Project: Ke 287/9 „Untersuchung der Mikrobialithe und Spongien-Assoziation im mit alkalischem Meerwasser gefüllten Kratersee von Satonda (Indonesien) als rezentes Beispiel fossiler Spongiolithfazies", Project Leader: S. Kempe (Darmstadt)

Microbialites and Hydrochemistry of the Crater Lake of Satonda – a Status Report

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Area of Study: Satonda Island, Indonesia
Environment: Marine soda lake
Stratigraphy: Holocene
Organisms: Algae, gastropods, microbes
Depositional Setting: Volcanic crater lake
Constructive Processes: Algae-microbialite reef
Destructive Processes: —
Preservation: —
Research Topic: Microbialites and hydrochemistry

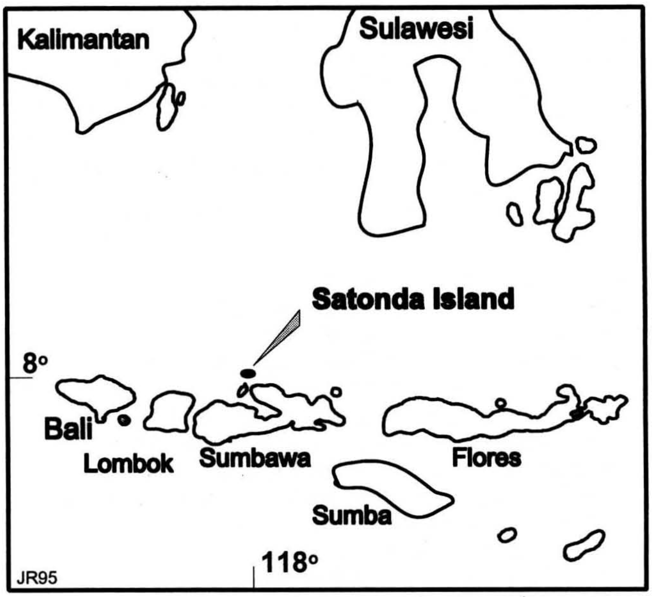

Fig. 1: Location of Satonda Island in the Sunda archipelago, Indonesia.

Abstract

The Satonda crater lake is up to now the only known "marine" lake with an increased alkalinity compared to seawater. Therefore, the lake contains a decreased amount of Ca^{2+}. Its pH values about 8.5-8.6. The lake was originally filled with freshwater, which is evident from peat deposits (3,150 ^{14}C-yrs BP). Shortly after the lake was rapidly filled with seawater and a marine fauna had established. Large input of organic matter has caused an intense oxygen consumption and, as a result, the bottom water of the lake became anaerobic. Thus, an intense sulfate reduction occurred producing high amounts of bicarbonate ions. The lake became stratified into three water bodies with various salinities separated by two pycnoclines. The surfaces water body is oxygenated and exhibits brackish conditions. The algae/microbialite reefs exhibit a vertical development which started with a serpulid framework, followed by loose crusts of the calcified red alga *Peyssonnelia* and thalli of the green alga *Cladophoropsis* calcified by cyanobacteria (microstromatolites). The top calcified layer is formed by a network of *Lithoporella*, *Peyssonnelia* and microbialites. On the top layer the living reef community is located.

REITNER, J., NEUWEILER, F. & GUNKEL, F. (eds., 1996): Global and Regional Controls on Biogenic Sedimentation. I. Reef Evolution. Research Reports. – Göttinger Arb. Geol. Paläont., **Sb2**, 59-63, Göttingen

1 Introduction

Satonda, a small Indonesian island, north of Sumbawa, features a world-wide unique habitat: a crater lake filled with seawater (Fig. 1). Today, lake and ocean waters cannot communicate anymore and the lake water has developed an alkalinity, pH and carbonate mineral saturation higher than in the original seawater. Such a milieu apparently is unfavorable for most marine macrobiota, even though several marine species had settled the lake originally. Instead we find prominent calcareous reef-like structures (Fig. 2) composed of red algae, serpulids, foraminifera, and, most important of all, mats of in situ calcifying cyanobacteria (Fig. 3). The morphology and the microstructure of these reefs remind of certain microbialites (i.e., deposits formed by the permineralization of microbial mats) from the geologic past. Satonda may therefore serve as a contemporary model environment simulating ancient oceanic conditions (KEMPE & KAZMIERCZAK 1990, 1993, 1994).

The site was discovered during the Dutch-Indonesian SNELLIUS II expedition in November 1984 (by S. Kempe). In the samples from the calcareous reef J. Kazmierczak noticed microbial structures similar to some early Paleozoic problematic fossils (KAZMIERCZAK & KEMPE 1990, 1992). A ten day campaign was conducted during the German-Indonesian SONNE 45b expedition (October 3-13, 1989) to study the lake and its carbonates for the first time. Within the framework of the German Research Foundation „Global and Regional Controls on Biogenic Sedimentation" we were invited by the Indonesian Forest Service to study the biota of the island during a joint three week survey in 1993 (October 5-25). A final sampling is underway – in cooperation with the Indonesian ministry LIPI – in May 1996 to characterize the lake after the rainy season in order to establish the amplitude of the seasonal signal in its hydrochemistry.

2 Results

We can now reconstruct parts of the history of the lake and its ecosystem.

The lake itself is 1.2 x 0.9 km wide. It is 69.5 m deep (average: 44 m), has a volume of 0.034 km^3 and a surface area of 0.77 km^2. The basin probably marks a caldera collapse more than 10,000 years ago. It consists of two nested craters, the smaller one to the northeast (Fig. 2). The crater walls rise up to 300 m and are covered by a dense savanna-type vegetation. To the south, the crater wall apparently has collapsed towards the sea, leaving only a thin, 60 m wide, and low (13 m above sealevel) remnant of the former wall. This gap forms the only access to the lake today. The slump scar formed a bay, while the slump mass (as traced by echo sounding) extends tongue-like underwater.

The lake was originally filled with fresh water. This is evident from peat deposits dated to 3,150 yrs BP (^{14}C-years) found below the quasi-marine deposits in digs along the shoreline of the lake. Shortly after, the lake was flooded with seawater. This flooding, or rather this percolation of seawater through the remnant crater wall, seems to be connected with a 1-1.5 m higher sealevel than today. This high sealevel stage is evident along all of the coasts of the region. At the time, seawater occupied the bay-like slump scar. The bay began to fill with beach deposits (as proven by digs) and the sealevel gradually receded, causing the percolation of seawater through the crater wall to become slower and slower. Today the lake level stands, at the end of the dry season, some 80 cm above the level of spring tides, clearly indicating the lack of any hydraulic communication between ocean and lake.

The lake shore digs indicate that several species of marine bivalves and gastropods colonized the lake together with foraminifera, ostracods and serpulids initially (KEMPE & KAZMIERCZAK 1993). First, serpulid reefs (Fig. 3) grew along the beach and all the way down to at least 35 m of depth. The next step was the onset of stratification of the water column at about 50 m because of the relative depth of the lake. The lack of strong enough wind mixing and the production of heavy brines in small shallows along the shore sinking to the bottom of the lake were probably the causes for this initial stratification.

The large input of organic matter from the crater walls must have caused a rapid consumption of oxygen and other electron acceptors such as NO_3, NO_2, Mn^{4+} and Fe^{3+} from the bottom layer which then became anaerobic quickly (Fig. 4). Then sulfate reduction fuels the further respiration of organic matter, and – because of the large concentrations of sulfate in seawater – high concentrations of H_2S are produced, purging all higher life from depth. In the process bicarbonate ions are generated in order to replace the negative charges of the removed sulfate ions:

$$53\ SO_4^{2-} + C_{106}H_{263}O_{110}N_{16}P + 14\ H_2O \rightarrow$$
$$53\ H_2S + 106\ HCO_3^- + HPO_4^{2-} + 16\ NH_4^+ + 14\ OH^-$$

(Organic matter is written here in its overall average elemental composition known as the Redfield ratio). In the reaction H_2S and bicarbonate are produced at a molar ratio of 1:2. A stratified basin, such as Satonda, in which a significant excess of alkalinity is produced (KEMPE 1990), is called an alkalinity pump (KEMPE & KAZMIERCZAK 1994). At the bottom of the lake almost all of the sulfate has been consumed and the alkalinity has increased to over 50 meq/kg, ca. 25 times that of normal seawater (Fig. 4). Because some mixing still occurs across the interface, even the upper water column became more alkaline than seawater with the consequence that pH and total saturation of carbonate minerals rise substantially. Saturation with regard to a certain mineral is defined as the ratio between the ion activity product (IAP) of the ions forming the respective mineral and the solubility (at a certain temperature and salinity). The Saturation Index (SI) is the log of that ratio:

$$SI_{Mineral} = \log(IAP/K_{Mineral})$$

Normal surface seawater is already carbonate mineral supersaturated (i.e., $SI_{calcite}$=0.4-0.6) but the biocalcifying organisms keep this supersaturation at a level precluding spontaneous precipitation (which seems to necessitate a SI

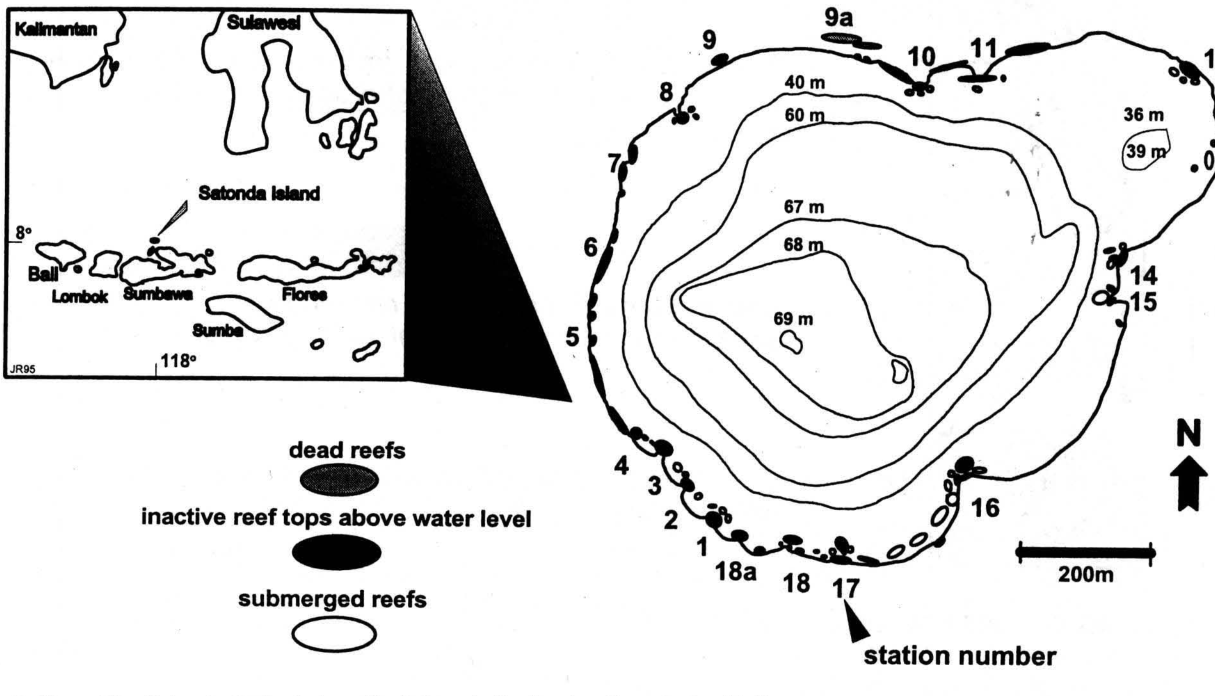

Fig. 2: Map of the Satonda Crater Lake with stations indicating location of microbialites.

of >0.8) (KEMPE & KAZMIERCZAK 1990). In Satonda (Fig. 4) supersaturation rose so quickly that the restricted fauna of biomineralizers was not able to remove enough $CaCO_3$ to regulate it. Supersaturation and alkalinity then rose to a level causing the extermination of all mollusks except for one gastropod species. Most probably, the SI rose to values even beyond of its present values which are 0.84 for $SI_{aragonite}$ and 0.98 for $SI_{calcite}$ in the surface layer down to 20.5 m. During this period the significantly increased level of carbonate supersaturation caused the formation of in situ calcified cyanobacterial microbialites in the lake epilimnion (Fig. 3). These internally well-laminated (i.e. stromatolitic) or cystous (*Wetheredella*-like) microbialites are often overgrowing individual filaments or tufts of non-calcifying siphonocladalean green algae (mostly *Cladophoropsis*) or intergrowing with arcuate thalli of calcareous red algae (*Peyssonnelia*). The microbialitic layer is up to 80 cm thick at the lake surface but decreases in thickness to a few cm at 20 m depth. In thin sections the microbialites show distinct, dark laminae composed of fine-grained high Mg-calcite alternating with usually much thicker, light laminae composed of fibrous, finely striated aragonite.

SEM inspection of acid-etched cross-sections of microbialite laminae shows that both dark and light laminae originally are composed of cells, 2-4 µm in diameter, gathered in subglobular groups, 30-100 µm in diameter. These groups are surrounded with a capsule-like common organic wall, which can be easily identified as remnants of gelatinous sheaths of benthic coccoid cyanobacteria (Pleurocapsales), identical with those living today on the reef surface. We think that the lamination and the varying mineralogy of the microbialites are results of seasonally changing supersaturation in the lake. During the wet season (November-April) the supersaturation of the lake is lowered due to the dilution of the surface waters by rain and the mat can grow unimpeded. During the dry season (May to October) the $CaCO_3$-supersaturation rises and in vivo precipitation of microgranular high Mg-calcite proceeds at the mat surface. Once the surface is permineralized, the mat below decays (mostly by sulfate reducing bacteria and fungi) under anaerobic sulfate reducing conditions. The alkalinity is raised internally and, due to the ongoing crystallization of $CaCO_3$, the Mg/Ca ratio rises, causing aragonite instead of calcite to form post mortem. This picture is consistent with the observation that the remains of the sheaths are not as well preserved in the aragonite as in the calcite layers.

The importance of finding these microstructures cannot be overestimated: In recent marine environments, in situ calcification of cyanobacterial mats does not occur. Almost all modern calcareous stromatolites are either formed by trapping of suspended material or the sites are clearly non-marine (e.g. in Lake Van, Turkey; KEMPE et al. 1991). In the past, in-situ calcification of marine cyanobacterial mats must, however, have occurred. Throughout the Precambrian the stromatolitic deposits they produced were the only wide-spread fossil remains.

The most recent phase of Satonda reef development, showing continuity with the biota living today on the reef surface, is characterized by domination of encrusting red algae and nubecullinid foraminifera with only a subordinate role of coccoid cyanobacteria (Fig. 3). A dense cyanobacterial and red algae (mainly *Lithoporella*) crust comprises the

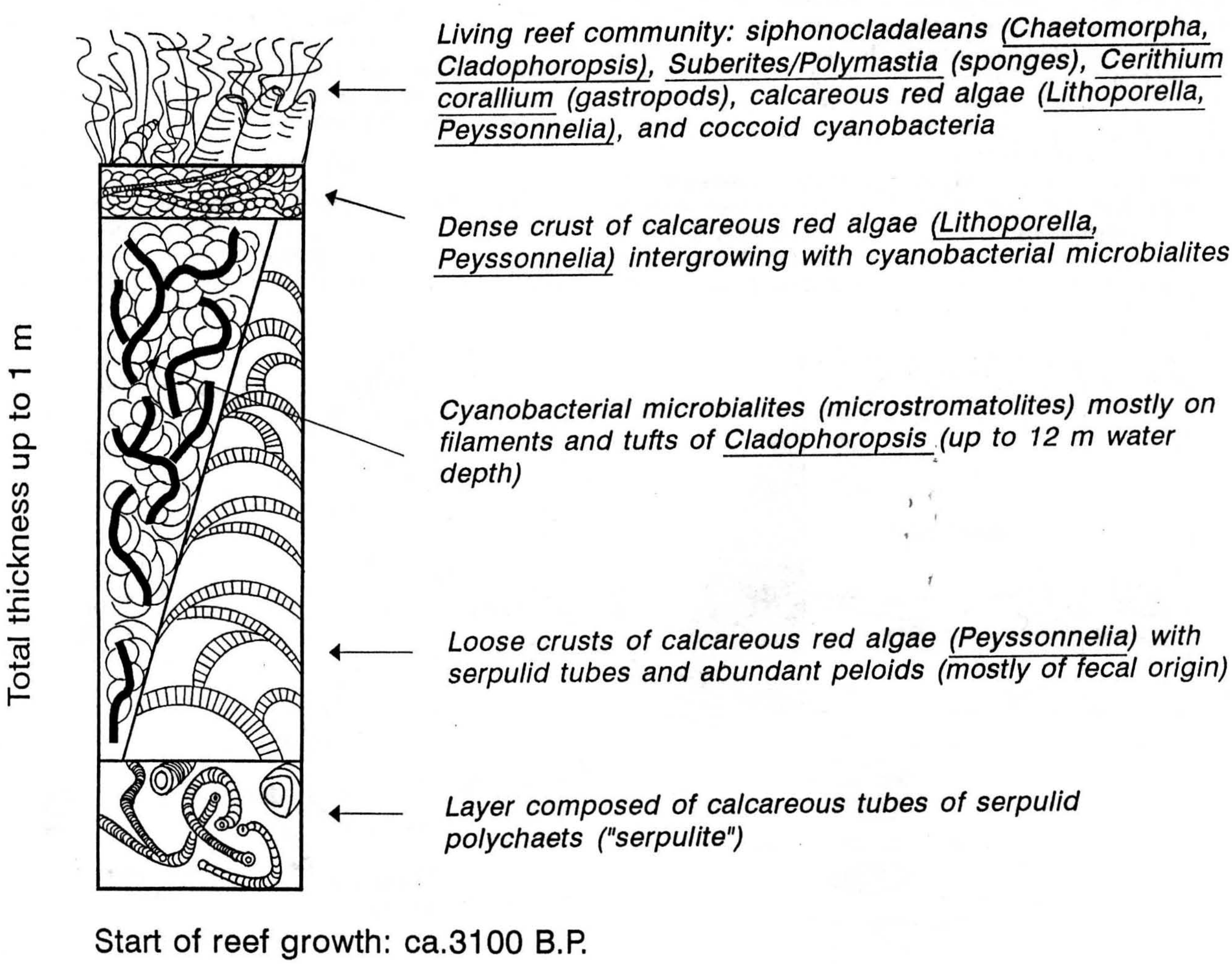

Fig. 3: Scheme of facies succession in Satonda Lake calcareous reefs.

few millimeters thick top layer of the reefs. Below this a 15-20 cm thick, much looser red algal crust occurs, composed of the aragonitic thalli of *Peyssonnelia*. Shells of a small cerithiid gastropod are often found immured in this layer. Very similar gastropods inhabit the lake today in large numbers which are now identified as *Cerithium corallium* with the possibility of being a subspecies endemic to Satonda. These graze on the thick pelt of siphonocladalean green algae overgrowing the reef surface together with a large community of sponges which also appears to represent a new endemic species of the hadromerid demosponge taxon *Suberites/Polymastia*.

The onset of the new biofacies type, which apparently heralded less alkaline and supersaturated conditions in the lake, may have been connected with the further stratification of the lake's water column. Today a well defined pycnocline (density interface) exists at a depth of 22 m (Fig. 4) separating the former epilimnion layer into a wind-mixed, oxygenated surface layer from a moderately anaerobic middle layer. The present aerobic surface layer has been diluted by rain water to about 90 % of seawater salinity and the layer below has a salinity of 108 % of ambient seawater. The freshening of the surface layer may either have climatic reasons, or it may have been initiated after the Tambora eruption in 1815 AD. Then the island was almost completely deforested and, due to the missing evapotranspiration, much more rainwater may have collected in the crater annually than previously, causing the freshening of the upper water column and inhibiting deep mixing for some time. At the same time, older, more salty, and anaerobic water was slowly pressed out of the lake through the porous volcanic rocks.

Even though conditions today seem to be more favorable to life in the crater lake than before, the alkalinity pump still works vigorously at depth. Between November 1986 and October 1993 the alkalinity in the surface layer increased from 3.6 to 4.2 eq/kg and the pH increased from 8.4 to 8.6. Apparently strong downward mixing occurred, eroding a small section of the pycnocline and causing the upwelling of alkalinity. At the same time, a certain amount of H_2S must have been released, an event which we think caused the death of most red algae at depth prior to our visit in 1993.

3 Outlook

The lake is therefore one of the most interesting „paleooceanographic laboratories“ presently known. Its microbialites remind of similar marine microfossils occurring in

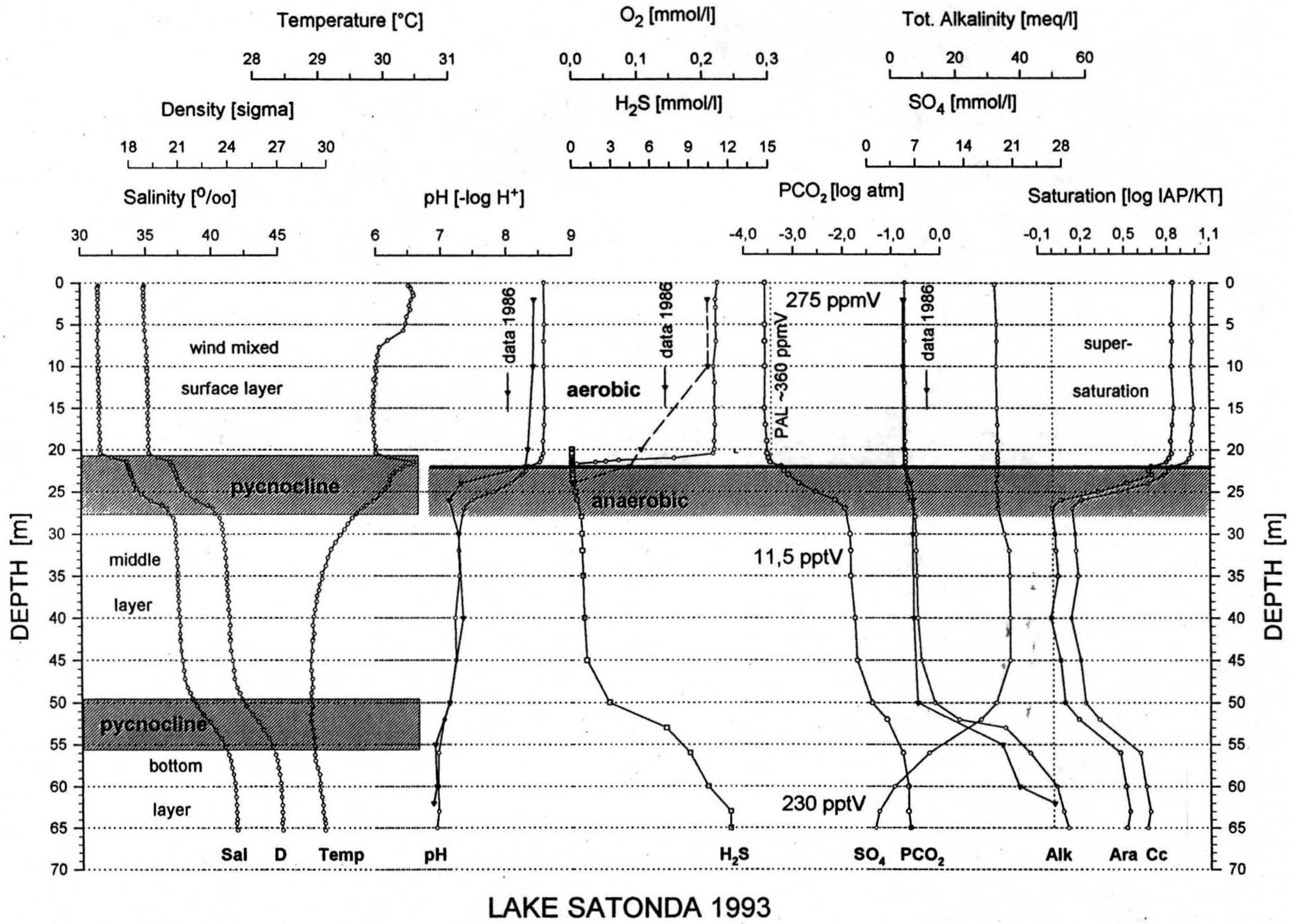

Fig. 4: Vertical structure of the water column in Lake Satonda. Data was collected during the 1993 survey of Satonda Island. Units: Salinity in parts per thousand (measured by salinometer and CTD-sensor); density in sigma units (difference from 1 g/cm^3 x 1000) (calculated from salinity and temperature); temperature in degree Celsius (measured by CTD sensor); pH (measured immediately after sample recovery); oxygen in mmol/l (measured by Winkler titration in the field); H_2S in mmol/l (measured by titration in the field); CO_2 pressure in log of parts per volume (calculated from pH, temp. and total ion concentrations by PHREEQE); total alkalinity in meq/l (measured by titration in the field); sulfate in mmol/l (measured by ion chromatography on preserved samples); saturation index of calcite and aragonite (calculated with PHREEQE). Note the separation of the water column by two high density gradients (pycnoclines), which prevent mixing of the water column. Below 22 m the water column is anaerobic with very high concentrations of H_2S and free CO_2 in the bottom layer but only moderate concentrations in the middle layer. Calcite is supersaturated throughout the water column, while aragonite is slightly undersaturated in the middle layer. Both are much higher supersaturated in the surface layer than in the open ocean.

the Precambrian and during events noticed in the younger, Phanerozoic sedimentary record. These events are often associated with ecosystem collapse (species-poor biota), mass appearance of calcareous microbialites, and often with the prolific occurrence of sponges, a feature which also fits for Satonda.

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