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Coral Reefs

Re-assessment of ossicle frequency patterns in sediment cores: rate of sedimentation related to *Acanthaster planci*

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Abstract. Data on *Acanthaster planci* skeletal element distribution in reefal subsurface sediment cores of two reefs of the central Great Barrier Reef (Walbran et al. 1989a, b) were shown to be readily interpretable after a time-scaled evaluation of element frequencies. After re-scaling using ^{14}C bulk sediment ages, high frequencies of elements were recognized in the top layers of John Brewer Reef sediment cores and attributed to the two recent *A. planci* population outbreaks. Beneath these top layers, the subsurface sediments contain consistently low element frequencies down to bulk-sediment ages of 7750 ± 100 years BP. From Green Island, the maximum abundance of skeletal elements was found in the sediment layers of about 1900 to 2300 years BP in some cores, but patterns were too inconsistent and the number of cores too small to suggest former *A. planci* outbreaks from these data. A strong correlation was found between the frequency of *A. planci* elements and the rate of sedimentation per time unit in sediment cores of all sites. This correlation was attributed to increased erosion of coral reefs as a consequence of the activities of high-density populations of *A. planci*. We conclude that reef erosion, after intense predation of reef-constructing organisms, has to be considered when causes of deterioriation of reef growth or termination of a reef facies in the geological past are discussed.

Introduction

The analysis of *Acanthaster planci* (COT) skeletal element distribution in surface and core sediments is an obvious approach to answer the question about prior changes in densities of crown-of-thorns starfish. Two recent publications by Walbran et al. (1989a, b), asked whether *A. planci* outbreaks were natural events which have occurred on coral reefs since the evolution of the starfish, or not. Based on the frequency of *Acanthaster planci* skeletal elements within surface and subsurface sediments of coral reefs of the Great Barrier Reef, the authors concluded that (1) "the down-core distribution of *A. planci* elements is consistent with a long period [...] of repeated *A. planci* outbreak cycles" (Walbran et al. 1989a, p.77); (2) "recurrent population outbreaks typify *A. planci* behaviour" and (3) *A. planci* outbreaks "have been an integral part of the ecosystem for at least 7000 years on John Brewer Reef and 3000 years on Green Island Reef" (p.67). Their assumptions have been questioned for a number of reasons (Keesing et al. 1992; Pandolfi 1992).

Walbran et al. (1989a, b) have the only detailed data on skeletal element distributions of *Acanthaster*. However, we consider that a re-evaluation of these data using an alternative method is essential. Any interpretation of sedimentology data is only valid when influences of the following are considered: varying rates of sedimentation; and artificial non-linear sediment compaction of vibrocores. This was not done by Walbran et al. who presented and interpreted their data as absolute numbers of elements per core intervals of approximately 250 g samples and 8 to 10 cm core length. Surface and subsurface samples are available from Green Island and John Brewer Reefs, whereas surface sediments only were taken from Heron Island. Sediment and skeletal element ages, achieved by liquid scintillation counting and accelerator mass spectrometry could be attributed both to certain samples and to the core depth from where the samples were taken (Figs. W4 and W5 in Walbran et al. 1989a; labelled with "W" to differentiate from our figures).

We re-investigated the data published by Walbran et al. (1989a) by scaling their subsurface *A. planci* element recovery values according to varying rates of sedimentation from ^{14}C sediment age data. The absolute number of skeletal elements per standardized sample weight was replaced by calculated element deposition numbers within intervals of 100 years. Additionally, we achieved data about the sedimentation rates per 100 years from these reefs, using the thickness of sediment in the related age intervals. The size of our sampling units (rates per 100 years) was chosen after considering the high degree of reworking and disturbance due to bioturbation (Tudhope and Scoffin 1984; Roberts et al. 1981) and storm activities, where any fine scaling blurs the patterns and thus does not provide additional information.

Scaling by time overcame the problem of dealing with highly variable rates of sedimenation which diluted the element densities to varying degrees, depending on the present sedimentation rates, and the problem of non-linear sediment compaction during coring. Moreover, a comparison of element numbers in subsurface cores with those in surface samples becomes unnecessary with this approach, since standardisation by time allows a direct comparison of sediment layers from different time periods.

Results

From *John Brewer Reef*, Walbran et al. (1989 a, Fig. W3) recovered 17 vibro-cores from the lagoon, a "notch" on the NE-side of the reef, and the leeward slope. They selected five of these cores for ^{14}C dating: JB6c and JB7d (lagoon), JB8b (notch), and JB12a and 13a (leeward slope), with each core from a different water depth. Our re-scaled element distribution data and the associated rates of sedimentation are presented as time-scaled core profiles, so-called "time-logs", in Fig. 1.

Datings of the cores from the lagoon and the leeward slope revealed old sediment ages, even in the top samples: JB6c = 2180±90, JB7d = 1870±90 , JB12a = 1480±90 years BP (Table 1). The sedimentation rate is up to 15 times higher above 200 cm core depth than below (e. g. core JB12a: mean sedimentation rate (RoS) per 100 years: 52.6 cm above, and 3.5 cm below 200 cm). The mean numbers of skeletal element per time interval show only moderate peaks. In the cores from the notch (JB8) with a top sample of age 310±80 years BP, the maxima both in element concentration and sedimentation rate are particularly evident. In contrast to the upper sections, the lower parts in all cores contain very low skeletal element frequencies and no significant peaks in sedimentation rates.

Core JB13a from the deep (39 m) leeward slope shows consistently low skeletal element frequencies (ApO) together with low rates of sedimentation down to a very old core base (7740±100 years BP). This evenness strongly contrasts to the presentation of Walbran et al. (1989 a, Fig. W4; also 1989 b Fig. W3) who use this core, in particular, to support their argument of high *Acanthaster* numbers in earlier times. Their scaling suggests a significant skeletal element maximum at a corrected core depth of about 225 cm and at the uncorrected core depth of 200 cm, respectively (see below).

We assume that the skeletal element maxima of the top sediment layers can partly be related to the two recent *Acanthaster* outbreaks. Only core JB13a from the deep leeward slope was obviously not affected by any COT event. The rather old ages of the tops of the cores JB6c, 7d, and 12a, may be attributable to drastic sediment disturbance and removal of the top layers by the severe Cyclone "Althea" which hit the reef during the *A. planci* outbreak in December 1971, and before the second outbreak in 1983/84 (Pearson 1975, 1981). In these cores, the relatively low element frequency may be explained by a dilution with old reworked sediments, whereas in the obviously protected area of the notch we find higher values for both RoS and skeletal elements.

From *Green Island Reef*, Walbran et al. (1989 a, Figs. W3 and W5) obtained 12 vibro-cores in two distinct areas: the reef flat (GI1b+c, and 5b+c) and the leeward shoal (GI2b+c, 3a+b, 4a+d, and 6b+c). Only three cores (GI2c, 5b, and 6b) were ^{14}C dated. A larger number of sample datings would be necessary to allow detailed conclusions about former COT populations on Green Is-

Table 1. Average rates of sedimentation (RoS) and average frequency of *A. planci* ossicles (ApO) in sediment cores of John Brewer Reef and Green Island Reef (central GBR). Mean "real ages" correspond to mean corrected ^{14}C datings. The conventional dating errors of ±70 to ±100 years BP are not included for clarity. Based on data from Walbran et al. (1989a)

Core	Corrected core depth (="penetration depth") (cm) dated sample		Difference in length (cm) (1)–(2)	Measured age: (mean "real age") (years BP)		Difference in age (y BP) (5)–(4)	ApO		RoS (cm/100 y) (3)/(6)×100
	Youngest (1)	Oldest (2)	(3)	Youngest at (1) (4)	Oldest at (2) (5)	(6)	*n* in (3) (7)	(N/100 y) (7)/100 (8)	(9)
John Brewer Reef									
JB 6c	0.0	448.5	448.5	2180	4530	2350	74	3.1	19.1
JB 7d	0.0	444.0	444.0	1870	3390	1520	53	3.5	29.2
JB 8b	0.0	413.0	413.0	310	2310	2000	106	5.3	20.7
JB 12a	0.0	328.0	328.0	1480	5320	3840	33	0.9	8.5
JB 13a	55.0	284.0	229.0	1770	7740	5970	44	0.7	3.8
Green Island Reef									
GI 2c	89.5	496.0	407.5	1410	2350	940	179	19.0	43.2
GI 5b	92.5	532.0	439.5	880	2960	2080	146	7.0	21.1
GI 6b	113.5	520.5	407.0	370	1550	1180	165	14.0	34.5
GI 6b[a]	113.5	469.0	355.5	370	1580	1210	157	13.0	29.4
GI 6c	357.0	456.0	99.0	1270	1760	490	50	10.2	20.2

[a] Calculated on the base of the oldest (=1580 years BP) but not the lowest (=1550 years BP) aged sample

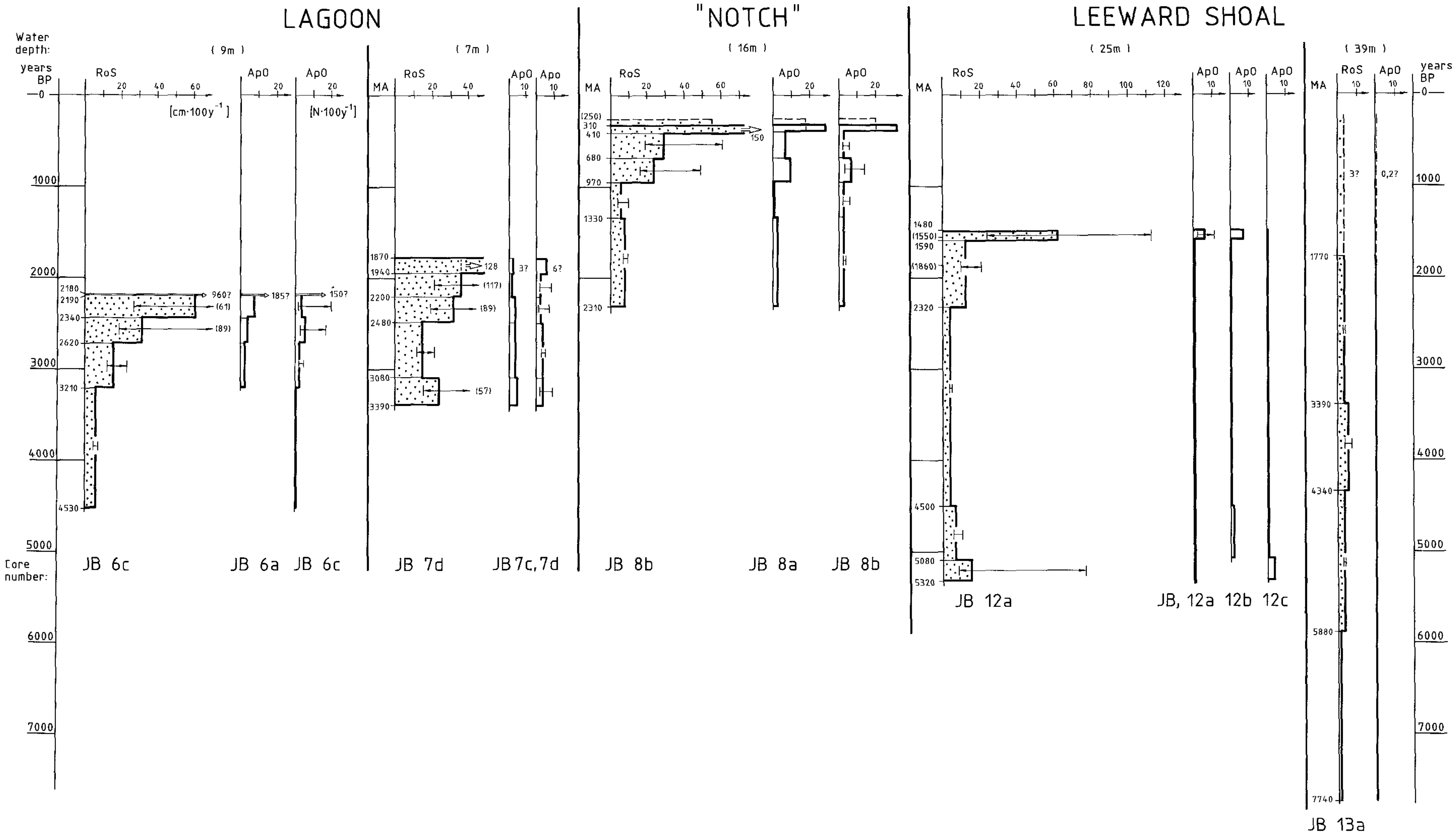

Fig. 1. John Brewer Reef: Subsurface age profiles of mean rate of sedimentation (RoS) per 100 years and mean number of *A. planci* ossicles (ApO) per 100 years. Age data and skeletal element numbers derived and recalculated from Walbran et al. (1989a, Figs. W4 and W5). Cores without age data (JB6c, 7c, 8a, 12b and 12c) are scaled in analogy to their dated replicates. Horizontal error bars are based on error values given by Walbran et al. (1989a). These represent average deviations of ±80 years from mean age. For the sake of clarity, these aging errors are not considered on the vertical axes

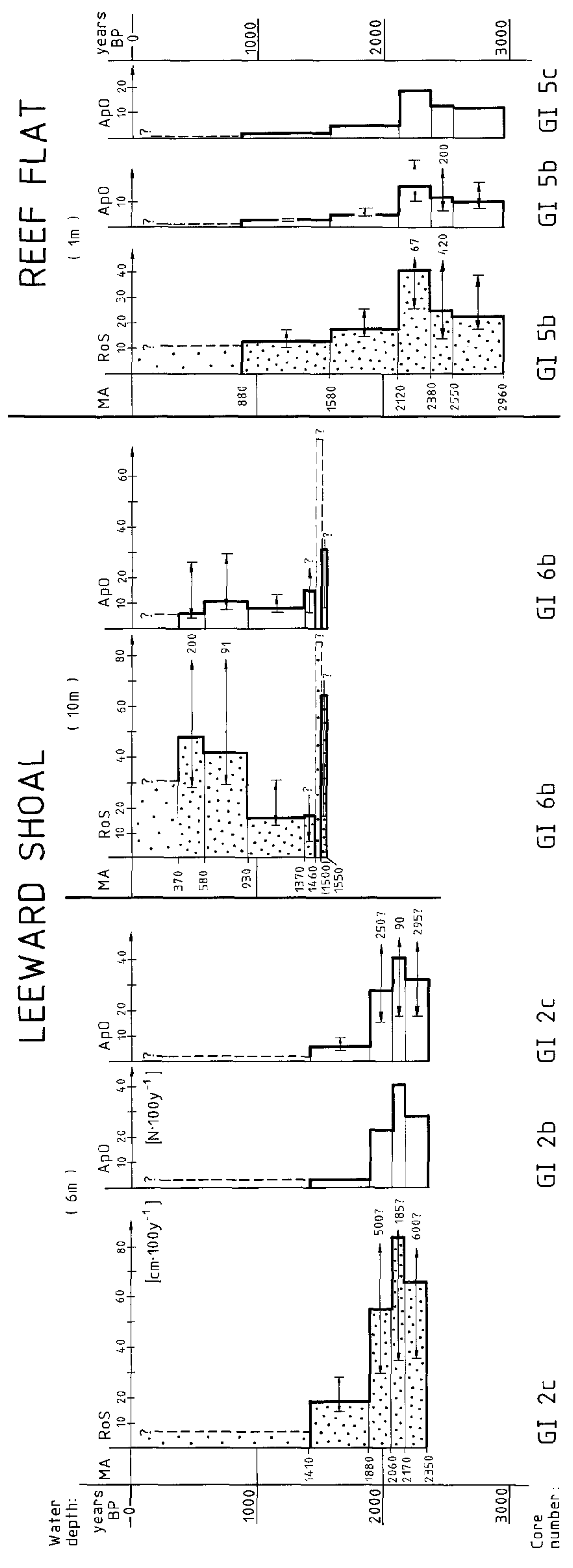

Fig. 2. Green Island Reef: Subsurface age profiles of mean rate of sedimentation (RoS) per 100 years and mean number of *A. planci* ossicles (ApO) per 100 years (as Fig. 1)

land: for the cores GI2b, 2c, 5b, and 5c (Fig. 2), a lack of datings in the top prevents a recognition of the modern outbreaks, and some of the given sample ages are uncertain because of time reversals in the sediment.

The time-logs from this reef nevertheless reveal new information. Patterns of high frequencies of skeletal element and high sedimentation rates some 2000 years ago emerge after re-scaling, which contrast strongly to the Walbran core-depth logs with only weak oscillations in element numbers and no significant peaks. Both high element concentrations and sedimentation rates are found in the lower parts of the cores GI2c and 5b within the time interval of about 1800 to 2500 years BP. Core GI6b does not reach down to sediment layers of this age, but yields both skeletal element and RoS peak values between 370 to 930 and 1460 to 1550 years BP. Only the older maximum correlates to some extent with the core-depth log GI6b of Walbran et al. (1989a, Fig. W5), while the skeletal element frequencies in all other core intervals do not correspond.

The new information achieved by scaling the skeletal element frequencies of the cores by time is, in most cases, quite different from the calculations of Walbran et al. (1989a, Figs. W4 and W5). The upper parts of some cores, especially from John Brewer Reef, show 10 times or higher skeletal element frequencies compared to sectors further down in the time-logs, whereas the uppermost sections of depth-scaled data show no increase in skeletal element concentrations (Fig. W4, Walbran et al. 1989a). The differences are also obvious at Green Island, though less striking.

The calculated values for sedimentation rates and element concentrations average the sedimentation processes of sometimes several hundred years. Nevertheless, general trends in the data are recognizable:

(1) The sedimentation rate on the mid-shelf John Brewer Reef is on average clearly below that of the nearshore reef Green Island, although it is highly variable (Table 2). The high rates of sedimentation on John Brewer, which we attribute to the modern *A. planci* outbreaks are, however, comparable to those of the sediment-rich Green Island;

(2) The mean element concentrations differ widely between the two reefs. Whereas John Brewer Reef sediments contain on average 3.1 ± 1.9 skeletal elements per 100 years, the average in Green Island cores is 16.1 ± 11.8;

(3) The numbers of skeletal elements and the sedimentation rates show high correlations in both John Brewer and Green Island cores. The level of significance (Spearman Rank Correlation test, Table 2 and Fig. 3) is $P < 0.005$ for John Brewer Reef, and $P < 0.001$ for Green

Table 2. Correlation between the rate of sedimentation and the number of *Acanthaster planci* ossicles in the sediment. The calculations are based on mean values per 100 years. – (n = number of samples; RoS = rate of sedimentation; ApO = *A. planci* ossicles; SD = standard deviation; r_{Sp} = Spearman Rank Correlation coefficient; P = level of significance of the correlation). Based on data from Walbran et al. (1989a)

	Green Island Reef	John Brewer Reef
n	14	19
Mean RoS (cm 100 years^{-1} ± SD)	7.96 ± 22.08	21.11 ± 17.00
n(ApO) (100 years^{-1} ± SD)	16.13 ± 11.78	3.09 ± 1.93
r_{Sp}	0.78	0.65
P	< 0.001	< 0.005

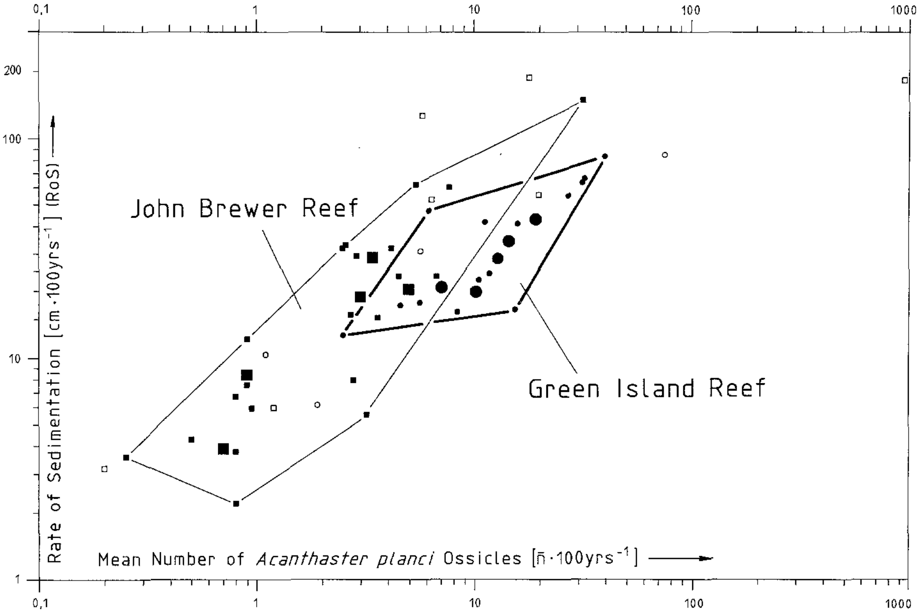

Fig. 3. Correlation between mean number of *A. planci* skeletal elements (ApO) per 100 years and rate of sedimentation (RoS) per 100 years. Only mean age values of the dated cores are plotted. The datum errors, ranging from ±70 to ±100 years, were neglected (see Figs. 1 and 2). Circles = Green Island Reef; squares = John Brewer Reef; small filled symbols (• ▪) = average values comprising the samples between two proximal datings; open symbols (○ □) = the same, but dating uncertain; large filled symbols (● ■) = average values between oldest and youngest age data of one core. Data based on Walbran et al. (1989a, Figs. W4 and W5)

Island Reef, using only the obviously reliable data of the LSC-aged samples of Walbran et al. (1989a). Similar highly significant results were achieved when all available data were included.

Discussion

Time-logs versus depth-logs

Sediment cores can be used to obtain valid information about pre-historic density patterns of organisms. But these patterns are only recognizable when the cores are adequately interpreted. Fig. 4 presents a comparison of the core JB8b in different scales: (a) shows the core-depth log of Walbran et al. (1989a, Fig. W4) with a bulge of element peaks between 300–400 cm corrected core depth. The core above 280 cm yields only few *A. planci* elements. The recent *Acanthaster* outbreaks (1969/71 and 1983/84) therefore cannot be recognized in this presentation. Whether the time reversal within the top core (310±80 years BP at the top, 250±70 years BP at core depth of 54 to 66 cm) is due to cyclone reworking, and/or bioturbation, remains uncertain. In (b) the same core, drawn as a time-log, displays quite a different pattern. The skeletal element frequency is only high in the uppermost part down to the 410±70 years BP sample. We presume that this peak is the combined signal of the 1969 and 1983 COT outbreaks on this reef. Earlier high COT population densities are not evident in this core.

Average frequencies of *A. planci* elements can certainly not trace single "outbreak events", i.e. periods of high *A. planci* densities within a time interval of only a few years. In principal, the numbers of elements retrieved from the sediment cannot be related to absolute population sizes within a given time period. Because only few cores were available to our re-scaling and there was no control core, e.g. from Heron Island, the re-scaled data still do not permit any positive conclusions about *Acanthaster* outbreak histories on these reefs. We are however able to trace marked changes in average COT population densities which could not be recognized in depth-scaled cores.

For Green Island Reef, the re-calculated data show a comparably high average number of *A. planci* over time; but more sediment age data are required to confirm this pattern, before we can decide whether the striking difference in element concentration between the two reefs has any biological significance and may be correlated to an increased susceptibility of Green Island Reef to high densities of *Acanthaster*. No indications exist for any period of high COT-density on John Brewer Reef prior to the *A. planci* plague a decade ago.

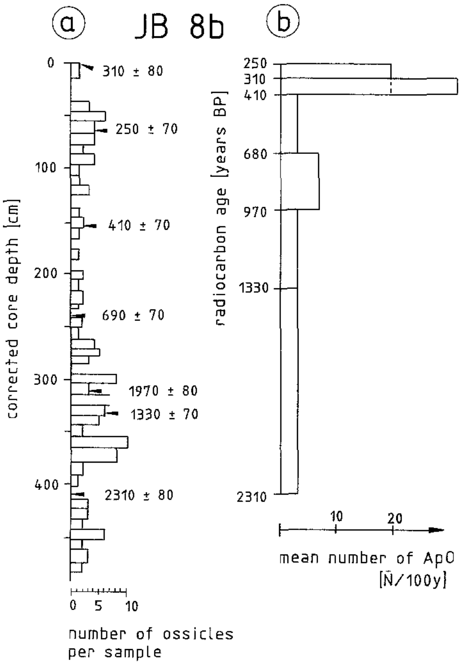

Fig. 4 a, b. Distribution of *A. planci* ossicles (ApO) in core JB8b from the northeastern "Notch" of John Brewer Reef. **a** Core-depth log (from Walbran et al. 1989a, Fig. 4). **b** Time-log based on the LSC data from the same source (l.c. Fig. 4 and Table 4)

Artificial non-linear sediment compaction may partly explain Walbran et al.'s (1989a, Table W2) finding that skeletal element frequencies increase below a core depth of 200 cm, which they interpreted as "the distributional pattern of (*A. planci*) elements within the sediment bodies as a whole". Their data imply only a linear correction of the difference between measured length of the sediment core inside the core barrel to the "penetration depth" measured at the outside of the barrel (the "core depth" values in Walbran et al. 1989b, p. 848, Fig. W2 have not been corrected). Their correction factors neglects any non-linear artificial compaction of sediment which occurs frequently in gravity cores, especially in vibro-cores. Little or almost no compaction occurs in the top part of such cores, increasing to a maximum at the base. A comparison of sectors above and below 200 cm core depth is not valid as an indication of past *A. planci* outbreaks when it is based on absolute numbers of elements per sample. In contrast to the core depth logs, time-log graphs are not influenced by this compactional distortion.

Acanthaster*-induced erosion compared to erosion by cyclones*

High rates of large-scale reef erosion, and rapid accumulation of organoclastic sediments within the reef facies, have to be considered as additional consequences of high-density *Acanthaster* populations on coral reefs. This may be concluded from the present sediment core data where the number of *Acanthaster* skeletal elements and the sedimentation rate are highly correlated.

The sedimentation rate referred to is an "effective" rate, resulting from the total sedimentation rate at the given place and time, minus the amount of sediment erosion. Thus, the clear correlation may partly be explained by a correlated sediment and skeletal element removal due to currents, wave driven sediment shifts etc.

Unprotected aragonitic skeletons of corals are much more susceptible to biogenic, chemical and mechanical destruction than skeletons covered by tissue of polyps. The bare coral framework begins to exode soon after *Acanthaster* has devastated a reef (Sano et al. 1984). The coral fragments are eventually transformed into loose and fine-grained sediments, and deposited into depressions on the reef, or on the bottom of the lagoon, or accumulate on the outer edge of the reef as a sedimentary talus. Thus, one should expect to find increased rates of deposition of sediment, and erosion of coral framework as a consequence of high densities of *A. planci.* No other biological factor is known to produce the same amount of coral death in situ which is then susceptible to biogenic and mechanical erosion.

Cyclones are another major reef-devastating force which can cause much regional damage to a reef and produce large quantities of coral debris. However, they rarely kill 90% of all living corals, as does an outbreak of *A. planci.* After a cyclone, most of the remaining coral branches and many of the coral fragments are still alive and continue to grow after the disturbance (Stoddart 1974; Schönberger 1989). Additionally, storm sediments differ in many respects from bio-erosional sediments, since "tempestites" are characterized mainly by their extremely coarse fractions with "poor" to "very poor" sorting, and also by indications of heavy mechanical wear.

It seems possible that reef erosion after intense coral predation, is a third major factor controlling reef development and termination of a reef facies in the geological past, in addition to the established factors of sea level changes and climatic changes. The question, whether reefs have been affected in earlier times similar to the present extent by coral eating organisms, remains unanswered.

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