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Sea-Level Changes over the Past 1,000 Years in the Pacific[1]

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ABSTRACT

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The absence of good information about sea-level change for the past 1,000 years in the Pacific is unfortunate given our much clearer understanding of the earlier Holocene and the past ~ 100 years. Yet such information is needed if we are to be able to properly understand the causes of late Neogene sea-level changes and to understand the environmental effects of predicted future changes.

Data are selected from sites in American Samoa, Fiji, the Gambier Islands, Guam, Kosrae, New Zealand, Rota and the Tuamotus which have been tectonically stable for the past thousand years. These data are plotted and a sea-level envelope drawn to characterise the most probable Pacific-wide course of sea-level change for the last millennium.

Sea level was close to its present level ~ 1000 years BP, then rose to perhaps 0.9 m above around 700 BP. This period of sea-level rise coincided with a period of warming named the Little Climatic Optimum. The transition to the Little Ice Age, when sea level stood lower, was marked by a transition around 690 BP when sea level (and ground temperatures) fell rapidly. A lack of data from the following ~ 200 years suggest that sea level was lower than the level to which it rose during the early part of the Little Ice Age. A gradual fall occurred during the later part of the Little Ice Age to as much as −0.9 m below present some 200 BP. The last part of the millennium has been characterised by a net rise of sea level. Several anomalous dates from the sites examined are most probably explicable by post-emergence contamination of reef limestones.

ADDITIONAL INDEX WORDS: *Pacific islands, last millennium, Little Climatic Optimum, Little Ice Age, anomalous dates.*

INTRODUCTION

It is somewhat ironic that our knowledge of sea-level variations over the past few thousand years, perhaps even during the latest Neogene (late Quaternary), is better known than those which occurred over the past 1,000 years. Admittedly, the latter changes were of much less magnitude than the former, but it is also an issue of precision. Latest Neogene sea-level changes can be known only comparatively imprecisely and there are often disputes involving several thousand years (or several metres) about particular events. This is obviously not possible with a single 1,000-year period; many of the techniques used to establish earlier palaeosea-level changes can not be used with such great effect for the last millennium.

Yet it is doubly ironic to consider that the last 100 years, for which there are comparatively large numbers of continually-monitored series of sea-level data, is also better known than the preceding 900 years. The existence of this "1,000-year hiatus" in our understanding of past sea-level changes is a major hindrance for only by successfully linking the distant to the recent past can we properly hope to understand how sea level might change in the future.

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There are other reasons for studying sea-level changes over the past millennium. One is that the study of their environmental effects will aid accurate prediction of the consequences of future sea-level rise. Another is that an understanding of last millennium sea levels allows insights into why environments changed. Further, the close relationship between changing sea levels and changing earth surface temperatures over many time scales means that the record of changing sea levels over the last millennium can be used as a proxy for contemporary temperature changes which, in turn, permits insights into climate changes.

This paper looks at sea-level changes over the past 1000 years in the Pacific islands, then looks at the environmental consequences of these and associated changes before going on to discuss future changes.

THE HOLOCENE CONTEXT

It is now reasonably well established that all Pacific island coasts experienced inundation associated with a sea level 1–2 m higher than present around 4000–2000 years BP (NUNN, 1995). It seems increasingly possible, both from interpretations of empirical data and from theoretical considerations, that Holocene sea level has oscillated for the past few thousand years (FAIRBRIDGE, 1992; NUNN, 1995).

In some places, such as French Polynesia (PIRAZZOLI and

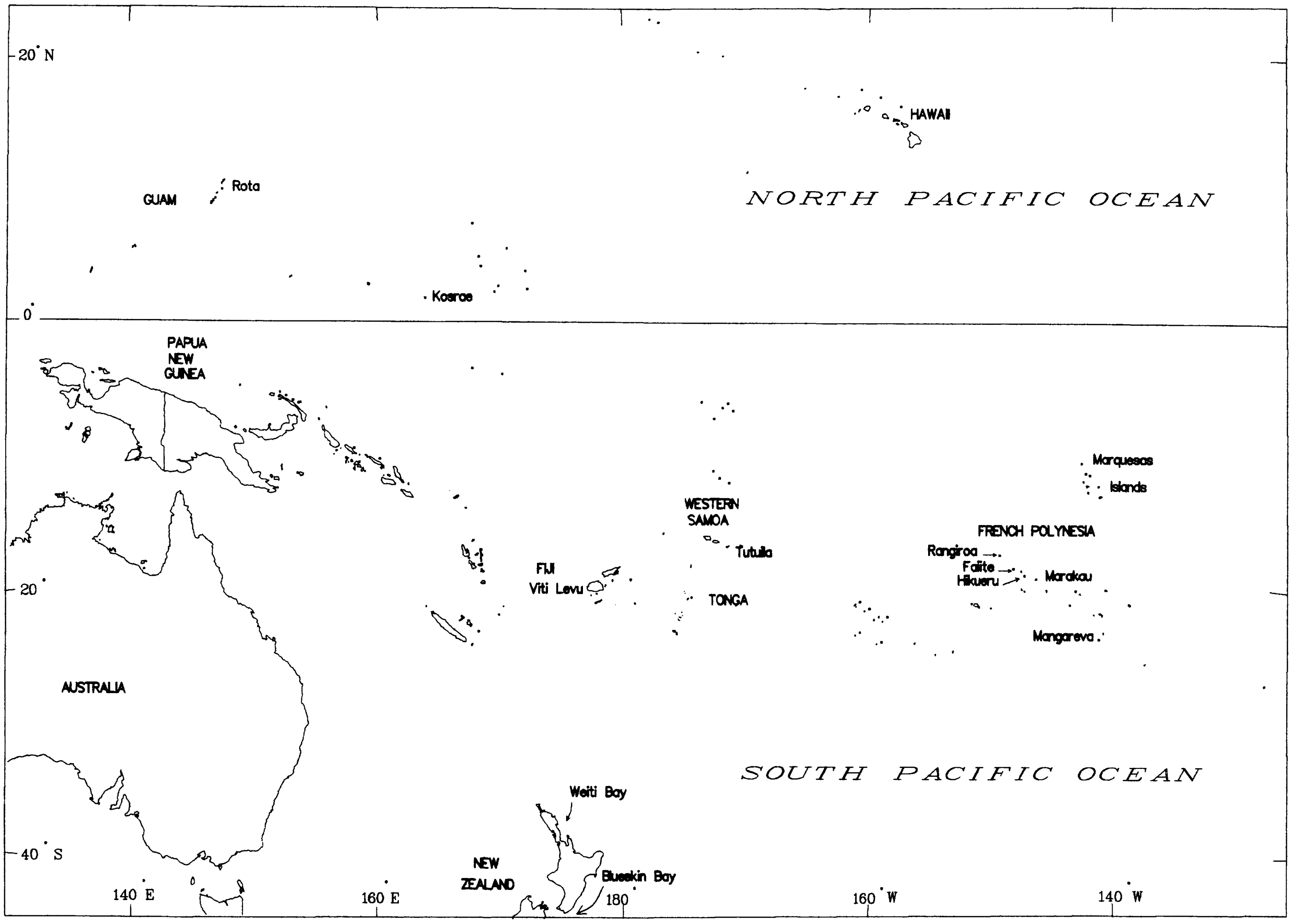

Figure 1. The Pacific islands showing the sites from which dates of emerged shorelines have been used to construct the curve of sea-level changes for the past 1,000 years. No error margins are shown.

MONTAGGIONI, 1986), the fall to the present general level within the last 2,000 years occurred comparatively abruptly compared to the fall in other places, such as Fiji and elsewhere (NUNN, 1990a), which apparently occurred more gently.

In most parts of the Pacific, the sea surface was probably at or close to its present level about 1200–900 years BP. Most records show little variation since that time.

THE LAST MILLENNIUM: FINDING SUITABLE SITES

Many Pacific islands are sites of dramatic, often sporadic, tectonic change which has complicated the derivation of late Neogene sea-level change records (NUNN, 1994a). Yet other islands, commonly in intraplate rather than plate-boundary locations, are believed to have been stable at least for much of the last few thousand years. Their shorelines can then be considered to have registered Holocene eustatic changes rather than these confused with tectonic changes; this was one reason why DALY chose to work on Pacific (and other) mid-ocean islands such as those in Samoa (DALY, 1920, 1924, 1934).

Another major problem is not so much finding suitable sites but finding suitable sites for which some dates of shoreline displacement over the past 1,000 years have been obtained. No studies in the Pacific islands to the author's knowledge have focused primarily on the last 1,000 years. Dates from this time period have been incidental to studies focusing on the earlier Holocene.

The locations of the "stable" sites selected for this study are shown in Figure 1. Each site is discussed briefly below and the case for its tectonic stability over the last 1000 years presented.

American Samoa

The Samoa islands form a somewhat atypical hotspot island chain. Hotspot volcanism is overprinted on a few islands by anomalous yet superficial volcanism associated with the tearing of the westward-moving Pacific Plate as it has been simultaneously pulled down into the trench at the northern end of the Tonga Trench (NATLAND and TURNER, 1985; KEATING, 1992; NUNN, 1997). Shorelines dating to a Holocene sea-level maximum around 1.5 m above present are found around the coasts of the islands in Western Samoa (NUNN, 1991a) and have been observed in parts of American Samoa (DALY, 1924; KIRCH *et al.,* 1990). This is good evidence that these islands have been comparatively stable over the past few thousand years.

The idea that the Samoa islands have been subsiding rapidly over this time period arose from a misinterpretation of the only Lapita site in the islands at Mulifanua on Upolu (NUNN, 1995). There is no evidence to suggest that significant subsidence has occurred here although dates from mangrove peats have been used here, as elsewhere, to support such a view (BLOOM, 1980). Mangrove peat dates can only be regarded as indicating minimum sea-level position because of the likelihood that such deposits have become more compact and subsided since they formed.

Recent investigations by the writer on Tutuila found emerged *in situ* reef at several locations. The most conspicuous of these is that in Vatia Bay, first reported by DALY (1924), which reaches 3.2 m above modern reef level. Like a similar block at nearby Afono, this reef has yielded only very young dates, the interpretation of which is discussed further below. A lower emerged reef, dated securely to the last millennium, is found near the western extremity of Tutuila about 0.5 km west of Poloa.

Fiji

The tectonic character of Fiji's islands was outlined by NUNN (1990a, 1991b). Many islands are rising or subsiding at rates which probably render suspect any attempt to discern eustatic changes over the past 1,000 years. One of the few places where there appears to be a reasonable chance of stability is the north coast of the largest island, Viti Levu, where large mangrove-filled deltas and an uncommonly complex pattern of offshore reefs also suggest late Holocene stability. Emerged notches around headlands and emerged beachrock at Natunuku are at levels consonant with the mid-Holocene sea-level maximum derived for Fiji and found elsewhere in the region.

Two pieces of emerged reef, representing a maximum 3 m of emergence, are found on the offshore reef named Sucutolu, described by RODDA (1990). Like the dates from Vatia and Afono on Tutuila (see above), those from Sucutolu are surprisingly young and are discussed further below.

Gambier Islands (French Polynesia)

The intraplate Gambier Islands form an "almost-atoll" around Mangareva. They formed 7.2–5.2 Ma (BROUSSE *et al.,* 1972) and are probably part of a hotspot trace which includes Pitcairn and Moruroa (Mururoa) islands (DUNCAN and CLAGUE, 1985). There is no reason why they should have been affected by significant tectonism during the latest Neogene. Evidence for a mid-Holocene sea-level maximum is widespread; the only record of emergence within the last 1,000 years is on the *motu* (sand island) named Tarauru Roa on the northeast barrier reef (PIRAZZOLI and MONTAGGIONI, 1987).

Guam

Guam is a large island in the northwest Pacific lying close to the convergent plate boundary in the region. No volcanism has occurred since the early Neogene (middle Miocene) but uplift associated with forearc deformation occurred within the later Neogene. The record of mid-Holocene sea levels from Aga Point suggests that late Holocene tectonism has been minimal at this site and that the two dates from the last millennium can be considered reasonable indicators of the contemporary reef surface (KAYANNE *et al.*, 1988). These dates are considered minima because it cannot be demonstrated that the contemporary reefs had reached their maximum level (relative to sea level) or were a little below it.

Kosrae, Caroline Islands

The islands of Kosrae in the eastern Caroline islands are the remains of volcanoes which formed some 4 Ma as part of a hotspot island chain. Recent work by KAYANNE *et al.* (1995) has shown that the maximum Holocene sea level occurred some 3800 BP and reached around 1 m above the present.

The history of later Holocene sea-level change has been determined largely by dates from mangrove peats which, for reasons stated above, yield only minimum levels for contemporary sea levels. Yet, assuming that the processes involved in mangrove peat displacement (compaction and subsidence) are continuous, then the younger the date the less the peat would be expected to have been displaced from the level (relative to the present) at which it formed. The peat formed on Kosrae some 720 BP is so close in level to other indicators of contemporary sea level that it is considered unlikely to have been displaced significantly from the level at which it formed.

New Zealand

Many parts of the islands of New Zealand are tectonically active, but this is well documented (PILLANS, 1986) and there are areas of little or no significant tectonism, particularly along the hinge zones between areas of subsidence and areas of uplift.

GIBB (1986) established the location of such "stable" areas of New Zealand by measuring the relative heights of the Last Interglacial shoreline. Any place where this was not 3.0 ± 0.3 m above its modern analogue was considered by Gibb to have been tectonically active during the subsequent period. Two places where such stability was found were the Blueskin Bay estuary in South Island, and the Weiti River estuary in North Island. Both these sites proved extremely fruitful in deciphering the course of late Holocene sea-level changes, including the last 1,000 years.

Rota

Like Guam (see above), Rota is an island along the Marianas forearc in the northwest Pacific. Unlike Guam, the highest Holocene emerged reef reaches almost 4 m above the modern reef, suggesting that the island has experienced late Ho-

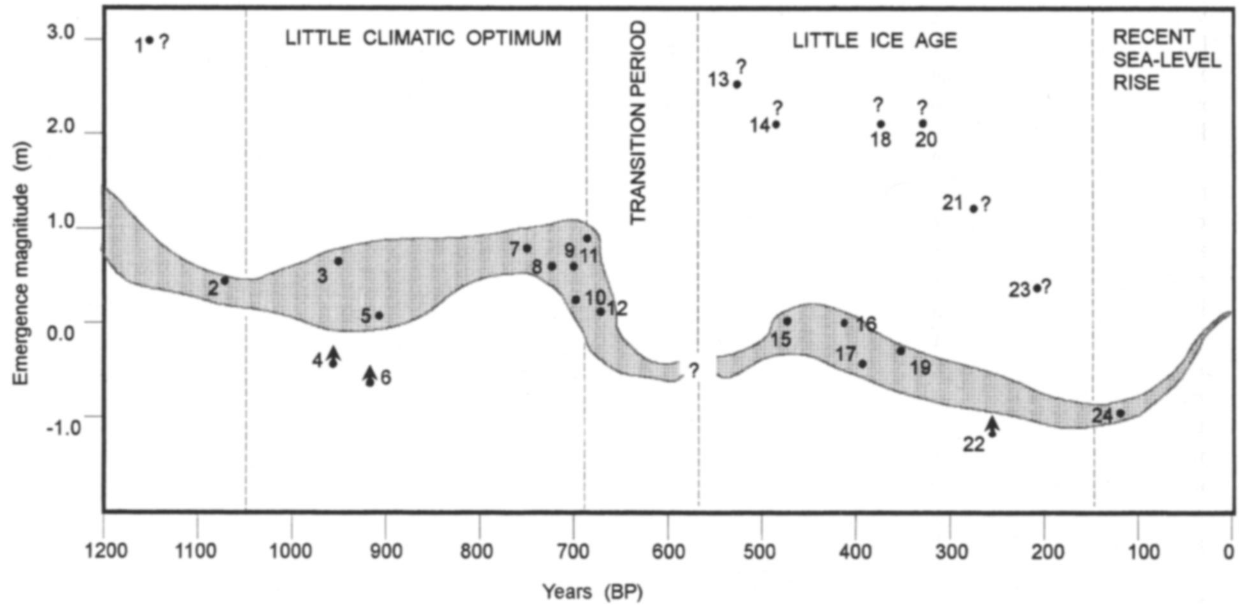

Figure 2. Sea-level changes over the past ~ 1,000 years. Dates and shoreline displacements are listed in Table 1 and sites shown in Figure 1.

locene uplift (KAYANNE *et al.*, 1988). Yet there is no evidence for uplift within the past few hundred years so the record from just 115 BP is considered likely to be a reliable indicator of contemporary sea level.

Tuamotus

The Tuamotu archipelago in French Polynesia comprises two main chains of islands, mostly atolls, which have been linked to a hotspot to the southeast. Most islands rise from volcanic basements of early Neogene age and have been subsiding slowly since that time. For short time periods such as the Holocene, these islands can be regarded as effectively stable, which is why there has been so much interest shown in them by researchers concerned with Holocene sea-level change (PIRAZZOLI and MONTAGGIONI, 1986, 1988; PIRAZZOLI *et al.*, 1988). Four dates from the last 1000 years are used in this study.

SEA-LEVEL CHANGES OVER THE PAST 1,000 YEARS

The 24 dates from the "stable" sites described above are plotted (age versus emergence magnitude) in Figure 2, and an envelope drawn around those which appear most representative. This envelope is intended to enclose the most likely course of sea-level change during this period in the Pacific. Unlike for earlier periods, for which contemporary sea level was perhaps not parallel to the present sea level on account of geoidal change (NUNN, 1986, 1994a), the past 1,000 years has probably not witnessed geoidal changes of magnitude sufficient to have caused significant intraregional variation. It would thus be expected that sea level would have changed at approximately the same rates and by the same amounts at the same times for the past 1,000 years. As a consequence, the envelope is drawn almost as narrowly as it can.

The account of last-millennium sea-level changes is divided for ease of discussion into four: the Little Climatic Optimum marked by sea-level rise (~ 1050 BP to 690 BP), the transition period between this and the following period (690 BP to ~ 575 BP), the Little Ice Age marked by generally lower than present sea levels (~ 575 BP to ~ 150 BP), and the period of recent warming (~ 150 BP to present).

The Early Period: Little Climatic Optimum sea-level rise

Around the beginning of this period, sea level was close, perhaps a little above, its present level. The early part is constrained by dates 3 and 5 and by minima from Guam (dates 4 and 6). The later part of this period, around 700 BP, marks the maximum sea level in the Pacific during the last millennium. Available data suggest that sea level may have reached as much as 0.9 m above its present level.

The sea-level rise during this period is coincident (as would be expected) with a period of temperature warming named the Little Climatic Optimum for which evidence has been reported parts of the world including the Pacific (NUNN, 1990b, 1992). On many Pacific islands, this time was marked by less rainfall compared to the present, which is believed to have inspired water-conservation strategies, such as terracing, by the contemporary inhabitants of many Pacific islands. It has also been argued that this time was marked by less cyclonic activity than at present and a higher frequency of clear skies which encouraged the successful long-distance colonisation of lands (such as Hawaii, Easter Island [Rapanui], New Zealand and the coast of Panama) remote from the Marquesas islands, the easternmost population centre in the Pacific islands at the time (BRIDGMAN, 1983; NUNN, 1992).

The Transition Around 690 BP

The available sea-level data for this period points to a comparatively abrupt fall followed by almost 200 years for which there are no data. Both observations are worthy of comment.

The sea-level fall ~ 700–650 BP has been found to have coincided with a rapid fall of ground temperature, which presumably drove it (NUNN, 1992). This time is also believed to have coincided with a short-lived rise in precipitation, perhaps associated with increased cyclonic activity arising from reorganisation of wind systems (NUNN, 1994b).

Support for these changes comes from consideration of island environments and their human inhabitants at this time. The falling temperature and vastly increased precipitation would have devastated contemporary agricultural systems, leading to catastrophic forest destruction and soil erosion in many places. On many islands, this time marks the approximate time at which food resources were perhaps dramatically depleted so that people had to compete (as they had never done before) for the few remaining resources. Excellent examples are provided by Easter Island, where the resulting societal strife is well marked in the archaeological record, and island groups like Fiji where a transition from unfortified coastal settlements to fortified hilltop settlements is conspicuous around this time.

The marked hiatus of around 200 years for which there are no sea-level data suggests that sea level had fallen so low that its subsequent rise (during the Little Ice Age ~ 430 BP—see below) obscured all records of shoreline change. For example, the fall of sea level of perhaps as much as 1.4 m during the transition would have forced most coral reefs to begin growing outwards; the reef-surface corals which grew at this time would have been covered by those which grew up to the subsequent maximum.

The possibility that the transition was coincident with increased storminess means that many nearshore sediment transport systems would have been disrupted and may not have recovered until the onset of drier conditions during the Little Ice Age (see below).

The Middle Period: Low Sea Levels of the Little Ice Age

Most dates presented in Table 1 suggest that the early part of the Little Ice Age was marked by a rise to a sea-level maximum perhaps a little above present sea level ~ 430 BP (Figure 2). The remainder of the Little Ice Age appears to have been marked by a slowly falling sea level which may have reached almost −0.9 m around 200 BP. This part of the curve is not particularly well constrained. A notable feature of the sea-level data from supposedly stable sites during the Little Ice Age are the dates (13, 14, 18, 20, 21, 23) which are clearly in excess of those contained within the sea-level envelope (Figure 2). A discussion of these is given separately below.

Evidence for the Little Ice Age has been found throughout the world (GROVE, 1988). Temperatures in the Pacific were significantly lower than those both of today and of the Little Climatic Optimum (THOMPSON *et al.*, 1986; QUINN *et al.*, 1993), and it is this which suggests that the sea-level envelope should be drawn as it is for the Little Ice Age in Figure 2 rather than at a higher level.

In the Pacific islands, the abrupt cessation of successful long-distance colonisation and interchange, even within archipelagoes like the Marquesas, suggests that storminess and cloudiness had both increased during the Little Ice Age compared to the Little Climatic Optimum (BRIDGMAN, 1983; NUNN, 1992). Many Pacific island societies felt the continuing effects of the climate change during the earlier transition (see above).

The Final Period: Recent Sea-Level Rise

There are no publicly available series of continually monitored sea-level data for the Pacific for the early part of this period. Yet ŠNITNIKOV (1969) reported that data from three unspecified stations in the Pacific between 143 and 0 BP (AD 1807–1950) indicated a sea-level rise of 11.8 cm.

The most dependable series of continually monitored sea-level data begin around the start of the twentieth century and indicate that Pacific sea level has been rising at net rates of 1.0–1.5 mm/year for the past ~ 100 years (WYRTKI, 1990; NUNN, 1992). This time has also been marked by rising temperatures and, as for most of the past millennium (NUNN, 1992; SALINGER *et al.*, 1995), it seems probable that temperature change has been driving sea-level change in the same direction.

Anomalous Data: Discussion

Dates 1, 13, 14, 18, 20, 21 and 23 (Table 1 and Figure 2) are clearly anomalous in relation to those used to characterise sea-level changes of the last millennium yet all these dates were assumed to have come from sites which had been tectonically stable over this period of time. An understanding of how these dates and the sites from which they were obtained came to be misinterpreted is instructive for anyone interested in reconstructing the course of past sea-level changes.

Aside from survey error, which is regarded as highly improbable, there are five explanations of these anomalous dates.

(a) It is possible that the sites have experienced uplift within the few hundred years since they formed. Given our present understanding of the longer-term tectonic history of the areas in question, particularly the levels at which the Holocene sea-level maximum was recorded, such an amount of uplift seems extremely unlikely.

(b) It is possible that sea level in these parts of the Pacific stood significantly higher than that shown within the envelope in Figure 2. For the Little Ice Age, the dates within the envelope are constrained mostly by those from New Zealand. Had the sea surface in the Pacific at the time not been parallel to the present sea level, this would allow such a situation, but it also requires the oceanic geoid in the region (between Samoa and New Zealand) to have deformed in level by ~ 3 m in the last 520 years BP. Such rates of geoidal deformation are greatly in excess of those which writers such as MÖRNER (1976) proposed. In addition, it would be remarkable if terrestrial evidence of sea levels ~ 3 m higher than pres-

Table 1. *Data referring to eustatic shoreline displacements at tectonically-stable sites in the Pacific islands over the past ~1,000 years. Locations shown in Figure 1, age-displacement data plotted in Figure 2.*

	Island	Place	Emergence Magnitude (m)	Age (years BP)	Source of Information
1	off Viti Levu, Fiji	Sucutolu	~3.0	1,150 ± 60	this paper
2	Faaite, Tuamotus	western coast	0.45 ± 0.2	1,080 ± 55	PIRAZZOLI *et al.*, 1988
3	Tarauru Roa, Gambier Islands	–	0.6	950 ± 70	PIRAZZOLI and MONTAGGIONI, 1987
4	Guam	Aga Point	−0.66 ± 0.03[1]	940 ± 120	MATSUMOTO and KAYANNE, 1988
5	South Island, New Zealand	Blueskin Bay estuary	0.02 ± 0.9	907 ± 62	GIBB, 1986
6	Guam	Aga Point	−0.72 ± 0.03[1]	900 ± 140	MATSUMOTO and KAYANNE, 1988
7	Tutuila, American Samoa	Poloa	0.745	740 ± 60	this paper
8	Kosrae, Caroline Islands	Utwa	0.6[1]	720 ± 80	KAWANA *et al.*, 1995
9	Rangiroa, Tuamotus	Tepaetia	0.6	705 ± 65	PIRAZZOLI and MONTAGGIONI, 1985
10	Hikueru, Tuamotus	Tekotaha	0.25 ± 0.1	700 ± 60	PIRAZZOLI *et al.*, 1988
11	Tutuila, American Samoa	Poloa	0.89	690 ± 70	this paper
12	North Island, New Zealand	Weiti River estuary	0.12 ± 0.23	670 ± 50	GIBB, 1986
13	off Viti Levu, Fiji	Sucutolu	~3.0	520 ± 35	this paper
14	Tutuila, American Samoa	Vatia Bay	2.11	490 ± 60	this paper
15	North Island, New Zealand	Weiti River estuary	0.0 ± 0.24	470 ± 50	GIBB, 1986
16	South Island, New Zealand	Blueskin Bay estuary	0.0 ± 0.5	413 ± 30	GIBB, 1986
17	North Island, New Zealand	Weiti River estuary	−0.46 ± 0.24	395 ± 34	GIBB, 1986
18	Tutuila, American Samoa	Vatia Bay	2.11	380 ± 60	this paper
19	North Island, New Zealand	Weiti River estuary	−0.23 ± 0.22	365 ± 30	GIBB, 1986
20	Tutuila, American Samoa	Vatia Bay	2.11	350 ± 50	this paper
21	Tutuila, American Samoa	Afono Bay	1.24	270 ± 60	this paper
22	Guam	Aga Point	−1.06 ± 0.04[1]	260 ± 135	MATSUMOTO and KAYANNE, 1988
23	Marokau, Tuamotus	northwest	0.4 ± 0.1	210 ± 70	PIRAZZOLI *et al.*, 1988
24	Rota	west	−0.77 ± 0.02	115 ± 160	MATSUMOTO and KAYANNE, 1988

[1] Original data for northwest Pacific islands presented relative to mean sea level were converted relative to the assumed mean level of the modern reef surface by subtracting 0.9 m

ent a few hundred years ago had eluded investigators up until this point.

(c) In some deep embayments along the north coast of Tutuila island in American Samoa corals are growing in rock-walled pools regularly sluiced by surf almost 3 m above the main reef level. Were surf unable to reach these pools, their corals would die and could easily be mistaken as emerged reef of much earlier date. The difficulty with this when applied to the sites on Tutuila is that at these there are blocks of massive reef coral, not isolated coral heads attached to volcanic slopes. This explanation is inapplicable to the open-ocean sites at Marokau and Sucutolu.

(d) It is also possible that these blocks of emerged reef are parts of the submarine reef which have been broken off during storms and thrown up on the modern reef flat. There are many of these on reefs in the tropical Pacific. Yet, since the corals in these blocks are all in growth position and, in some cases, it is also clear from reef stratigraphy that the blocks are the 'right way up', one can only conclude that it is chance which has caused these storm-tossed blocks to have landed on the reef flat in this way. The chance of this happening is so small that this explanation is likewise dismissed.

(e) The possibility that the dates obtained on these samples are too young because of post-emergence contamination of these reefs cannot be readily dismissed although no single contributory factor can be identified.

In conclusion, there is no satisfactory answer as to the origin of anomalous dates from Marokau, Sucutolu and Tutuila. The most likely explanation is that the emerged reefs were contaminated and consequently sample dates were too young. Further work on the sites in question would be useful.

CONCLUSIONS

This study shows that the sea level during the past 1,000 years in the Pacific was not unchanging but oscillated in a manner which may well mimic, albeit at lower amplitudes, the fluctuations of Holocene sea level (FAIRBRIDGE, 1992; NUNN, 1995).

The possibility that these oscillations may be cyclical and therefore reproducible has led to use of the sea-level rise during the Little Climatic Optimum as a proxy for the period of recent sea-level rise; such studies suggest that, irrespective of predicted sea-level rise associated with the human-enhanced greenhouse effect, sea level would probably continue rising until around the end of the twenty-first century (NUNN *et al.*, 1994).

This study has also shown that the record of sea-level change over periods as short as 1,000 years is possible although the likelihood of anomalous dates is high. The possibility that anomalous dates of the kind described here (dates 13, 14, 18, 20, 21 and 23 in Figure 2) have been inadvertently incorporated into other studies of Holocene and earlier sea-level change is manifest and serves to emphasise the need to ensure that the tectonic history of particular sites is known accurately, especially when dealing with such short time periods.

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