ATOLL RESEARCH BULLETIN

NO. 402

CHAPTER 4

GEOMORPHOLOGY OF THE COCOS (KEELING) ISLANDS

BY

C.D. WOODROFFE, R.F. McLEAN AND E. WALLENSKY

ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
FEBRUARY 1994

CHAPTER 4

GEOMORPHOLOGY OF THE COCOS (KEELING) ISLANDS

BY

C.D. WOODROFFE *, R.F. McLEAN ** AND E. WALLENSKY ***

INTRODUCTION

Charles Darwin's subsidence theory of coral reef development has gained wide acceptance. The initial idea had occurred to Darwin while he was in South America, and he refined it during his voyage across the Pacific, writing an early draft of a manuscript on Coral Islands, probably between Tahiti and New Zealand (see Stoddart 1962), much of which subsequently appeared in his book on the structure and distribution of coral reefs (Darwin 1842). The Cocos (Keeling) Islands, which Darwin visited in April 1836 during the voyage of *H.M.S. Beagle*, were the only coral atoll on which he ever landed. He sought evidence there in support of the theory of coral reef development, and he left convinced that he had found such support. He wrote enthusiastically to his sister Caroline on 29 April 1836, some days after leaving Cocos, saying "I am very glad we called there, as it has been our only opportunity of seeing one of these wonderful productions of the Coral polypi.- The subject of Coral formation has for the last half year been of particular interest to me. I hope to be able to put some of the facts in a more simple and connected point of view, than that in which they have hitherto been considered".

Lyell (1832) had earlier proposed that atolls, with their characteristic annular reef rims which encircle a central lagoon, consist of a thin veneer of coral growing over the rims of submerged volcanic craters. Darwin considered it improbable that so many volcanic rims would lie within the narrow depth range required for reef growth, and proposed that there "is but one alternative; namely, the prolonged subsidence of the foundations on which 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 p109).

Darwin used his observations during his brief visit to Cocos in support of his theory of coral reef development, and wrote a manuscript (termed the Cocos Coral Manuscript by Armstrong 1991) shortly after leaving the islands. Much of the debate for the next 100 years also centred around the Cocos (Keeling) Islands. Thus, although John Murray did not himself visit Cocos, during the voyage of *H.M.S. Challenger,* he funded the visit of Henry Brougham Guppy in 1888 (though his prime interest seems to have been to get Guppy to examine phosphate deposits on Christmas Island). Guppy

---

* Department of Geography, University of Wollongong, Northfields Avenue, Wollongong, New South Wales, 2522.

** Department of Geography and Oceanography, Australian Defence Force Academy, Canberra, Australian Capital Territory, 2601

*** Department of Biogeography and Geomorphology, Australian National University, P.O. Box 4, Canberra, Australian Capital Territory, 2601

was already critical of Darwin's subsidence theory of reef development, having observed fossil coral reefs elevated above modern sea level in the Solomon Islands, and was sympathetic to the alternative theory put forward by Murray (1889). Murray proposed that atolls were the result of solutional processes concentrated in the lagoon. Guppy (1889) clearly demonstrated that the Cocos lagoon was infilling with sediment, and he described the reef islands in detail. He was on Cocos for 10 weeks and he propounded the view that the reef rim was building out episodically , as Murray had suggested.

Wood-Jones was the doctor on the Cable Station on Direction Island, 1905-1906. He spent a considerable period examining the atoll, and based on his observations wrote a volume entitled *Coral and Atolls*, in which he put forward an alternative view, that the present morphology of the atoll had developed in response to the pattern of sediment production and deposition.

Thus the three views, summarised by Wood-Jones as the Subsidence, Solution, and Sedimentation hypotheses each had a particular connection with Cocos, and had each been tried and accepted by one of its major proponents in these islands. The only other hypothesis deserving serious consideration according to Davis (1928), in a review of the coral reef problem, was the glacial control hypothesis proposed by Daly (1915, 1934).

In this account we present results from a geomorphological reappraisal of the atoll based on a number of visits, and a series of surface and shallow subsurface observations. Our concern is primarily with the development of the surface morphology of the atoll rather than the atoll's structure, a distinction which needs to be made (Stoddart 1973), but which is not always clear in the preceding references. All of the surface features have formed in the mid-late Holocene, over a pre-Holocene surface; there are no surface outcrops of late Pleistocene or older materials anywhere on the atoll. Nevertheless, our interpretations of the surface morphology and Holocene evolution have implications for the structure and longer-term development of the atoll.

REGIONAL SETTING

The Cocos (Keeling) Islands comprise the main atoll of the South Keeling Islands (lat. 12°12'S, long. 96°54'E) and an isolated atollon, North Keeling (lat 11°50'S, long. 96°49'E), 27 km to the north. These are connected by a submerged ridge at a maximum depth of 1000 m. They comprise a single feature rising from an ocean floor depth of about 5000 m (Fig. 1). The age of the ocean floor at this location is not clear, but lies in the range 60-90 million years (Jongsma 1976). In this region the seafloor gets younger to the north, and appears to have been formed from a spreading centre that has been subducted into the Java Trench.

The Cocos (Keeling) Islands lie on the Cocos Rise. To the south, the Umitaka Mary seamount reaches to within 16m of the sea surface. This chain of seamounts, the Vening Meinesz seamounts, can be traced northeastwards towards Christmas Island. They are not, however as regular as linear chains of islands and seamounts seen in the Pacific, and it is uncertain whether they have developed from a single hotspot in the same manner as may Pacific seamounts (Scott and Rotondo 1983).

That Cocos represents a carbonate reefal capping on a volcanic seamount seems extremely likely although the depth to oceanic basalt is unknown. Magnetic surveys show an anomaly, reading 250nT in vertical intensity (Chamberlain 1960, Finlayson

1970). There is also a pronounced gravity anomaly over the island. In addition a basalt and tuff pebble has been dredged from the western end of the Cocos Rise (Bezrukov 1973), further supporting the idea that carbonate overlies a volcanic basement.

The southern atoll consists of a reef rim that surrounds the atoll with two major passages, one to the northwest and one to the northeast. A series of reef islands (described in detail by Woodroffe and McLean, this volume) occur on the horseshoe-shaped reef rim which is continuous from Direction Island to the northern end of West Island. Horsburgh Island is isolated at the north of the lagoon (see Fig. 2). Marine habitats of the atoll are described in detail by Williams (this volume); the reef front, which is relatively barren of living hard corals rises to the reef crest which is algal-veneered with surge channels at intervals of 50-250 m. The reef flat is covered by 1-2 m of water at high tide and part of it dries at low tide. The northern part of the lagoon averages around 15 m deep and is covered with dead coral or sand (see Smithers, this volume). The southern part of the lagoon is shallow, but contains a network of 'blue holes' (see Chapter 3, Fig. 5). Individual holes are 12-20 m deep, but their rims are emergent at low spring tides. Extensive sand flats and sand aprons occur around the margin of the lagoon (see Smithers, and Williams, this volume).

METHODS

Surface sediment characteristics were examined in exposures of lithified sediments, and along surveyed transects. Subsurface investigations were carried out by drilling and by seismic survey. The results of seismic reflection surveys within the Cocos lagoon are described by Searle (this volume). Seismic refraction on the islands was undertaken using a 12-channel Geometrics seismograph.

Drilling was undertaken during several visits. In addition to drilling, aimed specifically at unravelling the geomorphological history of the islands, drillcore logs and in some cases cores drilled as part of a water resources survey (see Falkland, this volume) were also examined. An initial reconnaissance visit was made by Woodroffe in 1986. In 1988 Woodroffe, McLean and Wallensky undertook drilling with a portable, trailer mounted Jacro 105 rotary drill, to depths of up to 9 m on Home Island, West Island and Pulu Wak Banka. In 1990 deeper drilling was undertaken using a Jacro 500, operated by P. Murphy; holes were sunk on Horsburgh, South, West and Pulu Blan Madar Islands. In 1991 seismic reflection surveys were undertaken in the lagoon, and exploratory drillholes were put down to 2.3 m using a hand-held Mindrill on the reef flat to the east and south of West Island. Several vibrocores were taken from the southern and eastern part of the lagoon (Smithers et al., in press), using 75 mm diameter aluminium pipe, vibrated into the lagoon floor with a concrete vibrator. Three long cores of up to 4.2 m length were recovered, together with several shorter ones. Sediment compaction was around 30% in most vibrocores.

Recovery in drillholes varied, but was rarely greater than 70%. Samples of coral and *Tridacna* recovered in the cores were submitted for radiocarbon dating. Samples of coral from the conglomerate platform, or from pits within islands were also submitted for dating. Radiocarbon dating was undertaken principally at the ANU Radiocarbon Dating Laboratory.

Marine carbonate samples usually require an environmental correction for ocean reservoir effect because organisms at their time of death are already somewhat depleted in radiocarbon, as the oceanic reservoir has a substantial circulation time. Marine carbonates therefore have an apparent age at the time of their death. For marine shells from the Australian coast this environmental correction varies, but is generally minus 450 ± 35 years from the conventional radiocarbon age (Gillespie and Polach 1979). On coral atolls there has been some questioning of the estimate of the correction factor, and indeed whether any correction needs to be made. In particular, Pirazzoli has argued that no correction should be necessary for dating of coral samples from within the lagoons of Tuamotu atolls, where there may be limited exchange of waters with open ocean (Pirazzoli et al. 1987). We have examined this in Cocos, taking advantage of earlier coral collections, and by dating samples of corals collected by Wood-Jones in 1906 and Gibson-Hill in 1941 (pre-1950 samples of known age are necessary for such dating as post-1950 samples have elevated radiocarbon levels as a result of radiocarbon released by bomb tests). Results are shown in Table 1, indicating the average correction to be 460 years. The correction is indeed around 450 years, and that is the value that we have used throughout this paper to conform with similar studies elsewhere.

PLEISTOCENE LIMESTONE

Boreholes undertaken as a part of a Water Resources survey of the Cocos (Keeling) Islands (see Falkland, this volume), together with our own drillholes, indicate that a well-lithified, but porous, limestone underlies the poorly consolidated coral shingle and sand deposits of the Cocos reef islands, at depths of around 11-14 m (see Chapter 2, Table 10 and Chapter 3, Fig. 1). This older limestone contains corals, with some travertine deposits in voids, and in at least one drillcore, cemented oolites. Uranium-series disequilibrium dating of a sample of coral at the top of this facies, from 12.6 m depth (10.5 m below MSL) in drillhole WI1 gave an age of 118,000 ± 7000 years B.P. on a bulk sample, but after preparation removing calcite under binocular microscope, the age determined was 123,000 ± 7000 years B.P. (Woodroffe et al. 1991). The age of this limestone suggests it formed during the last interglacial, when the sea was around or slightly higher than present, about 125,000 years ago.

The morphology of the Pleistocene atoll has been revealed in greater detail by seismic reflection profiling across the lagoon, results of which are discussed by Searle (this volume). Woodroffe et al. (1991) argued that the atoll had subsided at a rate of about 0.1 mm/yr based upon subsidence of this surface from above present sea level to 8-11 m below present sea level. The seismic results indicate that the surface actually has a considerable slope on it, becoming much deeper with distance into the lagoon, towards the centre of which it is more than 24 m below present sea level. This morphology seems likely to result from solution during subaerial exposure of the atoll when the sea was low, and Searle (this volume) suggests that the subsidence rate may be only 0.02 mm/yr.

CONGLOMERATE PLATFORM

An important feature of reef islands on Cocos is a platform of coral conglomerate which underlies most of the islands on the atoll rim. The platform was termed 'brecciated coral-rock' by Darwin (1842), 'reef conglomerate' by Guppy (1889), and 'breccia platform' by Wood-Jones (1912).

This near-horizontal conglomerate platform comprises cemented clasts of coral shingle or rubble, found especially along the oceanward shore of many of the islands, but also underlying part of the islands as shown in pits and wells. It occurs up to 0.5 m above MSL, and is thus inundated by the highest tides. Individual coral boulders of *Porites* of up to 2 m in diameter occasionally protrude from the platform, the highest points of which may reach up to 1 m above MSL.

In some places, notably on North Keeling and Horsburgh, and at the southwestern end of West Island, the surface of the conglomerate platform is composed of arcuate, seaward-dipping beds of cemented coral cobbles. These appear to have been interpreted as former reef crests by Guppy (1889), but there is nothing in their composition to substantiate this. Instead, they resemble the foot of the modern beach where there is a rubble component, and we interpret them as beach conglomerate, marking the former position of rubble-strewn beaches.

Guppy (1889) indicated that compositionally the conglomerate platform resembles the modern reef flat. The reef flat is characteristically 1.0-1.5 m lower than the surface of the platform, which is undergoing erosion on its seaward side. The reef flat often forms a hard, relatively smooth surface with encrustation by calcareous algae. This veneer may cover formerly truncated conglomerate platform. On the basis of constituent materials, gross fabric and surface morphology, we have interpreted the conglomerate platform as a fossil emergent reef flat (Woodroffe et al. 1990a, 1990b). Radiocarbon dates on corals from within the conglomerate platform indicate a spread of ages from 4010 ± 85 to 3050 ± 85 years B.P. (Table 2, Fig. 2).

There are a number of sites at which apparently in situ fossil *Porites* microatolls, both massive and branching, have been found within the conglomerate, and which further serve to indicate that sea level was higher than the modern sea level when the conglomerate was formed. These provide a discontinuous record of the pattern of sea-level change over the late Holocene, and are discussed in greater detail below.

Shallow drilling on Home Island and Pulu Wak Banka on the eastern rim of the atoll indicates that the platform is generally better cemented, and consists of coarser clasts nearer to the ocean. Shingle sticks of *Acropora*, often cemented by calcareous algae, form a major component of oceanward drillholes. Similar drilling on the modern reef flat has revealed that that it is also underlain by *Acropora* sticks cemented by calcareous algae. On lagoonward exposures of the platform drilling often encountered sand at 1-2 m depth.

HOLOCENE REEF GROWTH

The stratigraphy and chronology of the Holocene reef rim was examined along a series of transects around the atoll (Fig. 2), with drillholes through islands and the conglomerate platform which surrounds and underlies them, and through the reef flat.

Figure 3 shows a cross-section (transect I) of the southern part of Home Island where observations were obtained from a trench and associated drillhole in the trench floor (CK7). The conglomerate platform was encountered in the floor of the trench at the same elevation that it outcrops on the oceanward side of the island. A radiocarbon date of 5760 ± 95 years B.P. at 310 cm (-2.4 m below MSL) was obtained from the drillhole CK7. The island sediments, which are discussed in more detail in the next chapter, range in age from 1840 ± 125 years B.P. to 1440 ± 80 years B.P.

The age of the conglomerate platform on Home Island is indicated by a radiocarbon date of 3680 ± 105 years B.P. on a coral cemented into the top of the platform at the site of CK1, a drillhole in a sequence (transect II) on the platform at the southern end of this island. The cross-section at this point includes drillhole CK3 which is on the oceanward edge of this platform and is more then 6 m deep. This core contains coral shingle, generally well-cemented with calcareous algae, and at its base is dated 6160 ± 95 years B.P. (see Table 3). The ages above are reversed, but their errors render them statistically indistinguishable. There is apparently a decrease in age as the lagoon is approached with a radiocarbon date of 3490 ± 85 years B.P. at 2.4 m below MSL in the lagoonward core CK2. The platform is less well cemented in this core, and drilling was aborted in sand.

A similar sequence of drillholes was drilled through the conglomerate platform on transect III at the southern end of Pulu Wak Banka. The channel south of this island contains numerous living microatolls. A fossil microatoll was identified within the conglomerate, and this has been radiocarbon dated at 1960 ± 80 years B.P. (Fig. 5), indicating that some material has been added to the conglomerate platform on the margin of the channel in the last 2000 years. A coral within the conglomerate has been dated at 3220 ± 85 years B.P. just near the transect (Fig. 2). The conglomerate platform becomes thinner closer to the lagoon, and drilling in CK6 was aborted in sand. A core into the sand spit extending from the southern end of Pulu Wak Banka into the lagoon, contains coral shingle at about 1 m depth, which has been dated 3170 ± 85 years. It can also be inferred from this date that the lagoon has partially filled since the time of conglomerate platform formation.

Figure 6 indicates the stratigraphy beneath South Island on transect IV, and Figure 7 indicates the stratigraphy beneath Pulu Blan Madar. Both are similar, intercepting the Pleistocene limestone at 13.8 m depth (11.6 m below MSL) and 12.6 m depth (11.2 m below MSL) respectively. The cores recovered shingle or shingle and sand. Coral fragments at 10 m in CK15 dated 6790 ± 80 years B.P. and Tridacna at 6 m in CK14 dated at 6040 ± 80 years B.P.

Figure 8 shows shallow cores into the reef flat on transect VI, south of Pulu Maria. The reef flat appears about 1000 years older close to the oceanward edge, than beneath the island 750 m lagoonward. Radiocarbon dates of 5800 ±70 years B.P. at 2.15 m depth, and 5630 ± 205 years B.P. at 0.6 m depth in CK21 (not statistically significantly different), compare with a date of 4740 ± 85 years B.P. at 2.1 m depth in CK23 (Fig. 8). The conglomerate platform on Pulu Maria contains only relatively fine clasts, and recovery in CK23 was poor, but generally also indicated weakly cemented sand.

Figure 9 shows transect VI across the spits at the eastern end of West Island. Radiocarbon dates on coral shingle, recovered from a series of pits into the sandy spits, demonstrate progressive development of the spits from around 1400 years ago to present (Table 6), with the last spit giving a modern age. CV1 is a vibrocore sunk into the muddy sediments flanking the recent spit and penetrating sand and shingle, and from that vibrocore a date at around 0.9 m (about halfway down the core, allowing for compaction of the core) is 3240 ± 85 years B.P.. This date appears to reflect lagoonal infilling, which must have occurred before the spits began to form. Though hard pan was encountered beneath some spits, this area is not underlain by typical conglomerate platform.

Figure 10 at the southern end of West Island is a combination of several different drillholes undertaken at different times, and amalgamated schematically into a single transect (Transect VIII). Pleistocene limestone was encountered at 6.5 m below MSL. in

CK13, but was not encountered in CK9 which went slightly deeper. CK13, drilled next to a telok (lagoonlet), but through a shingle substrate, encountered mud at 2-4 m depth, similar to that being deposited in the telok, implying that the island sand and shingle have been deposited over the surface of a formerly larger telok (Fig. 10). The sequence of 4 radiocarbon dates from drillholes CK13, CK9 and CK10A show the opposite trend to that generally observed on other transects, in that the older dates (6140 ± 85 years B.P. at 4.4 m in core CK13) are to lagoonward, with younger dates beneath the reef flat (4770 ± 85 years B.P. at 1.5 m in CK10A).

Figure 11 shows transect IX which is at the southern boundary of the Quarantine Station on West Island and crosses the island where it is both especially low and particularly narrow. The most interesting feature of this transect is that there are a number of microatolls, up to 2 m in diameter, which are found along the shore, above the modern limit to coral growth. This together with elevated beachrock at this site provides convincing evidence that the sea has been relatively higher than it is at present. Radiocarbon ages of 2690 ± 85 and 2730 ± 85 years B.P. have been determined on two massive *Porites* microatolls at this site, where they are about 50-60 cm above their modern, living equivalents. In addition a sample of *Porites*, almost certainly a microatoll, was recovered from drillhole CK8 and dated 3190 ± 85 years B.P. at a very similar elevation, indicating that similar, though in this case slightly older microatolls continue beneath the island sediments. The significance of these emergent, in situ corals will be examined below.

Figure 12 shows the stratigraphy of two deep holes drilled on transect X on Horsburgh Island. The Pleistocene substrate was only encountered in the more oceanward drillhole, where it was found at a depth of 13.1 m (10.6 m below MSL). A coral sample from a massive coral colony recovered from almost directly above the Pleistocene/Holocene contact was radiocarbon dated 5540 ± 80 years B.P., while a coral from 4.8 m has been dated 5260 ± 80 years B.P.. These samples are more than 8 m apart and imply a rapid rate of reef accretion in the order of 25-30 mm/yr. CK11 at the lagoonward end of Horsburgh Island was presumably not drilled deep enough to encounter the Pleistocene surface, as subsequent seismic profiling in that part of the lagoon has indicated a reflector, believed to represent the last interglacial surface at depths of more than 20 m. Nevertheless the date of 4610 ± 85 years B.P. on a sample of *Tridacna* at the base of that core, indicates that sedimentation here lagged about 1000 years behind that on the more oceanward side of Horsburgh.

MICROATOLLS AND HOLOCENE SEA LEVEL

The radiocarbon dates from Tables 3, comprising dated samples from transects I-X, have been plotted on an age-depth plot in Figure 13. These ages do not permit the accurate reconstruction of early to mid-Holocene sea-level history on Cocos, because it cannot be established that the corals in the cores are in their position of growth, and even if they were in situ they could have grown in water depths of up to several metres. Samples from the conglomerate platform (Table 2) on the other hand are manifestly not in growth position, and do not indicate the level of the sea at time of deposition. Some corals, however, do record former sea level. Microatolls are flat-topped colonies of coral which have been constrained in their upward growth by subaerial exposure at low spring tides, and have therefore continued to grow only laterally (Scoffin and Stoddart 1978). Their upper surface is related to sea level and the upper surface of fossil microatolls can be used to reconstruct late Holocene sea-level change (Chappell 1982). On the Cocos (Keeling) Islands there are modern, living microatolls, of massive and branching *Porites*, on the reef flat, in interisland passages, and within the lagoon (Woodroffe and McLean 1990). These corals were described by Wood-Jones (1912), though he attributed their form to sedimentation on their upper surface. Detailed survey of modern microatolls around the atoll indicates that they occur in a relatively narrow elevational range (around 0.3 m below MSL), and supports the idea that they are limited by water level (Smithers, unpublished results).

Fossil microatolls, though by no means common, have been identified within the conglomerate platform at several sites on West Island, and on Pulu Pandan and South Island. At the southern end of West Island fossil microatolls of both massive and branching species of *Porites* are found together. Fossil microatolls can also be identified on the reef flat, and at one location in a telok on South Island, where the oldest microatolls so far dated on Cocos have been found (3560 ± 85 years B.P., see Fig. 2). The exact elevation of these remains uncertain, but they appear to be lower than younger specimens on West Island (Table 4). In addition, *Porites* cored in CK8 (CK8.1B/2) almost certainly represents a microatoll dated 3190 ± 85 years B.P. and at a similar elevation to those on the present shoreline (see transect IX, Fig. 11), and so too does that in CK5 (CK5.1B), dated 1960 ± 80 years B.P. and found at around MSL (see transect III, Fig. 5).

The upper surface of these microatolls gives an indication of the elevation of sea level. When compared with the modern elevation of microatolls (around -0.3 m MSL), these corals indicate a trend of gradually falling sea level (Fig. 13), from about 0.9 m above present around 3000 years ago, on the basis of branching microatolls on Pulu Pandan and slightly less if massive microatolls on West Island are considered. A discontinuous record of relative sea-level fall is preserved at the foot of the beach near the Quarantine station on West Island, where a series of microatolls is located (see plot in Fig. 13).

LAGOONAL INFILL

The nature of lagoonal sediments in the South Keeling Islands has been examined by Smithers (this volume), who demonstrates that sediments in the lagoon range from strongly fine skewed gravelly muds (as in the teloks and blue holes) to gravelly sands where sand aprons have encroached upon lagoonal corals. Compositionally they are entirely biogenic, dominated by three factors, coral sediments, molluscan sediments and sediments in which calcareous algal fragments and *Halimeda* plates are an important constituent (Smithers et al., in press).

The lagoon is particularly shallow around much of the southeastern corner, and the surface, which is covered by seagrass, dries out at low tide (Williams, this volume). There is anecdotal evidence that it has filled in rapidly in historical times. Captain John Clunies Ross established his settlement on the middle portion of South Island, where access is now extremely difficult for a boat of any draft at almost any stage of the tide. Rapid infill has been inferred by Forbes (1879, p779). Guppy detected sediment in suspension being carried into the lagoon through the passages, by the predominantly unidirectional currents. He made a series of calculations of sediment transport and sedimentation into the lagoon (Guppy 1889). His estimates were based upon rates of coral growth and sediment production, distributed across the area of the reefs and lagoon that contained coral cover. He calculated that 5000 tons of sediment was carried into the lagoon each year. The majority (5/6) he considered to be deposited in the first 700 m of the lagoon, on the sand aprons. He estimated that these aprons were prograding at a rate of around 1 m/yr (1 yard per year). Vertical sedimentation averaged over the southern part of the lagoon, Guppy estimated to be 1ft/100 years (c. 3mm/yr). Extending these calculations to the northern lagoon, Guppy considered that the lagoon would require a further 4000 years to infill, and that the total time from initiation to complete infill for a lagoon would be about 15-20,000 years.

Wood-Jones, not only realised the importance of this sediment accumulation in the lagoon, but he interpreted sedimentation as the prime control on the formation of the atoll. He compared the atoll as a whole with single colonies of *Porites* microatolls (he termed them an 'atoll reef in miniature', Wood-Jones 1912, p108-109), which he interpreted to be limited in their upward growth by sediment accumulation on their upper surface. Wood-Jones proposed his sedimentation theory of atoll development in opposition to Darwin's subsidence theory, and the solution theory of Murray.

We have examined lagoonal sedimentation in Cocos, based on a series of vibrocores taken in the southern and eastern lagoon. The stratigraphy, sediment grain-size and components, and radiocarbon dating from vibrocores indicate spatial and temporal variations in the nature and rate of sedimentation, controlled primarily by the pattern of sea-level change and the response of the atoll environments, particularly the formation of reef islands on the atoll rim (Smithers et al., in press).

The main contrast is between sand apron sediments, on the one hand, which are composed of skeletal grains typical of a reef flat assemblage, being coarse, clean sands and shingle, with fragments of the algal rhodoliths, *Spongites* sp., and island lee sediments, on the other hand, which are higher in mud content, with occasional coral fragments. The base of vibrocores contains more shingle, and coral, algae and *Halimeda* are generally more common, perhaps reflecting lagoon reefs which have been covered by sand apron and island lee sediments. Sand aprons have encroached episodically into the lagoon and sand appears to have spilled into blue holes as the sedimentation front advanced. It seems highly probable that the sands of the southeastern section of the lagoon have already filled over a patchwork of blue holes, and this may explain the patchy penetration of vibrocores; the shorter ones reaching shingle at much shallower depths than those which penetrated into former sand-filled blue holes.

The sands radiocarbon dated in vibrocores were all younger than 4000 years B.P. (Table 5); the base of CV11 dated 3850 ± 80, while CV1 and CV12 had dates of 3240 ± 85 and 3530 ± 80 years B.P. respectively. These older dates are in those cores closest to islands, and consequently also close to the reef. Cores further into the lagoon had younger dates: CV15 dated 420 ± 65, and CV10 910 ± 80 at its base 2.2 m below the sediment surface, and 130 ± 110 years B.P. in the centre, recording the present progradation of the sand sheets into the area of blue holes.

Radiocarbon dates record the time of death of the coral shingle, and not the time of its deposition. Sediments flooring the lagoon are also likely to be subject to considerable bioturbation. Nevertheless, despite minor age reversals in vibrocores such as in CV2, the dates are generally stratigraphically consistent and indicate the general trend of sedimentation. Vertical accumulation rates are higher in sand aprons than in island lee sediments, being 0.5-1.0 mm/yr in the former, and in the latter, over the last 2000 years, ranging from 0.25-0.5 mm/yr (Smithers et al., in press).

HOLOCENE EVOLUTION OF THE ATOLL

The Holocene atoll has developed over a Pleistocene limestone surface, which has been shown by seismic reflection profiling to be basin shaped probably as a result of solutional weathering during the glacial sea-level low (Searle, this volume). This surface has been flooded by the sea during the postglacial marine transgression. Seismic and drilling results indicate that there is a relatively continuous Pleistocene rim at about 9-10 m below MSL, around the western, southern and eastern sides of the atoll, with a deeper basin to the north, which opened out to the northeast, and perhaps also northwest. When the sea was 12-15 m below present, the Pleistocene rim was still emergent, and lagoonal exchange must have been predominantly through the northern passages. Since that surface has been inundated, as a result of the final stage of the postglacial marine transgression, there has been a phase of rapid vertical reef growth, following the rising sea level, recorded by radiocarbon dates from cores, and shown in Figure 13.

During periods of rising sea level reef growth has adopted one of three strategies, keep-up (where the reef closely tracks the rising sea), catch-up (where reef growth lags behind sea level) and give-up in which there is negligible net reef growth (Neumann and Macintyre 1985). As described above, the coral dates do not indicate the position of the sea, except for during the last 3000 years where there are dated microatolls which have been constrained by water level. Regional sea-level curves indicate a sea-level history in which sea level rose rapidly up until around 6000 years ago when it reached a level close to its present level and has changed by only a metre or so since (Thom and Chappell 1975, McLean et al. 1978, Geyh et al. 1979, Thom and Roy 1985). Vertical reef accretion on Cocos appears to have lagged behind sea level, as also shown on atolls in the Pacific (Marshall and Jacobsen 1985). The three modes of response can be found at different points around an atoll. Reef growth on Cocos has varied from place to place; nowhere does it seem to have kept up with sea level (there are no 6000 year dates at present sea level), but it has lagged behind sea level by different amounts at differing points on the atoll rim.

We identify this period of catch-up reef growth as the first of three phases in the Holocene development of the atoll. The second phase was a period of reef flat consolidation, represented by the conglomerate platform. On the basis of fabric and morphology we attribute the conglomerate platform to formation as a reef flat under conditions of sea level slightly higher than present. That the sea was higher than present is shown most convincingly by the presence of microatolls above the modern limit to coral growth (Table 4). Other data, such as the elevated beachrock (in Fig. 11), and the consistent difference between the conglomerate platform and the modern reef flat, also substantiate that the sea was relatively higher in the mid-Holocene.

Elsewhere similar conglomerate platform has been interpreted as lithified storm-rubble ridges or ramparts similar to those deposited as a result of Tropical Cyclone Bebe on Funafuti in Tuvalu in the Pacific, in front of the elongate reef islands, and subsequently observed to migrate landwards and redistribute over the shoreface (Baines and McLean 1976). We discount this interpretation of the conglomerate platforms on Cocos because of the horizontal nature and width of the platform, and the relatively narrow range of radiocarbon ages from coral clasts. Storm rubble is evidently a component of the platform, with addition of material under non-storm conditions, bound by biological and chemical processes, in a similar way that material is supplied to and incorporated into the interisland reef flat areas on the modern atoll. Reef blocks, as seen in the Pacific storm belt, are relatively rare, though there are blocks of more than 1 m diameter on the reef flat at the southern end of the atoll, one of which has been dated to 610 ± 75 years B.P. (Table 6).

The third phase is a phase of reef island development. The modern reef islands lie primarily on an oceanward outcrop of conglomerate platform, and the appearance of islands in their modern location and form must therefore postdate the formation of the platform. Islands have formed during the last 3000 years when the sea level has been undergoing a relative fall. The age structure of reef islands is still poorly known; some dates are given in Table 6, indicating substantial deposition in the period 1800-1000 years B.P. The issue is examined in greater detail in the next chapter (Woodroffe and McLean, this volume). Progradation of the southern end of West Island in the last 1400 years is apparent from Figure 9.

The three phases that are identified (Fig. 13), have not necessarily been discrete, but some overlap between them is likely. Reefs at the southern end of the atoll appear to have grown fastest, and although they did not keep up with sea level, they lagged only slightly (<1000 years) behind sea level, whereas reefs at Horsburgh appear to have undergone a greater lag before commencing to grow, but to have accreted vertically at a faster rate. Similarly the early stages of island formation appear to have occurred within the final stages of conglomerate platform development, as indicated by beachrock and beach conglomerate outcrops within the platform (i.e. Horsburgh, West Island, and North Keeling). Progression from one phase to another must have been accompanied by substantial changes of energy regime, particularly in the lagoon, which must have been a relatively high energy environment before the reef rim caught up with sea level, and subsequently underwent a further reduction in energy as reef islands were formed around the margin.

DISCUSSION

This three phase model of the Holocene evolution of the atoll incorporates components of each of the earlier theories on the development of atolls. We now examine some of these issues.

The first issue at Cocos is whether the atoll has subsided, and whether it is continuing to subside. As discussed above, the depth of the last interglacial surface is taken by us as an indication of subsidence. The exact elevation of the sea at the peak of the last interglacial is contentious; in some parts of the world it is considered to have been around 5-6 m above present, elsewhere up to 10 m above present. Lambeck and Nakada (1992) indicate that flexural responses of the earth's crust and upper mantle need to be taken into account, and that it need not have been any higher than present. There are many parts of the world where the last interglacial reef is found above present sea level, the nearest being Christmas Island, where coral-bearing reef reaches 12 m above present sea level, but with associated deposits reaching 30m (Woodroffe 1988). We believe that the last interglacial reef on Cocos would have caught up with sea level during the oxygen-isotope 5e sea-level high stand, and we attribute the fact that it is everywhere below present sea level to subsidence. Seismic results indicate that solution is likely to have occurred and deepened the lagoon, but we attribute the fact that contemporaneous limestones are around 12 m above sea level on Christmas Island and 12 m below sea level on Cocos to uplift of the former and subsidence of the latter. Indeed if the atoll were not subsiding, there would be no reason why interglacial limestones should occur in layer-cake fashion beneath the Holocene, as appears to be indicated by seismic profiling (Searle, this volume).

Darwin himself realised that confirmation of his subsidence theory would come from deep drilling of coral atolls. He postulated that such drilling should reveal extensive thicknesses of shallow water limestones, in excess of the present depth range over which corals can grow. The final proof came after World War II with drilling of Enewetak, Mururoa and Midway atolls in the Pacific, in which basalts were encountered beneath the coral limestones at depths down to 1200 m (Ladd et al. 1953, Emery et al. 1954, Lalou et al. 1966). Deep-drilling has not been undertaken on Cocos, and so the depth of the volcanic basement, probably around 400-500 m (Jongsma 1976), is still unknown.

Confirmation of the volcanic basement of open-ocean atolls, and more recently demonstration of the way in which plate tectonics can provide a mechanism (horizontal plate motion), by which subsidence can occur (Scott and Redondo 1983, Grigg and Epp 1989), give strong support to Darwin's theory of atoll origins. Relative and absolute dating of the basement volcanic rocks, and palaeontologic and diagenetic changes within the limestone, indicate that subsidence rates are "imperceptibly slow except in geological perspective" (Stoddart 1973).

While we believe that gradual subsidence is continuing at Cocos, we are unable to accept the local evidence that Darwin invoked to prove his theory. Darwin was shown erosion of the shoreline on West Island, with undercutting of coconuts, which he believed was "tolerably conclusive evidence" of subsidence. His interpretation of this geomorphological evidence has been disputed by several other scientists who have visited the atoll. Most vehement of those disagreeing with Darwin was John Clunies Ross, who was resident on Cocos but, much to his subsequent regret, had been absent on the occasion of Darwin's visit. Evidently concerned at Darwin's suggestion that the islands of which he was in possession were about to disappear beneath the sea, he claimed that a "moderable attentive investigation of the Cocos islets affords ample reasons for believing that they have stood up to the present time above the level of the ocean during hundreds if not thousands of years" (Ross 1855).

Guppy described each of the reef islands but decided that there was evidence for neither recent uplift nor recent subsidence of the atoll (Guppy 1889). On the other hand Forbes, and later Wood-Jones, believed that there was evidence that the sea had been higher with respect to the atoll. Wood-Jones wrote "the undermining of trees and the denudation of shore-lines do not necessarily indicate subsidence, for they are inconstant effects, and an area of land denudation is compensated for by an area of land construction at another part of the island ring" (Wood-Jones 1909 p674). Forbes had similarly argued that the erosion of islands was compensated by the debris being deposited further around the shore, and interpreted elevated fossil shells of clams and oysters on Workhouse Island (south of Direction Island, no longer existing as a distinct island), as an indication of former higher sea levels (Forbes 1879, 1885). The views of Forbes and Wood-Jones for a sea level higher than present revolved around their interpretations of the coral conglomerate that underlies much of the reef islands.

Our data confirm the interpretation of recent emergence (that is a slight fall of sea level relative to the atoll) since the mid-Holocene (Woodroffe et al. 1990a, 1990b). However, although the geomorphological data on the surface morphology of the atoll were misinterpreted by Darwin, the overall atoll structure we do attribute to gradual subsidence as Darwin postulated.

Radiocarbon dates from western, eastern and southern reef flat or oceanward conglomerate platform, imply that the reef near the reef crest lagged only about 1000 years behind sea level. The reef caught up first near the reef margin, and there was more gradual infill to lagoonward; thus on each of these sides we see radiocarbon ages getting younger with distance into the atoll lagoon.

This is contrary to most of the views of other geologists on the atoll. Thus Guppy, following the suggestion of Murray that reefs prograded out over their own talus, considered that there was proof that the reef flat had built out in a series of steps. His view appears to have been based upon description of the reef buttresses off the atoll given him by George Clunies-Ross, and his interpretation of the fossil reef rims as he viewed imbricated, arcuate ridges on North Keeling and Horsburgh Islands. The latter he called parallel lines of old reef margins that protrude above the reef flat, but we have interpreted these as beach deposits, marking instead the former foot of rubble-strewn beaches. Wood-Jones similarly supposed that the breccia (conglomerate platform) was oldest towards the lagoon and youngest toward the ocean (Wood-Jones 1909); whereas our results indicate the reverse trend.

In Figure 14 we summarise the late Quaternary development of the Cocos (Keeling) Islands. Wood-Jones recognised three theories, Subsidence, Solution and Sedimentation (ie. the theories of Darwin, Murray and himself respectively), to which we may add Sea-level (the glacial control theory of Daly).

The surface of the last interglacial at depths of 10-20 m below sea level indicates that the island was not planated as Daly has suggested at the time of sea level low, although our interpretation does emphasise sea-level fluctuations which have been the principal control over the late Quaternary of periods of reef establishment and their demise. We also interpret that it indicates that the atoll is continuing to subside as Darwin envisaged, although at a rate that is imperceptibly slow, even compared with rates of sea-level fluctuation. The form of the lagoon does not result from solution as Murray envisaged, but nevertheless solution does appear to have been important at times of low sea level in accentuating, through karst erosion, the basin-shape of the lagoon as inferred by Purdy (1974) in his antecedent karst hypothesis. Holocene reef morphology mimics this antecedent surface as suggested by Purdy. Finally, the lagoon has been one of the major areas of sediment accumulation, along with reef islands, over the last 3000 years, as envisaged by Wood-Jones, but we interpret this not as the cause of atoll morphology, but more as a response to the evolving morphology.

ACKNOWLEDGMENTS

This research has been funded by the Australian Research Council, National Geographic Society, and the Department of Arts, Sports, Environment and Territories. We are grateful to the Cocos (Keeling) Islands Administration, Cocos Island Council, the Cocos Co-operative, and Australian Construction Services for assistance on the island. We thank Peter Murphy, Scott Smithers and Paul Kench for their help in the field.

REFERENCES

Armstrong, P. 1991. Under the blue vault of heaven: a study of Charles Darwin's sojourn in the Cocos (Keeling) Islands. Indian Ocean Centre for Peace Studies, University of Western Australia.

Baines, G.B.K. and McLean, R.F. 1976. Sequential studies of hurricane bank evolution at Funafuti atoll. Marine Geol. 21: M1-M8.

Bezrukov, P. L. 1973. Principal scientific results of the 54th cruise of the R.V. Vitian in the Indian and Pacific Oceans (Feb-May 1973). Oceanology, 13: 761-766.

Chamberlain, N. G. 1960. Cocos Island magnetic survey, 1946. Bureau of Mineral Resources, Record, 1960/124.

Chappell, J. 1982. Evidence for smoothly falling sea levels relative to north Queensland, Australia, during the past 6000 years. Nature 302: 406-408.

Chappell, J. and Shackleton, N.J. 1986. Oxygen isotopes and sea level. Nature 324: 137-140.

Daly, R.A. 1915. The glacial-control theory of coral reefs. Proc. Am. Acad. Arts Sci. 51: 155-251.

Daly, R. A. 1934. The changing world of the Ice Age. New Haven: Yale University Press.

Darwin, C. 1842. The structure and distribution of coral reefs. London: Smith, Elder and Co.

Davis, W.M. 1928. The coral reef problem. Am. Geog. Soc. Spec. Pub. 9, 596pp.

Emery, K.O., Tracey, J.I. and Ladd, H.S. 1954. Geology of Bikini and nearby atolls. U.S. Geol. Surv. Prof. Pap. 260-A: 1-265.

Finlayson, D. M. 1970. First-order regional magnetic survey at Cocos Island, Southern Cross and Augusta. Bureau of Mineral Resources, Record, 1970/101.

Forbes, H.O. 1879. Notes on the Cocos or Keeling Islands. Proc. Roy. Geog. Soc. 1: 777-784.

Forbes, H.O. 1885. A Naturalist's wanderings in the Eastern Archipelago: A narrative of travel and exploration from 1878 to 1883. London, Sampson Row.

Geyh, M.A., Kudrass, H-R. and Streif, H. 1979. Sea-level changes during the late Pleistocene and Holocene in the Strait of Malacca. Nature 278: 441-443.

Gillespie, R. and Polach, H.A. 1979. The suitability of marine shells for radiocarbon dating of Australian prehistory. Proc. 9th Int. Conf. on Radiocarbon. Univ. California Press, 404-421.

Grigg, R.W. and Epp, D. 1989. Critical depth for the survival of coral islands: effects on Hawaiian Archipelago. Science 243: 638-641.

Guppy, H. B. 1889. The Cocos-Keeling Islands. Scott. Geogr. Mag. 5: 281-297, 457-474, 569-588.

Jacobsen, G. 1976. The freshwater lens on Home Island in the Cocos (Keeling) Islands. BMR J. Aust. Geol. Geophys. 1: 335-343.

Jongsma, D. 1976. A review of the geology and geophysics of the Cocos Islands and Cocos Rise. Bureau of Mineral Resources, Record, 1976/38.

Ladd, H.S., Ingerson, E., Townsend, R.C., Russell, M. and Stephenson, H.K. 1953. Drilling on Eniwetok Atoll, Marshall Islands. Am. Ass. Petrol. Geol. Bull. 37: 2257-2280.

Lalou, C., Labeyrie, J. and Delebrias, G. 1966. Datations des calcaires coralliens de l'atoll de Mururoa (archipel des Tuamotu) de l'époque actuelle jusqu'à -500,000 ans. C. R. Acad. Sci. Paris 263-D: 1946-1949.

Lambeck, K. and Nakada, M. 1992. Constraints on the age and duration of the last interglacial period and on sea-level variations. Nature 357: 125-128.

Lyell, C. 1832. Principles of Geology. London: Murray.

Marshall, J.F. and Jacobsen, G. 1985. Holocene growth of a mid-Pacific atoll: Tarawa, Kiribati. Coral Reefs 4: 11-17.

McLean, R.F., Stoddart, D.R., Hopley, D. and Polach, H.A. 1978. Sea level change in the Holocene on the northern Great Barrier Reef. Phil. Trans. Roy. Soc. Lond. A 291: 167-186.

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

Neumann, A.C. and Macintyre, I.G. 1985. Reef response to sea level rise: keep-up, catch-up, or give-up. Proc. 5th Int. Coral Reef Congr. 3: 105-110.

Pirazzoli, P. A., Delibrias, G., Montaggioni, L. F., Saliège, J. F., & Vergnaud-Grazzini, C. 1987. Vitesse de croissance latérale des platiers et évolution morphologique récente de l'atoll de Reao, îles Tuamotu, Polnésie française. Ann. Inst. Océanogr. 63: 57-68.

Purdy, E. G. 1974. Reef configurations, cause and effect. In L. F. Laporte (Eds.), Reefs in time and space (pp. 9-76.). Society of Economic Palaeontologists and Mineralogists Special Publication.

Ross, J.C. 1855. Review of the theory of coral formations set forth by Ch. Darwin in his book entitled: Researches in Geology and Natural History. Natuur. Tijds. voor Neder. Ind. 8: 1-43.

Scoffin, T.P. and Stoddart, D.R. 1978. The nature and significance of micro atolls. Phil. Trans. Roy. Soc. Lond. B 284: 99-122.

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

Smithers, S.G., Woodroffe. C.D., McLean, R.F. and Wallensky, E. in press. Lagoonal sedimentation in the Cocos (Keeling) Islands. Proc. 7th Int. Coral Reef Congr.

Stoddart, D.R. (editor) 1962. Coral Islands by Charles Darwin, with introduction, map and remarks. Atoll Res. Bull. 88.

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

Thom, B.G. and Chappell, J. 1975. Holocene sea levels relative to Australia. Search 6: 90-93.

Thom, B.G. and Roy, P.S. 1985. Relative sea levels and coastal sedimentation in southeast Australia in the Holocene. J. Sedim. Petrol. 55: 257-264.

Wood-Jones, F. 1909. The coral island question. Proc. Zool. Soc. 1909: 671-679.

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.

Woodroffe, C.D. 1988. Relict mangrove stand on Last Interglacial terrace, Christmas Island, Indian Ocean. J. Trop. Ecol. 4: 1-17.

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

Woodroffe, C. D., McLean, R. F., and Wallensky, E. 1990b. Darwin's coral atoll: geomorphology and recent development of the Cocos (Keeling) Islands, Indian Ocean. National Geographic Research 6: 262-275.

Woodroffe, C.D. and McLean, R.F. 1990. Microatolls and recent sea level change on coral atolls. Nature 344: 531-534.

Woodroffe, C.D., Veeh, H.H., Falkland, A.C., McLean, R.F. and Wallensky, E. 1991. Last interglacial reef and subsidence of the Cocos (Keeling) Islands, Indian Ocean. Marine Geol. 96: 137-143.

Table 1. Radiocarbon dating results on museum specimens of coral, Cocos (Keeling) Islands.

ANU Lab No.	Coral species	Date of collection	Conventional radiocarbon age	Age (pre-1950)	Reservoir correction
6151	*Acropora scherzeriana*	1906 [W-J]	370 ± 60	40	330 ± 60
6152	*Montipora foliosa*	1906 [W-J]	670 ± 60	40	630 ± 60
6153	*Porites nigrescens* (=*P. cylindrica*)	1906 [W-J]	410 ± 60	40	370 ± 60
7638	*Montipora ramosa*	1941 [G-H]	510 ± 70	10	500 ± 70
7639	*Montipora lobulata*	1941 [G-H]	480 ± 60	10	470 ± 60

Note: W-J = Wood-Jones, G-H = Gibson-Hill.

Table 2. Radiocarbon dating results on conglomerate platform Cocos (Keeling) Islands.

ANU Lab No.	Sample No.	Material	Location	Island	Conventional radiocarbon age	Environmentally corrected age
5411	C4	Coral	from conglomerate in base of well	West Is.	1770 ± 70	1320 ± 80
5412	C5	Coral	from conglomerate platform	West Is.	3890 ± 80	3440 ± 85
5414	C16	Coral, *Porites*	beneath beach conglomerate	North Keeling	3480 ± 80	3030 ± 85
5416	C26	Coral	from conglomerate platform	Direction Is.	3740 ± 80	3290 ± 85
5417	C43	Coral	from conglomerate platform	Pulu Wak Banka	3670 ± 80	3220 ± 85
5418	C48	Coral, *Porites*	cemented to conglomerate platform	North Keeling	4290 ± 80	3840 ± 85
5419	C59	Coral	lower unit of conglomerate platform	Pulu Labu	3950 ± 80	3500 ± 85
5420	C64	Coral	upper unit of conglomerate platform	Pulu Labu	3940 ± 80	3490 ± 85
5421	C65	Coral	from conglomerate platform	Home Is.	4000 ± 80	3550 ± 85
6220	CK1/5	Coral	from conglomerate platform	Home Is.	4130 ± 100	3680 ± 105
6221	C172	Coral	from conglomerate platform	South Is.	3500 ± 80	3050 ± 85
6222	C158	Coral, *Porites*	from conglomerate platform	West Is.	4460 ± 80	4010 ± 85
6224	C154	Coral	from conglomerate on transect IX	West Is.	3550 ± 80	3100 ± 85
7134	C202	Coral, *Pocillopora*	In upper conglomerate	West Is. transect VIII	3690 ± 80	3240 ± 85

Table 3. Radiocarbon dating results from drillholes; Cocos (Keeling) Islands

ANU Lab No.	Sample No.	Material	Location	Island	Elevation (m)[a]	Conventional radiocarbon age	Environmentally corrected age
6223	C153	Coral fragments	from lagoonal infill	Pulu Wak Banka	-1.0	3620 ± 80	3170 ± 85
6227	CK3-5B-4	Coral	Depth 6.2m in core CK3	Home Is.	-6.1	6610 ± 90	6160 ± 95
6641	CK10A.1B	Coral, *Porites*	150cm in core on reef flat	West Is.	-1.9	5220 ± 80	4770 ± 85
6642	CK9.3B	Coral, Faviid	230cm in core on conglomerate	West Is.	-1.7	6000 ± 80	5550 ± 85
6643	CK9.4B	*Tridacna*	380cm in core on conglomerate	West Is.	-3.0	6370 ± 90	5920 ± 95
6644	CK8.1B/2	Coral, *Porites*	140cm in core through beachrock	West Is.	+0.2	3640 ± 80	3190 ± 85
6645	CK7.3B	Coral	310cm in core	Home Is.	-2.4	6210 ± 90	5760 ± 95
6646	CK5.1B	Coral, *Porites*	5cm in core on conglomerate	Pulu Wak Banka	0.0	2410 ± 70	1960 ± 80
6647	CK3.3B	Coral	300cm in core on conglomerate	Home Is.	-3.0	5530 ± 80	5080 ± 85
6648	CK3.2B	Coral	140cm in core on conglomerate	Home Is.	-1.4	5610 ± 80	5160 ± 85
6649	CK2.2B	Coral	In core on conglmerate	Home Is.	-2.4	3940 ± 80	3490 ± 85
7546	CK11/10B	*Tridacna*	1305cm in core	Horsburgh Is.	-11.1	5060 ± 80	4610 ± 85
7547	CK12/3B	Coral fragments	480cm in core	Horsburgh Is.	-2.4	5710 ± 70	5260 ± 80
7548	CK12/12B	Coral Flaviid	1300cm in core	Horsburgh Is.	-10.6	5990 ± 70	5540 ± 80
7549	CK13/5B	Coral	440cm in core	West Is.	-3.0	6590 ± 80	6140 ± 85
7550	CK14/5B	*Tridacna*	600cm in core	South Is.	-2.5	6490 ± 70	6040 ± 80
7551	CK15/6B	Coral fragments	1000cm in core	Pulu Blan Madar	-9.0	7240 ± 70	6790 ± 80
8196	CK21 215	Coral	215cm in core on reef flat	south of West Is.	-2.4	6250 ± 60	5800 ± 70
8198	CK21 60	Coral	60cm in core on reef flat	south of West Is.	-0.8	6080 ± 200	5630 ± 205
8200	WI16/12	Coral	1220cm in core	West Is.	?	41,100 ± 890	
8201	WI16/5	Coral	500cm in core	West Is.	?	6170 ± 70	5720 ± 80
8404	HI12/15	Coral, *Acropora*	1550cm in core	Home Is.	-14.0	7480 ± 110	7030 ± 115
8197	CK17-235	Coral	235cm in core	West Is.	-2.5	6410 ± 70	5960 ± 80
8199	CK23-210	Coral	210cm in core on reef flat	Pulu Maria	-1.7	5190 ± 70	4740 ± 85

Note: [a] metres relative to Mean Sea Level.

Table 4. Radiocarbon dating results on fossil microatolls; Cocos (Keeling) Islands

ANU Lab No.	Sample No.	Material	Location	Island	Elevation (m)[a]	Conventional radiocarbon age	Environmentally corrected age
5415	C18	Microatoll, branching *Porites*	in situ within conglomerate platform	Pulu Pandan	+0.6	3400 ± 80	2950 ± 85
6218	C156	Microatoll, massive *Porites*	in situ adjacent to C155	West Is.	+0.15	3180 ± 80	2730 ± 85
6226	C174	Coral, *Porites*	microatoll in lagoon sediments	South Is.	-0.15	4010 ± 80	3560 ± 85
6228	C155	Microatoll, massive *Porites*	in situ beneath beachrock	West Is.	+0.15	3140 ± 80	2690 ± 85
7135	C 204	Microatoll, massive *Porites*	in situ in conglomerate	West Is.	+0.35	3690 ± 80	3240 ± 85
7136	C 206	Coral, branching *Porites*	in situ in conglomerate	West Is.	+0.35	3710 ± 80	3260 ± 85
7552	μ2	Microatoll, *Porites*	foot of beach	West Is.	-0.2	1500 ± 60	1050 ± 70
7553	μ4	Microatoll, *Porites*	foot of beach	West Is.	+0.1	2990 ± 70	2540 ± 80
7554	μ6	Microatoll, *Porites*	foot of beach	West Is.	+0.15	3470 ± 80	3020 ± 85
8408	μ4	Microatoll, *Porites*	foot of beach	West Is.	+0.1	3160 ± 50	2710 ± 60
8409	μ5	Microatoll, *Porites*	foot of beach	West Is.	+0.07	3430 ± 60	2980 ± 70

Note: [a] metres relative to Mean Sea Level.

Table 5. Radiocarbon dating results from vibrocores; Cocos (Keeling) Islands

ANU Lab No.	Sample No.	Material	Location	Island	Conventional radiocarbon age	Environmentally corrected age
7531	CV2-240	Coral fragments	240cm in vibrocore	Lagoon	2780 ± 100	2330 ± 105
7532	CV2-300	Coral fragments	300cm in vibrocore	Lagoon	3050 ± 90	2600 ± 95
7533	CV2-414	Coral fragments	414cm in vibrocore	Lagoon	2660 ± 130	2210 ± 135
7534	CV3-80	Coral fragments	80cm in vibrocore	Lagoon	1670 ± 110	1220 ± 115
7535	CV3-240	Coral fragments	240cm in vibrocore	Lagoon	2980 ± 70	2530 ± 80
7536	CV10-110	Coral fragments	110cm in vibrocore	Lagoon	580 ±100	130 ± 105
7537	CV10-222	Coral fragments	222cm in vibrocore	Lagoon	1360 ± 80	910 ± 85
7538	CV12-50	Coral fragments	50cm in vibrocore	Lagoon	2520 ± 110	2070 ± 115
7539	CV12-158	Coral fragments	158cm in vibrocore	Lagoon	3980 ± 80	3530 ± 85
7540	CV1-90	Coral fragments	90cm in vibrocore	Lagoon	3690 ± 80	3240 ± 85
7541	CV5-66	Coral fragments	66cm in vibrocore	Lagoon	2490 ± 80	2040 ± 85
7542	CV6-48	Coral fragments	48cm in vibrocore	Lagoon	1850 ± 90	1400 ± 95
7543	CV8-76	Coral fragments	76cm in vibrocore	Lagoon	2970 ± 120	2520 ± 125
7544	CV11-96	Coral fragments	96cm in vibrocore	Lagoon	4300 ± 80	3850 ± 85
7545	CV15-130	Coral fragments	130cm in vibrocore	Lagoon	870 ± 60	420 ± 70
8398	CV3 378	Coral fragments	378cm in vibrocore	Lagoon	3190 ± 50	2740 ± 60
8400	CV3 320	Coral fragments	320cm in vibrocore	Lagoon	3140 ± 60	2690 ± 70
8402	CV2 360	Coral fragments	360cm in vibrocore	Lagoon	3180 ± 50	2730 ± 60

Table 6. Radiocarbon dating results on reef island sediments; Cocos (Keeling) Islands

ANU Lab No.	Sample No.	Material	Location	Island	Conventional radiocarbon age	Environmentally corrected age
5413	C7	Coral	boulder exposed in eroded ridge	North Keeling	2070 ± 70	1620 ± 80
6219	C171	Coral, *Porites*	reef block on reef flat	southern atoll rim	1060 ± 70	610 ± 80
6225	C138	Coral, *Pocillopora*	in bedded sand in wall of trench	Home Is.	1890 ± 70	1440 ± 80
7127	C 72	Coral, *Porites*	In pit	West Is.	1570 ± 80	1120 ± 85
7128	C 104	Bulk sand, foraminifera	In pit, eastern ridge	West Is.	102.6 ± 3.7 %M	MODERN
7129	C 106	Coral, *Pocillopora*	80cm in pit	West Is.	1550 ± 90	1100 ± 95
7130	C 118	Coral, *Acropora*	70cm in pit	West Is.	830 ± 100	380 ± 105
7131	C 133	Coral sand and shingle	in trench	Home Is.	2290 ± 120	1840 ± 125
7132	C 135	Coral sand and shingle	in trench	Home Is.	2020 ± 170	1570 ± 175
7133	C 136	Coral shingle *Porites*	in trench	Home Is.	1950 ± 70	1500 ± 70
7747	C 108	Coral	20-30cm in pit	West Is.	1890 ± 60	1440 ± 60

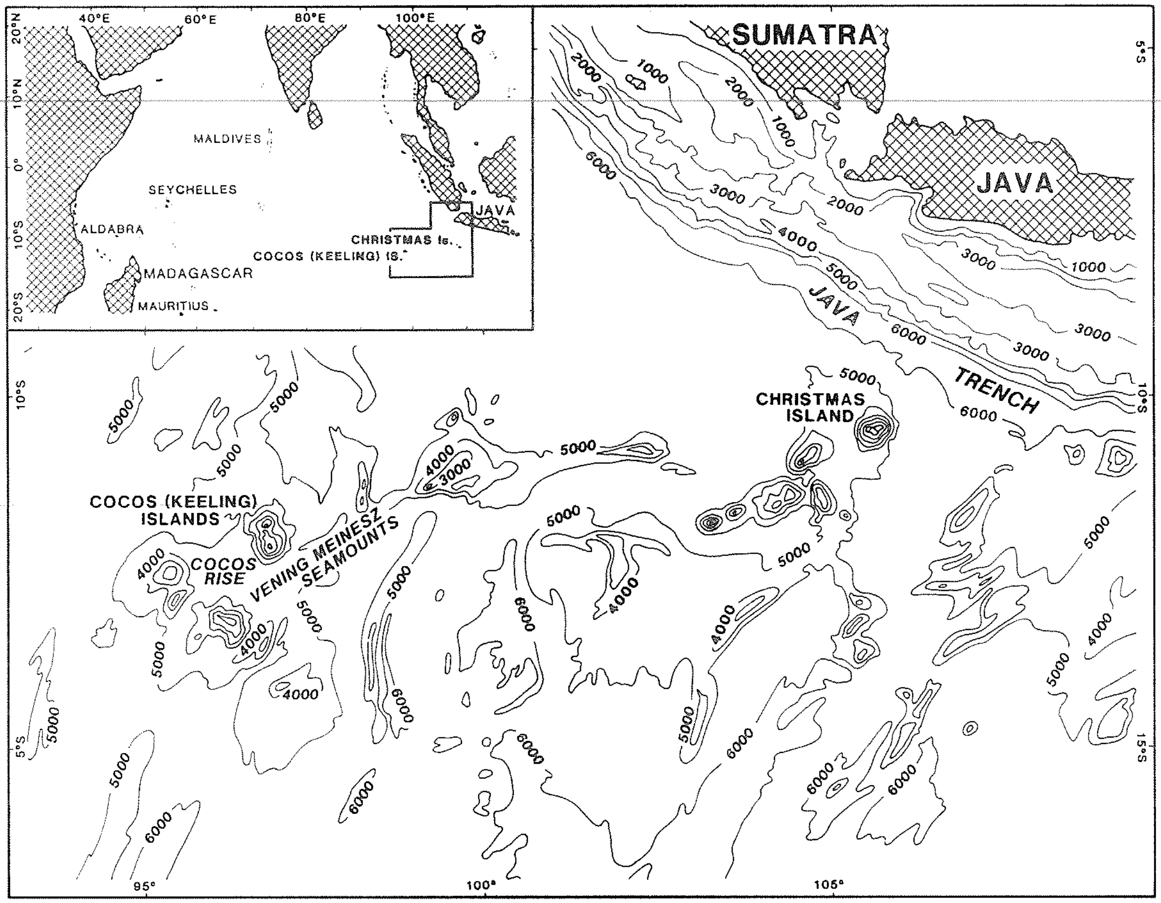

Figure 1. Location of the Cocos (Keeling) Islands and bathymetry (in metres) of the northeastern Indian Ocean.

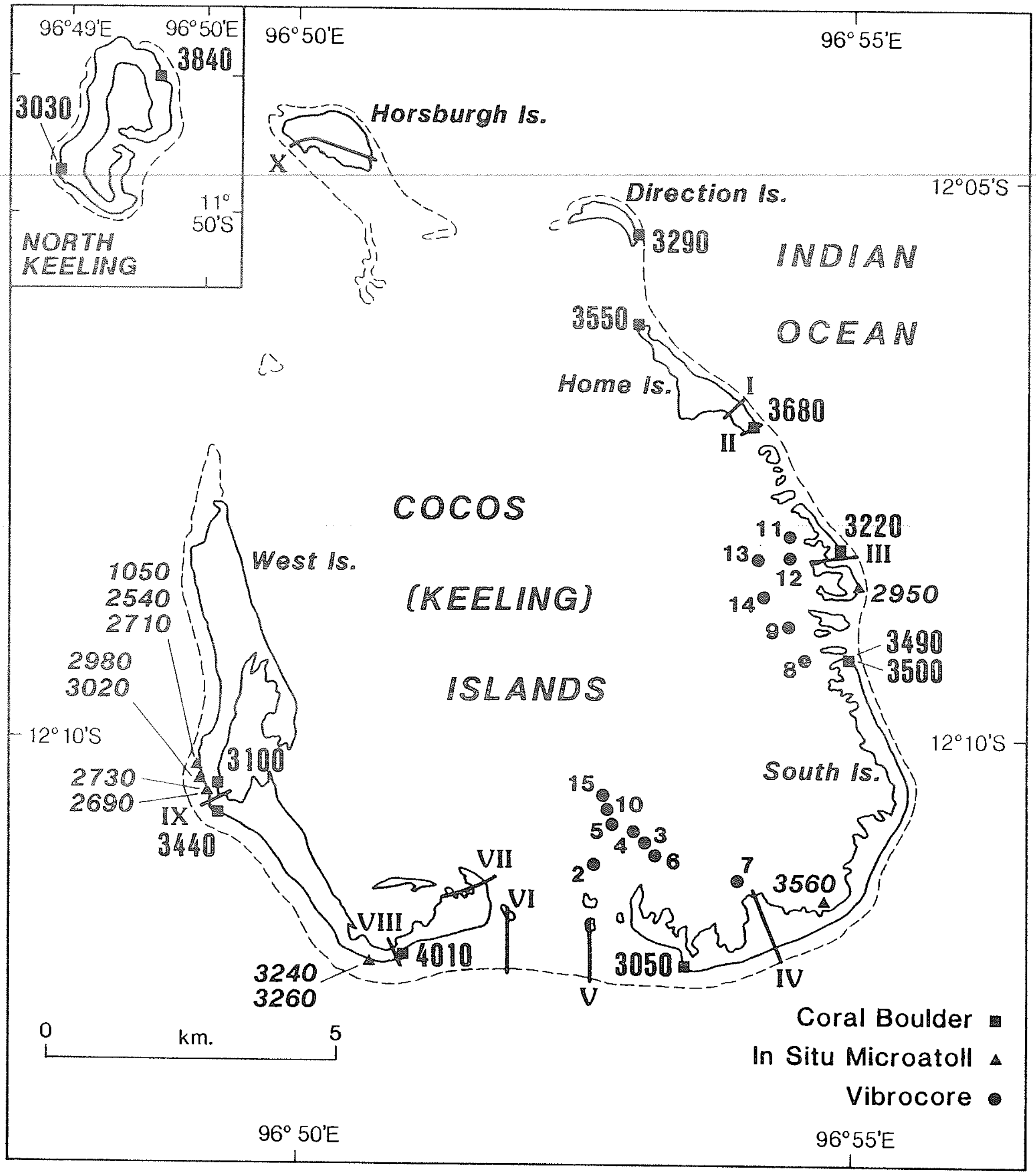

Figure 2. Cocos (Keeling) Islands, showing locations of stratigraphic transects I-X, vibrocores, and radiocarbon dates on coral from conglomerate platform (Table 2) and fossil microatolls (Table 4).

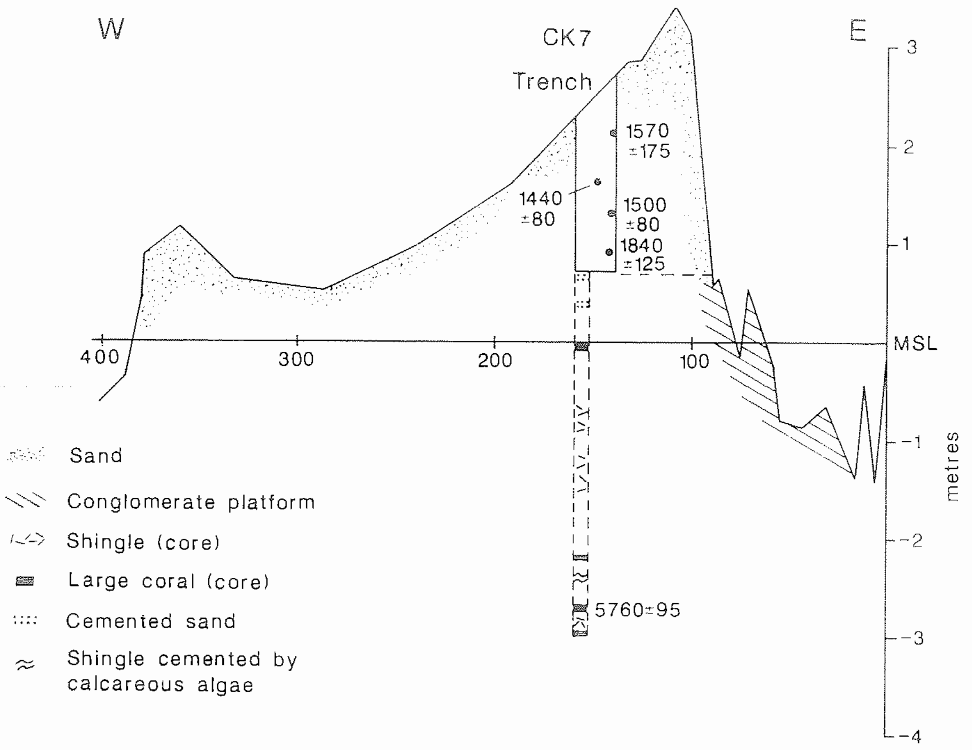

Figure 3. Transect I, Home Island (see Fig. 2 for location): stratigraphy and radiocarbon dates.

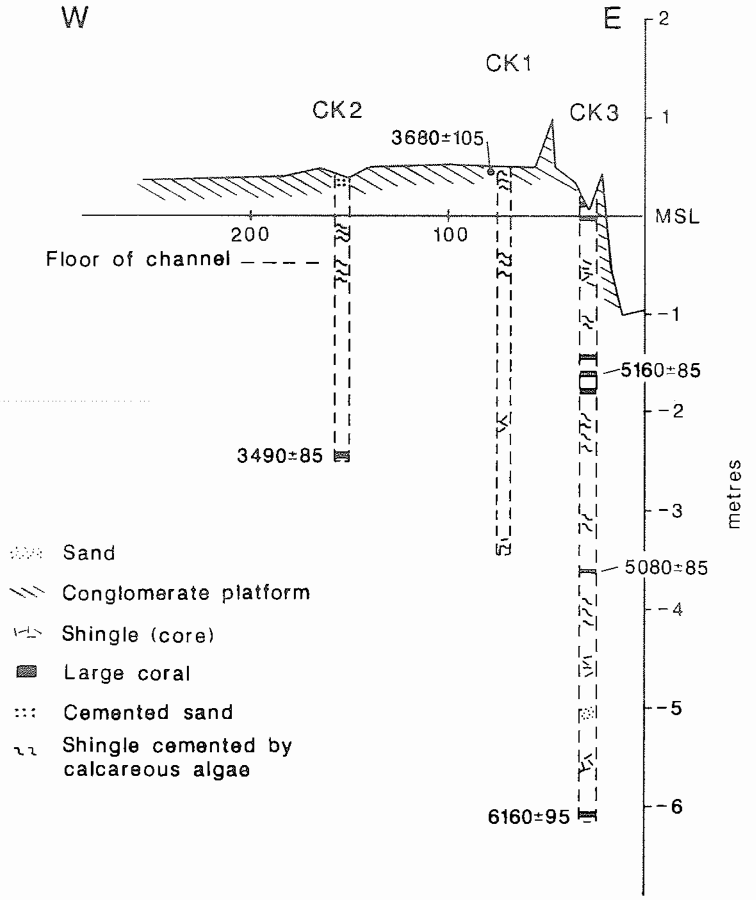

Figure 4. Transect II, Home Island (see Fig. 2 for location): stratigraphy and radiocarbon dates.

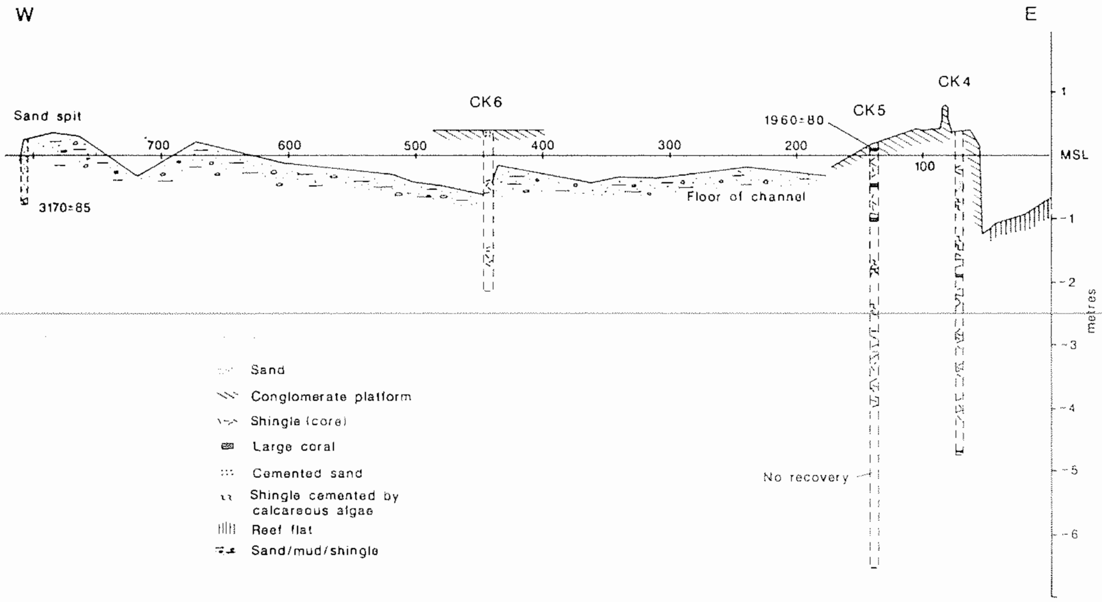

Figure 5. Transect III, Pulu Wak Banka (see Fig. 2 for location): stratigraphy and radiocarbon dates.

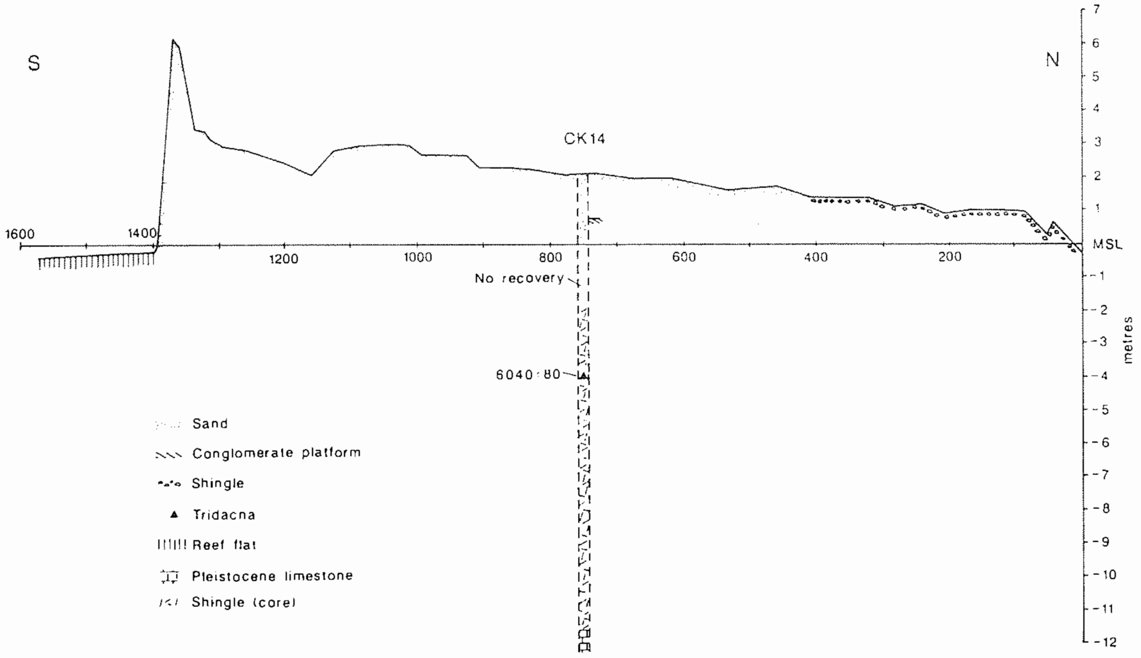

Figure 6. Transect IV, South Island (see Fig. 2 for location): stratigraphy and radiocarbon dates.

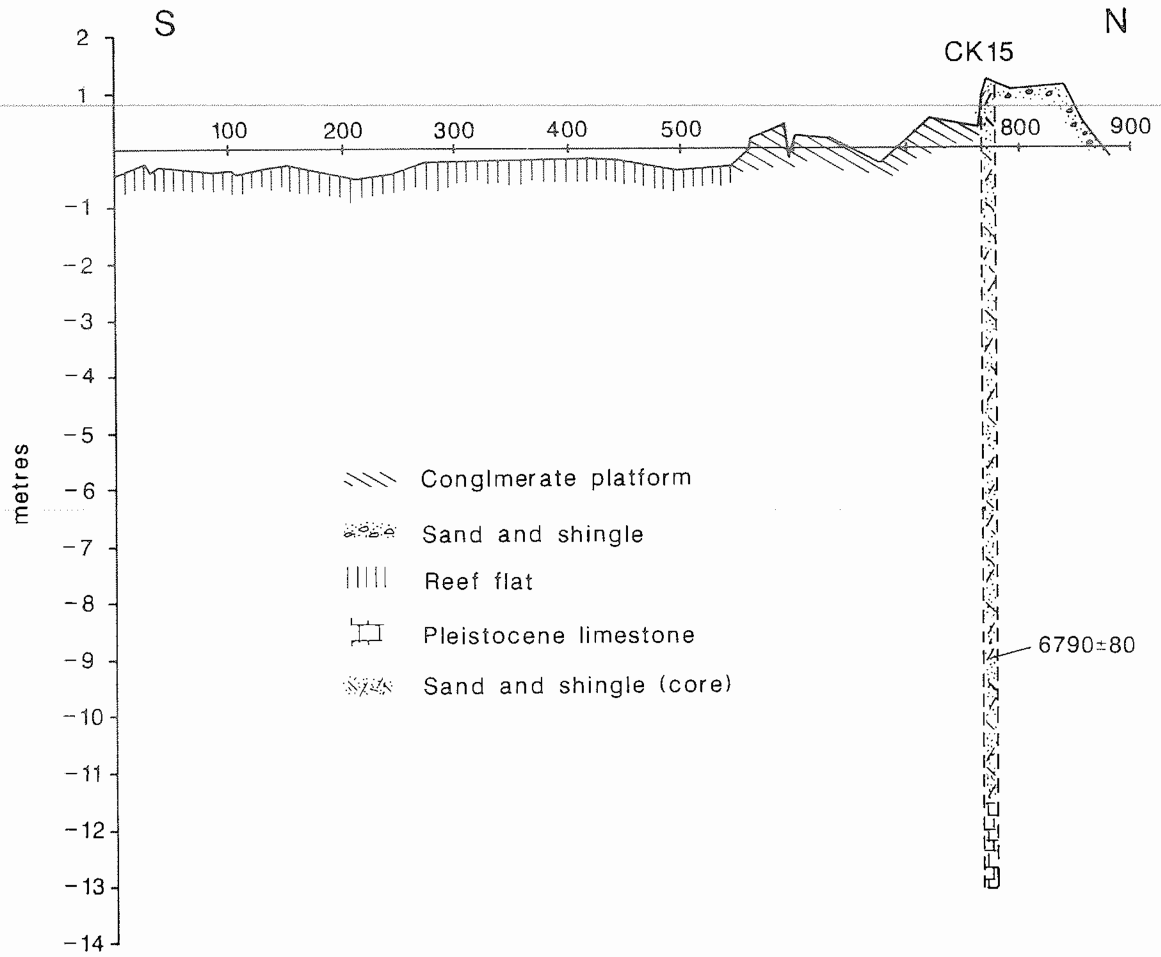

Figure 7. Transect V, Pulu Blan Madar (see Fig. 2 for location): stratigraphy and radiocarbon dates.

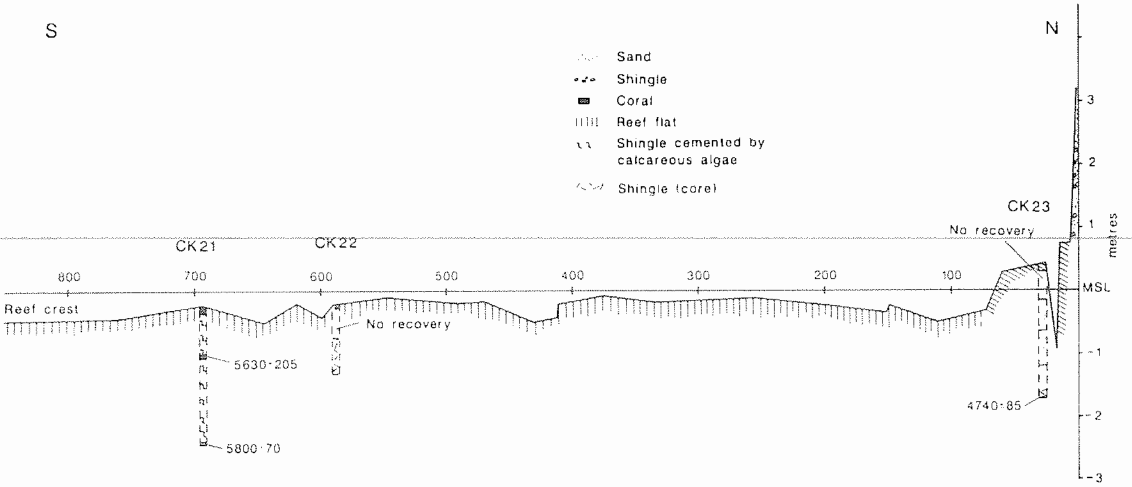

Figure 8. Transect VI, Pulu Maria (see Fig. 2 for location): stratigraphy and radiocarbon dates.

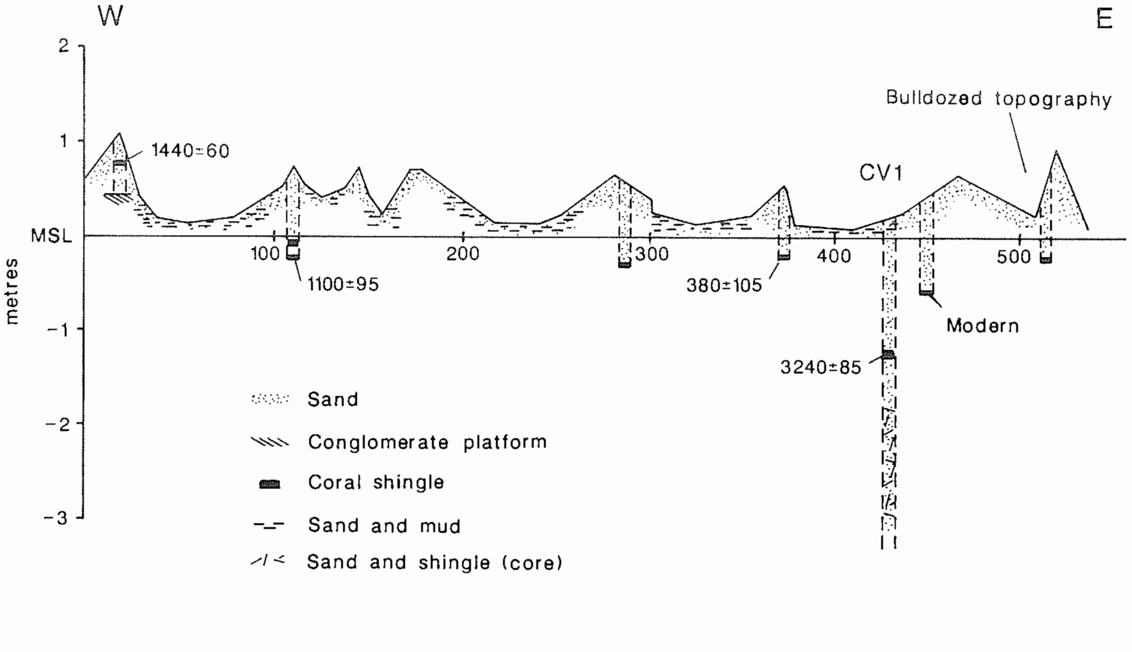

Figure 9. Transect VII, eastern end of West Island (see Fig. 2 for location): stratigraphy and radiocarbon dates.

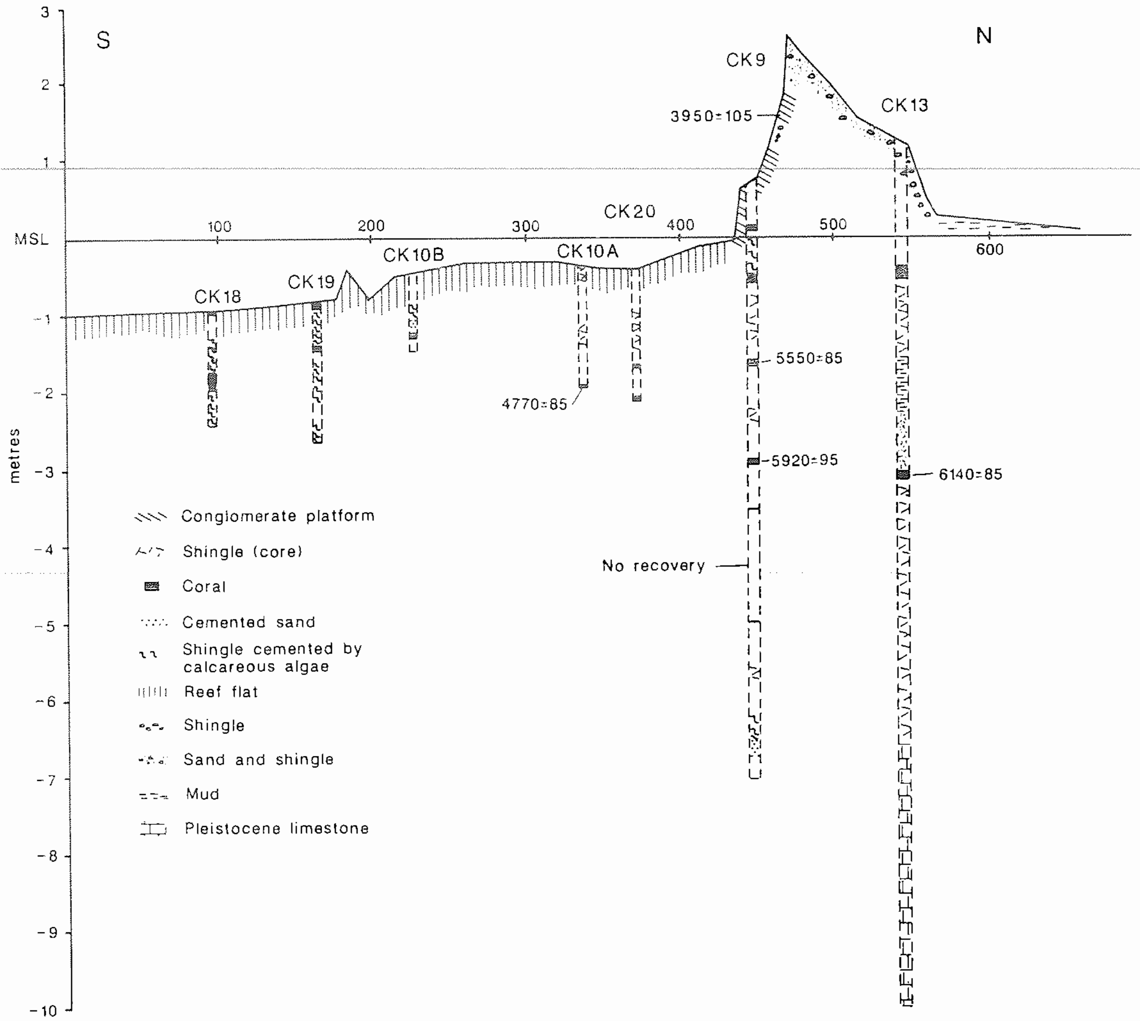

Figure 10. Transect VIII, southern West Island (see Fig. 2 for location): stratigraphy and radiocarbon dates.

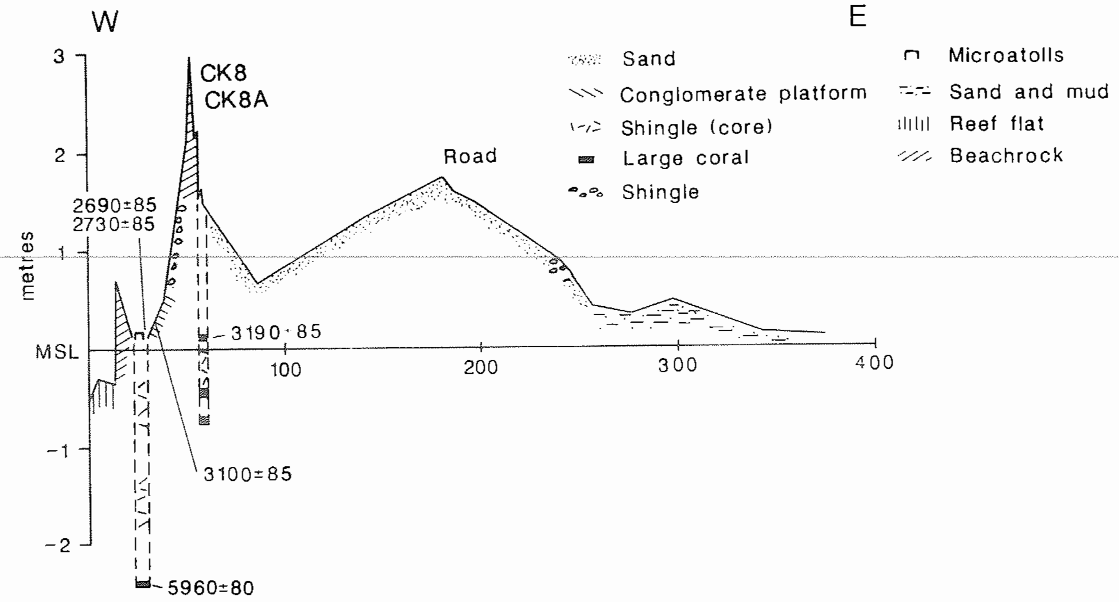

Figure 11. Transect IX, Quarantine station (see Fig. 2 for location): stratigraphy and radiocarbon dates.

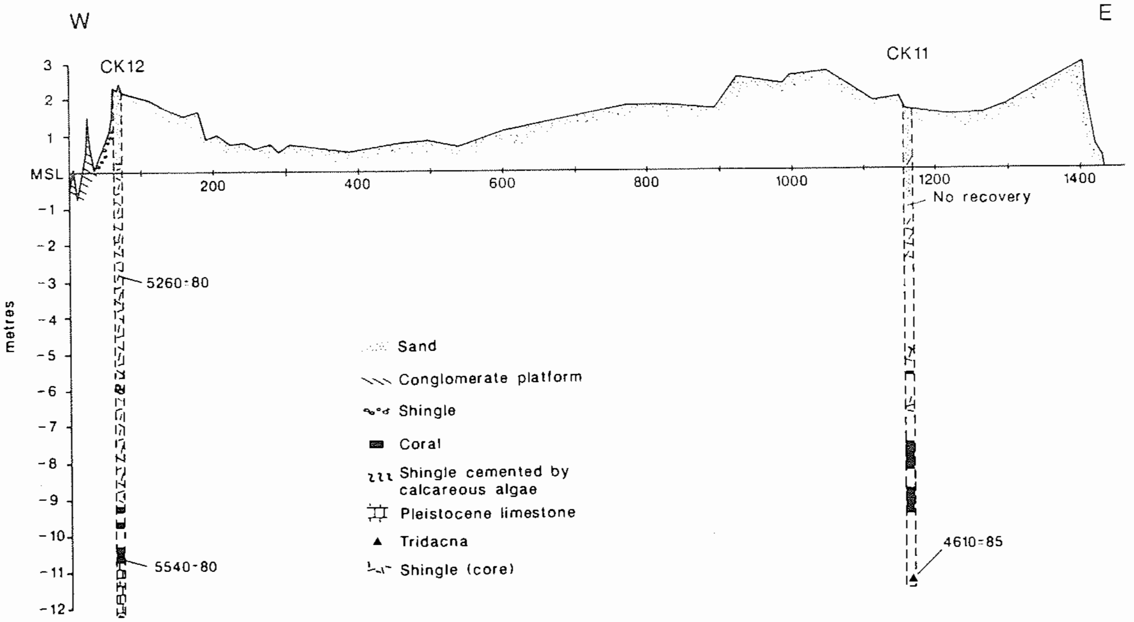

Figure 12. Transect X, Horsburgh Island (see Fig. 2 for location): stratigraphy and radiocarbon dates.

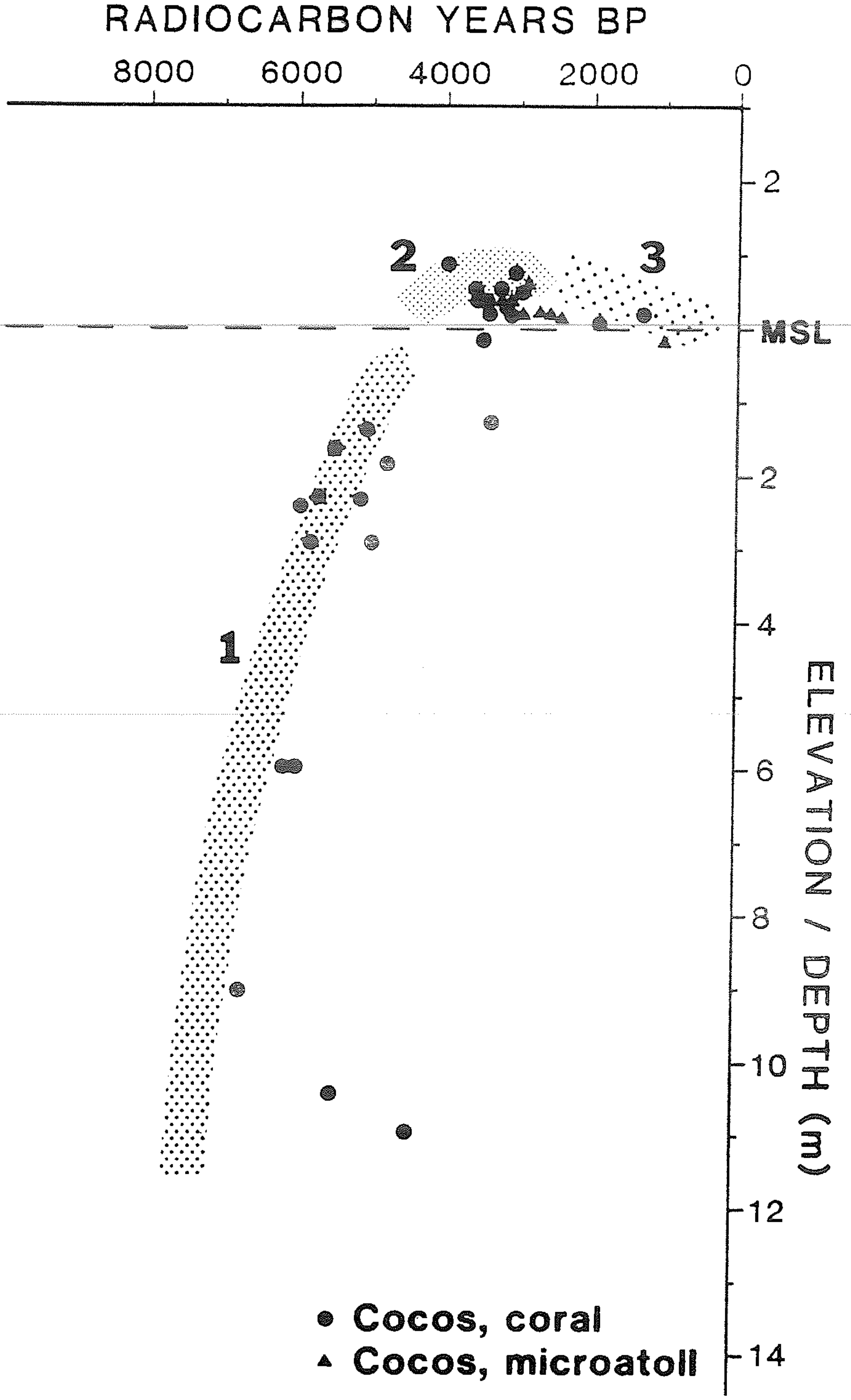

Figure 13. Age-depth plot of radiocarbon dates from Cocos, showing dates from drillholes (Table 3), from conglomerate platform (Table 2) and from fossil microatolls (Table 4). Three phases can be recognised: 1) catch-up reef growth, 2) reef flat consolidation, and 3) reef island formation. See text for details.

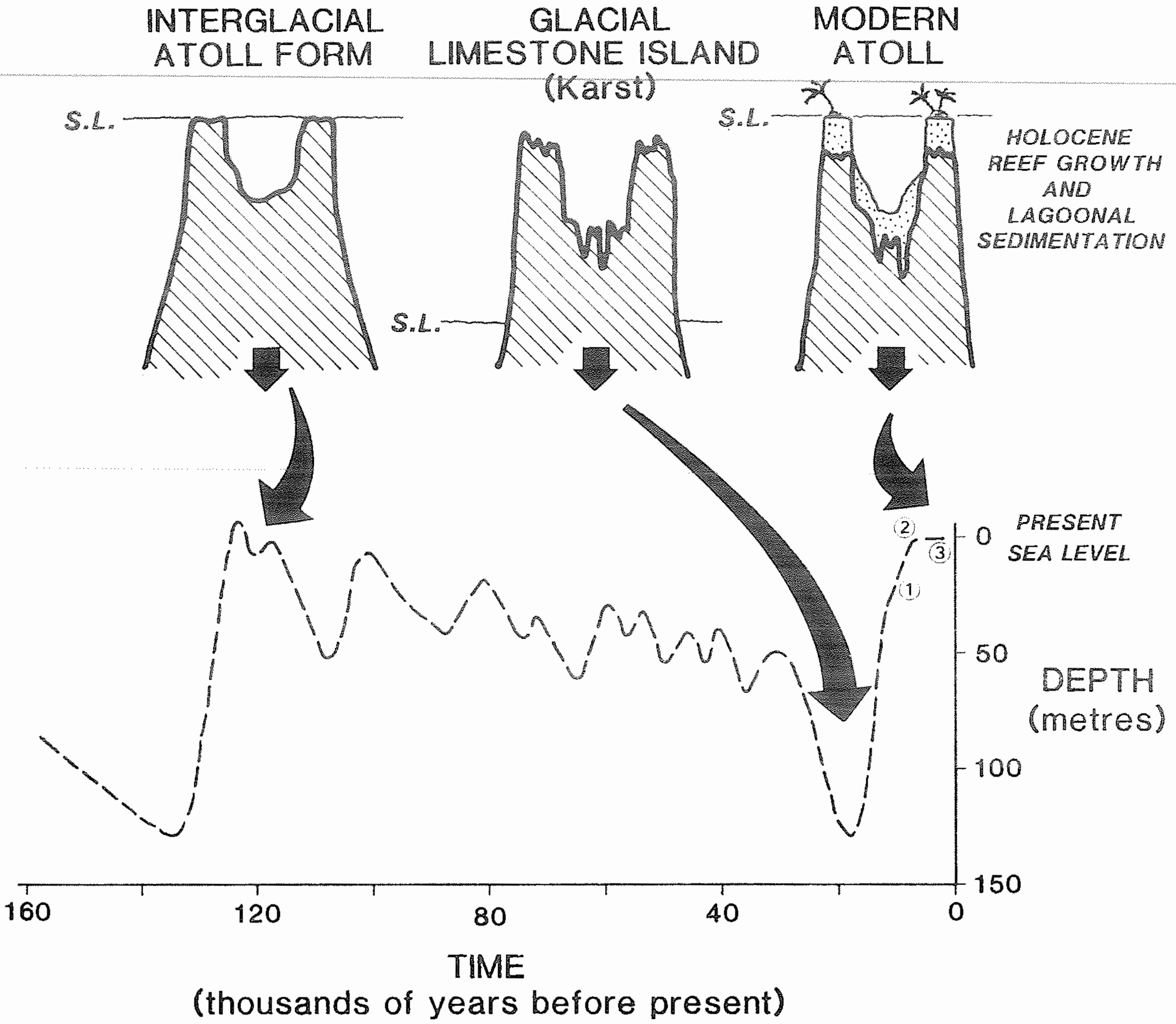

Figure 14. A model of the late Quaternary development of the Cocos (Keeling) Islands. The sea-level curve is derived from Chappell and Shackleton (1986). The atoll is gradually subsiding. The interglacial atoll surface is subject to solutional weathering particularly when the sea is low. During the postglacial marine transgression reefs have re-established over the pre-Holocene surface and the three phases of Holocene atoll development identified in Figure 13 can be recognised.