January 2011

Atolls

Colin D. Woodroffe
University of Wollongong, colin@uow.edu.au

Naomi Biribo
University of Wollongong, nb766@uowmail.edu.au

Atolls

Keywords
atolls, GeoQUEST

Disciplines
Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details
Woodroffe, C. D. & Biribo, N. (2011). Atolls. In D. Hopley (Eds.), Encyclopedia of Modern Coral Reefs: structure, form and process (pp. 51-71). The Netherlands: Springer.

A

ATOLLS

Colin D. Woodroffe and Naomi Biribo
School of Earth and Environmental Sciences,
University of Wollongong, Wollongong, Australia

Definition

Atolls are annular mid-ocean reefs; the reef rim supports isolated, or near-continuous, reef islands composed of unlithified or poorly consolidated sand or gravel, and encloses a central lagoon.

Introduction

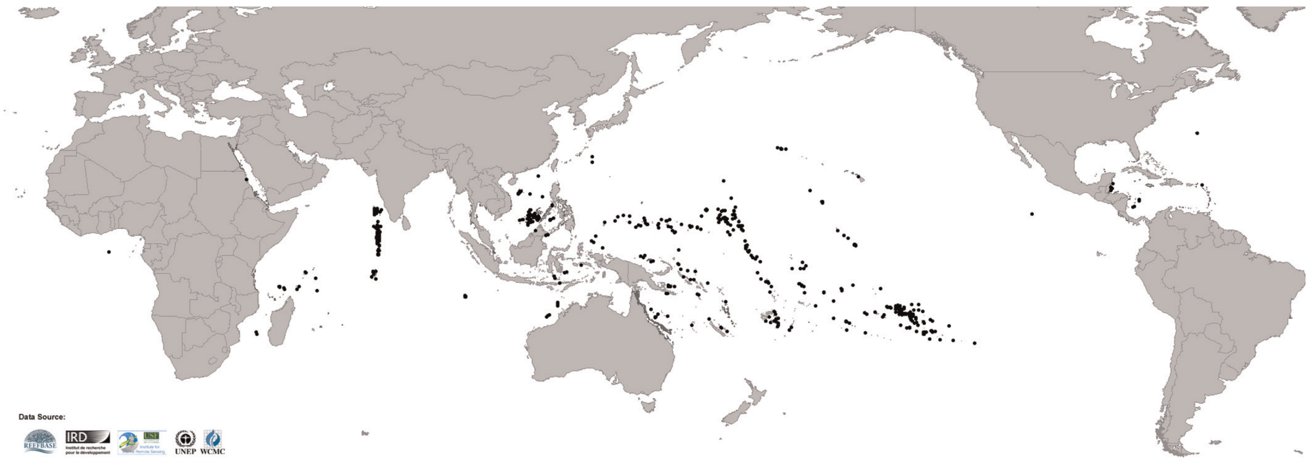
The term "atoll" is derived from a Maldivian (divehi) word, *atolu*. Atolls are ring-shaped reefs that occur in mid-ocean, often in linear island chains or archipelagoes. The most extensive groups of atolls occur in the Pacific Ocean but there are also numerous atolls in the central Indian Ocean (Figure 1). The reef platforms that form atolls are generally characterized by reefs that reach sea level, especially on the windward margin of the reef platform, although there is considerable variation in the extent to which the reef crest is continuous around the entire perimeter of the central lagoon. There are several hundred atolls which occur across a wide range of climatic and oceanographic conditions (Bryan, 1953), and show a wide variety of shapes (Stoddart, 1965; Shimazaki et al., 2006).

Although there is consensus that many mid ocean reefs are atolls, it is more difficult to settle on an unambiguous definition of what constitutes an atoll. The scientific study of atolls owes a considerable debt to Charles Darwin, first because of his insight into reef development and the evolution of atolls, but also because he produced a map of the distribution of known atolls, as well as other reef types, which focused on the geological factors related to where atolls have formed.

Definitions of an atoll vary, but emphasize several factors in common. Shepard considered an atoll: "an oval-shaped coral reef surrounding a lagoon in which there are no islands other than slightly emerged reefs or small sand cays" (Shepard, 1948, p. 251). Wiens, in his book on atolls, suggested that atoll shape is too irregular to be captured by this definition, and believed that the definition by Kuenen is preferable: "all more or less continuous reefs surrounding a distinctly deeper lagoon with or without lagoon reefs… which rise from a sea bottom which is too deep for the growth of coral reefs" (Newell and Rigby, 1957, p. 21, following Kuenen). Wiens proposed his own definition: "an atoll is a more or less continuous emerged or slightly submerged calcareous reef surrounding a distinctly deeper lagoon or several such lagoons without emerged volcanic islands, which stand apart from other islands, and whose upper seaward slopes rise steeper than the repose angle of loose sediments from a generally volcanic foundation too deep for the growth of reef corals" (Wiens, 1962, p. 8).

Although most atolls have a lagoon, sheltered from open ocean swell by the peripheral reef, there are also numerous small platforms, which instead of a lagoon, may be dominated by a single island in the middle of these smaller platforms. These are generally called table reefs, following Tayama (1952), and on those where an extensive reef-top island has formed there is often a swampy central depression.

In the Pacific Ocean there are more than 80 atolls in French Polynesia, most in the Tuamotu Archipelago (Agassiz, 1903a; Guilcher, 1988). There is a prominent chain of atolls that used to be known as the Gilbert and Ellice islands; the Ellice Islands now form Tuvalu. The Gilbert chain is now part of Kiribati; it comprises a sequence of atolls (Richmond, 1993), and there are additional atolls in the Phoenix and Line groups (Keating, 1992). Atolls are extensive through the Marshall and



Atolls, Figure 1 The global distribution of atolls, map produced courtesy of Reefbase (http://www.reefbase.org).

Caroline Islands, with several other atolls in the Federated States of Micronesia. Many of the Cook Islands are atolls, and three atolls comprise Tokelau. The northernmost atoll is Kure in the northwestern Hawaiian Islands at 28°45′N (Riegl and Dodge, 2008). The southernmost is Ducie Island in the Pitcairn Islands group (24°40′S), although Elizabeth Reef in the Tasman Sea at 29°58′S is further south, but may not be a true atoll as it might have formed over a truncated volcanic basement (Woodroffe et al., 2004).

In the Indian Ocean, the Maldives comprise a double linear chain of atolls (Figure 2). The Maldives were the subject of detailed descriptive accounts by Alexander Agassiz (1903b) and Stanley Gardiner (1903). This chain extends through the Laccadives (Lakshadweep) Islands to the north, as a single chain. Minicoy, which was described in detail by Gardiner in his descriptions of Maldive reefs (Gardiner, 1903, 1931), is the southernmost of this group which has received much less study (Siddique, 1980). A more variable group of reefs comprises the Chagos archipelago to the south (Sheppard and Seward, 1999). There are outlying atolls in the Seychelles and southwest Indian Ocean (Stoddart, 1973a), and the Cocos (Keeling) Islands in the eastern Indian Ocean (Woodroffe and Berry, 1994).

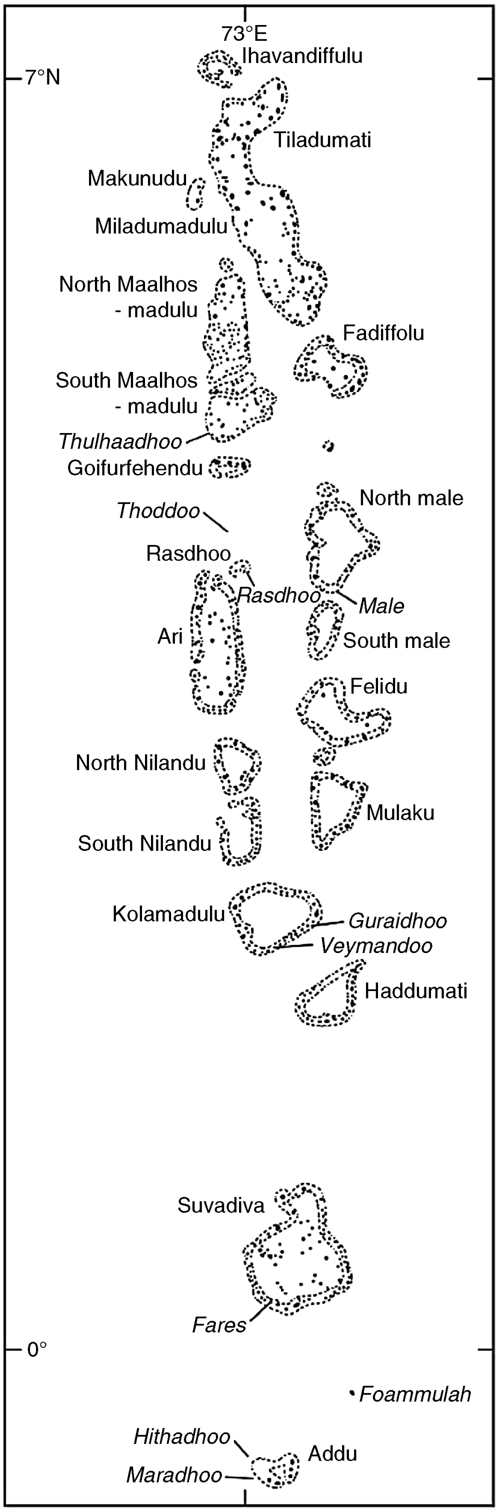
Atolls are relatively rare in the Caribbean; Stoddart (1965) suggested that there were 27, but Milliman (1973) considered only 10 to be atolls. Reefs such as Hogsty Reef in the Bahamas and Roncador Bank off the east coast of Nicaragua have been described as atolls; however, they clearly differ in origin and morphology from Indo-Pacific atolls. Three atolls have been described just east of the Belize barrier reef (Stoddart, 1962; Gischler, 1994).

The largest atoll is Suvadiva (Huvadhoo) in the Maldives with an area of 2,800 km^2; the largest land area is on Christmas Island (Kiritimati) in Kiribati with an area of 321 km^2. Raroia in the Tuamotu has a lagoon area of 171 km^2. Kwajalein measures 120 by 32 km, Rangiroa 79 by 34 km, and Tijger, south of Sulawesi, 72 by 36 km.

There are several types of atoll. Atolls can be classified into ocean atolls and shelf atolls (Ladd, 1977). The ring-shaped reefs in open ocean, which we now realize to be in a mid-plate setting, were mapped in detail by Darwin and are unambiguously atolls. However, there are several other groups of islands that contain reefs that have been classified as atolls. For example, the numerous reefs of the Indonesia archipelago contain some of the most diverse of island groups (Kuenen, 1933). At least 55 are considered atolls by Tomascik et al. (1997). There are also a series of reefs in the South China Sea, where three types of atolls have been recognized: ocean atolls, shelf atolls, and slope atolls (Wang, 1998). Whereas the South China Sea islands include true oceanic atolls, such as Scarborough Reef (Huangyan Dao, Wang et al., 1990), those further north are shelf atolls and there are also a series of 70 continental slope atolls in intermediate water depth. Although shelf atolls are also found elsewhere, such as off the northern coast of Australia (e.g., Rowley Shoals and Seringapatam Atoll on Timor Shelf, see Western Australian reefs), slope atolls have rarely been described.

A further variant of an atoll is a reef called an almost atoll. This term has been used differently by different authors; sometimes it has been used to refer to a rapidly subsiding volcanic island that did not form an atoll. However, it is generally taken, in the sense used by Davis (1928), to refer to a residual volcanic island that is surrounded by an annular reef, and which will be an atoll when the remaining volcanic rock has subsided below the level of the sea. Chuuk (Truk) is a classic example, but Aitutaki is an almost atoll in the southern Cook Islands, which has been described in detail by Stoddart (1975).

There has also been recognition of a class of bank atolls, sometimes referred to as submerged atolls, that includes banks on which reef growth does not reach sea level. There are examples in Palau and the Caroline Islands, and Saya de Malha in the Indian Ocean. A further category comprises atolls that are “raised” or emergent, in which older



Atolls, Figure 2 The Maldive archipelago which for much of its length comprises a double chain of atolls, but reduces to single reef platforms to the south.

limestones are exposed. Reef limestones of last interglacial age have been found to underlie the rim of atolls at depths of 10–20 m (described below), and on several atolls these outcrop at the surface, or as in the case of Aldabra and Henderson Island, are the dominant subaerial limestone (Braithwaite et al., 1973; Pandolfi, 2008). Elevated atolls include Maré, Lifou and Ouvea in Vanuatu, Makatea in French Polynesia, Nauru, and Niue. Older limestones record successive periods of accretion, and many of these limestones are dolomitized or contain phosphate deposits that have often been mined. Mataiva in the Tuamotu Archipelago also has exposures of Tertiary limestone.

Surface morphology

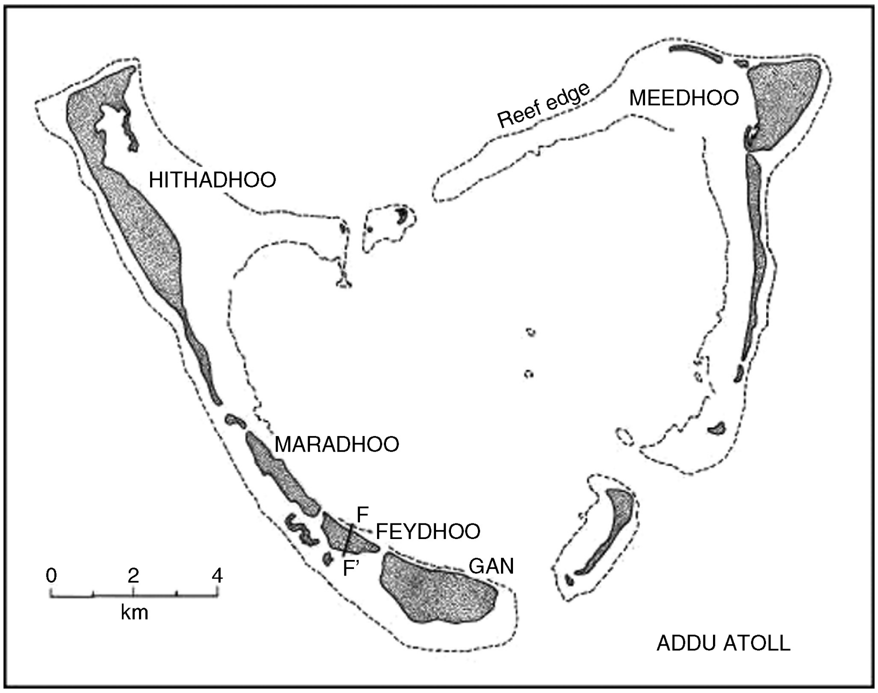
The general topography and geomorphology of atolls was outlined in a book by Wiens, entitled *Atoll Environment and Ecology*, based on detailed studies sponsored by the Pacific Science Board and focused on the Marshall Islands, as well as selected other Pacific atolls (Wiens, 1962). In this account, and in a major review by Stoddart (1969), three features are distinguished: the outer reef, the reef rim, and the lagoon. These are considered below.

Outer reef

The outer reef of an atoll is near continuous and is generally subject to ocean swell that breaks on all sides (Figure 3). The windward rim of the atoll is generally more continuous than the leeward; for example, the major passages through the reef and into the lagoon are more often on the leeward side of the atoll, as seen in the Tuamotu Archipelago (Guilcher, 1988). In many cases, reef islands are more abundant on the windward reef than on the leeward. In the case of many of the atolls in Kiribati, the leeward margin does not reach sea level, and many of the larger atolls, such as Tabiteuea and Tarawa have a much better developed eastern windward margin (see Figure 4).

The reef front is steep and rises abruptly from the ocean floor, often from as deep as 4,000 m. Although there is a rain of sediment sourced from the living reefs that cascades down the forereef, many atolls margins are characterized by a steep drop-off which exceeds the angle of repose, indicating that the reef has been built by vertical accretion. Much of the forereef of Mururoa (q.v.), below 10 m water depth, is at an angle of 45° (Chevalier et al., 1969).

The reef front often has one or more distinct terraces; for example at 15–20 m depth on the reef front of Marshall Island atolls (Emery et al., 1954). The shallow reef front commonly has a prominent spur and groove (q.v.) morphology (Munk and Sargent, 1954). This consists of broad ridges, covered by coral or coralline algae, which run at right angles to the reef margin, oriented into the dominant wave direction. The ridges are interpreted as constructional, interspersed with sand-filled channels that may



Atolls, Figure 3 Addu Atoll, the southernmost of the Maldives, showing a near continuous rim around the more exposed margins.

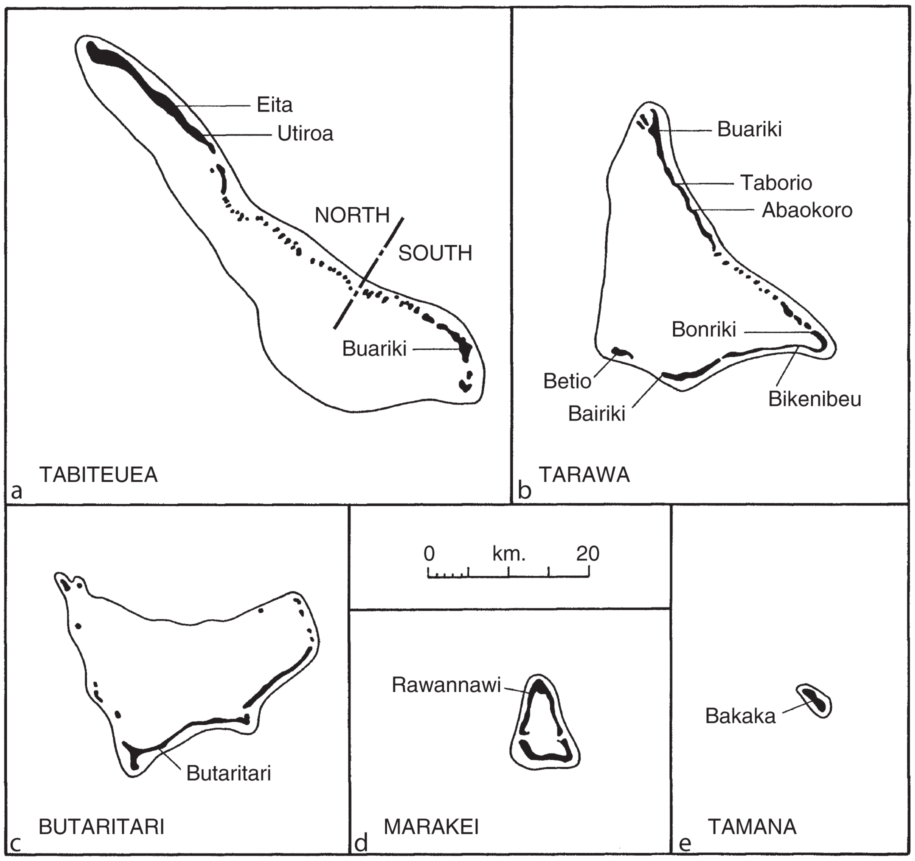
be erosional. Spur and groove are best developed on high-energy reef fronts and merge into surge channels at the reef crest (see Reef front wave energy).

The reef crest is generally dominated on the windward side of the atoll by a prominent crest, veneered by pink algae (*Porolithon* or *Lithothamnion*) forming an algal rim (q.v.) on higher-energy trade-wind dominated windward reef crests. Waves break on all sides of an atoll, if the reef reaches sea level, but the largest breakers are on the margin that faces the swell direction.

Reef rim

The reef rim can be of variable width and contains islands in some instances, or can be a broad reef flat in others. Typically, the reef flat (q.v.) is between 100 and 1,000 m wide; many of the north Pacific atolls have an average width of about 500 m (Wiens, 1962). The reef flat is shallow, or commonly much of it may be exposed during lowest tide. In other settings, distinct zones can be discriminated across the upper surface. The algal rim, over which coralline algae are dominant, often merges into a backreef zone that has detrital material on its surface. In the higher energy setting, this is a discontinuous scatter of boulders of dead and detached corals, or fragments of reef limestone. In less exposed sites, such as lower energy atolls rims or the leeward margin of otherwise high-energy atolls, the fragments are smaller and less frequent. Corals thrive in pools of water that remain deep enough over a tidal cycle, and the reef crest and immediate backreef are some of the most productive settings. Turf algae can be abundant and benthic foraminifera are epiphytic on these algae or under loose boulders and within crevices on the reef (Collen and Garton, 2004).

The reef flat that forms on Pacific and Indian Ocean atolls is usually broad and flat. On some atolls a slightly deeper channel may occur behind the boulder zone, usually with thickets of branching *Acropora* and *Monitpora* corals, and this has been called the boat channel (q.v.) as it is adopted as the preferred route to navigate a small boat along the reef rim. If the reef flat is at an elevation that it is exposed during low tide, then the surface is generally veneered by coralline algae, but deeper pockets enable corals to persist. Where there is sufficient water over the reef top for them to establish, massive corals, particularly of the genus *Porites*, are often limited in their upward growth by exposure during low tide and adopt a microatoll growth form. These microatolls (q.v.) can grow laterally in some cases to several meters diameter. There is also often the distinctive blue octocoral *Heliopora* in this setting. The elevation of the reef flat is critical in determining whether there is suitable substrate for coral to establish, and, as will be discussed below, slight changes of sea level can alter the nature of the habitat on the reef flat. In many cases the reef flat can be interpreted to have formed under a slightly higher sea level, and the gradual fall of sea level over recent millennia has resulted in substrates on which coral previously grew, now being emergent at low tides and no longer suitable for modern corals to colonize. Aerial reconnaissance often reveals a backreef zone that appears aligned,



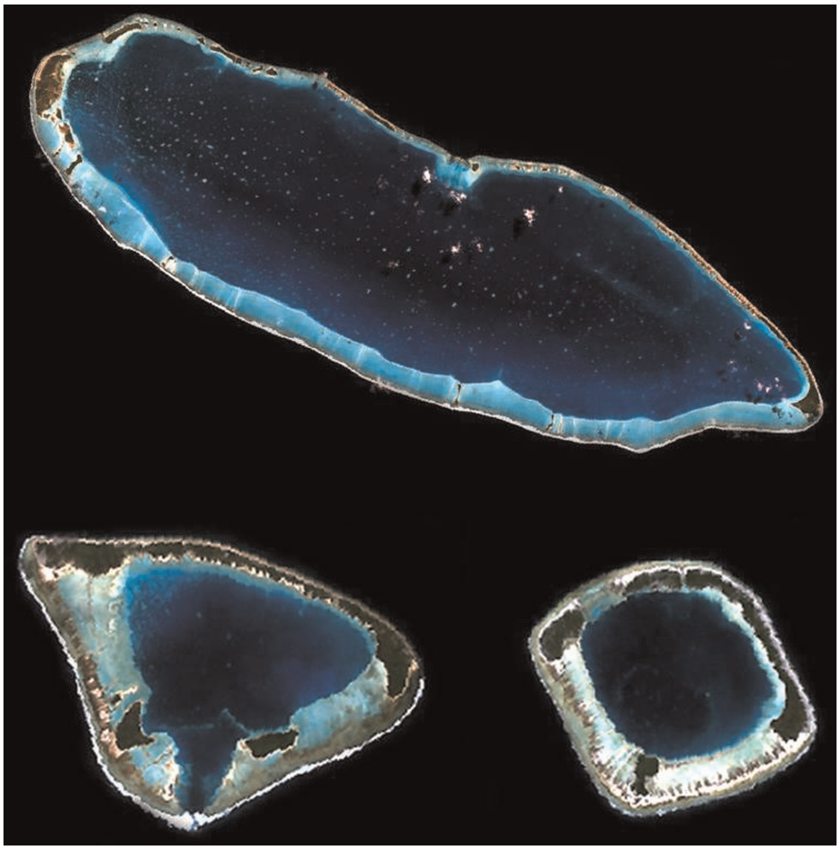
Atolls, Figure 4 Several of the atolls in the Gilbert chain, Kiribati, showing a selection of atoll outlines. Tamana is an example of a table reef on which there is a single island on a smaller reef platform.

with linear reef-crest normal stripes extending into the lagoon. Whereas this aligned coral zone (q.v.) suggests a response by corals to the directions of flow across the reef, such patterning is rarely apparent when actually on the reef flat.

In a number of cases, evidence of a higher former sea level can be seen, such as fossil corals in their growth position (including microatolls that grew at an elevation at which they can no longer grow). On a few atolls mushroom shaped rocks indicate that such a higher surface is being actively undercut (e.g., Mopelia Atoll in the Society Islands), although in a few cases in the Tuamotus these older remnants, termed *feo*, are Pleistocene in age. On a few atolls there is also a fossil algal ridge stranded several hundred meters inshore of the modern algal rim. Fossil algal rims of late Holocene age have been dated on Suwarrow Atoll in the Cook Islands (Woodroffe et al., 1990a) and Nukutipipi Atoll in the Tuamotus (Salvat and Salvat, 1992).

Reef islands develop on many of the reef rims of atolls. The details of these islands are examined below, but one of the most significant features is the degree of continuity along the reef. Where there are no islands, the reef flat extends from reef crest to lagoon. Major passages into the lagoon are significant because they enable significant water exchange between ocean and lagoon; they also interrupt the chain of islands along the rim. The Polynesian term for large and deep passages is *ava*. Smaller and shallower passages between islands are called *hoa* (Figure 5). The degree to which the lagoon of an atoll is enclosed, and the nature of the passages is a key feature in relation to circulation in, and flushing of, the lagoon (see lagoons and lagoon circulation).

Those atolls with numerous or large *ava* are generally effectively flushed by tidal circulation, whereas atolls that have almost continuous reef rims around their perimeter (see Tauere Atoll, Figure 5) are more likely to be flushed through the action of waves overtopping the reef rim (Callaghan et al., 2006). The nature of flow, and the degree to which sediment is transported through inter-island passages (*hoa*), varies as a function of depth, distance from the reef crest, and tidal and wave energies. Similar passages occur between islands on the rim of Indian Ocean atolls. For example, Guppy (1889) made important observations in the passages that feed the lagoon on the Cocos (Keeling) Islands on the basis of which he made a first estimate of the rate of sediment infill, inferring that the lagoon would require several thousand years to fill with sediment.



Atolls, Figure 5 Three atolls in the Tuamotu. The *upper* is Kaukura Atoll which is about 48 km from west to east; the *lower*, Haraiki and Tauere Atolls, are both about 7 km from west to east (satellite imagery courtesy of Serge Andréfouët).

The significance of these interisland passages has been further examined by Kench and McLean (2004).

Where *hoa* do connect with the lagoon, they can be conduits for sediment transport and a sand apron, comprising material sourced from the reef or reef flat, which accumulates at the lagoonward mouth of the *hoa*. In atolls that have a large enough lagoon that sufficient wave energy can be generated across the lagoon, these sediments can be further reworked alongshore along the reef island lagoon shores, such that a spit can form, in some cases closing the *hoa* and forming a closed pond known in Polynesia as *tairua*; an example of an atoll where this has happened is Taiaro.

Sheltered locations on the lagoonal shore may be colonized by mangroves; several species of mangroves occur on atolls in the Maldives, and in the Marshall Islands, Kiribati and Tuvalu. Mangroves are absent from the Cook, Tokelau and Tuamotu islands, although introduced to the Society Islands. Mangroves decrease in species abundance from west to east across the Pacific although with a disjunct species *Rhizophora samoensis* occurring from New Caledonia to Samoa (Woodroffe, 1988).

Lagoon

The lagoon is sheltered in comparison to the outside of the atoll, and may contain scattered patch reefs (q.v.), which have also been called pinnacles or knolls. Some lagoons (q.v.) may have few such patch reefs, but in other atolls there can be an intricate mesh of reefs forming a reticulate network of shallow reefs, such as Mataiva (see also reticulated reefs). The narrow ridges of reef separate deeper holes, termed “blue holes” (q.v.). Lagoons vary considerably in depth; they can be shallow, or tens of meters deep (Gischler, 2006). Reginald Daly believed that there was an overall similarity in the depth of many atolls, which he considered provided support for his theory of glacial control (described below, see also Daly). However, it is now recognized that there is considerably more variation in depth than envisaged by Daly. Atolls in the southern Maldives, for example, contain lagoons that are more than 70 m deep, but other lagoons may partially dry at low tide (the southern end of the lagoon of the Cocos (Keeling) Islands, for example, q.v.).

The lagoon is a prominent feature of most atolls. Lagoons are gradually infilling both with sediment produced within the lagoon, but more especially with sediment derived from the more productive reef rim. Purdy and Gischler (2005) propose an "empty bucket" model of lagoon infill, capturing the stages of infill after the surrounding reefs have caught up with sea level (Neumann and Macintyre, 1985). The pattern of infill is likely to depend on the nature of the reef rim, and sediment production may be proportional to the atoll's perimeter (Tudhope, 1989).

The lagoon at Enewetak has been described in a detailed study by Emery et al. (1954). It reaches a depth of 55 m, and the benthic communities form a series of concentric zones (Colin, 1986), with foraminifera a conspicuous component of lagoon sediments, and a patch reef zone (termed knolls or pinnacle reefs by Emery) (Wardlaw et al., 1991). Similar concentric zones are known to occur in the sediments of Rongelap and Bikini Atolls (Emery et al., 1954) and also in the case of Kapingamarangi Atoll (McKee et al., 1959). More recent studies reaffirm the significance of foraminifera, particularly *Calcarina* and *Heterostegina* in each of Kayangel in the Palau Islands, and Enewetak and Majuro in the Marshall Islands (Yamano et al., 2002). There is much variability in the lagoon floor sediments of Tarawa Atoll, in Kiribati, but foraminifera are a prominent component (Weber and Woodhead, 1972; Lovell, 2000; Paulay, 2001). The calcifying alga *Halimeda* is one of the most prominent features of the sediments of some of the deeper lagoons; it dominates much of the interior of the lagoon of Suwarrow (Tudhope et al., 1985). In the case of Cocos, much of the lagoon is dominated by sediments produced within the lagoon (Smithers et al., 1992). Mud may accumulate in localized embayments within the islands, termed *teloks* on Cocos and *barachois* on Diego Garcia (Soddart, 1971). On highly enclosed atolls, such as Marakei in the Gilbert chain of Kiribati, lagoon sediment is mud, with reef flat foraminifera found only at the entrance to the narrow reef passage on the eastern margin (Woodroffe, 2008). Mud is typical of the lagoon floor within the reticulated reefs of Mataiva Atoll in French Polynesia (Adjas et al., 1990).

Although active vertical reef growth implies that the reef rim might be a constructional feature, it has been apparent since the study of MacNeil (1954) that solution of the interior of the lagoon occurs during subaerial exposure when the sea is lower than present during glaciations. This view, examined further below in relation to the geological evolution of atolls, has been especially promoted by Purdy and Winterer (2001).

The geomorphology and biogeography of atolls has been mapped in detail where ground reconnaissance has been undertaken, notably through the extensive studies of David Stoddart (q.v.), or in a few instances where aerial photography is available at suitable scales (Woodroffe and McLean, 1994). Recently, high-resolution satellite imagery has been used in conjunction with state-of-the-art remote sensing algorithms to map reef geomorphology and habitat distribution (Andréfouët et al., 2001, 2003, Naseer and Hatcher, 2004; Yamano et al., 2006).

Geological evolution of atolls

As the oceans were explored during the seventeenth and eighteenth centuries, atolls became more broadly known. We do not know when atolls first became a feature of familiarity to European explorers, but they have certainly been known since the Spaniard Mendana landed on an atoll in Tuvalu. In the early nineteenth century, Charles Lyell (q.v.) promulgated the view that atolls represented a coral veneer around the margin of submerged volcanic craters, in his *Principles of Geology* published in the 1830s, a book that was to have a profound influence on Charles Darwin.

Charles Darwin (q.v.) proposed an alternative theory, his theory of coral reef formation, after witnessing evidence of the vertical movement of land during surveys by *HMS Beagle* on the coast of South America. Darwin's subsidence theory (q.v.) considered 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 might 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 to sea level, had occurred to Darwin after observing the evidence of uplift in South America, before he ever saw a reef. His hypothesis was reinforced when he viewed the fringing reefs around Moorea from the slopes of Tahiti. Although the Beagle passed atolls in the Pacific, it did not stop at any. Darwin wrote the first draft of his theory of reef development as the ship sailed to New Zealand (Stoddart, 1995). The *Beagle* had passed through the Tuamotu Archipelago in what is now French Polynesia, but the only atoll that Darwin set foot on was the Cocos (Keeling) Islands in the eastern Indian Ocean. Here he keenly accepted observations of the undercutting of coconuts and the erosion of the shoreline as "tolerably conclusive evidence" in support of his theory.

It is important to discriminate that Darwin's theory applies to the *structure* of reefs, based on their long-term evolution, at timescales of millions of years, whereas the *surface morphology* of the atolls reflects late Holocene formative processes that operate over much shorter timescales (Stoddart, 1973b). Stoddart (q.v.) has emphasized the difference in time scale; reef structure (q.v.) being the outcome of millions of years of geological evolution, whereas the surface morphology results from the most recent (Holocene) adjustments of form to the processes that operate, including subtle changes in sea level. At the time Darwin proposed his theory, the significance of sea-level fluctuations associated with the glaciations was unknown, but it is possible to incorporate our latest understanding of the oscillations of sea level into the gradual formation of the sequence of limestones that underlie a typical atoll.

Darwin's subsidence theory of atoll evolution (q.v.) was tested by deep drilling on Funafuti Atoll (q.v.) in 1896–1898 which, although it failed to reach the underlying volcanic basement, recovered more than 300 m of shallow-water carbonates implying subsidence (Spencer et al., 2008). Subsidence of volcanic basements upon which atolls are founded was eventually substantiated by drilling on the atolls of Bikini and Eniwetak in the Marshall Islands (see a synthesis in Guilcher, 1988, and Chapters for Bikini Atoll and Enewetak Atoll). Daly recognized the significance of sea-level fluctuations (Daly, 1934) and documented evidence from across the Pacific that recorded a sea level above present level. However, the glacial control hypothesis (q.v.) that Daly advocated to explain reef development, further developed by Wiens (1959, 1962), presumed that reefs were totally planed off at low sea level and that the entire structure of modern reefs was Holocene. The antecedent karst hypothesis advocated by Purdy (1974) corrected this mistaken view, and recognized the significance of antecedent platforms (q.v.), often of late Pleistocene age. It has now been widely shown that the reef rim on modern atolls is underlain by older Pleistocene reefs (McLean and Woodroffe, 1994; Montaggioni, 2005).

Darwin's theory was enthusiastically adopted by several other prominent scientists, most notably Dana (q.v.), and became widely debated. An alternative view proposed by Murray (1889) revolved around a belief that atolls developed as a result of solution of lagoons. Although considered by Gardiner (1931), this view became discredited when it was realized that seawater was supersaturated with calcium carbonate. Wood-Jones (1912) proposed an alternative view based on his time in the Cocos (Keeling) Islands. He thought that it was the production of sediment around the margin of an atoll and its transport and deposition in the interior that prevented coral growth in the center of reef platforms. However, this sedimentation theory was not widely supported. W.M. Davis (q.v.), in his review of the origin of reefs (Davis, 1928), considered that the only real contender against Darwin's view was the glacial control theory proposed by Daly, and in a subsequent review, Cotton (1948) regarded the subsidence, glacial control and antecedent topography theories as plausible.

In addition to his observations on Cocos, Darwin undertook a substantial compilation of information on reefs, and in his book published in 1842, he included a map of the distribution of atolls, which provided further evidence of the fact that most atolls occur in mid ocean (Darwin, 1842).

Further exploration was to extend knowledge about atolls. The distinguished American geologist, James Dana (q.v.), extended Darwin's ideas as a result of his visits to Kiribati, Tuvalu, the Tuamotu Archipelago, the Society Islands, Fiji, and the Phoenix and Hawaiian Islands. He was a firm supporter of the subsidence hypothesis (q.v.). Alexander Agassiz (q.v.) undertook extensive studies of reefs on extended voyages at the turn of the twentieth century. His 9-month cruise on *Albatross* in 1899–1900 enabled him to describe 30 atolls in the Tuamotu Archipelago and 28 in Tuvalu, and the Marshall and Caroline Islands. He followed this with further descriptions of the Maldives Archipelago in 1901–1902, where his observations built on those of Gardiner who had mounted an expedition in 1899–1900. Agassiz attempted to drill Wailangilala atoll in Fiji, but recovered material only from the upper 26 m. The Chagos Archipelago was described during the Percy Sladen expedition, and a fuller account of this period of reef exploration is given by Spencer et al. (2008). The Cocos (Keeling) Islands (q.v.) were examined by Guppy (1889); Wood-Jones (1912); and Gibson-Hill (1947), making this one of the best known atolls by mid-twentieth century.

Darwin had realized that drilling through an atoll was the optimal way to test his theory and he wrote before his death to Agassiz in an effort to encourage such drilling (see Chapter Darwin). Such drilling was finally undertaken on Funafuti Atoll. The Royal Society (q.v.) sponsored a program involving a series of expeditions in the 1890s to Funafuti. The objective was 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 (q.v.) and George Sweet, and the final stage of drilling, although still in shallow-water carbonates, was overseen by Alfred Finckh in 1898. At the time the fact that the core did not reach volcanic basement at more than 300 m depth appeared inconclusive, although it was clear that shallow-water carbonates persisted below depths at which they are now forming. In retrospect we now know from the strontium isotope stratigraphy that dolomite in the lower core was formed through diagenesis between 1 and 2 million years ago. The upper 26.4 m of the core has been radiocarbon dated indicating a history of sea-level rise during the past 8000 years (Ohde et al., 2002).

During the Quaternary, atolls have evolved in response to a series of sea-level oscillations. It was Daly who gave these Quaternary ice ages such prominence in geological interpretations of oceanic islands. His glacial control theory involved the eradication of coral reefs from areas at their poleward limits, which he called marginal seas during successive glaciations (although this view is not supported by study of reefs at their latitudinal limit (q.v.)). He also believed that the reef rim had been planed off during glacial lowstands, and by inference that the entire reef rim had accreted during the postglacial. Daly's views were further promoted by Wiens (1959, 1962), but are no longer supported (see Chapter on the glacial control hypothesis).

Significant further studies on atolls occurred after World War II. American research in the Pacific involved a focus on the atolls of the Marshall Islands. Geological studies were prominent and the stratigraphy of atolls became better known because of selection of sites for atomic bomb testing, as well as through scientific curiosity. Seismic studies in 1946 and 1950 provided the first hint that the carbonates were underlain by volcanic rocks (Raitt, 1954), together with the recovery of noncarbonate rocks dredged from depths greater than 1,400 m on the flanks of these islands. In 1951, drilling on Bikini Atoll encountered basalt at depths of 1,287 and 1,411 m respectively in two boreholes. Examination of the limestones indicated that they had been deposited in shallow water, and the presence of solutional unconformities supported the episodic exposure of these during successive sea-level lowstands (Schlanger, 1963).

Subsequently drilling on Mururoa has revealed 400–500 m of carbonate over the volcanic basement that underlies that atoll (q.v.), with a similar stratigraphy also on neighboring Fangataufu (Lalou et al., 1966). A Quaternary history of the past 300,000 years has been derived (Camion et al., 2001) implying that the atolls became more atoll-like as a result of dissolution of the lagoon and buildout of the periphery through reef growth. On Midway Atoll in the Hawaiian Islands (q.v.), volcanic basement has been encountered at 55 m beneath Sand Island and 378 m beneath reef to the north of the lagoon, further supporting Darwin's subsidence theory (Ladd et al., 1967, 1970).

A series of further studies were initiated by the Pacific Science Board during the period 1946–1969. This included fieldwork on Arno, Ifaluk and Kapingamarangi Atolls in what are now the Federated States of Micronesia, Onotoa in Kiribati, and Raroia in French Polynesia. A compilation of this work led to the publication of the book on atolls by Wiens in 1962. This was also a period during which the Atoll Research Bulletin was initiated (Fosberg and Sachet, 1953; Spencer et al., 2008).

Quaternary evolution of atolls

Shallower drilling on several atolls has encountered Pleistocene reef limestone, often dated to the Last Interglacial, at depths of 10–20 m below the modern atoll rim. In the Cocos (Keeling) Islands Pleistocene limestone, shown to be of Last Interglacial age, occurs at depths of 8–13 m below sea level beneath each of the major islands, and seismic reflection profiling records a reflector that correlates with this discontinuity beneath the lagoon (Searle, 1994; Woodroffe et al., 1994). This karstified Pleistocene limestone underlies the rim composed of Holocene limestones. Pleistocene limestone has been shown to underlie the rim of Tarawa Atoll (Marshall and Jacobson, 1985), Funafuti Atoll (Ohde et al., 2002), several atolls in the northern Cook Islands (Gray et al., 1992), as well as atolls in the Maldives and Chagos Archipelagoes (Woodroffe, 2005). In some that have been drilled to deeper depths, such as Eniwetak and Mururoa, it is apparent that the last interglacial limestone is underlain by older reef limestones deposited during preceding highstands (Szabo et al., 1985; Camoin et al., 2001).

When sea level was high during the last interglacial (and presumably former interglacials) an atoll rim similar to the modern existed, although no evidence remains as to whether it contained islands (Perrin, 1990). During glaciation the reef limestones 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 (Scott and Retondo, 1983, see subsidence theory), so when sea level rose again during postglacial times it flooded the platform around 8000 years ago. There are several atolls on which last interglacial limestone is exposed at the surface (e.g., Aldabra in the western Indian Ocean, Braithwaite et al., 1973; Anaa in French Polynesia, Pirazzoli et al., 1988; and Christmas Island in eastern Kiribati, Woodroffe and McLean, 1998). 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); erosion appears to have accentuated lagoon morphology on many atolls.

Accretion of the reef rim

Holocene reef growth has been constrained by the pattern of sea-level change; there appears to have been a lag before corals reestablished over the Pleistocene substrate around 8000 years ago. The reef grew in an effort to catch-up with sea level, as revealed in the case of Cocos in the Indian Ocean (Woodroffe et al., 1994) and Tarawa in the Pacific Ocean (Marshall and Jacobson, 1985). After reefs caught up with sea level, lateral progradation of the reef seems to have occurred, particularly in those situations such as Suwarrow and Nukutipipi where there are fossil algal rims abandoned behind the modern reef crest.

The majority of polar ice melt appears to have been completed by 6000 years ago, and the volume of water in the ocean at that time is likely to have been similar to that of today. However, hydro-isostatic adjustments mean that the details of relative sea-level history vary geographically (Lambeck, 2002, see Chapter Mid Holocene). In particular, a fall of sea level occurred relative to far-field remote islands, which has been termed ocean siphoning (Mitrovica and Peltier, 1991). Whether the sea-level curve at far-field sites peaked abruptly around 6000 years ago and fell since then (through ocean siphoning) or whether there has been post-6000 year melt, with a more gradual peak around 4000 years is difficult to discriminate from atolls, because it was necessary for the reef rim to accrete to sea level before evidence would be preserved (Nunn and Peltier, 2001). The atoll rims have grown from the surface of the Pleistocene limestone to catch up with sea level, so the timing of the initiation of a reef flat in mid Holocene varies geographically from atoll to atoll. Hydro-isostatic adjustments mean that the elevation of mid-Holocene reefs can also vary between atolls.

The conglomerate platform on some atolls contains within it evidence of corals in growth position that formed a part of a former reef flat (see Chapter Conglomerates). Fossil microatolls (q.v.) are especially useful in this respect, but other reef flat corals such as *Heliopora* can also be important in differentiating units within the conglomerate platform that mark former reef flat surfaces and indicate higher than present sea level, and overlying storm deposits. Radiocarbon dates on corals from conglomerate record inputs of corals detached during storms. For example, ages of 4000–3000 years BP have been obtained on corals from within the conglomerate platform on the Cocos (Keeling) Islands (Woodroffe et al., 1994). Ages from other atolls seem broadly comparable, with evidence for variation in Kiribati-Tuvalu (the Gilbert-Ellice chain), from north (where it may have been as old as 4000 years ago) to south (where reefs may have reached sea level since 2000 years ago, McLean and Hosking, 1991). Radiocarbon ages as old as 5500 years BP have been reported from atoll surfaces in the Tuamotu Archipelago (Pirazzoli and Montaggioni, 1988).

Since the reef rim reached sea level and the reef flat was formed, there has been further carbonate sediment produced which has continued to infill the lagoon (Purdy and Gischler, 2005) and has seen the accumulation of sediments to form reef islands around the margin. Several researchers suggested that island formation on atolls occurred as a result of this slight fall of sea level (Cloud, 1952; Schofield, 1977a, b; Dickinson, 2004).

David and Sweet (1904) undertook mapping of the islands and reef flats around Funafuti Atoll (q.v.), and considered that large *Porites* corals in growth position indicated that the sea had been above its present level relative to the atoll in the past. Similarly Cloud (1952) described outcrops of *Heliopora* in growth position, above the elevation that it presently reaches on the reef flat as evidence of emergence on Onotoa. There has been an ongoing debate about the extent to which conglomerate of this type is formed by storms. An expedition to the Caroline and Marshall Islands (CARMARSEL expedition) specifically to resolve whether the conglomerate was a storm deposit or as an indicator of higher sea level reached no consensus (Shepard et al., 1967; Newell and Bloom, 1970). The most accurate reconstructions of former sea level have been derived where a fossil sea-level indicator can be related to its modern equivalent (see Sea level indicators on reefs), and the two most appropriate types of indicator are microatolls of massive coral and reef flat outcrops of *Heliopora*.

Outcrops of conglomerate have been used to infer higher sea level in the Maldives (Gardiner, 1903; Sewell, 1936), but the evidence is fragmentary. Dated *in situ* coral from Addu Atoll was interpreted to infer that the reef flat had reached modern sea level by around 3000 years BP (Woodroffe, 1993). Two recent subsequent studies have proposed detailed sea-level curves for the Maldives during the Holocene, but differ on whether or not it is possible to identify evidence to support sea level higher than present in mid Holocene (Gischler et al., 2008; Kench et al., 2009). Based on detailed mapping of conglomerate around Cocos, several *in situ* microatolls have been radiocarbon dated and indicate that there has been a gradual fall of sea level from an elevation 0.5–0.8 m above present over the past 3000 years (Woodroffe et al., 1990b; Woodroffe, 2005).

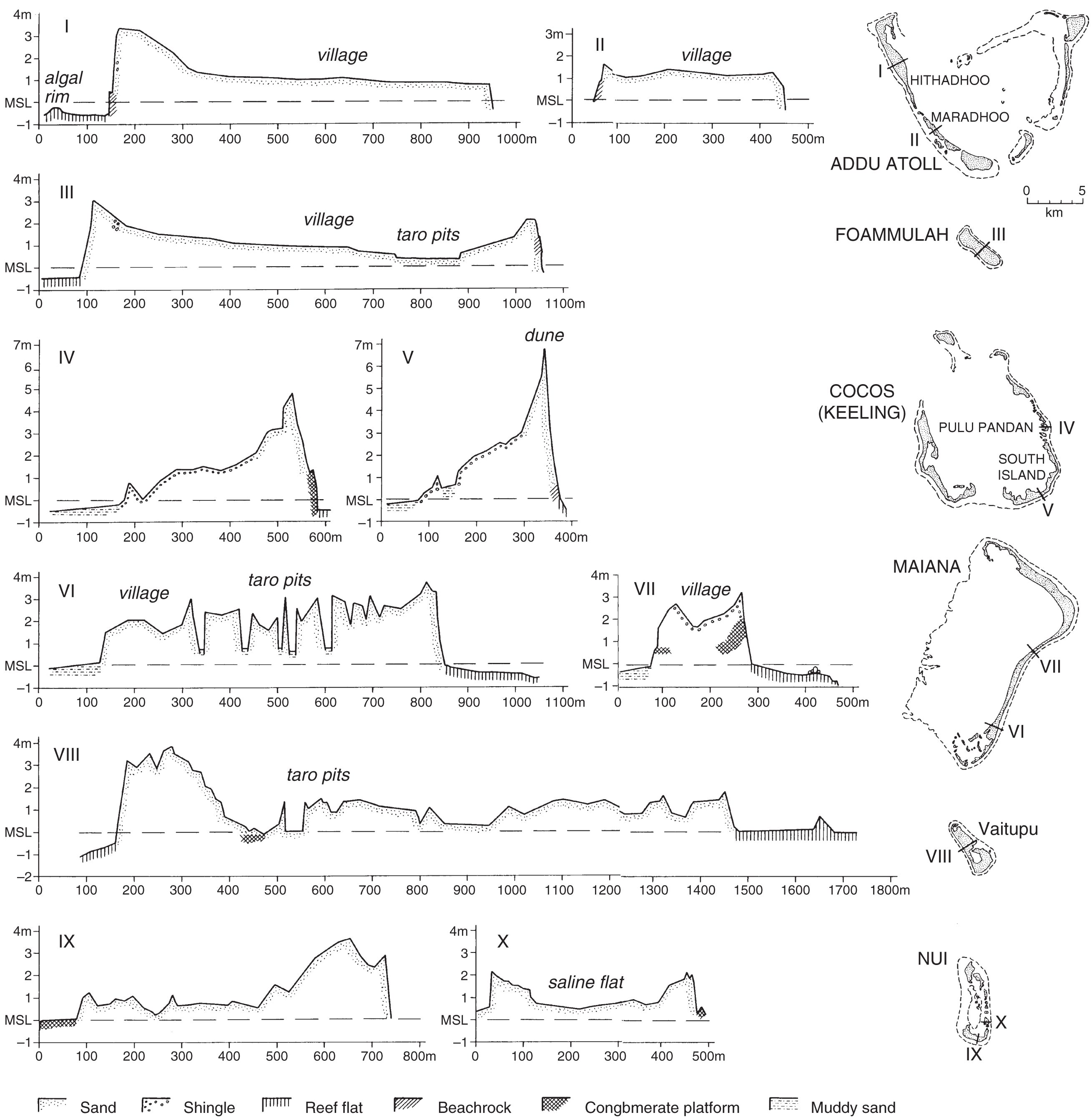
In the case of islands in the Pacific Ocean there has been a similar debate. The radiocarbon ages reported by Schofield (1977a) from Kiribati and Tuvalu appear to be from corals from the conglomerate that were not in their growth position. The conglomerate in the northern part of the Gilbert chain is composed of a lower unit that contains *Heliopora* in its growth orientation at a few localized sites (Falkland and Woodroffe, 1997; Woodroffe and Morrison, 2001), overlain by an upper unit of disoriented cemented coral clasts. There have been several attempts to infer sea level either geographically (Grossman et al., 1998) or at a site (e.g., French Polynesia, Pirazzoli et al., 1987; Pirazzoli and Montaggioni, 1986, 1988; Funafuti, Dickinson, 1999), but these have not discriminated the *in situ* corals from the more extensive larger conglomerate outcrops. Large sea-level oscillations or abrupt changes appear unlikely, and studies that identify large anomalous fluctuations of sea level have generally been rebutted. For example, evidence for an abrupt fall of sea level around 1300 AD inferred by Nunn (1998) has been criticized by Gehrels (2001) both on the basis of how dating evidence was handled as well as because evidence from a wide geographical area is brought together without regard to spatial variability.

Reef islands on atolls

A generalized cross-section of an atoll reef island suggests a typical cross-island morphology comprising a distinct oceanward ridge and a lesser lagoonward ridge, with a pronounced swale in the middle. Figure 6 demonstrates considerable variation in reef island morphology, as well as human modification. Waves represent the principal processes that build islands. Open ocean swell is filtered at the reef crest, but a component of the wave energy crosses the reef flat and reaches the island shore. As a consequence, reef islands are low-lying; on many Pacific atolls, and also on the Cocos (Keeling) Islands, only about 33% of the reef island surface is more than 2 m above mean sea level, and $<$8% exceeds 3 m above mean sea level. In the Maldives the islands appear even lower, with around 4 and 1% of the total island area above 2 and 3 m above mean sea level, respectively (Woodroffe, 2008).

Island sediments

Atoll reef islands are built from sediments that are entirely calcareous, being derived from the skeletal fragments of organisms living on the reefs, such as coral, coralline or calcifying algae, molluscs, and foraminifera. Genera of benthic foraminifera, such as *Calcarina*, *Amphistegina* and *Baculogypsina*, produced on the reef crest and the reef flat close to the crest, are a major contributor to the sands from which the islands are composed in Kiribati, Tuvalu, and the Marshall Islands (Woodroffe and Morrison, 2001; Collen and Garton, 2004; Fujita et al., 2009). Elsewhere islands may be composed of coarser material, including coral rubble and shingle. Islands composed of coarser material are often referred to by the Polynesian



Atolls, Figure 6 Reef island cross sections surveyed across a selection of atolls and illustrating the variability in surface topography. Several of the reef islands have been modified through the excavation of pits for cultivation of taro.

term *motu* (q.v.) and differentiated from sandy islands that are called cays (Stoddart and Steers, 1977).

Prominent on many atolls is a conglomerate of disoriented coral blocks, often forming a platform that represents highly resistant substrate where it occurs. Many reef islands appear to be anchored on such outcrops of conglomerate (Montaggioni and Pirazzoli, 1984). Although disoriented coral boulders and cobbles give the conglomerate an irregular appearance, the upper surface is often relatively horizontal, and internal structure may contain distinct beds of various thicknesses. The conglomerates (q.v.) are cemented by coralline algae and marine cements such as isopachous rims of fibrous aragonite or high-magnesian calcite.

Less well-lithified outcrops around the margins of islands include beachrock, which is cemented beach sand, preserving the dip of the original beach. The sands appear to have been cemented beneath the water table, and beachrock (q.v.) may be preserved where sand has been eroded away, indicating former shoreline positions. Cay sandstone is a less well-cemented limestone; this poorly lithified carbonate is horizontally bedded and seems to form associated with the water table within the island interior. On a few islands, the droppings of nesting seabirds have infiltrated into sands in the island interior and they are cemented with a phosphatic cement (Rodgers, 1989). Island surfaces can also be colonized by vegetation, which contributes both directly through roots that stabilize sand and humus that gives the soil greater structure.

Morphological differences have been identified between atolls in storm-prone areas, and those closer to the equator where tropical cyclones (typhoons, hurricanes) are not experienced. Where storms are frequent, reef flats contain abundant coral rubble and large blocks of reef limestone called reef blocks (Bayliss-Smith, 1988). For example, megablocks (q.v.) up to 4 m high and 10 m long were reported to have been deposited on the reef flat of Nukutipipi Atoll in the Duke of Gloucester group in the Tuamotu Archipelago, by the cyclones Veena and Orama that occurred in 1983 (Salvat and Salvat, 1992). Significant impacts were observed after a storm on Jaluit (Blumenstock, 1961). Under some circumstances it appears that tsunami may detach and emplace large blocks of similar dimensions on coral reefs (Bourrouilh-Le Jan, 1998), but as a tsunami has only a small amplitude in mid ocean, the prevailing view is that these megablocks are emplaced by cyclones. Rubble ramparts are often formed by individual storms (Scoffin, 1993); for example the "Bebe" bank on Funafuti (Maragos et al., 1973; Baines et al., 1974). This rampart has been gradually reworked shoreward across the reef flat, since it was thrown up during Cyclone Bebe, and in places it has accreted onto similar, but earlier storm-derived deposits on the reef islands (Baines and McLean, 1976). Where storms are less frequent, boulders may accumulate and contribute to a conglomerate that underpins the island. In those atolls closest to the equator and outside the storm belt, such as the Maldives, the islands are predominantly built of sand. Boulder ramparts (q.v.) and shingle ridges (q.v.) are indicators of former storm events, and may be eroded and only partially preserved (Pirazzoli, 1987). Rubble storm ridges, deposited over the past 3000 years, are prominent features on islands in Lakshadweep (formerly the Laccadives) to the north of the Maldives (Siddiquie, 1980).

Processes of island formation

Almost all material which comprises reefs islands is amenable to radiocarbon dating, and a series of models of reef-island formation on atolls was proposed by Woodroffe et al. (1999). Radiocarbon ages yield estimates of the time of death of skeletal organisms, and deposition may occur some time later, after an undefined period of transport, breakdown, erosion, and redeposition. However, a pattern of gradual oceanward accretion of reef islands appears to have occurred on an elongate island (West Island) on Cocos (Woodroffe et al., 1999), and on Makin at the northern end of the Gilbert chain in Kiribati (Woodroffe and Morrison, 2001). These, and results from comparison of multitemporal aerial photography or satellite imagery (Webb, 2006), indicate ongoing accretion, where sediment production and transport are sustained, on many of the oceanward shores of atoll islands. In other settings there may be more complex trends in shoreline erosion and deposition (Richmond, 1992). For example, detailed resurveys of beaches on the islands of Betio and Buariki in South Tarawa indicate fluctuations of island outline that correspond with wind changes associated with the El Niño-Southern Oscillation phenomenon (Gillie, 1993; Solomon and Forbes, 1999), and in the Maldives seasonal adjustments follow reversal of the monsoon (Kench et al., 2006). An alternative model of island build-up has been proposed for the small sandy islands that occur on patch reefs in the center of the lagoons on atolls in the northern Maldives (Kench et al., 2005). A further approach to determining island formation has been recently developed with the use of computer modeling (Barry et al., 2007, 2008).

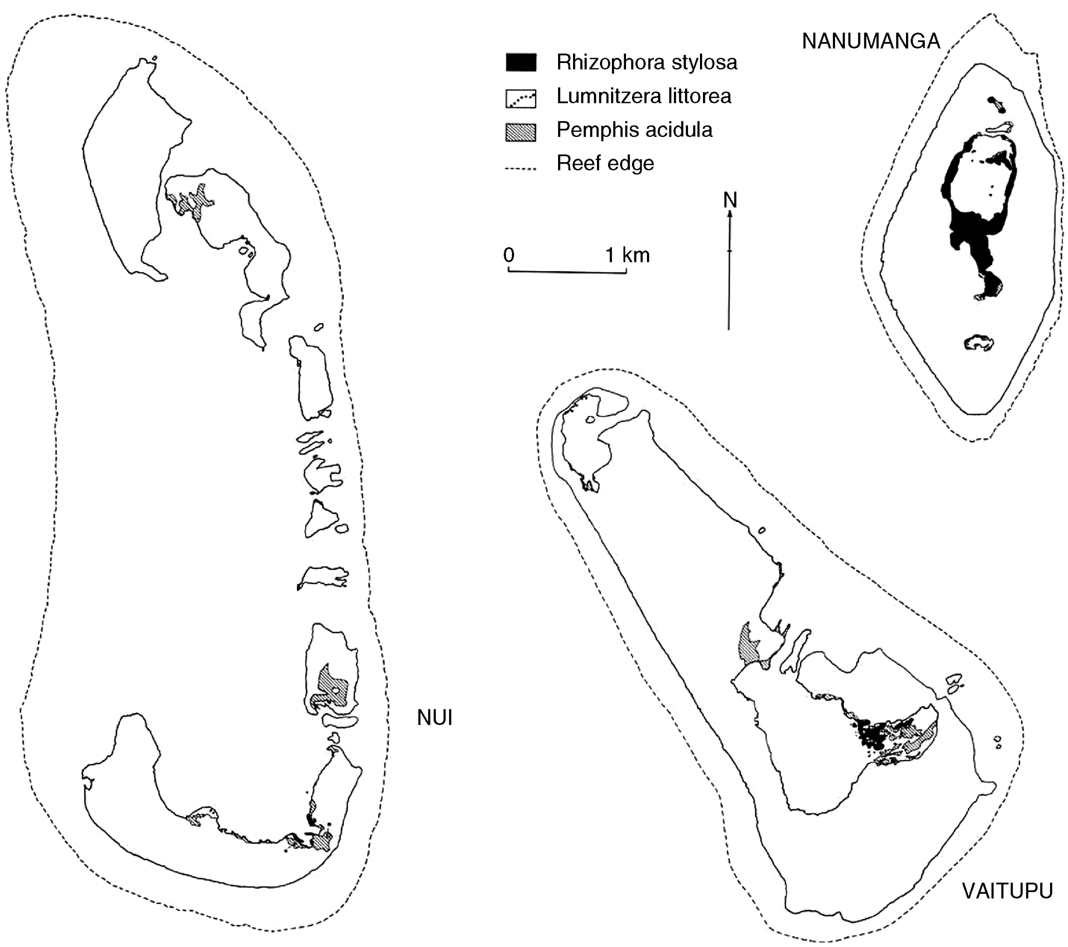
Island soils, vegetation, and ecosystems

The calcareous sediments that form reef islands on the margin of atolls produce poorly developed and immature soils (Morrison, 1990; see also Chapter Coral Cays – Soils of Low Elevation Structures). Soil characteristics depend primarily on the incorporation of plant matter and the development of a humus layer. An exception is the occurrence of phosphate-rich areas, first identified by Fosberg (1957), but subsequently described in several situations where the vegetation is, or was previously, dominated by the tree *Pisonia grandis.* This tree attracts seabirds and the phosphate enrichment appears related to bird guano.

In contrast to neighboring high islands, the atolls and low islands of the Indian and Pacific Oceans have a relatively species-poor flora. There is a distinct pantropical group of plants that are dispersed effectively across large distances. Many of these plants are strand plants that have seeds that float and can be easily washed up on the beaches around the margins of atolls. Early descriptions of the vegetation and floristics of atolls were undertaken by Raymond Fosberg (1974, 1992), and a major compilation on the vegetation of the tropical Pacific outlines the principal vegetation associations (Mueller-Dombois and Fosberg, 1998).

Several creepers can occur on the beach, such as *Ipomoea pes-caprae* and *Vigna marina.* A coastal fringe of shrubs develops on those sand cays that are not ephemeral, and a broad belt of *Scaevola taccada* and *Suriana maritima* is frequent, often with *Tournefortia argentea* (*Argusia [Messerschmidia] argentea*), which can grow into a small tree. On the larger islands a peripheral belt of shrubs often grades into a forest with trees such as *Cordia subcordata*, *Calophyllum inophyllum*, *Hernandia peltata*, *Guettarda speciosa*, and *Pisonia grandis*. On many atolls the interior is covered with coconut woodland, but in most cases this has been planted and is maintained because the coconut (*Cocos nucifera*) is important for subsistence and often as the basis of a commercial copra industry. A zonation with increasing maturity of vegetation and soils into the interior of reef islands can be recognized, often representing a temporal succession (see Coral Cays – vegetational succession).

The smaller islands tend to contain the least species, and the relationship between number of plant species and island area, particularly based on a study of the vegetation of Kapingamarangi Atoll (Niering, 1963) provided support for the development of ideas on island biogeography by MacArthur and Wilson (1967). However, it is also apparent that the smallest islands, particularly those less than 100m wide, are too small to support a freshwater lens, and only have a restricted strand flora (Whitehead and Jones, 1969). Although on predominantly sandy reef islands there are more species on the larger islands, two further factors are important. On the remote atoll of Suwarrow in the Cook Islands, it is evident that plants are influenced by the substrate, with extensive stands of *Pemphis acidula* sprawled across outcrops of conglomerate (Woodroffe and Stoddart, 1992). Mangrove habitats are also restricted in extent to those few locations where it is sheltered and there is brackish water. Mangroves may occur around the margins of a lagoon (e.g., on Nui in northern Tuvalu, or in the more enclosed embayments as in Vaitupu, Tuvalu, and can also be found in completely enclosed depressions in the center of table reefs, such as Nanumanga, Tuvalu) (Figure 7). On the islands with settlements there are generally many introduced plants (Woodroffe, 1985), including crops such as breadfruit (*Artocarpus*), pandanus, banana and taro (*Calocasia, Cyrtosperma*) and ornamentals, such as the frangipani (*Plumeria*) (Dawson, 1959). Giant taros provide the traditional stable food and are planted in excavated pits. These



Atolls, Figure 7 Three atolls in Tuvalu, showing distribution of mangrove and *Pemphis*, and the degree that these environments are impounded (after Woodroffe, 1988).

pits are dug until ground water level is reached. Taros are planted just above the groundwater level and surrounded by woven coconut fronds or pandanus leaves that provide a retaining wall for the plant compost.

On the most remote atolls, where human visitation is minimal, reef islands can support huge colonies of seabirds. Noddy and sooty terns, boobies, and frigate birds nest in enormous numbers, and if unused to human presence, sit unconcerned while the occasional visitor wanders amongst them. Typically, the ecosystems which develop on atolls are composed of widespread easily dispersed species, and there tends to be a low degree of endemism, presumably because islands have only appeared in the past few millennia on most atolls. Land birds are generally few in number, although there are flightless rails on several atolls. Endemic species are found where the atoll has remained emergent over glacial-interglacial cycles, and not undergone complete submergence during the postglacial sea-level rise. Aldabra in the western Indian Ocean is a noteworthy example with its population of giant tortoises (Arnold, 1976; Stoddart, 1984).

Atoll hydrology

The small reef islands around the margin of atolls rarely contain freshwater lakes (e.g., Washington in the Line Islands). However, rainwater percolates through the soil and can accumulate as a freshwater lens beneath the island surface. The freshwater lens floats above seawater, and has been characteristically described by the Ghyben-Herzberg principle, that is that the surface elevation of the lens extends above the level of the sea by about 1/40 of the depth to which the lens occurs. The characteristic shape of a Ghyben-Herzberg lens is rarely actually found beneath reef islands because of significant variations in the degree and extent of lithification of the reefal material and in porosity of the limestone (see: Coral Cays Geohydrology). A dual aquifer model has been proposed which recognizes the significance of the greater porosity of the Pleistocene limestone that is found beneath the rim of most atolls (Buddemeier and Oberdorfer, 1986). The hydrogeology of several atolls is summarized in reviews by Falkland (1991) and Vacher and Quinn (1997). The elevation of the surface topography influences the water level, and the shape of the lens can also be constrained by well-cemented conglomerate, which may confine the aquifer, as seen in the example of the island of Deke on Pingelap Atoll (Figure 8) in the Marshall Islands (Ayers and Vacher, 1986).

Human impacts on atolls

The formation of habitable reef islands occurred in mid Holocene, as described above. The history of human occupation therefore is also restricted to the late Holocene, and depends on sea-level history and the accretion of islands of suitable size to colonize. In the case of remote atolls in the Pacific, this is often marked by the appearance of *Lapita* pottery (Bellwood, 1987; Weisler, 1994; Nunn, 1999). Human occupation has shaped atoll ecosystems in a number of ways. The vegetation of many has been modified with the planting of coconut plantations, and the introduction of plants as described above.

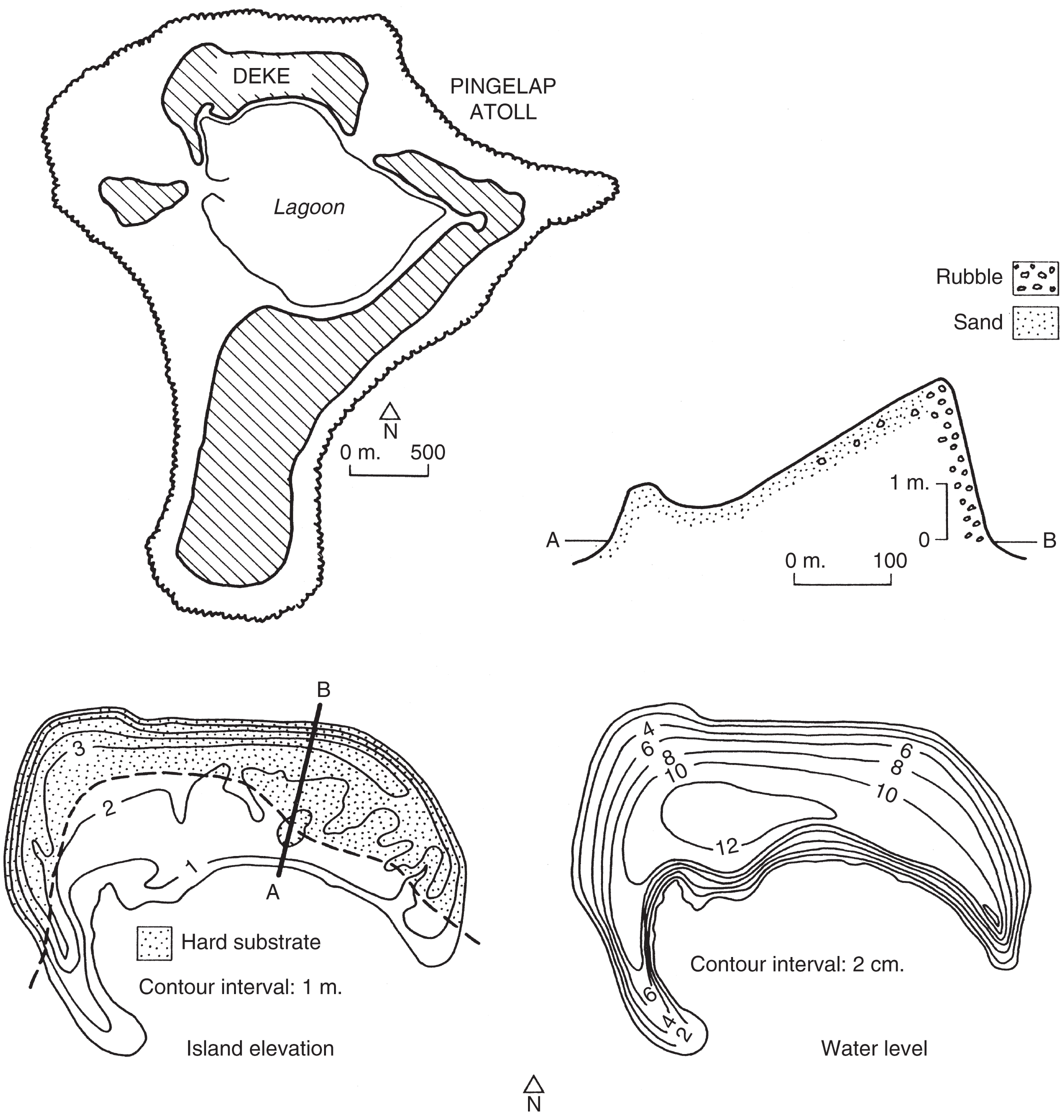
Human activities have had the greatest impact where there are high population densities (See Chapters Mining and Quarrying of Coral Reefs; Engineering on Coral Reefs with Emphasis on Pacific Reefs). Impacts have affected corals and other carbonate producing organisms. Corals suffer mortality when smothered by sediment (Zann, 1982). Seawater contamination is indicated by increased nutrient levels. Sewerage contains nutrients, and contamination of seawater is often measured by using coliform counts. Increased nutrients can cause localized coral mortality as observed by a high incidence of dead corals on the oceanward reef flat in front of Bikenibeu, a densely populated island on the southern rim of Tarawa Atoll, which has received sewerage outfall in the past (Lovell, 2000).

Domestic waste poses a further threat to ecosystems on some atolls. Certain macrofauna located in the shallow areas of the lagoon at Tarawa may have been organically enriched from land-based anthropogenic sources (Kimmerer and Walsh, 1981; Newell et al., 1996). Also, direct disposal of raw sewerage into the sea has likely increased the seawater nutrient level causing bacterial contamination of the lagoon seawater at Tarawa, but the lagoon ecosystem has been flourishing as a result (Kelly, 1994).

On atolls such as those in the Marshall Islands, Funafuti in Tuvalu and Tarawa in Kiribati increasing population pressure has led to houses being built in inappropriate locations, such as near active beaches and on low-lying areas. In South Tarawa this has prompted the construction of coastal protection structures to avoid overtopping during storms and high water events. There are a large number of reclamations of varying designs and materials built to expand the land area (Figure 9). Betio, Bairiki, and Bikenibeu, the administrative centers of Kiribati, have grown significantly compared to the comparatively pristine islands of Buariki and Abatao on the same atoll, with reclamations and seawalls (both Government and private). Causeway construction between reef islands can have negative physical and biological, as well as social, effects. The position, length, construction method, width of the reefs, and the pattern of water exchange and current strengths mean that causeways can have an influence on both water and sediment transport.

Seawalls pose particular problems. Many are temporary structures built to protect land or expensive assets from erosion. On Tarawa and in the Marshall Islands, they are generally built of coral boulders and beachrock on the margin of land and often extend out onto or across the active beach. Where vertical walls are constructed, these tend to reflect wave energy and can cause scouring at their base and undercutting (Figure 9). Alternatively, wave overtopping causes infiltration of water leading to structural collapse.

Reclamation and backfilling with sand have provided many people with extra space on small reef islands.



Atolls, Figure 8 The atoll of Pingelap, Micronesia, showing a cross-section of Deke Island, and the elevation of the island and the surface elevation of the freshwater lens (after Ayers and Vacher, 1986).

Reclamations act like groynes blocking sediment transport along active beaches, with sediment accumulating on the updrift side of structures, while the downdrift side experiences coastal erosion as has occurred on Majuro Atoll (Xue, 2001). Other disturbances to sediment transport pathways can also have severe implications, for example, boat channels, blasted or excavated across the reef flat to provide access for boats at all stages of the tide, also provide conduits for beach sand to be lost over the reef edge. This and similar interventions further disrupt longshore sediment transport, as has occurred on Fongafale, on Funafuti Atoll in Tuvalu (Yamano et al., 2007).

The scarcity of building materials has led to people extracting beach sand and aggregates in large quantities for construction on atolls with a large population. These demands represent a further disruption to the sediment budget causing detrimental impacts such as coastal erosion. On Majuro, chronic erosion has been experienced along lagoonal shores due largely to beach mining (Xue, 2001). Similarly in Vaitipu, Tuvalu, increased sand mining activities in the intertidal zone have reduced beach berm levels, increasing the island's vulnerability to cyclones.

Perhaps the most serious impacts of human activities are yet to be experienced. The impacts of climate change, and in particular sea-level rise, appear particularly ominous for atolls (McLean and Tysban, 2001; Nicholls et al., 2007). There have been several assessments of the vulnerability of atoll reef islands to sea-level rise (e.g., Roy and Connell, 1989, 1991; Lewis, 1989, 1990).

Atolls, Figure 9 Human impacts on atoll shorelines, illustrated with examples from Tarawa Atoll, Republic of Kiribati: top left, Oceanside seawall at Nanikai, which reduces access to the ocean; *top right*, private reclamation; *lower left*, large reclamation for Mormon Church, Bairiki; *lower right*, private reclamation that has resulted in erosion of shoreline.

Studies of the regional pattern of sea-level rise indicate that the sea is rising with respect to most atolls (Church et al., 2006). The principal impacts anticipated fall into three categories: shoreline erosion, inundation and flooding, and saline intrusion into the water table (Mimura, 1999). Widespread flooding in the interior of Fongafale on Funafuti Atoll in Tuvalu 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) reconstructed 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 urbanization, has exacerbated the problem in this instance. Settlement in this densely populated part of the administrative center has encroached on low-lying areas or depressions excavated during military operations (Yamano et al., 2007).

Reef islands are particularly low-lying, although there is considerable geomorphological variability around the margin of any one atoll (Woodroffe, 2008). Islands exhibit a degree of physical resilience, and many may be continuing to build as further sediment is produced through the growth of calcareous organisms on surrounding reefs and as that sediment is transported onshore. Those parts of atolls that are most resilient, and which can be used sustainably, need to be enhanced by various levels of cultural, or other socioeconomic resilience (Connell, 2003), to reduce the likelihood that atoll communities will collapse in the face of climate or sea-level change (Barnett and Adger, 2003).

Summary

Atolls represent some of the most remote and lowest-lying land on the planet. Each atoll comprises a reef rim that encloses a lagoon, which may be completed infilled on the smallest table reefs, but can be tens of meters deep on the largest. Lagoons vary considerably in the extent to which they are connected to the surrounding ocean. Carbonate sediment is produced by the growth of reef organisms, and it is swept by oceanic processes, particularly waves, toward the lagoon. On the rims of many atolls, sediment has accumulated as reef islands, which have been colonized first by salt-tolerant plants and in many case by trees. A freshwater lens underlies the larger islands, and these have attracted human settlements often resulting in coconut plantations and the introduction of other plants and animals. Human impacts threaten the integrity of both terrestrial and marine ecosystems on atolls. Climate change appears likely to exacerbate many of these problems unless a more sustainable approach is adopted to augment the natural resilience of atoll ecosystems.

Bibliography

Adjas, A., Masse, J.-P., and Montaggioni, L. F., 1990. Fine-grained carbonates in nearly closed reef environments: Mataiva and Takapoto atolls, Central Pacific Ocean. *Sedimentary Geology*, **67**, 115–132.

Agassiz, A., 1903a. The coral reefs of the tropical Pacific. *Memoirs of the Museum of Comparative Zoology Harvard College*, **28**, 1–410.

Agassiz, A., 1903b. The coral reefs of the Maldives. *Memoirs of the Museum of Comparative Zoology Harvard College*, **29**, 1–168.

Andréfouët, S., Claereboudt, M., Matsakis, P., Pagès, J., and Dufour, P., 2001. Typology of atoll rims in Tuamotu Archipelago (French Polynesia) at landscape scale using SPOT HRV images. *International Journal of Remote Sensing*, **22**, 987–1004.

Andréfouët, S., Kramer, P., Torres-Pulliza, D., Joyce, K. E., Hochberg, E. J., Garza-Pérez, R., Mumby, P. J., Riegl, B., Yamano, Y., White, W. H., Zubia, M., Brock, J. C., Phinn, S. R., Naseer, A., Hatcher, B. G., and Muller-Karger, F. E., 2003. Multi-site evaluation of IKONOS data for classification of tropical coral reef environments. *Remote Sensing of Environment*, **88**, 128–143.

Arnold, E. N., 1976. Fossil reptiles from Aldabra Atoll, Indian Ocean. *Bulletin of the British Museum (Natural History)*, **29**, 85–116.

Ayers, J. F., and Vacher, H. L., 1986. Hydrogeology of an atoll island: a conceptual model from detailed study of a Micronesian example. *Ground Water*, **24**, 185–198.

Baines, G. B. K., and McLean, R. F., 1976. Sequential studies of hurricane deposit evolution at Funafuti Atoll. *Marine Geology*, **21**, M1–M7.

Baines, G. B. K., Beveridge, P. J., and Maragos, J. E., 1974. Storms and island building at Funafuti Atoll, Ellice Islands. *Proceedings of the 2nd International Coral Reef Symposium*, **2**, 485–496.

Barnett, J., and Adger, N., 2003. Climate dangers and atoll countries. *Climatic Change*, **61**, 321–337.

Barry, S. J., Cowell, P. J., and Woodroffe, C. D., 2007. A morphodynamic model of reef-island development on atolls. *Sedimentary Geology*, **197**, 47–63.

Barry, S. J., Cowell, P. J., and Woodroffe, C. D., 2008. Growth-limited size of atoll-islets: morphodynamics in nature. *Marine Geology*, **247**, 159–177.

Bayliss-Smith, T. P., 1988. The role of hurricanes in the development of reef islands, Ontong Java Atoll, Solomon Islands. *Geographical Journal*, **154**, 377–391.

Bellwood, P., 1987. The impact of sea level changes on Pacific prehistory. *The Journal of Pacific History*, **22**, 106–108.

Blumenstock, D. I., 1961. A report on typhoon effects upon Jaluit Atoll. *Atoll Research Bulletin*, **75**, 1–105.

Bourrouilh-Le Jan, F. G., 1998. The role of high-energy events (hurricanes and/or tsunamis) in the sedimentation, diagenesis and karst initiation of tropical shallow water carbonate platforms and atolls. *Sedimentary Geology*, **118**, 3–36.

Braithwaite, C. J. R., Taylor, J. D., and Kennedy, W. J., 1973. The evolution of an atoll: the depositional and erosional history of Aldabra. Philosophical Transactions of the Royal Society of London. *B, Biological Sciences*, **266**, 307–340.

Bryan, E. H. Jr., 1953. Checklist of atolls. *Atoll Resources Bulletin*, **19**, 1–38.

Buddemeier, R. W., and Oberdorfer, J. A., 1986. Internal hydrology and geochemistry of coral reefs and atoll islands: key to diagenetic variations. In Schroeder, J. H., and Purser, B. H. (eds.), *Reef Diagenesis*. Berlin: Springer-Verlag, pp. 91–111.

Callaghan, D. P., Nielson, P., Cartwright, N., Gourlay, M., and Baldock, T. E., 2006. Atoll lagoon flushing forced by waves. *Coastal Engineering*, **53**, 691–704.

Camoin, G. F., Ebren, Ph., Eisenhauer, A., Bard, E., and Faure, G., 2001. A 300 000-yr coral reef record of sea level changes, Mururoa atoll (Tuamotu archipelago, French Polynesia). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **175**, 325–341.

Chevalier, J.-P., Denizot, M., Mougin, J.-L., Plessis, Y., and Salvat, B., 1969. Etude géomorphologique et bionomique de l'atoll de Mururoa (Tuamotu). *Cahiers du Pacifique*, **13**, 9–144.

Church, J. A., White, N. J., and Hunter, J. R., 2006. Sea-level rise at tropical Pacific and Indian Ocean islands. *Global and Planetary Change*, **53**, 155–168.

Cloud, P. E., 1952. Preliminary report on geology and marine environments of Onotoa Atoll, Gilbert Islands. *Atoll Research Bulletin*, **12**, 1–73.

Colin, P. L., 1986. Benthic community distribution in the Enewetak Atoll lagoon, Marshall Islands. *Bulletin of Marine Science*, **38**, 129–143.

Collen, J. D., and Garton, D. W., 2004. Larger foraminifera and sedimentation around Fongafale Island, Funafuti Atoll, Tuvalu. *Coral Reefs*, **23**, 445–454.

Connell, J., 2003. Losing ground? Tuvalu, the greenhouse effect and the garbage can. *Asia Pacific Viewpoint*, **44**, 89–106.

Cotton, C. A., 1948. The present-day status of coral reef theories. *New Zealand Science Review*, **6**, 111–113.

Daly, R. A., 1934. *The Changing World of the Ice Age*. New Haven: Yale University Press, 271 pp.

Darwin, C., 1842. *The Structure and Distribution of Coral Reefs*. London: Smith, Elder and Co., 214 pp.

David, T. W. E., and Sweet, G., 1904. The geology of Funafuti. In *The Atoll of Funafuti: Borings into a Coral Reef and the Results*. The Royal Society, London, pp. 61–124.

Davis, W. M., 1928. The coral reef problem. American Geographical Society, Special Publication, 9, 596 pp.

Dawson, E. Y., 1959. Changes in Palmyra Atoll and its vegetation through the activities of man, 1913–1958. *Pacific Naturalist*, **1**, 1–51.

Dickinson, W. R., 1999. Holocene sea-level record on Funafuti and potential impact of global warming on central Pacific atolls. *Quaternary Research*, **51**, 124–132.

Dickinson, W. R., 2004. Impacts of eustasy and hydro-isostasy on the evolution and landforms of Pacific atolls. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **213**, 251–269.

Emery, K. O., Tracey, J. I., and Ladd, H. S., 1954. *Geology of Bikini and nearby atolls*. U.S. Geological Survey Professional Paper, 260-A, pp. 1–265.

Falkland, A. (ed.), 1991. *Hydrology and Water Resources of Small Islands: A Practical Guide*. Paris: UNESCO, 1–9 pp.

Falkland, A. C., and Woodroffe, C. D., 1997. Geology and hydrogeology of the Tarawa and Christmas Island (Kiritimati), Kiribati, Central Pacific. In Vacher, H. L., and Quinn, T. M. (eds.), *Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology*. Vol. 54, pp. 577–610.

Fosberg, F. R., 1957. Description and occurrence of atoll phosphate rock in Micronesia. *American Journal of Science*, **255**, 584–592.

Fosberg, F. R., 1974. Phytogeography of atolls and other coral islands, In *Proceedings of the Second International Coral Reef Symposium*, Brisbane, pp. 389–396.
Fosberg, F. R., 1992. Pacific island plants: taxonomic and distributional notes. *Micronesia*, **25**, 175–199.
Fosberg, F. R., and Sachet, M.-H., 1953. Handbook for atoll research. *Atoll Research Bulletin*, **17**, 1–129.
Fujita, K., Osawa, Y., Kayanne, H., Ide, Y., and Yamano, H., 2009. Distribution and sediment production of large benthic foraminifers on reef flats of the Majuro Atoll, Marshall Islands. *Coral Reefs*, **28**, 29–45.
Gardiner, J. S. (ed.), 1903. *The Fauna and Geography of the Maldive and Laccadive Archipelagoes, Being an Account of the Work Carried on and of Collections Made by an Expedition During Years 1899 and 1900*. Cambridge: Cambridge University Press.
Gardiner, J. S., 1931. *Coral Reefs and Atolls*. London: Macmillan, 182 pp.
Gehrels, W. R., 2001. Discussion of: Nunn, Patrick D., 1998. Sea-level changes over the past 1,000 years in the Pacific. *Journal of Coastal Research*, **14**, 23–30. *Journal of Coastal Research*, **17**, 244–245.
Gibson-Hill, C. A., 1947. Notes on the Cocos-Keeling Islands. *Journal of the Malayan Branch of the Royal Asiatic Society*, **20**, 140–202.
Gillie, R. D., 1993. *Historical changes of shoreline accretion and erosion, Betio Islet, South Tarawa, Kiribati*. SOPAC Technical Report, 179, 22 pp.
Gischler, E., 1994. Sedimentation on three Caribbean Atolls: Glovers Reef, Lighthouse Reef and Turneffe Islands, Belize. *Facies*, **31**, 243–254.
Gischler, E., 2006. Sedimentation on Rasdhoo and Ari Atolls, Maldives, Indian Ocean. *Facies*, **52**, 341–360.
Gischler, E., Hudson, J. H., and Pisera, A., 2008. Late Quaternary reef growth and sea level in the Maldives (Indian Ocean). *Marine Geology*, **250**, 104–113.
Gray, S. C., Hein, J. R., Hausmann, R., and Radtke, U., 1992. Geochronology and subsurface stratigraphy of Pukapuka and Rakahanga atolls, Cook Islands: Late Quaternary reef growth and sea level history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **91**, 377–394.
Grossman, E. E., Fletcher, C. H., and Richmond, B. M., 1998. The Holocene sea-level highstand in the equatorial Pacific: analysis of the insular paleosea-level database. *Coral Reefs*, **17**, 309–327.
Guilcher, A., 1988. *Coral Reef Geomorphology*. Chichester: Wiley, 228 pp.
Guppy, H. B., 1889. The Cocos-Keeling Islands. *Scottish Geographical Magazine*, **5**, 281–297, 457–474, 569–588.
Keating, B., 1992. Insular geology of the Line Islands. In Keating, B. H., and Bolton, B. R. (eds.), *Geology and Offshore Mineral Resources of the Central Pacific Basin*. New York: Springer-Verlag, pp. 77–99.
Kelly, D. J. 1994. *The effects of domestic waste on marine and groundwater quality in Tarawa Atoll*. Republic of Kiribati, SOPAC Technical Report 72.
Kench, P. S., and McLean, R. F., 2004. Hydrodynamics and sediment flux of hoa in an Indian Ocean atoll. *Earth Surface Processes and Landforms*, **29**, 933–953.
Kench, P. S., Brander, R. W., Parnell, K. E., and McLean, R., 2006. Wave energy gradients across a Maldivian atoll: Implications for island geomorphology. *Geomorphology*, **81**, 1–17.
Kench, P. S., McLean, R. F., and Nichol, S. L., 2005. New model of reef-island evolution: Maldives, Indian Ocean. *Geology*, **33**, 145–148.
Kench, P. S., Smithers, S. G., McLean, R. F., and Nichol, S. L., 2009. Holocene reef growth in the Maldives: evidence of a mid-Holocene sea-level highstand in the central Indian Ocean. *Geology*, **37**, 455–458.
Kimmerer, W. J., and Walsh, W., 1981. Tarawa atoll lagoon: circulation, nutrient fluxes and the impact of human waste. *Micronesica*, **17**, 161–179.
Kuenen, P. H., 1933. Geology of coral reefs. *Snellius-Expedition Report*, **5**, 1–129.
Ladd, H. S., 1977. Types of coral reefs and their distribution. In Jones, O. A., and Endean, R. (eds.), *Biology and Geology of Coral Reefs*, Vol. 4, Geology 2, pp. 1–19.
Ladd, H. S., Tracey, J. I., and Gross, M. G., 1967. Drilling on Midway Atoll, Hawaii. *Science*, **156**, 1088–1094.
Ladd, H. S., Tracey J. I., and Gross, M. G., 1970. *Deep drilling on Midway Atoll*. Geological Survey Professional Paper 680-A. U.S. Government Printing Office, Washington DC.
Lalou, C., Labeyrie, J., and Delebrias, G., 1966. Datations des calcaires coralliens de l'atoll de Mururoa (archipel des Tuamotus) de l'époque actuelle jusqu'à – 500,000 ans. *Comptes Rendus Academie de Sciences, Paris*, **263-D**, 1946–1949.
Lambeck, K., 2002. Sea-Level Change from Mid-Holocene to Recent Time: An Australian Example with Global Implications. In Mitrovica J. X., and Vermeersen, B. (eds.), *Glacial Isostatic Adjustment and the Earth System*. Washington DC: American Geophysical Union, pp. 33–50.
Lewis, J., 1989. Sea-level rise: some implications for Tuvalu. *Ambio*, **18**, 458–459.
Lewis, J., 1990. The vulnerability of small island states to sea level rise: the need for holistic strategies. *Disasters*, **14**, 241–248.
Lovell, E., 2000. *Coral Reef benthic surveys of Tarawa and Abaiang Atolls, Republic of Kiribati*. SOPAC Technical Report, 310, 88 pp.
MacArthur, R. H., and Wilson, E. O., 1967. *The Theory of Island Biogeography*. New Jersey: Princeton University Press, 203 pp.
MacNeil, F. S., 1954. The shape of atolls: an inheritance from subaerial forms. *American Journal of Science*, **252**, 402–427.
Maragos, J. E., Baines, G. B. K., and Beveridge, P. J., 1973. Tropical cyclone creates a new land formation on Funafuti atoll. *Science*, **181**, 1161–1164.
Marshall, J. F., and Jacobson, G., 1985. Holocene growth of a mid-plate atoll: Tarawa, Kiribati. *Coral Reefs*, **4**, 11–17.
McKee, E. D., Chronic, J., and Leopold, E. B., 1959. Sedimentary belts in lagoon of Kapingamarangi Atoll. *American Association of Petroleum Geologists Bulletin*, **43**, 501–562.
McLean, R. F., and Hosking, P. L., 1991. Geomorphology of reef islands and atoll motu in Tuvalu. *South Pacific Journal of Natural Science*, **11**, 167–189.
McLean, R. F., and Tsyban, A., 2001. Coastal zones and marine ecosystems. In McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., and White, K. S. (eds.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge: Cambridge University Press, pp. 343–379.
McLean, R. F., and Woodroffe, C. D., 1994. Coral atolls. In Carter, R. W. G., and Woodroffe, C. D. (eds.), *Coastal Evolution: Late Quaternary Shoreline Morphodynamics*. Cambridge: Cambridge University Press, pp. 267–302.
Milliman, J. D., 1973. Caribbean coral reefs. In Jones, O. A., and Endean, R. (eds.), *Biology and Geology of Coral Reefs*, Vol. 1, Geology 1, pp. 1–50.
Mimura, N., 1999. Vulnerability of island countries in the South Pacific to sea level rise and climate change. *Climate Research*, **12**, 137–143.
Mitrovica, J. X., and Peltier, W. R., 1991. On postglacial geoid subsidence over the equatorial oceans. *Journal of Geophysical Research*, **96**, 20053–20071.
Montaggioni, L. F., 2005. History of Indo-Pacific coral reef systems since the last glaciation: development patterns and controlling factors. *Earth Science Reviews*, **71**, 1–75.

Montaggioni, L. F., and Pirazzoli, P. A., 1984. The significance of exposed coral conglomerates from French Polynesia (Pacific Ocean) as indications of recent sea-level changes. *Coral Reefs*, **3**, 29–42.

Morrison, R. J., 1990. Pacific atoll soils: chemistry, mineralogy and classification. *Atoll Research Bulletin*, **339**, 1–25.

Mueller-Dombois, D., and Fosberg, F. R., 1998. Vegetation of the tropical Pacific islands. New York: Springer, 733 pp.

Munk, W. H., and Sargent, M. S., 1954. *Adjustment of Bikini Atoll to ocean waves*. U.S. Geological Survey Professional Paper, 260-C, pp. 275–280.

Murray, J., 1889. Structure, origin, and distribution of coral reefs and islands. *Nature*, **39**, 424–428.

Naseer, A., and Hatcher, B. G., 2004. Inventory of the Maldives' coral reefs using morphometrics generated from Landsat ETM+ imagery. *Coral Reefs*, **23**, 161–168.

Neumann, A. C., and Macintyre, I., 1985. Reef response to sea level rise: keep-up, catch-up or give-up. *Proceedings of the 5th International Coral Reef Congress*, **3**, 105–110.

Newell, N. D., and Bloom, A. L., 1970. The reef flat and 'two-meter eustatic terrace' of some Pacific atolls. *Geological Society of America, Bulletin*, **81**, 1881–1894.

Newell, N. D., and Rigby, J. K., 1957. Geological studies on the Great Bahama Bank. Society of Economic Paleonologists and Mineralogists, Special Publication, 5, pp. 15–79.

Newell, P. F., Clavier, J., and Riley, J., 1996. The biodiversity of the invertebrate faunas of the soft sediments from the Great Astrolabe reef (Kadavu Group, Fiji) and Tarawa (Kiribati) lagoons in the South Pacific. In *Biodiversity and Dynamics of Ecosystems*. DIPWA series, pp. 237–245.

Nicholls, R. J., Wong, P. P., Burkett, V. R., Codignotto, J. O., Hay, J. E., McLean, R. F., Ragoonaden, S., and Woodroffe, C. D., 2007. Coastal systems and low-lying areas. Climate Change 2007: Impacts, Adaptation and Vulnerability. In Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., Hanson, C. E., (eds.), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, pp. 315–356.

Niering, W. A., 1963. Terrestrial ecology of Kapingamarangi Atoll, Caroline Islands. *Ecological Monographs*, **33**, 131–160.

Nunn, P. D., 1998. Sea-level changes over the past 1,000 years in the Pacific. *Journal of Coastal Research*, **14**, 23–30.

Nunn, P. D., 1999. *Environmental Change in the Pacific basin*. Chichester: Wiley, 413 pp.

Nunn, P. D., and Peltier, W. R., 2001. Far-field test of the ICE-4G model of global isostatic response to deglaciation using empirical and theoretical Holocene sea-level reconstructions for the Fiji Islands, southwestern Pacific. *Quaternary Research*, **55**, 203–214.

Ohde, S., Greaves, M., Massuzawa, T., Buckley, H. A., van Woesik, R., Wilson, P., Pirazzoli, P. A., and Elderfield, H., 2002. The chronology of Funafuti Atoll: revisiting an old friend. *Proceedings of the Royal Society Series A*, **458**, 2289–2306.

Pandolfi, J. M., 2008. Geomorphology of the uplifted Pleistocene atoll at Henderson Island, Pitcairn Group. *Biological Journal of the Linnean Society*, **56**, 63–77.

Patel, S. S., 2006. A sinking feeling. *Nature*, **440**, 734–736.

Paulay, G., 2001. Benthic ecology and biota of Tarawa atoll lagoon: influence of equatorial upwelling, circulation, and human harvest. *Atoll Research Bulletin*, **487**, 1–41.

Perrin, C., 1990. Genèse de la morphologie des atolls: le cas de Mururoa (Polynésie Française). Comptes Rendus. *Académie des Sciences*. Série II, **311**, 671–678.

Pirazzoli, P. A., 1987. A reconnaissance and geomorphological survey of Temoe Atoll, Gambier Islands (South Pacific). *Journal of Coastal Research*, **3**, 307–323.

Pirazzoli, P. A., and Montaggioni, L. F., 1986. Late Holocene changes in the northwest Tuamotu Islands, French Polynesia. *Quaternary Research*, **25**, 350–368.

Pirazzoli, P. A., and Montaggioni, L. F., 1988. Holocene sea-level changes in French Polynesia. *Palaeogeography Palaeoclimatology and Palaeoecology*, **68**, 153–175.

Pirazzoli, P. A., Delibrias, G., Montaggioni, L. F., Saliège, J. F., and Vergnaud-Grazzini, C., 1987. Vitesse de croissance latérale des platiers et évolution morphologique récente de l'atoll de Reao, îles Tuamotu, Polnésie française. *Annales de L'Institut Oceanographique*, **63**, 57–68.

Pirazzoli, P. A., Koba, M., Montaggioni, L. F., and Person, A., 1988. Anaa (Tuamotu Islands, Central Pacific): an incipient rising atoll? *Marine Geology*, **82**, 261–269.

Pittock, A. P., 2005. *Climate Change: Turning up the Heat*. Earthscan: CSIRO Publishing, 316 pp.

Purdy, E. G., 1974. Reef configurations, cause and effect. In Laporte, L. F. (ed.), *Reefs in Time and Space*. Society of Economic Palaeontologists and Mineralogists Special Publication, pp. 9–76.

Purdy, E. G., and Gischler, E., 2005. The transient nature of the empty bucket model of reef sedimentation. *Sedimentary Geology*, **175**, 35–47.

Purdy, E. G., and Winterer, E. L., 2001. Origin of atoll lagoons. *Geological Society of America Bulletin*, **113**, 837–854.

Raitt, R. W., 1954. *Seismic refraction studies of Bikini and Kwajalein Atolls*. U.S. Geological Survey Professional Paper, 260-K.

Richmond, B. M., 1992. Development of atoll islets in the central Pacific. *Proceedings of the 7th International Coral Reef Congress*, **2**, 1185–1194.

Richmond, B., 1993. *Reconnaissance geology of the Gilbert Group, Western Kiribati*. SOPAC Technical Report, 77, pp. 1–65.

Riegl, B. M., and Dodge, R. E. (eds.), 2008. *Coral Reefs of the USA*. New York: Springer.

Rodgers, K. A., 1989. Phosphatic limestones from Tuvalu (Ellice Islands). *Economic Geology*, **84**, 2252–2266.

Roy, P., and Connell, J., 1989. *Greenhouse: impact of sea level rise on low coral islands in the South Pacific, 6*. Research Institute for Asia and the Pacific Occasional Paper, 55 pp.

Roy, P., and Connell, J., 1991. Climatic change and the future of atoll states. *Journal of Coastal Research*, **7**, 1057–1075.

Salvat, F., and Salvat, B., 1992. Nukutipipi Atoll, Tuamotu Archipelago: geomorphology, land and marine flora and fauna and interrelationships. *Atoll Research Bulletin*, **357**, 1–43.

Schlanger, S. O., 1963. *Subsurface geology of Eniwetok Atoll*. United States Geological Survey, Professional Paper, 260-BB: pp. 991–1066.

Schofield, J. C., 1977a. Late Holocene sea level, Gilbert and Ellice Islands, west Central Pacific Ocean. *New Zealand Journal of Geology and Geophysics*, **20**, 503–529.

Schofield, J. C., 1977b. Effect of Late Holocene sea-level fall on atoll development. N.Z. *Journal of Geology and Geophysics*, **20**, 531–536.

Scoffin, T. P., 1993. The geological effects of hurricanes on coral reefs and the interpretation of storm deposits. *Coral Reefs*, **12**, 203–221.

Scott, G. A. J., and Rotondo, G. M., 1983. A model to explain the differences between Pacific plate island atoll types. *Coral Reefs*, **1**, 139–150.

Searle, D. E., 1994. Late Quaternary morphology of the Cocos (Keeling) Islands. *Atoll Research Bulletin*, **401**, 1–13.

Sewell, R. B. S., 1936. An account of Horsburgh or Goifurfehendu Atoll. John Murray Expedition to the Indian Ocean, 1933–1934. *Scientific Reports*, **1**, 109–125.

Shepard, F. P., 1948. *Submarine Geology*. New York: Harper, 348 pp.

Shepard, F. P., Curray, J. R., Newman, W. A., Bloom, A. L., Newell, N. D., Tracey, J. I., and Veeh, H. H., 1967. Holocene changes in sea level: evidence in Micronesia. *Science*, **157**, 542–544.

Sheppard, C. R. C., and Seaward, M. R. D. (eds.), 1999. *Ecology of the Chagos Archipelgo*. London: Linnean Society. Occasional Publications, 2, 350 pp.

Shimazaki, H., Yamano, H., Yokoki, H., Yamaguchi, T., Chikamori, M., Tamura, M., and Kayanne, H., 2006. Global mapping of factors controlling reef-island formation and maintenance. In *Proceedings of the 10th International Coral Reef Symposium*, pp. 1577–1584.

Siddiquie, H. N., 1980. The ages of the storm beaches of the Lakshadweep (Laccadives). *Marine Geology*, **38**, M11–M20.

Smithers, S. G., Woodroffe, C. D., McLean, R. F., and Wallensky, E., 1993. Lagoonal sedimentation in the Cocos (Keeling) Islands, Indian Ocean, In *Proceedings of the 7th International Coral Reef Symposium*. Guam, pp. 273–288.

Solomon, S. M., and Forbes, D. L., 1999. Coastal hazards, and associated management issues on South Pacific islands. *Ocean and Coastal Management*, **42**, 523–554.

Spencer, T., Stoddart, D. R., and McLean, R. F., 2008. Coral reefs. In Burt, T. P., Chorley, R. J., Brunsden, D., Cox, N. J., and Goudie, A. S. (eds.), *The History of the Study of Landforms, or the Development of Geomorphology, Vol 4. Quaternary and Recent Processes and Forms (1890–1965) and the Mid-Century Revolutions*. The Geological Society of London, pp. 863–922.

Stoddart, D. R., 1962. Three Caribbean atolls: Turneffe Islands, Lighthouse Reef and Glover's Reef, British Honduras. *Atoll Research Bulletin*, **87**, 1–151.

Stoddart, D. R., 1965. The shape of atolls. *Marine Geology*, **3**, 369–383.

Stoddart, D. R., 1969. Ecology and morphology of recent coral reefs. *Biological Review*, **44**, 433–498.

Stoddart, D. R., 1971. Geomorphology of Diego Garcia Atoll. *Atoll Research Bulletin*, **149**, 7–26.

Stoddart, D. R., 1973a. Coral reefs of the Indian Ocean. In Jones, O. A., and Endean, R. (eds.), *Biology and Geology of Coral Reefs, I, Geology I*. New York: Academic Press, pp. 51–92.

Stoddart, D. R., 1973b. Coral reefs: the last two million years. *Geography*, **58**, 313–323.

Stoddart, D. R., 1975. Almost-atoll of Aitutaki: geomorphology of reefs and islands. *Atoll Research Bulletin*, **190**, 31–57.

Stoddart, D. R. (ed.), 1984. Biogeography and ecology of the Seychelles Islands. The Hague: Dr W. Junk Publishers.

Stoddart, D. R., 1995. Darwin and the seeing eye: iconography and meaning in the Beagle years. *Earth Sciences History*, **14**, 3–22.

Stoddart, D. R., and Steers, J. A., 1977. The nature and origin of coral reef islands. In Jones, O. A., and Endean, R. (eds.), *Biology and Geology of Coral Reefs IV, Geology II*. New York: Academic press, pp. 59–105.

Szabo, B. J., Tracey, J. I., and Goter, E. R., 1985. Ages of subsurface stratigraphic intervals in the Quaternary of Eniwetak Atoll, Marshall Islands. *Quaternary Research*, **23**, 54–61.

Tayama, R., 1952. Coral reefs of the South Seas. *Bulletin of the Hydrographic Department, Tokyo*, **11**, 1–292.

Tomascik, T., Mah, A. J., Nontji, A., and Moosa, M. K., 1997. The ecology of Indonesian seas. Part 2, Periplus Editions.

Tudhope, A. W., 1989. Shallowing-upwards sedimentation in a coral reef lagoon, Great Barrier Reef of Australia. *Journal of Sedimentary Petrology*, **59**, 1036–1051.

Tudhope, A. W., Scoffin, T. P., Stoddart, T. P., and Woodroffe, C. D., 1985. Sediments of Suwarrow Atoll. *Proceedings of the Fifth International Coral Reef Congress, Tahiti*, **6**, 611–616.

Vacher, H. L., and Quinn, T. M. (eds.), 1997. Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology, Elsevier, 54.

Wang, G.,1998. Tectonic and monsoonal controls on coral atolls in the South China Sea. In Camoin, G. F., and Davies, P. J. (eds.), *Reefs and Carbonate Platforms in the Pacific and Indian Oceans*. International Association of Sedimentologists, Special Publication, 25, pp. 237–248.

Wang, G., Lu, B., and Quan, S., 1990. Sedimentary characteristics of coral reefs in the northern part of the South China Sea. *Atoll Research Bulletin*, **346**, 1–23.

Wardlaw, B. R., Henry, T. W., and Martin, W. E., 1991. *Sediment facies of Enewetak Atoll Lagoon*. U.S. Geological Survey Professional Paper, 1513-B, pp. B1–B30.

Webb, A., 2006. *Coastal change analysis using multi-temporal image comparisons – Funafuti Atoll*. South Pacific Applied Geoscience Commission (SOPAC) Technical Report, no 54 (EU EDF 8/9).

Weber, J. N., and Woodhead, P. M. J., 1972. Carbonate lagoon and beach sediments of Tarawa atoll, Gilbert Islands. *Atoll Research Bulletin*, **157**, 1–28.

Weisler, M. I., 1994. The settlement of marginal Polynesia: new evidence from Henderson Island. *Journal of Field Archaeology*, **21**, 83–102.

Whitehead, D. R., and Jones, C. E., 1969. Small islands and the equilibrium theory of insular biogeography. *Evolution*, **23**, 171–179.

Wiens, H. J., 1959. Atoll development and morphology. *Annals of the Association of American Geographers*, **49**, 31–54.

Wiens, H., 1962. *Atoll Environment and Ecology.* New Haven: Yale University Press.

Wood-Jones, F., 1912. *Coral and Atolls: A History and Description of the Keeling-Cocos Islands, with an Account of Their Fauna and Flora, and a Discussion of the Method of Development and Transformation of Coral Structures in General*. London: Lovell Reeve and Co., 392 pp.

Woodroffe, C. D., 1985. Vegetation and flora of Nui Atoll. *Atoll Research Bulletin*, **283**, 1–28.

Woodroffe, C. D., 1988. Pacific Island Mangroves: distribution and environmental settings. *Pacific Science*, **41**, 166–185.

Woodroffe, C. D., 1993. Morphology and evolution of reef islands in the Maldives, *Proceedings of the 7th International Coral Reef Symposium*, **2**, 1217–1226.

Woodroffe, C. D., 2005. Late Quaternary sea-level highstands in the central and eastern Indian Ocean: a review. *Global and Planetary Change*, **49**, 121–138.

Woodroffe, C. D., 2008. Reef-island topography and the vulnerability of atolls to sea-level rise. *Global and Planetary Change*, **62**, 77–96.

Woodroffe, C. D., and Berry, P. F., 1994. Scientific studies in the Cocos (Keeling) Islands: an introduction. *Atoll Research Bulletin*, **399**, 1–16.

Woodroffe, C. D., and McLean, R. F., 1994. Reef Islands of the Cocos (Keeling) Islands. *Atoll Research Bulletin*, **403**, 1–36.

Woodroffe, C. D., and McLean, R. F., 1998. Pleistocene morphology and Holocene emergence of Christmas (Kiritimati) Island, Pacific Ocean. *Coral Reefs*, **17**, 235–248.

Woodroffe, C. D., and Morrison, R. J., 2001. Reef-island accretion and soil development, Makin Island, Kiribati, central Pacific. *Catena*, **44**, 245–261.

Woodroffe, C. D., and Stoddart, D. R., 1992. Substrate specificity and episodic catastrophe: constraints on the insular plant geography of Suwarrow Atoll, northern Cook Islands. *Atoll Research Bulletin*, **362**, 1–19.

Woodroffe, C. D., Kennedy, D. M., Jones, B. G., and Phipps, C. V. G., 2004. Geomorphology and Late Quaternary development of Middleton and Elizabeth Reefs. *Coral Reefs*, **23**, 249–262.

Woodroffe, C. D., McLean, R. F., Polach, H., and Wallensky, E., 1990b. Sea level and coral atolls: Late Holocene emergence in the Indian Ocean. *Geology*, **18**, 62–66.

Woodroffe, C. D., McLean, R. F., Smithers, S. G., and Lawson, E., 1999. Atoll reef-island formation and response to sea-level change: West Island, Cocos (Keeling) Islands. *Marine Geology*, **160**, 85–104.
Woodroffe, C. D., McLean, R. F., and Wallensky, E., 1994. Geomorphology of the Cocos (Keeling) Islands. *Atoll Research Bulletin*, **402**, 1–33.
Woodroffe, C. D., Stoddart, D. R., Spencer, T., Scoffin, T. P., and Tudhope, A., 1990a. Holocene emergence in the Cook Islands, South Pacific. *Coral Reefs*, **9**, 31–39.
Xue, C., 2001. Coastal erosion and management of Majuro Atoll, Marshall islands. *Journal of Coastal Research*, **17**, 909–918.
Yamano, H., Kayanne, H., Matsuda, F., and Tsuji, Y., 2002. Lagoonal facies, ages, and sedimentation in three atolls in the Pacific. *Marine Geology*, **185**, 233–247.
Yamano, H., Kayanne, H., Yamaguchi, T., Kuwahara, Y., Yokoki, H., Shimazaki, H., and Chikamori, M., 2007. Atoll island vulnerability to flooding and inundation revealed by historical reconstruction: Fongafale Islet, Funafuti Atoll, Tuvalu. *Global and Planetary Change*, **57**, 407–416.
Yamano, H., Shimazaki, H., Matsunaga, T., Ishoda, A., McClennen, C., Yokoki, H., Fujita, K., Osawa, Y., and Kayanne, H., 2006. Evaluation of various satellite sensors for waterline extraction in a coral reef environment: Majuro Atoll, Marshall Islands. *Geomorphology*, **82**, 398–411.
Zann, L. P., 1982. *The marine ecology of Betio Island, Tarawa Atoll, Republic of Kiribati*. CCOP/SOPAC Technical Report, 23, 9 pp.

Cross-references

Agassiz, Alexander
Algal Rim
Antecedent Platforms
Atlantic/Caribbean Reefs
Atoll Islands (Motus)
Bank Reefs
Beach Rock
Bikini Atoll
Blue Hole
Boat Channel
Boulder Zone/Ramparts
Channels, Inter Reefal
Cocos (Keeling) Islands
Conglomerates
Coral Cays – Processes of Formation
Coral Cays – Soils
Coral Cays – Vegetational Succession
Daly, R.
Dana, J.D.
Darwin, Charles
David, Edgeworth T.
Davis, W.M.
Eastern Indian Ocean
Emerged Reefs
Enewetak Atoll
Faroes Reefs
Funafuti Atoll
Gardiner, J.S.
Glacial Control Hypothesis
Halimeda
Holocene Reefs – Thickness and Characteristics
Indian Ocean Reefs
Indonesian Reefs
Lagoon Circulation
Lagoons
Lyell, Charles
Makatea
Maldives
McNeil, F. Stearns
Megablocks
Micro Atolls
Mid Holocene
Midway Atoll
Mururoa Atoll
Pacific Reefs
Patch Reefs
Phosphatic Cay Sandstone
Recent Sea Level Trends
Reef Flat
Reef Flat Sediments
Reef Front Wave Energy
Reef Island Hydrology
Reef Structure
Reef Typology
Reticulated Reefs
Sea Level Changes and Effects on Reef Growth
Sea Level Indicators on Reefs
Shingle Ridges
Spur and Groove
Stoddart, D.R.
Submerged Reefs
Subsidence Hypothesis
Western Australia

http://www.springer.com/978-90-481-2638-5

Encyclopedia of Modern Coral Reefs
Structure, Form and Process
(Ed.)D. Hopley
2011, XXX, 1206 p. 812 illus., 412 in color., Hardcover
ISBN: 978-90-481-2638-5