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SEA-LEVEL CHANGE AND THE ORIGIN OF SAND CAYS: RADIOMETRIC EVIDENCE

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1. Problematic features of reefs and islands

Sand cays are accumulations of reef-derived sediments standing on reef flats and rising above present sea level. During the first thirty years of this century, many students described features of such islands which they considered indicated a slight Recent fall in sea level. Gardiner (1903, 36) found a reef conglomerate at 2 m. elevation on Minikoi Atoll, which he thought indicated a fall in sea level of at least 7.3 m. 'Nearly every large coral island,' he concluded (1930, 13), 'gives evidence of a eustatic shift.... I do not think that any habitable coral islands would exist today were it not for this.' Gardiner finally estimated the sea level fall at 2.4-3 m. in the equatorial seas of the Indo-Pacific, but with wider fluctuations in higher latitudes and near continental land (1931, 35).

Steers (1929, 1931, 1937) subsequently described benches on the Queensland coast and conglomerate platforms on Great Barrier Reef islands, one awash at high water and a second 4.6-5.2 m. above low water or 3-3.3 m. above mean sea levels. In Indonesia, Kuenen (1933) found evidence for stillstands at 0.5-1, 1.5-2 and 4-5 m. above present sea level. Exposed conglomerate terraces have also been described from the Maldive Islands by Sewell (1928, 1935), at Funafuti by David and Sweet (1904, 70-71), and in the Marshall Islands (Emery, Tracey and Ladd 1954). Charles Darwin found 'breccia platforms' at Cocos-Keeling Atoll (1842, 11-12).

Such an inferred negative movement of the sea would expose not only islands and conglomerate platforms but surrounding reefs as well. Cloud (1952, 52-55) found an elevated and truncated *Heliopora* reef at Onotoa Atoll, Gilbert Islands, and referred it to a 1.5-1.8 m. stillstand; and Stearns (1945) described bare, eroding 'decadent' reef as evidence of a similar sea-level shift at Eniwetok Atoll, Marshall Islands. Evidence of this kind was summarised by Tayama after wide-ranging studies in the West Pacific (1952, 271):

> 'The so-called sea level coral reefs are not of Recent origin.... Most of the present reef-flats are abrasion surfaces, like pavements, displaying cross-sections of truncated reef-building corals, benches and mushroom rocks. The so-called Recent coral reefs are relicts of coral reefs of corals of the age of the Younger Raised Coral Reef Limestone. As Dr. H. Yabe has stated, the coral reefs, in the recent seas, are in process of destruction rather than of construction. The scope of the destruction, however, is limited to an area approximately 2 metres above low tide.'

Clearly, if such a negative sea-level shift did take place during the last few thousand years, it would have the effect of bringing deeper reefs to shallower levels, and of exposing others, thus providing ideal platforms for debris accumulation and island formation. Kuenen (1933, 70) concluded from his Indonesian work that

> 'very many and probably most islands have been formed as a result of the emergence of their flats. Without the negative movement the number of islands on reefs would be quite small and if no further movements occur their number and extent will in the course of time undergo considerable reduction.'

Kuenen (1933, 72 ; 1950, 449) clearly envisaged the early accumulation of debris to form islands on abnormally high flats, followed by the truncation of the high flat to seaward, the erosion of the seaward shores of the cay and gradual migration of the island lagoonward, and finally the establishment of a new low equilibrium reef flat level, when the island sediments are completely washed off the flat into the lagoon. In this scheme, therefore, reef islands are essentially temporary phenomena directly resulting from a Holocene fall in sea level.

Apparently confirmatory evidence of Holocene high sea level stands was obtained by Daly (1934) on many tropical and mid-latitude high islands and on continental coasts. In Samoa, at St. Helena, at Curacao and Cayman Brac, and in South Africa he found emerged benches at 4.9-6.1 m. above present sea level, which he referred to a 6 m. strandline of probably 'Late Neolithic' age (*c.* 3,500 a B.P.). The 2-2.5 m. bench found by Chubb (1930) in the Marquesas led him to doubt whether the movement was purely eustatic. As Fairbridge (1961) has commented, Daly's attempt to interpret these features in terms of a single Holocene level in fact confused many different features of different altitudes and ages.

2. Possible Holocene high stands of the sea

The development of ^{14}C dating techniques provided a means for reconstructing the course of the Flandrian (post-glacial) transgression. Controversy continues over the nature of the transgression, particularly during the last 5,000 a. Studies on the Gulf of Mexico coast indicate that the sea reached its present level between 5,000 and 3,000 B.P. (Le Blanc and Bernard 1954, Gould and McFarlan 1959): at this time, therefore, growth of corals at present low neap levels could begin, with accumulation of debris to form islands on the reef flats. The Gulf coast evidence suggests that no transgression above the present level has taken place since c. 6,000 B.P. Fairbridge (1958, 1961), on the other hand, using ^{14}C data from mainly tropical areas, argues that sea level has fluctuated from +4 to −4 m. between 6,000 and 1,000 B.P. His analysis calls for the following main transgressive stages, each preceded by lower levels :

Older Peron ..	3-4.6 m.	6,000-4,600 B.P.
Younger Peron ..	3	4,000-3,400
Abrolhos ..	1.5-1.8	2,600-2,100
Rottnest ..	0.6-0.9	1,600-1,000

Some of Fairbridge's levels could correlate with the terraces and benches of coral reefs and islands already described, and such a sequence of higher stands during the Holocene could account for (a) the widely developed abrasional surfaces of reef flats, and (b) for the formation of high platforms on which modern sand cays have accumulated.

The problem of sand cay origin is thus inseparable from that of Recent sea-level history. Were cays formed as a result of wave action on reef flats under conditions of stable sea level over the last 6,000 a, or as a result of abnormally high reef flat formation during Fairbridge's series of transgressions? Did cay formation begin when the Flandrian transgression reached present sea level close to 5,000 a ago, or did they only form during the relative sea level stability of the last 1,000 a? Is it possible that present reef flats are much older features, pre-dating the last low level of the sea, flooded by the Flandrian transgression, and forming platforms for sand cay formation, the detailed features of which have a much longer history than the Holocene?

3. Evidence of Holocene raised reefs

Since Fairbridge's review in 1961, many reef areas have been re-examined and samples of beach and reef sediments which appear elevated with respect to original depositional environment have been dated radiometrically. Table 1 lists ^{14}C dates reported from tropical areas for samples at or above present sea level, in the age-range 0-8,000 B.P. Dates for samples below present sea level are not included. More than seventy dates are recorded; Figure 1 shows the age distribution, with one-third in the interval 2,000-3,000 B.P. Most of the sample elevations are less than 2 m., except in the case of some Australian samples where elevations range up to 3.7 m. The concentration of dates brackets the Pelham Bay Regression and Abrolhos Transgression of Fairbridge (1961).

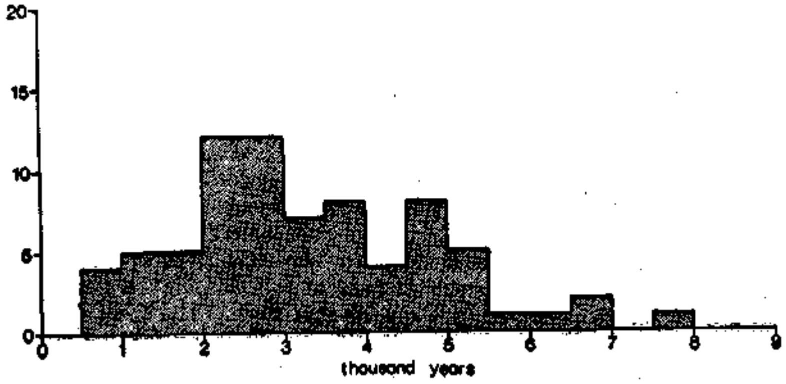

Fig. 1. Age-distribution of Holocene radiocarbon dates.

Great caution is required in the interpretation of an array of dates of this sort. Three main groups of problems need to be considered. First, problems of dating technique. Dates obtained prior to 1963 are mostly based on a half-life value for ^{14}C of 5,730 $\pm$ 40 yrs., and those after 1963 on a value of 5,570$\pm$30; dates quoted in this paper have been standardised to the latter figure. All the ages quoted are in 'radiocarbon years' which do not bear a simple relationship to sidereal years: an approximate conversion can be made (Stuiver and Suess 1966), but this has not been done here. Sample contamination can also lead to considerable errors in dating (Olson and Broecker 1958), and these are often only recognised when the date is inconsistent with geological evidence or dates obtained by other methods. There are also other problems inherent in the technique which cannot be considered here.

TABLE 1

Holocene radiocarbon dates for samples above present sea-level

Sample number	Location	Elevation, m. and datum if known	Age B.P.	Reference
TUAMOTU ISLANDS				
	Mururoa	1	2920±200	Lalou *et al.* 1966
Gif 634	Mururoa	0.8	3020±200	Delibrias *et al.* 1969
Gif 629	Mururoa	3	3610±200	Delibrias *et al.* 1969
LJ 1372	Rangiroa	0	4900±300	Hubbs and Bien 1967
L 258A	Raroia	0	*2760±93	Broecker *et al.* 1956
SOCIETY ISLANDS				
LJ 1371	Moorea	0.2-0.5 LT	2730±200	Hubbs and Bien 1967
LJ 1369	Bora Bora	0.5 MLT	3400±200	Hubbs and Bien 1967
LJ 1370	Bora Bora	0.5 MLT	3700±500	Hubbs and Bien 1967
	Bora Bora	0.8-1	2250±130	Guilcher *et al.* 1969
	Mopelia	0.8	3450±130	Guilcher *et al.* 1969
HAWAIIAN ISLANDS				
LJ 570	Oahu	1.5	†7540±300	Hubbs *et al.* 1965
	Midway	0.5	1230±250	Gross *et al.* 1969
	Midway		2420±300	Gross *et al.* 1969
	Midway		2090±200	Gross *et al.* 1969
	Midway		2180±250	Gross *et al.* 1969
	Kure	0.5	1480±250	Gross *et al.* 1969
COOK ISLANDS				
	Rarotonga	1 LT	2030	Wood 1967
MARSHALL ISLANDS				
I 2811	Ailinglapalap	1	2660±100	Buckley and Willis 1969
I 2823	Ailinglapalap	1-1.3	2785±100	Buckley and Willis 1969
I 2814	Lukunor	0.5	1880±100	Buckley and Willis 1969
I 2817	Ebon	1.5	2580±100	Buckley and Willis 1969
I 2818	Ebon		2920±100	Buckley and Willis 1969
I 2811	Ebon		2830±100	Buckley and Willis 1969
I 2825	Ebon	0	3450±105	Buckley and Willis 1969
I 2820	Jaluit		4475±105	Buckley and Willis 1969
I 2821	Jaluit		2730±105	Buckley and Willis 1969
I 2822	Jaluit		2290± 95	Buckley and Willis 1969
CAROLINE ISLANDS				
I 2812	Trunk	0.5	2880±100	Buckley and Willis 1969
I 2813	Truka	0	2050± 95	Buckley and Willis 1969
I 2815	Pingelp	0.6	4350±110	Buckley and Willis 1969
I 2816	Kusai	1.3	3250±105	Buckley and Willis 1969
W 1842	Ifaluk	0.6	2140±200	Marsters *et al.* 1969
SAMOA				
NZ 278	Upolu	1.5	1180±55	Grant-Taylor *et al.* 1963
NZ 374	Gataivai	4.6	760±50	Grant-Taylor *et al.* 1963
NZ 375	Gataivai		715±50	Grant-Taylor *et al.* 1963
NZ 376	Puapua	1.5	1850±80	Grant-Taylor *et al.* 1963
WEST PACIFIC				
W 370	Guam, Facpi Pt.	0.9-1.2	*3502±258	Rubin and Alexander 1958
UCLA 194	New Caledonia, Tuoho	0	4900±200	Fergusson and Libby 1963
ANU 165	New Guinea, Huon	3	6700±60	Veeh and Chappell 1970
ANU 153	New Guinea, Huon	5	6800±100	Veeh and Chappell 1970
I 2515	Sabah, Klias Pen.	1.8	4400±110	Buckley and Willis 1969
I 2487	Sabah, Klias Pen.	1.8	4790±115	Buckley and Willis 1969
MC 1, 2	Viet Nam, Ca Na	3.5	4500±250	Thommeret and Rapaire 1964

TABLE 1—*contd.*

Holocene radiocarbon dates for samples above present sea-level—contd.

Sample number	Location	Elevation, m. and datum if known	Age B.P.	Reference
AUSTRALIA : QUEENSLAND				
GaK 1543	Eclipse Ils.	2.4	4100±90	Hopley in Gill 1968
GaK 1545	Curacoa Il.	1.8	5070±110	Hopley in Gill 1968
GaK 1546	Curacoa Il.	1.8	5250±100	Hopley in Gill 1968
GaK 1546	Curacoa Il.		2620±90	Hopley in Gill 1968
LJ 949	Deception Bay	3.0-3.7	1000±140	Hubbs *et al.* 1965
LJ 950	Facing Il.	HT	1500±160	Hubbs *et al.* 1965
LJ 951	Deception Bay	2.4-3.0	1510±170	Hubbs *et al.* 1965
NZ 280	Byrones Creek	2.7	3720±85	Grant *et al.* 1963
W 443	Moreton Bay	3	*3821±258	Rubin and Alexander 1958
NZ 195	Babinda		6270±120	Dury 1964
GXO 305	Karumba	6.1	3320±125	Dury 1966
AUSTRALIA : NEW SOUTH WALES AND VICTORIA				
LJ 451	Long Reef	0.3 HT	3980±150	Hubbs *et al.* 1963
LJ 128	Long Reef	3.6 HT	* 927±155	Hubbs *et al.* 1960
LJ 130	Long Reef	3.6 HT	* 927±155	Hubbs *et al.* 1960
W 170	Essendon	3	*4965±206	Rubin and Suess 1955
WEST AUSTRALIA				
ORINS 16	Shark Bay	0.3-0.6 MSL	4860±235	Noakes *et al.* 1967
ORINS 39	Shark Bay	1.5	3910±200	Noakes *et al.* 1967
ORINS 41	Shark Bay	supratidal	5040±165	Noakes *et al.* 1967
Y 324	Point Peron	4.9 LT	*5274±134	Deevey *et al.* 1959
Y 337	Rottnest	4.6 LT	*3924±93	Deevey *et al.* 1959
NZ 515	Nickol Bay	0.6	2080±80	Dury and Smith 1968
INDIAN OCEAN				
LJ 207	Ceylon, Hokkaidu	0.9 LT	*3080±227	Hubbs *et al.* 1962
	S. Madagascar	1.1-1.4	*2317±433	Battistini 1963
	Red Sea, Aqaba	0	4770±140	Friedman 1965
BAHAMAS				
W 330	Andros	0.4-0.6	*1725±206	Rubin and Alexander 1958
W 453	Andros	0.4-0.6	*1056±412	Rubin and Alexander 1958
L 418D	Andros	0.6	*2400±103	Olson and Broecker 1959
L 321A	North Bimini	1.8 HT	*2369±206	Broecker and Kulp 1957
GULF OF MEXICO				
Tx 154	Laguna Madre	2.4	2340±100	Pearson *et al.* 1965
BRAZIL				
LJ 970	Rio de Janeiro	4.8 MSL	4800±250	Hubbs *et al.* 1965
LJ 1364	Rio de Janeiro	4.8 MSL	5200±400	Hubbs and Bien 1967
LJ 1367	Recife	MLW	5900±300	Hubbs and Bien 1967
I 695	Paranaguia Bay	0.8	2675±150	Trautman and Willis 1966

*Published date based on half-life of 5730± 40 a ; multiplied by 1.03 to correspond to a half-life of 5570± 30 a, on which all other dates quoted are based.

†Date inconsistent with other dates : reject according to reference.

LT—Low Tide

MLT—Mean Low Tide

MSL—Mean Sea Level

HT—High Tide.

Second, the absolute altitude of samples dated is often difficult to determine with precision from the published record. The quoted altitude is often estimated, and is usually not referred to a precise datum. In almost all cases no indication is given of tidal range which will clearly affect the significance of heights referred to any particular sea-level datum. Differences in wave intensity can also affect the heights of beach ridges formed at any given sea-level, as Lind (1969) has shown for depositional sequences on windward and leeward coasts in the Bahamas. Direct comparisons of elevations in Table 1 are therefore open to wide error.

Third, if inferences are to be drawn regarding Holocene sea-levels from these data, it is essential that the deposits dated can be referred to a particular sea-level position at the time of their formation. In the case of reef deposits, for example, reef corals need to be shown to be in the position of growth rather than storm rubble deposits. Because of the diversity of reef fabrics this is by no means simple. Thus Guilcher *et al.* (1969) believe raised reefs at Mururoa Atoll to be in the position of growth ; ledges at similar elevations in Micronesia are thought to be rubble deposits resulting from storm action by Shepard *et al.* (1967), and a similar conclusion has been reached for platforms on Aitutaki, Cook Islands, by Stoddart (in litt.). In the case of coastal platforms it is important to establish that the samples dated are contemporary with the feature from which they are taken and are not adventitious, as is suspected for certain Australian samples used in terrace dating (Shepard 1961).

On the evidence in Table 1 it is difficult to demonstrate whether or not Holocene sea-levels have been higher than the present. Certainly it is difficult to ignore the absence of transgressive marine sediments of Holocene age in the Gulf coast and Florida, and the evidence of Australian freshwater peats against such a transgression (Thom, Hails and Martin 1969). Conversely, if, as Fairbridge believes, the sea reached its present level at 6,000 B.P., or even, as the Florida data indicate, since 3,500 B.P. (Scholl, Craighead and Stuiver 1969), it is surprising that supposedly storm deposits are so clearly clustered between 2,000 and 3,000 B.P. This concentration must either indicate that storms were particularly active at that time, or that sea-level was indeed marginally higher than now. If sea-level were higher, then a sequence of cay development similar to that outlined by Kuenen could be taking place, and the oldest cays might be only 3,000 a. old. It is, however, possible that the platforms on which they stand are much older, and that accumulation began as soon as the sea reached its present level, as much as 5-6,000 a. ago.

4. Interstadial and Interglacial sea-levels

We must therefore consider dating evidence for older stillstands of the sea at or slightly above present sea-level, at which reefs could have formed such platforms. Milliman and Emery (1968) have used ^{14}C dates to define a curve for the last major regression, from a stand close to present sea-level at 30,000-35,000 B.P., to—130 m. at 14,000 B.P., followed by the Holocene transgression already discussed. Their curve was based on 38 dates for the period before 8,000 B.P. Table 2 lists 43 dates for reef and other tropical areas, for samples at or slightly above present sea-level, in the age range 8,000-45,000 B.P. Figure 2 shows that half of these dates lie in the interval 25,000-35,000 B.P. Great caution is needed in accepting dates in this age range because of the probability of contamination : where uranium-series dates are also available for ^{14}C-dated samples (e.g. L 423B from Eniwetok), the discrepancies may be considerable. Shepard (1963) was inclined to seek a local rather than a eustatic explanation for samples from the Hawaiian Islands at heights of 1.5 to 3.7 m.

dating at 14,000-32,000 yr. Guilcher (1969) considers this interstadial stand a possibility, but no more.

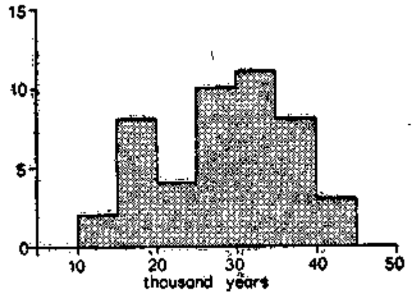

Fig. 2. Age-distribution of radiocarbon dates for samples at or above present sea-level 10,000-45,000 a B.P.

More data are available from tropical and sub-tropical areas as a result of the development of uranium-series and other radiometric dating methods, which extend the range of absolute dating to more than 5,00,000 yr. It is, however, difficult to compile a table of dates so far reported: in some cases different dates and even different analytical results have been given in different papers for what appear to be the same samples, and, more seriously, in few papers are the dated samples unambiguously identified by laboratory numbers. The main series of dates reported are as follows:

Tuamotu Islands	..	Lalou *et al.* 1966.
Central Pacific Islands	..	Veeh 1965, 1966.
Indian Ocean	..	Veeh 1965, 1966.
Mediterranean coasts	..	Stearns and Thurber 1965, 1967.
Bahamas	..	Broecker and Thurber 1965.
Barbados	..	Broecker *et al.* 1968; Ku 1968; Mesolella *et al.* 1969.
Florida	..	Broecker and Thurber 1965; Ormond *et al.* 1965.
California coast	..	Veeh and Valentine 1967; Valentine and Veeh 1969; Bradley and Addicott 1968; Szabo and Rosholt 1969.
New Guinea	..	Veeh and Chappell 1970.

Several of these dates are for samples from features, particularly raised coral reefs in the Pacific and Indian Oceans, formerly referred to Daly's Holocene high stand of the sea, and which are thus shown to be much older than Daly supposed. Figure 3 shows the age-distribution of the dates so far reported, with a major concentration between 70,000 and 1,80,000 a B.P. and a lesser concentration between 1,90,000 and 2,40,000 a B.P. The first of these concentrations may broadly correspond to the last interglacial (Emian). Approximately one-third of the dates fall between 1,00,000 and 1,30,000 a. Dates for samples from close to present sea-level, or in cases where active tectonic uplift can be allowed for, indicate sea-levels in the age ranges quoted of between 0 and +10 m. Several workers have claimed to identify clusterings of dates referable to particular sea-levels within the range covered by the dates. Thus Emiliani and Rona (1969) identify sea-level stands at 81, 100, 122, 147, 173, 211 and 235×10^3 a; and Veeh and Chappell (1970) relatively high sea-levels at 35-50, 74, 118-140, and $180\text{-}190\times10^3$ a B.P.

TABLE 2

Radiocarbon dates 10,000–45,000 a B.P. from reef areas

Sample number	Location	Elevation, m and datum if known	Age B.P.	Reference
TUAMOTU ISLANDS				
Gif 637	Mururoa	−7	17300±800	Delibrias *et al.* 1969
HAWAIIAN ISLANDS				
LJ 205	Oahu	+1.5	*29046±1300	Hubbs *et al.* 1962
LJ 206	Oahu	+3.7	*18612±463	Hubbs *et al.* 1962
LJ 253	Oahu	+1.5	*24864±824	Hubbs *et al.* 1962
LJ 254	Oahu	+3.7	*32486±1339	Hubbs *et al.* 1962
LJ 322	Oahu	+1.5	*27439±1133	Hubbs *et al.* 1962
LJ 323	Oahu	+3.7	*32795±1030	Hubbs *et al.* 1962
LJ 899	Oahu	+3.5	18000±600	Hubbs *et al.* 1965
LJ 948	Oahu	+1.5LT	39100±1500	Hubbs *et al.* 1965
LJ 573	Kauai	−18	8370±250	Hubbs *et al.* 1965
LJ 916	Kauai	+0.9 to −1.8	15000±600	Hubbs *et al.* 1965
MARSHALL ISLANDS				
L 482E	Eniwetok	−19.5 to −21	*33990±1545	Olson and Broecker 1961
L 423B	Eniwetok	−10.4 to −11	*24205±103	Olson and Broecker 1959
WEST PACIFIC				
MC 4	Vietnam	+15	18500±250	Thommeret and Rapaire 1964
I 3179	Solomon Ils.	+4.6	33200+2400 −1900	Stoddart 1969*a*
ANU 103	New Guinea, Huon		43000+2500 −1000	Polach *et al.* 1969
ANU 107	New Guinea, Huon	+110	39130+1840 −1500	Polach *et al.* 1969
ANU 113	New Guinea, Huon	+135	30150±800	Polach *et al.* 1969
ANU 116	New Guinea, Huon	+42	35770+1620 −1350	Polach *et al.* 1969
ANU 117	New Guinea, Huon	+42	35350+1420 −1210	Polach *et al.* 1969
ANU 150	New Guinea, Huon	+75	30900±920	Polach *et al.* 1969
ANU 156	New Guinea, Huon	+23	29265±780	Polach *et al.* 1969
ANU 160	New Guinea, Huon	+20	28475±570	Polach *et al.* 1969
ANU 162	New Guinea, Huon	+85	33010±1320 1140	Polach *et al.* 1969
ANU 163	New Guinea, Huon	+145	40350+1520 −1280	Polach *et al.* 1969
WEST AUSTRALIA				
ORINS 21	Shark Bay	+3MSL	15980±230	Noakes *et al.* 1967
ORINS 32	Shark Bay	+4.6 to +6.1	32640±300	Noakes *et al.* 1967
ORINS 40	Shark Bay	+0.9 to +1.5	28850±400	Noakes *et al.* 1967
ORINS 78	Dirk Hartog I.	+4.6 to +6.1	36888±2750	Noakes *et al.* 1968
ORINS 80	Dirk Hartog I.	+3	27861±630	Noakes *et al.* 1968
INDIAN OCEAN				
Y 419	Red Sea, Abulat	+10	*25471±2575	Deevey *et al.* 1959
A 359	Red Sea, Dahlak	+6	17200±330	Damon *et al.* 1963
A 447	Red Sea, Entdebir	+7	28000±600	Haynes *et al.* 1966
A 448	Red Sea, Entdebir	+12	16400±150	Haynes *et al.* 1966

TABLE 2—*contd.*

Radiocarbon dates 10,000–45,000 *a B.P. from reef areas*—contd.

Sample number	Location	Elevation, m and datum if known	Age B.P.	Reference
INDIAN OCEAN—*contd.*				
I 3840	Aldabra	+2	38800+3700 −2800	Stoddart *et al.* 1970
I 3841	Aldabra	+2	37000+2900 −2200	Stoddart *et al.* 1970
I 3842	Aldabra	+2	34900±2200 1800	Stoddart *et al.* 1970
I 4431	Aldabra	+2	26950±900	Stoddart *et al.* 1970
I 4433	Aldabra	+2	34300±1900	Stoddart *et al.* 1970
I 4435	Aldabra	+2	28700±950	Stoddart *et al.* 1970
GULF OF MEXICO				
Tx 155	Laguna Madre	+1	35200+2400 −1800	Pearson *et al.* 1965
Tx 156	Laguna Madre	0	24900±700	Pearson *et al.* 1965
CARIBBEAN SEA				
GrN 2651	St Eustatius		22400±100	Vogel and Waterbolk 1964
GrN 2656	St Eustatius		32960±300	Vogel and Waterbolk 1964
GrN 2653	St Kitts		44720±1150	Vogel and Waterbolk 1964
SOUTH AMERICA				
GRO 462	Guyana	−103	*12530±360	De Vries and Waterbolk 1958
GRO 473	Guyana	−135	*11907±247	De Vries and Waterbolk 1958

*Published date based on half-life of 5730±40a ; multiplied by 1.03 to correspond to a half-life of 5570±30a, on which all other dates quoted are based.
LT—Low Tide.
MSL—Mean Sea-Level.

TABLE 3

Radiocarbon dates from Coral Islands

Sample number	Location	Description	Age B.P.	Reference
L 258B	Raroia	Soil, depth 1.2-1.5 m	*927±134	Broecker *et al.* 1956
L 258C	Raroia	Coral, depth 1.2-1.5 m	*1792±237	Broecker *et al.* 1956
W 764	Utirik	Black loam, top 0.33m	*Less than 200	Rubin and Alexander 1960
W 763	Utirik	Sand, depth 0.46-1.22 m	*3368±206	Rubin and Alexander 1960
	Heron Island	Soil samples	Not datable	Wolf and Ostlund 1967
ML 83	Green Cay Bahamas	Beach sand	1890±60	Ostlund *et al.* 1965
LJ 975	Isla Cancun Yucatan	Beach sand	2580±130	Hubbs *et al.* 1965
LJ 976	Isla Cancun Yucatan	Beach sand	2080±150	Hubbs *et al.* 1965

*Published date based on half-life of 5730±40 a ; multiplied by 1.03 to correspond to a half-life of 5570±30 a, on which all other dates quoted are based.

Whether one or several distinct stillstands of the sea can be identified in the last quarter million years, the evidence suggests a prolonged period of stillstand

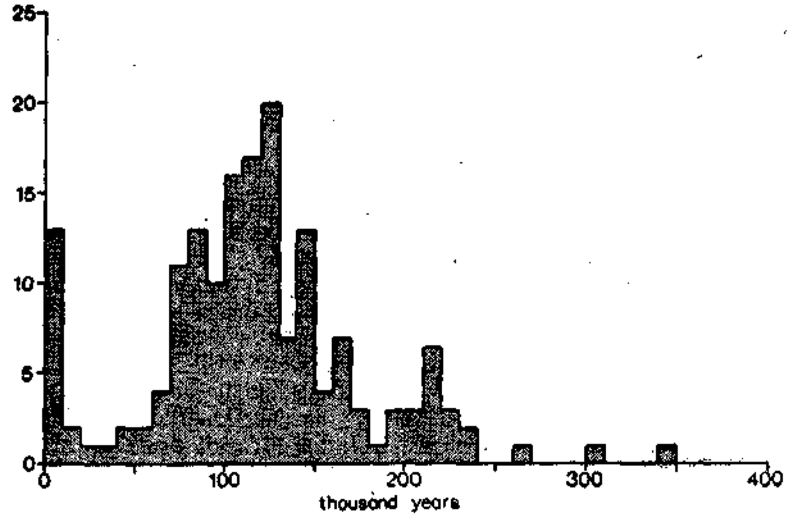

Fig. 3. Age-distribution of uranium-series dates.

close to present sea-level, when reef building could take place over a time span up to an order of magnitude greater than the time span available for reef growth in the Holocene. From our knowledge of the relative rates of reef growth and reef-limestone erosion, it is likely that many major features of modern reefs, including reef flats, were built in this period and only slightly modified during the last glacial low sea-level stand (Stoddart 1969b).

5. Evidence from reef islands

By contrast with the multiplicity of dates from raised reefs and coastal benches, very few indeed are available from sand cays and reef islands. The few dates either for humic soil horizons or for beach sands recorded in Table 3 indicate only that the sediments dated are less than 3,500 a old. The dates give no real indication either of a Holocene transgression or of Holocene sea-level stability. Suites of specimens were collected from both rubble terraces and sand cays in the Cook Islands in 1969 to determine more precisely the relationship between reef and coral cay formation, but results from this study are not yet available.

It is thus not yet possible to determine precisely the date of origin of modern reef islands ; nor is it possible to reach firm conclusions on sea-level behaviour in the critical period 6,000-3,000 B.P. Geomorphic evidence from the islands themselves, however, may indicate the direction of contemporary sea-level changes. The contemporary rise in sea-level has been demonstrated by tide gauge data, and is apparently the result of climatic amelioration (Fairbridge 1961, 102-105). Gutenberg (1941) found evidence of a eustatic rise in sea-level of 0.12 m. over 1880-1930, and Kuenen (1950) of 0.12-0.14 m. over 1832-1942. Fairbridge and Krebs (1962) suggest a total eustatic rise from 1900-1950 of 0.06 m., an average rate of 1.2 mm. yr^{-1}. The rise has in fact been irregular, reaching 5.5 mm. yr^{-1} in the decade 1946-1956, This documented small rise in sea-level correlates with widespread evidence of the erosion and retreat of seaward shores of sand cays in modern times. This is shown by shore cliffing, truncated vegetation patterns, relict beach rock on seaward reef flats, and historical evidence, and appears to be universal in the reef seas (Stoddart 1962, 109-111). Schwartz (1967) has recently suggested the present rise in sea level as a cause of beach erosion on continental coasts. It should be noted that much of the evidence of geomorphic change relating to this sea-level rise is identical to the evidence formerly used by Kuenen and others to explain the adjustment of sand cays and reefs to a sea level fall.

Thus in spite of the amount of radiometric data reviewed in this paper, considerable ambiguities remain, both regarding the origin of sand cays and also the interpretation of their specific geomorphic features. In conclusion, it may be suggested that attention be focussed on coral reefs developed close to continental land, where the record of the reefs and islands themselves may conveniently be related to the transgressive sequences of major river valleys and deltaic plains. Continental coasts are, however, often devoid of reefs even in the reef seas, as in the case of the Queensland coast. Attention could particularly be concentrated, in the Indian Ocean, on the reef sequences of the East African coast, and on the reefs and fluvial deposits of Gujarat and Mandapam in India, some of which are already under study.

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