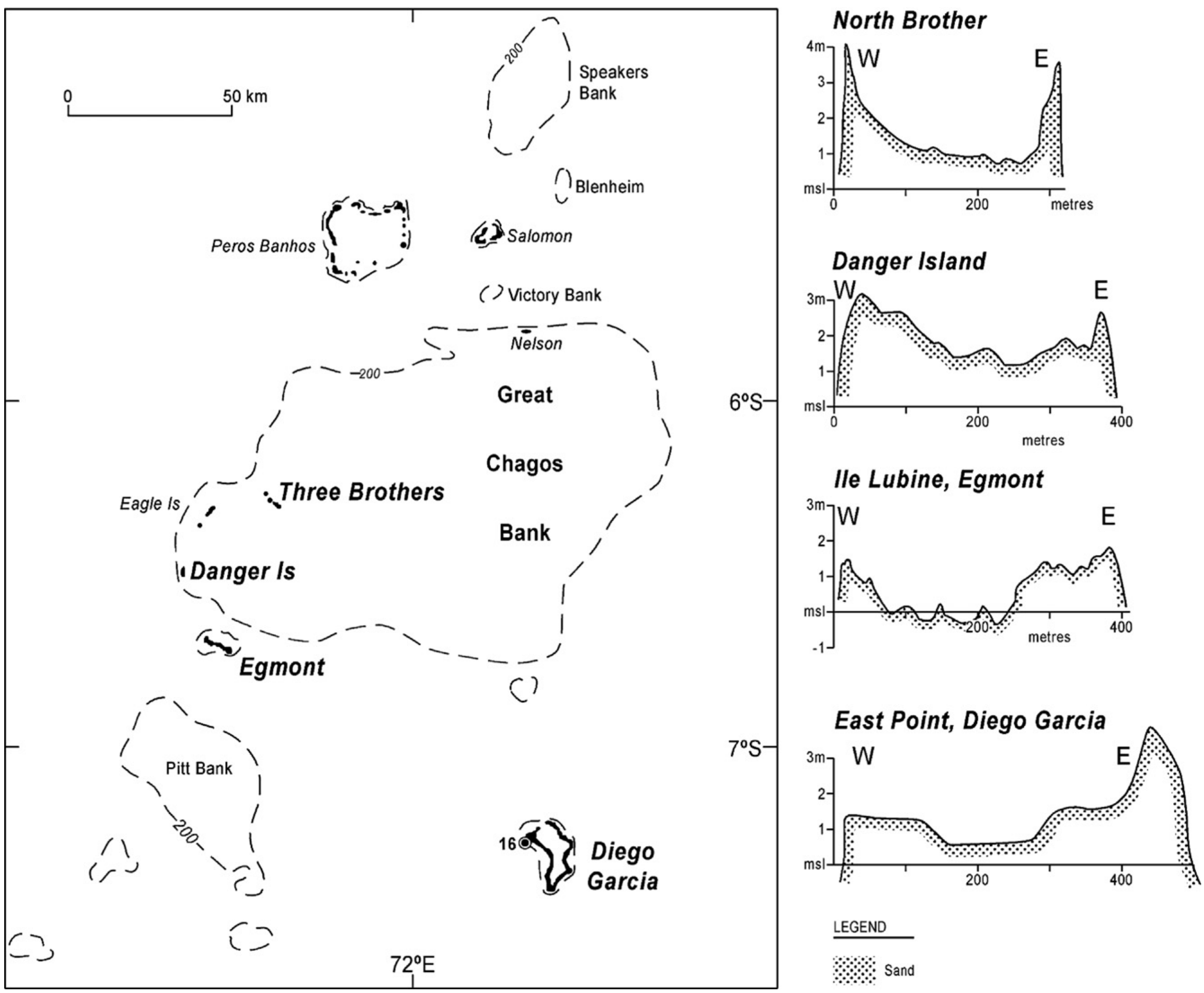

Fig. 5. The Chagos Archipelago, showing selected profiles across reef islands (based on surveys in Stoddart, 1971, and Sheppard 2002).

runs parallel to the main reef island, giving rise to a muddy 'fish pond' occluded between the sandy ridges. In the case of this atoll, the lagoon comprises fine muds, in contrast to the biogenic sands of the reef flat; foraminifera that are abundant on the reef flat and constitute the most prominent component of beach sediments, occur in the lagoon only in a very limited area at the western extremity of the eastern passage into the lagoon.

The morphology of other islands in the Gilbert chain of Kiribati, and in Tuvalu, demonstrates similarities. Atolls can be discriminated from table reefs, reef platforms on which there is a single island (or is some cases more than one island, frequently two (Kuria, Nanumea), and sometimes a chain of islands in mid platform, as on Makin). In Kiribati the eastern atoll rim is dominated by elongate islands, and on many the western rim contains few if any islands (e.g. Tarawa, Onotoa, Maiana). On several islands the oceanward ridge is composed of shingle or coral rubble. Cloud described such morphology on Onotoa (Cloud, 1952), although he considered that the oceanward shingle ridge was emplaced first and sand was then deposited in its lee by transport from the reef flat, through passages and along the lagoonward shore by longshore drift.

In Tuvalu, the typical morphology of islands on Funafuti was mapped in meticulous detail by David and Sweet (1904), and has recently been re-evaluated (Webb, 2006a; Yamano et al., 2007). Further mapping of other islands was undertaken as part of a Tuvalu Land Resources Study, summarised by McLean and Hosking (1991). On Funafuti, oceanward ridges, particularly on the windward side of the atoll, are often gravel ridges (termed outer hurricane bank by David and Sweet). Leeward ridges, and lagoonward ridges, are sandy; there is often a central depression between oceanward and lagoonward ridges. The origin of the central depression is not by solution or corrosion as David and Sweet thought, but in most cases results from the development of ocean and lagoon shore ridges in parallel, as on Marakei. In some cases low-lying areas in interior of islands are sealed off lagoonal re-entrants, for example these embayments (resembling in location, but not shape, the teloks on Cocos) can be seen at various stages of occlusion around the lagoon of Nui.

Oceanward ridges reach a higher elevation than lagoon shores; in some cases there is a double ridge, or sequence of ridges, generally running parallel to the reef edge. However, highest land on many of the atolls is often spoil from the

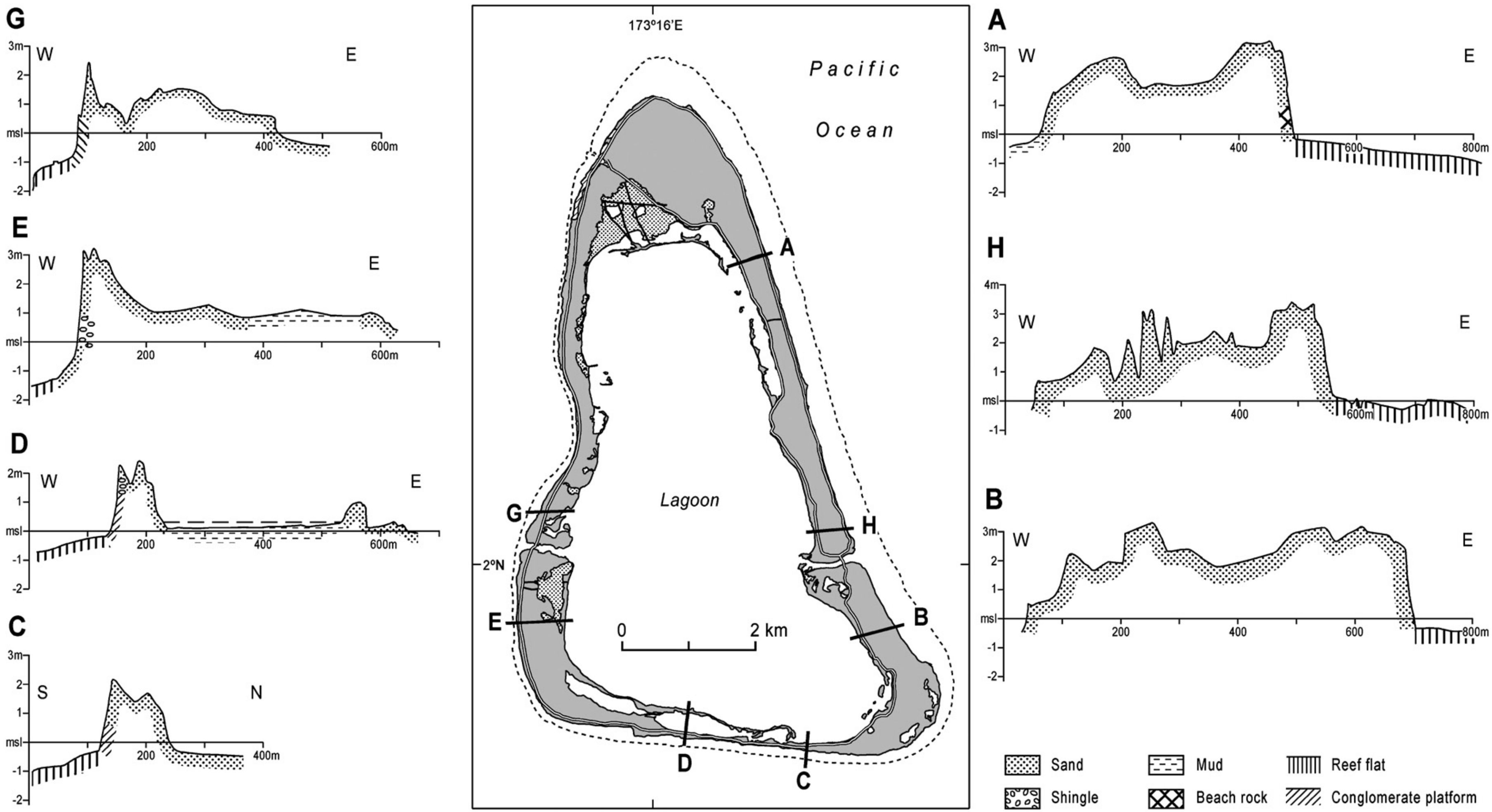

Fig. 6. The atoll of Marakei in Kiribati showing profiles across reef islands.

excavation of pits for taro (called *babai* in Kiribati and *pulaka* in Tuvalu). Pits are dug so that taro can be planted close to the water table of the freshwater lens. Other major modifications involve construction of an airstrip, as on Funafuti.

Conglomerate occurs on many of the islands. Although it extends across lagoon shores on Nui, it is more common on oceanward shores on other atolls, and can form transverse outcrops across the reef flat (see Fig. 8c). In the case of Maiana, molluscs typical of the lagoon are found in pits excavated along the lagoonward parts of the island, indicating that there has been substantial lagoonward accretion of sediment. Lagoonward ridges rarely exceed 1–2 m in height, and their formation depends on exposure and lagoon fetch. In Tarawa lagoonal sediments include foraminifera (Weber and Woodhead, 1972), but as described above, on Marakei lagoonal sediments are muddy and a much smaller volume of sediment appears to have been contributed to lagoon shores.

The morphology of islands on table reefs is different from that of reef islands on the rim of an atoll with a lagoon. The examples of Vaitupu in Tuvalu (McLean and Hosking, 1991) and Little Makin at the northern end of the Gilbert chain (Woodroffe and Morrison, 2001) show several features in common. Both demonstrate a higher ridge to west than to east, although this may be because both transects were taken at a point where the eastern shore flanks a broad reef flat, and is related to the development and infill of active or former lagoonlets in the island interior. On Vaitupu a sequence of ridges occurs on the transect with a dual ridge on the western side, whereas Makin comprises a single broad ridge to the west, which has been shown by radiocarbon dating to have formed through gradual accretion of sand on the western shore (Woodroffe and Morrison, 2001). On Makin, the beach reaches a maximum of 4 m at its highest, but most is around 3.6 m high and at the northern end of the island the beach ridge is generally less than 3 m high, showing a gradual increase in beach height towards the south.

3.6. Other Pacific atolls

Although this review focuses on the morphology of atolls within the eastern Indian Ocean and western Pacific Ocean, an area for which Church et al. (2006) have demonstrated a pattern of sea-level rise over the past 5 or more decades, other atolls in the Pacific Ocean are likely to show similar geomorphological characteristics. There have been studies on several other atolls in the Pacific, including those in the Marshall and Caroline Islands (Emery et al., 1954; Wiens, 1962), in the Cook Islands (Wood and Hay, 1970), and Tuamotu Islands in French Polynesia (Pirazzoli and Montaggioni, 1986). However, more detailed topographical surveys would be needed to establish the local variability across these archipelagoes.

4. Morphological synthesis

4.1. Reef-island topography

Several aspects of reef-island topography affect their susceptibility to impacts as a result of future sea-level rise. First, it is clear that large areas of these islands are low-lying, and the majority of the land lies below 2 m above MSL. Reef islands are almost always higher on the oceanward margin. On the more exposed margins, the oceanward ridge frequently rises to around 3 m above MSL. The morphology of the Cocos (Keeling) Islands and the atolls in the Kiribati–Tuvalu chain show a similar distribution of elevations, with about a third of the land above 2 m and only around 8% above 3 m above MSL. Chagos atolls, although variable, are somewhat lower, and the Maldives are the lowest with only 4% of land area assessed to be above 2 m above MSL based on the surveyed profiles (Table 1). Particularly noteworthy is that villages on Maldivian reef islands appear to be constructed only tens of centimetres above high water level.

Although this assessment is based on only a limited number of cross-sections, a similar morphology is indicated on other survey lines, or where other reef islands in the region have been visited. The pattern of elevations is characteristic of islands where more extensive topographical data are available, for example contoured maps of parts of Home and West Islands in the case of Cocos. Preliminary analysis of a photogrammetrically-derived digital terrain model (DTM) of the islands of Tarawa atoll in Kiribati using geographical information systems (GIS), also indicates that these proportions are representative across reef islands other than those surveyed.

On atolls exposed to persistent winds, oceanward ridges may be topped by dunes, as in tradewind-dominated Cocos and Diego Garcia, but also on Christmas Island, eastern Kiribati, where persistent easterly winds have built dunes in particularly exposed locations (Woodroffe and McLean, 1998). In Kiribati and Tuvalu the highest ground is often the spoil banks around taro pits.

The relationship of the land to the highest water level is particularly significant, but is generally difficult to determine. Tidal range is between 1 m and 2 m for each atoll, but it would be misleading to draw a value for highest astronomical tide (HAT) on the cross-sections as it is clear that the maximum water level around the islands is spatially variable and is not the same as that observed in the stilling well of a tide gauge. Tide gauges are generally placed in a sheltered lagoonal location open to oceanic influence (they are often on wharves that are located to enable ships to enter, in some cases through dredged passages). The atolls experience a range of swell conditions, but oceanic wave characteristics are further modified by the reef environment. Water levels at the oceanward shoreline are also subject to wave set-up and wave runup, meaning that swash reaches well above HAT on the more exposed beaches. Open-ocean swell and locally generated seas are filtered by the reef

Table 1
Proportion of reef islands at elevations above MSL based on surveyed cross-sections

Atoll or archipelago	% above 2 m above MSL	% above 3 m above MSL
Cocos (Keeling) Islands	33	8
Maldives	4	1
Chagos	18	7
Marakei	32	8
Gilbert chain/Tuvalu	34	7

crest. Waves that travel across reef flats are considerably lower amplitude than outside the reef, and are a function of water depth on the reef flat, rather than incident wave energy at the reef crest (Nelson, 1994). As a consequence there is less variation in the height and morphology of oceanward shores than might have been anticipated from the different wave climates.

On lagoonward shores, by contrast, there is less wave energy, but it is likely to be more variable, reflecting factors such as the size of the lagoon, fetch, and water depth. Lagoon water levels may be tidally modulated if the lagoon is well connected with the open ocean through deep passages; the lagoon may be flushed primarily by waves where such passages are absent (Callaghan et al., 2006), or the lagoon may experience only very limited water exchange with the open ocean as in the case of the almost land-locked lagoon at Marakei. The elevation of lagoon ridges, therefore, is very variable, being imperceptible in some cases, and forming distinct ridges but of little elevation in others.

4.2. Role of storms

It is clear that storm events play an important role on those atolls that experience hurricanes/typhoons/tropical cyclones (Bayliss-Smith, 1988). The role of storms is illustrated in Fig. 8. Those atolls that experience storms tend to have coarse shingle or rubble ridges on their oceanward shores. The best-documented example is Funafuti that was hit by Cyclone Bebe in October 1972 (Maragos et al., 1973). The storm constructed a hurricane bank that added 10% to the land area of the atoll. It had a similar effect on neighbouring Nukufetau. Subsequently the rubble has been redistributed by ambient wave conditions, and the ridge has migrated landwards across the reef flat (Baines and McLean, 1976) and in places has resulted in further accretion of the island shoreline. Geological mapping by David and Sweet (1904) recognised an outer hurricane bank (the seaward ridge) that had been formed by previous storms and the 1972 storm has, in places, added a modern ridge to that feature.

Storms are both constructional agents and erosional agents. Fig. 8 contrasts the most notable differences between atolls in the storm belt, where the reef flat may contain boulders and reef blocks, with those outside the reach of major storms. In areas that experience only occasional storms rubble may occur along the most exposed beaches, and shingle may veneer otherwise sandy islands where the reef flat is narrowest (as seen in eastern Cocos). Storms appear to have had a role in transporting larger material to construct the conglomerate platform, although as discussed above the presence of this platform may also depend on sea-level history as well as suitable conditions to cement the material. In those areas remote from storms, islands are predominantly sandy, and conglomerate is rarer (though not necessarily totally absent). Storms have played a role in construction of extensive conglomerate on Minicoy to north of the Maldives, and in building storm ridges described in Lakshadweep (the Laccadives, Siddiquie, 1980). A similar transition occurs between the sandy Kiribati islands and the shingle islands of Tuvalu that are in the storm belt. Those atolls that are relatively free of storms, such as the Maldives or the Gilbert chain in Kiribati, comprise reef islands largely built from sand, although as seen in the case of eastern Tarawa (Fig. 8) there may still be outcrops of conglomerate that exert an influence on the location of the oceanward shore.

4.3. Shoreline erosion

Perhaps the most common impact foreshadowed for atolls as a consequence of sea-level rise, particularly in popular accounts, is shoreline erosion. It is argued here that, although some lagoonal shorelines may be undergoing net erosion, long-term accretion is more likely to outweigh short-term erosion on oceanward beaches. Many of the oceanward beaches on atolls show ephemeral evidence of erosion, including prominent scarps, undercutting of vegetation, and the presence of outcrops of beachrock that formed when the beach was stable, but which are now exposed by the removal of unconsolidated sand, leading Stoddart and Steers (1977) to suggest that erosion of oceanward beaches is nearly ubiquitous. However, several factors imply that such oceanward beaches are net sinks of sediment. First, radiocarbon chronologies indicate incremental accretion; second sediment, produced on or near the reef crest, is transported by the unidirectional progression of waves across reef flats, implying accumulation, and finally, multi-temporal image and photographic analysis indicates shoreline progradation.

The reef islands that occur on Indo-Pacific atolls have formed over the past few millennia, in some cases during a gradual fall of sea level. Dickinson (2004) has suggested that a fall in sea level acted as a trigger for islands to form, invoking a fall of sea level around 1700 yr ago as detected in French Polynesia. However, this pattern of abrupt fall has not been demonstrated throughout the region; where sea-level fall has occurred it has generally been considered to be gradual (Grossman et al., 1998). In addition, radiocarbon dating evidence for the age of the islands themselves implies gradual accretion rather than rapid deposition at one point in time (Woodroffe et al., 1999; Woodroffe and Morrision, 2001).

Carbonate production on the reef crest, and to a lesser extent over the reef flat, or in lagoons, has produced sand and shingle composed of the skeletal remains of organisms living on the reef, such as coral, coralline algae, molluscs and foraminifera. The rate of calcification controls the growth of these organisms and influences the amount of sediment produced that can be supplied to islands. Many atolls have reef flats that appear largely barren of sediment, indicating little sediment storage on the reef flat. Radiocarbon dated profiles have been described for West Island in the Cocos (Keeling) Islands, and for Little Makin, the northernmost island in Kiribati. In each study, conventional radiocarbon dating of large fragments of coral or bulk sand samples (which can be misleading, because of reworking and the incorporation of older material before final deposition, Woodroffe et al., 2007) has been supplemented by AMS dating of a range of components to determine the age of the youngest component. In the case of West Island on Cocos, ages record predominantly oceanward accretion (with minor lagoonward addition as suggested by Darwin) over the past 3000 yr. The clearest chronology comes from transect P in Fig. 3, and the 3000-year record of progradation coincides with the microatoll record of a fall of sea level. Both appear to have been gradual and incremental (Woodroffe et al., 1999; Woodroffe, 2005). A slightly shorter chronology (since 2600 yr BP) of oceanward accretion has been reconstructed on the western end of a transect across Makin (Fig. 7), with this section of the island building gradually westwards (Woodroffe and Morrison, 2001). These, and other results, indicate ongoing oceanward accretion, where sediment production and transport are sustained.

Also indicating the potential for oceanward accretion of shorelines on atolls are studies that use multi-temporal imagery and aerial photography, or other resurveys, and record islands getting larger. In the case of Cyclone Bebe, 10% was added to the land area of the atoll by the single storm (Maragos et al., 1973), and the landward migration of rubble ridges has continued to add material to oceanward shores (Baines and McLean, 1976). Assessment of other shorelines around Funafuti has also indicated an overall increase in the size of islands (Webb, 2006a). On those atolls in Kiribati on which detailed comparisons can be made, there is also evidence for accretion of some oceanward shorelines (Webb, 2006b, Naomi Atauea, pers. comm.).

The popular view that sea-level rise is leading to oceanward shoreline erosion on reef islands perpetuates a similar fallacy to that made by Darwin when he inferred that such shoreline erosion was 'tolerably-conclusive' evidence for the gradual subsidence of atolls. Although, Darwin's hypothesis of gradual subsidence appears correct for most atolls, we now understand that this occurs at an imperceptibly slow rate, and that rates of sea-level change have been several times faster. Most Indo-Pacific atolls have experienced a slight relative fall of sea level over past millennia, during which time islands have accreted on the emergent reef rim (rather than experiencing a relative sea-level rise as would occur if subsidence was occurring more rapidly). Radiocarbon dating indicates that the conglomerate platform on Cocos is composed of corals with ages of between 4000 and 3000 radiocarbon years BP (Woodroffe et al., 1990; 1994), and that the islands have accumulated over the past 3000 yr as sea level has fallen gradually relative to Cocos (Woodroffe et al., 1999). Both Darwin's evidence, and the present debate about the possible impact of sea-level rise and the probability that erosion will lead to the disappearance of the islands, invoke short-term geomorphological phenomena to support inferred long-term response to almost imperceptible land–sea adjustments.

The paradox can be understood by appreciating that Darwin's subsidence theory applies to the *structure* of reefs, based on their long-term evolution, at timescales of millions of years, as opposed to the *surface morphology* of the reef rim and islands, which is an outcome of processes over the past few millennia. The formative processes and timescales are quite different (Stoddart, 1973). Gradual subsidence, as envisaged by Darwin, appears likely to occur at rates of the order of 0– 0.02 mm yr^{-1}. Hydro-isostatic adjustment (ocean siphoning), where this has occurred, is likely to result in rates of relative sea-level fall of the order of 0.0–0.2 mm yr^{-1}. Both of these rates are considerably less than the ongoing rate of sea-level rise, which is around 2–3 mm yr^{-1}. Ecological responses of the reefs occur several times faster than the geophysical processes; for example corals grow and extend their skeleton at rates of 10–100 mm yr^{-1}, but reef growth, which is the aggregate vertical accretion by corals and associated organisms, occurs at rates of around 1–10 mm yr^{-1}. In contrast to these gradual long-term trends, there are much shorter oscillations of water level, such as tidal variations, and in the case of the central Pacific, fluctuations of mean sea level of the order of 20–30 cm between El Niño and La Niña events, as well as the effects of individual storms.

Erosion of an individual shoreline is far more likely to result from local or proximal causes (such as a particular storm), than to be attributable to the imperceptible gradual subsidence or steric sea-level rise. It seems likely that misrepresentation of local shoreline erosion is all-too-frequently used to support the pre-supposition that the islands will disappear beneath the sea through erosion of exposed shorelines in response to ongoing rise of sea level averaging a few millimetres a year.

In some instances, detailed resurveys of beaches have shown trends to be cyclic; for example, on the islands of Betio and Buariki in South Tarawa fluctuations of island outline correspond with wind changes associated with ENSO cycles of several years (Solomon and Forbes, 1999), and in the Maldives seasonal adjustments follow reversal of the monsoon (Kench et al., 2006). In other cases erosion has been presumed as a result of misapplication of the Bruun rule, based on conservation of mass and its redistribution, to the oceanward shore of reef islands. The Bruun rule was devised for sandy shores where beach and nearshore are interconnected and sand can be transferred from one to the other to maintain a continuous equilibrium profile. On atolls, sandy reef islands sit unconformably over a solid reef flat. There is a distinct break both topographically (see Figs. 3–6) and sedimentologically (see Fig. 8). The pathway of sediment transport is overwhelmingly from reef flat to island and it is not appropriate to presume Bruun-type equilibrium or assign a depth of closure where the lower shoreface is a solid reef flat unable to be reshaped over sufficiently short timescales, rather than a continuation of the sandy foreshore seawards.

4.4. Inundation and salinisation

Inundation of reef islands is perhaps the most certain consequence of a rise in extreme water levels, amplified by sea-level rise. Inundation is defined here as the diffusion of a high water level into or across an island, and flooding as the accumulation or flow of water from adjacent areas, as when rainwater ponds in island interiors during heavy precipitation such as may accompany tropical cyclones. The morphology shown in the selected profiles demonstrates that the interior of many islands is already at an elevation below the highest tides, and there are already situations where the highest tides result in inundation. Atolls occur in microtidal settings, being in mid-ocean where tidal range is limited. Their susceptibility to high

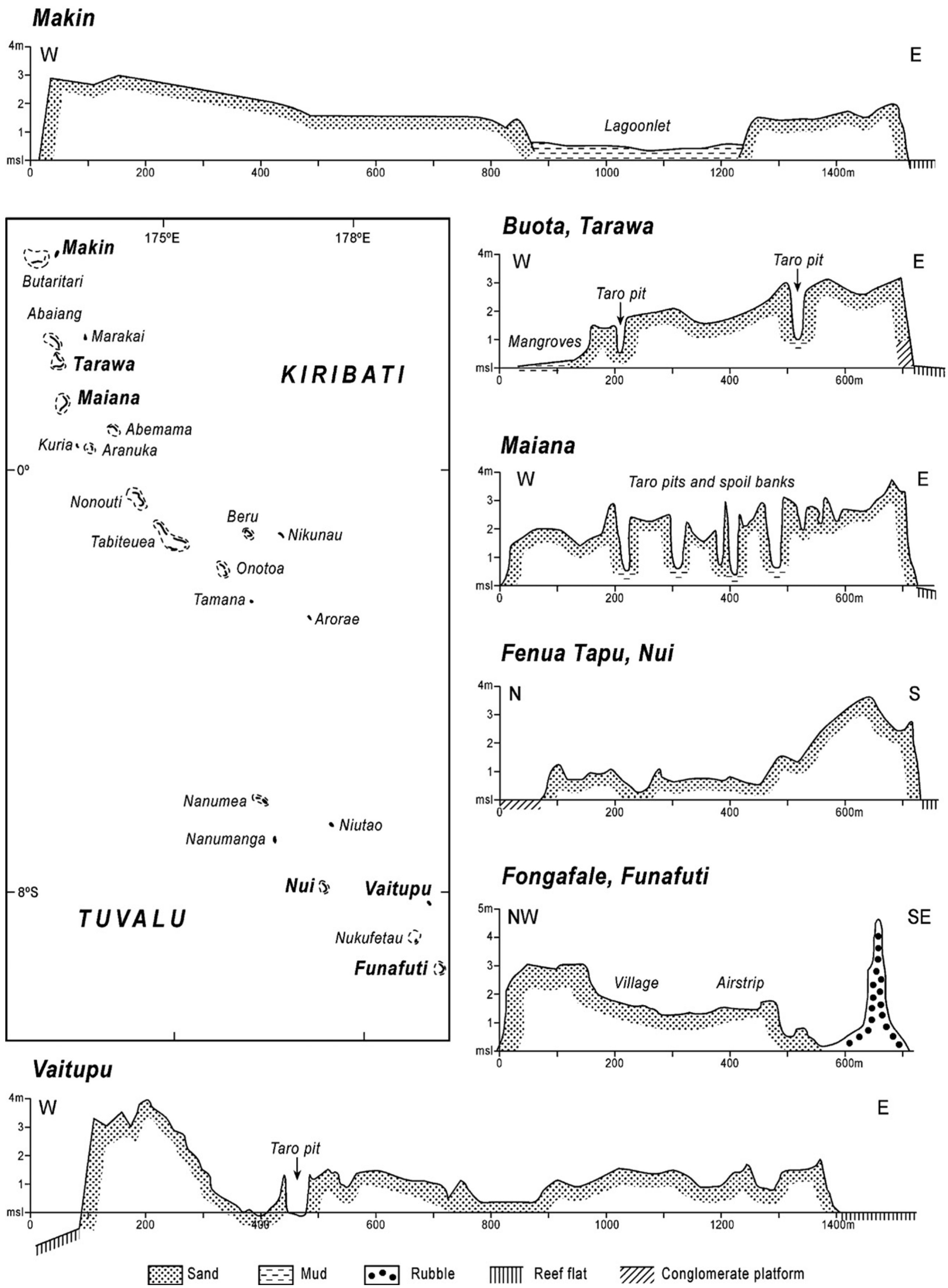

Fig. 7. Atolls and reef islands of the Gilbert chain, Kiribati and of Tuvalu (formerly the Ellice islands), showing profiles across selected islands.

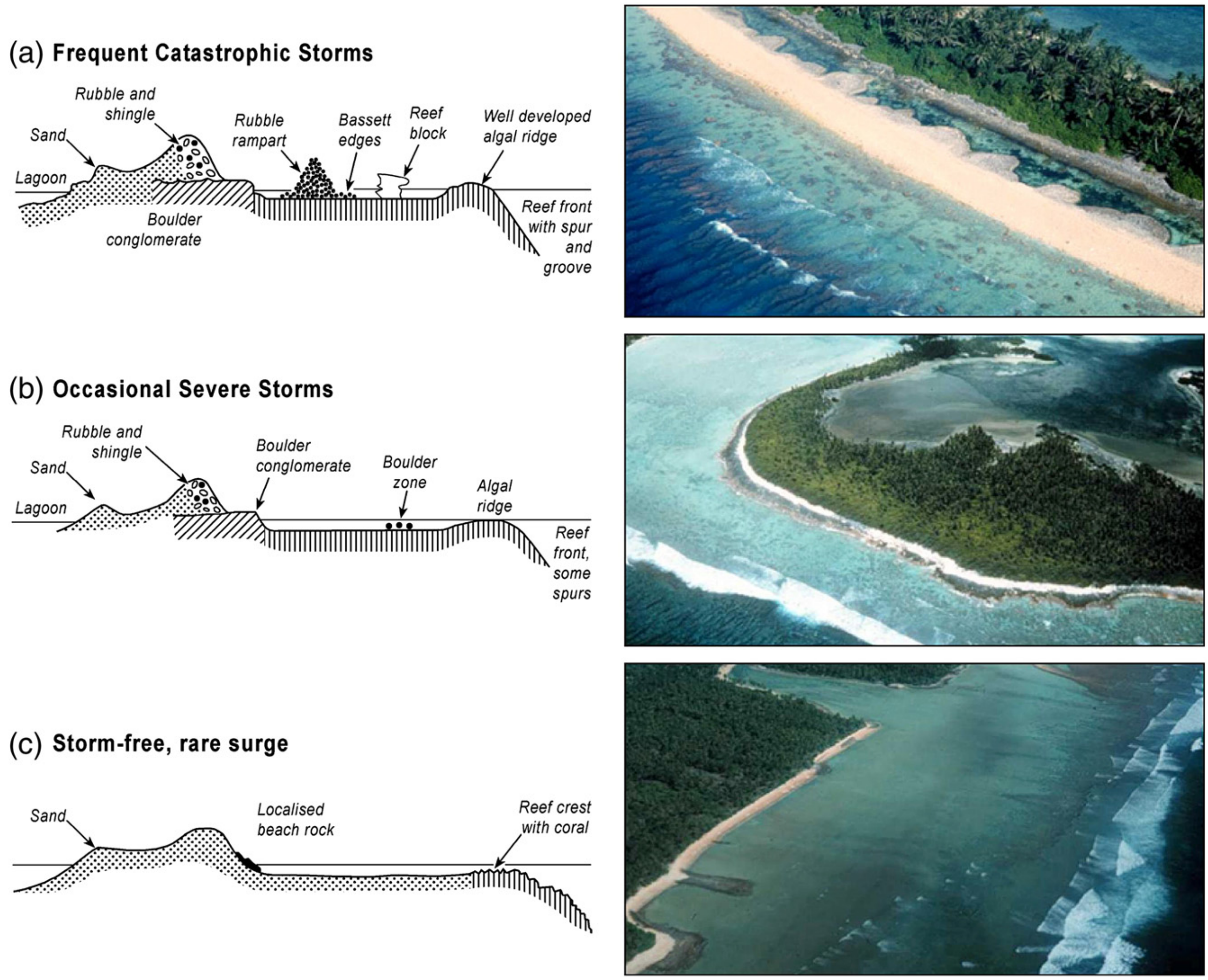

Fig. 8. Characteristic morphology of reefs and reef islands in areas of different storm occurrence (based on McLean and Woodroffe, 1994), illustrated by examples. The reef flat on southern Fongafale, Funafuti with the rubble bank deposited during Cyclone Bebe; reef islands on the eastern rim of the Cocos (Keeling) Islands; sandy reef islands on the eastern rim of Tarawa, Kiribati.

spring tides is amplified when these are superimposed on longer-term sea-level fluctuations such as ENSO and Pacific Decadal Oscillation (PDO). Some of the low-lying depressions were former tidal areas that have been occluded by formation of ridges (this particularly occurs where lagoonward ridges or spits cut off former inlets such as the teloks on Cocos), and are particularly susceptible to inundation. Such inundation would appear most likely to occur on lagoonward shores of reef islands as these are generally of lower elevation.

Christmas (Kiritimati) Island in eastern Kiribati provides an example of the natural variability in these conditions; much of the interior of this large atoll remains under water in extreme El Niño years, such as 1998, through a combination of inundation because monthly mean sea level is considerably higher (c 0.3 m) than in non-El Niño years, together with extensive flooding from the considerably enhanced rainfall (Falkland and Woodroffe, 1997).

Widespread flooding in the interior of Fongafale on Funafuti is often cited as evidence of the effects of sea-level rise, or confirmation that the 'islands are sinking' (Pittock, 2005; Patel, 2006). However, Yamano et al. (2007) reconstruct historical conditions showing that the interior of this island was already subject to flooding at the time of the Royal Society expedition in the 1890s. They indicate that construction of an airstrip over former mangrove wetlands further increased the area subject to inundation, and that a considerable degree of human modification, including urbanisation, has exacerbated the problem in this instance.

In addition to the concern about flooding of the central depression, there is also concern that saline intrusion into taro pits will endanger production of these root crops. Such inundation is already apparent on islands such as Foammulah in the Maldives as well as on many of the Tuvalu and Kiribati reef islands. It is not clear to what extent this results from any general changes to the climate or sea level, as opposed to local factors. Similarly, there is concern that a higher sea level will lead to saltwater penetration into the freshwater lens, although in the case of the islands of Kiribati, recharge of the lens is highly correlated to ENSO, which has a major effect on rainfall as well as sea level (Falkland and Woodroffe, 1997).

5. Discussion

A morphodynamic approach to considering the vulnerability of atoll reef islands to sea-level rise is needed, as a basis both for assessing the natural dynamics of such islands, and for planning management that enhances this resilience. In common with other morphodynamic approaches to coastal landforms, this needs to be founded upon two principles; first, that coastal systems can survive and prosper in the face of rising sea levels if there is a sufficient supply of sediment to maintain the morphological character, and second, that coastal areas can be managed to enhance their resilience to sea-level rise and other adverse changes by promoting the natural functioning of coastal fringes and ecosystems (Capobianco et al., 1999).

The cross-sections of selected reef islands demonstrate several morphological similarities between different reef islands, and imply morphodynamic adjustment between process and form. There is an urgent need to better understand the geomorphological behaviour of these islands and their response to differing rates of sediment supply and sea-level change. Geological investigations indicate that reefs have flourished during periods of sea-level rise, but there is no paleoenvironmental record that reef islands existed prior to stabilisation of sea level in mid Holocene. Reef islands appear to have been present on Indo-Pacific reefs only during the past few millennia during which relative sea level has fallen or been stable over much of the region. That islands can form under gradual rates of sea-level rise is clear from the occurrence of sand cays on Caribbean reefs (including atolls such as those off Belize) where the sea has been rising at a decelerating rate over past millennia, but more rapid rates of sea-level rise as experienced during postglacial ice melt, presumably exceeded the capacity for islands to keep up.

Geomorphological investigations imply that many reef islands show some morphological resilience (Woodroffe et al., 1999; Kench et al., 2005). Unvegetated sand cays appear to accumulate at key locations on the surface of reef platforms, particularly where wave processes are focused; they have some capacity to persist over time (Smithers et al., 2007). Shingle is less prone to erosion than sand, and still greater stability is produced once vegetation is established, both through the binding properties of root systems, and through the greater structure that humus imparts to the soil. Islands develop even greater resilience as a result of lithification, whether beachrock, cay sandstone, phosphate rock or conglomerate. Outcrops of conglomerate platform increase the resistance of islands further, forming an anchor on which islands have accreted.

A morphodynamic approach needs to be informed by a combination of at least four types of research: i) chronostratigraphic studies that decipher how reef islands have formed (e.g. Woodroffe et al., 1999), ii) process studies that establish sediment transport pathways (e.g. Kench et al., 2006), iii) multitemporal reconstructions of past shoreline positions (e.g. Webb, 2006a), and iv) morphodynamic models using computer simulations (e.g. Barry et al., 2007a,b). Identification and sensitivity testing of the rates at which processes operate and shorelines respond, and determination of the critical thresholds, are important objectives of such studies and the associated modeling. This morphodynamic approach can then provide a framework in which human actions can be modeled, such as sand and aggregate mining, or beach protection, which might have conflicting impacts on the natural shoreline dynamics.

The response of the rim of coral atolls to sea-level rise is inadequately understood at present. Several different processes operate, but at significantly different rates, and contradictory responses have been proposed. Sea-level rise, in itself, need not endanger all elements of atoll systems, at least not until critical thresholds are exceeded. Relative sea-level fall during past millennia, largely through isostatic adjustment, means that many Indo-Pacific reef flats presently occur at elevations too high to be suitable for coral growth. Emergent reef flats may be re-colonised by coral and flourishing reefs may undergo further keep-up growth, providing further sediment that is likely to be transported to the oceanward shores (Buddemeier and Hopley, 1988; Hopley, 1993; Hopley et al., 2007). A contrary view is that greater water depth over the reef flat will result in greater wave energy reaching shore, especially following disintegration of degraded reefs after coral bleaching, and that this will accelerate shoreline erosion (Sheppard et al., 2005).

Also unclear is what effect increased wave runup will have on reef islands. It may build the ridge crest higher; alternatively waves may overwash the oceanward ridge and inundate the island interior. The nature of this response is also likely to differ from place to place, and there is presumably a threshold beyond which reef islands may experience more frequent overtopping and may be less desirable places to live than they have been while sea level has been falling or stable.

Islands are spatially heterogeneous. The summary of reef-island topography presented here indicates several characteristics. Islands in the Maldives appear particularly low-lying. On other atolls in the eastern Indian Ocean and western Pacific Ocean, oceanward shores are characterised by a pronounced ridge that seems more likely to accrete sediment than to experience persistent erosion. Lagoonal shores appear more vulnerable, particularly to inundation. Detailed topographic surveys could be undertaken to extend these preliminary observations using photogrammetry or airborne LiDAR. In order to assess vulnerability of different parts of individual islands, it will also be necessary to achieve a clearer understanding of the spatial variation of water levels during extreme events, supplementing tidal planes with observations on wave runup, water table behaviour and the ponding of water in island interiors.

Shoreline response is also a function of the degree of lithification and the coastal vegetation, both of which vary around islands. The resilience of the shoreline will vary from place to place, depending on natural system behaviour, as well as other factors, such as the width of the reef, the frequency and intensity of extreme events, and human modification of the shoreline. Islands depend upon production and transport of sediment, and this will be reduced where the health of the reef is impaired, such as through eutrophication of reef flats, or where sediment pathways are interrupted. Adaptation, such as revegetation of beach ridges, and more active management through nourishment of shorelines with sediment and, where coastal protection is needed, construction of breakwater or seawalls, should be based on the natural resilience of these islands. Susceptibility can be reduced through the reduction of mismanagement, preventing mining of reef material or removing of sand from the beach for use as aggregate, where these activities adversely impact shoreline behaviour.

6. Conclusions

This preliminary synthesis of the topography of atolls in the Indian Ocean and western Pacific Ocean indicates that the predominantly sandy reef islands on different atolls show several morphological and sedimentological similarities. They have been built by wave processes, and in storm-prone areas shingle islands (motu) are common as a consequence of the greater incidence of storm activity. In storm settings, islands may accrete as a result of the impact of large storms; however, it is important to recognise the devastation storms cause to the island community and its economy.

Examination of the morphology of reef islands on atolls indicates that all are low lying, but lagoon shores are generally much lower than oceanward shores which are typically around 3 m above MSL except where dunes have accreted on top of the ridge. There seems little doubt that inundation that is already experienced during the highest tides and during storms events on reef islands on atolls will be exacerbated by sea-level rise, particularly affecting lagoon shores and the low-lying interiors of islands. Reef islands in the Maldives Archipelago represent some of the lowest islands, on many of which there has been only localised ridge-building, and villages are frequently less than 0.5 m above high water.

Oceanward ridges are the highest ground on most reef islands (except for spoil heaps beside pits excavated for taro). Several studies indicate that these oceanward shores are often accretionary, although localised evidence of periodic coastal erosion may persist. Erosion is generally the result of one or more extreme events, and it is generally inappropriate to infer that such erosional events can be related to either subsidence or sea-level rise, processes which occur over much longer time scales. Shoreline erosion is too often considered a sign of climate change on atolls (foreshadowing the ultimate demise of reef islands), without consideration of the geomorphological cause of any individual erosion event and whether it is part of a general trend or merely one phase in a cycle that includes re-deposition.

Detailed studies will be needed to establish the extent to which a particular catastrophe is a consequence of a change in sea level rather than a natural process, or a result of deterioration through other anthropogenic pressures on fragile island systems. More research is needed on the processes that operate on atoll rims to understand island growth over 3000 or more years, and the morphological persistence of reef islands, and then to determine their long-term response to climate change. A morphodynamic approach provides a framework within which to map and manage the relative vulnerability of different shorelines at a range of scales, from archipelagoes, to individual atolls or table reefs, and to the shores of individual islands within each atoll. Some shores are more resilient than others. Island resilience may be expressed by the degree of lithification of sediments and extent of vegetation cover, such that cemented and vegetated islands will not experience the same degree of erosion as unconsolidated or unvegetated islands. On this basis, coastal managers on these atolls may be able to assess vulnerability and better plan sustainable development.

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