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THE TIMING OF THE POSTGLACIAL MARINE INVASION OF KAU BAY, HALMAHERA, INDONESIA

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ABSTRACT. Kau Bay, Halmahera, Indonesia is a small marine basin that is separated from the adjacent SW Pacific Ocean by a shallow sill, 40m deep. Radiocarbon dating on piston cores in combination with a study on microfossils demonstrate that Kau Bay was a freshwater lake in Weichselian times. At 10,000 BP, the Bay became reconnected with the open ocean. If sill depth did not change in the intervening years, sea level at 10,000 BP stood 40m below the present level.

INTRODUCTION

Kau Bay, Halmahera, Indonesia is a small, 470m deep, pear-shaped basin separated from the deep southwest Pacific Ocean by a flat-floored, 30km wide, 40m deep sill (Fig 1). About 60 years ago, Kuenen (1943) already suggested that sediment cores taken from Kau Bay would reveal that freshwater conditions prevailed during glacial times, when sea level stood beneath sill depth. Unfortunately, he was unable to prove this idea because the cores he took in Kau Bay in 1930 during the Snellius I expedition failed to penetrate deep enough. Oceanographic observations made at the time, however, clearly showed that, below a depth of ca 350m, the bay waters were devoid of oxygen and had a high concentration of dissolved hydrogen sulphide (Van Riel, 1943).

THE 1985 KAU BAY EXPEDITION, OBJECTIVES AND METHODS

Kau Bay was visited again in April 1985 during the Snellius II expedition (Van der Linden *et al*, 1986). The main objectives set this time were to portray Late Quaternary bottom and surface water conditions and to study the changes in sediment and pore water chemistry to monitor mineral formation and (early) lithogenesis in this unique environment. We were also interested in testing Kuenen's hypothesis to learn whether, indeed, Kau Bay was a freshwater lake during glacial time and, if so, we would like to know at what time full marine conditions were restored. Further, if the elevation of the sill did not change appreciably in time, then the level of this barrier can be used to establish at what time sea level stood 40m below the present level.

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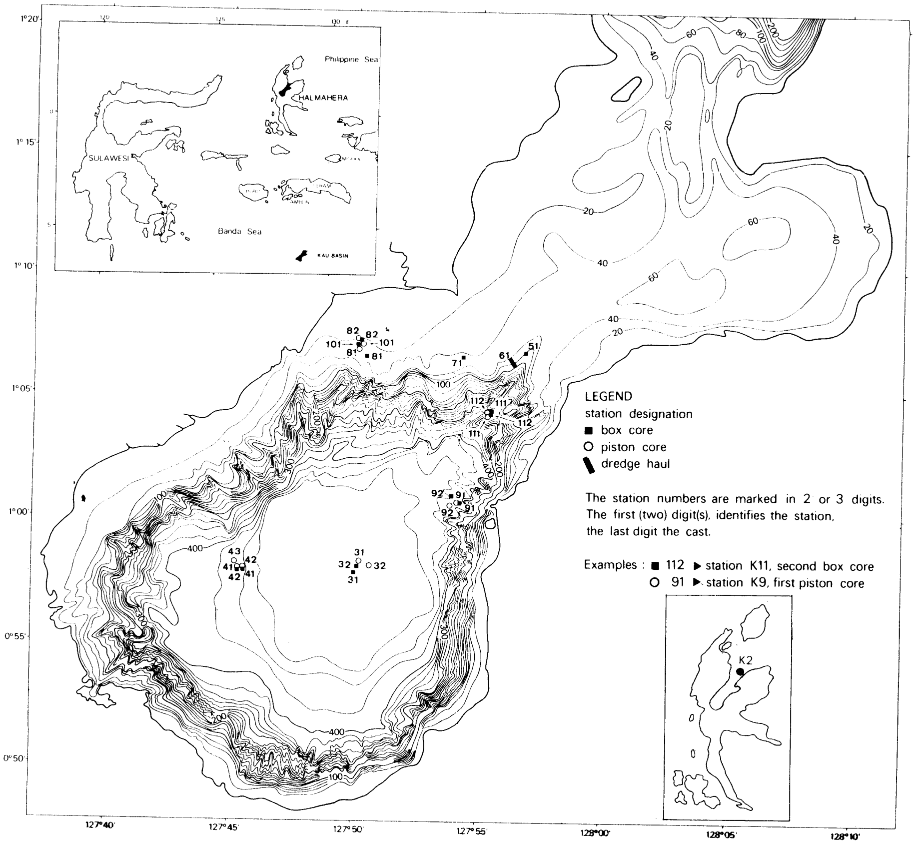

Fig 1. Bathymetry of Kau Bay and position of samples (after Van der Linden *et al,* 1986)

To tackle these problems, we occupied nine selected stations in Kau Bay where we recovered a total of 12 piston cores, 13 box cores and 1 dredge sample (Fig 1). At least two cores of 9cm diameter per site were needed for subsequent analyses and reference. Cores were taken as much as possible from undisturbed sites as far as could be judged from 3.5 kHz acoustic profiles.

RADIOCARBON STRATIGRAPHY AND DEPOSITIONAL REGIME

Cores P1 and P3 at station K4 bottomed into dark-colored dehydrated clays. The presence of a hard dolomitic layer within these clays appears to coincide with a distinct 3.5 kHz acoustic reflector, 10–12m below the basin floor (Van der Linden, Suharno & Sukardjono, 1988). Other cores obviously did not penetrate deep enough to hit this salient lithological horizon. Apart from the dark-colored dehydrated clay and the dolomitic layer in cores Pl and P3 at station K4, there are no other lithological characteristics nor clear-cut (micro)faunal/floral events in the cores that enabled reliable time-stratigraphic correlations across Kau Bay. Also, the odd volcanic ash layer found in some cores cannot be traced basinwide.

Thus, to design a Late Quaternary time-stratigraphic framework, we relied heavily on accurate ^{14}C ages. We used the Utrecht Accelerator Mass Spectrometer (AMS) which requires only 1mg organic carbon for accurate

Table 1: Radiocarbon dates of samples from Kau Bay

Sample[a] name	code no.[b] no	Depth[c] (m)	δ^{13}[d] (°/oo)	Age[e] (yr BP)
K3P2#9;26-28.5	UtC-518	0.27	-0.84	780(140)
K3P2#8;52-54.5	UtC-533	1.53	-0.17	650(140)
K3P2#4;56-58.5	UtC-535	5.57	-28.56	1180(90)
K3P2#3;64.5-67	UtC-534	6.66	0.63	2340(140)
K3P2#2;94.5-97	UtC-481	7.95	0.39	1820(80)
K3P2#1;90-92.5	UtC-517	8.91	-1.34	1940(130)
K4P3#8;35-37.5	UtC-478	0.36	-0.11	780(110)
K4P3#7;7.5-11	UtC-475	0.74	0.38	1480(120)
K4P3#6;37-39	UtC-480	2.03	0.75	2710(150)
K4P3#5;35.5-38	UtC-476	3.03	0.14	3790(140)
K4P3#4;49.5-52	UtC-474	4.17	-1.17	5960(120)
K4P3#3;38-40.5	UtC-479	5.05	-0.40	7600(200)
K4P3#2;39-41.5	UtC-472	6.06	-4.18	9900(200)
K4P3#2;61.5-64	UtC-477	6.29	-4.06	9920(140)
K4P3#2;90-94.5	UtC-473	6.59	-4.04	9670(140)
K4P1#2;12.5-15	UtC-646	7.66	-2.93	9890(140)
K4P1#2;17.5-20	UtC-647	7.71	-3.36	10030(140)
K9P1#6;0-4	UtC-484	0.02	-0.62	1300(110)
K9P1#5;24.5-27	UtC-516	0.94	-1.29	1270(80)
K9P1#5;94-96.5	UtC-515	1.63	-0.48	1560(90)
K9P1#4;44-46.5	UtC-514	2.13	-0.92	1570(150)
K9P1#3;86.5-89	UtC-519	3.56	-0.98	1450(100)
K9P1#2;51-53	UtC-483	4.20	-0.02	1580(140)
K9P1#1;87.5-90	UtC-482	5.57	-0.07	1970(130)
K11P1#6;95-97.5	UtC-614	1.84	0.01	2530(110)
K11P1#5;92.5-95	UtC-615	2.92	0.15	4210(120)
K11P1#4;76.5-79	UtC-616	3.76	-0.16	5520(130)
K11P1#3;83-85.5	UtC-617	4.72	-0.32	6260(90)
K11P1#2;6.5-9	UtC-618	5.06	-0.28	6410(110)
K11P1#1;5-7.5	UtC-619	6.04	-0.78	7610(140)

[a] Sample identification; material is calcite except for UtC-535 for which organic material has been used, as is also reflected by the δ^{13}-value

[b] Code number of Van de Graaff Laboratorium, Rijksuniversiteit Utrecht, The Netherlands

[c] Depth below sea-floor

[d] δ^{13}-values measured at Earth Sciences Department, Rijksuniversiteit, Utrecht

[e] Age in years before present (BP) determined from measured ^{14}C activity by means of AMS

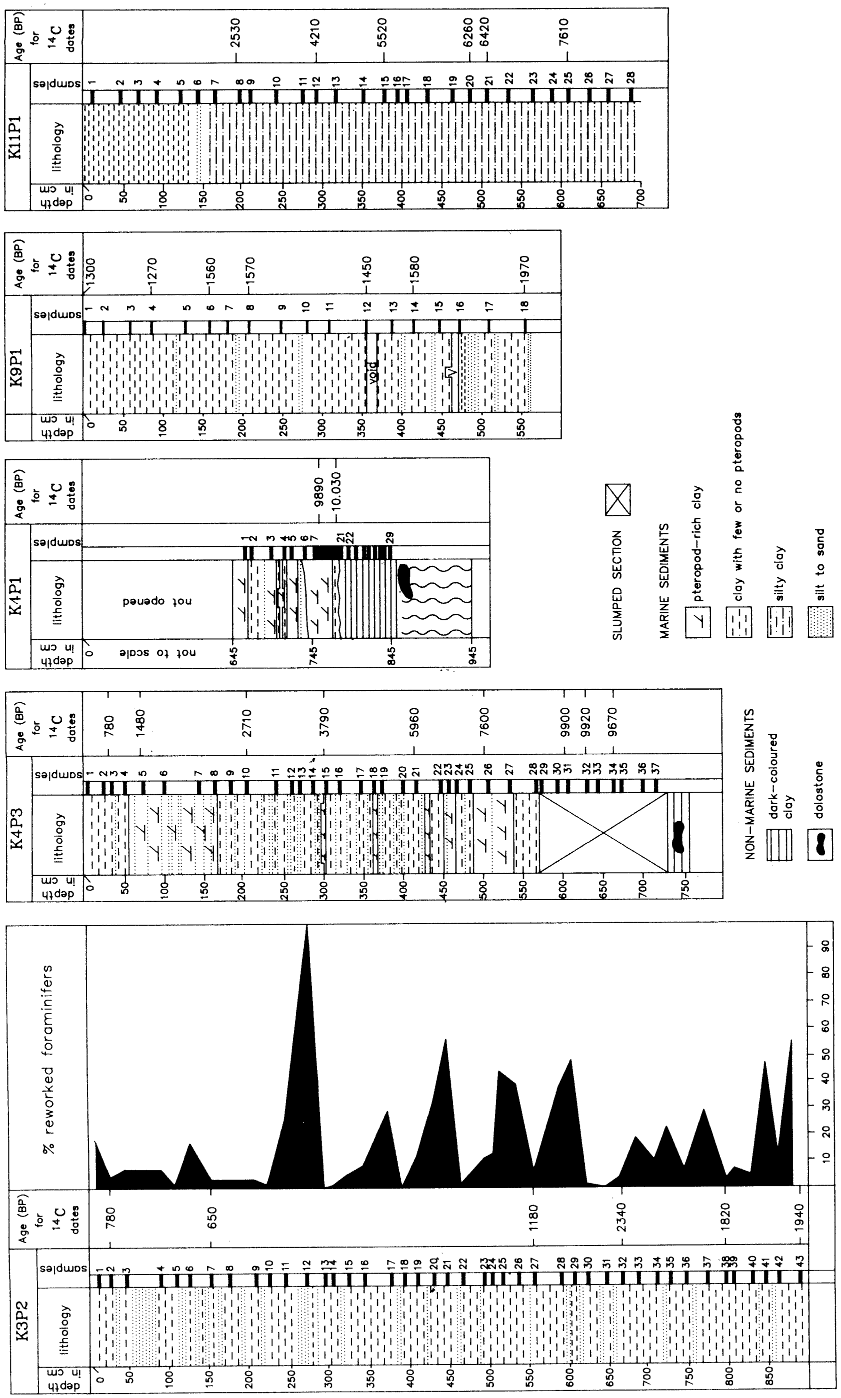

Fig 2. Lithology and ${}^{14}C$ ages of cores (after Barmawidjaja *et al*, in press)

^{14}C determinations (Van der Borg *et al,* 1987). We obtained a 1mg sample of carbon from ca 10mg of biogenic carbonate derived from pteropods. Altogether, 30 levels of 2cm thick dispersed over 5 piston cores were dated. Table 1 gives an overview of the Kau Bay ^{14}C ages and Figure 2 shows the lithology of the cores and their ^{14}C stratigraphy.

An important observation that can be made from Figure 2 is that the cores at stations K4 (down to 566cm) and K11 show a fairly consistent age progression with depth, while the ^{14}C chronology at stations K3 and K9 is thoroughly disturbed, even though the sediments at the latter stations are well stratified.

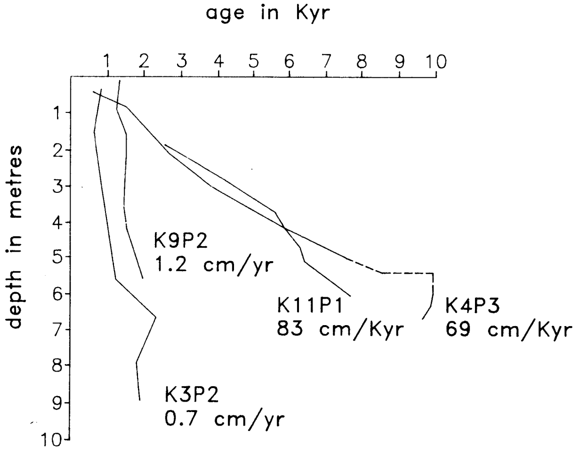

Fig 3. Sediment accumulation rates at stations K3, K4, K9 and K11 (after Barmawidjaja *et al,* in press)

Figure 3 shows that average sedimentation rates are high at stations K3 and K9 (0.7 and 1.2cm/yr, respectively) and low at stations K4 and K11 (69 and 83cm/kyr, respectively). Differences in sedimentation rate in the deepest basin are also observed in seismic reflection profiles (Van der Linden, Suharno & Sukardjono, 1988), which show that station K4 is located at the top of a horst block with a tight sedimentary cover, whereas station K3 is located at the top of a down-faulted block with comparatively expanded sedimentary fill. Numerous turbidities and high percentages of reworked Pliocene planktonic foraminifera at station K3 indicate that large amounts of mass-transported sediments are trapped in the deepest part of Kau Bay. Station K9 is at the foot of a relatively steep slope and, thus, massive slumps of fine-grained slope sediments most likely contributed to the very high sedimentation rate. In contrast to this, large amounts of sediment may be expected to bypass station K11 which is somewhat isolated on a ledge (Van der Linden, Suharno & Sukardjono, 1988).

SEA LEVEL RISE AT PLEISTOCENE/HOLOCENE TIME

The dark-colored dehydrated clay and associated dolomitic layer recovered at station K4 is rich in freshwater diatoms. The sole marine mi-

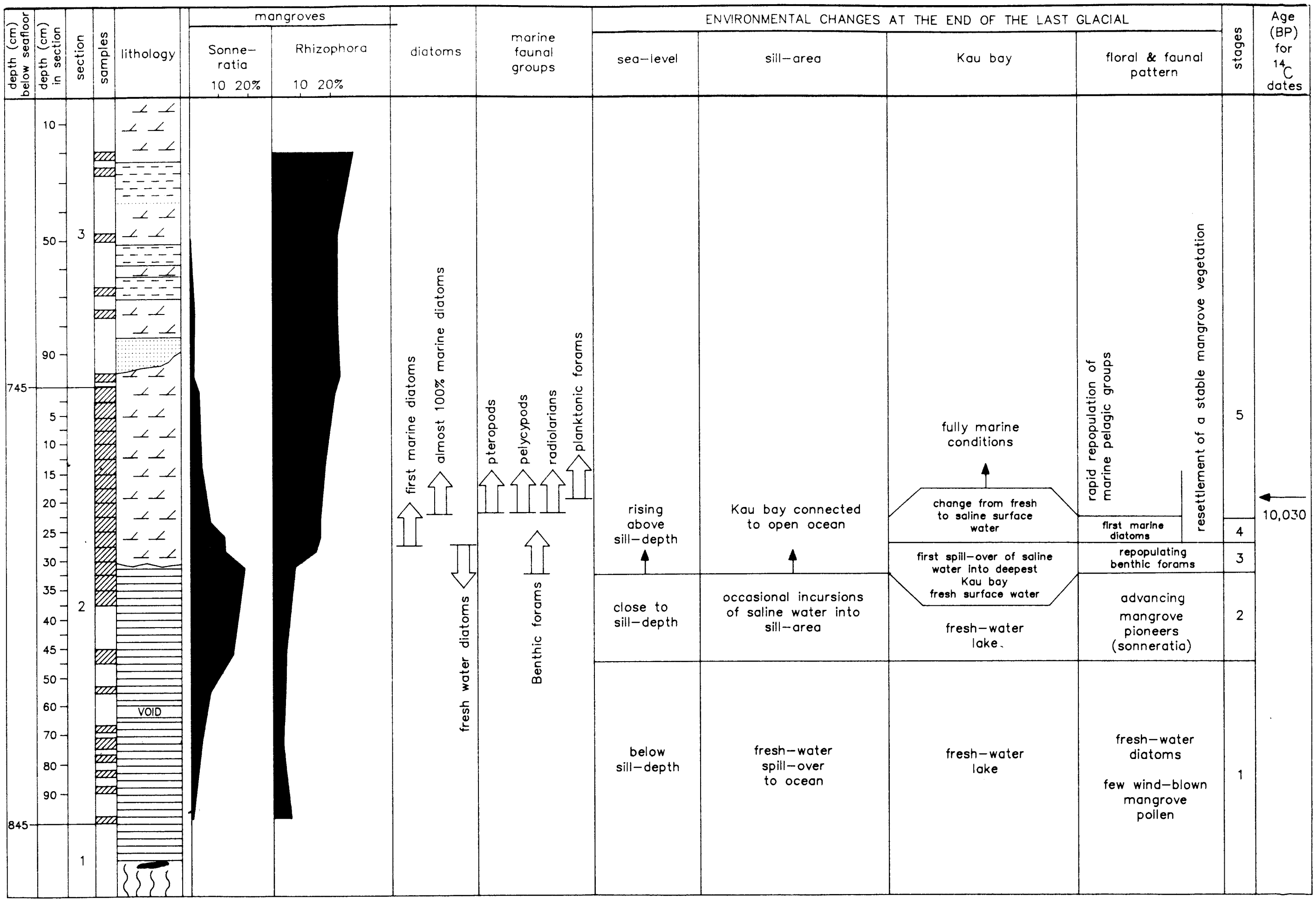

Fig 4. Sequence of events across the freshwater – marine transition in core K4P1 (after Barmawidjaja *et al*, in press). For lithology, see legend of Fig 2.

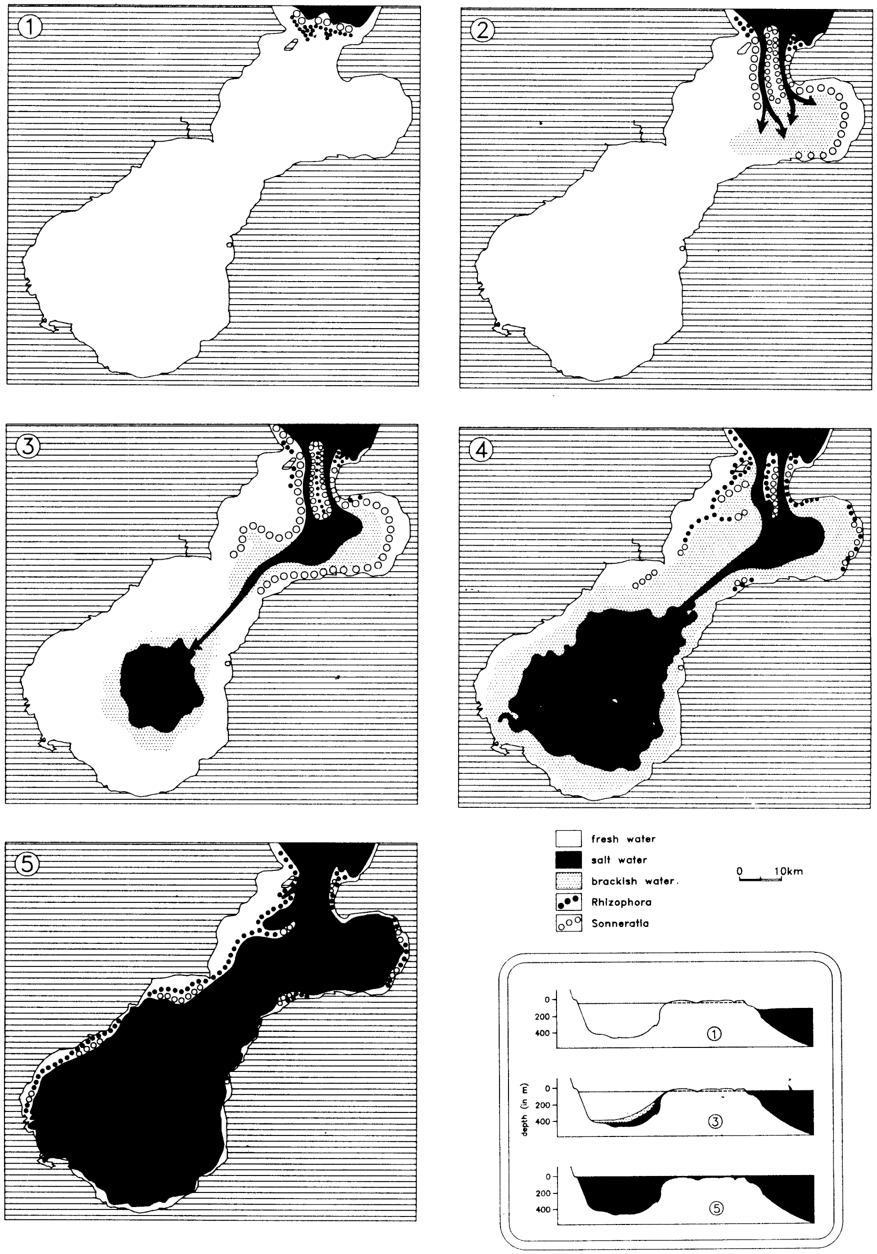

Fig 5. The Weichselian-Holocene marine invasion of Kau Bay in 5 (numbered) stages (after Barmawidjaja *et al*, in press). Explanation given in text.

crofossils are a few mangrove pollen which most likely are blown in from the vicinity of Halmahera. The virtual absence of a mangrove vegetation in Kau Bay and the exclusive freshwater diatom flora indicate that the Bay at that time was a freshwater lake spilling over the sill into the ocean. In core P3, the changeover from lacustrine to marine conditions is disturbed by slumping between 566cm and the dolomitic layer (Fig 3). Only core P1 provides an undisturbed section across the freshwater-marine transition (Fig 3). The sequence of biotic and environmental changes across the transitional interval of core P1 are given in Figure 4 and is the basis for Figure 5 in which the marine invasion of Kau Bay is illustrated in five successive stages.

During stage 1, Kau Bay was a freshwater lake, while sea level stood well below sill depth (Fig 5.1). Stage 2 is characterized by an increase in mangrove pioneers (represented by *Sonneratia* in Fig 4), suggesting the occasional inflow of saltwater through the deepest parts of the sill, *ie,* two (?) river valleys (*cf* Fig 1), at times of exceptionally high tides and/or during storms. The exclusively freshwater diatom flora indicates that Kau Bay itself remained a freshwater lake (Fig 5.2). During Stage 3, benthic foraminifera invaded the deep water of the Bay (Fig 4), which demonstrates that saltwater started to spill over the sill and sink to the bottom. Surface waters, however, remained fresh since pelagic organisms exclusively consist of freshwater diatoms. At that time, Kau Bay became permanently reconnected with the open ocean (Fig 5.3). Surface waters changed from fresh to saline during Stage 4, as is evidenced by the first marine diatoms (Fig 4). At the same time, the pioneer mangrove was taken over by a stable vegetation (represented by *Rhizophora* in Fig 4) which rapidly expanded along the shores of Kau Bay (Fig 5.4). The invasion of pteropods, pelecypods and radiolarians into Kau Bay at the base of Stage 5 (Fig 4) indicates that full marine conditions were re-established at that time (Fig 5.5).

The earliest level permitting ^{14}C determination on biogenic carbonate is the base of Stage 5 and shows a ^{14}C age of 10,000 BP (Fig 4). Since this level is only 10cm above the level at which Kau Bay becomes permanently reconnected with the open ocean (Fig 4) it seems justified to suppose that the time when sea level had risen to sill depth is close to 10,000 BP. If the elevation of the sill did not change appreciably since that time, which, at first seems unlikely, considering the local volcanic and seismic activity, then sea level at 10,000 BP stood 40m below the present level. It is however, at least remarkable that this figure fits well to the Late Quaternary eustatic sea level curves of Curray (1965) and Oldale and O'Hara (1980) for the US east coast and is close to the Dillon and Oldale (1978) sea-level-rise curve for the same region. That it also fits the sea-level curve for the Huon Peninsula in nearby Papua, New Guinea (Chappell, 1983) adds rather more weight to our Kau Bay estimate.

Therefore, the age-calibrated sea-level mark for Kau Bay could be an important reference point in Late Quaternary sea-level history.

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