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Water Chemistry and Hydrology of the "Blood of Sanvitores", a Micronesian Red Tide

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Abstract—According to local legend, the "Blood of Sanvitores" occurs every spring as red water in Tumon Bay (Guam) in remembrance of the execution of Padre Diego Luis de Sanvitores on 2 April 1672. Red waters are described in accounts from every century since then. Since 1985, red tides have occurred within days of the anniversary of his death, as well as in the months of January, March, June, July, August, and November. Usually, unialgal blooms ($>10^8$ cells ml^{-1}) of *Scrippsiella*, *Peridinium*, or *Gymnodinium* spp. occur for about two weeks, but a recent sample contained species of both *Scrippsiella* and *Peridinium*. The algae do not appear to adversely affect fish. Strong, noxious odors are uncommon, but can occur downwind of high-density bloom waters during calm weather. Flood tides that occur at sunrise transport bloom waters back towards the northeastern corner of the bay. Here they are maintained in an area of poor circulation that is enriched with N, P, and Fe from aquifer waters that seep from numerous inter- and subtidal springs. The bloom circulates within the bay until ebb waters begin to occur soon after sunrise which is when the organisms migrate upwards from sediments. Then, ebb waters can export the bloom either out of the bay or sufficiently far from the nutrient sources so as to increase doubling to times longer than those of water exchange.

Introduction

Van Peenen's (1974) compilation of local legends describes Father Diego Luis de Sanvitores as a naive but glib and persuasive forty-one year-old padre. He finagled his way back to Guam to convert the "poor and unhappy" Chamorros (already decimated by soldiers and ship-borne diseases) by persuading a bunch of soldiers to sail to Guam (instead of to Mexico) from Peru, all in defiance of the Governor of the Philippines. Later, Chief Quipuha allowed himself to be baptized by the padre, although probably to befriend the ruthless Spaniards. The padre then persuaded another respected Chamorro, Choco, to be baptized. These were the first great Chamorro errors, and allowed the Spaniards to disrupt their culture. Subsequent baptisms of the sick and dying produced none of the promised miracles, and the colonists established control over the Chamorros. Finally, Chief

Matapang's wife insisted on having her son baptized against her husband's wishes. Matapang enlisted the help of Chief Irao, who had been held hostage by the Spanish to avoid retribution for killing Chief Guafao, and the two chiefs beheaded the padre on 2 April 1672. Since then, "... every year, on the day of the death of Father Sanvitores, the waters of Tumon Bay turn red" (Van Peenen 1974, p. 15).

"Red tides" of toxic and non-toxic dinoflagellates (Pyrrophyta) commonly occur in coastal waters throughout the world. Some species cause paralytic shellfish poisoning, although both the color of the bloom and its associated tetrodotoxin may be produced by bacteria such as *Alteromonas*, *Vibrio*, and *Pseudomonas* spp. that are often isolated from toxic bloom waters (Evans 1973, Buck & Pierce 1989). Cysts hibernate in anoxic, dark, bottom sediments (Tyler & Seliger 1978, Anderson et al. 1987), although isolates do not germinate in the laboratory until their endogenous circannual flowering occurs (Anderson & Kaefer 1987).

Tyler & Seliger (1978) and Incze & Yentsch (1981) argued that the occurrence of red tides is due, in part, to embayment morphology and hydrology, while Pingree et al. (1975) attributed them to both nutrient exchange and density stratification across coastal sea fronts. Glover (1978) and Matsunaga et al. (1984) associate blooms that occur in open bays with levels of iron. The chelating effects of organic substances may also be a factor (Prakash & Rashid 1968, Doig & Martin 1974). Reviews of these occurrences can be found in Taylor & Seliger (1979) and in the Proceedings of the First International Symposium on Red Tides (Okaichi et al. 1989). A bibliography has also been published (Maclean & Temprosa 1989).

In March–April and November 1987, January, March and August, 1988, and April 1990, I obtained samples of red tides (that appear rust-brown) from northeastern Tumon Bay on the west central (leeward) coast of Guam. Other blooms occurred but were not sampled and red tides have not been observed elsewhere on Guam. The blooms were limited to an area of restricted circulation and low water velocity that is distal from tidal channels and close to sources of nutrient-rich aquifer waters. These and other aquifer waters have been shown to supply large amounts of nutrients to coastal areas (Capone & Bautista 1985, Johannes 1980, Zolan 1982, Matson 1987, 1991). I report the results of chemical analyses of waters within and adjacent to the blooms and offer an hypothesis on the maintenance and dissipation of the "Blood of Sanvitores".

Materials and Methods

THE STUDY SITE

Tumon Bay (Plate I) is enclosed behind a fringing reef that has one large channel in the northcentral portion for a majority of tidal exchange with the ocean. Average depth is ca. 1.3 m, the maximum tidal range is 0.70 m, and tides flood essentially into the wind that prevails from the northeast (ca. 20 kph) and which cascades over the hills bordering the corner of the bay. During the ebb, winds augment mixing and net export from this area.

SAMPLING AND ANALYTICAL TECHNIQUES

Approximately 8 to 12 water samples were taken randomly within and outside of bloom waters in acid-cleaned seawater-rinsed, linear polyethylene (LPE), 500 ml bottles. The bottles were also rinsed three times with ambient waters at the site immediately prior to sample collection. Other samples were taken from flood tide waters and from aquifer discharge points nearshore. The samples were returned (<3 hr) to the University of Guam Marine Laboratory and filtered at <120 mm Hg through precombusted Gelman type A/E glass fiber filters. After filtration, subsamples were analyzed for Si^- (molybdate/tungstate; Stainton et al. 1973), P (as filterable reactive phosphate [FRP], molybdate; Parsons et al. 1984), $NO_2^- + NO_3^-$ (NO_x, Cd reduction; Jones 1984; nitrites were rarely >0.10 μM, Matson 1991), Fe (Ferrozine; Stookey 1970, Murray & Gill 1978), and Cl^- (automated $AgCl_2$ precipitation; Buchler–Cotlove Digital Chloridometer). Salinity was calculated from Cl^- using 550 mM Cl^- as 35 ‰ seawater (Stumm & Morgan 1981). The first ca. 100 ml of each filtrate was used to rinse the filter and vessel and was then discarded, and the remainder was kept for analysis. The filters were then gently rinsed with deionized water to remove salts and dried to constant weight at 50 C for an estimate of total dry weight (TDW) of algal mass. Samples taken in 1988 were analyzed for chlorophylls *a*, *b*, and *c*, and carotenoids (Parsons et al. 1984), and cell counts of 13 samples were performed in quadruplicate in a hemacytometer. The first bloom was sampled on 19 March 1987 (although it had begun at least two days earlier), it lasted until about 10 April, and data were collected on 23, 26, and 30 March. Other blooms sampled occurred in November 1987, March 1988, and April 1990.

Results and Discussion

The "Blood of Sanvitores" has been a frequent event since at least the 1700s (Van Peenen 1974) and is apparently restricted to northeastern Tumon Bay. The blooms reported here occurred (1) for never more than 5 weeks (often for about 1 week), and (2) regardless of surface runoff and season. Guam's dry season occurs between January and June, and blooms have occurred in January, March, April, May, July, August, and November (Marsh 1977; this study). Since March of 1990, several short-duration blooms (less than 2 to 3 days) have been observed by swimmers who swim the length of the bay daily (C. McCann, pers. comm., September 1990). In the spring of 1990, live and formalin- and iodine-preserved samples were express-mailed to F.J.R. Taylor for identification. He found members of the genera *Scrippsiella* and *Peridinium* in a mixed bloom (and see Plate IB).

Blooms largely occur at salinities greater than 25 ‰ and are associated with low levels of NO_x and often elevated levels of FRP (Marsh 1977) (Fig. 1). This is largely due to the strong stratification that is caused by the constant flow of aquifer water into the northeastern corner of the bay. This cooler, ca. 3.5 ‰ aquifer water floats in a 1 to 8 cm thick layer on the surface, whereas the cells occur in a layer up to 50 cm thick in the lower water layers, but off the bottom.

Often, however, nutrient-rich aquifer water mixes rapidly with ambient bay water so that conservative dilution of NO_x and Si^- occurs (Fig. 2). This may obscure any statistically significant relationship with cell numbers or mass and nutrient content: No such relationship was found. The occurrence of these bloom organisms almost exclusively at high salinities (Fig. 1) distinguishes them from those that occur predominantly at low salinity (Tyler & Seliger 1987, Incze & Yentsch 1981). Some of the increased weights at low salinities were due to unavoidable entrainment of bottom sediments in samples taken near shore and are not due to algal mass.

Linear regressions of nutrient content on salinity have been used to predict nutrient content in full-strength seawater (35 ‰) after complete mixing with shoreline aquifer seep water (Table 1). Except for nitrate, these predicted concentrations are substantially lower than those observed within the bay, largely because salinity in this section of the bay rarely attains 35 ‰ (Figs. 1 and 2). This implies that nutrients are often depleted faster than conservative mixing indicates and that depletion is due to biological uptake during blooms. Other forms of P, such as dissolved organic P, were not measured. Marsh (1977) observed a two-fold decrease in ambient NO_x^- and an increase in FRP concentrations of these waters during blooms in July and August and attributed them to terrestrial runoff.

Blooms that occurred in January and March of 1988 were examined for cell densities, weight, and the suite of chlorophylls (Table 2, Figs. 3 and 4). Regression equations for these data are included in Table 3. The negative *y* intercept in regressions of cell number and chlorophyll content on dry weight implies that either a significant fraction of the TDW estimate was attributable to dead cells or that the TDW estimate contains particles, such as sediments, that do not contain much chlorophyll. The latter did not include weight of zooplankton which, in November 1987 were found (almost exclusively copepods) in densities of only 1.1 ± 0.4 to 4.5 ± 1.0 per liter (n = 11) within a dense bloom (23 ± 30 × 10^7 cells per liter, n = 11).

Table 1. Chemical composition of a large aquifer seep in northeast Tumon Bay, and predicted (by linear regression) concentrations in seawater assuming conservative mixing and no contribution from seawater.[a]

	Aquifer		Predicted SW Conc.
	Average	± 1 S.D.	
Cl^- (Seawater = 550)	55.9	8.9	550
Nitrate	114	15.8	12
Reactive P	0.75	0.25	0.076
Fe	0.20	0.19	0.020
Si^-	16	4.5	1.6

[a] N = 59, all in μM, except Cl^- (mM). Samples taken approximately weekly between May 1988 and September 1989 (Matson 1991).

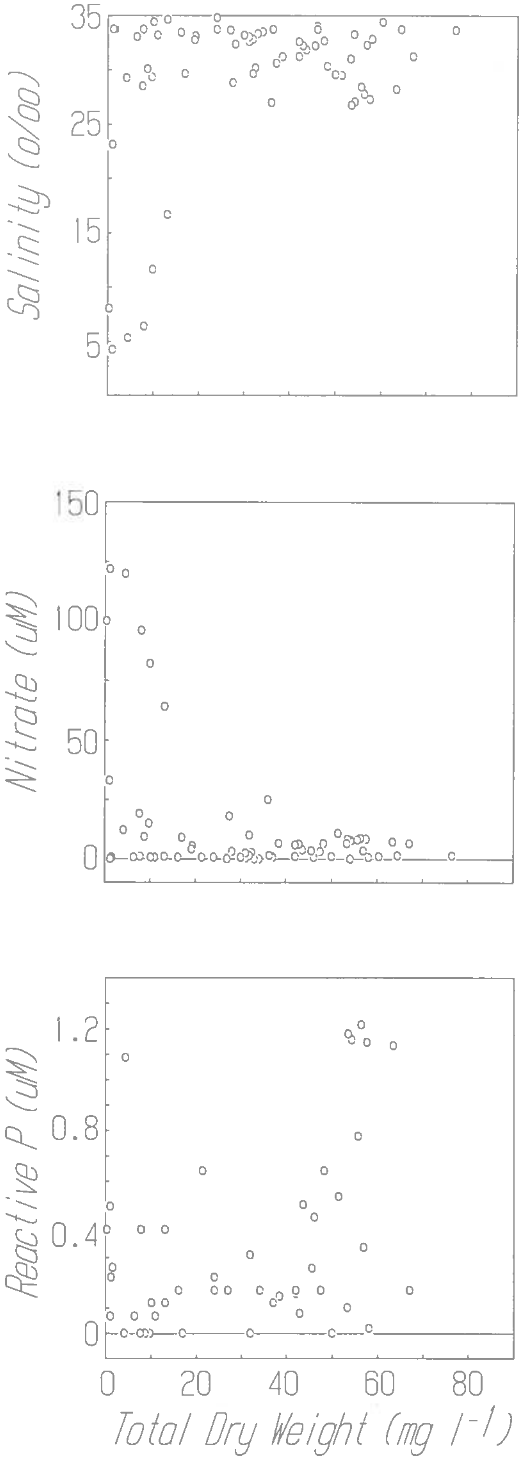

Figure 1. Salinity, nitrate, and reactive P *vs.* total dry weight of cells.

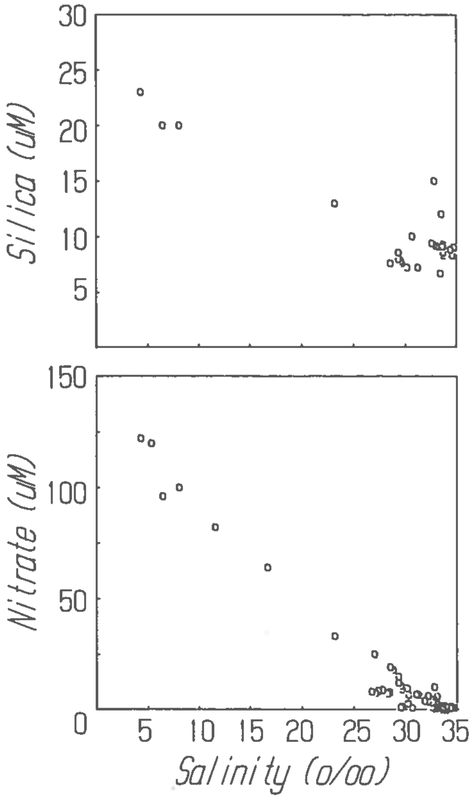

Figure 2. Silica and nitrate *vs.* salinity.

Of the macronutrients measured, NO_x would be expected to have the greatest effect on bloom densities because of the high concentrations in aquifer waters relative to P (N/P of >200). However, neither NO_x nor FRP were ever completely removed from bloom waters, although NO_x levels often approached detection limits of ca. 0.05 μM. This is perhaps 10-fold greater than physiological level (ca. tens of nM) and probably did not affect uptake of FRP. But lack of a significant relationship with any nutrient indicates that either some other nutrient or micronutrient (e.g. vitamin B_{12} or a cofactor, Bold & Wynne 1978, Yang 1989), or some physical aspects of the bloom influences its density, size, and duration.

From these studies of nutrients and cell mass it appears that there is no straightforward chemical relationship to explain the occurrence of the blooms. The chlorophyll *a* and *c* contents and cell densities are all similar to those reported at a recent symposium (Okaichi et al. 1989). Except for an apparent lack of toxicity (at least to small fish that congregate within the bloom), the Sanvitores red tide therefore appears "typical" in all aspects: numbers, chlorophyll content, diel migration, occurrence in stratified waters, and duration of the blooms (rarely longer than 1 month).

Table 2. Cell mass (total dry weight), pigments, and nitrate content during the January and March 1988 red tide.

Salinity ‰	TDW mg/l	Cells/ml millions	Nitrate μM	Pigments (μg/l)			
				chl *a*	chl *b*	chl *c*	carotenoids
28.8	27.6	37	18	74	6.5	48	5.9
34.4	60.4	82	1.2	173	0	43	13
34.0	46.0	60	1.3	57	0	20	5.0
33.7	36.4	33	1.3	77	0	19	6.5
33.7	64.4	110	1.4	160	0	49	16
27.0	36.0	32	25	67	0	53	1.8
33.6	76.4	150	1.3	196	0	168	19
30.2	32.4	19	2.7	33	0	17	1.6
32.3	28.0	16	3.0	39	0	13	3.0
33.1	19.2	10	5.7	4	7.5	0	0
11.6	9.90	no data	82	1.1	0	0	0.047
33.0	31.0	″	2.6	0.75	0	0.17	0.050
33.2	30.0	″	0.8	5.9	0.48	1.0	0.42
33.9	46.0	″	0.1	22	1.7	0.53	2.2
33.3	54.0	″	0.1	67	0	8.6	4.7
33.7	27.0	″	0.3	27	0.58	1.2	2.4
32.6	31.0	″	0.3	29	0.41	2.2	2.3
33.3	33.0	″	0.1	26	2.9	1.8	2.0
32.7	19.0	″	4.3	0	0	0	0.0060
16.7	13.0	″	64	5.2	0.92	1.3	0.24

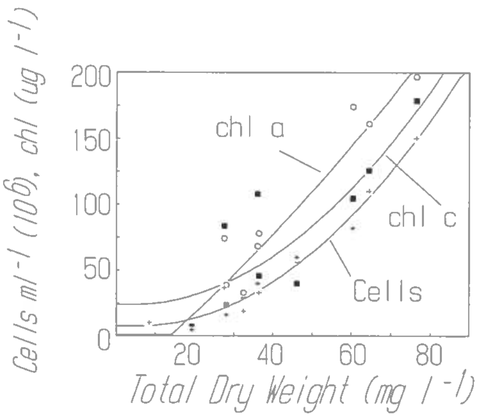

Figure 3. Cell density and chl *a* and *c* *vs.* total dry weight of cells.

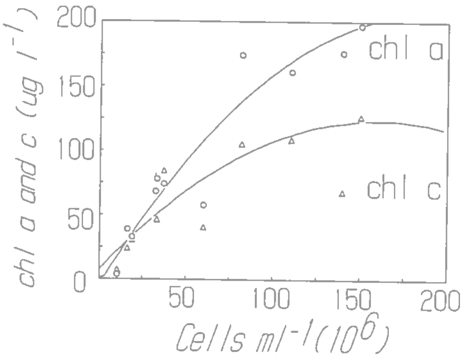

Figure 4. chl *a* and *c* *vs.* cell density.

It is likely that calm, dry weather that occurs during many blooms stimulates the upward flux of sedimentary pore water nutrients (especially FRP) to the surface waters (Matson 1989). This is due to upward migration of the sedimentary redox discontinuity layer during calm weather. These sedimentary redox conditions may also stimulate cyst germination that initiate blooms elsewhere (An-

Table 3. Least squares linear regressions ($y=mx+b$) for cell numbers, mass, and chlorophyll content. All significant at $P<0.005$.

X	Y	N	m	b	r^2
Dry weight	Cell numbers	10	2.4	−47	0.97
Dry weight	chl *a*	17	3.0	−54	0.87
Dry weight	chl *c*	17	1.4	−30	0.71
Cell numbers	chl *a*	10	1.3	16	0.93
Cell numbers	chl *c*	10	0.76	−0.75	0.84

derson et al. 1987). Also, the organisms migrate into the nutrient-rich sediments during the night and take up nutrients (Harrison 1976) for subsequent use during daylight when they migrate back into the water column.

This diel migration was observed on several occasions in Tumon Bay. Observation of these blooms with SCUBA reveal (1) they cannot be found in the water column at night with dive lights, and (2) they migrate at sunrise from the sediments up to the base of the nutrient-rich, surface aquifer water layer that floats on the surface. This presumably keeps the cells away from excess sunlight, within the layer of seawater that contains normal amounts of carbonate, but also adjacent to relatively nutrient-rich eddies that occur between the stratified layers. Bloom material was never observed in the top ca. 5 cm of water. This diel pattern may be similar to that of other flagellates that divide during the day and migrate to deeper water at night to obtain nutrients (Takahashi & Hara 1989, Yamochi 1989). Further, in a review of a recent symposium, it was said that: "... swimming behavior ... serves several fundamental ecological roles. It influences retention within an area; it is a mechanism of depth keeping; it is sensitive to the nutrient field; it facilitates accumulation. These, in turn, influence seeding and bloom dynamics. Motility per se, however, does not appear to be a mode of nutrient uptake ..." (Smayda 1989, pp. 27).

Apparently then, something other than macronutrient availability regulates the Tumon Bay blooms. For example, in a study of nearshore Tumon Bay blooms of the green macroalga *Enteromorpha clathrata*, biomass was related to both the availability of substratum (physical control) for attachment (dead coral rubble, especially *Acropora* spp.) as well as to NO_x^- from the aquifer (chemical control). Reported levels of both Fe and Mn were low, but detection limits (1 μM) of the Fe method were several fold greater than ambient seawater concentrations (Fitzgerald 1978). In this study, a more sensitive method for Fe analysis was used and Fe averaged 0.2 μM (ca. 20× the detection limit) in both aquifer seep water and seawater (Table 1). Nevertheless, neither Fe nor any other measured nutrient was significantly related to cell mass or numbers.

Some physical control of bloom maintenance and dissipation (but not initiation) is then suggested. The bloom of March 1987 was first reported to me by Cathryn McCann who has worked at a beachfront bistro there for several years. She drew maps of the bloom area three times per day beginning 21 March, two days after the bloom was first noticed (19 March) and continued to record its position until 25 March (Fig. 5, copies of the originals). Note that the bloom was restricted to the northeastern end of the bay during high tides, and, during the single observation made at sunrise, was distributed far to the southwest. These drawings plus observations of subsequent blooms made it evident that (1) the bloom was restricted to the northeastern end of the bay and (2) it rotated within this area.

It is possible then that tidal flow and circulation regulate the position and maintenance of blooms once they begin. First, at the beginning of the flood, seawater enters the bay through tidal channels southwest of the bloom area and then flows to the northeast corner (from right to left in photo in Plate IA). Then, when the water level is higher than the reef crest, the remaining flood waters (ca. 10 to 20% of the tidal prism) enter over the entire reef crest. The bloom is then transported towards shore. Next, at the beginning of the ebb, waters exit directly over the reef crest and transport the bloom away from shore until the water level drops below the level of the crest. Thereafter, the bloom waters are transported southwest towards the tidal channels until slack low water occurs. The cycle is then repeated on the flood, when bloom waters move back to the northeast. The most dense bloom areas remain immediately in front, or tens of meters to the southwest of the Okura Hotel (Plate IA).

Calculated average water motion due to tidal excursion (distance an average parcel of water moves between tidal extremes) is 127 m, which, depending upon lunar phase, occurs over a ca. 6 to 10 hr tide. This is about 33% of the distance to the tidal channel (Plate IA). Because equivalent transport may occur on the flood, several days to weeks is required to export the bloom out of the bay. Further, unless doubling times are sufficiently fast, nutrient depletion could occur during the residence time of the bloom. Estimates of population growth (total cell counts) in a sample bottle left in the laboratory averaged 29 ± 5% per day (N = 7), which is about equal to the rate of water exchange.

Hence, both the timing of ebb and the doubling time are critical, especially if ebb flow begins just after sunrise when the cells are migrating upwards from the sediments. The blooms may be maintained when either slack water or the beginning of the flood occur at sunrise so as to carry them northeast rather than towards the tidal channels. This increases both their residence time within the enriched water and their potential growth rate. Once the tides begin to change or if nutrients are depleted because of extended residence within nutrient-enriched water, the bloom will dissipate.

This sequence, plus the essentially constant flow (ca. 79 m^3 m^{-1} shoreline d^{-1}; Emory 1962, Matson, in preparation) of nutrient-rich waters from the aquifers all along the beach appear to maintain blooms for up to 5 weeks. Low tides occurred during the pre-dawn hours (when the organisms are within the surface sediments) for several days immediately preceding all blooms studied (Fig. 6). In addition to maintaining the bloom waters within the northeast corner of the bay, pre-dawn low tide waters are also enriched with higher concentrations of nutrients than during high tide simply due to lower volume. Further, the weeks

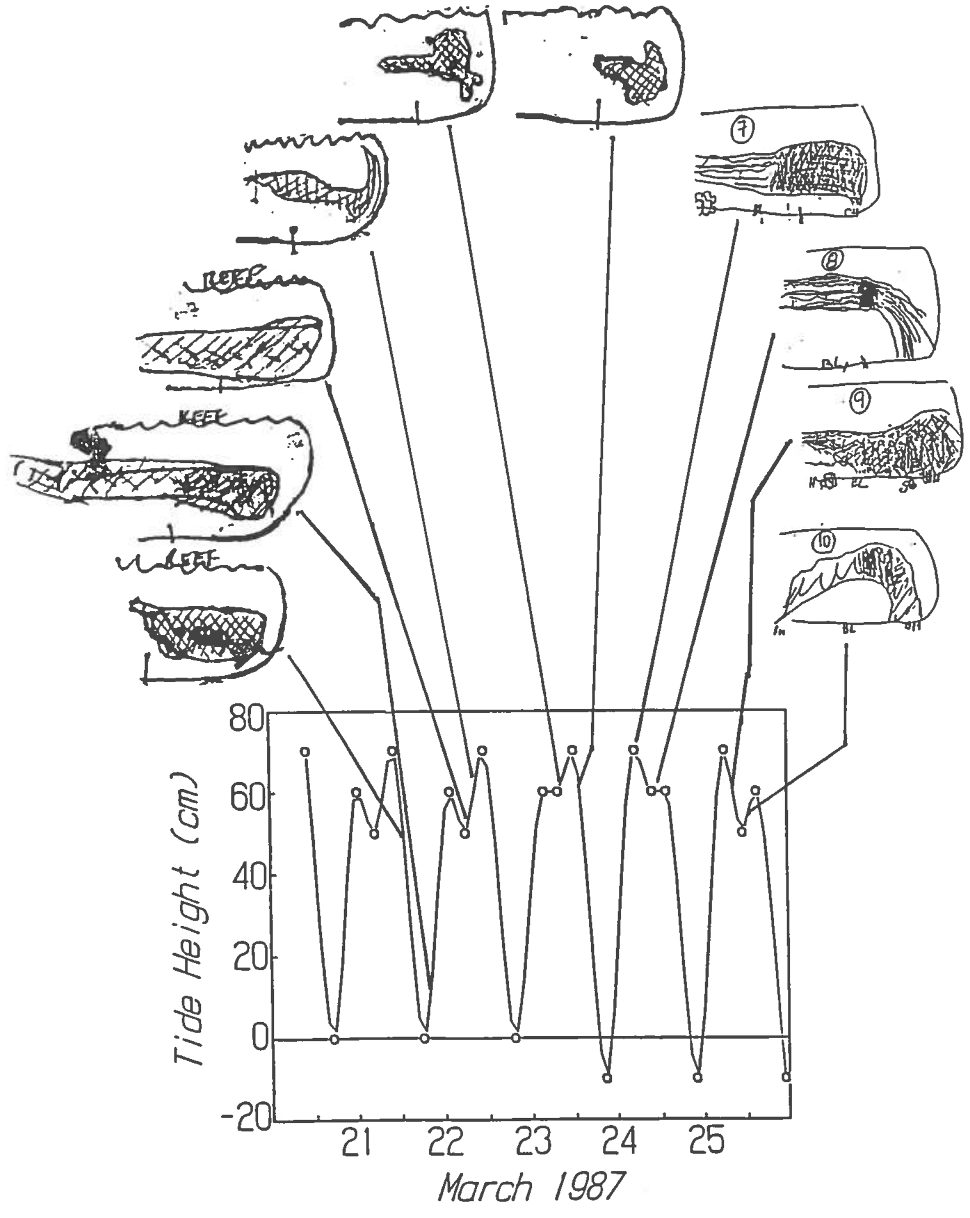

Figure 5. Original sketches (by C. McCann) of the position of the bloom (as seen from an elevation of 5 m above MHW and 100 m southwest of the Okura Hotel, compare with Plate IA) superimposed on tide level. Note that low tides occurred after sunset.

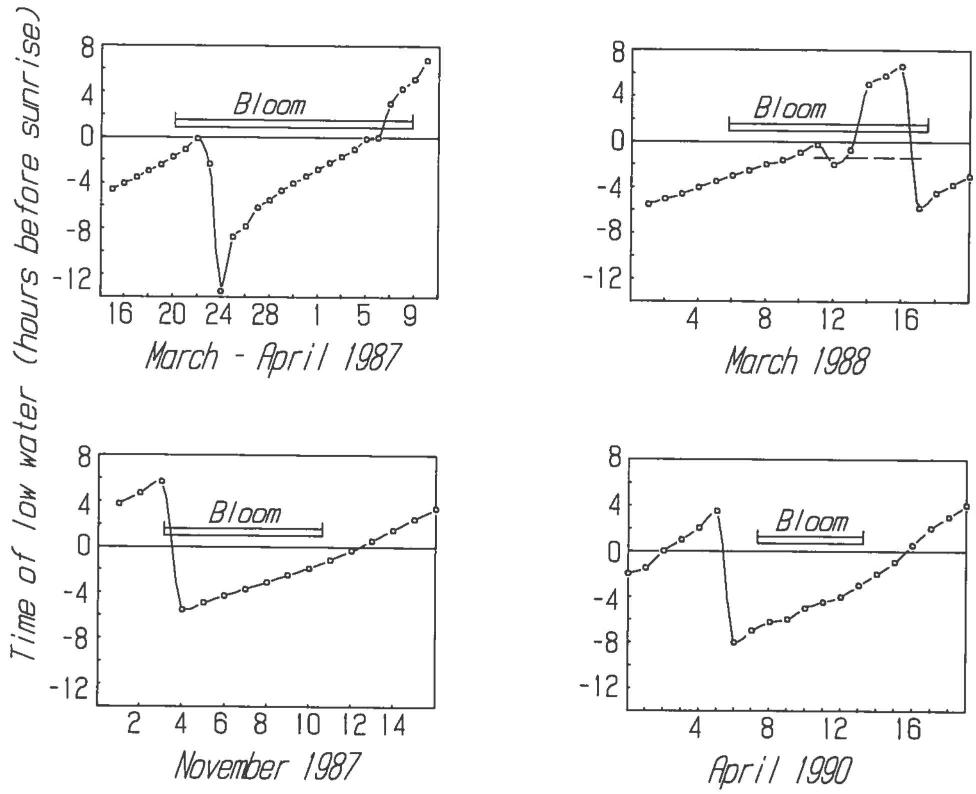

Figure 6. Number of hours before sunrise (negative numbers) at which MLW occurred during four red tides. The dashed line in March 1988 indicates occurrenct of high low water levels with predawn changes in tide height of 0.1 ft or less between HHW and LHW.

and months prior to the onset of the March 1987 bloom were calm (which may promote bloom development, Bold & Wynne 1978) and sufficiently dry to set 36 year low rainfall records, thus eliminating surface runoff as a factor.

Thus, Tumon Bay works like a chemostat: as aquifer waters enrich the bay with nutrients, blooms are maintained. Flood cycle characteristics keep the bloom within this end of the bay. "Washout" (bloom dissipation) then begins to occur when either the ebb waters occur at sunrise when the cells begin to migrate up into the water column or, regardless of tide, when nutrients approach depletion because doubling times have been much faster than water exchange.

Further study of tidal exchange, micronutrients, the occurrence of siderophores and of cyst germination rhythms should help clarify the mechanisms that initiate and maintain this common flowering.

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References

Anderson, D. M. & B. A. Kaefer. 1987. An endogenous annual clock in the toxic dinoflagellate *Gonyaulax tamarensis*. Nature 325: 616–617.

Anderson, D. M., C. D. Taylor & E. V. Armbrust. 1987. The effects of darkness and anaerobiosis on dinoflagellate cyst germination. Limnol. Oceanogr. 32: 340–351.

Bold, H. C. & M. J. Wynne. 1978. Introduction to the Algae: Structure and Reproduction. Prentice-Hall, Englewood Cliffs, 706 pp.

Buck, J. D. and R. H. Pierce. 1989. Bacteriological aspects of Florida red tides: A revisit and newer observations. Est. Coast. Shelf Sci. 29: 317–326.

Capone, D. G. & M. F. Bautista. 1985. A groundwater source of nitrate in nearshore marine sediments. Nature 313: 214–216.

Doig, M. T., III & D. F. Martin. 1974. The effect of naturally occurring organic substances on the growth of a red tide organism. Wat. Res. 8: 601–606.

Emory, K. O. 1962. Marine Geology of Guam. U.S. Geol. Survey Prof. Pap. 403-B: 1–76.

Evans, E. E. 1973. The role of bacteria in the Florida red tide. Environm. Lett. 5: 37–44.

Fitzgerald, W. J., Jr. 1978. Environmental parameters influencing the growth of *Enteromorpha clathrata* (Roth) J. Ag. in the intertidal zone on Guam. Bot. Mar. 21: 207–220.

Glover, H. E. 1978. Iron in marine coastal waters: Seasonal variation and its apparent correlation with a dinoflagellate bloom. Limnol. Oceanogr. 23: 534–537.

Harrison, W. G. 1976. Nitrate metabolism of the red tide dinoflagellate *Gonyaulax polyedra* (Stein). J. Exp. Mar. Biol. Ecol. 21: 199–209.

Incze, L. S. & C. M. Yentsch. 1981. Stable density fronts and dinoflagellate patches in a tidal estuary. Estuar. Coast. Shelf Sci. 13: 547–556.

Johannes, R. E. 1980. The ecological significance of the submarine discharge of groundwater. Mar. Ecol. Progr. Ser. 3: 365–373.

Jones, M. N. 1984. Nitrate reduction by shaking with cadmium: Alternative to cadmium columns. Wat. Res. 18: 643–646.

Maclean, J. L. and R. M. Temprosa. 1989. Bibliography on Indo-Pacific Red Tides. Int. Centr. Living Ag. Resources Mgmnt. (ICLARM) MC Box 1501, Makati, M.M. Philippines. 23 pp.

Marsh, J. A., Jr. 1977. Terrestrial inputs of nitrogen and phosphorus on fringing reefs of Guam. pp. 331–336 *In* Proc. Third Int. Coral Reef Symp., Miami.

Matson, E. A. 1987. Groundwater nitrate intrusion into coral sediments and a reef moat of Guam. Eos 68: 1689.

Matson, E. A. 1989. Biogeochemistry of Mariana Islands Coastal Sediments: Terrestrial influence on $\delta^{13}C$, Ash, $CaCO_3$, Al, Fe, Si, and P. Coral Reefs 7: 153–160.

Matson, E. A. 1991. Nutrient chemistry of the coastal waters of Guam. Micronesica 24: 109–135.

Matsunaga, K., K. Igarashi, S. Fukase & H. Tsubota. 1984. Behaviour of organically-bound iron in seawater of estuaries. Estuar. Coast. Shelf Sci. 18: 615–622.

Murray, J. W. & G. Gill. 1978. The geochemistry of iron in Puget Sound. Geochim. Cosmochim. Acta 42: 9–19.

Okaichi, T., D. M. Anderson & T. Nemoto (eds.). 1989. Red tides: Biology, Environmental Science, and Toxicology. Elsevier, New York, 489 pp.

Parson, T. R., Y. Maita & C. M. Lalli. 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon Press, New York, 173 pp.

Pingree, R. D., P. R. Rugh, P. M. Holligan & G. R. Forster. 1975. Summer phytoplankton blooms and red tides along tidal fronts in the approaches to the English Channel. Nature 258: 672–677.

Prakash, A. & M. A. Rashid. 1968. Influence of humic substances on the growth of marine phytoplankton: dinoflagellates. Limnol. Oceanogr. 13: 598–606.

Stainton, M. P. M. J. Capel & F. A. J. Armstrong. 1974. The Chemical Analysis of Fresh Water. Environm. Canada Misc. Publ. 25. Res. Devel. Direct., Freshwater Inst. Winnipeg.

Stookey, L. L. 1970. Ferrozine—a new spectrophotometric reagent for iron. Anal. Chem. 42: 779–781.

Stumm, W. & J. J. Morgan. 1981. Aquatic Chemistry: An Introduction Emphasizing Chemical Equilibria in Natural Waters. Wiley-Interscience, John Wiley & Sons, New York, 780 pp.

Takahashi, M. & Y. Hara. 1989. Control of diel vertical migration and cell division rhythm of *Heterosigma akashiwo* by day and night cycles. *In* T. Okaichi, D. M. Anderson & T. Nemoto (eds.), Red tides: Biology, Environmental Science, and Toxicology, pp. 265–268. Elsevier, New York.

Taylor, D. L. & H. H. Seliger, (eds). 1979. Toxic Dinoflagellate Blooms. Elsevier/North Holland, Amsterdam.

Tyler, M. A. & H. H. Seliger. 1978. Annual subsurface transport of a red tide dinoflagellate to its bloom area: Water circulation patterns and organism distribution in the Chesapeake Bay. Limnol. Oceanogr. 23: 227–246.

Van Peenen, M. W. 1974. Chamorro Legends on the Island of Guam. University of Guam, Micronesian Area Research Center, Publ. No. 4.

Yamochi, S. 1989. Mechanism for outbreak of *Heterosigma akashiwo* red tide in Osaka Bay, Japan. *In* T. Okaichi, D. M. Anderson & T. Nemoto (eds.), Red tides: Biology, Environmental Science, and Toxicology, pp. 253–256. Elsevier, New York.

Yang, D. B. 1989. Nutrients and chlorophyll *a* variations during the red tides in Jinhae Bay, Korea. *In* T. Okaichi, D. M. Anderson & T. Nemoto (eds.), Red tides: Biology, Environmental Science, and Toxicology, pp. 237–240. Elsevier, New York.

Yentsch, C. M., B. Dale & J. W. Hurst. 1978. Coexistence of toxic and nontoxic dinoflagellates resembling *Gonyaulax tamarensis* in New England coastal waters (N.W. Atlantic). J. Phycol. 14: 330–332.

Zolan, W. J. 1982. A Preliminary Study of Natural Aquifer Discharge on Guam. Univ. of Guam Water and Energy Res. Inst. Tech. Rpt. 34. Mangilao. 40 pp.

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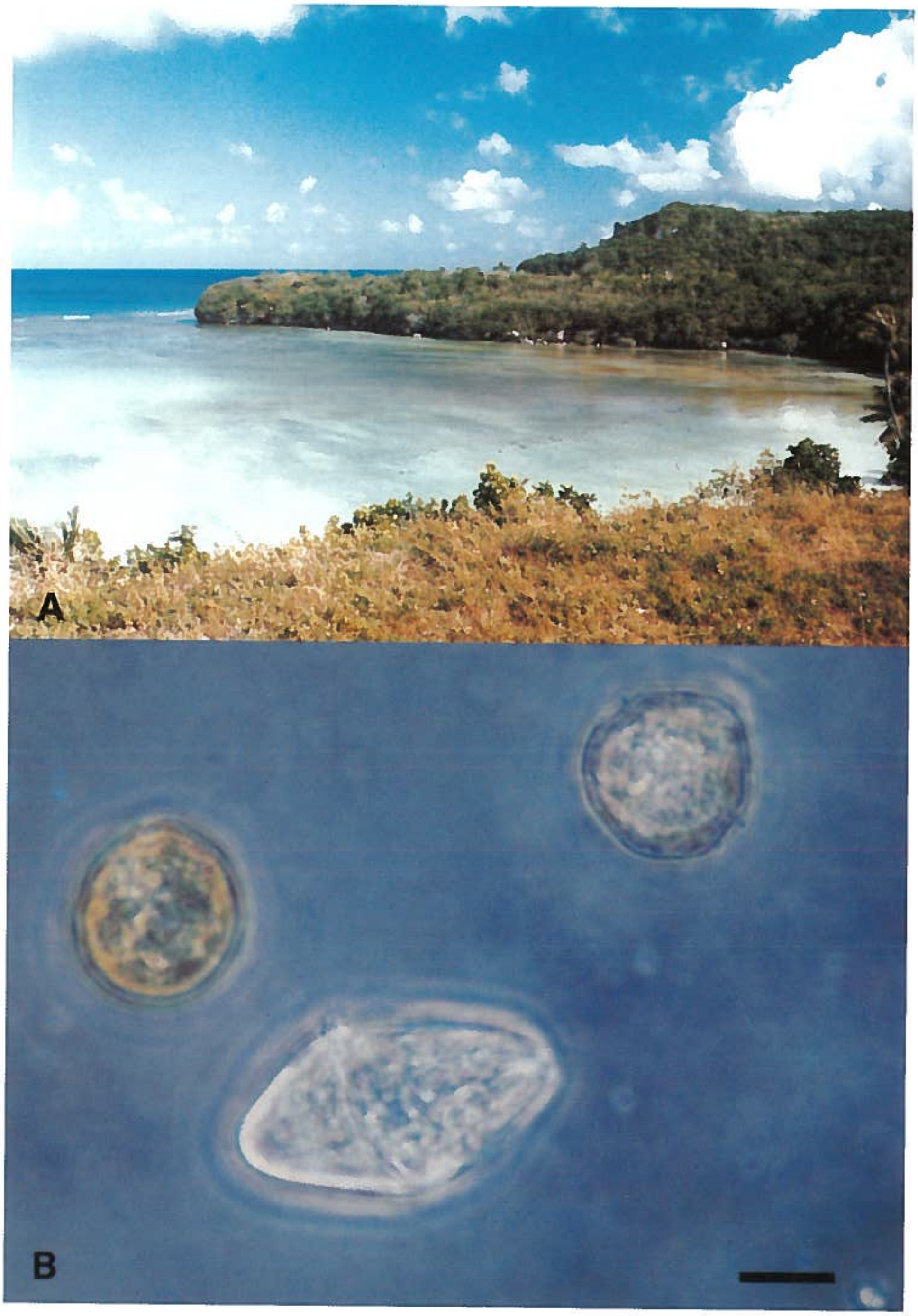

Matson—Plate I. A: Tumon Bay, Guam, with a view of the March 1988 bloom. B: photomicrograph of two dinoflagellates from a 1990 bloom. The colorless cell is a *Gyrodinium* sp., and the pigmented cells are *Scrippsiella*. Scale bar = 10 μm.