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Low-latitude accumulation of the surf-zone diatoms *Anaulus australis* Drebes & Schulz and *Asterionellopsis glacialis* (Castracane) Round species complex in the eastern coast of Brazil

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High concentrations of diatom cells (high primary production) had been observed in numerous exposed sand beaches at temperate and hot-temperate latitudes (CAMPBELL; BATE, 1988; ODEBRECHT et al., 2010). These results disagree with the idea that those regions are dominated by heterotrophic organisms (BROWN; MCLACHLAN, 1990). Several surf zones in sand beaches worldwide have persistent and visible dark-brown patches that result from the accumulation of diatom cells, generally from one or two diatom species (ROMER; MCLACHLAN, 1986; TALBOT et al., 1990). Only seven species have previously been linked to this phenomenon, including *Anaulus australis* Drebes & Schulz, *Asterionellopsis glacialis* (Castracane) Round (but see revised species complex in KACZMARSKA et al., 2014) *Asterionellopsis socialis* (Lewin & Noris) Crawford & Gardner, *Attheya armata* (West) Crawford, *Aulacodiscus johsonii* Arnott, *Aulacodiscus kittonii* Arnott and *Aulacodiscus petersii* Ehrenberg (ODEBRECHT et al., 2014).

Previous studies (LEWIN; SCHAEFER, 1983; LEWIN et al., 1989) have indicated that this phenomenon is natural and does not result from water pollution or any other anthropogenic cause (BATE; MCLACHLAN, 1987). These patches are formed from the accumulation of cells in the surface foam, which results from the abilities of these diatoms to rise to the surface. Once on the surface, these diatoms can be trapped in air bubbles that are formed when waves break (LEWIN; SCHAEFER, 1983). Beach topography, minimal length, hydrology, wind direction, wind speed, nutrient supply and rainfall are important for the accumulation of these diatoms (LEWIN; SCHAEFER, 1983; TALBOT et al., 1990). Surf diatom accumulations have been reported in 15 countries in about 90 sandy beaches located at latitudes between 47°55’N and 42°10’S (CAMPBELL, 1996; ODEBRECHT et al., 2014). Records for the South American Atlantic coast extend from Ceará (Brazil, 3°44’S) to Peuhen-Co (Argentina, 39°S) (ODEBRECHT et al., 2014).

Dark-brown patches have been observed by fishermen along the Brazilian eastern coast for more than 30 years and are regionally known as “slime”. Despite their odd appearance, fishermen have reported that certain fish species are attracted to these patches, especially mullet (*Mugil* spp.). Thus, fishermen frequently fish in these areas. The aim of this work was to study the occurrence of patches caused by the accumulation of diatoms in the surf zones in Ilhéus, eastern coast of Brazil and the possible factors that condition their presence.

The study area is the Municipality of Ilhéus, State of Bahia, eastern Brazilian coast. It extends from Sargi Beach to the Acuípe River, an approximately 67 km long coastline of exposed sandy beaches (Figure 1). The estuaries formed by Almada River and Cachoeira River are important components of this landscape. The Cururupe River is subjected to low-scale exploitation for tourism, with cottages and hotels at its mouth. Prior to 2003, a waste disposal unit operated 1 km upstream in the margins of this river, which potentially resulted in some environmental disturbance (ALVES; SOUZA, 2005).

The annual rainfall in this region is always greater than 1,900 mm, with an annual average of 2,000 mm. September and October are the driest months of the year and March and April are the wettest (BAHIA, 2001). Various physical forcing mechanisms (e.g., wind, continental water inflow and ocean interaction) affect the dynamics in water mass and sediment circulation over the continental shelf. Atmospheric circulation throughout the

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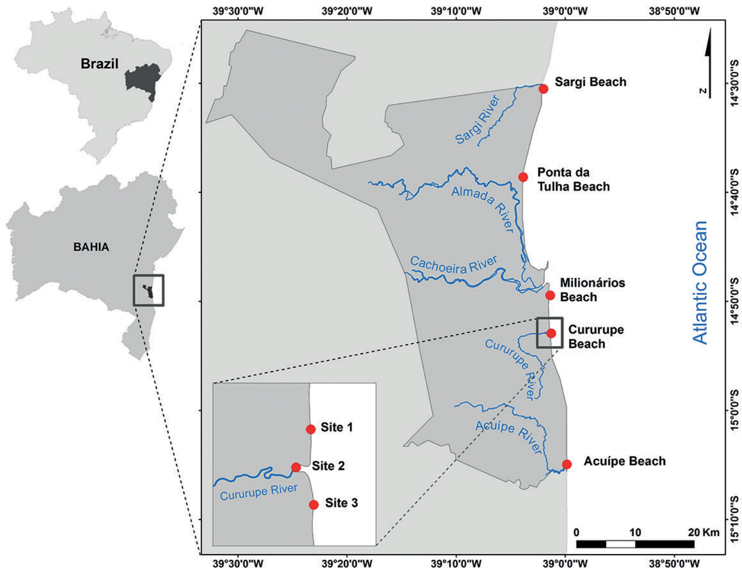

Figure 1. Map of study area with sampling points.

year mainly consists of northeastern and eastern winds during the spring-summer and southeastern and eastern during autumn-winter, altered by the inflow of cold fronts with winds from the southern and southeastern quadrant (BITTENCOURT et al., 2000). This circulation system is responsible for the general pattern of wave fronts reaching the coastline and the sediment dispersion along the coast of Bahia (DOMINGUEZ et al., 1992).

Sampling was conducted biweekly at Cururupe Beach between December 03, 2004 and August 18, 2005, to determine the factors that may be associated with the occurrence of the surf-diatom patches. Surf-zone surface water samples were collected with a bucket at three stations (Figure 1). Air temperature, rainfall, and wind velocity/direction were considered for the sampling date and the two preceding days. These data were provided by the weather station of Ilhéus Airport (INFRAERO, at *ca*. 7 km from the sampling points). Salinity (optical refractometer) and temperature (mercury-in-glass thermometer) of the water were measured *in situ*. To determine the dissolved inorganic nutrient concentrations, water samples were collected, filtered through a Whatman GF/F fiberglass filter, and analysed according to the methods of STRICKLAND; PARSONS (1972) for nitrate, GRASSHOF et al. (1983) for nitrite, SOLÓRZANO (1969) for ammonium, KOROLEFF (1983a) for phosphate and KOROLEFF (1983b) for silicate. Chlorophyll-*a* and phaeopigments were estimated with the fluorometric method according to LORENZEN (1967). Phytoplankton quantitative analysis was performed with an inverted microscope (UTERMÖHL, 1958) on water samples preserved with a neutral formaldehyde solution (0.4% final concentration). Net samples (20 µm mesh) were also sampled for qualitative analysis of the microplankton. Diatom identification followed classical and modern revisions. *Asterionellopsis glacialis* was identified as a species complex based on recent taxonomic revision, which showed there are at least five cryptic species into this group (KACZMARSKA et al., 2014).

Occasionally, dark patches were sampled to verify the extent of this phenomenon and to determine the species involved in the formation of the patches. These samples were collected along the Ilhéus coast by the local community (i.e., fishermen and the beachfront bar owners that observed the sea daily). Simple collection "kits" were distributed containing 125 mL bottles with formaldehyde neutralized to 4% final concentration and a plastic cup to collect the surface water on the dark patches. Samples were periodically sent to the laboratory for qualitative and quantitative analysis (UTERMÖHL, 1958).

Principal Component Analysis (PCA) was performed on a matrix of environmental data to identify trends and highlight the possible relationships between the environmental data and phytoplankton biomass (chlorophyll-*a*). This analysis was performed with Statistical Package for the Social Sciences (SPSS) software and PCA with Multivariate Statistical Package (MVSP). Grouping based on species data was performed by a two-way cluster analysis, using Bray-Curtis distance and taxa with frequency of occurrence higher than 15% in the dataset. This analysis was performed in PC-ORD 6 program.

During this study, hydrologic conditions in the Cururupe beach showed considerable oscillations, especially for temperature (24–30°C; mean=27.55±1.65°C) and salinity (24–37; mean=33.77±2.39). The reduced water column in the surf zone made this environment more susceptible to variations. Lower water temperatures during winter (mean=25.89±1.08°C) resulted from the greater inflow of cold fronts. Lower salinity values in station 2 during the summer (mean=31.17±4.12) were associated to the freshwater inflow from the Cururupe River.

We detected a high oscillation in the concentrations of nitrate (below detection to 1.13 mg/L; mean=0.20±0.26µg/L), nitrite (below detection to 0.26 µg/L; mean=0.05±0.07 µg/L), ammonium (0.18–4.56 µg/L; mean=0.18±4.56 µg/L), silicate (0.21–45.38 µg/L; mean=7.41±7.04 µg/L) and phosphate (below detection to 0.38 µg/L; mean=0.18±0.10 µg/L). These concentrations are considerably lower relative to the values recorded in exposed sandy beaches around the world (e.g., GAYOSO; MUGLIA, 1991; MCLACHLAN; LEWIN, 1981; ODEBRECHT et al., 2010; RÖRIG et al., 2006) and likely reflected the influence of the oligotrophic tropical water of the Brazil Current in this region.

Chlorophyll-*a* concentrations (1.54–106.5 µg/L; mean=16.25±22.77 µg/L), phaeopigment (below the detection to 88.78 µg/L; mean=10.88±19.66 µg/L) and the relative contribution of phaeopigments to total chlorophyll (22–100%; mean=48%) showed high variability in Cururupe beach. In spite of the variations of chlorophyll-*a*, the mean concentration in this study was lower than those observed in the Brazilian southern beaches: Cassino beach, state of Rio Grande do Sul, with 36.1 µg/L (ODEBRECHT et al., 2010) and 50.2 µg/L (RÖRIG; GARCIA, 2003); Navegantes beach, state of Santa Catarina, with 11,080.21 µg/L (RÖRIG et al., 1997).

The PCA results from the environmental variables explained 50.73% of the total variance (Figure 2). The first axis was linked to the climatic variables in the region and its influence on the local hydrology. In general, samples located at the negative side of axis I (especially the lower, left quadrant) were related to the high hydrodynamic periods, linked to intense S-SE winds, while units located on the positive side were related to warmer and calm periods, when the influence of the Cururupe River water plume was more noticeable. The second axis was potentially associated with the autotrophic biomass, in which the most of samples with dark patches were plotted in the positive side.

As strong southern and southeastern winds revolve the bottom sediment and resuspend nutrients in the water column, chlorophyll-*a* and nutrient contents increased during cold fronts and decreased during calm periods. In Cururupe beach, low coastal hydrodynamism due to weak winds favoured a high riverine inflow on the surf-zone and higher concentrations of silicate were associated with rainfall (Figure 2). Another relevant aspect is the presence of “spillways” along of Ilhéus coast. These waterways impact the flow of continental waters and part of the coastal rain drainage. Little is known about the pattern of drainage, morphodynamic behavior, spatial distribution and the influence on the balance of sedimentary spillways. Nevertheless, its has been recognized as an erosive agent, carrying and setting down on the coastal system (SILVA et al., 2003) and the rainfall rates may represent an important factor on nutrient input from the spillways.

In Cururupe beach, dark patches were observed five times in the surf-zone, which corresponded to 28% of the samples. *A. glacialis* species complex and/or *A. australis* cell were numerically dominant (10^4–10^6 cells/L) at 44% of the samples, but patches were not evident. The highest densities of *A. glacialis* species complex (6.72 x 10^7 cells/L) and *A. australis* (2.2 x 10^7 cells/L) were observed at site 1 on August 18, 2005. The highest chlorophyll-*a* concentrations were recorded between April and August, which corresponded to the peak of phytoplankton abundance (Figure 3). Peaks of phaeopigments corresponded to the highest cell concentrations of *A. glacialis* species complex.

The total number of phytoplankton cells ranged from 2.1 x 10^5 (December 17, 2004 – site 1) to 9.54 x 10^7 cells/L (August 18, 2005 – site 1). Microphytoplankton (20–200 mm long) showed greater variability and was more abundant during periods of patch formation. Diatoms contributed to 82% of the total microphytoplankton, dominated by *A. australis* and *A. glacialis* species complex, while the nanoplanktonic fraction (2–20 µm long) was dominated by coccolithophores (43%), other flagellates (33%), diatoms (23%) and dinoflagellates (1%). In general, the phytoplankton was numerically dominated by nanoplankton in Cururupe beach. It is widely assumed that oligotrophic conditions, such as those recorded at Cururupe beach, favour small-sized cells that perform

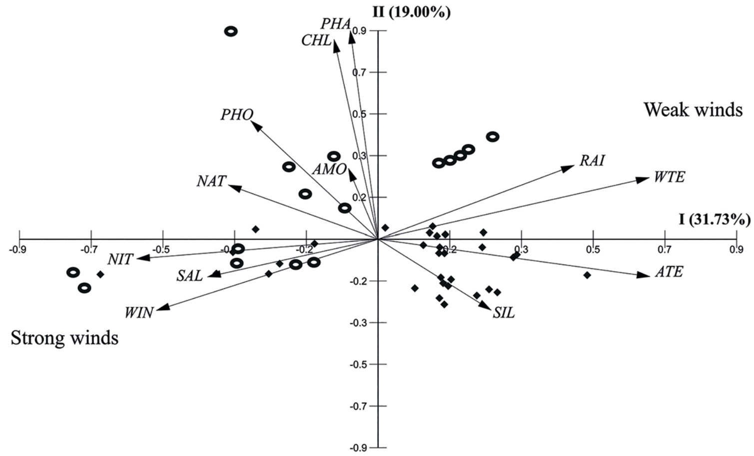

Figure 2. Principal components analysis: position of the samples in the factorial plan I-II according to environmental variables. AMO: ammonium, ATE: air temperature, CHL: chlorophyll, RAI: rainfall, NAT: nitrate, NIT: nitrite, PHA: phaeopigments, PHO: phosphate, SAL: salinity, SIL: silicate, WIN: wind intensity and WTE: water temperature. The large circles represent the samples with the occurrence of visible patches.

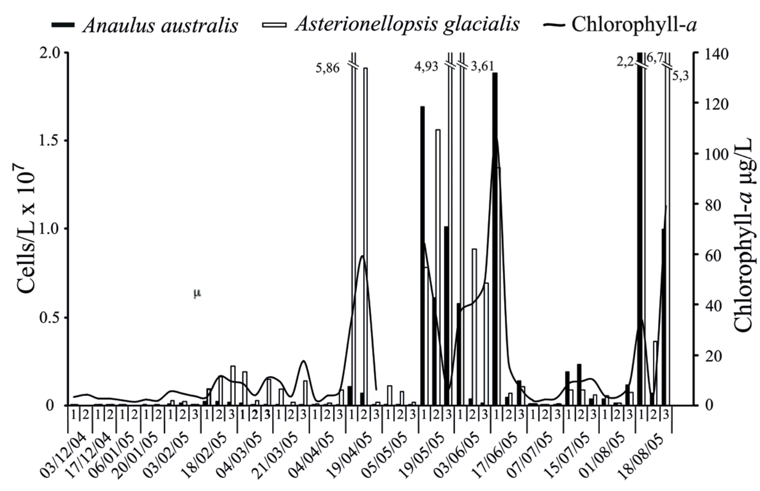

Figure 3. *Anaulus australis* and *Asterionellopsis glacialis* species complex cell number and Chlorophyll a variation during the biweekly sampling in Cururupe beach.

high reproduction rates (MARAÑÓN, 2015). Under the high hydrodynamism conditions of the surf-zone (due to the passing of cold fronts), this study indicated that episodes of high microplankton peaks mainly resulted from increased diatom cell concentrations of *A. australis* and *A. glacialis* species complex.

The total of 154 microplankton taxa was identified in the net samples, including 109 diatoms, 23 tintinnids, 20 dinoflagellates and 2 cyanobacteria. The two-way cluster analysis showed a clear group of units sampled at turbulent periods (strong winds) at 46.1% of information remaining (Figure 4). This group was associated with ticoplanktonic or benthic species, such as *A. australis*, *A. glacialis* species complex, *Campylosira cymbelliformis* (A.Schmidt) Grunow ex Van Heurck, *Cerataulus turgidus* (Ehrenberg) Ehrenberg, *Bellerochea malleus* (Brightwell) Van Heurck, and *Thalassionema nitzschioides* (Grunow) Mereschkowsky. Into this group, visible dark patches were grouped at 65.5% of information remaining, which are closely related to *A. glacialis* species complex and *A. australis* abundance.

In ten dark patches analysed along the Ilhéus coast, *A. glacialis* species complex and *A. australis* were present in all of them, with alternating dominance (Table 1). The

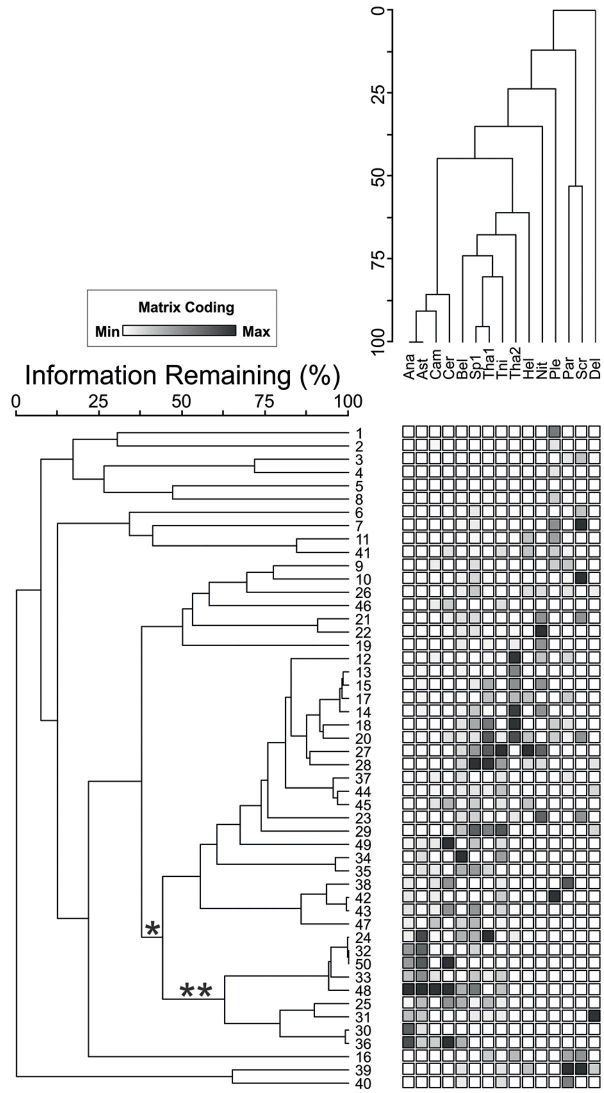

Figure 4. Dendrogram derived from two-way cluster analysis of the phytoplankton data in Cururupe beach. Only the taxa that were present in more than 15% of the samples were considered. ANA=*Anaulus australis,* AST=*Asterionellopsis glacialis* species complex, BEL=*Bellerochea malleus*, CAM=*Campylosira cymbeliformis*, CER=*Cerataulus turgidus*, DEL=*Delphineis* sp., HEL=*Helicotheca tamesis*, NIT=*Nitzschia longissima*, PAR=*Paralia sulcata*, PLE=*Pleurosigma* sp., SCR=*Scrippsiella* sp., SP1=unidentified centric diatom, THA1=*Thalassiosira* sp. 1, THA2=*Thalassiosira* sp. 2 and TNI=*Thalassionema nitzschioides*. * indicates the group of samples under influence of strong winds. ** indicates the subgroup with visible patches.

total number of cells for these two species in the patches ranged from 3.2 x 10^7 (May 18) to 2.6 x 10^9 cells/L (April 24). The minimum cell concentrations for *A. glacialis* species complex (1.8 x 10^9 cells/L) and *A. australis* (7.8 x 10^8 cells/L) were also observed on April 24, 2003.

The frequent occurrence of *A. glacialis* species complex*, Thalassionema nitzschioides* and *Pseudo-nitzschia* spp. was verified as a characteristic of the phytoplankton community in the surf-zone at Pontal do Sul beach in the State of Paraná, southern Brazil (REZENDE; BRANDINI, 1997) and at the sandy beaches on the coast of São Paulo, southeastern

Table 1. Percentage of *Anaulus australis* and *Asterionellopsis glacialis* species complex collected in visible patches along the coast of Ilhéus.

Local	Date	*Anaulus australis* (%)	*Asterionellopsis glacialis* (%)
Sargi Beach*	24.04.03	66	34
Milionários Beach*	24.04.03	30	70
Milionários Beach*	18.05.03	12	88
Milionários Beach*	26.06.03	1	99
Cururupe Beach	19.04.05	2	98
Cururupe Beach	19.05.05	31	69
Cururupe Beach	03.06.05	11	89
Cururupe Beach	17.06.05	58	42
Cururupe Beach	18.08.05	21	79
Ponta da Tulha Beach	12.10.05	99	1

*Samples collected in 2003 during a pilot project.

Brazil (VILLAC; NORONHA, 2008). These diatoms form chains of elongated frustules, which elevate their surface-volume ratio. This process is considered as an important strategy for survival in waters with high hydrodynamism (SMAYDA; REYNOLDS, 2001). VILLAC; NORONHA (2008) observed the dominance or co-dominance tendencies of *A. australis* and *A. glacialis* species complex in surf-zones of exposed beaches. In despite their high concentrations (10^6 cells/L), the formation of patches was not detected. Our results suggest that densities from 3 x 10^7 cells/L become visible to the naked eye.

In southern Brazil, the occurrence of diatom cell patches was mainly associated with the presence of *A. glacialis* species complex. The first recorded patches occurred along Cassino beach, State of Rio Grande do Sul, where dense and frequent accumulations were primarily treated with classic blooms (AGUIAR; CORTE-REAL, 1973; ROSA; AGUIAR, 1973). Later, studies that were more specific were conducted regarding the seasonal patterns of the patches and their associations with precipitation and onshore winds (GIANUCA, 1983; ODEBRECHT et al., 1995). Along Navegantes beach, State of Santa Catarina, RÖRIG et al. (1997) observed the co-occurrence of *A. australis* and *A. glacialis* species complex. This co-occurrence was similar to that observed along beaches in South Africa (TALBOT et al., 1990).

RÖRIG et al. (2006) discussed the role of temperature in the distribution and co-dominance of *A. australis* and *A. glacialis* species complex. They proposed that *A. australis* was dominant at higher temperatures and that *A. glacialis* species complex was dominant at lower temperatures along the Brazilian coast. In addition, these authors proposed that these species were co-dominant in waters of intermediate temperature. In the coast of Ilhéus, which is relatively warm throughout the year, the dominance of either *A. australis* or *A. glacialis* species complex does not seem to be related to temperature. The maximum value that was recorded for *A. glacialis* species complex (1.81 x 10^9 cells/L) in the patches along the coast of Ilhéus was similar to the maximum value that was observed along the beaches of Atlantic South America (1.0 x 10^8 cells/L – ODEBRECHT et al., 2010; 1.30 x 10^8 cells/L – ABREU et al., 2003; 4.40 x 10^8 cells/L – RÖRIG; GARCIA, 2003). The average cell count of *A. glacialis* species complex in the patches of Ilhéus region (7.23 x 10^6 cells/L) was slightly lower than the values that were recorded by RÖRIG; GARCIA (2003) along Cassino beach (2.53 x 10^7 cells/L). In the Navegantes beach surf zone, RÖRIG et al. (1997) recorded the presence of 1.44 x 10^{10} cells/L of *Anaulus* sp. in patches. This value exceeds the maximum value that was observed for this species in this study (7.78 x 10^8 cells/L). However, patches in Ilhéus coast was mixed with high concentrations of *A. glacialis* species complex (1.81 x 10^9 cells/L). High concentrations of phaeopigments observed at same time that high concentrations of *A. glacialis* species complex may be associated to the process of resuspension of debris and organic material of the bottom that are adhered to the cell chains.

Beach morphodynamics, metereological regime and nutrient availability were decisive factors in controlling the formation and maintenance of diatom accumulations in ca. 90 surf zones studied until now (ODEBRECHT et al., 2014). Among these mechanisms, high wind intensity associated with cold fronts and inflow of nutrients from continental drainage appears to be determinant for the occurrence of patches containing *A. glacialis* species complex and *A. australis* in the region of Ilhéus.

The general processes leading to surf diatom accumulations in high-energy beaches are well understood however several questions remain to be answered. Despite the complexity of the Ilhéus coast surf zone environment, some patterns appear as a sudden local interference on the gradual succession of the coastal phytoplankton, being the cold fronts passage the main interference factor.

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